Implementation of Renewable Energy to Reduce Carbon Consumption and Fuel Cell as a Back-up Power for National Broadband Network (NBN) in Australia

By

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Declaration

"I, Kannan Jegathala Krishnan, declare that the PhD thesis entitled "Implementation of Renewable Energy to Reduce Carbon Consumption and Fuel Cell as a Back-up Power for National Broadband Network (NBN) in Australia" is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

Dated: ……………………………………

Signature: ………………………………

Dedicated to my beloved PARENTS and GURU

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List of Abbreviations

AC	Alternating Current
ARENA	Australian Energy Agency
BHK	Bedroom Hall Kitchen
BSC	Base Switching Centre
BTS	Base Transceiver Stations
CE	Cumulative Exposure
CH_4	Methane
COE	Cost of Energy
CO_2	Carbon dioxide
DC	Direct Current
DOE	Department of Energy
ERF	Emission Reduction Fund
HOMER	Hybrid Optimization Model of Electric Renewable
H_2O	Water
IEA	International Energy Agency
K_2CO_3	Potassium Carbonate
LBNS	Lawrence Berkeley National Laboratory
LSS	Load Sharing System
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane Exchange Membrane
MPL	Micro-porous Layer
MSC	Mobile Service Centre

NBN	National Broadband Network
NO_2	Nitrous-Oxide
NREL	National Renewable Energy Laboratory
OECD	Organization of Economic Co-operation and Development
OH & S	Occupation Health and safety
O&M	Operating and Management Cost
PMG	Permanent Magnet Generator
PEMFC	Proton Exchange Membrane Fuel Cell
PSI	Pounds Square Inch
PV	Photovoltaic
RAPS	Remote Area Power System
SBI	Special Background Investigation
SEFCA	Sustainable Energy Fuel Cells Australia
SOFC	Solid Oxide Fuel Cell
SPFC	Solid Polymer Fuel Cell
TL	Transformer Less
TFR	Tampered Failure Rate
UN	United Nations
VAWT	Vertical Axis Wind Turbine
VRLA	Valve Regulated Lead Acid Batteries
WBI	Wind Box Interface

Acknowledgement

I place on **record** my deep sense of gratitude to my parents (KAMALA JOGHEE and KRISHNAN JEGATHHALA LINGAN), my GURU (YOGIN SATHYAMURTHY MAHALINGIAH and GODMOTHER REVATHI SATHYAMURTHY**),** my wife and our daughter (Dr. RADHIGA CHANDRAN and VARTHINI KANNAN) and dedicate my doctoral studies to them.

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Abstract

A reliable power is paramount and loss of power to communication equipment can mean loss of service to clients and loss of millions of dollars to industries. Also, climate is changing; greenhouse gas emissions from human activity are the major cause for global warming.

When called upon, under any contingency and back-up power is required at telecommunication sites, the ideal choice will be diesel generator which requires fuel storage, it produces combustion emissions, it is noisy and the maintenance costs are high. The valve regulated lead-acid battery banks (VRLA) which is prone to self-discharge, needs replacement every 3 years. Also they are bulky, heavy and costly to maintain. New battery technologies, ultra capacitors and flywheels have been employed recently but disadvantage of each technology are significant. P-21 GMBH (Germany), Dantherm Power A/S (Denmark), Plug Power Inc. (USA) and Hydrogenics (Canada) are some of the companies already offering Fuel Cell back-up power by using H_2 bottles and this is expensive to run and requires trucks travelling long distances to several sites carrying H_2 bottles to a rural site, in particular.

Recent collaboration between Victoria University, Sustainable Energy Fuel Cells Australia (SEFCA) and ACTA Energy has resulted in thorough laboratory testing for H_2 generation and data compilation of Fuel Cells in Power Systems Research Laboratory based at Victoria University is discussed in this thesis. The H_2 Generator and Proton Exchange Membrene (PEM) Fuel Cell system generates H_2 on-site and is capable to compete with traditional technologies and can be implemented as a back-up power in telecommunication system where there will be need for reliable back-up power supply.

To avoid the increased costs of delaying action on climate change, cut carbon pollution, drive Australian innovation and to reshape economy the previous Australian Labor Government's Clean Energy Future (which includes - Carbon price, Energy efficiency, Renewable energy and Land usage) and the current Coalition Government's Clean Environment Plan is highlighted in this thesis. This thesis suggests that the use of 4.5kW Wind/Solar micro-generation system is capable to reduce carbon consumptions by implementing it in every independent home in Australia. This thesis examines the energy produced by the Wind/Solar 4.5kW micro-generation system and energy consumed in both a 3 Bedroom Hall Kitchen (BHK) residence in a Melbourne suburb and Building D, Level 5, Footscray Park Campus at Victoria University, and various readings of monthly, weekly, daily and partially curves are recorded at regular intervals.

This thesis also aims to investigate the economic, technical and environmental performance of the micro-generation system which includes, Hydrogen Energy, Fuel Cell Power Generation System and 4.5kW Wind/Solar system under Victorian climatic conditions by using Hybrid Optimization Model for Electric Renewables (HOMER). Finally, this thesis also examines the reliability analysis of a Hydrogen Energy, Fuel Cell power generation system and 4.5kW Wind/Solar system using MATLAB simulation. The benefits of this research are directed towards the Australian National Broadband Network (NBN) where there will be need for a reliable back-up power supply and requires clean energy delivery to remote communities in order to reduce carbon consumptions.

Chapter 1

Introduction

Global warming is presently of a tremendous public interest and has become a threat to every individual. Earth's atmosphere consists of primary greenhouse gases like water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2) and other minor gases that absorb and emit infrared radiations. These radiations keep earth's climate warm and habitable and act like a "blanket" to the earth which is referred as "natural" greenhouse effect" [1.1-1.2].

However, since industrial revolution more greenhouse gas is being emitted into the atmosphere by burning the of fossil fuels and other different sources known as "man-made" greenhouse effect. These greenhouse gases which are emitted from fossil fuels and other different sources trap more heat inside the atmosphere causing the "blanket" of gases around the earth to become thicker and thicker. This causes the earth to warm up slowly by increasing its average temperature near surface-areas and ocean which is referred to as "global warming". Global warming makes the sea level to rise causing several impacts to the environment [1.1-1.2].

Huge quantities of CO_2 are emitted to the atmosphere by burning of fossil fuels to produce electricity in power plants and burning of gasoline in aeroplanes and vehicles. Enormous amount of greenhouse gasses are sent into the air when garbage is burnt in landfills. Cutting down of trees and other plants which collect CO_2 a greenhouse gas which is inhaled and which gives back oxygen (O_2) which is exhaled makes global warming worse [1.3-1.4].

According to the prediction of energy consumption worldwide from both International Energy Agency (IEA) and American Energy Information Administration the energy consumption will continue to increase 2% per year which means energy consumption will be doubled every 35 years. Doubling of energy consumption leads to enormous amount of CO_2 emissions to the atmosphere, by burning of fossil fuels to produce electricity by power plants and burning of gasoline in aeroplanes and vehicles. As a result the greenhouse gases trap more heat and make the earth's temperature to increase further [1.1-1.2].

US has huge H_2 production facilities, H_2 and natural fueling stations, traffic volume and country population data. In Australia the H_2 production facilities, fueling stations are very low compared with US. Thomson ISI Web of knowledge Science Citation Index Expanded database show the number of world science H_2 publications in various fields like H_2 production; H_2 separation; H_2 distribution and storage; H_2 engines; H_2 fuel cells; and facilitating technologies. The bibliometric analysis showed that US produce more than 26% of the world's publications and Australia produced only 1.69% from 1980 to 2006, and has increased to 1.78% more recently and holds 16th place in the world for H_2 publications [1.5]

Now it is time for Australia to switch to Hydrogen Energy, Fuel Cell technology and Hybrid Systems inclusive of Renewable Energy to avoid the impact of global warming [1.1-1.2].

1.1 Benefits of Switching from Fossil Fuels to Hydrogen Energy, Fuel Cell Technology and Hybrid Systems inclusive of Renewable Energy

Hydrogen Energy promises to eliminate the problems created by the fossil fuels. The benefits of switching to Hydrogen Energy are the elimination of pollution and greenhouse gases, the elimination of economic dependence and distributed productions. When the H_2 comes from electrolysis of H_2O and used in Fuel Cell to create power the by-product is only heat and H_2O. The H_2 also adds no greenhouse gases to the atmosphere. As a result the problems caused by fossil fuels like pollution and greenhouse gases are eliminated [1.1-1.2].

If Hydrogen Energy is used for electric power generation in power plants, as fuels in automobiles and industries then we do not have to depend on Middle East and its oil reserves, this means the elimination of economic dependence. H_2 can also be produced anywhere where electricity and H_2O is available and also in homes with relatively simple technology and therefore distributed production is viable in Hydrogen Energy but not in fossil fuels. For instance, consider US which is the largest oil importer in the world which imports 13.5 million barrel per day (mbd) and to about 20.6 mbd is used daily which accounts to about 65% of oil imported. US imports 17% of oil from Middle East and this dependence is still growing. The growing dependence of oil has become a National Security Threat and government believes the country will import 68 % of oil by 2025. US by using fossil fuels it eliminates more pollution and greenhouse gases which leads to environmental impact. Again, it mainly depends upon Middle East for oil; this situation affects the country’s economic health. Presently US requires more creativity and genuine effort, switching towards Hydrogen Energy and Fuel Cell technology and make it viable for distributed production in its home. This applies for most of the countries which depend on fossil fuels to produce electricity in power plants and use as fuel for automobiles and industries [1.1-1.2].

The benefit of switching from fossil fuels to Hydrogen Energy, Fuel Cell technology and Hybrid Systems inclusive of renewable energy reduces the impact of global warming, elimination of pollution caused by fossil fuels and greenhouse gases, economic dependence and distributed production [1.1-1.2].

1.2 List of Publications

Following are publications related to this work:

Journal Publication

1. K. J. Krishnan, A. Kalam and A. Zayegh, "Techo-economic Simulation and Optimization of 4.5kW Wind/Solar Micro-generation System for Victorian Climate," Australian Journal of Electrical and Electronics Engineering (AJEEE)**,** pp., 2013 (Under Review).

2. K. J. Krishnan, A. Kalam and A. Zayegh, "Reliability Analysis of Hydrogen Energy, Fuel Cell Power Generation System and Wind/Solar 4.5kW Micro-generation System with Load Sharing System," JEA Journal of Electrical Engineering (JEA-JEE)**,** pp., 2013 (Under Review).

3. <u>K.J. Krishnan,</u> A. Kalam and A. Zayegh, “H_2 Optimisation and Fuel Cells Application on Electrical Distribution System and its Commercial Viability in Australia,” Heat Transfer Engineering**,** a Taylor and Francis Journal, vol. 35, issue 14-15, pp 1298-1308, 2014.

4. <u>K. J. Krishnan</u>, A. Kalam and A. Zayegh, “Energy Management of 4.5kW Solar/Wind Micro-generation System to CO_2 Emissions in Australia,” International Journal of Environmental Studies (IJES)**,** a Taylor and Francis Journal, pp., ISSN: 0020-7233 (Print), 1029-0400 (Online), 2013 <u>(Accepted with suggested corrections</u>).

5. <u>K. J. Krishnan,</u> A. Kalam and A. Zayegh, “Experimental Investigation of H_2 Generator and PEM Fuel Cell as a Remote-Area Back-Up Power,” Elsevier Journals (Procedia Engineering), Vol. 49, pp. 66-73, 2012.

6. <u>K. J. Krishnan,</u> A. Kalam and A. Zayegh, “Experimental Analysis of H_2 Generator as Back-up Power to Implement for National Broadband Network (NBN) in Australia**,”** Journal of Computing Technologies**,** Vol. 2, No. 1, pp. 1-8, 2012.

7. <u>K. J. Krishnan,</u> A. Kalam and A. Zayegh, “An Experimental Investigation of a Solar/Wind 4kW Micro Generation System and T-1000 1.2kW PEM Fuel Cell**,”** International Journal of Energy Technology and Policy**,** Vol. 8, No. 1, pp. 14-31, 2012.

8. <u>K. J. Krishnan</u> and A. Kalam, “Hydrogen Energy Technology - An Overview Focussing to Equalise the Australian Hydrogen Price with US,” International Journal of Emerging

Technologies and Applications in Engineering Technology and Sciences, pp.41-48, ISSN: 0974-3588; ISBN: 978-81-8465-360-1, 2010.

Refereed Conference Proceedings

1. K. J. Krishnan, A. Kalam and A. Zayegh, “H_2 Optimisation and Fuel Cell as a Back-up Power for Telecommunication Sites,” Proceedings of ICCPCT 2013 –IEEE International Conference on Circuit, Power & Computing Technologies, March 21-22, India, 2013.

2. K. J Krishnan, A. Kalam and A. Zayegh, “Experimental Analysis of Solar/Wind 4 KW Micro-generation System to Reduce Carbon Tax in Australia,” Proceedings of SASG 2012- Saudi Arabia Smart Grid, December 8-11, Saudi Arabia, 2012.

3. K. J. Krishnan, A. Kalam and A. Zayegh, “Experimental Investigation of H_2 Generator and PEM Fuel Cell as a Remote-Area Back-Up Power,” Proceedings of ECOGEN 2012 - The International Clean Energy Conference, September 17 - 19, Sydney, Australia, 2012.

4. R. Mohammed, K. J. Krishnan, A. Kalam and A. Zayegh, “Reliability Analysis of T-1000 1.2kW PEMFC Power Generation System with Load-Sharing using MATLAB,” Proceedings of the International Conference on Renewable Energy Utilization, paper number RES- 017, January 4-6, Coimbatore, India, 2012.

5. K. J. Krishnan, R. Mohammed, M. Rostamlou, A. Kalam and A. Zayegh, “Reliability Analysis of a Solar/Wind 4kW Micro Generation System with Load Sharing using

MATLAB," Proceedings of the International Conference on Renewable Energy Utilization, paper number RES- 108, January 4-6, Coimbatore, India, 2012.

6. K. J. Krishnan, A. Kalam and A. Zayegh, "Experimental Analysis of T-1000 1.2kW PEMFC Power Generation System to Implement for National Broadband Network (NBN) in Australia," Proceedings of the International Conference on Renewable Energy Utilization, paper number RES-098, January 4-6, Coimbatore, India, 2012.

7. K. J. Krishnan, A. Kalam and A. Zayegh, "Smart Electrical Power Grid is the Future for Australia," Proceedings of the International Conference on Renewable Energy Utilization; paper number SG-010, January 4-6, Coimbatore, India, 2012.

8. K. J. Krishnan, A. Kalam and A. Zayegh, "Fuel Cells Application on Electrical Distribution System and its Commercial Viability in Australia**,"** Proceedings of the International Conference on Thermal Energy and Environment, paper number EMR 129, March 24 – 26, Madurai, India, 2011.

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13. K. J. Krishnan, A. Kalam and A. Zayegh, "Carbon Sequestration and Hydrogen Energy - A Comparative Study to Eradicate Global Warming Impacts**,"** Proceedings of the National Conference on Electrical Systems and Renewable Energy, March 18, Trichy, India, vol., no., and pp.244-249, 2011.

14. K. J. Krishnan and A. Kalam, "Man-made Greenhouse Gases Trigger Unified Force to Start Global Warming Impacts Referred to as "Climate Change", Proceedings of the International Conference on Power Generation Systems and Renewable Energy Technology (PGSRET), November 28 – December 2, Islamabad, Pakistan, and pp.378-385, 2010. ISBN: 978-969-9635-00-7.

15. K. J. Krishnan, J. Claveria, L. Varadharajan and A. Kalam, "Experimental and Computational Analysis of a 1.2kW PEMFC Designed for Communications Backup Power Applications," Proceedings of the International Conference on Power Generation Systems and Renewable Energy Technology, November 28 – December 2, Islamabad, Pakistan, pp.343-350, 2010. ISBN: 978-969-9635-00-7.

16. K. J. Krishnan and A. Kalam, "Unified Force and its relation with Global Warming Crave for Hydrogen Energy and Promote Fuel Cell Technology," Proceedings of the International Conference on Power Generation Systems and Renewable Energy Technology (PGSRET), November 28 – December 2, Islamabad, Pakistan, pp.184-190, 2010. ISBN: 978-969-9635-00-7.

Refereed Poster Presentations

1. K. J. Krishnan and A. Kalam, Poster Presentation. "Unified Force and its relation with Global Warming Crave for Hydrogen Energy and Promote Fuel Cell Technology," Australian Institute of Energy-Postgraduate Student Energy Awards. Melbourne, Victoria, Australia. 6/10/2010 & 7/10/2010.

2. K. J. Krishnan, A. Kalam and A. Zayegh, 3MT Presentation. "H_2 Optimization & Fuel Cells Application on Electrical Distribution System and its Commercial Viability in

Australia," 2011 FoHES Postgraduate Research Conference (2011 FoHES PRC), Melbourne, Australia. 20/07/2011.

3. K. J. Krishnan and A. Kalam, Poster Presentation. "Implementation of Renewable Energy to Reduce Carbon Tax in Australia and Fuel Cell as a Back-up Power for National Broadband Network (NBN) in Australia," Australian Institute of Energy-Postgraduate Student Energy Awards. Melbourne, Victoria, Australia. 10/10/2012 & 11/10/2012.

1.3 Original Work

A summary of the original work presented in this thesis is as follows:

1. To verify the behaviour, reliability and long run capabilities of EL100 H_2 generator and T-1000 PEM Fuel Cell when called upon for back-up power in telecommunication sites like NBN.

2. To determine whether a completely off-grid, stand alone solution be reliably deployed combining Solar and H_2?

3. The industry claims a H_2 purity of 99.95%, to ascertain that this is correct.

4. From Valve Regulated Lead Acid (VRLA) batteries of 48V, 120A to verify how much H_2 can be produced.

5. To find out whether a system be setup to produce H_2 at the same time it is using it for power.

6. To experimentally determine how long it will take to produce enough H_2 to run 1.2kW T-1000 PEM Fuel Cell for 1, 4 and 8 hours.

7. To run both EL100 H_2 generator and T-1000 PEM Fuel Cell system simultaneously to meet the required 8 hours back-up power for telecommunications site at desired load of 1kW.

8. To examine the energy produced from 4.5kW Wind/Solar micro-generation system to reduce CO_2 emissions for an independent home application in Australia.

9. To manage techo-economic Simulation and Optimization of 4.5kW Wind/Solar Micro-generation System under Victorian Climate.

10. To conduct reliability Analysis of Hydrogen Energy, Fuel Cell Power Generation System and 4.5kW Wind/Solar micro-generation system with Load Sharing System.

1.4 Organization of this Thesis

This thesis comprises eight chapters. Organization of the remaining seven chapters is presented as follows:

Chapter 2 presents number of past efforts related to the current work. It presents literature review about the problems of conventional energy technologies and advantages of renewable energy for electricity generation. H_2 Energy and Fuel Cell technology to implement as a back-up power for National Broadband Network (NBN) is discussed. Hybrid system inclusive of renewable energy to reduce Carbon Tax in Australia, simulation and optimization of hybrid systems inclusive of renewable energy and also reliability analysis of H_2 Energy, Fuel Cell technology and 4.5kW Wind/Solar micro-generation system is introduced in Chapter 2 and are examined in detail in the subsequent Chapters.

The work in Chapters 3 and 4 are examined to produce H_2 on-site by rain H_2O and to run T-1000 PEM Fuel Cell system for long run capabilities (8 hours) at 1kW to meet back-up power for telecommunication site and also can have satisfactory usage in Australian NBN. Chapters 3 and 4 mainly focus on planning of laboratory testing and evaluation of EL100 H_2 generator and T-1000 PEM Fuel Cell. Analysis and evaluation of the laboratory results are examined addressing some of the research questions and are presented in both the Chapters 3 and 4. Chapter 3 points out the vision, strategy and government initiatives of NBN in Australia and Fuel Cell technology. EL100 H_2 generator and T-1000 PEM Fuel Cell, its advantages and description of the system installed are explained in Chapters 3 and 4.

The experimental analysis of 4.5kW Wind/Solar micro-generation system to reduce carbon tax or emission trading scheme in Australia, simulation and optimization of 4.5kW Wind/Solar micro-generation system for the load profile obtained from the Facilities Department, Victoria University, are examined in Chapters 5 and 6.

The Australian Government's Plan for Clean Energy Future or Clean Environment Plan, the Power Systems Research Laboratory's guideline for 4.5kW Wind/Solar micro-generation system and the monitoring and data transmission are explained in Chapter 5. Energy produced by the Solar/Wind 4.5kW micro-generation system, the energy consumed in Building D, Level 5, Victoria University and the energy consumption of a 3 Bedroom Hall Kitchen Residence in Melbourne are examined in Chapter 5. The repeal of the carbon tax or emission trading scheme and the introduction of the Direct Action Plan and trouble-shooting of 3kW Vertical Axis Wind Turbine (VAWT) are discussed in Chapter 5. The work in Chapter 6 aims to investigate the economic, technical and environmental performance of the implemented 4.5kW Wind/Solar micro-generation under Victoria (Australia) climatic conditions. The 4.5kW Wind/Solar micro-generation is simulated and optimized by Hybrid Optimization Model for Electric renewable (HOMER) and the economic, technical and environmental results are presented in Chapter 6.

Chapter 7 provides the limitations of different modelling concepts of Load Sharing Systems (LSS). The reliability of LSS for Hydrogen Energy, Fuel Cell Power Generation System and 4.5kW Wind/Solar micro-generation system focussing on 'k-out-of-n' system with exponential distributions using MATLAB simulation is presented in this Chapter. Chapter 8 summarizes the work as well as presents future directions.

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[1.1] K. J. Krishnan, A. Kalam, “Man-made Greenhouse Gases Trigger Unified Force to Start Global Warming Impacts Referred to as “Climate Change”, Proceedings of the International Conference on Power Generation Systems and Renewable Energy Technology (PGSRET), November 28 – December 2, Islamabad, Pakistan, pp.343-350, 2010. ISBN: 978-969-9635-00-7

[1.2] K. J. Krishnan, A. Kalam, “Unified Force and its relation with Global Warming Crave for Hydrogen Energy and Promote Fuel Cell Technology,” Proceedings of the International Conference on Power Generation Systems and Renewable Energy Technology (PGSRET), November 28 – December 2, Islamabad, Pakistan, pp.184-190, 2010. ISBN: 978-969-9635-00-7

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Chapter 2

Literature Review

2.1 Introduction

The demand for energy continues to rise exponentially due to the development process and increase in population in Australia. In the past energy was cheap, systems utilising technologies like cogeneration could not compete directly with traditional form of electricity generation, on economic grounds. However, with restructuring in the electricity supply industries in many of the industrialised countries and constrained put on them through international agencies to reduce consumption of fossil fuels and CO_2 production, technologies like cogeneration will be used more widely [2.1].

The need for bringing about efficiency in the usage of non commercial fuels such as firewood and agricultural residues is important, while at the same time, renewable sources of energy such as sun; wind and wave potential have to be harnessed for meeting the increasing demand of energy in the rural areas. Renewable sources of energy being decentralised in nature, are cost effective in modular form and help cut transmission/ transportation cost [2.2-2.5]. Due to the seasonal variation of the wind and solar energy, Hydrogen (H_2) storage is required. In hybrid system inclusive of renewable energy excess of solar and wind energy can be used to produce H_2

by water electrolysis. The H_2 storage sub-system comprising an electrolyser, a hydrogen storage tank and a Fuel Cell, is an integral part of a hybrid systems inclusive of renewable energy for back-up power for telecommunication sites and also supplying power to the household. To supply electricity to the load during low wind speed or low solar insolation the stored H_2 can be used in the Fuel Cell. The produced H_2 can be stored for a long period of time and the main advantage of such a system is that it has zero emissions, when the system is in operation and low maintenance [2.6].

Technological development and mass production of key components like (Solar panels, Wind turbines, Electrolysers, Fuel Cells and H_2 storage facilities), the cost of hybrid system inclusive of renewable energy can be reduced. Hence such systems for remote applications promise to achieve significant market penetration in the near future. One area where H_2 and Fuel Cells are set to make a big impact is in the area of cogeneration [2.6].

Researches and Scientists with Special Background Investigation (SBI) estimated that the Fuel Cell market grew from $353 million to $478 million from the year 2005 to 2009. Analysts with SBI also predicted by 2014 the annual growth rate of Fuel Cell market will increase by 20% [2.7].

Section 2.2 of the chapter looks at the problems of the conventional energy technologies in generating electricity by both fossil and nuclear fuels. Section 2.3 explains the advantages of renewable energy for the generation of electricity. Back-up power for National Broadband Network (NBN) in Australia is highlighted in Section 2.4 and factors seeking Hydrogen Energy and Fuel Cell technology to eradicate environmental disasters like production losses due to power outages, carbon sequestration etc. are pointed out in Section 2.5.

H_2 production pathways using various energy sources including renewable and non-renewable, hydrogen safety and barriers of hydrogen energy are highlighted in Section 2.6. Section 2.7 discusses Fuel Cells application on electrical distribution system, different type of Fuel Cells and the recommended methods and experimental design for optimal energy planning in Australia is discussed in Section 2.8.

Section 2.9 explains the hybrid system inclusive of renewable energy to reduce carbon or emission trading tax in Australia and the benefits like economic, environmental and social benefits of are discussed in section 2.10. Simulation and Optimization of hybrid systems inclusive of renewable energy is discussed in Section 2.11. Section 2.12 highlights the reliability analysis and summary of the Chapter is pointed out in Section 2.13.

2.2 Conventional Energy

Currently, the majority of the world electricity is generated by fossil fuels, nuclear power and hydropower. However, due to the following problems/concerns encountered in using conventional energy technologies, the renewable energy sources plays important roles in electricity generation and sooner or later, today's alternatives will become tomorrow's main sources for electricity [2.8].

2.2.1 Conventional energy sources are not renewable

Both the fossil fuels (coal, oil and natural gas) and nuclear fuels are not renewable. The reserves of these fuels will run out some day in the future. A long term energy development strategy is therefore important for sustainable and continuous economy growth [2.8].

2.2.2 Conventional generation technologies are not environmentally friendly

The use of conventional technology to produce electrical power normally results in pollution that affects everyone. It often relies on the burning of fossil fuels that produce dangerous gases that often end up in the atmosphere. People and animals breathe in the polluted air and plants absorb the pollution [1.8]. The radioactive waste of nuclear power plants has always been a big concern to the environment. The dam and reservoirs of hydropower can be disruptive to surrounding aquatic ecosystems [2.9].

2.2.3 The cost of using fossil and nuclear fuels will go higher and higher

Since the conventional fuel sources are not renewable and while the world energy demand is rapidly increasing, it is obvious that the price of these fuels will go higher. Taking the world crude oil price for example, the price has been increased by 45% within two years from $35.16 per barrel in July 2005 to $63.92 per barrel in May 2007. Compared to natural gas and petroleum, coal is cheap for electricity generation. However, if the cost for reducing emissions is taken into account, the actual price of generating electricity from coal would be much higher.

The growing cost of using conventional technologies will make alternative power generation more competitive and will justify the switchover from conventional to alternative ways for electric power generation [2.10].

2.3 Renewable Energy

On the other hand, compared to conventional electricity generation technologies, renewable power has the following advantages:

2.3.1 Future prospects for the poor population

Electricity generated from renewable energies lie in its decentralised use. Here, the benefits of renewable truly come to bear. Particularly in poor rural areas where it would be uneconomical to set up electricity network, renewable energy can offer new prospects to the rural population and thus make a valuable contribution to the fight against poverty. Renewable energies can help many developing countries to reduce their dependency on fossil fuel import and the financial stress caused by price fluctuations on the world market [2.11].

2.3.2 Renewable energy resources are not only renewable, but are also available in abundance

One major advantage with the use of renewable energy is that it is renewable. It is therefore sustainable and so will never run out. For example, 70% of solar energy from the sun approximately amounts to 3.8 million exajoules (EJ), which is more than 10,000 times the rate of consumption of fossil and nuclear fuels, that was 370 EJ in 2002 [2.12].

2.3.3 Renewable energy is environmentally friendly

From this energy system, renewable energy produces little or no waste products such as carbon dioxide or other chemical pollutants, so it has minimal impact on the environment [2.13]. In general, due to the ever increasing energy consumption, the rising public awareness for environmental protection, the exhausting density of fossil-fuel, and the intensive political and social concerns upon the nuclear power safety, alternative power generation systems have attracted continued interest.

2.4 Back-up Power for National Broadband Network (NBN) in Australia

Greater digital economy can boost Australia's productivity, global competitiveness and improved social well-being. The Australian government's aim is that, by 2020 to build the enabling infrastructure for the digital economy, in particular the commitment to build the National Broadband Network (NBN) [2.14].

Digital communities, broadband for seniors, smart grid, smart city, sustainable Australia-managed motorways, telework forum, telehealth trails are some of the government initiatives to advance the digital economy goals. Since NBN will be rolling out several hundred points of presence (POP's) there will be need for reliable back-up power supply. The use of H_2 Generator and Fuel Cell is capable to compete with traditional technologies to offer back-up power by producing H_2 on-site and can be implemented as a back-up power in telecommunication systems and in the recent layout of NBN [2.14].

Reliability, long service life, outdoor operation capability, compact design, minimum maintenance, reduced environmental impact compared to current technologies are some of the advantages of using Hydrogen Energy and Fuel Cell solutions for emergency power supplies [2.14].

2.5 Factors Seeking Hydrogen Energy & Fuel Cell Technology to Eradicate Environmental Disasters

Large quantities of greenhouse gases are released into the atmosphere via both natural and human activities. The greenhouse gases which are emitted from different sources like transportation, industry, power plants, residential, agriculture and land use are as shown in Figure 2.1 trap more heat inside the atmosphere and warming the earth by increasing its average temperature near the surface-areas and ocean which is referred to as ‘global warming’. Renewable energy and Nuclear from all sources accounts for only about 8% and 6% of global energy production. The major cause for global climate changes about 86% of global energy are coming from fossil fuels are as shown in Figure 2.2. The fastest growing energy source is coal and provides more than 1/4th of the world’s energy and about 1/3rd of total energy is consumed by petroleum and it is predicted there will be an increase in demand of oil, coal and gas heading towards 2020 and 2030 [2.15]. Figure 2.3 shows the population estimations tend to increase; as the industrialization has progressed, the demand of energy will also increase and the amount required is directly proportional to the global population. Table 2.1 shows that almost 3.2% of world production value losses are due to the power outages caused by environmental disasters. Figure 2.4 shows that the study conducted by Lawrence Berkeley National Laboratory (LBNS) for the U.S. Department of Energy’s (DOE) office of Electric Transmission and Distribution and estimated electric power outages and blackouts cost the nation of about $79 billion annually. In the previous federal elections in Australia during August 2010, much has been mentioned on the risk of climate change and major irreversible impacts, however the impact is much more as there is significant changes in the temperature due to food yield and consumption; water availability and sea level rises; ecosystems are affected with danger to coral reefs marine species extinction and extreme weather events like bushfires, storms, drought, floods and excessive heating [2.15].

The compressed liquid forms of leaked for Carbon dioxide (CO_2) can mix with ground water (H_2O) and make it toxic and unsuitable for human consumption. The whole ecosystem will be disturbed and make difficult for the flora and fauna, if the CO_2 leaks in the lower layers of the ocean. Leakage of CO_2 from underground reservoirs replaces the O_2 near the earth’s surface and leads to the loss of both animal and plant life. Compressing CO_2 better known as Carbon sequestration into the liquid form is more expensive, requires a lot of energy and also has to be monitored constantly. Permanence of storage system, energy penalty, cost and excessive usage of Carbon sequestration which slows down the search for non-polluting sources of energy are the issues for Carbon sequestration [2.15]. These are the factors that needs to be considered and will require of usage of Hydrogen Energy and Fuel Cell Technologies which in turn will eradicate global warming impacts referred to as “Climate Change” .

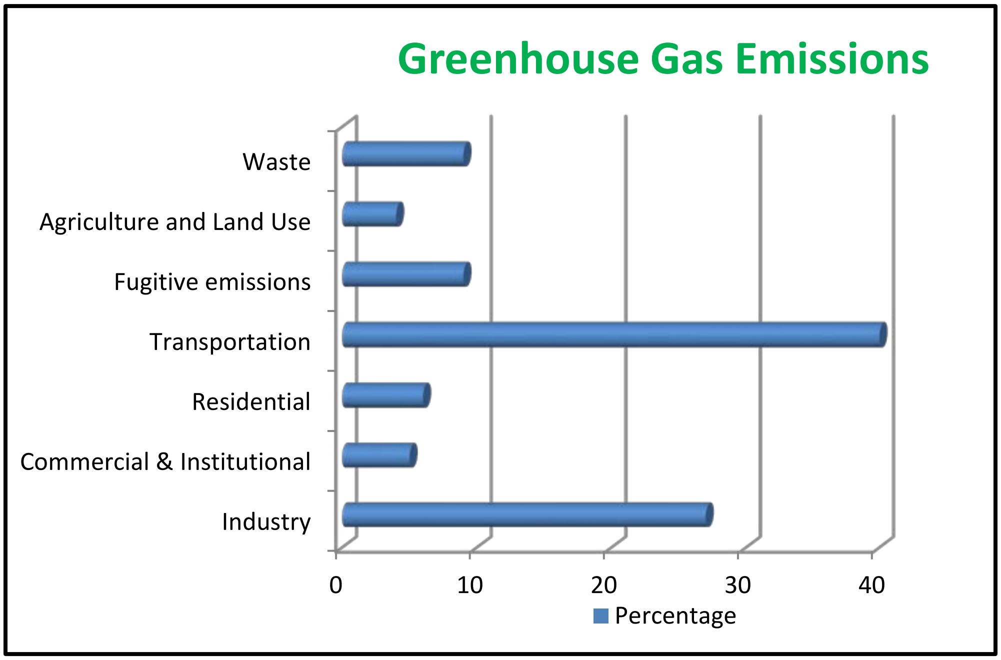

Figure 2.1 Greenhouse Gas Emissions from different Sources [2.15]

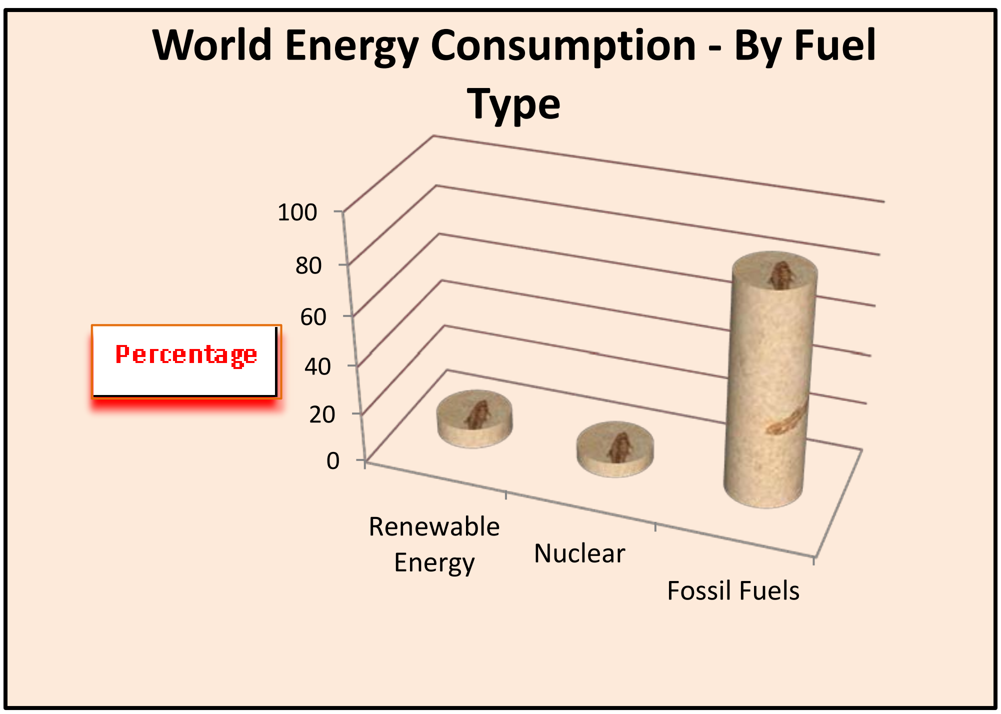

Figure 2.2 World Energy Consumption by fuel type [2.15]

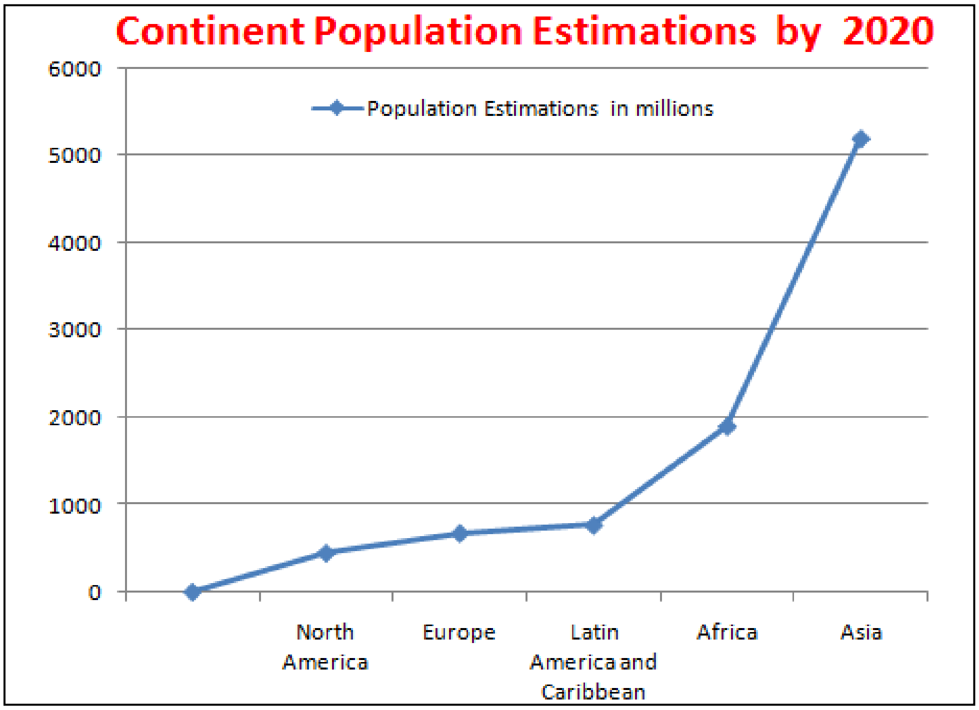

Figure 2.3 Population Estimations [2.15]

Table 2.1 Production value losses due to power outages [2.15]

Country	**Production value losses in percentage (Due to Grid Interruptions)**
South Africa	0.9
Thailand	1.8
China	1.9
Vietnam	1.9
Turkey	2.3
Brazil	2.5
Indonesia	4.2
Philippines	7.1
India	9.0
WORLD MEAN	**3.2**

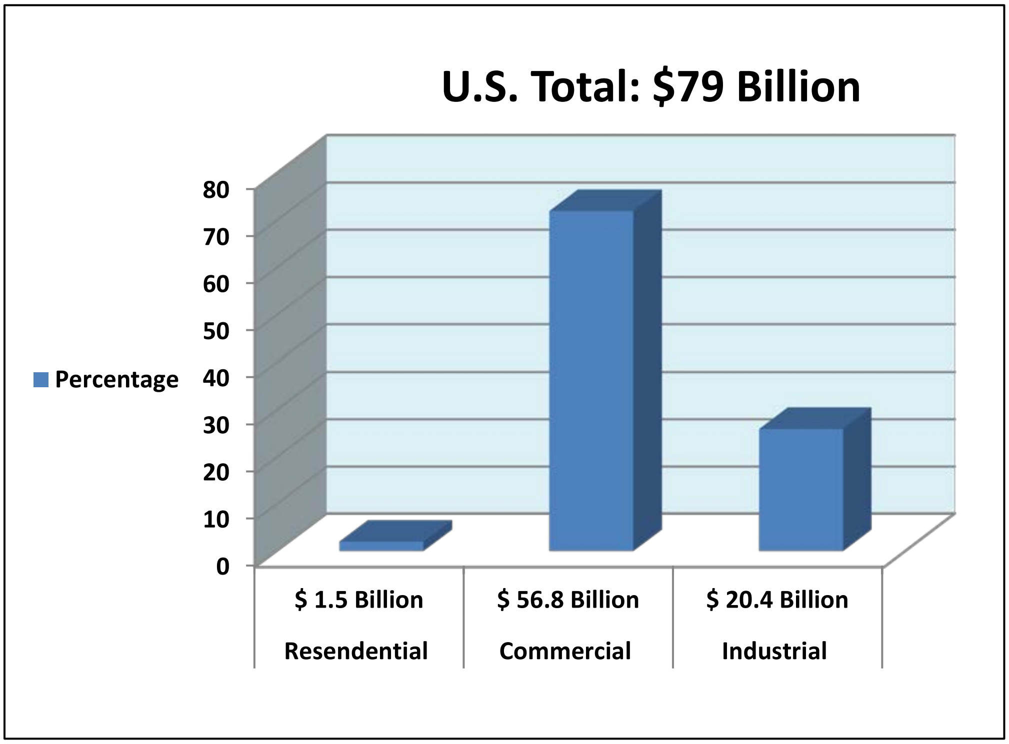

Figure 2.4 Estimation of the Annual Cost of Power Interruptions by LBNL [2.15]

2.6 Hydrogen

The lack of economic independence, the demand of energy, the emission of fossil fuels degrading the quality of air, the diminishing of the raw materials for the fossil fuel economy suggest that the current economy is not sustainable. The 'most alternative' form of alternative fuels is H_2. The sustainable energy economy can be achieved by the benefits of H_2. H_2 is the simplest, ultimate clean energy carrier and has the highest energy content per unit of weight of any fuel. H_2 has been described as "the fuel for the future" because it is abundant in nature and is colourless, non-toxic, odourless and tasteless. H_2 can be found in combination with other elements like H_2O, hydrocarbons, NH_4, fossil fuels (coal, oil and natural gas), nuclear power and renewable energy like (direct solar, biomass, solar PV, wind, geo-thermal) [2.16-2.17].

2.6.1 H_2 production pathways

H_2 is produced from H_2O using various energy sources including renewable and non-renewable, and then used to carry energy as an electric current for industries, residential, transportation, commercial etc. The by-product is H_2O and heat after the current caries the energy as shown in Figure 2.5. When Fuel Cell systems are fuelled by pure H_2 and O_2/air to create electric power the by-product is heat and H_2O and no carbon based greenhouse gases are emitted into the atmosphere [2.16-2.17]. The most common and best H_2 production pathways are described in Table 2.2 [2.16].

Table 2.2 Best H_2 Production Pathways [2.16]

<table>
<tr><th>Source</th><th>Process</th><td rowspan="8">H_2</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Crude Oil
Coal
Natural Gas
Wood
Organic Waste
Biomass</td><td>Reformer</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Nuclear Power Plant
Geothermal Power Plant</td><td>Electrolyte</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Solar Generator
Wind Generator
Hydro Generator
Wave Generator</td><td>Electrolyte</td></tr>
<tr><td colspan="2"></td></tr>
</table>

Figure 2.5 Hydrogen Energy System in Power Systems laboratory, Victoria University

Photo electrolysis, thermal decomposition of water, photo biological production and plasmatron are the other production pathways under research could be commercially viable later. To fuel cars, solar energy and a virus named M13 are used by researchers Massachusetts Institute of Technology (MIT) to split H_2O into H_2 and O_2. A new aluminium alloy is used by engineers from Purdue University to produce H_2 by splitting water. The aluminium alloy is a combination of aluminium, gallium, tin and indium where aluminium consists of 95% and the total of gallium, tin and indium together consists of only 5%. The cost of H_2 produced from this technique would be competitive with other technologies. Gallium is expensive and its reduced use, allows H_2 production at low cost [2.16]. Researchers at the Indian Institute of Technology, Kharagpur have discovered a novel way by using a strain of bacteria that produces 40% more H_2 than other strains. To generate H_2 scientists have developed a new method from ethanol which comes from the fermentation of crops and H_2 generated would be used to power fuel cells without the need of combustion. Artificial photosynthesis splitting of H_2O using algae, bacteria or harmless viruses is an important emerging field right now and it's a matter of time that one can see large scale of energy to become commercially viable. French researchers are working on a method replacing Pt with Co in the production of H_2 that acts both as a photo-sensitiser and catalyst. The reason is to replace the expensive metal Pt used in fuel cells and in electrolysers [2. 17].

2.6.2 Hydrogen safety

To address public's perception and concerns about the safety of H_2 organisations such as the society for Automotive Engineers and also the US Nation Fire Protection Agency are working with international standards. The Hindenburg disaster has proved that H_2 did not burn in the disaster. Several tests were undertaken by BMW and the University of Miami and found safety of the H_2 fuel to be sufficient. Both H_2 and gasoline cars, set fire in its test by the University of Miami, the gasoline fire resulted in total damage of the entire car whereas H_2 flame vented vertically and did not damage the rest of the vehicle [2.16-2.17].

2.6.3 Barriers of Hydrogen Energy

Hydrogen economy represents a vision strategy: however, two barriers must to overcome to make the hydrogen economy a reality. The infrastructure that provides seamless transitions from production, storage, utilisation and distribution must be connected which make up the hydrogen economy is the first barrier and the second one is the demonstration in the market place that the H_2 as an energy carrier which is economically competitive. To overcome the environmental impacts an innovative research aimed at making revolutionary advances in lowering the cost, increasing the performance of the hydrogen economy and its reliability is required [2.16-2.17]. Once H_2 is made economically viable then large amount of greenhouse gases emitted to the atmosphere will be reduced drastically, resulting in eradication of the environmental impacts from global warming.

2.7 Fuel Cell

Fuel cell was first demonstrated by William Grove (barrister-cum-inventor) in 1839. However, the application of fuel cells was accelerated by its utilisation in the US space programme to produce useful power, in 1960s. Currently most other application of fuel cell is in the research stage, but with recent debates on environmental concerns, pollution and energy conservation, future of fuel cells is very promising [2.20-2.22].

Electricity from Fuel Cell is produced without rotating machines, and at efficiencies considerably higher than those obtained from conventional fuel-burning engines and power stations. Fuel Cells have the added benefit that it has silent operation [2.20-2.22].

Fuel Cells, with their high efficiencies (even at low powers), silent operation, simplicity, reliability, produces low concentrations of NO_x, and utilise gas feedstock's (viz. natural gas, CH_4, CO and H_2) can be the best type of energy converter, provided the fuel cost could be reduced. Fuel Cells boost has been given recently with the Californian law of ‘zero emission’ on their new cars. It states 2% of the new car sales will be required to have ‘zero emission’ by 1998 rising to 5% in 2000. Other North American states have similar directives [2.20-2.22].

Fuel Cells will be preferred to storage batteries as the latter requires difficult charging regimes and low power densities. The DC output from Fuel Cells can be converted to AC via power conditioning systems known as invertors, which means they can supply electrical power comparable to that from the electricity grid [2.20-2.22].

Hence the main likely users of Fuel Cells will therefore be electric vehicles and cogeneration. Other broad potential application ranges from small remote area power systems and telecommunication installations through to commercial buildings and ultimately to multi-megawatt power stations. Figure 2.6 shows the PEM Fuel Cell in Power Systems Research Laboratory at Victoria University, Melbourne. A fuel (nearly always H_2) reacts with water and the overall reaction is shown in equation (2.1) as:

$$2H_2 + O_2 = 2H_2O \tag{2.1}$$

However, this reaction does not readily take place, and unless special materials are used for the electrodes and the electrolyte, the current produced per square centimetre is extremely small and the ohmic losses in the electrolyte very large [2.20-2.22]. To overcome these problems, various types of fuel cell have been developed, and the most successful and promising types are shown in Table 2.3 [2.18]. The different varieties are distinguished by the electrolyte used; also the construction of the electrodes in each case is different. However, in all types there are separate reactions at the anode and cathode, and charged ions move through the electrolyte while electrons move round an external circuit. Another common feature is that the electrodes must be porous, because the gases must be in contact with the electrode and the electrolyte at the same time [2.20-2.22].

In order to see the movements of ions and electrons, consider the actions of simple fuel cells: The reaction in the alkaline Fuel Cell shows that OH^- ions move through the electrolyte, and water forms at the anode as shown in equation (2.2) [2.20-2.22]. Cathode (where the cations are formed as shown in equation (2.3) is electrically positive terminal (EE engineers find this phenomenon very surprising!).

Anode $$2H_2 + 4OH^- = 4H_2O + 4e^- \tag{2.2}$$
Alkali electrolyte through electrolyte
Cathode $$O_2 + 4e^- + 2H_2O = 4OH^- \tag{2.3}$$
Water forms at the anode through external circuit.

In case of phosphoric-acid fuel cells, H^+ ions are free to move, and water forms at the cathode as shown in equation (2.4) and (2.5).

Anode $$2H_2 = 4H^+ + 4e^- \tag{2.4}$$
Acid electrolyte through electrolyte
Cathode $$O_2 + 4e^- + 4H^+ = 2H_2O \tag{2.5}$$
Water forms at the cathode through external circuit.

The operating voltage of each working cell is about 0.7V, so in order to get useful power one has to have stack of cells. The cathode of one of the cell is joined to the anode of the other and so on, with lowest possible resistance. It is not sufficient to join the electrodes at the edges; instead a conductive plate is put between each cell, which should have the best possible electrical contact with the faces of the electrodes. The plate in the same instant has to separate the air fed over the cathode and the H_2 fed over the anode. Design of such bipolar separators is difficult [2.20-2.22].

A major problem with Fuel Cell application is that H_2 fuel is not readily available, so that more accessible fuels such as natural gas have to be converted into H_2 and CO_2. This adds to the size and cost of the unit [2.20-2.22].

In the case of Solid Oxide Fuel Cell (SOFC), methane can be converted internally, without a separate unit. The materials consist of zirconia-based electrolyte covered on each side with specialised electrode materials. At around 1000^{o}C zirconia is an excellent O_2 ion conductor, hence when a fuel gas like H_2 is passed over one surface and an oxidant (usually air) is passed over the electrode, a potential difference is created and a flow of negatively charged O_2 moves across the electrolyte to oxidise the fuel [2.19].

Electrons generated at the fuel electrode then migrate through any external load to complete the circuit. Electrical power is available as long as fuel and air flows are maintained to the cell. Because of its efficiency and waste heat quality Westinghouse (USA) has produced 25kW units and Sulzer (Germany) has developed 2kW units [2.19].

Molten Carbonate Fuel Cell (MCFC) operates at 650^oC and use gases like natural gas and coal gas. At the cathode O_2 and CO_2 react to form carbonate ions, which pass through the molten carbonate electrolyte. These react with H_2 or CO at the anode to produce H_2O and CO_2 and release two electrons. Main problem of MCFC is the design of the electrodes (uses Ni catalyst). They have to work longer in the electrolytes (mixture of Li and K_2CO_3), which is hot and corrosive. A plant in Santa Clara, USA of 2MW capacity is being built [2.18].

Phosphoric Acid Fuel Cell [2.18, 2.19] runs at 200^oC. A 200kW unit runs on natural gas and is commercially produced in USA. Cost of about $3,000/kW is not competitive, but due to government environmental package incentives the cost is about $2,000/kW. They have good track record, as it has now been running for about a year, has no maintenance requirements. Their disadvantage being the temperature is not high enough to internally convert methane; as such it requires an extra unit adding to the cost and size.

Amongst the low temperature cells alkali cell has gained commercial success. It is used to supply power in space vehicles. It is superior to other power sources, as it has high power density and produces water as a by-product. The problems with this are that very high Pt loadings on the electrodes is required to get the high power (high cost) and KOH reacts with CO_2 to form K_2CO_3, which degrades the electrolytes and clogs up the pores of the electrodes [2.20].

The Solid Polymer Fuel Cells (SPFC) are being used in vehicles. Research in UK has produced high performance electrodes using very low Pt loadings. Costs are involved in the electrolytes utilising ‘proton exchange membrane (PEM)’ and bipolar plates. In Vancouver Fuel Cell powered buses are being used. This has ‘zero exhaust emissions’ and many transit authorities are showing interest in this type of vehicles. SPFC is very competitive with petrol engine in terms of power density, and if mass produced costs can become competitive. A problem with these vehicles is that cells have to be fuelled with H_2 from cylinders. However, small, safe and efficient converter for converting liquid fuel to H_2 is giving satisfactory performance [2.18].

Figure 2.6 Proton Exchange Membrane Fuel Cell in Power Systems Laboratory at Victoria University

Major developments in Fuel Cells are in (1) Japan - demonstration fuel cell units have been developed, (2) USA, UK and Canada - pioneers in this area. Other small demonstration units are now available, eg. a small Methanol Fuel Cell producing enough power to drive small motors and it costs around $30. This is an Alkali Fuel Cell, but instead of H_2 it uses alcohol as the fuel. Fuel Cells are now proving to be an emerging energy option and very soon will be used in cogeneration systems and in 'zero emission' vehicles [2.15].

Table 2.3 Data for various Fuel Cell types [2.18]

Type	**Operating Temperature**	**Power Density**	**Approximate Cost**	**Applications**
Alkali	50-100^0 C	80kW/m^3 100W/kg	Very high	Space vechiles, e.g. Gemini, Apollo, Shuttle; η>70%
Solid Polymer	50-100^0 C	190kW/m^3 100W/kg	$500/kW (1998)	Buses and cars
Phosphoric acid	~ 200^{0}C	4kW/m^3 10W/kg	$3000/kW $1500/kW (1998)	Medium scale cogeneration Systems
Molten Carbonate	~600^{0}C	35kW/m^3 70W/kg	N/A	Medium to large scaled cogeneration systems; coal gasification plants
Solid Oxide	500-1000^0 C	>100kW/m^3	N/A	All cogeneration systems (2KW to multi MW) early stage of development
Diesel generator		15-45kW/m^3 25-100W/kg	$150-200/kW	20 -750kW (Diesel Storage tanks not included in cost)
Petrol engine (Standard cars)		~300kW/m^3 ~500W/kg	$40-100/kW	Peak power from engine only (no electricity generated

2.8 Recommended Methods and Experimental Design for Optimal Energy Planning in Australia

The research shall apply quantitative and qualitative methods for optimal energy planning. Systems approach is holistic in nature and provides scope for integration of technique for analysing large and complex power systems of Australia. The need is to develop a viable and optimal plan for such a vast region. Techniques are required to investigate viable policy options in these contexts with implications for micro policy planning [2.23].

A quantitative technique such as Delphy study, idea engineering and HARVA method analysis has been tried. Also other qualitative techniques such as experimentation, H_2 optimization, testing and results has been tried to arrive at feasible solutions as shown in Figure 2.7 [2.23].

A renewable energy source such as Fuel Cells applications has been extremely successful in vehicles, in particular the mass transit system; however in this project the application is on electrical distribution system providing feasible/optimal solutions. It will be necessary to generate electric power directly from these sources so that one can use it for certain applications such as water heating systems (to avoid the use of electric geyser) heating and cooling (to avoid commercial air conditioning). This technology can also be rapidly applied to remote and inaccessible areas where Australia is currently facing severe energy shortages. The use of Fuel Cell system with suitably available fuel option in the region has been looked into. The availability of cheap fuel is area specific or depends on geographical situation. The type of fuel cell use depends on the available and these will be analysed to obtain maximum system efficiency with minimum capital and running cost [2.23].

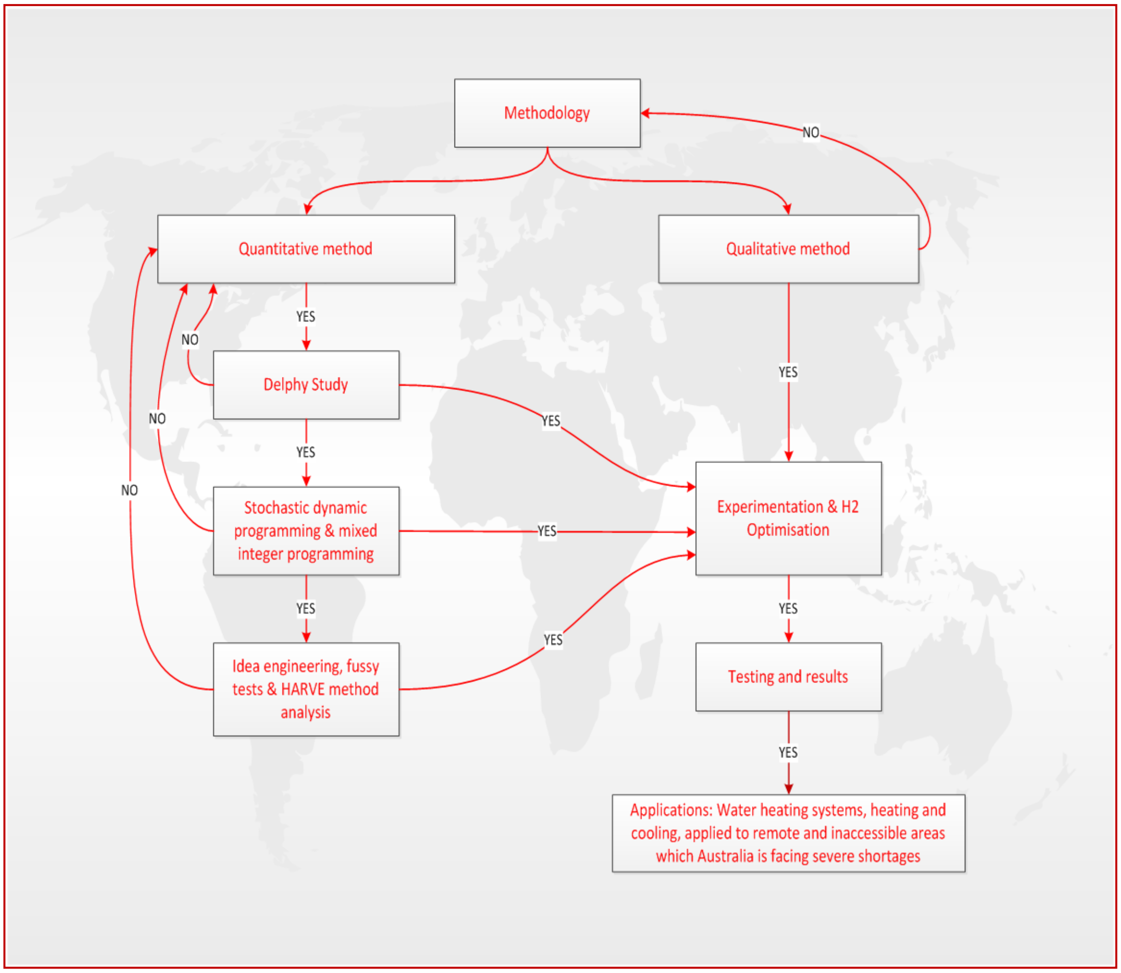

Figure 2.7 Methods and design for optimal energy planning in Australia [2.23]

2.9 Hybrid Systems Inclusive of Renewable Energy to Reduce Carbon Tax in Australia

Economists from around the world, Productivity Commission and respected institutions such as Organisation for Economic Co-operation and Development (OECD) recognised that putting a price on carbon is the most environmentally effective and economically efficient way to reduce pollution [2.24].

To avoid the increased costs of delaying action on climate change, cut carbon pollution, drive Australian innovation and to reshape economy, the Australian Government has built a Clean Energy Future (Carbon price, Energy efficiency, Renewable Energy Target and efficient Land usage). Treasury modelling released by the former Deputy Prime Minister and Treasurer and the Minister for Climate Change and Energy Efficiency estimates that under a carbon price average income in Australia are expected to increase by 16% from current levels and also 1.6 million jobs are projected to increase by 2020 in Australia [2.24].

The use of Solar/Wind micro-generation system is capable to reduce CO_2 emissions by implementing it in every independent home in Australia. Support for communities and regions, supporting jobs in industries with a strong regional presence, low carbon communities, delivering clean energy to remote communities and to reduce carbon tax are some of the benefits of implementing Solar/Wind micro-generation system in Australia [2.24].

Hybrid systems inclusive of renewable energy as shown in Figure 2.8 are attractive in Remote Area Power systems (RAPS) due to the high cost of grid extension, high transmission and distribution losses. Individual houses, mining operations, telecommunication installations, satellite facilities and surveillance system are some of the type of remote sites. H_2 and Fuel Cell applications appear to be an attractive alternative for long-term energy storage and for distribution of electricity since wind and solar energy cannot produce power steadily. The power production rate of wind and solar varies by season, month, day and hour [6].

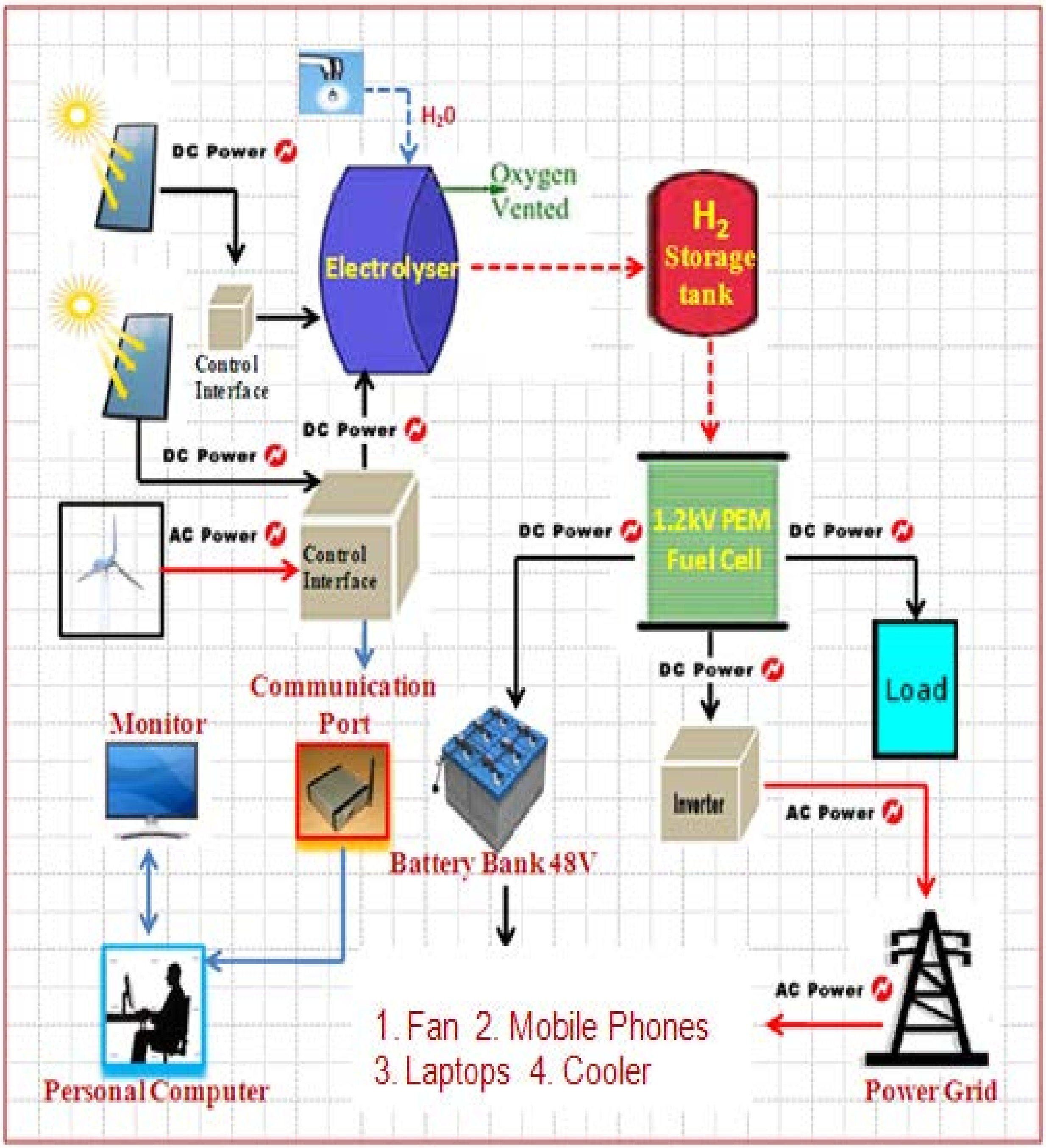

Figure 2.8 Hybrid systems inclusive of renewable energy

The basic hybrid systems inclusive of renewable energy system for RAPS application consists of a photovoltaic array, wind generator, H_2 electrolyser, H_2 storage and a fuel cell. There are two different types of hybrid system inclusive of renewable energy [6].

- Hybrid systems inclusive of renewable energy for RAPS, meeting the load directly from the PV/Wind and excess available energy to produce H_2 [6].

- Hybrid systems inclusive of renewable, feeding all the available PV/Wind energy to the electrolyser producing H_2 and the fuel cell to meet the load [6].

2.10 Benefits of Hybrid Systems Inclusive of Renewable Energy

2.10.1 Economic Benefits

At present, hybrid systems inclusive of renewable energy are very costly, as a result of the high cost of the photovoltaic modules, wind turbine, electrolyser, fuel cell, hydrogen storage, Wind box Interface (WBI) (DC-to-AC converter) and inverter (DC-to-AC converter). If the capital cost of this system can be reduced then this reduction in capital cost will reduce the unit cost of power delivered by the hybrid system inclusive of renewable energy. The prospects of this systems becoming economically competitive in certain RAPS applications will thus be enhanced. More generally, if cost-competitive hybrid systems inclusive of renewable can be developed, it will open up opportunities for further economic benefits through the growth of firms producing, commercialising and installing such systems in Australia and overseas [6]. The other economic benefits will be reduced oil dependence, economic independence, distributed production [30] and more job opportunities are some of the benefits of Fuel Cell technology.

2.10.2 Environmental Benefits

The main greenhouse gas-CO_2 comes largely from the burning of fossil fuels from ten different sources like power plants, cement production, road transport, iron & steel manufacture, deforestation, oil & gas production, garbage, livestock, fertilizers and aviation. Climate changes are mainly due to the increase in concentration of greenhouses gases like CO_2, CH_4, NO_X, water vapour and aerosols [6].

By widespread implementation of hybrid systems inclusive of renewable energy in remote applications, a considerable amount of greenhouse gas emissions can be avoided. Hybrid systems inclusive of renewable energy produce zero greenhouse emissions in operation, and do not present problems of toxic electrolyte handling fuel cells are used. Through using this system, remote households, communities, tourist operations and businesses will move towards a clean, renewable and sustainable energy system [6].

Less greenhouse emissions, less air pollutants, eradication of global warming [2.23], liberation from top ten surprising results of global warming like aggravated allergies, heading for the hills, artic in the boom, pulling the plug, the big thaw, survival of the fittest, speedier satellites, rebounding mountains, ruined ruins and forest fire frenzy [2.24] are some of the other environmental benefits of hybrid system inclusive of renewable energy.

2.10.3 Social Benefits

As the hybrid system inclusive of renewable energy is a new technology, it will be important for the manufacturers, marketers and installers to build-up confidence and trust in these systems with potential users. The acceptance of hybrid systems inclusive of renewable energy by users will depend upon user education about the new system, establishing reliability and simplicity of system operation and design and setting up appropriate safety procedures and standards. If the barriers of hybrid system inclusive of renewable energy are overcome successfully, then this technology will reduce Australia's total dependence on fossil fuel technology and enhance national energy security [6].

2.11 Simulation and Optimization of Hybrid Systems Inclusive of Renewable Energy

For either grid-connected or off-grid environment with input like solar photovoltaic, wind turbines, batteries, H_2 generators and conventional generators etc, designing and analyzing hybrid systems inclusive of renewable energy Hybrid Optimization Model for Electric Renewables (HOMER) is widely used in many countries [2.25].

Distributed generation and hybrid systems inclusive of renewable energy continue to grow and mitigation of financial risk for hybrid systems inclusive of renewable energy projects is served by HOMER to obtain the most cost-effective, best component size and the project's economics of the hybrid systems inclusive of renewable energy. The benefit of using HOMER for micro-power optimization model and the determination for realistically financing renewable energy or energy efficiency projects is presented in this project [2.25].

2.12 Reliability Analysis

A hardware product (electronic or mechanical), a software product or even a manufacturing process which will continue to perform its intended function, without failure for a specified period of time, under stated condition is defined as reliability. Traditional reliability models do not describe load-sharing systems and often postulate that component failures are statistically independent. In a load-sharing system (mechanical, thermal and electrical structures) the failure of one or more component increases the load on other non-failed components, thereby increasing their chances of failure. In most circumstances, an increased load may induce a higher component failure rate in a Hydrogen Energy, Fuel Cell power generation system and Wind/Solar 4.5kW micro-generation system [2.26].

Reputation, customer satisfaction, warranty costs, repeat business, cost analysis, customer requirements and competitive advantage [2.26] are some of the reasons why reliability is an important product attribute?

2.13 Summary

In Australia most of the energy comes from fossil fuels, the Australian energy consumption is dramatically increased by the increasing population and high standard of living. In this Chapter the problems of conventional energy, the benefits of renewable energy, back-up power for NBN in Australia and the factors seeking for Hydrogen Energy and Fuel Cell technology to eradicate environmental disasters are discussed. The Hydrogen Energy, H_2 production pathways, H_2 safety, barriers of Hydrogen Energy and Fuel Cell applications on electrical distributing system and its commercial viability in Australia are explained. The hybrid systems inclusive of renewable energy to reduce carbon tax and its economic, social and environmental benefits are discussed in this chapter. Finally, simulation and optimization of hybrid systems inclusive of renewable energy and reliability analysis are also highlighted in this Chapter.

Based on the researches Australia could switch from conventional energy to hybrid system inclusive of renewable energy and contribute more R&D into suggested methods and experimental design for optimal energy planning in Australia. Therefore increased R&D will lead to more funding from federal and state governments. Early stage funding from government will lead increased market potential and Australia will enjoy the benefits of fuel cell technology like elimination of pollution and greenhouse gases, eradication of global warming, to reduce carbon tax in Australia and can be used in NBN and Telecommunications in Australia.

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Chapter 3

EL100 H_2 Generator as a Back-up Power to Implement for National Broadband Network (NBN) in Australia

3.1 Introduction

As mobile telephones, computers and high-speed internet have become more common and the telecommunication industry has expanded rapidly. Therefore, telecommunication facilities and number of cell phone towers has increased dramatically. The number of mobile telecommunication network stations worldwide was 4.7 million in 2011 [3.2, 3.3]. Base Transceiver Stations (BTS), Base Switching Centre (BSC) and Mobile Service Switching Centre (MSC) are the most important parts of wireless networks for mobile phone services. BTS are needed for direct connection to the users with mobile phones. Users between wireless and wired network are connected by MSC and also BSC are needed to control several Base Stations. To keep their towers, equipment and networks operational from power outages most telecommunication providers install some form of back-up power [3.1, 3.3]. Energy can be accumulated in various forms like electric charge in capacitors and ultracapacitors, superconducting magnetic electric storage, pressurised air, hydro power, kinetic energy in flywheel and electrochemical in batteries. Batteries and flywheels are mostly used in uninterruptible power supply (UPS) systems. For uninterrupted service, back-up power systems consists of UPS and electric generators. Lead acid batteries are used for accumulating electric energy in most of the UPS. Only batteries are used in most of the UPS installations to supply for several minutes. UPS must be coupled with a diesel generator as a prime mover for longer back-up time. In the case of power net outage the UPS is used to bridge the power from network and generator and provide time to start the generator [3.3].

Factors like high start-ability, large costs of periodic checks and exercises for diesel and gasoline fuelled generators and the price of base material for lead acid batteries are some of the drivers for H_2 Energy and Fuel Cell technology deployment in back-up power market. The effect on CO_2 reduction will be significant, if battery UPS are replaced by H_2 Energy and Fuel Cell technology. The average for one replacement of battery system by Fuel Cell reduction in CO_2 production is about 0.789 ton a year in Europe. The total reduction in CO_2 emissions would be 329 thousand tons CO_2 yearly, multiplying 0.789 ton by number of base stations in Europe [3.3].

Section 3.2 of the chapter highlights the vision and strategy of NBN and Hydrogen Energy is discussed in Section 3.3. Section 3.4 of the chapter describes the EL100 H_2 generator and its advantages. The planning of laboratory evaluation and testing at Power Systems Research Laboratory, Victoria University are explained in Section 3.5 and Section 3.6 describes the system installed in detail. Section 3.7 points out the analysis and evaluation of the laboratory results and finally, Section 3.8 provides the summary of this chapter.

3.2 National Broadband Network (NBN)

The establishment of NBN will provide the vital enabling infrastructure to achieve the government's vision to be among the world's leading digital economies by 2020. The Australian Government invites industry, state and territory governments and local council to focus on the eight 'Digital Economy Goals' to maximise its benefits. On-line participation by Australian households, on-line engagement by Australian businesses and non-profit organisations, smart management of environment and infrastructure, improved health and aged care, expanded on-line education, increased tele-working, improved online education delivery and engagement and greater digital engagement in regional Australia are the eight areas of 'Digital Economy Goals' set by the Australian Government [3.4, 3.5].

Downloading internet speed up to 1 Gigabit a second, the support for high-speed download and upload services, the capacity of future upgrades, the stability and reliability of internet service, ubiquitous coverage and uniform national wholesale pricing are the several specific characteristics of NBN. Radio-broadcasters and television took 38 and 13 years to reach an audience of 50 million but internet took only 4 years [3.4, 3.5].

3.2.1 Vision

The Australian Government said the digital economy refers to **“Internet, mobile and sensor networks are the information and communication technologies that enables the global network of economic and social activities”.** By 2020, Australia will rank in the top five OECD countries using on-line opportunities in households, business and not for profit organisations to enable jobs growth, expand their customer base and to improve productivity. Opportunity for on-line virtual learning, narrow the gap between households and business in capital cities and those in regional areas and double its level of tele-working are some of the goals set by the government to measure the progress in realising the vision by 2020 [3.4, 3.5].

3.2.2 Government Initiatives

The government has provided $10.4 million over 4 years from July 2011 to Broadband for Senior Program, to ensure that older Australians will participate in an NBN-empowered digital economy. Towards the implementation of Smart Grid, Smart City project, in 2009 the government has provided $100 million to investigate the synergies of the NBN and other utilities. In contrast to reduce congestion and improve traffic demand management and overall efficiency of the transport network the government has already provided $61.4 million over 3 years for Sustainable Australia-managed motorways to implement in major cities [3.4, 3.5].

To establish a ‘Digital Hub’ in each of the 40 communities the government will provide $23.8 million over 3 years to participate safely and securely and have trust and confidence in the digital economy for local residents. To investigate and test some preliminary developments to improve people’s ease of access to government services the Australian government will provide $2.3 million and $12.4 million over 3 years to provide advice and support services to Australian business and not-for-profit organisations. Google and MYOB, the Getting Aussie Business Online campaign and the recent Australian Retailer Association’s Engage in e-tail seminar series has already helped more than 10,000 small business to setup new websites and 150 retailers to engage in the online market place. These are some of the government initiatives to advance the Digital Economy Goals by 2020 [3.4, 3.5].

3.2.3 Strategy

In 2008-09, Australians aged 15 years or over (26%); retired persons (69%); low-income earners (34%) and people living in outer regional and remote areas (34%) did not use the internet. ABS reports 2009 indicated that only 27.1% of Australian business took orders via internet. The Skills Australia Report 2010 stated that 66.9% TAFE staff were aged 45 years or more in 2005 and concluded that in future TAFE sector would be without qualified and experienced staff. About 69.5 million (62%) transactions are made on-site in Australian Government, Department of Human Services (Centrelink) currently. Due to the rapid growth of Australian cities the vehicles (cars and trucks) are under congested conditions on urban roads use more fuels and emit more pollutants than vehicles under free-flow conditions [3.4, 3.5].

By 2020, 90% of high priority consumers such as older Australians, mothers and babies can access individual health records including those with a chronic disease. To remote patients about 25% of Medical specialists will be participating in delivering tele-health consultations. Students and learners who cannot access courses via traditional means in Australian schools, TAFE's, universities and higher education on-line virtual learning facilities will be offered [3.4, 3.5].

Allen Consulting Group (ACG) commissioned by the Department of Broadband, Communications and Digital Economy estimates that Australia would gain $2.4 billion a year in current prices, if the numbers of Australian household connect to the internet by 10% points through time saving activities (price/product discovery, education and knowledge, on-line shopping, media, engagement in on-line community etc.). These are some of the essential strategies towards positioning Australia as a leading digital global economy by 2020 [3.4, 3.5].

3.3 Hydrogen Energy

H_2 is most abundant, efficient and clean fuel but the problem is that it is not free. Electrolysis is required to separate H_2 from H_2O. Non-renewable or renewable energy sources are required for electrolysis process to decompose H_2O into H_2 and O_2 gas [3.6, 3.8]. Between two electrodes separated by aqueous electrolyte, H_2 is produced by decomposition of H_2O by passing an electric current. The two main types of electrolysers which are well developed are proton exchange membrane (PEM) electrolysers and alkaline electrolysers. At anode, H_2O reacts to form O_2, electrons and positively charged ions (protons) as shown in equation (3.1). The electrons flow through external circuit and H_2 ions move across the PEM to the cathode, where they recombine to form H_2 as shown in equation (3.2). The total reaction for H_2O decomposition is shown in equation (3.3) [3.6-3.8].

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{3.1}$$

$$4H^+ + 4e^- \rightarrow 2H_2 \tag{3.2}$$

$$H_2O + \text{electrical energy} \rightarrow H_2 + 1/2\ O_2 \tag{3.3}$$

3.4 EL100 H_2 Generator

The EL100 H_2 generator as shown in Figure 3.1 is a device that produces H_2 directly from H_2O by means of an electrolysis process. Both compressed gas tanks and metal hydride absorption tanks can be used for storing H_2 gas. The EL100 unit serves to produce a clean, low cost fuel, requires little maintenance, easy to use and is the first H_2 generator that can be installed in any setting and its specifications are shown in Table 3.1. It produces H_2 that powers electrical equipment such as power generators (Fuel Cells) and electrical vehicles (scooters, craft with outboard/inboard and work vehicles) in a complete safe and environmentally sound manner. Electricity from the mains or from renewable sources and demineralised H_2O are supplied to produce H_2 gas which can also be used in home [3.9].

The EL100 unit is contained in a metal casing with a quick socket to connect to the device requiring H_2, power lead and H_2 relief valve. The control unit of EL100 contains On/Off main switch (C), button (D) to start H_2 production and red light (E), warning of malfunctioning of the unit, indicating the device must be repaired at an authorised help centre. The depletion of the H_2O is indicated by orange fixed light (need to restore the liquid level in the reservoir G), the blinking orange light indicates over heating of the device (need to shut down the device to restore operating temperature) and the green light indicates the tank is full (stop adding any more liquid in the tank G). The green LED on the button (D) flashes during the electrolysis process as shown in Figure 3.2a [3.9].

Figure 3.1 EL100 H_2 generator [3.9]

The EL100 solution (made up of demineralised H_2O with the addition of 1% in weight of electrolyte non-consumed K_2CO_3) through an electro-chemical process generates about 83.6 standard litres per hour (slph) of H_2 is during the process. The output and the pressure of H_2 produced are controlled by the safety system inside the unit making the EL100 unit to use both indoor and outdoor settings. EL100 unit is a completely automated system and this technology is ideal for remotely located homes and can be used in NBN and telecommunication sites [3.9].

Table 3.1 Specifications of EL100 H_2 Generator [3.9]

Product Specifications EL100	
Flow rate for Hydrogen produced (max)	83.6 slph
Operating pressure	15 bar
Purity of Hydrogen	99.52% @ 15 bar
Internal accumulation of Hydrogen	none
Power Supply	220/50
Power Consumption	440 W
Quality of Electrolyte	K_2CO_3 solution – 1% in weight
Tank Volume	4.5 l
Quality of Demineralized Water	
Max conductivity at 250C	5-10µS/cm
pH	6 - 7
Water consumption (max)	0.068 l/h
Size	3460*260*500mm
Weight	27 kg

The advantages of EL100 H_2 generator [3.9] includes

- Acquiring a considerable independence from power distribution networks.
- Reduction of pollution and greenhouse gases.
- Clean and silent technology.
- No noisy polluting engines and
- Self-contained energy supplies using H_2O and electricity by means of a simple and safe instrument.

3.5 Planning of Laboratory Evaluation and Testing at Power Systems Research Laboratory, Victoria University

The evaluation and testing of EL100 H_2 generator for back-up power solution in telecommunication application like NBN was the goal of the project and was performed at Power Systems Research Laboratory at Victoria University. After the installation of EL100 unit, system commissioning included several checks for the leaks in the gas line planning.

The initial point of testing was to demonstrate a very high reliability of EL100 unit compared to the traditional systems (battery banks and diesel-generator sets). To determine the complete back-up power solution all aspects of EL100 H_2 generator were studied and evaluated including starting logic, gas line planning, H_2 delivery procedure and maintenance.

3.5.1 Phase I

The EL100 H_2 generator was started and stopped at regular intervals. The aim of Phase I was to verify the behaviour, reliability and long run capabilities of H_2 generator when called upon for back-up power in telecommunication sites like NBN.

3.5.2 Phase II

The purpose of Phase II was to verify the safety signals of EL100 H_2 generator like green light (D), orange light (F) and red light (E) as shown in Figure 3.2a [3.9].

3.5.3 Phase III

The purpose of the Phase III was to verify the automatic switching 'OFF' process and over-long charge time of EL100 H_2 generator [3.9].

3.5.4 Phase IV

In this phase EL100 H_2 generator was started to fill the H_2 storage tank of capacity 150 litres at 215 psi. The main focus was to monitor how much bottles of H_2 is generated, how long it will take to generate one bottle of H_2 tank of capacity 150 litres at 215 psi and the H_2O consumed between the maximum and the minimum liquid level of the H_2 generator.

3.5.5 Phase V

The purpose of Phase V was to address the research questions in this section:

- Industry claims a H_2 purity of 99.95%. Is this correct?
- From Valve Regulated Lead Acid (VRLA) batteries of 48V, 120A how much H_2 can be produced?
- Can a completely off-grid, stand alone solution be reliably deployed combining Solar and H_2?

3.5.6 Phase VI

The aim of Phase VI was testing of EL100 H_2 generator and T-1000 PEM Fuel Cell and its integration into telecommunications site for back-up power solution when both are working together simultaneously.

3.6 Description of the System Installed

The experimental setup at Power Systems Research Laboratory at Victoria University as shown in (Figures 3.2a to 3.2c) consists of 1.5kW monocrystalline solar panels, 1.5kW solar charger, battery bank of 48V (240A), 2kW Pure Sine Wave Power Inverter, EL100 H_2 generator, 150 litres of H_2 storage tank at 14.5 bar, T-1000 1.2 kW PEMFC**,** battery bank of 48V (60A), resistor load which provides a variable load to T-1000 was used to test its dynamic performance, circuit breakers, voltmeters and ammeters.

The H_2 delivery system installed at Power Systems Research laboratory complies with all applicable local, state, federal or internal codes and standards. During the installation of T-1000 PEM Fuel Cell system and EL100 H_2 generator, UL252 listed regulators for the use of H_2 were used. To monitor excess residual H_2 gas T-1000 PEM Fuel Cell was equipped with internal and external H_2 sensor. An alarm activates and blocks the operation of the system in the event of excess H_2 gas was detected. The installed H_2 piping systems adhere to NFPA Article 5.5 and ASME B31.3. For all threaded pipe joints anaerobic sealant was used. All H_2 connections are tested for leakage using approved soap solution [3.10].

The H_2 storage tank is connected to two pressure regulator at 50 PSI and 5 PSI and was connected to a safety valve in order to avoid accidental gas depletion. A 48V battery with 60Ah was used for Fuel Cell start-up. H_2 was generated from EL100 H_2 generator and stored in 150 litres of H_2 storage tank at 215 PSI. T-1000 PEM Fuel Cell was a solid state DC power that converts H_2 and O_2 into electricity and the only by- products are heat and H_2O.

Figure 3.2a Power Systems Research Laboratory, Victoria University

Figure 3.2b Power Systems Research Laboratory, Victoria University

Figure 3.2c Power Systems Research Laboratory, Victoria University

3.7 Analysis and Evaluation of the Laboratory Results

3.7.1 Phase I

The most important result of laboratory testing after the installation of EL100 unit was the verification of reliability: when start-up required and several checks for leaks in gas the line planning. The EL100 unit performed as designed when start-up was required throughout laboratory testing resulting in 100% reliability and several leaks was found in the gas line planning and was fixed without any leakage thereafter [3.11]. Experiments were conducted several times to fill the H_2 storage tank of 150 litres at 215 psi. The results obtained from Phase I of laboratory testing were satisfactory behaviour of long run capabilities of EL100 H_2 generator.

3.7.2 Phase II

The results obtained from Phase II of the laboratory testing were

1. Green light (F): when maximum liquid level was reached [3.9].

2. Steady orange light (F): The process automatically interrupted when the liquid level for the process has reached the minimum level and was noted during the laboratory testing [3.9].

3. Blinking orange light: The internal temperature was higher than the maximum allowed and EL100 unit was stopped for few hours to restore the working conditions [3.9].

4. Red light (E): A serious error was noted few times and the EL100 unit was stopped and started again. The EL100 unit was working again in either case when started immediately or after few minutes. The ACTA Energy Help Centre was contacted to check the system if there is any safety system or sensor seriously malfunctions.

5. Green light (D) Off: During installation, EL100 unit has passed all safety checks and signal green light (D) Off was not found during laboratory testing.

3.7.3 Phase III

As mentioned earlier, the third phase was performed to verify the automatic switching-off of the process. The process was automatically interrupted indicating different signals as discussed in Phase II, when the liquid level for the process reached the minimum level and also due to serious malfunction in the system during the laboratory testing. The automatic switching-off of process **before completion of the charging** and **due to over pressure** was not achieved during the laboratory testing (H_2 generator generates H_2 at 15 bar and the storage tank used to fill H_2 was 14.5 bar). Another goal of this phase was to determine over-long charge time; due to serious malfunction of the EL100 unit as discussed in Phase II ACTA Energy Help Centre was contacted to check the system.

3.7.4 Phase IV

Experiments were conducted several times to fill the H_2 storage tank of 150 litres capacity at 215 psi and time consumed to fill the tank increased every time (31.5, 39.73, 60 and 75.10 hours to fill 200 psi) resulting in unsatisfactory behaviour of Phase IV during laboratory experimentation. Figure 3.3 shows the H_2 generation in psi and time consumed in minutes for first 200 psi.

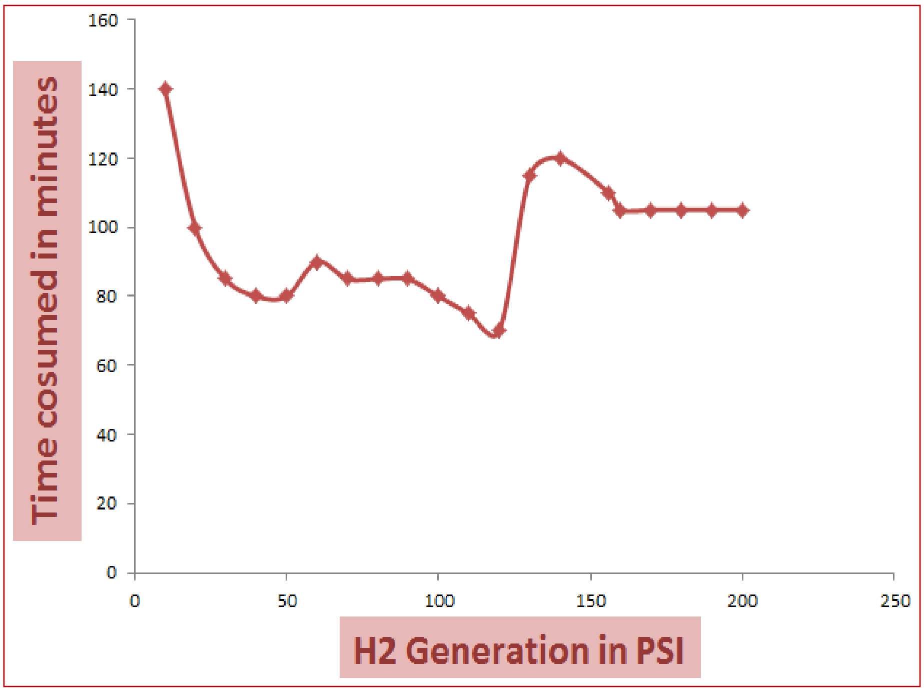

Figure 3.3 H_2 generation in psi (VS) time consumed in minutes for first 200 psi

Another goal of laboratory experimentation was to determine over-long charge time; ACTA Energy Help Centre was contacted to check the system due to serious malfunction of the stack as shown in Figures (3.4a & 3.4b) and thereafter the stack was replaced by ACTA Energy.

The main focus of this phase was to monitor H_2 generation and H_2O consumed between maximum and minimum liquid level of EL100 H_2 generator.

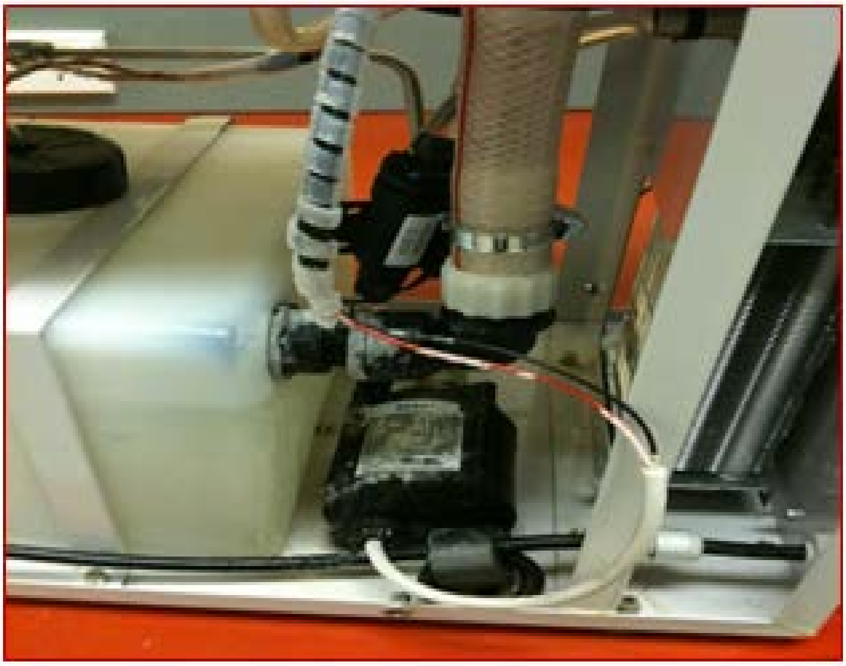

Figure 3.4a Faulty Stack (Over Long Charge Time)

Figure 3.4b Faulty Stack (Over Long Charge Time)

The capacity of the tank was 4.5 litres and approximately 3.1 litres of H_2O was filled few times between the maximum and minimum liquid level during experimentation and about 2 bottles of H_2 was generated at 208 psi of capacity of 150 litres and it took about 25.75 hours to generate one bottle of H_2 as shown in Table 3.2 and Figure 3.5. During experimentation, it was monitored that the time taken to fill first 10 psi was only 60 minutes and this confirms that no air has entered into the H_2 storage tank, during depletion of H_2 from the H_2 storage tank and the time taken to fill from 200 psi to 208 psi was only 60 minutes. H_2 generator was continued to run up to 60 minutes after reaching 208 psi as shown in Figure 3.6 and there was no increase in pressure.

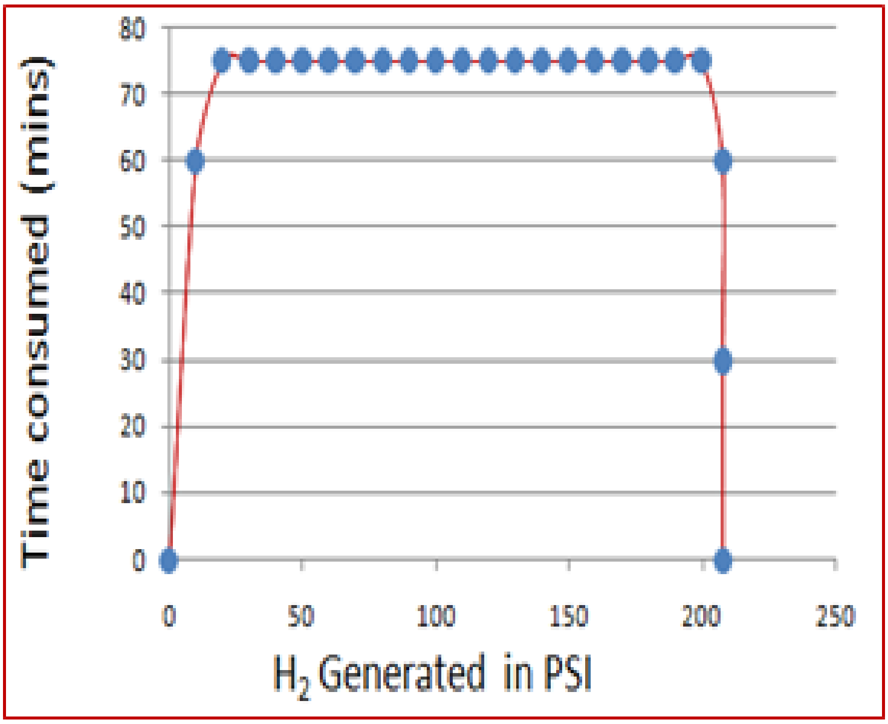

Figure 3.5 Laboratory results of H_2 generation

Table 3.2 Laboratory results of H_2 generation

S. No	H_2 generation (PSI)	Time consumed (mins)	Remarks
1	0	0	H_2 generator - Started
2	10	60	
3	20	75	
4	30	75	
5	40	75	
6	50	75	
7	60	75	
8	70	75	
9	80	75	
10	90	75	
11	100	75	
12	110	75	
13	120	75	
14	130	75	
15	140	75	
16	150	75	
17	160	75	
18	170	75	
19	180	75	
20	190	75	
21	200	75	
22	208	60	
23	208	60	H_2 generator - Stopped
Total time taken to generate H_2 at 208 PSI of capacity of 150 litres is about 25.75 hours			

Experiments were conducted about 10 times to fill the H_2 storage tank of 150 litres capacity at 215 psi and time consumed to fill the tank was always constant 25.75 hrs resulting in satisfactory behaviour of Phase IV during laboratory experimentation. After 10 times of experimentation, ACTA Energy Help Centre was contacted to check the system due to serious malfunction of the stack and thereafter the ACTA Energy provided potassium carbonate (KCO_3) to be dissolved entirely in 2.5 litres of distilled water. Experiments were conducted and in 25.75 hours only about 70 PSI H_2 was generated resulting in unsatisfactory behaviour during laboratory experimentation.

Figure 3.6 Pressure Gauge (H_2 Storage Tank)

3.7.5 Phase V

The purpose of Phase V was to address some of the research questions.

- Firstly the rain H_2O was distilled and used to generate H_2 by EL100 H_2 generator and satisfactory results were obtained resulting in generating pure H_2 as shown in Figure 3.7. This confirms that the industry claims a purity of 99.95% H_2 is correct.

Figure 3.7 Distillation of Rain Water

- Secondly, experiments were conducted three times to fill the H_2 storage tank of capacity 150 litres at 215 psi from **VRLA batteries of 48V, 120A.** During experimentation it was monitored that H_2 generator was continued to run up to **8 hours on an average producing 66 psi**, and also the batteries were recharged after H_2 generation and it was absorbed during experimentation that it took about 40 hours to recharge the batteries to charge up to 48V. Tables (3.3a to 3.3c) show the 1st set of readings monitored during experimentation. When the battery voltage was below **42V±2.0V**, a buzzer went on alarm, which indicated the DC voltage was descending and when the input voltage was below **40V±2.0V**, AC output was automatically shut off, a buzzer went on alarm and alarm/warning light turns red at the same time. The specification of Pure Sine Wave Inverter is shown in Table 3.4.

Table 3.3a Laboratory results of H_2 generation form VRLA batteries (48V, 240A)

Day	Voltage (V)	Current (A)	Time interval (mins)	Time	Total Time (mins)
				Start Time 11:45 hours	
1	48.8	7.09	15		
1	48.8	7.4	15		
1	48.7	11.47	15		
1	48.6	11.98	15	12:45 hours	60 mins
1	48.5	10.72	15		
1	48.5	7.84	15		
1	48.5	7.9	15		
1	48.5	12.39	15	1:45 hours	120 mins
1	48.2	10.5	15		
1	48.22	11.52	15		
1	48.2	10.83	15		
1	48.1	7.54	15	14:45 hours	180 mins
1	48.1	7.5	10		**190 mins**
	I Set of Readings on Day 1			Stop Time 14:55 hours	

Table 3.3b Laboratory results of H_2 generation form VRLA batteries (48V, 240A)

Day	Voltage (V)	Current (A)	Time interval (mins)	Time	Total Time (mins)
				Start Time 20:15 hours	
1	46.4	6.1	0		
1	46.3	6	15		
1	46	5.8	15		
1	46	6	15		
1	45.7	6.4	15		60 mins
1	45.5	6.8	15	21:30 hours	
1	45.5	6.8	30		**105 mins**
	3rd Set of Readings on Day 1			Stop Time 22:00 hours	

Table 3.3c Laboratory results of H_2 generation form VRLA batteries (48V, 240A)

Day	Voltage (V)	Current (A)	Time interval (mins)	Time	Total Time (mins)
				Start Time 15:10 hour	
1	48	6	15	15:15 hours	
1	48	5.5	15		
1	47.9	5.2	15		
1	47.8	6	15		
1	47.8	6.1	15	16.15 hours	65 mins
1	47.7	5.5	15		
1	47.4	6	15		
1	47.3	5.5	15		
1	47.2	5.75	15	17.15 hours	125 mins
1	47.1	5.5	15		
1	47.1	5.5	15		
1	46.8	6.5	15		
1	46.8	5.53	15	18.15 hours	185 mins
1	46.7	6	15		
1	46.6	5.3	15		
1	46.4	5.5	15		**230 mins**
	2nd Set of Readings on Day 1			Stop Time 19:00 hours	

Table 3.4 Specification of Pure Sine Wave Inverter

S. No	Time	Total Time (mins)
1	Input Voltage	40-60Vdc (48 Version)
2	Output Voltage	220V-240V±10%
3	Output frequency	50/60Hz
4	Efficiency	>90%
5	Continuous Power	2400W
6	Surge Power	4000W
7	No Load Current Draw	<0.9A
8	Weight	3.8kgs

- Finally, another goal of this phase was to determine, whether a completely off-grid, stand alone solution be reliably deployed combining Solar and H_2?

After experiments were conducted three times to fill the H_2 storage tank of capacity 150 litres at 215 psi from VRLA batteries of 48V (240A), the batteries were charged by battery charger up to 45.6V.

1.5kW monocrystalline solar panel was connected to 1.5kW solar charger and the battery was charged by solar energy as shown in Figure 3.8. Experiments were conducted for 3.5 hrs to fill the H_2 storage tank of 150 litres at 215 psi. The result obtained was satisfactory and about 28 psi of H_2 was generated as shown in Table 3.5 and this answers that a completely off-grid, stand alone solution can reliably deployed combining Solar and H_2.

Table 3.5 H_2 generation from Solar Energy

Voltage (V)	**Current (A)**	**Time interval (mins)**	**Time**	**Total Time (mins)**
			Start Time 08:15 hours.	
45.6	5.4	15		15 mins
45.1	5.5	30		
44.8	8	30		75 mins
44.6	6	30		
43.8	6.5	30		135 mins
43.1	11.5	30		
40.8	8.5	30		195 mins
			Stop Time 11:45 hours	**210 mins (28 psi)**

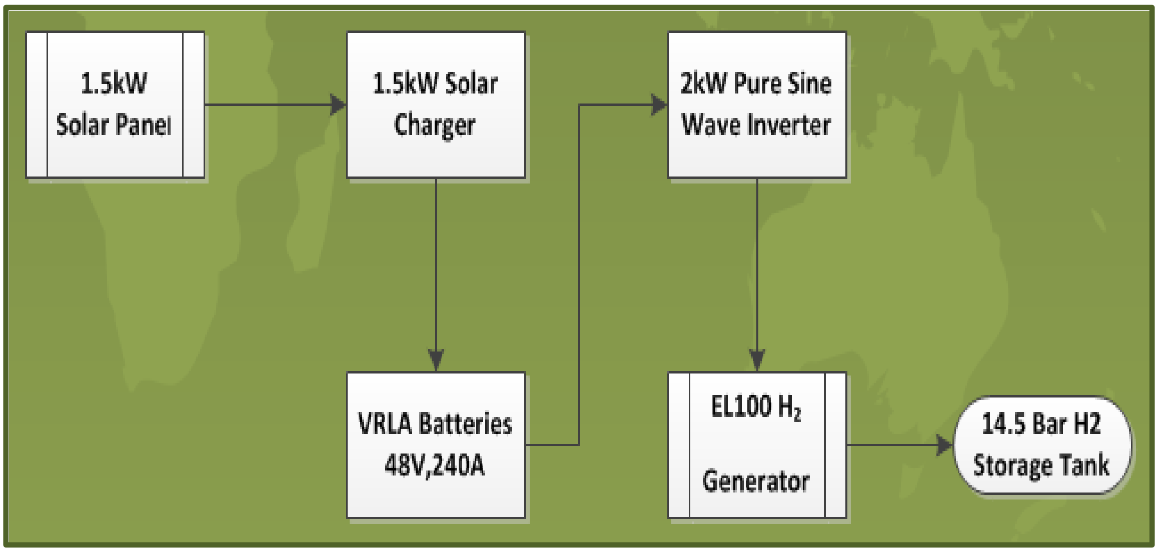

Figure 3.8 Block diagram of H_2 generation from Solar Energy

3.7.5 Phase VI

During Phase VI of the laboratory testing period, the most important result is the satisfactory behaviour of EL100 H_2 generator and T-1000 PEM Fuel Cell when both were working together simultaneously and excellent interface with the other devices like batteries, H_2 storage tank, load and measuring units.

Figure 3.9 shows the generated power trend: 5.5 hours behaviour of the system. Therefore Phase VI represents that on-site H_2 can be produced in telecommunication sites for back-up power and also can be used in NBN.

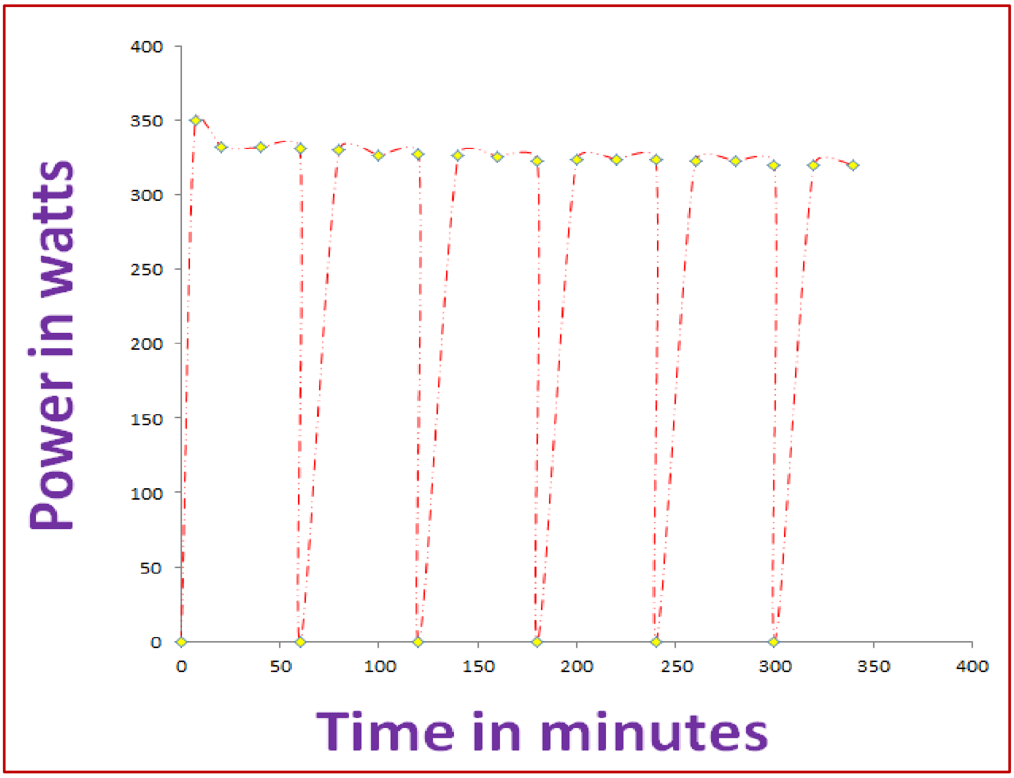

Figure 3.9 Generated power trend: 5.5 hours behaviour

3.8 Summary

At the end of the current laboratory analysis and testing, the most important result was the satisfactory behavior of EL100 H_2 generator in terms of reliability, long run capability, safety signals and excellent interface with other devices. The unsatisfactory results obtained from laboratory analysis were over-long charge time and automatic switching-off of process before completion of the charging and due to over pressure. The laboratory results in Phase IV shows that 2 bottles of H_2 can be generated from 3.1 litres of H_2O and each bottle of H_2 can be generated in 25.75 hours. During Phase V satisfactory results were obtained in generating pure H_2 from rain H_2O and a completely off-grid stand alone solution can be reliably deployed combining Solar and H_2. Also H_2 generator was continued to run up to 8 hours on an average producing 66 psi from VRLA batteries of 48V, 240A. Satisfactory results were obtained in Phase VI when EL100 H_2 generator was working with T-1000 PEM Fuel Cell and other devices like batteries, H_2 storage tank, load and measuring units. This work mainly focused to produce H_2 on-site by rain H_2O and to run T-1000 PEM Fuel Cell system for long run capabilities (8 hours) at 1kW to meet back-up power for telecommunications site and it can have satisfactory usage in Australian NBN.

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Chapter 4

T-1000 Proton Exchange Membrane (PEM) Fuel Cell as a Back-up Power for Telecommunication Sites and Techo-economic Simulation and Optimization of H_2 Energy and Fuel Cell Power Generation System

4.1 Introduction

The National Broadband Network (NBN) initiated by Australian Federal Government ($43 billion) will provide 93% of Australian homes with high-speed broadband for remaining 7% of the premises next-generation wireless and satellite technologies will be provided [4.1-4.2]. To ensure the operability of cell towers, to maintain constant power supply and to prevent power outages telecommunication providers rely on back-up power. Usually electrical power from public electrical grid line provides ac voltage and telecommunications equipment needs dc voltage, rectifier is used for power conversion in telecommunication sites [4.2-4.4]. The electrical grid is subject to disruption by natural and man-made causes and the required back-up power for telecommunications by regulation is 8 hours. Lengthy back-up power capability is required between 24 to 72 hours to cater for unexpected long-duration outages and many telecommunication operators oversize their Valve Regulated Lead Acid (VRLA) battery banks as much as 300% (up to 24 hours back-up time). Most of the telecommmunication sites rely on VRLA battery banks for back-up power or, in some higher power situations diesel generators with a small battery bridge. Ultracapacitors, flywheels and new battery technologies have been employed recently. Although each technology has some advantages the service providers are searching for alternatives because disadvantages of each technology are significant. To meet back-up power requirements in stationary applications Fuel Cell manufactures have responded by designing Fuel Cell systems to compete with traditional technologies [4.2-4.4].

Section 4.2 of the chapter highlights the Fuel Cell technology and its benefits. Relion T-1000 Fuel Cell System and its advantages and Valve Regulated Lead Acid (VRLA) batteries are discussed in Sections 4.3 and 4.4. The planning of laboratory testing and experimentation at Power Systems Research Laboratory, Victoria University are explained in Section 4.5 and Section 4.6 describes the system installed in detail. Section 4.7 points out the analysis and evaluation of the laboratory results and trouble-shooting of T-1000 PEM Fuel Cell are highlighted in Section 4.8. Section 4.9 examines the Simulation and Optimization of H_2 Energy and Fuel Cell Power generation System and finally Section 4.10 provides the summary of this chapter.

4.2 Fuel Cell Technology

A Fuel Cell is a solid state dc power that converts chemical energy of H_2 and O_2 into electricity and the only by-products are heat and H_2O. Both the benefits of traditional technologies i.e. very quick start-up (battery based UPS) and long run time (diesel genset) are achieved by Fuel Cells.

Regardless of weather, time of day and location Fuel Cells can deliver power as long as the fuel (in this case H_2) and air are supplied [4.5-4.7]. The different types of Fuel Cells and the chemical reaction of alkaline Fuel Cell and phosphoric acid Fuel Cells are explained in Chapter 2. The direct current (dc) bus voltage is continuously sensed by the Fuel Cell system, it takes over critical loads if the dc bus falls below a customer determined set point [4.7-4.11]. The most appropriate and commercially available Fuel Cell today for use with wireless telecommunications site is the Proton Exchange Membrane (PEM) Fuel Cell as shown in Figure 4.1. Due to its low operating temperature, silent operation, quick start-up characteristics and better performance PEM Fuel Cell is also attractive for residential use and automotive industry [4.5-4.7]. In PEM Fuel Cell electrolyte is in the centre, anode and cathode are located in both sides of the membrane which is referred as Membrane Electrolyte Assembly (MEA) and Nafion is generally used for MEA. A micro-porous layer (MPL) is included to provide a transition between the electrode and the backing layer to assist H_2O transport. H_2 dissociates into protons (H^+) and electrons (e^-) at the anode. To produce electricity for a given load, electrons are insulated and forced to travel through an external circuit by a polymer known as 'Ionomer' and the protons travel through the electrolyte to the cathode. At the cathode side protons, electrons and O_2 combine to form H_2O and heat as by-product. H_2 is oxidised and O_2 is reduced to H_2O as shown in the equations (4.1) and (4.2) [4.5-4.7].

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{4.1}$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{4.2}$$

No pollutant emissions, less noise emissions, reduced maintenance; high electrical efficiency and low operating temperature are some of the benefits of PEM Fuel Cell [4.5-4.7].

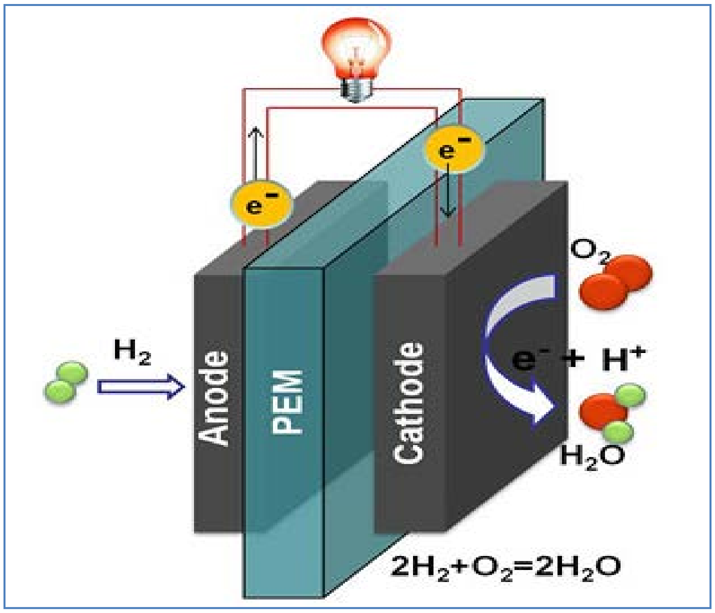

Figure 4.1 Schematic working principle of a Fuel Cell [4.3]

4.3 T-1000 PEM Fuel Cell System

T-1000 PEM Fuel Cell system is hot-swappable as shown in Figure 4.2 for “always on” operations and is designed with modular cartridge technology as shown in Figure 4.3 based on proton exchange membrane (PEM) technology. This modular approach provides clean, quiet, reliable power for back-up power applications and ease of service. Electronic cards and Fuel Cell cartridges can be added, removed or replaced while the system is in service and delivering power. This facility allows the system configuring from 600W to 1200W at any time. T-1000 Fuel Cell system is self-hydrating (eliminating the need for a separate source of water) and air-cooled (eliminating the need for liquid pumps and heat exchangers) [4.8].

T-1000 Fuel Cell system remains in standby mode until called into service using

- Low Voltage,
- Contact Start,
- Remote (User Interface) and
- Manual (Front panel button) [4.8].

Low Voltage and Contact Start methods are designed to operate automatically. Using the Run Screen of the User Interface the unit can be started remotely selecting the start function. By pressing the On/Standby button on the controller card the unit can be manually started from the front panel. ReliOn's modular cartridge technology reduces single point of failure and simplifies maintenance. Each cartridge is able to supply a nominal power of up to 200W. When fully configured T-1000 Fuel Cell system will provide up to 1200W and can also partially be configured to smaller loads. In the event that cartridge should fail during operation, the system will take cartridge off-line and the replacement can be performed in few seconds. T-1000 fuel system will operate at reduced power with the remaining cartridge till the cartridge is replaced. The specifications of T-1000 PEM Fuel Cell system are shown in Table 4.1 [4.8].

4.3.1 Advantages of T-1000 Fuel Cell system

Several strong features of T-1000 PEM Fuel Cell system in comparison with other commercial fuel cell systems include

- Modular System,

- High redundancy and
- Focussed systems [4.8].

Figure 4.2 T-1000 PEM Fuel Cell [4.8]

Figure 4.3 T-1000 PEM Fuel Cell cartridges [4.8]

Table 4.1 Specifications of T-1000 PEM Fuel Cell system [4.8]

Product specifications T-1000 Fuel Cell system		
Physical	Dimensions (w x d x h)	35.6cm x 54.6cm x 66cm
	Weight	98 to 164 lbs / 44 to 74 kg
	Mounting	19” rack mount
Performance	Rated net power	0 to 1,200 Watts
	Rated current	0 to 25A 48Vdc
	dc voltage	24 or 48 Vdc nominal
Fuel	Composition	Standard industrial grade hydrogen (99.95%)
	Supply pressure to unit	3.5 to 6 psig / 24 to 41 KPag
	Consumption	16.9 slpm @ 1200 Watts
Operation	Ambient temperature	35^{o}F to 115^{o}F / 2^{o}C to 46^{o}C
	Relative humidity	0-95% non-condensing
	Altitude	-197 ft to 13,800 ft / -60m to 4206m
	Location	Indoors
Emission	Water	Max. 30mL / kWh
	Noise	53 dBA @ 3.28 ft / 1 meter

4.4 VRLA Batteries for Back-up Power in Telecommunications sites

The most back-up power systems used in telecommunication sites today rely on VRLA batteries as shown in Figure 4.4

- VRLA batteries with higher energy/volume and higher/weight ratio provide the telecommunication industry in easy installation. VRLA batteries also provide the telecommunication industry with safe, reliable, space efficient and cost-effective standby power systems. To enable VRLA batteries to be fully charged, reduce overcharge and extend life many charging methods have been evolved recently [4.9-4.11].

- VRLA battery management system has been developed, to measure voltage and ambient temperature of each cell remotely in order to ensure that a reliable telecommunications is maintained to prevent unexpected power failures. To ensure a highly reliable power supply, an electrolyte leakage detection function and resistance measurement function have been added to VRLA battery remote management system [4.9-4.11].

Figure 4.4 Valve Regulated Lead Acid (VRLA) Batteries (48V, 60A) in Power Systems Research Laboratory

4.5 Planning of Laboratory Testing and Experimentation at Power Systems Research Laboratory, Victoria University

The goal of the project, which involved strong collaboration between Victoria University, SEFCA and Acta Energy, was the testing of T-1000 PEM Fuel Cell and its integration into telecommunications site for back-up power solution that can be used in telecommunication application like NBN. The initial point of the testing was the need to demonstrate a very high reliability as compared to the traditional systems (battery banks and diesel-generator sets). The described evaluation was performed on the units integrated at Power Systems Research Laboratory at Victoria University. All aspects of T-1000 PEM Fuel Cell were studied and evaluated including H_2 delivery procedure, maintenance, starting logic and gas line planning to determine the complete back-up power solution. After the installation of the system at Power Systems Research Laboratory at Victoria University, system commissioning included several checks of the alarm system and for leaks in the gas line planning (from EL100 H_2 generator to storage tank and T-1000 PEM Fuel Cell), the calibration of the control units and the transmission of the data generated from T-1000 PEM Fuel Cell System [4.3].

4.5.1 Phase I

The purpose of Phase I was to verify the behavior of T-1000 PEM Fuel Cell system. In this phase the Fuel Cell was started for every 30 minutes and stopped for 15 minutes at regular time interval until 100 psi of H_2 was consumed from the H_2 storage tank of 150 litres at 215 psi [4.3].

4.5.2 Phase II

The aim of Phase II was testing the long run capabilities of the back-up power systems when both T-1000 fuel system and EL100 H_2 generator are working together simultaneously [4.3]. The main focus of this Phase II was to address, "**Can a system be setup to produce H_2 at the same time it is using it for power".**

4.5.3 Phase III

The main focus of Phase III was to examine EL100 H_2 generator and T-1000 PEM Fuel Cell system for long run capabilities since the required back-up power for **telecommunications by regulation is 8 hours** for the desired load of 1kW.

4.5.4 Phase IV

The purpose of Phase IV was to monitor, "**How long it will take to produce enough H_2 to run 1.2kW T-1000 PEM Fuel Cell for 1, 4 and 8 hours".**

4.5.5 Phase V

The main aim of Phase V was to examine how long VRLA Batteries (48V, 60A) will run to meet back-up power for telecommunications site for the desired load of 1kW.

4.6 Description of the System Installed

The Fuel Cell system was connected in parallel with the batteries in telecommunications site to be a back-up power solution as shown in Figure 4.5. In case of low back-up battery voltage and loss of electrical grid power H_2 generator and Fuel Cell were configured for start-up [4.3]. The H_2 storage tank was connected to a safety valve in order to avoid accidental gas depletion. Two pressure regulators at 50 psi and 5 psi were installed in front of each safety valve in order to reduce the final pressure valve (ranging from 3.5 psi to 6 psi) [4.3, 4.8].

Until the output voltage decreases to 44V±0.5V due to overload or the depletion of H_2, the 48V Fuel Cell continues operation. During operation, if T-1000 PEM Fuel Cell system detects that the bus output voltage was below the low voltage start parameter (50V at 48Vdc) fuel cell will starts and provides power to the load and the system achieves float voltage (52.5V at 48Vdc). For dc back-up power systems 20Ahr per kW for a 48V was required for Fuel Cell start-up. The battery capacity should be increased to accommodate operation at ambient temperature above 40^0C as shown in equation (4.3) [4.8].

$$(\text{Ahr})_i = 32/V \times (\text{Load}) \times (\text{Runtime}) \times (\text{Temp} - 40^0\text{C}) \tag{4.3}$$

Where, $(\text{Ahr})_i$ = Battery capacity increment for high ambient temperature, Amp-hr.

V = Nominal voltage (48).

Load = Nominal equipment load, kW.

Run Time = Anticipated Fuel Cell Run Time, Hours.

Temp = Ambient Operating Temperature, ^{0}C.

If the ambient temperature operation is below 40^0 C, then the equation (4.3) does not apply. T-1000 Fuel Cell system requires a minimum of 3 to a maximum of 6 cartridges. To determine the number of cartridges, the load is multiplied by 1.2 and the result is divided by 200 (Watts per cartridge) and rounded up to get the number of cartridges for the required load. A computer with a serial port and a serial cable is connected to the T-1000 Fuel Cell system's I/O Card serial port. The minor error codes like "Cartridge # failed, Low fuel alarm, Converter # failed" and major error codes like "No fuel, I/O identity failed, Low bus voltage" are monitored from the computer [4.8].

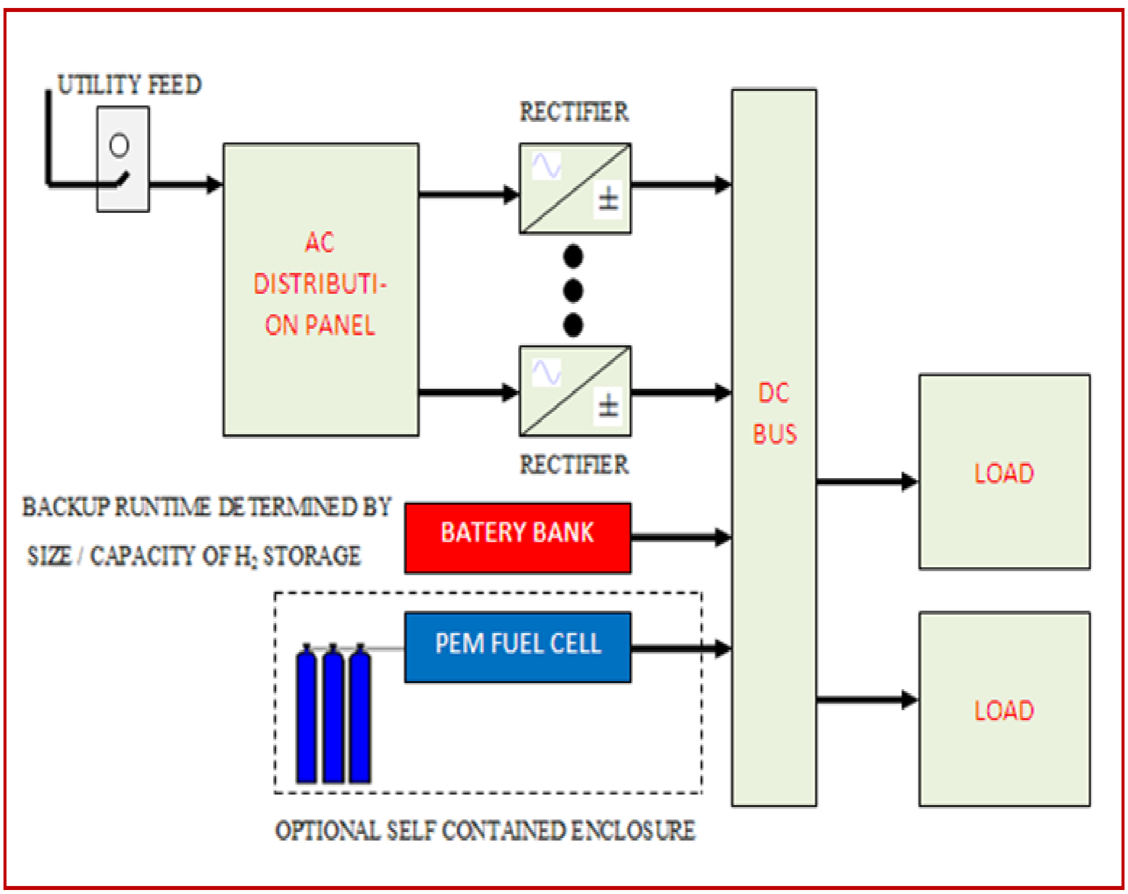

Figure 4.5 Typical Site Back-up Power System – Fuel Cell [4.8]

4.7 Analysis and Evaluation of the Laboratory Results

4.7.1 Phase I

The most important result of laboratory testing of Phase I was the verification of reliability: when start-up required by T-1000 PEM Fuel Cell. The unit performed as designed when start-up was required throughout the laboratory testing resulting in 100% reliability [4.3].

4.7.2 Phase II

As mentioned earlier, the Phase II was performed to verify the reliability of the systems in extended tests as when both T-1000 fuel system and EL100 H_2 generator is working together simultaneously. During laboratory experimentation satisfactory results were obtained when both T-1000 fuel cell and EL100 H_2 generator were working together simultaneously resulting in 100% reliability [4.3] as shown in Table 4.2. Another goal of this phase was to determine "**Can a system be setup to produce H_2 at the same time it is using it for power**" and this was **achieved throughout the laboratory testing for 4.5 hours** until 100 psi (from H_2 storage tank) and 23 psi (generated by H_2 generator) was consumed as shown in Figure 4.6. Therefore Phase II confirms that on-site H_2 can be produced in telecommunication sites for back-up power and also can be used in NBN. The other result obtained from Phase II of laboratory experimentation was **H_2 depletion signal from the H_2 storage tank** and different types of alarm (No fuel alarm, Low fuel alarm and door alarm) was monitored remotely as shown in Figure 4.7.

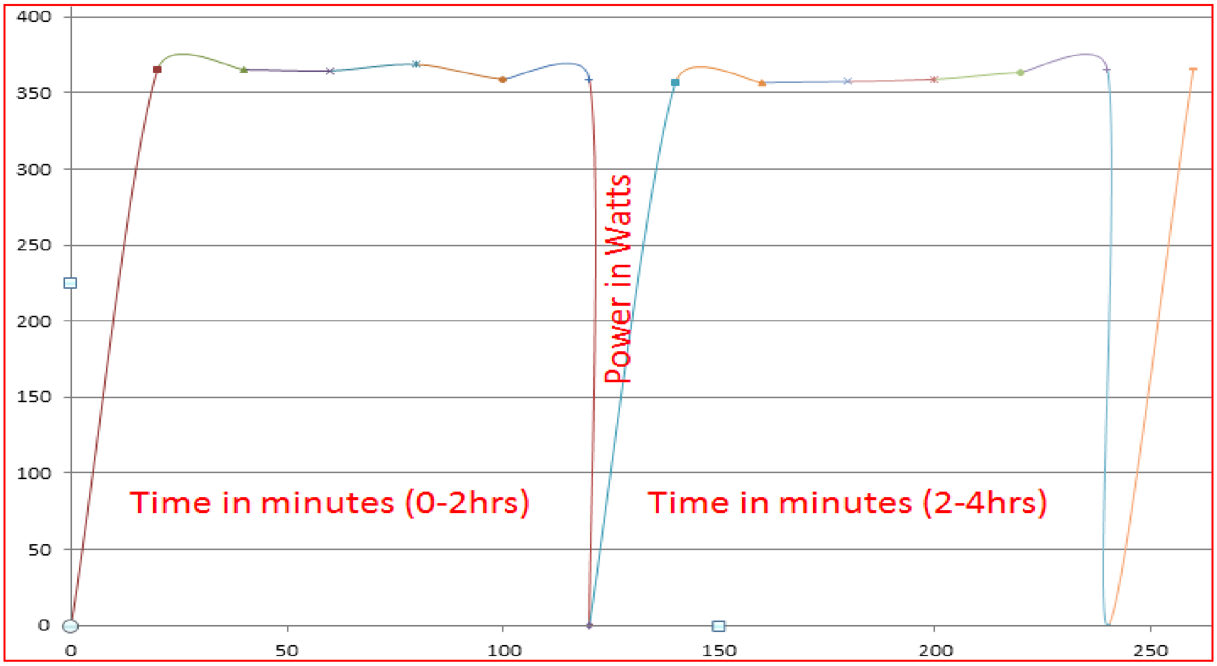

Figure 4.6 Generated power trend: 4.5 hours behaviour

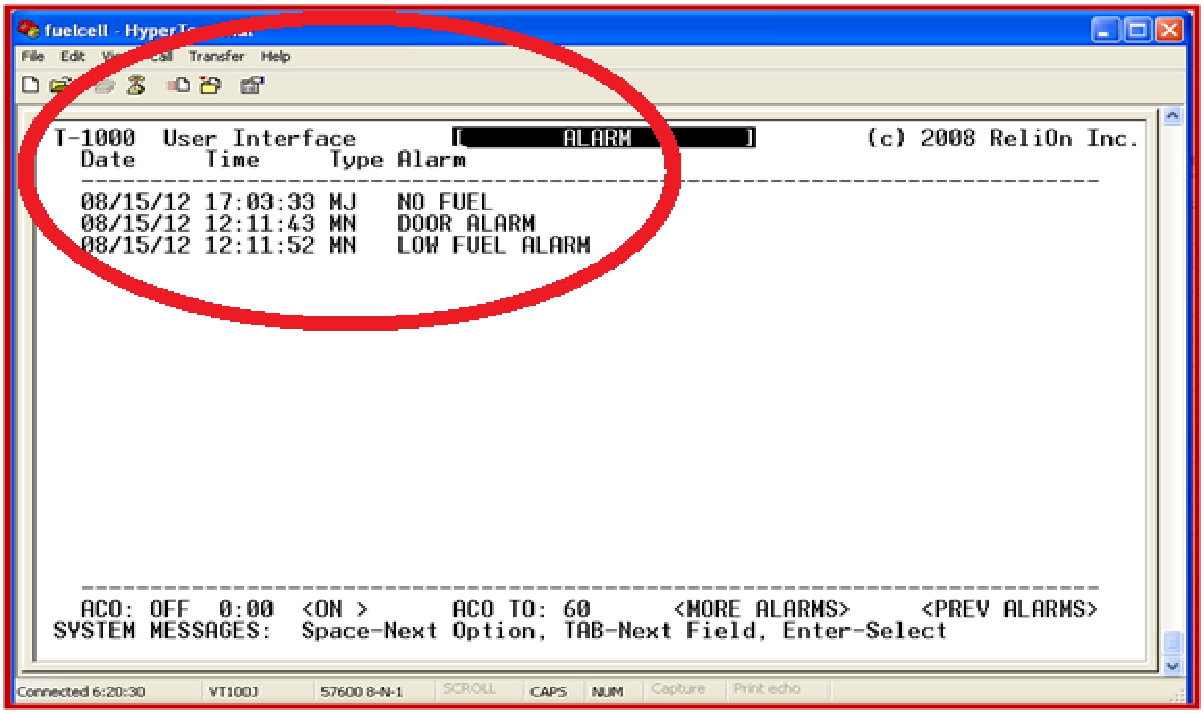

Figure 4.7 H_2 depletion signal and door alarm

Table 4.2 Laboratory results of T-1000 PEM fuel cell and EL100 H2 generator when both are working together simultaneously

No Load Voltage			
Battery	52.2	Time	3:40pm 17/4/2010
Fuel Cell	52.4		
Load	52.3		

Battery			Fuel Cell				Load			Time in munites	
Voltage	Current	Power	Voltage	Current	Power	Pressure reading	Voltage	Current	Power		
50.8	8.1	411.48	49.3	0.9	44.37	160	47.8	7.35	351.33	0	3:40pm 17/4/2010
50.6	4	202.4	50.8	3.5	177.8	160	48.7	7.5	365.25	20	4:00pm 17/4/2010
50.5	3.2	161.6	51	4.6	234.6	150	48.7	7.5	365.25	40	4:20pm 17/4/2011
50.3	3.2	160.96	49.1	4.3	211.13	140	48.6	7.5	364.5	60	4:40pm 17/4/2011
50.2	3.2	160.64	48.1	4.4	211.64	140	48.5	7.6	368.6	80	5:00pm 17/4/2012
50	3	150	50.6	4.5	227.7	130	48.2	7.45	359.09	100	5:20pm 17/4/2013
49.9	2.8	139.72	50.6	5	253	120	48.2	7.45	359.09	120	5:40pm 17/4/2014
49.8	2.3	114.54	50.6	5.2	263.12	110	48.1	7.42	356.902	140	6:00pm 17/4/2013
49.8	2.3	114.54	50.7	5.5	278.85	100	48.2	7.4	356.68	160	6:20pm 17/4/2011
49.8	1.8	89.64	50.9	5.8	295.22	100	48.3	7.4	357.42	180	6:40pm 17/4/2011
49.9	1.3	64.87	51	6.7	341.7	90	48.5	7.4	358.9	200	7:00pm 17/4/2012
49.9	0.9	44.91	51.4	7.1	364.94	80	48.6	7.48	363.528	220	7:20pm 17/4/2013
49.9	0.6	29.94	51.4	7.4	380.36	70	48.7	7.5	365.25	240	7:40pm 17/4/2014
50	0.5	25	51.6	7.3	376.68	60	48.8	7.5	366	260	8:00pm 17/4/2013
THE FUEL SYSTEM WAS STOPPED AT 8:10 P.M. TOTAL WORKING HOURS = 4 hours 30 minutes consumed 100 PSI of H2 in 150 Litres H2 tank										270	4/17/2013 8:10

4.7.3 Phase III

In Phase III the work mainly focuses to produce H_2 on-site by rain H_2O and to run T-1000 PEM Fuel Cell system for long run capabilities (8 hours) at 1kW to meet back-up power for telecommunications site and also can have satisfactory usage in NBN. Experiment shows that 150l H_2 gas bottle at 15 bar can run the Fuel Cell for **very near to 8 hours** at 250W load as shown in Table 4.3 when both EL100 H_2 generator and T-1000 PEM Fuel Cell system were running simultaneously. At 1kW load T-1000 1.2kW PEM Fuel Cell consumed 1**29 psi to run for 2 hours and 20 minutes** resulting in unsatisfactory behaviour to meet the **required 8 hours** of back-up power for telecommunications site. **Changing 50 psi regulator to 10 psi** as shown in Figure 4.8, Fuel Cell can run for about 8 hours at 400W load. It is recommended by our experimentation that 150l H_2 bottle at 30 bar **(increasing the pressure from 15 bar to 30 bar**) can run the Fuel Cell for 8 hours at 1kW load.

Table 4.3 Laboratory Results of El00 H_2 generator and T-1000 PEM Fuel Cell for different loads

S. No	Load in Watts	Fuel Cell Run Time in Hrs	H_2 Consumed		Total H_2 Consumed
			From H_2 Storage Tank	Generated from H_2 Generator	
1	200	9 hrs. 30 mins.	110 psi	76 psi	186 psi
2	250	7 hrs. 50 mins.	110 psi	62 psi	172 psi
3	300	6 hrs. 45 mins.	110 psi	54 psi	164 psi
4	**1000**	**2 hrs. 20 mins.**	**110 psi**	**19 psi**	**129 psi**

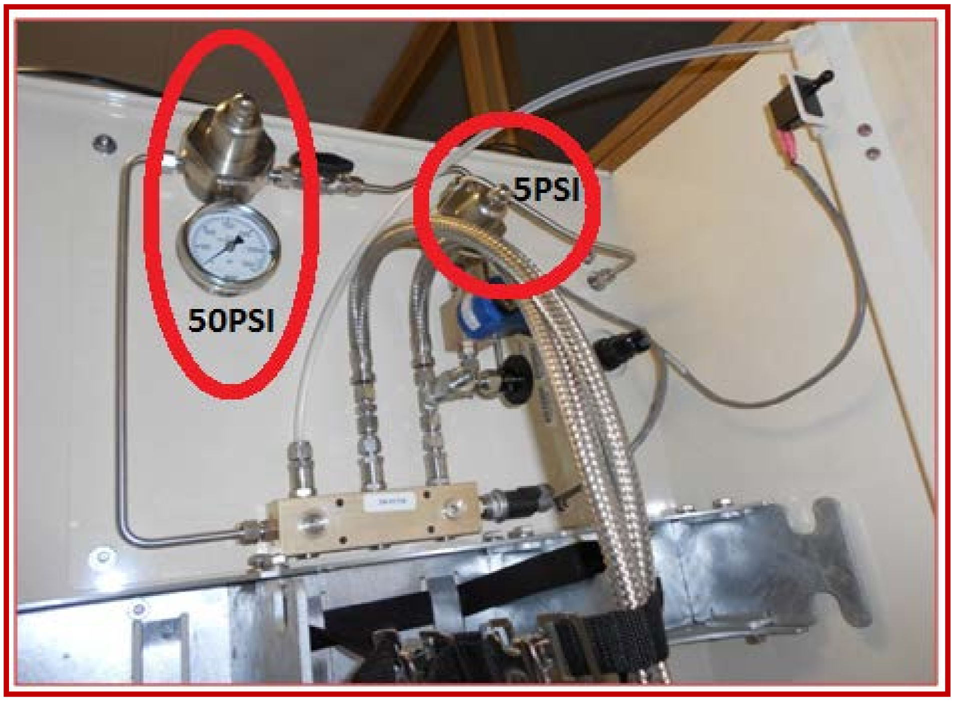

Figure 4.8 Regulators of T-1000 PEM Fuel Cell (50 PSI & 5 PSI)

4.7.4 Phase IV

Experiments were conducted during Phase IV to monitor the time consumed to produce enough H_2 to run T-1000 PEM Fuel Cell for 1, 4 and 8 hours. The time consumed to produce enough H_2 for 1kW load was calculated for 1, 4 and 8 hours as shown in Table 4.4 since the required back-up power for **telecommunications by regulation was 8 hours** for the desired load of 1kW.

4.7.5 Phase V

During Phase V experiments were conducted to examine how long VRLA Batteries (48V, 60A) will run to meet back-up power for telecommunications site for the desired load of 1kW. During experimentation VRLA batteries were stopped at 43.5V since T-1000 PEM Fuel Cell will stop operating due to low battery voltage (44±0.5V) or once the output voltage decreases to 44±0.5V due to overload or depletion of H_2. Also during Phase V experiments were conducted to examine the run time of VRLA batteries for different loads as shown in Tables 4.5 and 4.6.

Table 4.4 Laboratory results to calculate the time consumed to run 1.2kW for 1, 4 and 8 hours

S. No	Load	T-1000 PEM fuel cell run time	H_2 consumed by T-1000 PEM Fuel cell	Time consumed to generate H_2 from EL100 H_2 Generator
1	1kW	1 hr	55 psi	6.62 hours
2	1kW	4 hrs	220 psi	27.25 hours
3	1kW	8 hrs	440 psi	54.75 hours

Table 4.5 Experimental readings of VRLA batteries for different loads
(200, 250, 300 and 1000 Watts)

S. No	Load in Watts	Total run-time in minutes by VRLA Batteries (48V, 60A)
1	200	57 mins.
2	250	45 mins.
3	300	28 mins.
4	1000	8 mins.

Table 4.6 Battery Readings for load (250W)

<table>
<tr><th rowspan="2">S. No</th><th colspan="2">Battery</th><th rowspan="2" colspan="2">Time (mins)</th></tr>
<tr><th>Voltage (V)</th><th>Current (A)</th></tr>
<tr><td>1</td><td>49.1</td><td>4</td><td>0</td><td rowspan="7">Total run time: 45 mins
Load: 250W
No Load Voltage: 50.3V</td></tr>
<tr><td>2</td><td>47.4</td><td>3.5</td><td>10</td></tr>
<tr><td>3</td><td>46.4</td><td>3.8</td><td>20</td></tr>
<tr><td>4</td><td>44.7</td><td>3.5</td><td>30</td></tr>
<tr><td>5</td><td>43.9</td><td>3.3</td><td>40</td></tr>
<tr><td>6</td><td>43.5</td><td>3</td><td>45</td></tr>
<tr><td colspan="4">Started at 5.25 p.m. on 4th May 2013
Stopped at 6.10 p.m. on 4th May 2013</td></tr>
</table>

4.8 Trouble-shooting of T-1000 PEM Fuel Cell

During experimentation at one stage, it was monitored that H_2 was consumed very quickly by T-1000 by PEM Fuel Cell from the H_2 storage tank of capacity 150 litres at 215 PSI. Therefore, all H_2 connections were tested for leakage using an approved soap solution. During the test, it was monitored that there was a leakage of H_2 in the high pressure regulator (50 PSI) as shown in Figure 4.9 and the results are shown in Table 4.7 and the leakage was fixed thereafter. Towards the end of the laboratory experimentation period, it was monitored that when T-1000 PEM Fuel Cell was started, it stopped producing power within 15- 20 minutes as shown in Figure 4.10. Sustainable Energy Fuel Cell Australia (SEFCA) was contacted to test the T-1000 PEM Fuel Cell system.

Table 4.7 Laboratory Results of El00 H_2 generator and T-1000 PEM Fuel Cell

(During H_2 leakage at 50 PSI High Pressure Regulator)

PEM FUEL CELL READINGS - NO LOAD VOLTAGE: 49.8V (Load 300W)				
S.NO	**VOLTAGE**	**CURRENT**	**H_2 READINGS NOTED FROM MONITER IN PSI**	**TIME**
1	**47.9**	**0.2**	**160**	1.30 P.M.
2	**46.8**	**3.5**	**130**	2.00 P.M.
3	**46.8**	**5.6**	**100**	2.30 P.M.
4	**47.2**	**6.5**	**70**	3.00 P.M.
T-1000 PEM FUEL CELL STOPPED AT 3.05P.M. **ALARM:NO FUEL ALARM**				

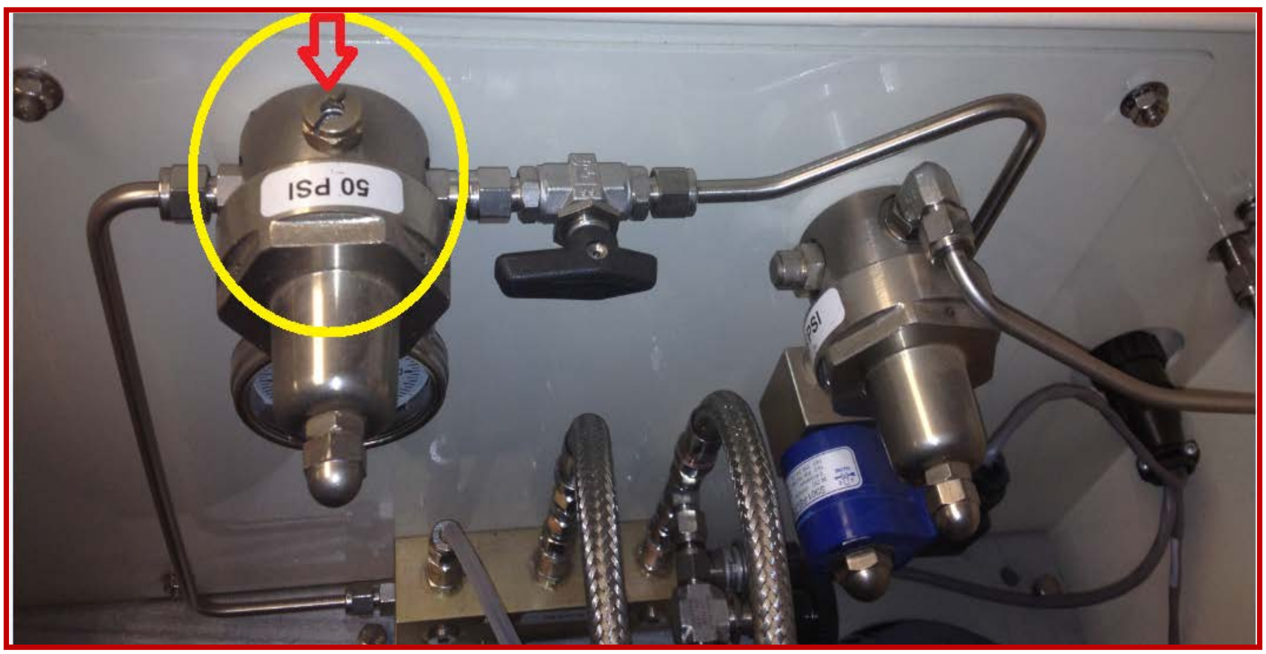

Figure 4.9 H_2 leakages at High Pressure Regulator (50 PSI)

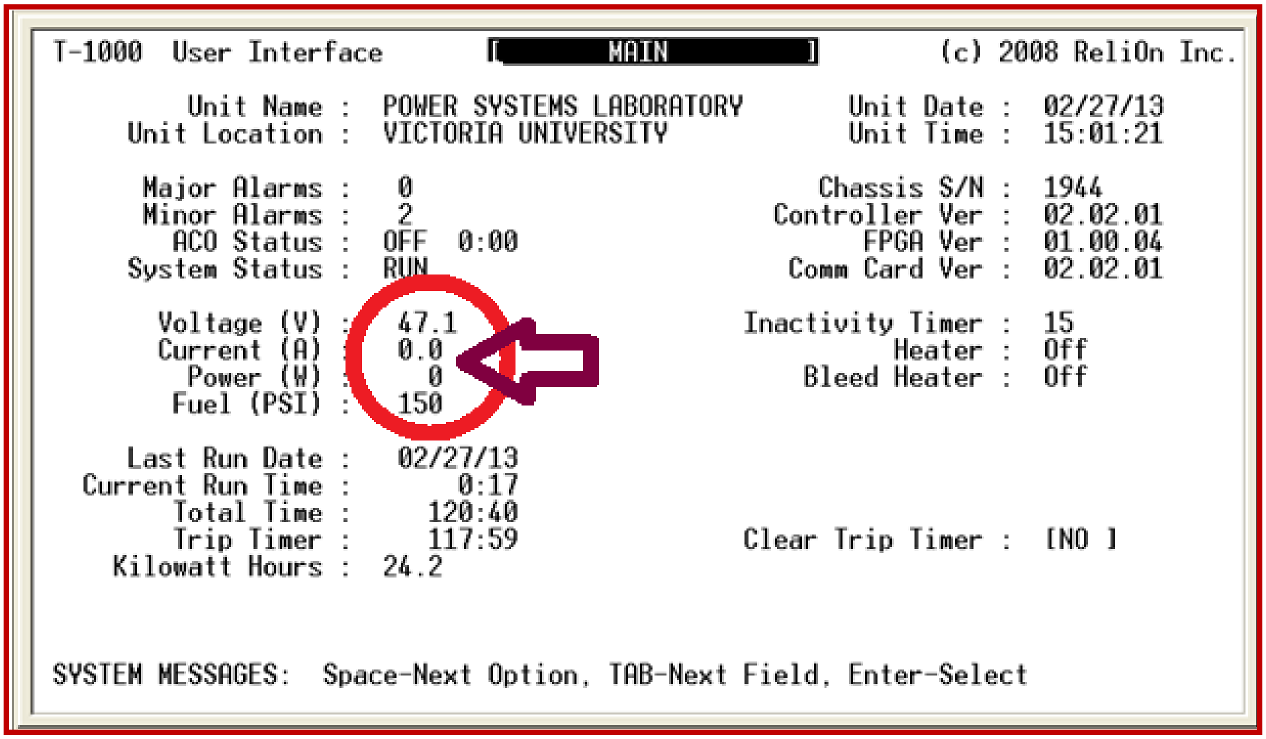

Figure 4.10 T-1000 User Interface (No power produced after 17 mins)

4.9 Techo-economic Simulation and Optimization of H_2 Energy and Fuel Cell Power Generation System

The Hybrid Optimization Model for Electric Renewable (HOMER) software was used to model the implemented H_2 Energy and Fuel Cell Power Generation System. The H_2 Energy and Fuel Cell Power generation System with a grid connected system (also known as distributed generation or DG systems) and an off-grid system with that of grid extension, “Compare stand-alone system to grid-connected” was simulated by the HOMER coding as shown in Figures 4.11 (a and b). Since the implemented H_2 Energy and Fuel Cell Power Generation System was posed as an optimization problem, corresponding to the system constraints and performances the objective functions were formulated. The study in this Chapter aims to investigate the economic, technical and environmental performance of the implemented H_2 Energy and Fuel Cell Power Generation System at Power Systems Research Laboratory at Victoria University. Using global solar irradiation as in Figures 4.12 (a and b) as solar energy data shown, load data (1kW required for back-up power for telecommunication sites) as shown in Figures 4.13 (a and b), the price of (PV array, T-1000 PEM Fuel Cell, H_2 generator, H_2 storage tank, converters and batteries) as shown in Table 4.8, grid electricity tariff and sale-back tariff as inputs of economic analysis, H_2 Energy and Fuel Cell Power Generation System was simulated and optimized by HOMER [4.12]. Single rate meter from AGL Energy tariff [4.13] and Premium feed-in tariff [4.14] was used to optimize system in this chapter which is explained in detail in Chapter 6.

The simulation results presented in this section as shown in Tables 4.9 and 4.10 show the long term implementation of H_2 Energy and Fuel Cell Power generation System, where the electricity load per day is 1kWh/d and 1.9kW peak and economical, technological and environmental performances are the three type of results presented and discussed in this section. In terms of economic consideration for the H_2 Energy and Fuel Cell Power Generation System with a grid connected system (also known as distributed generation or DG systems) it was found that

- The COE is 0.961 $/kWh and an off-grid system with that of grid extension, “Compare stand-alone system to grid-connected.”
- The COE increases rapidly to 57.146 $/kWh.

Based on the analysis of simulation results, it has been found that DG systems are cheaper than off-grid system with that of grid extension.

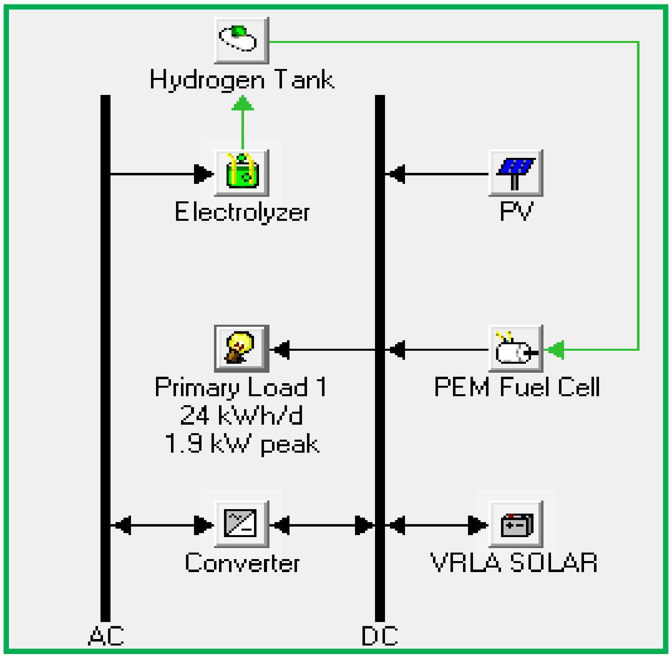

Figure 4.11a HOMER CODE: To compare stand-alone systems to grid extension

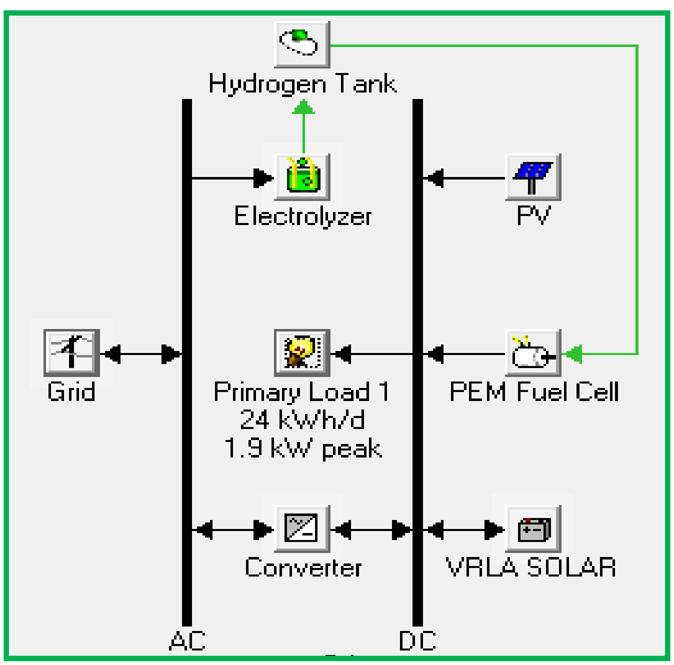

Figure 4.11b HOMER CODE: Grid Connected system

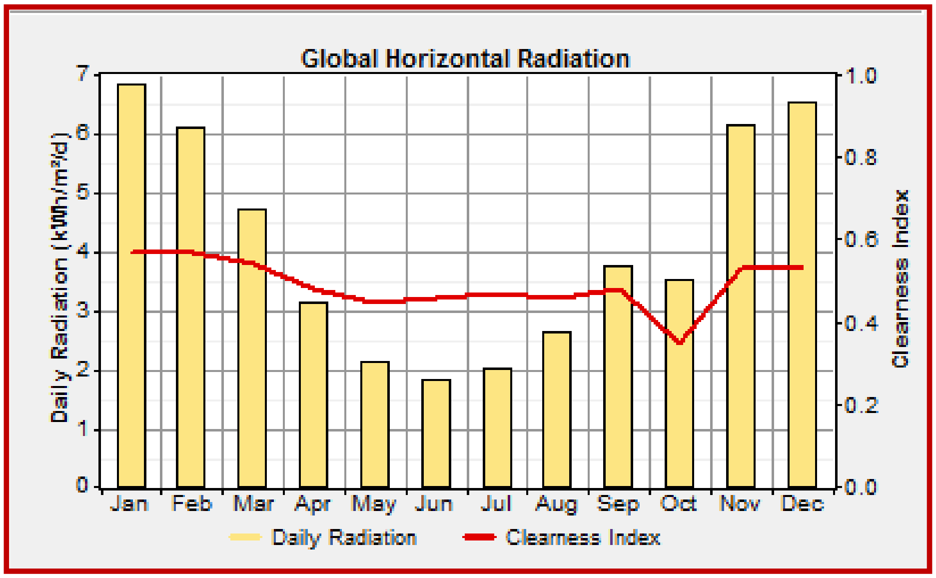

Figure 4.12a Global solar radiations (kW/m^2) per annum of Victoria, Australia

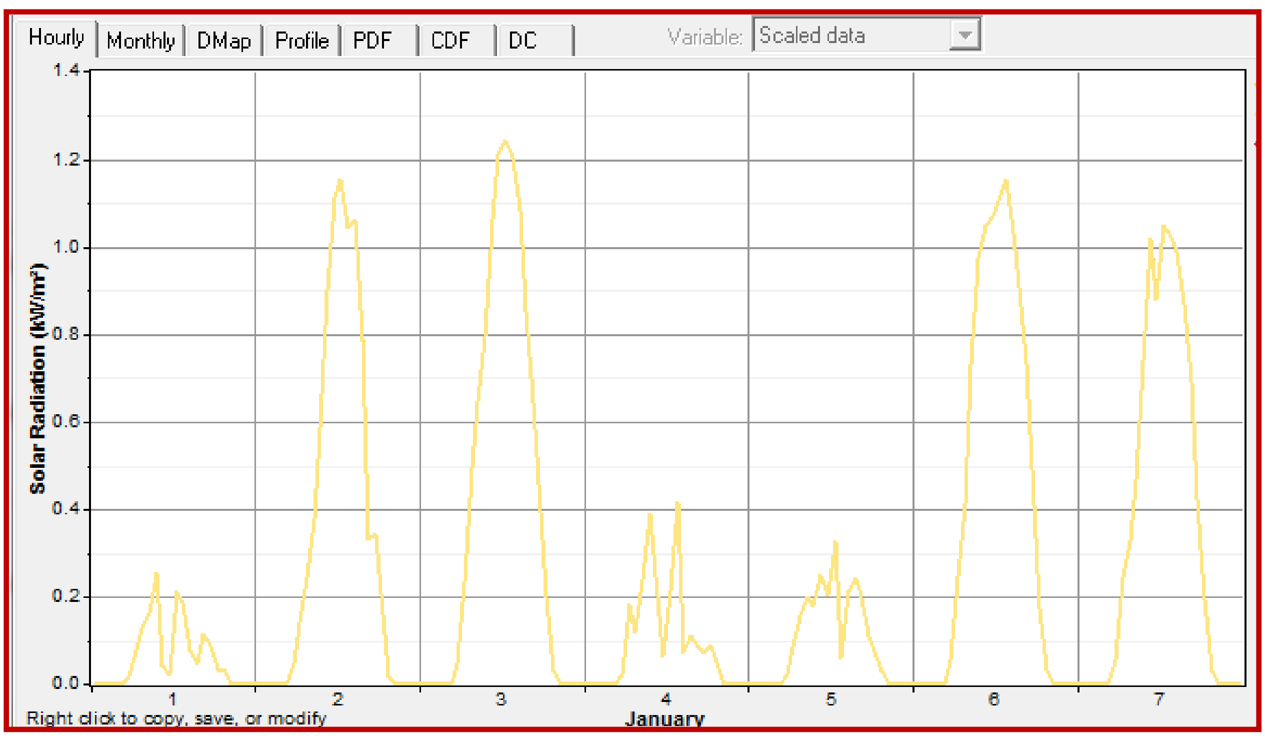

Figure 4.12b Global solar radiations (kW/m^2) for 7 days during the month of January

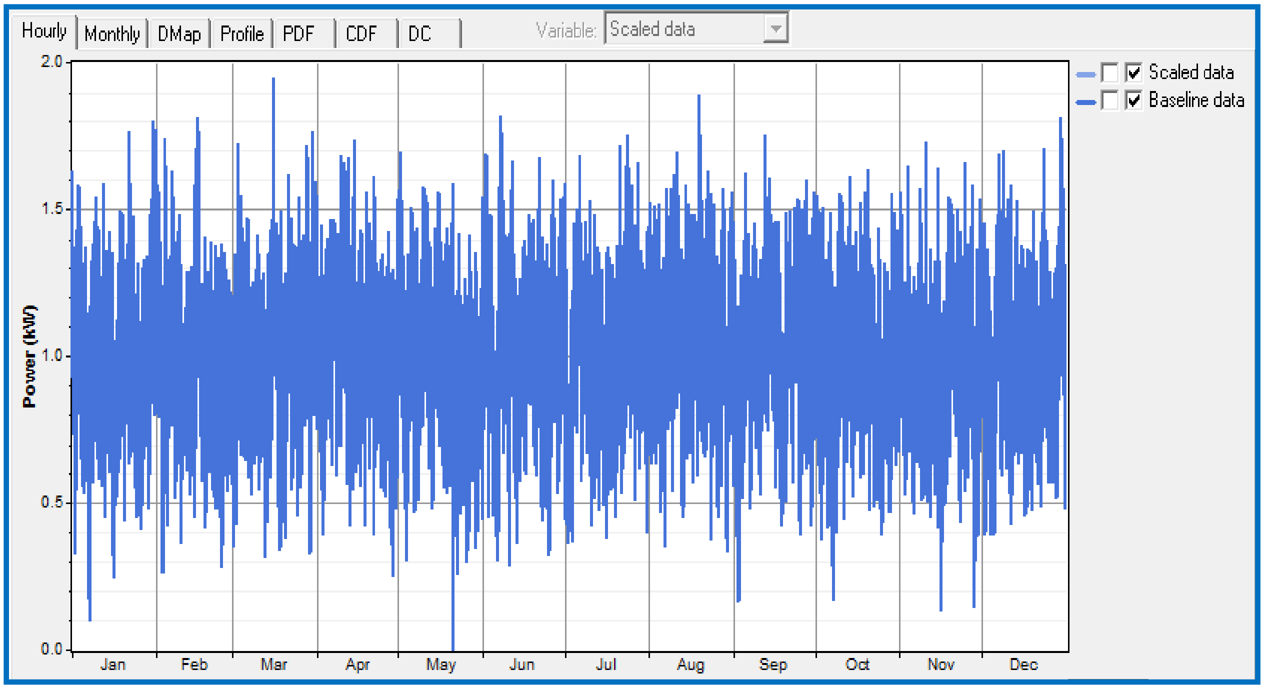

Figure 4.13a Hourly Load profile of telecommunication sites per annum

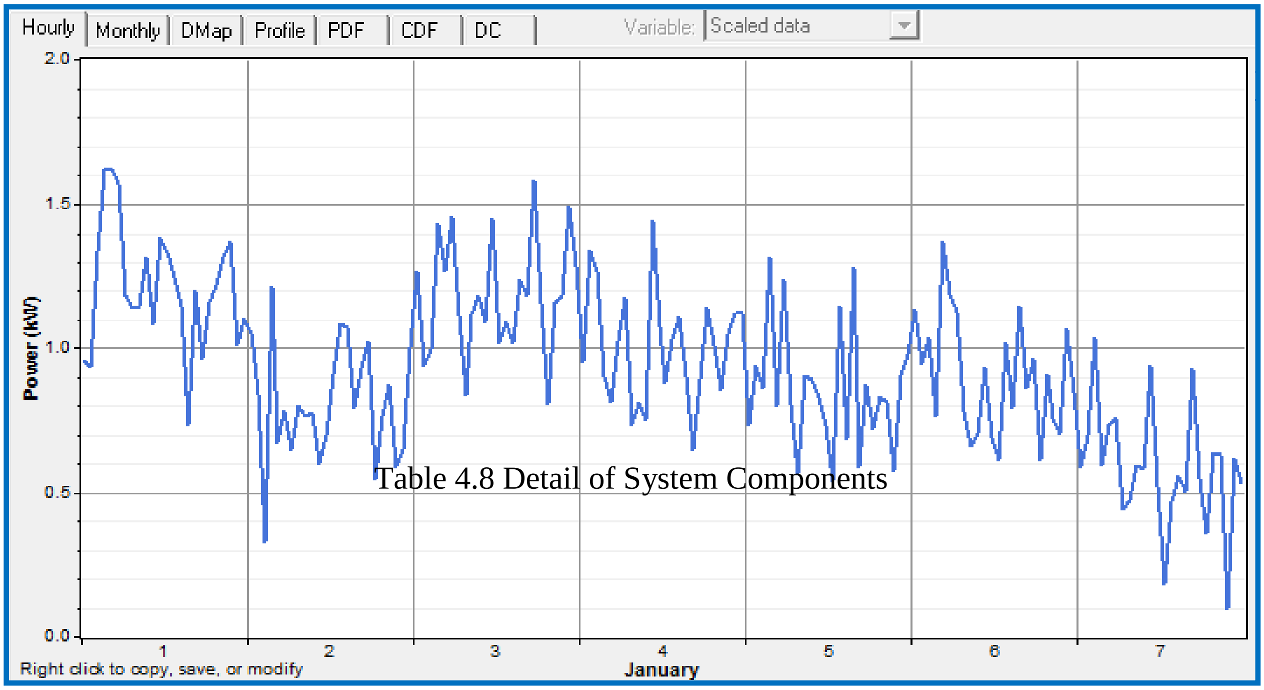

Table 4.8 Detail of System Components

Figure 4.13b Hourly Load profile of telecommunication sites for 7 days during month of January

Table 4.8 Detail of System Components

S. No	Components	Capital cost ($)	Efficiency (%)	Life time
1	1.5kW PV Array	3520.00	20	20
2	1.2kW PEM Fuel Cell	19,151.00	30	10
3	EL100 H_2 generator	9,333.00	85	10
4	H_2 storage tank	1,750.00	-	10
5	Converters	7,000.00	85	15
6	Batteries	2,000.00	80	3

Table 4.9 Simulation results: Grid connected system

PEM Fuel Cell	Converter	Electrolyzer	H_2 Storage Tank	Grid	Initial Capital	Total NPC	COE	Renewable Fraction	Capacity Shortage
kW	kW	kW	(kg)	kW	$/kWh	$/kWh	$/kWh		
1.2	3.5	0.6	150	1000	$37,234	$61,991	0.961	0.00	0.00

Table 4.10 Simulation results: To compare stand-alone systems to grid extension

PV	PEM Fuel Cell	Electrolyzer	H_2 Storage Tank	Initial Capital	Total NPC	COE	Renewable Fraction	Capacity Shortage
kW	kW	kW	(kg)	$/kWh	$/kWh	$/kWh		
100	100	0.6	150	1,841,667	1,814,679	57.146	1.00	0.56

4.10 Summary

In this Chapter, Fuel Cell technology, the working principle of PEM Fuel Cell and the description of the system installed are presented. The reasons why most back-up power systems used in telecom sites today rely on VRLA batteries is discussed. Trouble- shooting of T-1000 PEM Fuel Cell was highlighted in the Chapter. Techo-economic Simulation and Optimization of H_2 Energy and Fuel Cell Power Generation System were examined. Experimentation shows that satisfactory behavior of T-1000 PEM Fuel Cell and the excellent interface with the other devices like EL100 H_2 generator, batteries, H_2 storage tank, load and measuring units.

The most important results obtained from laboratory experimentation were

- Reliability: Both units performed well when called upon with a tested reliability of 100%.
- The system set-up produced at the same time it consumed H_2.

- Unsatisfactory behavior to meet the required 8 hours of back-up power for telecommunications site for desired load of 1kW.
- The run time of VRLA batteries for different loads and the time consumed to run T-1000 PEM Fuel Cell system for 1, 4 and 8 hours were examined.
- DG systems are cheaper than off-grid system with that of grid extension.

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Chapter 5

4.5kW Wind/Solar Micro-generation System to Reduce Carbon Consumption in Australia

5.1 Introduction

Man-made greenhouse gases are being emitted into the atmosphere by burning of fossil fuels through ten different sources namely power plants, cement production, road transport, iron and steel manufacture, deforestation, oil and gas production, garbage, livestock, fertilizers and aviation. Global warming impact referred to as 'Climate Change' is a global problem requiring an immediate global solution. The evidence is clear that the globe is continuing to warm, including warming oceans and melting snow and ice, both of which contribute to rising sea levels. Australia relies heavily on fossil fuels to meet energy demands and also is one of the highest per capita polluters in the world [5.1-5.2].

Flooding in Queensland during the summer of 2011 and bush fire in Victoria during the summer of 2009 are quantifiable set of environmental results of global warming in Australia. Corals threatened by huge volume of polluted fresh water in Queensland and Australian bushfires have accounted for over 800 deaths and also the total accumulated cost due to bushfire is estimated at

$1.6 billion. Wind/solar 4.5kW micro-generation system may be one of the key components for the solution of global warming in Australia. Recently 90 countries have made pledges to limit their emissions and these countries account for over 80% of global emissions. United Nations (UN) Climate Conference in Mexico during December 2010 pledges to reduce national greenhouse emissions and United Nations Climate Change Negotiations in Durban, South Africa (28th November to 10th December 2011) opened a new international framework for reducing greenhouse gas emissions [5.1-5.2].

Section 5.2 of this chapter highlights the Australian Government's Plan for clean energy future or clean environment plan. Section 5.3 explains the 4.5kW Wind/Solar micro-generation system in Power Systems Research Laboratory, Victoria University. Section 5.4 of this chapter describes the Power Systems Research Laboratory's guideline for 4.5kW Wind/Solar micro-generation system. Section 5.5 highlights the monitoring and data transmission of a 4.5kW Wind/Solar micro-generation system for a period of one month after implementation. Section 5.6 examines the energy produced by the 4.5kW Solar/Wind micro-generation system and various readings of monthly, weekly, daily and cumulative curves are recorded at regular intervals. Sections 5.7 and 5.8 examines the energy consumed in Building D, Level 5, Victoria University and the energy consumption of a 3 Bedroom Hall Kitchen Residence (BHK) in Melbourne. Section 5.9 explains the repeal of the carbon tax or emission trading scheme and introduction of the Direct Action Plan. Results and discussions are pointed out in Section 5.10. Trouble-shooting of 3kW VAWT are explained in Section 5.11. Finally, Section 5.12 provides summary of this Chapter.

5.2 Australian Government's plan for Clean Energy Future or Clean Environment Plan

To ensure Australia can compete and remain prosperous in the future, the previous Australian Labor Government's plan for securing a clean energy future had four pillars: a carbon price; renewable energy; energy efficiency; and action on land that will cut pollution and drive investment. Most companies which generated over 25,000 tonnes of carbon dioxide (CO_2) emissions each year were under carbon price mechanism. The preliminary list included 248 companies based on greenhouse gas emissions data; New South Wales had 81 entities while Queensland had 64. Victoria accounts for 39 entities and 45 entities come from Western Australia while other states had fewer than 10 each. Latrobe Valley giants Loy Yang, International Power, TRUE Energy, BHP, Rio Tinto and Alcoa are some of the companies who had direct impact under the carbon price mechanisms [5.1].

On 1st July 2011, the Australian Labor Government announced the establishment of $3.2 billion Australian Energy Agency (ARENA) and around $1.7 billion to Australian Energy Agency (ARENA) and funding to provide financial assistance for research, development, demonstration, deployment and commercialization of renewable energy technologies. The smart way of using energy at home and at work leads to lowering carbon pollution, improving energy security and helping business and households to save money and cope with rising energy prices. Low Carbon Communities and Remote Indigenous Energy Program are the measures taken by the previous Australian Labor Government to improve energy efficiency and it was the third element for a clean energy future, along with carbon price, renewable energy and action on the land [5.1].

The fourth element for a clean energy future was action on the land (Land Sector Package) helped farmers to reduce their emissions, and they were not required to pay for on-farm emissions. Filling the Research Gap, Action on the Ground, Extension and Outreach and Conversation tillage refundable tax offset are the four components of the Carbon Farming Future program delivered by Department of Agriculture, Fisheries and Forestry by the Australian Labor Government. In the next six years the Labor Government's Plan were to invest over $1.7 billion of carbon revenues through various funding programs namely Carbon Farming Futures, Refundable Tax Offset and Biodiversity Fund etc. [5.1].

The current Coalition Government since winning the September 2013 election began the process for clean environment plan. Clean Air; Clean Land; Clean Water and National Heritage are the four pillars of clean environment plan for protecting and improving Australia's environment for future generations. To improve Australia's environment the Australian Government's plan was to reach its emission reduction target efficiently and effectively through its Clean Air plan and this will be done primarily through Emissions Reduction Fund. National Climate Change Adaptation Research Facility, Asia-Pacific Rainforest Summit, Global Rainforest Recovery Agreement, Renewable Energy Target, Solar Towns and Solar Schools are some of the additional program of current Coalition Government [5.3]. Australia has an abundance of solar and wind energy sources and by implementing 4.5kW Wind/Solar micro-generation system as shown in Figure 5.1 in every independent home, CO_2 emissions can be reduced drastically and clean energy future/clean environment plan can be secured in Australia [5.1].

5.3 4.5kW Wind/Solar micro-generation system at Power Systems Research Laboratory, Victoria University

3kW wind turbine (using a generator) converts the mechanical energy from wind into the three-phase AC voltage. Depending on the wind speed the voltage and frequency of the ac generated by the wind turbine varies. The ac generated by the wind system is converted by 4kW Wind Box (WBI) into dc. This energy is turned into ac by a 3.6 kW inverter and this energy is fed back into the utility grid. 1.5kW photovoltaic panels transform the solar radiation into electrical energy in the form of dc. This energy is turned into ac by a 2kW inverter and this energy is fed back into the utility grid [5.2].

The different operating modes of the wind system as shown in Table 5.1 are: off mode; grid check mode; export mode; export and diversion mode and grid fail. To allow operation of the system in the off mode there was insufficient energy from the wind turbine. In the grid check mode, there was sufficient energy to power the WBI properly. Wind inverter was connected to the utility grid and exporting power to the utility grid in the export mode and the WBI output voltage was higher than 530 Vdc. The diversion load is switched on when the bulk voltage exceeds 530 Vdc and remains on until the bulk voltage drops below approximately 430 Vdc. When the bulk voltage exceeds 530 Vdc the wind inverter is disconnected from the utility grid [5.4-5.5].

For 1.5kW photovoltaic solar micro-generation system, the minimum required input voltage to start the initial grid connection is 200 Vdc. The input range is 90 Vdc to 580 Vdc for the solar system to stay connected and export energy on the grid. The minimum input current can be 10 Adc for 2kW inverter and is capable of handling a single array [5.6].

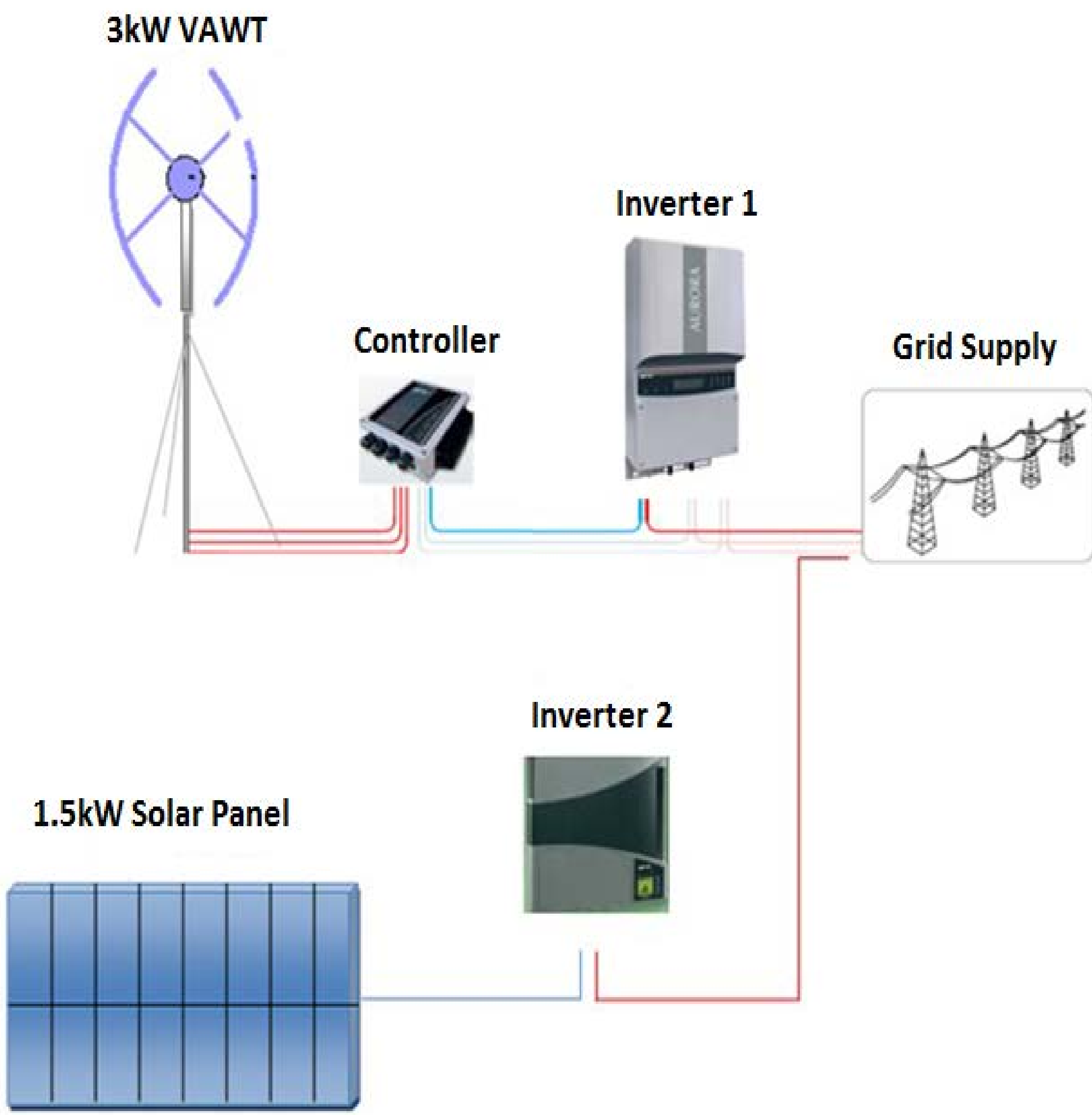


Figure 5.1 Block diagram of 4.5kW Wind/Solar micro-generation system

Table 5.1 Operating modes of the wind speed [5.4]

Mode	WBI Output Voltage (Vdc)	WBI	Diversion Load	Inverter
Off	< 50 Vdc	Un properly powered	OFF	OFF
Grid Check	50 < Vdc <530	Operative	OFF	Grid Check
Export	50 < Vdc < 530	Operative	OFF	Grid Check
Export & Diversion	Vdc > 530	Operative	ON	Exporting to Grid
Grid Fail	Vdc > 530	Operative	ON	Grid check
Wait the wind	< 50 Vdc	Un properly powered	OFF*	Connected to grid and back powered from grid (limited time)

Note: * Dimension diversion load in this state

5.4 Power Systems Research Laboratory's guideline for implementing 4.5kW Wind/Solar micro-generation system

Cost, health issues and bad deaths and disrupting the appearance of natural landscapes and are the main issues of possible downsides of wind power. Headaches, sleep problems, ringing in the ears (tinnitus), mood problems etc. are some of the symptoms of wind-turbine syndrome. Researchers studying wind-turbine syndrome recommend 2 kms buffer zone around wind turbines to protect from any ill effects and engineers are hoping new wind-power technology (with sound-dampening systems) which can cancel out multiple sound frequencies and reduce sound related problems associated with wind farm communities [5.1].

Permanent magnet generator offers many advantages like noise reduction, increased lifetime, high torque at low speed, drive stiffness and more efficient. Considering all the above problems and advantages 3kW H-shaped Vertical axis wind turbines (VAWT) with permanent magnet generators were selected since VAWT can be used in suburban settings, lower noise, next to no vibration, yaw mechanism and wind vane is not required, is easily visible to wildlife (appear as a solid object when spinning or at rest) and produce energy at lower wind speeds [5.1].

The existing 1.5kW monocrystalline solar panel at Victoria University is used for experimentation. The 4.5kW solar/wind micro-generation system at Power Systems Research laboratory at Victoria University are shown in Figure 5.2.

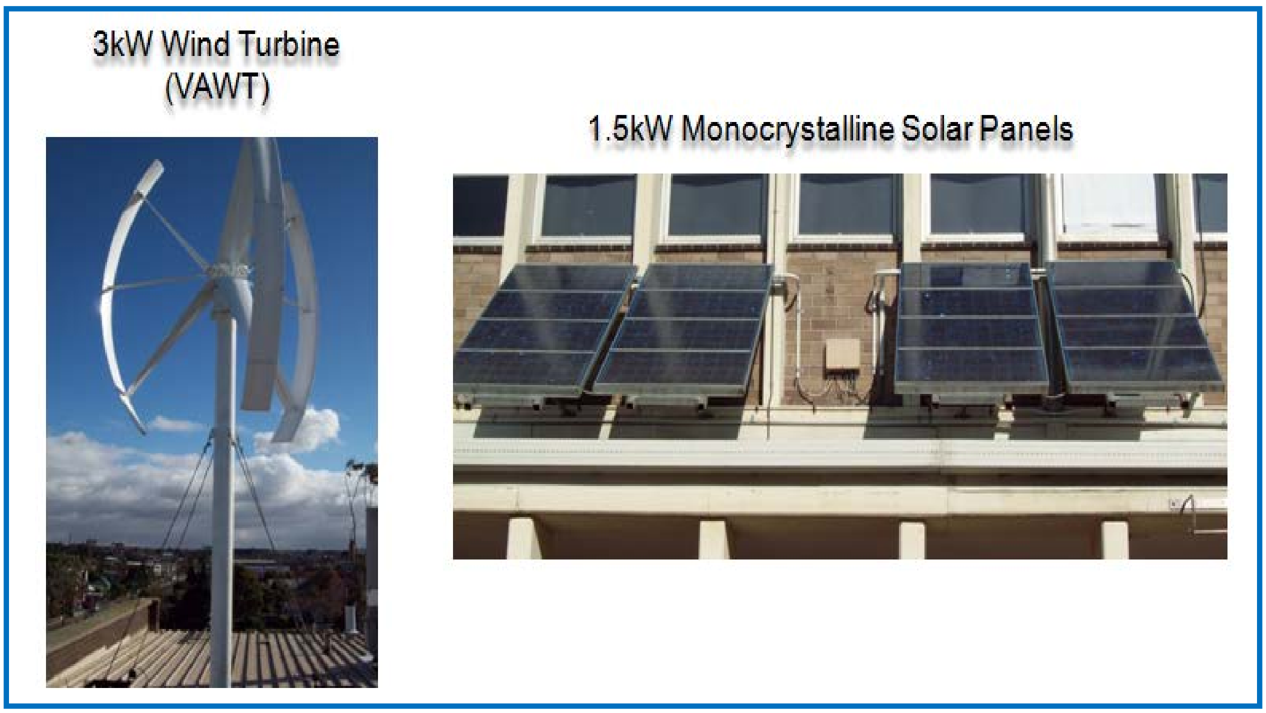


Figure 5.2 4.5kW Wind/Solar 4.5kW micro-generation system in Power Systems Research Laboratory, Victoria University

Aurora Wind Box Interface (WBI) was selected because it is an integral part of wind energy system and its specification is shown in Table 5.2. The WBI serves four purposes namely wind speed feed-back; overvoltage protection; diversion load control and to rectify ‘wild ac’ from the wind turbine generator into dc input for the inverter [5.4].

Table 5.2 Specifications of the WBI [5.4]

S. No	**Description**	**Value Aurora WBI**
1	Input voltage range (no damaging)	0 Vac to 400 Vac
2	Input voltage range (operating)	40 Vac to 400 Vac
3	Input frequency range	0Hz to 600Hz *
4	Max. operating input current	Up to 16.6 A (rms)
5	Input over current (fuse protected)	Up to 20 A **
6	Max. output power (@400Vac, PFC≥0.7)	2500W-4000W-7200W
8	Efficiency (@400Vac, PFC≥0.7)	99.4%
9	Output Voltage range	0-600 Vdc
10	Output Voltage range (@ full output power)	200-600Vdc (PVI-4000-W-I) ***
11	Operating ambient temperature	-25°C to +55°C (-13°F to 140°F)
15	Size (height x width x depth):	29 26 x 9.5 cm

Notes:

* When using wind speed feedback, the frequency range by factory setting is 5–200 Hz; contact factory for different range shifting.

** The over current protection fuses shall be sized depending on the generator/alternator short circuit current, this value shall be determined by the generator/alternator supplier. PVI-4000-W-I is equipped with 6A fuses by factory.

*** Limited by the maximum continuous output current (20Adc).

Aurora Inverters were selected since they were one of the first Transformer-Less inverters in the market based on the safety tests (Anti-Islanding Protection, dc Injection Control and Ground Fault) adhering to German, American, Australian and several other countries defined by VDE0126 and their specifications are shown in Tables 5.3 and 5.4 [5.5].

Table 5.3 Specifications of the wind inverter [5.5]

S. No	CHARACTERISTICS	PVI-3.6-OUTD-XX-W PVI-W
1	Output Power Rating ac [W]	3600
2	Absolute Max Input Voltage [Vdc]	600
3	Max. Power Tracking Window range [Vdc]	50 to 580 (360 nominal)
4	Max Input current [Adc]	32
5	Max Power Voltage Range	180Vdc-530Vdc
6	Nominal ac Voltage (Range) [Vrms]	Single-phase 200-245 Vac (180-264Vac)
7	Nominal ac Frequency [Hz]	50
8	Line Power Factor	1
9	Maximum ac Line Current [Arms]	17.2
10	Max Efficiency [%]	96,8% (96,0% Euro; 96,0% CEC)
11	Operating Ambient Temperature [°C]	-25 to +60 Derating per Tamb>55°C
12	Losses [W]	<8
13	Size (height x width x depth) [mm]	547 x 325 x 208
14	Weight [kg]	17

The advantages of Aurora Transformer Less inverters are maximised efficiency, in case of intentional or unintentional service interruption by the public utility the inverter immediately ceases energising the grid by sensing the ‘islanding’ event and also Aurora Transformer Less inverters incorporate 4 relays in order to ensure ’INTRINSIC SAFETY’ (in case of faults in mains) and REDUNDANCY (in case of high mismatch on the measurement result) [5.5].

Table 5.4 Specifications of the solar inverter [5.6]

S. No	CHARACTERISTICS	PVI -2000
1	Nominal input voltage	360 Vdc
2	Input Voltage range	From 90 Vdc to 600 Vdc
3	Minimum input voltage for grid connection	200 Vdc
4	Max. operating input current	10 Adc
5	Max. input power	2200 W
6	Nominal output power	2000 W
7	Grid voltage maximum range	From 200 to 270 Vac
8	Nominal grid voltage	230 Vac
9	Grid frequency, maximum range	From 45 to 55 Hz
10	Grid frequency, nominal	50 z
11	Maximum efficiency	>95%
12	Operating ambient temperature	From -25^0 C to 55^{0}C
13	Dimensions (H*W*D):	440 * 465 * 57 mm
14	Weight	6 Kg

Aurora communicator monitoring software can be used to monitor a single inverter by means of USB port and multiple inverters by means of RS485 bus. By default in the main application window Inverter List, General Status, Today Energy and Power can be seen. While monitoring the system, Aurora Communicator generates several charts, in order to collect data for the statistics [5.5-5.6].

5.5 Monitoring and data transmission of a 4.5kW Wind/Solar micro-generation system

Both the solar and wind inverters operate automatically and needs no particular supervision. The wind inverter disconnects automatically and goes into the standby mode if the turbine speed is not enough to generate power for the grid [5.5]. The solar inverter disconnects automatically and goes into the standby mode if the input voltage range is less than 90 Vdc [5.6]. The real-time operating data for the 4.5kW Wind/Solar micro-generation system can be transmitted over the communications lines. The inverter stores internally the lifetime counter of energy connection time and the energy transferred to the grid. Partial counter of grid connection time, partial counter of energy, last 100 fault conditions with error code, last 100 variations to the grid connection parameters are also stored internally in the inverters. The LCD display monitors the inverter status of the 4.5kW Wind/Solar micro-generation system and collects statistical data that allows assessing the system performance. The quantity of CO_2 saved compared to the energy produced, the currency and energy cost per kWh can also be monitored by the 4.5kW wind/solar micro generation system [5.5-5.6].

5.6 Energy Produced by 4.5kW Wind/Solar micro-generation system

To note the reading the aurora communicator software, the monitor tool for aurora inverters are used. **Aurora communicator window** shows the status of the inverters connected to the system. **Inverter** shows the general details and **Energy harvesting** shows the statistics of the energy. **System** shows the summary of the system and the **PV array** shows the status of the photovoltaic array. Several charts are generated by the Aurora communicator namely daily, weekly, cumulative, monthly and lifetime energy. Figures 5.3 and 5.4 show the generation of wind energy and generation of system statistics (both solar and wind energy) for single day. Figure 5.5 shows life time of wind energy from 21st of June to 5th July 2011. Figure 5.6 shows the partial wind energy from 21st of June to 30th of July 2011. Life time energy, input power, output power and single day energy of solar and winds are shown in Figure 5.7. The plant information of solar and wind are shown in Figure 5.8 [5.5-5.6]. Energy produced from 4.5kW Wind/Solar micro-generation system for one month during the examination period from 21st of June, 2011 to 20th of July, 2011 was 75kWh.

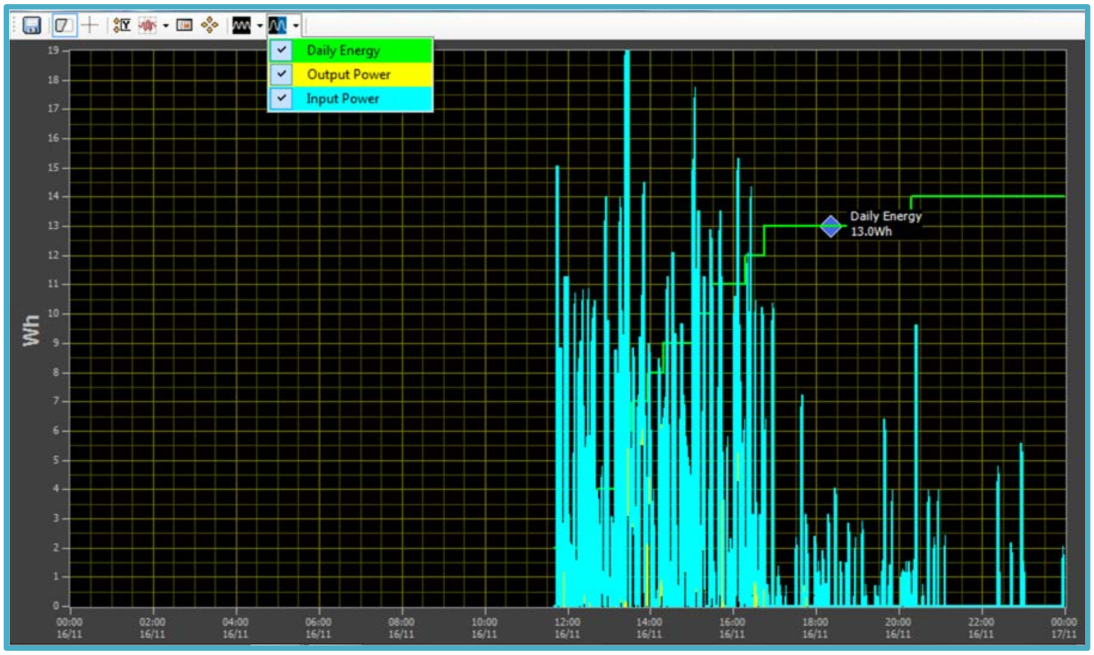


Figure 5.3 Wind energy generation for single day

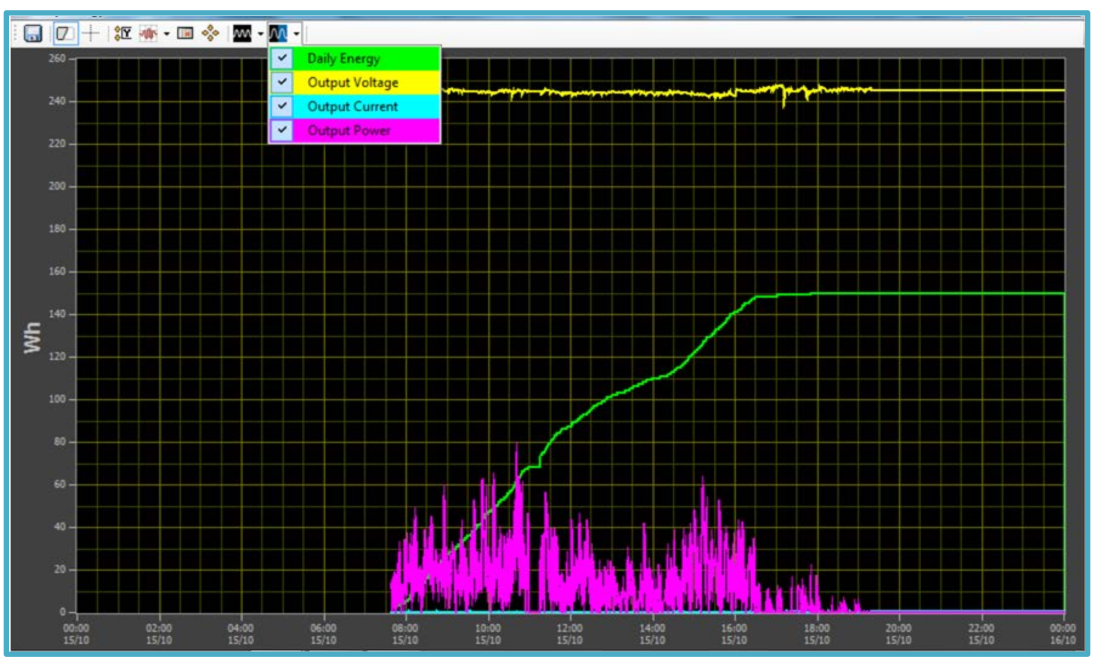


Figure 5.4 Generation of system statistics for single day

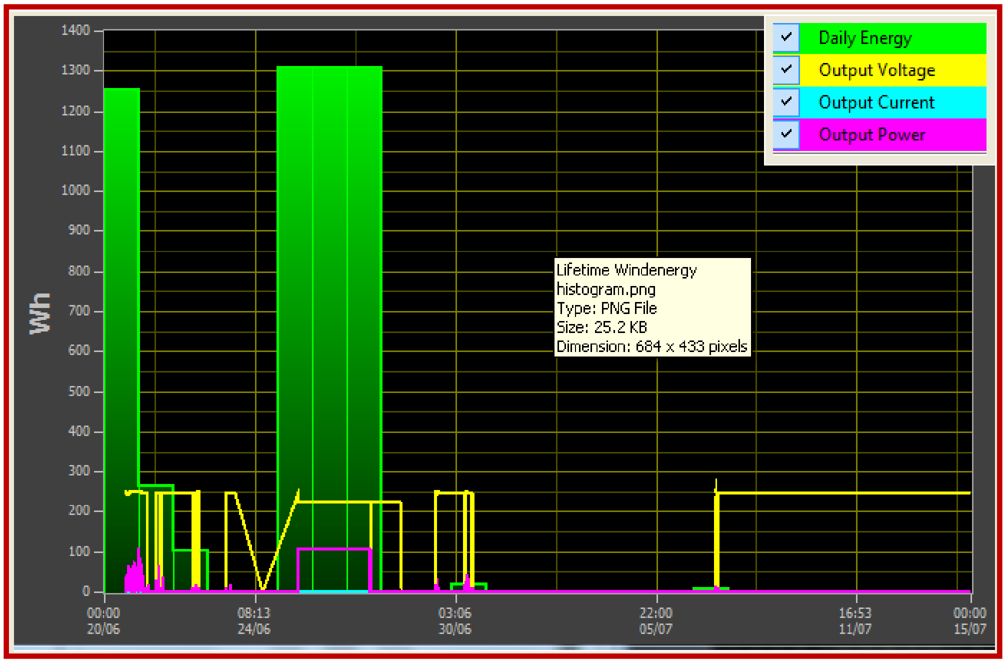


Figure 5.5 Life time of wind energy from 21st of June to 5th July 2011

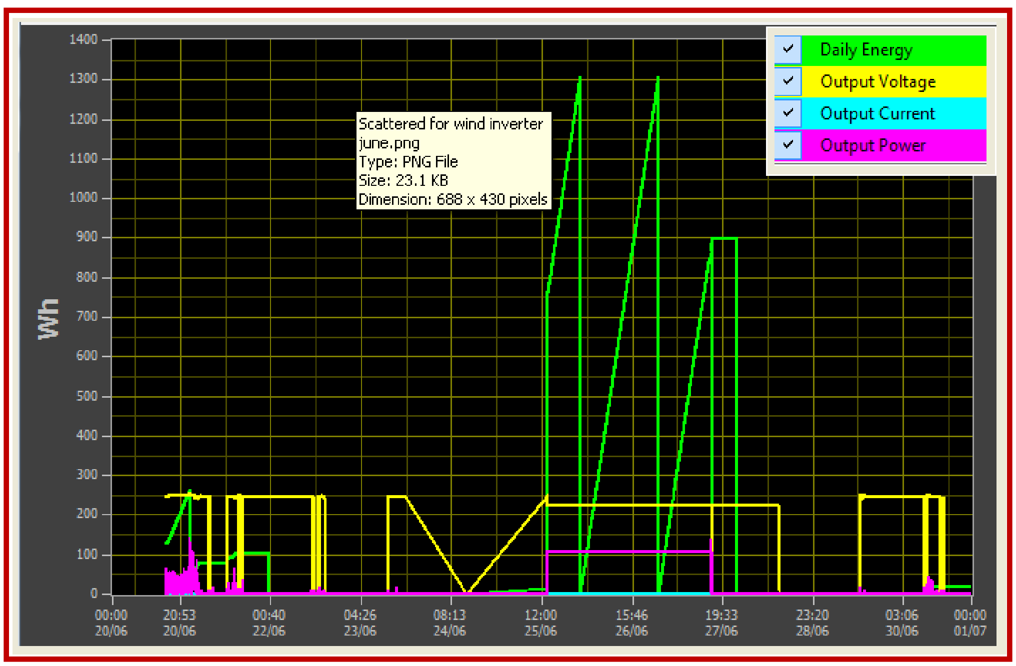


Figure 5.6 Partial wind energy from 21st of June to 30th of July 2011

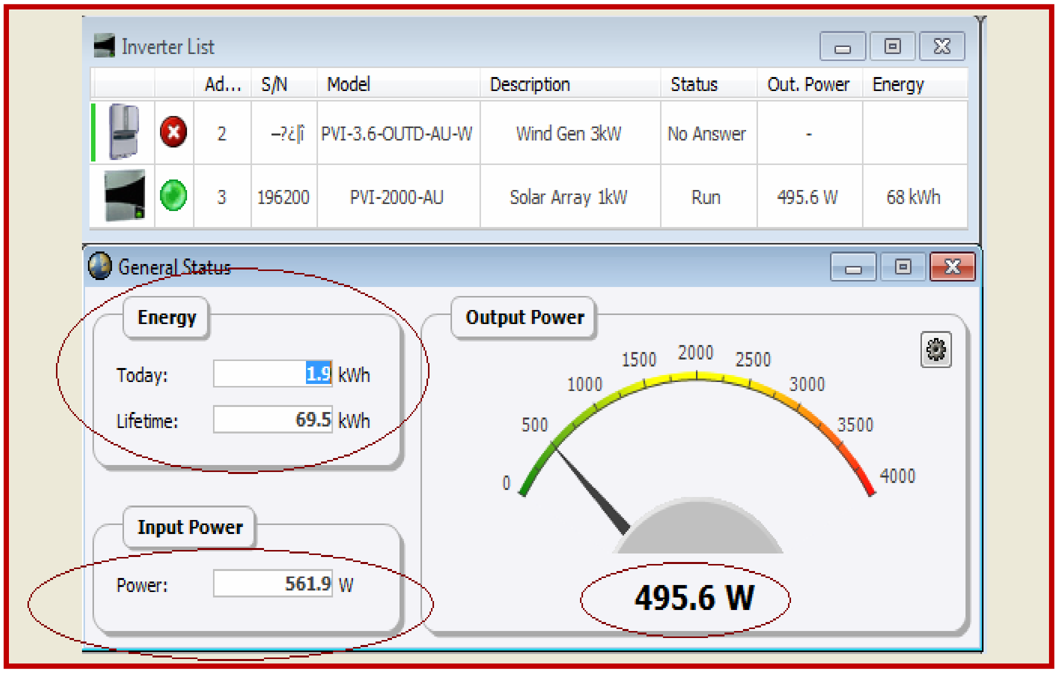


Figure 5.7 Life time energy, input & output power and single day energy of the system

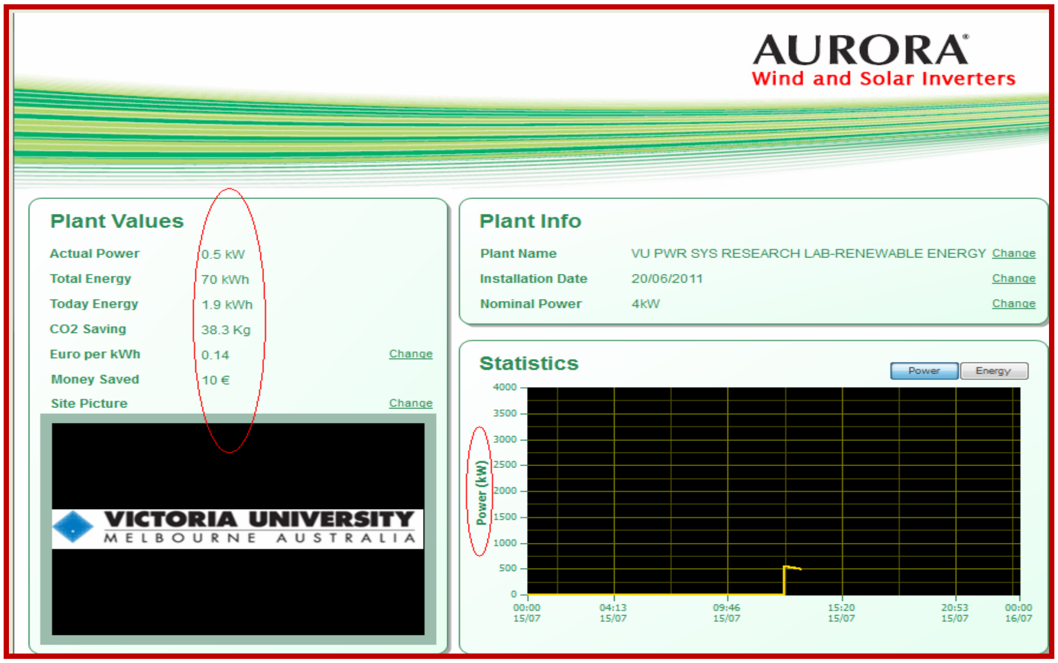


Figure 5.8 Plant information of the system

5.7 Energy Consumption by Building D, Level 5, Footscray Park Campus, Victoria University, Melbourne

The data of energy consumed by Building D, Level 5, Footscray Park Campus, Victoria University for one month during the period of June, 2011 are shown in Figure 5.9 and the data of energy consumed from 21st of June 2011 to 20th of July 2011 as shown in Tables 5.5 and 5.6 is collected from the Facilities Department, Victoria University. The access and mobility map of Footscray Park Campus, Victoria University, Melbourne is given Chapter 6 [5.7]. It is examined that the energy produced from 4.5kW Wind/Solar micro-generation system for one month during the period from 21st of June, 2011 to 20th of July, 2011 was 75kWh. The energy consumed by Building D, Level 5, Footscray Park Campus during the same period from 21st of June, 2011 to 20th of July, 2011 was 229,730.6kWh. The energy produced from the system contributed only 0.03% towards the energy consumption by Building D, Level 5, Footscray Park Campus. Therefore, simulation and optimization of 4.5kW Wind/Solar micro-generation system for the given load profile is examined in Chapter 6.

5.8 Energy Consumption of a 3 BHK residence in Melbourne

The energy consumption of a 3 BHK residence in Melbourne is examined in this section. Energy bill generated for residences in Australia is generally for duration of 3 months. During the account period from 01 April, 2011 to 01, July 2011 (91 days) the total energy consumed by 3 BHK residence in Melbourne was 840kWh as shown in Figure 5.10 [5.1].

Table 5.5 Data of Energy Consumed for the Month of June 2011 by Building D, Level 5, Footscray Park Campus, Victoria University, Melbourne

S. No	Date	Energy consumed for 6 Hrs in kWh	Energy consumed for 12 Hrs in kWh	Energy consumed for 18 Hrs in kWh	Energy consumed for 24 Hrs in kWh
1	01/06/2011	1589.2	3996.9	6591.5	**8493**
2	02/06/2011	1632.4	3969.4	6604.5	**8549**
3	03/06/2011	1621.7	3925.7	6477.5	**8340.6**
4	04/06/2011	1485	3006.4	4613.6	**6208.3**
5	05/06/2011	1518.7	3036.9	4630.9	**6222.4**
6	06/06/2011	1601.9	3921.1	6466.9	**8363**
7	07/06/2011	1570.3	3988.2	6667.4	**8550.3**
8	08/06/2011	1587.4	4050.9	6821.7	**8801.5**
9	09/06/2011	1604.4	3907.8	6404.3	**8303.9**
10	10/06/2011	1558.2	3752.3	6084.4	**7857.6**
11	11/06/2011	1457.8	2963	4542.9	**6069**
12	12/06/2011	1476.2	2963.3	4558.7	**6137.2**
12	13/06/2011	1484.2	3382.7	5314.3	**6977.8**
14	14/06/2011	1577.5	3901.3	6411.4	**8275.5**
15	15/06/2011	1554.9	3893.1	6441.8	**8287.6**
16	16/06/2011	1589.2	3996.7	6583.3	**8499.6**
17	17/06/2011	1620	3903.1	6302.1	**8109.7**
18	18/06/2011	1467.4	2971.9	4507	**6009.2**
19	19/06/2011	1485.7	2980.4	4586.8	**6138.8**
20	20/06/2011	1582.4	3925.2	6496.7	**8345.9**
21	21/06/2011	1624.1	3932.5	6535.2	**8374.5**
22	22/06/2011	1652.6	4045.8	6583.5	**8434.4**
23	23/06/2011	1663.1	4011.3	6483.3	**8295.6**
24	24/06/2011	1652	3973.2	6368.3	**8162.6**
25	25/06/2011	1518.4	3132.6	4759.3	**6333.4**
26	26/06/2011	1584.6	3305.9	5053.7	**6601**
27	27/06/2011	1591.9	3885.9	6307	**8096.1**
28	28/06/2011	1653.3	3958	6377.5	**8168.8**
29	29/06/2011	1550.9	3882.9	6359.1	**8162.4**
30	30/06/2011	1552.8	3812.2	6262.6	**8077.7**

Table 5.6 Data of Energy Consumed from 21st June 2011 to 20th July 2011 by Building D, Level 5, Footscray Park Campus, Victoria University, Melbourne

S. No	Date	Energy consumed for 6 Hrs in kWh	Energy consumed for 12 Hrs in kWh	Energy consumed for 18 Hrs in kWh	Energy consumed for 24 Hrs in kWh
1	21/06/2011	1624.1	3932.5	6535.2	**8374.5**
2	22/06/2011	1652.6	4045.8	6583.5	**8434.4**
3	23/06/2011	1663.1	4011.3	6483.3	**8295.6**
4	24/06/2011	1652	3973.2	6368.3	**8162.6**
5	25/06/2011	1518.4	3132.6	4759.3	**6333.4**
6	26/06/2011	1584.6	3305.9	5053.7	**6601**
7	27/06/2011	1591.9	3885.9	6307	**8096.1**
8	28/06/2011	1653.3	3958	6377.5	**8168.8**
9	29/06/2011	1550.9	3882.9	6359.1	**8162.4**
10	30/06/2011	1552.8	3812.2	6262.6	**8077.7**
11	01/07/2011	1513.5	3721.6	6063.7	**7853.7**
12	02/07/2011	1461.8	2961.2	4484.2	**5979.8**
12	03/07/2011	1488.7	2868	4378.7	**5879**
14	04/07/2011	1578.8	3880.3	6402.2	**8203.9**
15	05/07/2011	1518.8	3878.8	6418.2	**8231.4**
16	06/07/2011	1595.9	3956.4	6432.1	**8231.8**
17	07/07/2011	1595.9	3956.4	6432.1	**8231.8**
18	08/07/2011	1522.6	3843.9	6324.1	**8079.2**
19	09/07/2011	1508.8	3058.2	4630.2	**6151.8**
20	10/07/2011	1482.9	2968.5	4485	**6018.8**
21	11/07/2011	1510.3	3884.4	6453	**8237**
22	12/07/2011	1528.1	3876.1	6402.8	**8190.6**
23	13/07/2011	1576.7	3863.7	6315.1	**8108.5**
24	14/07/2011	1512.2	3796.4	6289	**8077.4**
25	15/07/2011	1571.1	3879.3	6307.6	**8070.1**
26	16/07/2011	1483.3	2992.4	4608.4	**6184.3**
27	17/07/2011	1536.5	3077.1	4661.5	**6240**
28	18/07/2011	1538.2	3854	6476.2	**8350.5**
29	19/07/2011	1526.8	3809.9	6367	**8174.6**
30	20/07/2011	1528.9	3798.6	6338.9	**8169.2**

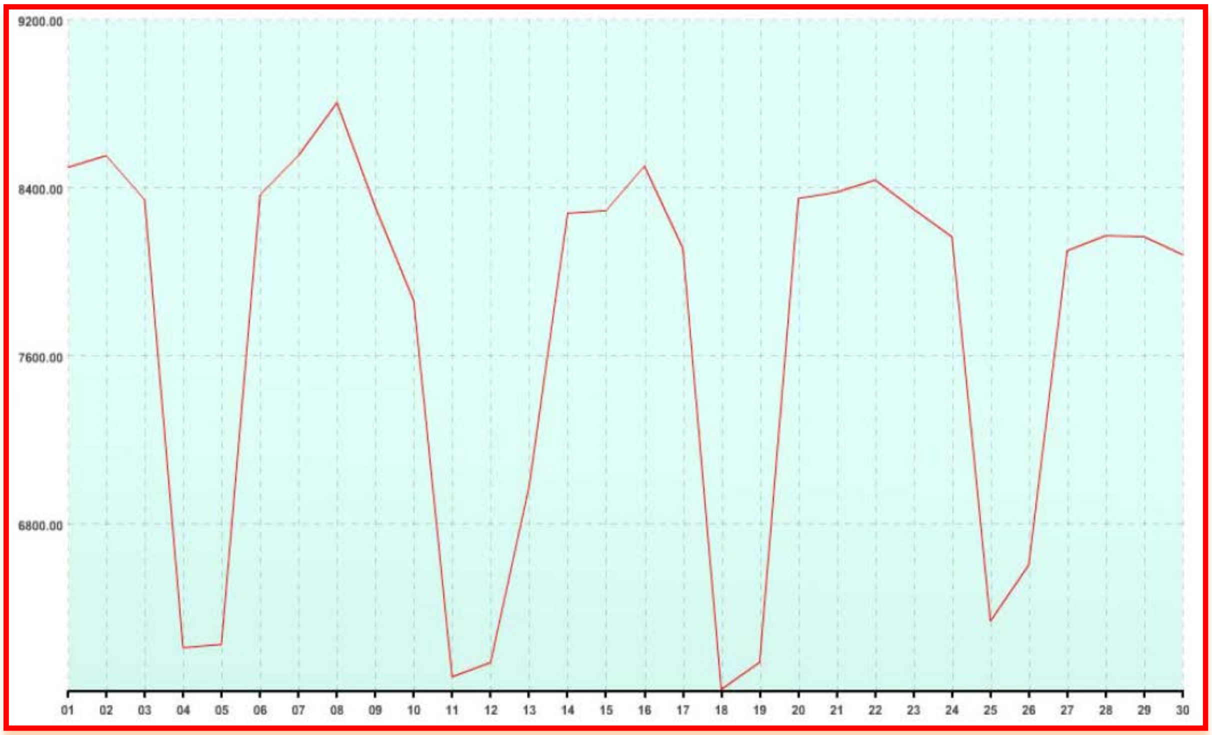
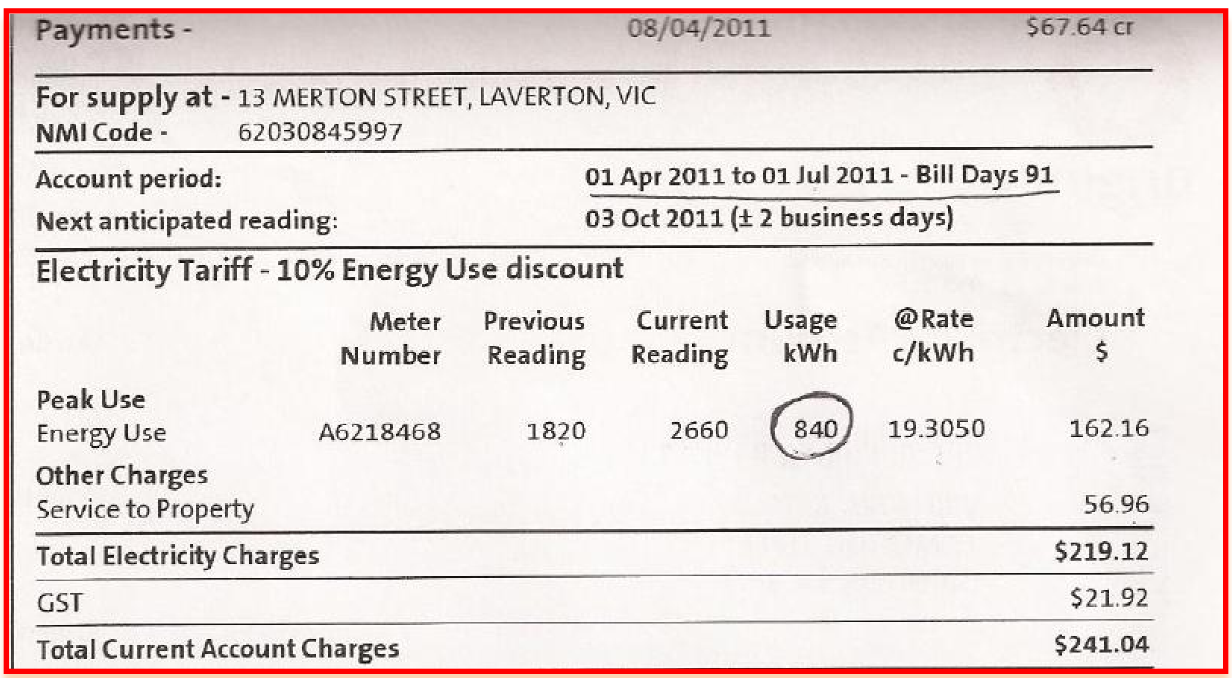


Figure 5.9 Y axis: Data of energy consumed and X axis: For the month June, 2011



Payments - 08/04/2011 $67.64 cr

For supply at - 13 MERTON STREET, LAVERTON, VIC
NMI Code - 62030845997

Account period: **01 Apr 2011 to 01 Jul 2011 - Bill Days 91**
Next anticipated reading: **03 Oct 2011 (± 2 business days)**

Electricity Tariff - 10% Energy Use discount

	Meter Number	Previous Reading	Current Reading	Usage kWh	@Rate c/kWh	Amount $
Peak Use						
Energy Use	A6218468	1820	2660	840	19.3050	162.16
Other Charges						
Service to Property						56.96
Total Electricity Charges						**$219.12**
GST						$21.92
Total Current Account Charges						**$241.04**

Figure 5.10 Energy bill generated for a 3BHK Residence at Footscray, Melbourne [5.2]

5.10 Repeal of the carbon tax or emission trading scheme and introduction of the Direct Action Plan

The previous Australian Labor Government introduced carbon tax during 1st July, 2013 as a fixed price of $23 per tonne of CO_2 equivalent in order to reduce Australia's emission to 50% below 2000 levels by 2020 [5.8]. The carbon tax was shifted to emissions trading scheme during July, 2013 by the previous Prime Minister Kevin Rudd and it was fixed a floating price of between $6 and $10 per tonne [5.9].

The Australian Prime Minister Tony Abbott since winning the recent Federal election during September, 2013 has begun the process of abolishing the carbon tax or emission trading scheme. Prime Minister Abbott on Wednesday, 13 November, 2013 introduced a bill to scrap the carbon tax and it was said that it will reduce electricity costs by 9% and gas prices by 7% with an annual power bill saving of $550 for an average household in Australia [5.10]. To deliver improvements to the environment and reduce Australia's greenhouse gas emissions the Australian government had introduced Direct Action Plan which includes Emissions Reduction Fund (ERF), targeted funding for urban trees and one million solar roofs [5.3].

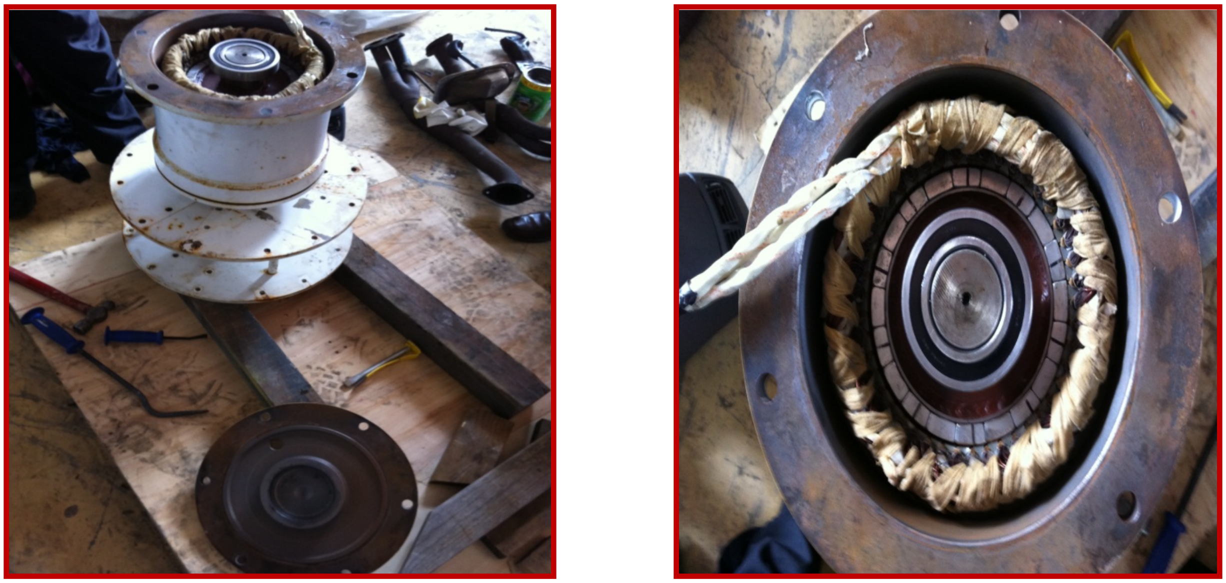
5.10 Results and Discussions

The energy consumed by Building D, Level 5, Footscray Park Campus during the examination period was very high (229730.6kWh) compared with monthly energy produced by 4.5kW Wind/Solar micro-generation system (75kWh). In 91 days the total energy consumed by 3 BHK residence in Melbourne was 840kWh. For a period of 3 months the approximate energy produced by 4.5kW Wind/Solar micro-generation system is about 225kWh-250kWh. Electricity tariff in explained in detail in Chapter 6. The 4.5kW Wind/Solar micro-generation was eligible for Premium feed-in tariff, a credit of 60c/kWh for excess electricity fed back into the grid since the system was installed during June 2010 [5.11]. Based on the experiment conducted for a period of one month under laboratory conditions at the Power Systems Research Laboratory at Victoria University the work notably shows that if 4.5kW Wind/Solar micro-generation system when implemented in a 3 BHK residence in Melbourne ¼ of CO_2 emissions can be reduced and about A$45 can be saved every month from the electricity bill.

5.11 Trouble-shooting of 3kW VAWT

To ensure that research is being conducted in a safe environment and to satisfy the government safety legislation and procedures the 4.5kW Wind/Solar micro-generation system was stopped after 40 days of implementation. The system was started again after satisfying the guidelines of Occupation Health and Safety (OH&S) and it was monitored that 3kW VAWT ran very slowly or is stopped without any output resulting in unsatisfactory behavior.

Even with high wind speed 3kW VAWT accelerated for few minutes and slowed down [5.4]. Greenova Solutions Private Limited was contacted to check the 3kW VAWT. After the bulk output voltage and Diversion LED status was measured and verified by Greenova Solutions Private Limited, then the 3kW VAWT was taken to the industry for trouble shooting by trained and qualified personnel. Since the 3kW VAWT accelerated and slowed down the wires from permanent magnet generator (PMG) and WBI were also verified to check the possible cause whether the generator leads were shorted together [5.4] as shown in Figures (5.11a to 5.11d).



Figures 5.11 (a & b) Permanent magnet generator (PMG)

Figures 5.11 (c & d) Permanent magnet generator (PMG)

5.12 Summary

In this Chapter, the Australian Government's clean energy future or clean environment plan was presented. The 4.5kW Wind/Solar micro-generation system, its monitoring and data transmission and the guidelines for implementing at Power Systems Research laboratory was discussed. The energy produced by 4.5kW Wind/Solar micro-generation system was compared with both the energy consumption of Building D, Level 5, Footscray Park Campus and a 3 BHK residence in Melbourne. Since the energy produced by the system contributed only 0.03% towards the energy consumption of Building D, Level 5, Footscray Park Campus, Victoria University the simulation and optimization was carried out and is discussed in the subsequent chapter. The experimental analysis of a 4.5kW Wind/Solar micro-generation system clearly indicates that the energy produced is between 225–250 kW for three months. Therefore, about 25% of energy consumption and ¼ of CO_2 emissions can be reduced from each 3 BHK residence if the system was implemented. The introduction of the Direct Action Plan, repel of the carbon tax or emissions trading scheme and the trouble-shooting of 3kW VAWT was also presented in this chapter.

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[5.11] “AGL, Energy in action”. [Online] Viewed 2012 June 21. Available: http://www.agl.com.au/

Chapter 6

Techo-economic Simulation and Optimization of 4.5kW Wind/Solar Micro-generation System for Victorian Climate

6.1 Introduction

The study in this Chapter aims to investigate the economic, technical and environmental performance of the implemented 4.5kW Wind/Solar micro-generation under Australian (Victorian) climatic conditions. Using global solar irradiation and wind speed as solar and wind energy data, load data (Building D, Level 5 at Victoria University, Footscray Park Campus), the price of PV array, Vertical Axis Wind Turbine (VAWT), converters, grid electricity tariff and sale-back tariff as inputs of economic analysis, 4.5kW Wind/Solar micro-generation system was simulated and optimized by Hybrid Optimization Model for Electric Renewable (HOMER) [6.1]. Section 6.2 presents the methodology, simulation model, system simulation tool, components modeling and system optimization problem. Section 6.3 provides the study locations and their climatic data, load profile, details of system components and electricity tariff. Section 6.4 highlights the economic, technological and environmental results. Finally, Section 6.5 provides the summary of this Chapter.

6.2 Methodology

The implemented 4.5kW Wind/Solar micro-generation system in Power Systems Research Laboratory at Victoria University was undertaken for research in this chapter by using computer-based energy simulation tool. Simulation software and system optimization objective [6.1] are introduced in this section with economic data, collected weather data and load data as inputs.

6.2.1 Simulation model

The 4.5kW Wind/Solar micro-generation system as shown in Figure 6.1 has a direct current (DC) 1.5kW PV array and alternating current (AC) 3kW VAWT as the energy generator. The system has also rectifier converting electricity between AC to DC as well as inverter converting electricity between DC to AC as the load and the grid is AC.

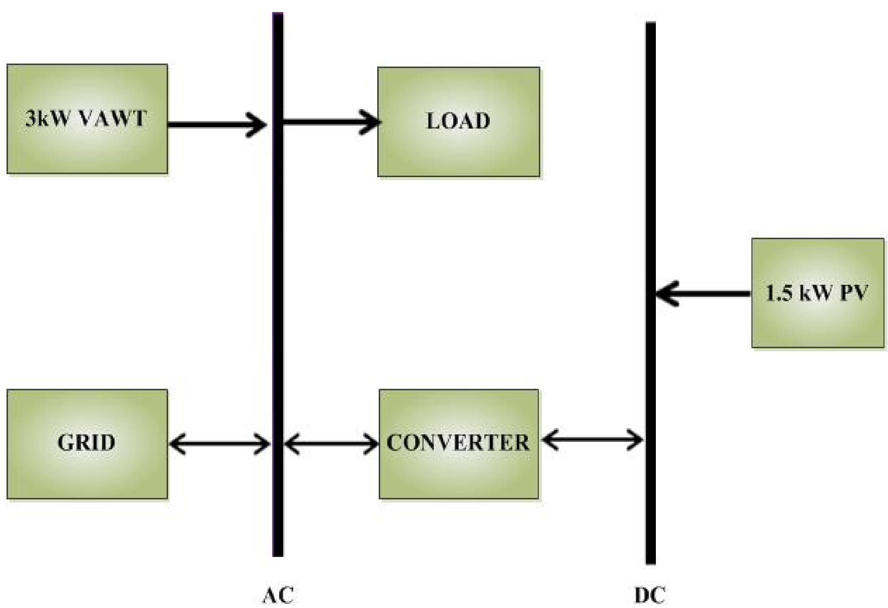

Figure 6.1 4.5 kW Wind/Solar micro-generation system configuration

6.2.2 System simulation tool

The HOMER software was used to model the implemented 4.5kW Wind/Solar micro-generation system. It is a micro power optimization model that simplifies the task of designing distributed generation (DG) system both on and off-grid developed by National Renewable Energy Laboratory (NREL), US. HOMER simulates the operation of the system and performs energy balance calculations for each system configuration. It also estimates the cost of installing and operating the system over the life time of the project and supplies the optimized system configuration and components sizing. For simulation and optimization of conventional and renewable energy system HOMER is widely used in many countries [6.2]. The 4.5kW Wind/Solar micro-generation system is simulated by the HOMER coding as shown in Figure 6.2.

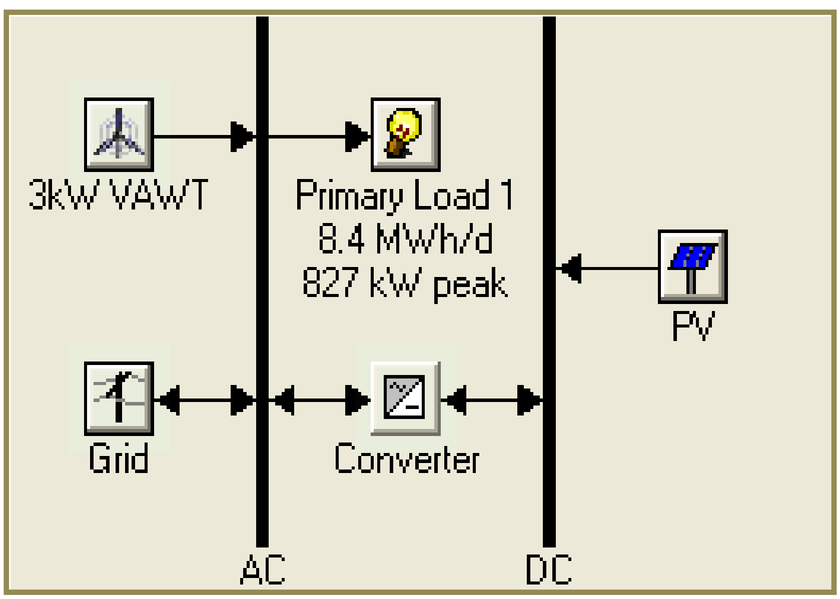

Figure 6.2 HOMER codes for 4.5 kW Wind/Solar micro-generation system

6.2.3 Components modeling

The solar energy is converted into DC electricity by the PV array in direct proportion to the solar radiation incident upon it [6.1]. The PV array is placed at a tilt angle of 30^0 in order to achieve higher insolation level to the solar radiation incident upon it. HOMER calculates the PV array output [6.2] as shown in equation (6.1) and the radiation incident on PV array [6.2] as shown in equation (6.2).

$$P_{PV} = Y_{PV} f_{PV} \left[\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right] \left[1 + \alpha_p \left(T_c - T_{c,STC}\right)\right] \tag{6.1}$$

where:

Y_{PV} = rated capacity of the PV array [kW]

f_{PV} = PV derating factor [%]

$\bar{G}_T$ = solar radiation incident on the PV array in the current time step [kW/m^2]

$\bar{G}_{T,STC}$ = incident radiation at standard test conditions [kW/m^2]

α_p = temperature coefficient of power [%/^{0}C]

T_c = PV cell temperature in the current time step [^{0}C]

$$\bar{G}_T = (\bar{G}_b + \bar{G}_d A_i) R_b + \bar{G}(1 - A_i) \left(\frac{1 + \cos\beta}{2}\right) \left[1 + f \sin^3\left(\frac{\beta}{2}\right)\right] + \bar{G}_{\rho g} \left(\frac{1 - \cos\beta}{2}\right) \tag{6.2}$$

where:

$\bar{G}_b$ = beam radiation [kW/m^2]

$\overline{G}_d$ = diffuse radiation [kW/m^2]

A_i = anisotrophy index, dimensionless

R_b = ratio of beam radiation on the tilted surface to beam radiation on the horizontal radiation

$\overline{G}$ = global solar radiation [kW/m^2]

β = slope of the surface, in degree

f = more diffuse radiation comes from the horizon than from rest of the sky

$\overline{G}_{\rho g}$ = ground reflectance [%]

For wind modeling, during each hour of the year, the base line data is a set of 8,760 values representing the average wind speed expressed in meters per second. From twelve average wind speed values: one for each month of the year, HOMER builds a set of 8,760 values, or one wind speed value for each hour of the year. The synthesized data sequence has the specified Weibull distribution, autocorrelation, seasonal and daily patterns [6.1-6.5].

For converter modeling, capital and replacement cost, its annual operating and management (O&M) cost and their expected life times are the economic properties. The important physical property is its size and the other property is the inversion and rectification efficiencies which are assumed to be constant [6.1-6.5].

The electricity utility charges for energy purchased from the grid referred to as power price, in $/kWh; and the utility pays for the grid demand referred to as sale-back rate, in $/kWh. There are the two type of prices for economic modeling of the grid. The grid is modeled as a component from which the system can purchase and sell AC electricity [6.1-6.5].

6.2.4 System Optimization problem

Since the implemented 4.5kW Wind/Solar micro-generation system was posed as an optimization problem, corresponding to the system constraints and performances the objective functions were formulated. Various configurations of wind turbines, PV arrays and converters combining with different sizes are the different options of the system [6.1]. The optimized system has the lowest costs in the life cycle when producing electricity and therefore the objective of optimization [6.2] is given by a function as shown in equation (6.3).

$$f(\vec{x}) = \left[\left(\sum_{i=1}^{n} kC_i * N_i\right) + \left(\sum_{y=1}^{Y}\sum_{i=1}^{n}(O\&M)_i * N_i\right) + \left(\sum_{y=1}^{Y}\sum_{i=1}^{n} R_i * N_i\right) + \left(\sum_{y=1}^{Y}\sum_{h=1}^{H} E_{g,p} * P_{g.p} - \sum_{y=1}^{Y}\sum_{h=1}^{H} E_{g,s} * P_{g,s}\right)\right] \tag{6.3}$$

where:

C_i = investment cost [$]

N_i = number of each system components [$]

$O\&M_i$ = operation and maintenance cost [$]

R_i = replacement cost [$]

$E_{g,p}$ = electricity purchased from the grid [kWh]

$P_{g.p}$ = price of electricity purchased from the grid [$/kWh]

$E_{g,p}$ = electricity purchased from the grid [kWh]

$P_{g.p}$ = price of electricity purchased from the grid [$/kWh]

6.3 Study Locations and their climatic data

The 4.5 kW Wind/Solar micro-generation system in Power Systems Research Laboratory at Victoria University was optimized for five selected suburbs in Victoria: Melbourne, Mildura, Nhill, Broadmeadows and Sale. Table 6.1 shows the climate indicators related to solar energy resources for all the five selected suburbs in Victoria. The monthly global clearness index and daily radiation for Victoria, Australia were collected from HOMER's help file [6.2] and NASA's Surface Solar Data Set website [6.6] as shown in Table 6.2. The global solar radiation per annum of Victoria, Australia is shown in the Figure 6.3. In Victoria during the month of (January to March) and (October to December) there is more exposure and intensity and the solar irradiation is more. During (April to September) there is less solar exposure and intensity of solar irradiation is less as shown in Figure 6.3.

Table 6.1 Climate indicators for Victorian Suburbs [6.2], [6.6]

State	Climate data location	Coordinator	Elevation, m	Time zone
Victoria	Melbourne	37^0 41'S 144^0 51'E	131	UTC + 10
Victoria	Mildura	34^0 14'S 142^0 05'E	49	UTC + 10
Victoria	Sale	38^0 06'S 147^0 09'E	4	UTC + 10
Victoria	Broadmeadows	37^0 44'S 144^0 54'E	85	UTC + 10
Victoria	Nhill	36^0 20'S 141^0 39'E	129	UTC + 10

Table 6.2 Global clearness index and daily radiation for Victoria, Australia [6.2], [6.6]

S. No	Month	Clearness index	Daily Radiation ($kWh/m^2/d$)
1	Jan	0.57	6.350
2	Feb	0.57	5.840
3	Mar	0.54	4.600
4	Apr	0.48	3.290
5	May	0.45	2.300
6	Jun	0.46	1.850
7	Jul	0.47	2.050
8	Aug	0.46	2.780
9	Sep	0.48	3.710
10	Oct	0.35	4.850
11	Nov	0.53	5.710
12	Dec	0.53	6.220
Latitude: 37^0 47'S ; Longitude: 144^0 58' E			

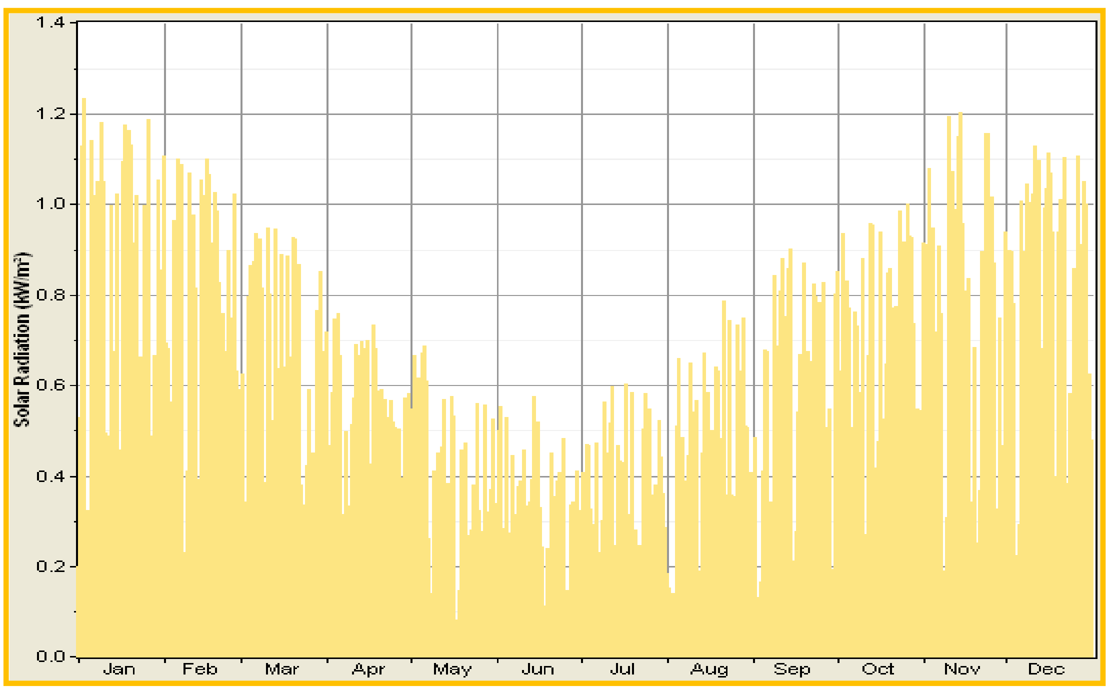

Figure 6.3 Global solar radiations (kW/m^2) per annum of Victoria, Australia [6.2], [6.6]

Wind speed data for the selected five suburbs were obtained from weather base website [6.7]. Table 6.3 shows the global wind speed data for all the five suburbs in Victoria, Australia. Figure 6.4 shows the hourly wind speed data for the suburb Melbourne for one year. It is also seen from Table 6.5 while Melbourne has more wind speed, Nhill has the least wind speed and Mildura has the second least wind speed data. Figures (6.5-6.8) show the monthly average wind speed data of Mildura, Nhill, Sale and Broadmeadows [6.7] and Figure 6.9 shows the power curve [6.8] of 3kW VAWT.

Table 6.3 Global Wind speed data for selected Victorian suburbs, Australia [6.7]

Month	**Winds speed (m/s)**				
	Melbourne	**Mildura**	**Nhill**	**Sale**	**Broadmeadows**
Jan	5.28	4.44	3.33	5.27	5.27
Feb	7.77	4.44	3.33	5.55	4.72
Mar	5.55	3.89	2.5	4.72	4.44
Apr	5.55	3.33	2.22	5.27	5.56
May	5.55	2.5	2.5	4.72	5.56
Jun	6.11	2.5	2.5	4.72	6.11
Jul	6.94	3.89	3.33	4.72	6.11
Aug	6.94	4.44	3.33	5.27	6.94
Sep	6.94	4.72	3.33	5.55	6.94
Oct	6.94	3.89	3.33	5.55	6.94
Nov	5.28	3.89	3.89	6.11	4.72
Dec	5.28	4.44	3.89	5.55	5.28

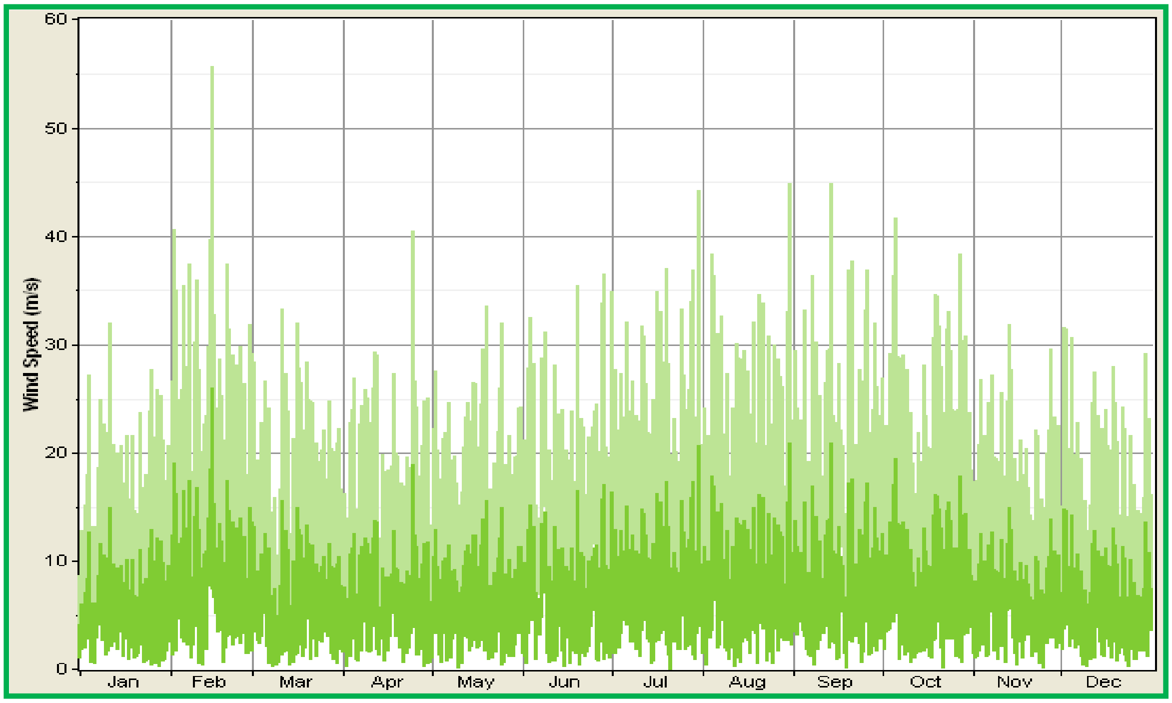

Figure 6.4 Wind resources – Hourly wind speed data per annum for Melbourne [6.7]

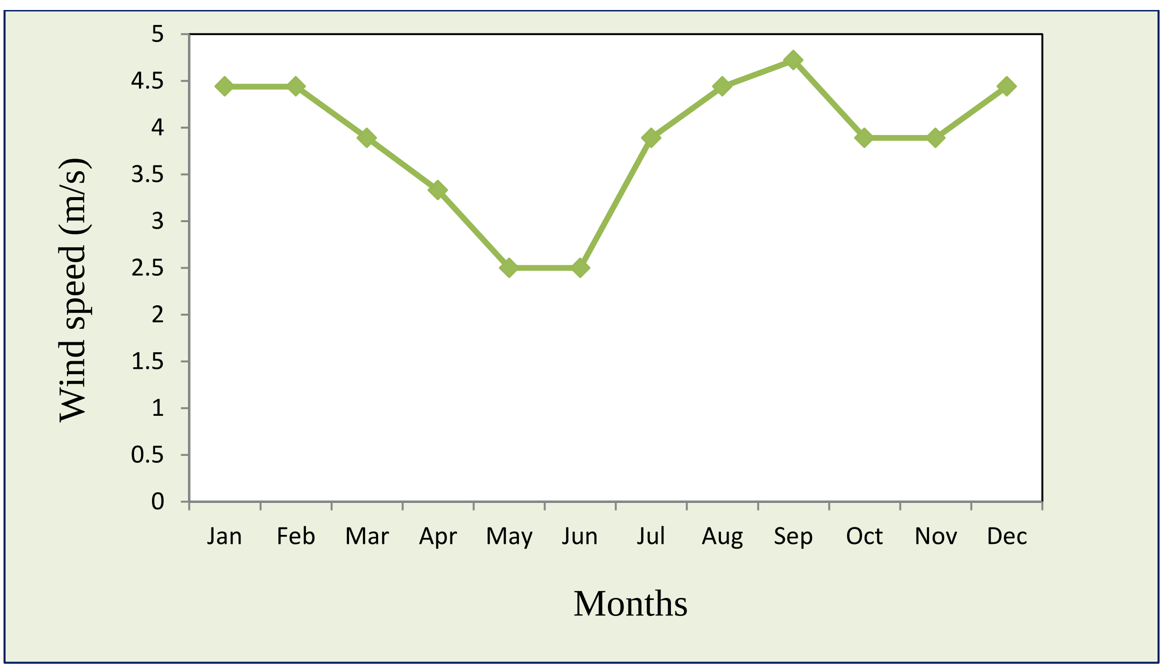

Figure 6.5Wind resources – Monthly average wind speed for Mildura [6.7]

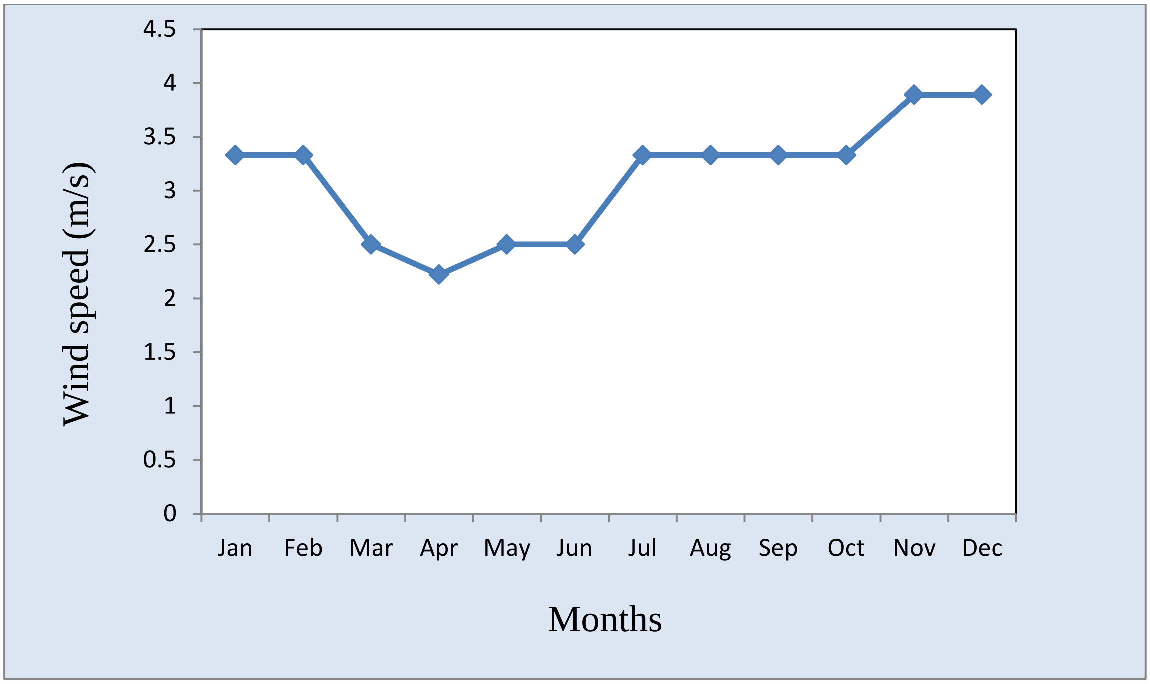

Figure 6.6 Wind resources – Monthly average wind speed for Nhill [6.7]

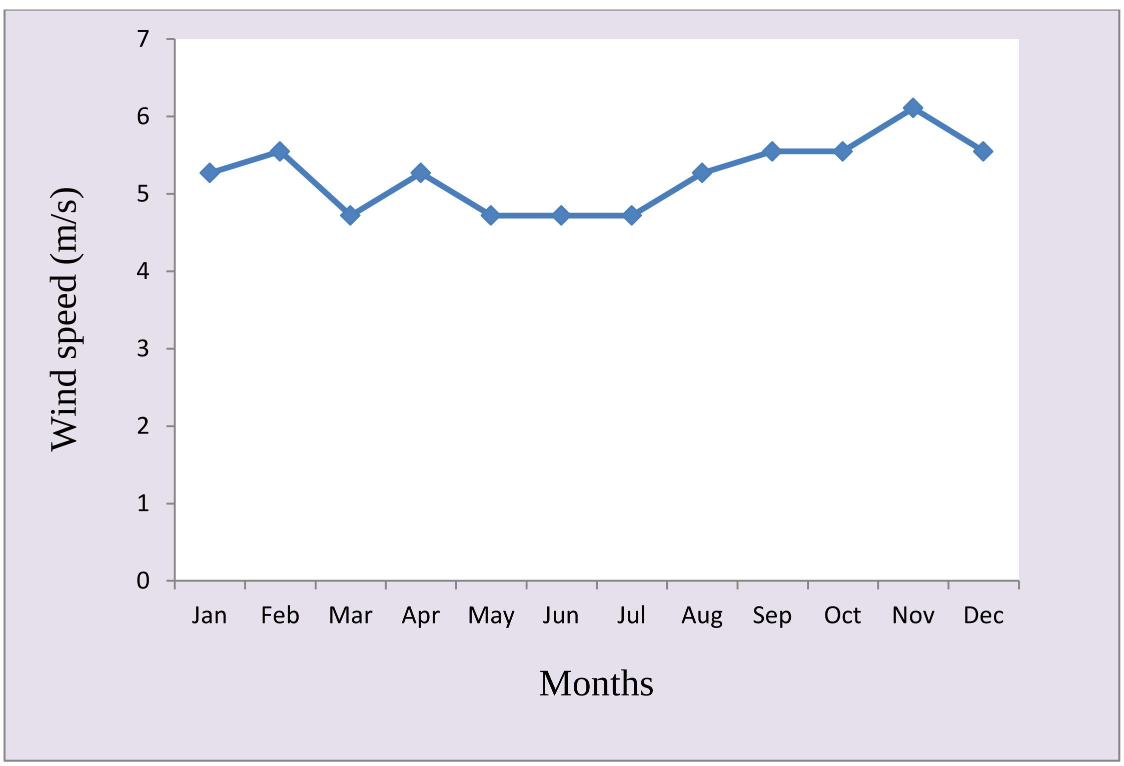

Figure 6.7 Wind resources - Monthly average wind speed for Sale [6.7]

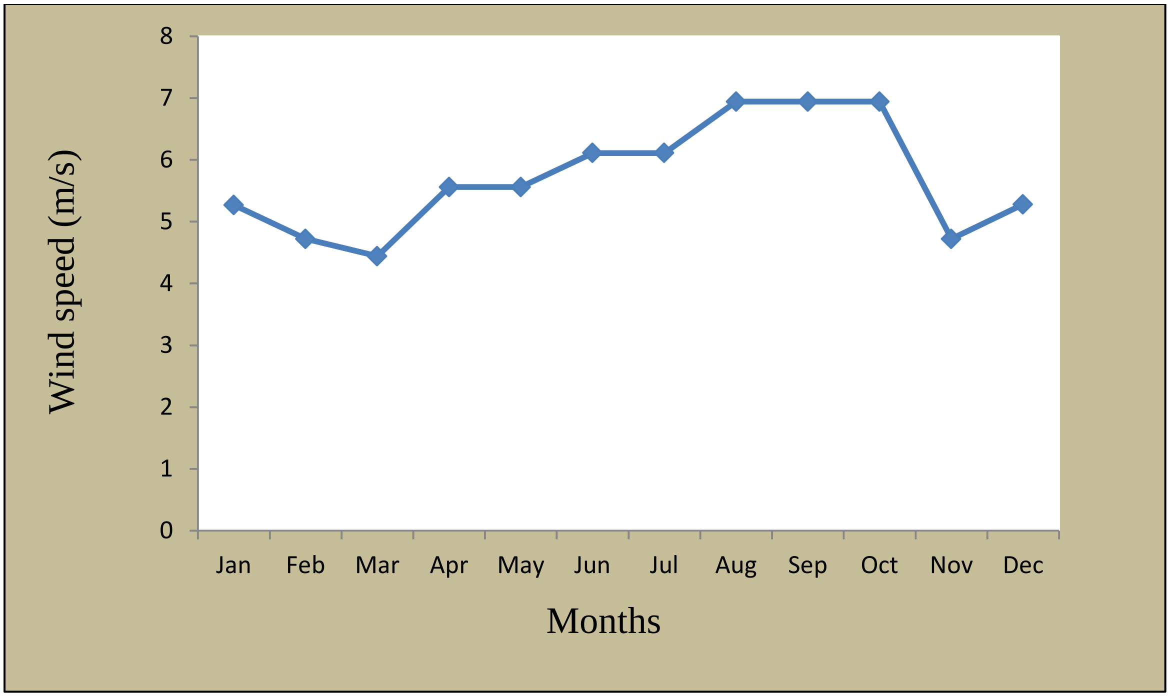

Figure 6.8 Wind resources - Monthly average wind speed for Broadmeadows [6.7]

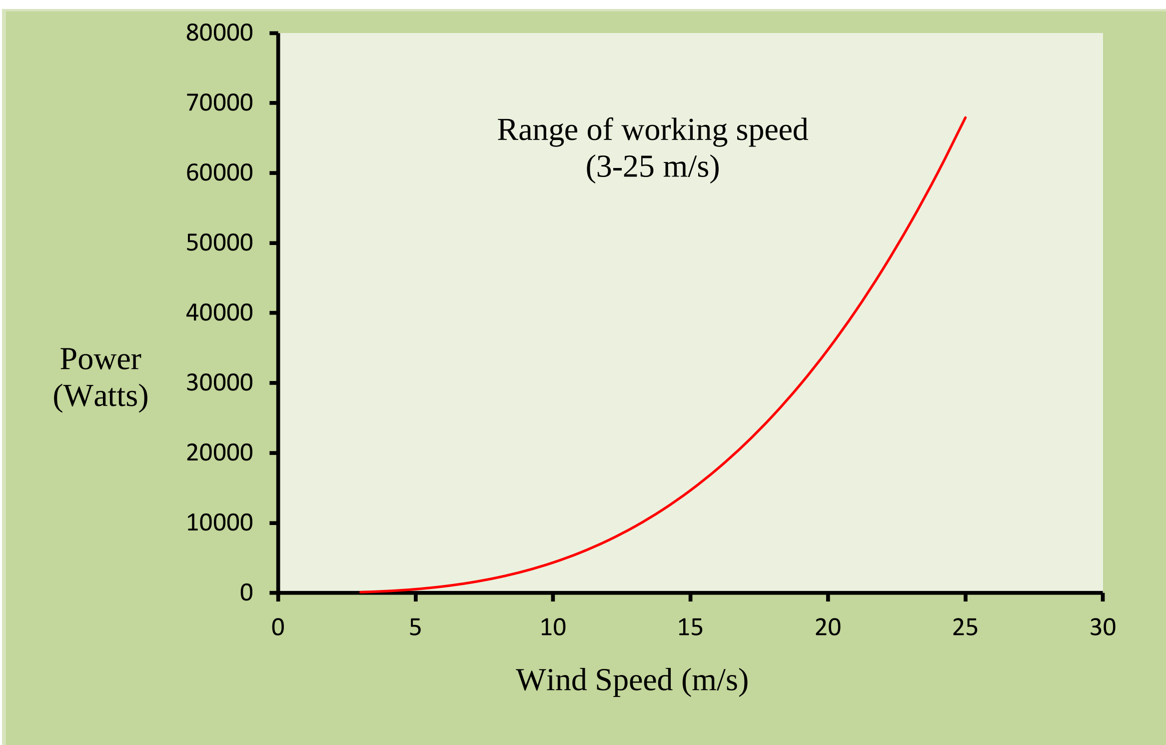

Figure 6.9 Power curve of 3kW VAWT [6.8]

6.3.1 Load profile

Footscray Park Campus is the largest campus of Victoria University and situated next to parklands along the Maribyrnong River and looks over Flemington Racecourse. There are 9 Buildings (A,C,D,E,G,K,L,M & P) up to 7 levels. Figure 6.10 shows the access and mobility map of Footscray Park Campus, Victoria University [6.9].

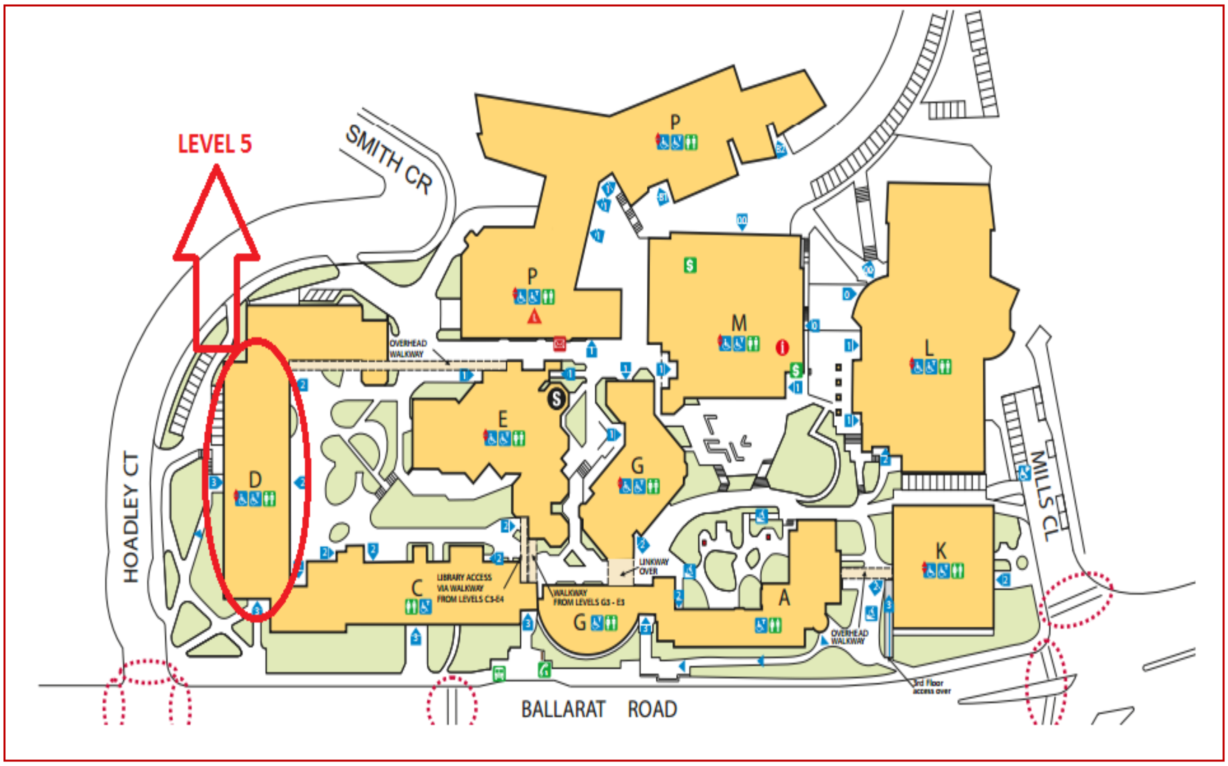

Figure 6.10 Victoria University, Footscray Park Campus access and mobility map [6.9]

The 3kW VAWT is installed on the roof top of Building D, Level 7 and 1.5kW mono-crystalline Solar panels are installed on Building C, Level 2. The 4.5kW Wind/Solar micro-generation system is connected to a grid in Building D, Level 5 [6.9].

An electric hourly load profile for Building D, Level 5 [6.9] is obtained from Facilities Department, Victoria University as shown in Figure 6.11. Table 6.4shows the hourly load profile for 24 hours with a peak demand from 9.00 a.m. to 5.00 p.m.

Table 6.4 Hourly load profile of Building D, Level 5, Victoria University

S. No	Date	Duration (Hourly)	Load profile of Building D, Level 5, Victoria University (kW)
1	1st June 2010	00:00 PM - 01:00 AM	249.6
2	1st June 2010	01:00 AM - 02:00 AM	251.6
3	1st June 2010	02:00 AM - 03:00 AM	252.9
4	1st June 2010	03:00 AM - 04:00 AM	270.2
5	1st June 2010	04:00 AM - 05:00 AM	281
6	1st June 2010	05:00 AM - 06:00 AM	283.9
7	1st June 2010	06:00 AM - 07:00 AM	286.5
8	1st June 2010	07:00 AM - 08:00 AM	340.2
9	1st June 2010	08:00 AM - 09:00 AM	413.6
10	1st June 2010	09:00 AM - 10:00 AM	457.2
11	1st June 2010	10:00 AM - 11:00 AM	453.9
12	1st June 2010	11:00 AM - 12:00 PM	456.3
13	1st June 2010	12:00 PM - 13:00 PM	456.2
14	1st June 2010	13:00 PM - 14:00 PM	451.7
15	1st June 2010	14:00 PM - 15:00 PM	444.5
16	1st June 2010	15:00 PM - 16:00 PM	441.1
17	1st June 2010	16:00 PM - 17:00 PM	409
18	1st June 2010	17:00 PM - 18:00 PM	392.1
19	1st June 2010	18:00 PM - 19:00 PM	363
20	1st June 2010	19:00 PM - 20:00 PM	348
21	1st June 2010	20:00 PM - 21:00 PM	336.1
22	1st June 2010	21:00 PM - 22:00 PM	305.6
23	1st June 2010	22:00 PM - 23:00 PM	287.3
24	1st June 2010	23:00 PM - 24:00 PM	261.5

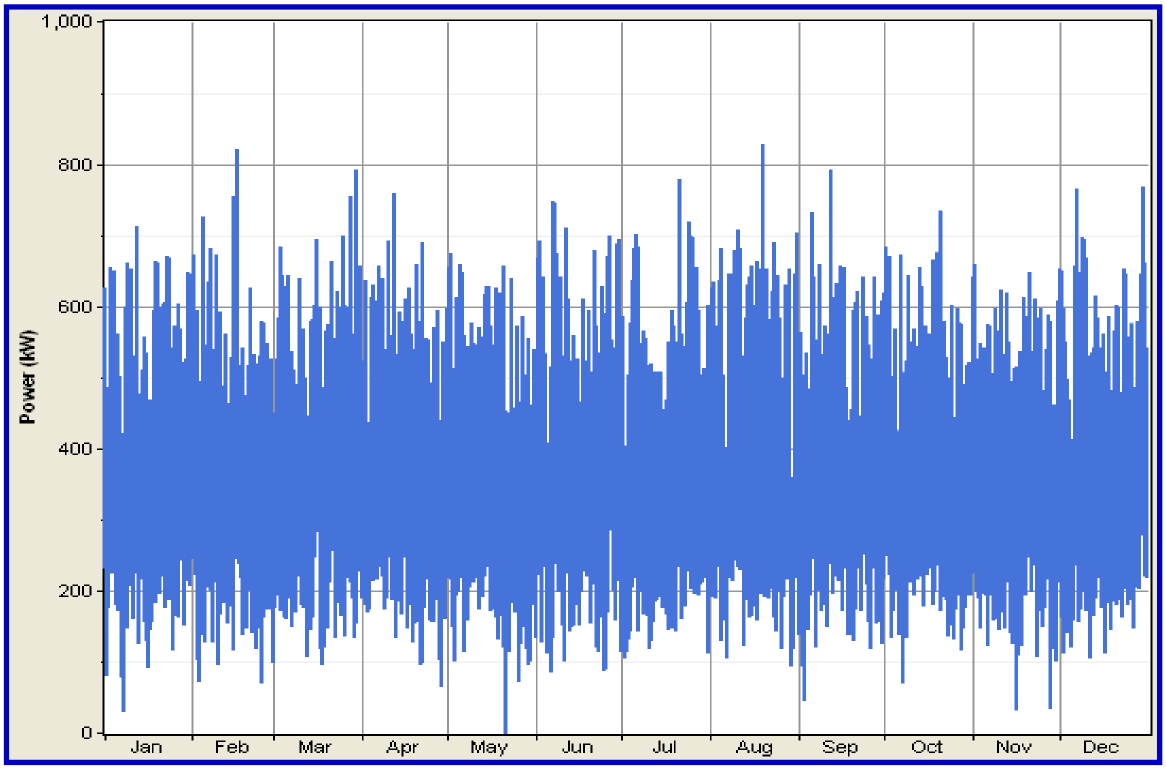

Figure 6.11Hourly load profile of Building D, Level 5 for one year

6.3.2 Details of System Components

Cost, efficiency and lifetime of the major components are shown in Table 6.5.

Table 6.5 Details of System Components

S. No	Components	Capital cost ($)	Efficiency (%)	Life time
1	3kW VAWT	21,410	30	15
2	1.5kW PV Array	3,520	17	20
3	Converters	10,000	97	20

6.3.3 Electricity tariff

The electricity involved in the 4.5kW Wind/Solar micro-generation system includes electricity purchasing tariff and electricity sale-back tariff (feed-in-tariff) [6.10-6.11]. When a continuous supply of electricity day or night is provided by the grid to all domestic and commercial appliances, the users need to pay the electricity bill calculated by different types of tariffs. Taking an example of the AGL Energy tariff, single rate meter tariff is 29.238 c/kWh inclusive of GST, two rate meter tariff which allows a permanently wired storage hot water unit to be heated overnight then for 8 hours each night is 19.701 c/kWh inclusive of GST and a time of use meter that measures electricity during peak and off-peak times is 36.850 c/kWh and 20.471c/kWh [6.10]. For the promotion of renewable energy systems in Australia feed-in-tariff has been enacted by several State Governments. In Victoria, State Government has introduced different feed-in tariff schemes for people producing their own renewable energy for the excess power they feed into the grid, who install sustainable energy systems of less than 100kW in size. The feed-in-tariff for new applicants, Standard feed-in tariff (closed for new applicants on 31stDecember 2012), Transitional feed-in tariff (closed to new applicants on 31st December 2012) and Premium feed-in tariff (closed to new applicants on 29th December 2011) are the different types of tariff in Victoria. Since the 4.5kW Wind/Solar micro-generation system was installed during June 2010, it was eligible for Premium feed-in tariff offered to small scale renewable energy systems for 5kW or less a credit of at least 60c/kWh for excess electricity fed back into the grid [6.11]. Single rate meter from AGL Energy tariff [6.10] and Premium feed-in tariff [6.11] was used to optimize 4.5kW Wind/Solar micro-generation system in this chapter.

6.4 Results and discussion

The simulation results presented in this section show the long term implementation of the prototype 4.5kW Wind/Solar micro-generation system where the electricity load per day is 8.4MWh/d with 827kW peak. Economical, technological and environmental performances are the three type of results presented and discussed in this section. As the indicators of economic performance initial cost, total net present cost (NPC) and cost of energy (COE) are used to measure financial quantity. System components size, renewable fraction and capacity shortage are used to measure the systems technological performance [6.1-6.5].

The systems life cycle cost is represented by the total NPC and HOMER calculates the NPC [6.2] as shown in equation (6.4)

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\,(i, R_{proj})} \tag{6.4}$$

where:

$C_{ann,tot} =$ total annualized cost [$/yr]

CRF () = capital recovery factor

'i'= interest rate [%]

$R_{proj} =$ project lifetime [yr]

The average cost per kWh of useful electrical energy produced by the system is defined as the levelized COE. HOMER divides the annual cost of produced electricity by the total useful electric energy production [6.2] as shown in equation (6.5).

$$\mathrm{COE} = \frac{C_{ann,tot} - C_{boiler} E_{thermal}}{E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales}} \tag{6.5}$$

where:

$C_{ann,tot}$ = total annualized cost of the system [$/yr]

C_{boiler} = boiler marginal cost [$/kWh]

$E_{thermal}$ = total thermal load served [kWh/yr]

$E_{prim,AC}$ = AC primary load served [kWh/yr]

$E_{prim,DC}$ = DC primary load served [kWh/yr]

E_{def} = dererrable load served [kWh/yr]

$E_{grid,sales}$ = total grid sales [kWh/yr]

The energy originated from renewable power sources is referred to as renewable fraction and HOMER calculates the renewable fraction [6.2] as shown in equation (6.6).

$$f_{ren} = \frac{E_{ren} + H_{ren}}{E_{tot} + H_{tot}} \tag{6.6}$$

where:

E_{ren} = renewable electrical production [kWh]

H_{ren} = renewable thermal production [kWh]

E_{tot} = total electrical production [kWh]

H_{ren} = renewable thermal production [kWh]

A shortfall between the required operating capacity and the amount of operating capacity the system can provide is defined as the capacity shortage. HOMER calculates the capacity shortage over the year [6.2]. The ratio between the total capacity shortage and the total electric load is known as capacity shortage fraction and HOMER calculates the capacity [6.2] as shown in equation (6.7).

$$f_{cs} = \frac{E_{cs}}{E_{tot}} \tag{6.7}$$

where:

$E_{cs} =$ total capacity shortage [kWh/yr]

$E_{tot} =$ total electric load [kWh/yr]

The performance profiles of the optimized systems of all 5 Victorian suburbs for grid connected system with 9.6kW converter size, grid connected system with 4.5kW converter size and off-grid system are shown in Tables (6.6-6.19). From Tables (6.6-6.19) the system configuration, component sizing, initial capital cost, operating cost, total NPC, COE, renewable fraction and capacity shortage can be found.

6.4.1 Economic performance

The grid connected system with 9.6kW converter size which is implemented in Power Systems Research Laboratory at Victoria University has the best economic performance in Melbourne as shown in Table 6.6 (since the system shows the minimum NPC) and the least economic performance being in Nhill as shown in Table 6.12 (since the system shows the maximum NPC). Similar results are obtained for the grid connected system with 4.5kW converter size, Melbourne has the best economic performance as shown in Table 6.7 and Nhill has the least economic performance as shown in Table 6.13. The initial capital cost, the operating cost and the total NPC of 4.5kW converter size for Melbourne and Nhill as shown in Tables (6.7 and 6.13) is less than the initial capital cost, the operating cost and the total NPC of 9.6kW converter size as shown in Tables (6.6 and 6.12) because of the difference in price of converters (4.5kW converter is $5000 cheaper than 9.6kW converter).

COE for grid connected system with both 9.6kW converter size and 4.5kW converter size for all 5 suburbs Melbourne, Mildura, Nhill, Sale and Broadmeadows is 0.279 $/kWh. For off-grid system Melbourne has the least COE of 0.236 $/kWh and Nhill and Sale has the most COE of 0.239 $/kWh as shown in Tables (6.8, 6.14 and 6.17).

6.4.2 Technological performance

The system configuration and components for grid connected system with both 9.6kW converter size and 4.5kW converter size is almost similar for all five suburbs.

For off-grid system with 1.5kW PV and 400 units of 3kW VAWT, capacity shortage varies for all 5 suburbs. Mildura have the least capacity shortage of 22% as shown in Table 6.11, Melbourne and Broadmeadows have 24% of capacity shortage as shown in Tables (6.8 and 6.20). Nhill and Sale have the most capacity shortage of 25% as shown in Tables (6.14 and 6.17).

For all the five suburbs if the capacity shortage is decreased by 5% to 10% the COE increases rapidly. To maintain COE of off-grid system equal to the grid connected system the capacity shortage (22% - 25%) has to be met from either batteries, diesel generators or from grid.

Table 6.6 Optimization Results: Grid connected system for Melbourne (9.6kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	9.6	1000	$34,930	856,006	$17,155,048	0.279	0.04

Table 6.7 Optimization Results: Grid connected system for Melbourne (4.5kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	4.5	1000	$29,930	855,906	$17,148,048	0.279	0.04

Table 6.8 Optimization Results: Off-grid system for Melbourne

PV (kW)	3kW VAWT	Converter (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction	Capacity Shortage
1.5	400	4.5	$8,572,520	171,370	$11,999,920	0.236	1.00	0.24
1.5	750	4.5	$16,066,020	321,170	$22,489,420	0.433	1.00	0.20
1.5	4000	4.5	$85,648,520	1,712,170	$119,891,920	2.233	1.00	0.15

Table 6.9 Optimization Results: Grid connected system for Mildura (9.6kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	9.6	1000	$34,930	856,480	$17,164,538	0.279	0.04

Table 6.10 Optimization Results: Grid connected system for Mildura (4.5kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	4.5	1000	$29,930	856,380	$17,157,538	0.279	0.04

Table 6.11 Optimization Results: Off-grid system for Mildura

PV (kW)	3kW VAWT	Converter (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction	Capacity Shortage
1.5	400	4.5	$8,572,520	171,370	$11,988,000	0.238	1.00	0.22
1.5	1000	4.5	$21,418,520	428,170	$29,981,920	0.574	1.00	0.19
1.5	5000	4.5	$107,058,520	2,140,170	$149,861,920	2.787	1.00	0.15

Table 6.12 Optimization Results: Grid connected system for Nhill (9.6kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	9.6	1000	$34,930	857,017	$17,175,264	0.279	0.04

Table 6.13 Optimization Results: Grid connected system for Nhill (4.5kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	4.5	1000	$29,930	856,917	$17,168,264	0.279	0.04

Table 6.14 Optimization Results: Off-grid system for Nhill

PV (kW)	3kW VAWT	Converter (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction	Capacity Shortage
1.5	400	4.5	$8,572,520	171,370	$11,999,920	0.239	1.00	0.25
1.5	1000	4.5	$21,418,520	428,170	$29,981,920	0.577	1.00	0.20
1.5	6000	4.5	$128,468,520	2,568,170	$179,831,920	3.362	1.00	0.15

Table 6.15 Optimization Results: Grid connected system for Sale (9.6kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	9.6	1000	$34,930	856,211	$17,159,148	0.279	0.04

Table 6.16 Optimization Results: Grid connected system for Sale (4.5kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	4.5	1000	$29,930	856,111	$17,152,228	0.279	0.04

Table 6.17 Optimization Results: Off-grid system for Sale

PV (kW)	3kW VAWT	Converter (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction	Capacity Shortage
1.5	400	4.5	$8,572,520	171,370	$11,999,920	0.239	1.00	0.25
1.5	1000	4.5	$21,418,520	428,170	$29,981,920	0.577	1.00	0.20
1.5	5000	4.5	$107,058,520	2,140,270	$149,863,920	2.795	1.00	0.15

Table 6.18 Optimization Results: Grid connected system for Broadmeadows

(9.6kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	9.6	1000	$34,930	856,460	$17,164,138	0.279	0.04

Table 6.19 Optimization Results: Grid connected system for Broadmeadows

(4.5kW Converter size)

PV (kW)	3kW VAWT	Converter (kW)	Grid (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction
1.5	1	4.5	1000	$29,930	856,360	$17,157,138	0.279	0.04

Table 6.20 Optimization Results: Off-grid system for Broadmeadows

PV (kW)	3kW VAWT	Converter (kW)	Initial Capital	Operating Cost ($/year)	Total NPC	COE ($/kWh)	Renewable Fraction	Capacity Shortage
1.5	400	4.5	$8,572,520	171,370	$11,999,920	0.238	1.00	0.24
1.5	1000	4.5	$21,418,520	428,170	$29,981,920	0.575	1.00	0.19
1.5	5000	4.5	$107,058,520	2,140,170	$149,861,920	2.797	1.00	0.15

6.4.3 Environmental performance

Figure 6.12 shows the sum of reduction of carbon emissions for Victorian suburbs and Figure 6.13 shows the capacity shortage of all 5 suburbs for off-grid system at COE (0.236 to 0.239 $/kWh). If capacity shortage is decreased, carbon emission can also be decreased.

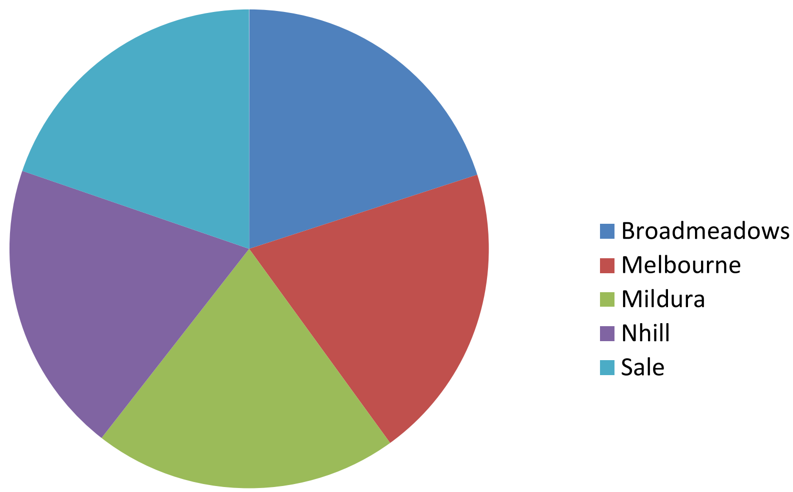

Figure 6.12 Sum of reduction of Carbon emissions for Victorian Suburbs

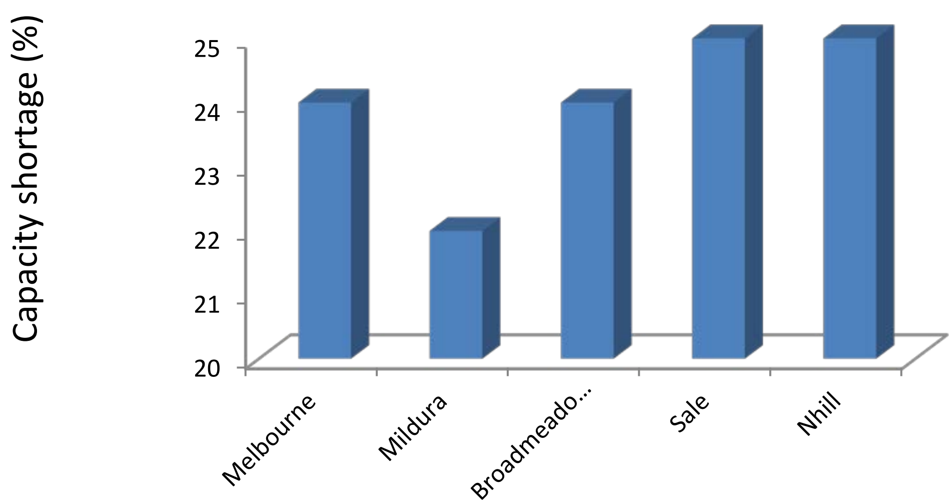

Figure 6.13 Capacity shortage for Victorian Suburbs (COE at 0.236 to 0.239 $/kWh)

6.5 Summary

The techo-economic performance of 4.5kW Wind/Solar micro-generation system in Victoria, Australia for the load data of 8.4MWh/d of Building D, Level 5 obtained from Facilities department of Victoria University, Footscray Park campus was studied. The system configuration, the system costs, capacity shortage and carbon emissions of the system were analyzed for all the five selected suburbs in Victoria.

In terms of economic consideration for 4.5kW Wind/Solar micro-generation system grid connected system for both 9.6kW converter size and 4.5kW converter size it was found that the COE is 0.279 $/kWh for all the five selected suburbs. In terms of off-grid system it was found that Melbourne has the least COE of 0.236 $/kWh with 24% capacity shortage, Nhill and Sale has the most COE of 0.239 $/kWh with capacity shortage 25%. It was also found that the COE increases rapidly as the capacity shortage is reduced in steps of 5%.

Therefore the capacity shortage has to be met from grid, batteries or diesel generators. Based on the analysis of simulation results, it has been found that a bigger size of Wind/Solar system is required and needs a larger amount of primary investment while is able to reduce up to 75% - 78% of carbon emissions from off-grid system for all selected suburbs.

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Chapter 7

Reliability Analysis of Hydrogen Energy, Fuel Cell Power Generation System and 4.5kW Wind/Solar micro-generation System with Load Sharing System

7.1 Introduction

In most circumstances, an increased load may induce a higher component failure rate in power generation systems. If Hydrogen Energy and Fuel Cell Power Generation System and a 4.5kW Wind/Solar micro-generation system are proportionately loaded according to their respective capacities, such synchronized usage prevents excessive load and ensures all the subsystems and individual components in each subsystem are at the same stage of their life span. Resulting from unexpected failure in a system can be prevented by better maintenance planning [7.1].

However in Load Sharing System (LSS), on each of the surviving components a higher load is resulted due to the failure of a component, thereby inducing a higher failure rate in the system [7.2, 7.3]. Both Hydrogen Energy and Fuel Cell Power Generation Systems and a 4.5kW Wind/Solar micro-generation system are LSS, and if a component fails; the same workload is shared by the remaining components, resulting in increased load on each survival component. Thus a higher component failure rate is induced in both the systems. The workload strongly affects the component failure rate in both the systems and this has been proven by many other empirical studies in mechanical and computer systems. Pumps in hydraulic system, CPU's in a multiprocessor and in power plants electric generators sharing an electric load are some of the examples of LSS [7.2, 7.3]. 'K-out-of-n system' with exponential distributions is used in this chapter to find the reliability of Hydrogen Energy and Fuel Cell Power Generation System and a 4.5kW Wind/Solar micro-generation system since this method can solve k-out-of-n systems in a short time. The reliability analysis of both the power generation systems with LSS is examined by using MATLAB simulation. This chapter will assist reliability engineers to accurately model the LSS that arises in many other practical solutions [7.2-7.6].

'K-out-of-n cold standby systems', 'k-out-of-n warm standby systems', tampered failure rate (TFR) model, cumulative exposure (CE) model, stochastic reward approach model, bounds and approximation, 'k-out-of-n system' with TFR model and "k-out-of-n system' with exponential distributions are some of the models for LSS [7.2-7.6].

'K-out-of-n system' with exponential distributions are further divided into three different cases [7.2-7.6]

Case 1: All failure rates are equal

Case 2: All failure rates are distinct

Case 3: All failure rates are neither equal nor distinct

Further, there is not much published work on reliability analysis of load-sharing in Hydrogen Energy and Fuel Cell Power Generation System and a 4.5kW Wind/Solar micro-generation system with components subjected to general failure distributions. The reliability analysis of load-sharing in both the power generation systems, ‘k-out-of-n system’ with exponential distributions are used mainly focussing on CASE 2 where all failures are distinct and the results are analysed using MATLAB simulation [7.2-7.6].

Section 7.2 of the chapter provides the limitations of different modelling concepts of load sharing systems. Section 7.3 presents the reliability of LSS for both the power generation systems focussing on ‘k-out-of-n system’ with exponential distributions. Section 7.4 points out the special cases of ‘k-out-of-n systems’ with series, parallel and both series & parallel systems of LSS in a Wind/Solar 4kW micro-generation system. Section 7.5 highlights the results of ‘k-out-of-n system’ with exponential distributions for both the power generation system using MATLAB simulation. Finally, Section 7.6 provides the summary as well as directions for future work.

7.2 Limitations of Different Modelling Concepts of LSS

It should be noted that in LSS, the load varies at random time intervals. Hence, analysing the LSS at random time intervals is more complex in the TFR model. In the CE model, whilst calculating failure rate, the solution provided is too complex. In addition, by using multi-dimensional integrals the sequence of each failure rate is calculated corresponding to the failure sequence. Even using MATLAB in the CE model, solution can be applied for simple systems for identical components and for non-identical components this method can be applied only for ($n \leq 4$). Hence, for solving any realistic system CE model cannot be used [7.2-7.6].

In the stochastic reward models, the exact solution for the reliability of LSS consists of 1000 states. In addition, bound and approximation model, the LSS consist of 10^6 states can be found easily. The exact values can be computed only by using 'k-out-of-n system' with exponential distributions for both identical and non-identical components. Therefore, 'k-out-of-n system' with exponential distributions model is used to find the reliability of LSS in Hydrogen Energy and Fuel Cell Power Generation System and 4.5kW Wind/Solar micro-generation system by using MATLAB simulation [7.2-7.6].

7.3 Reliability Analysis of LSS

A system functions properly if there are at least k good components. Let L be the total load on the system and k be the number of components required for successful operation of the system [7.2-7.6].

Notations:

N number of components in the system.

K minimum number of components required for successful operation of the system.

L total load on the system.

Assumptions:

1. There are ‘n’ identical components in the system
2. The system functions successfully if there are at least ‘K’ good components
3. When a component fails the load will be distributed equally among all the remaining good components
4. The system and its components are non-repairable

The sub-system functions successfully if and only if there are at least *k* good components. Let *L* be the total load of the sub-system. If there are *i* $(0 \leq i \leq n\text{-}k)$ component failures in the system, the load is shared by the remaining (*n-i*) components. Hence, the load on each component is $Li = L/n\text{-}i$. Let λi be the failure rate of each of the surviving components when there are *i* failures. The value of λi can be found using load-life relationship. The power-law load-life relationship is used as shown in eqn. (7.1) [7.2-7.6].

$$\alpha(j) = (\mathrm{n} - \mathrm{i}) * \left(\frac{\mathrm{n}}{\mathrm{n}-\mathrm{i}}\right)^{\delta} * \mathrm{FRO} \tag{7.1}$$

When the subsystem is put into operation at time zero, all components are working, and they are equally sharing the constant load that the system is supposed to carry. In this case, the failure rate of every working component is denoted by FROi (base line failure rate (λ_0) for λ_0 subsystem ‘i’. Because there are ‘n’ working components in the subsystem, the first failure occurs as the rate of $\alpha_1 = \mathrm{n}.\mathrm{FROi}$ [7.2-7.6].

Case 1: When alpha which means failure rate is equal, in order to calculate the reliability of the sub-system the following formula as shown in eqns. (7.2) and (7.3) are used [7.2-7.6].

$$R(t) = \sum_{i=0}^{n-k} \frac{(\alpha t)^i.\exp(-\alpha t)}{i!} \tag{7.2}$$

R (t) =

$$\frac{(\alpha t)^0.\exp(-\alpha t)}{0!} + \frac{(\alpha t)^1.\exp(-\alpha t)}{1!} + \frac{(\alpha t)^2.\exp(-\alpha t)}{2!} + \frac{(\alpha t)^3.\exp(-\alpha t)}{3!} + \frac{(\alpha t)^4.\exp(-\alpha t)}{4!} + \cdots \tag{7.3}$$

Case 2: When alpha which means failure rate are distinct, in order to calculate the reliability of the sub-system the following formula as shown in eqns. (7.4) and (7.5) are used [7.2-7.6].

$$\mathrm{R}(t) = \sum_{i=1}^{\mathrm{n-k+1}} \mathrm{A_i}.\exp(-\,\alpha_\mathrm{i}.\mathrm{t}) \tag{7.4}$$

$$\mathrm{A_i} = \prod_{\substack{\mathrm{j=1} \\ j \neq i}}^{\mathrm{n-k+1}} \frac{\alpha_\mathrm{j}}{\alpha_\mathrm{j} - \alpha_\mathrm{i}} \tag{7.5}$$

$\mathrm{R}(t) =$

$$\mathrm{A_1}.\exp(-\alpha_1.\mathrm{t}) + \mathrm{A_2}.\exp(-\alpha_2.\mathrm{t}) + \mathrm{A_3}.\exp(-\alpha_3.\mathrm{t}) + \mathrm{A_4}.\exp(-\alpha_4.\mathrm{t}) + \mathrm{A_5}.\exp(-\alpha_5.\mathrm{t}) + \mathrm{A_6}.\exp(-\alpha_6.\mathrm{t}) \tag{7.6}$$

$$\mathrm{A_1} = \frac{\alpha_2}{\alpha_2-\alpha_1} * \frac{\alpha_3}{\alpha_3-\alpha_\mathrm{i}} * \frac{\alpha_4}{\alpha_4-\alpha_\mathrm{i}} * \frac{\alpha_5}{\alpha_5-\alpha_\mathrm{i}} * \frac{\alpha_6}{\alpha_6-\alpha_\mathrm{i}} \tag{7.7}$$

$$\mathrm{A_2} = \frac{\alpha_1}{\alpha_1-\alpha_2} * \frac{\alpha_3}{\alpha_3-\alpha_2} * \frac{\alpha_4}{\alpha_4-\alpha_2} * \frac{\alpha_5}{\alpha_5-\alpha_2} * \frac{\alpha_6}{\alpha_6-\alpha_2} \tag{7.8}$$

$$\mathrm{A_3} = \frac{\alpha_1}{\alpha_1-\alpha_3} * \frac{\alpha_2}{\alpha_2-\alpha_3} * \frac{\alpha_4}{\alpha_4-\alpha_3} * \frac{\alpha_5}{\alpha_5-\alpha_3} * \frac{\alpha_6}{\alpha_6-3} \tag{7.9}$$

Case 3: When alpha which means failure rate is neither equal nor distinct [7.2-7.6].

The reliability of LSS in Hydrogen Energy and Fuel Cell Power Generation System as shown in Figure 7.1 and 4.5kW Wind/Solar micro-generation system as shown in Figure 7.2 is examined on ‘k-out-of-n system’ with exponential distributions mainly focussed on Case 2 when all failures are distinct and the results are analysed using MATLAB simulation [7.2-7.6].

7.3.1 Reliability Analysis of LSS for Hydrogen Energy and Fuel Cell Power Generation System

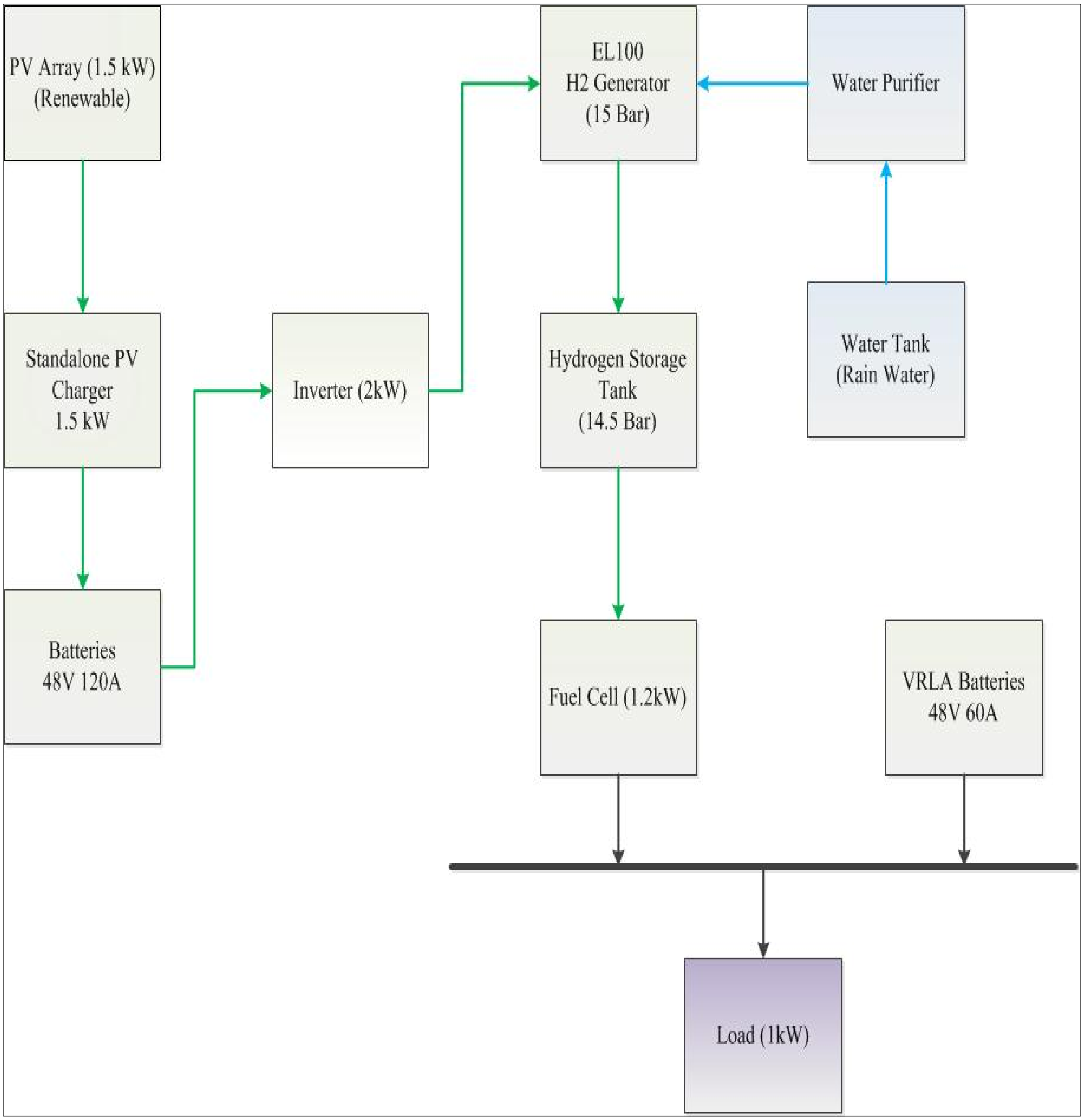

Figure 7.1 Block diagram with different components to find Reliability Analysis of Hydrogen Energy & Fuel Cell Power Generation System

Load-life distribution follows the power-law as in eqn. (7.4), n=11, k=7, t=1000, δ=1.5 and FRO=0.0001[7.5].

Failure Rate of 11 components when all components are working and when the load on the system is L

$$\alpha(1) = (11 - 0) * \left(\frac{11}{11-0}\right)^{1.5} * 0.0001 \tag{7.10}$$

$\alpha(1)$ = 0.0011 (one failure per 909 hours)

If 1 component fails then the failure rate of remaining 9 components, when the load on the system is same L

$$\alpha(2) = (11 - 1) * \left(\frac{11}{11-1}\right)^{1.5} * 0.0001 \tag{7.11}$$

$\alpha(2)$ = 0.00115368973 (one failure per 867 hours)

If 2 component fails then the failure rate of remaining 8 components, when the load on the system is same L

$$\alpha(3) = (11 - 2) * \left(\frac{11}{11-2}\right)^{1.5} * 0.0001 \tag{7.12}$$

$\alpha(3)$ = 0.00121609575 (one failure per 822 hours)

If 3 component fails then the failure rate of remaining 7 components, when the load on the system is same L

$$\alpha(4) = (11 - 3) * \left(\frac{11}{11-3}\right)^{1.5} * 0.0001 \tag{7.13}$$

$\alpha(4)$ = 0.0012898643 (one failure per 775 hours)

If 4 component fails then the failure rate of remaining 6 components, when the load on the system is same L

$$\alpha(5) = (11-4) * \left(\frac{11}{11-4}\right)^{1.5} * 0.0001 \tag{7.14}$$

$\alpha(5)$ = 0.0013789229 (one failure per 725 hours)

If 5 component fails then the failure rate of remaining 5 components, when the load on the system is same L

$$\alpha(6) = (11-5) * \left(\frac{11}{11-5}\right)^{1.5} * 0.0001 \tag{7.15}$$

$\alpha(6)$ = 0.0014894070 (one failure in every 671 hours)

If 6 component fails then the failure rate of remaining 5 components, when the load on the system is same L

$$\alpha(7) = (11-6) * \left(\frac{11}{11-6}\right)^{1.5} * 0.0001 \tag{7.16}$$

$\alpha(7)$ = 0.0016315636 (one failure in every 613 hours)

If 7 components fail then the failure rate of remaining 5 components, when the load on the system is same L

$$\alpha(8) = (11-7) * \left(\frac{11}{11-7}\right)^{1.5} * 0.0001 \tag{7.17}$$

$\alpha(8)$ = 0.0018241436 (one failure in every 548 hours)

The system fails when more than (n-k) component fails. Hydrogen Energy and Fuel Cell Power Generation System fails when more than 7 component fails (11-4=7). Therefore, if 8 component fails then we don't have to calculate the failure rate of the remaining 4 components because the system fails [7.5].

7.3.2 Reliability Analysis of LSS for 4.5kW WIND/SOLAR micro-generation system

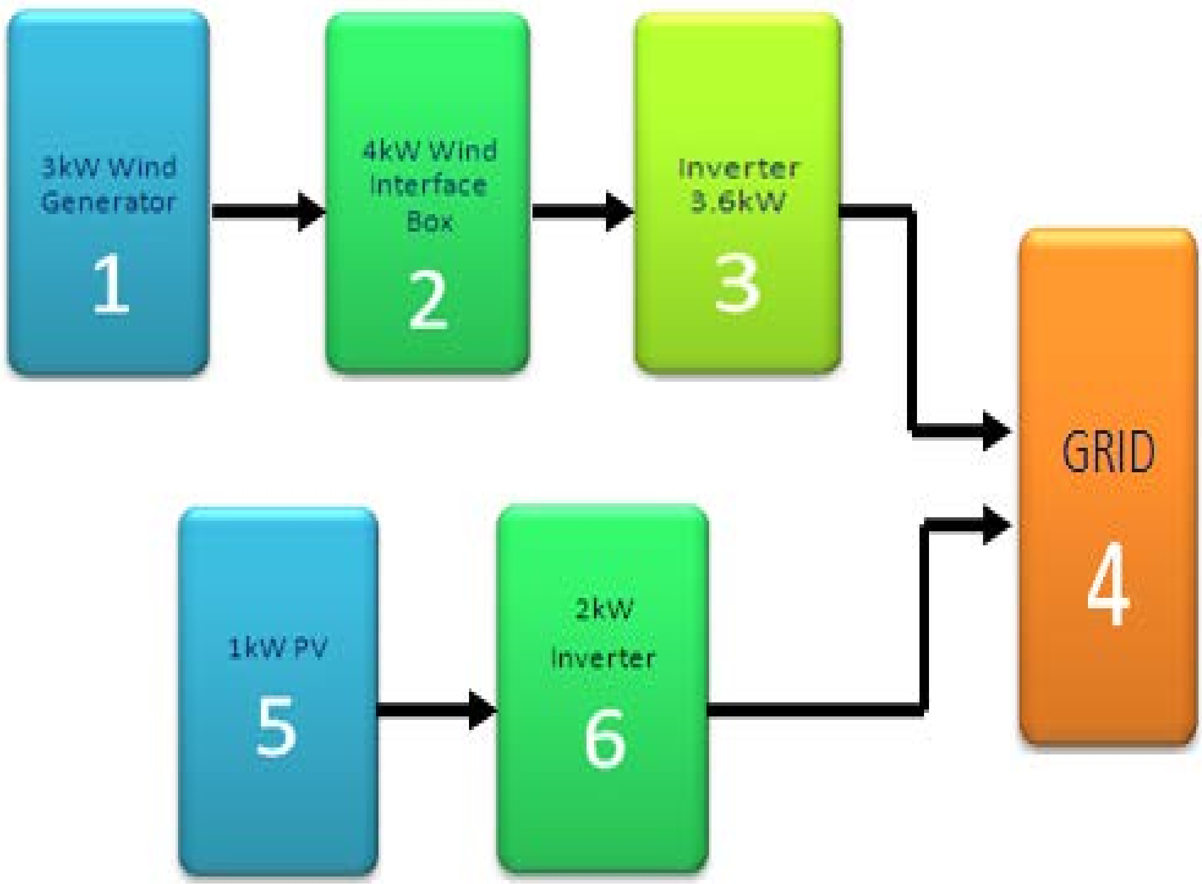

Figure 7.2 Block diagram with different components (numbered) to find Reliability Analysis of 4.5kW Wind/Solar micro-generation system [7.5]

Load-life distribution follows the power-law as in eqn. (7.4), n=6, k=3, t=1000, δ=1.5 and FRO=0.0001[7.5].

Failure Rate of 6 components when all components are working and when the load on the system is L

$$\alpha(1) = (6-0) * \left(\frac{6}{6-0}\right)^{1.5} * 0.0001 \tag{7.18}$$

α(1) = 0.0006 (one failure per 1667 hours)

If 1 component fails then the failure rate of remaining 9 components, when the load on the system is same L

$$\alpha(2) = (6-1) * \left(\frac{6}{6-1}\right)^{1.5} * 0.0001 \tag{7.19}$$

α(2) = 0.0006572670 (one failure per 1521 hours)

If 2 component fails then the failure rate of remaining 8 components, when the load on the system is same L

$$\alpha(3) = (6-2) * \left(\frac{6}{6-2}\right)^{1.5} * 0.0001 \tag{7.20}$$

α(3) = 0.0007348469 (one failure per 1361 hours)

If 3 component fails then the failure rate of remaining 7 components, when the load on the system is same L

$$\alpha(4) = (6-3) * \left(\frac{6}{6-3}\right)^{1.5} * 0.0001 \tag{7.21}$$

α(4) = 0.0008485281 (one failure per 1179 hours)

The system fails when more than (n-k) component fails. 4.5kW Wind/Solar micro-generation system fails when more than 3 components fail (6-3=3). Therefore, if 4 components fail then we don't have to calculate the failure rate of the remaining 3 components because the system fails [7.5].

7.4 Special Cases of k- out - of- n System

Series and parallel systems are the special cases of k-out-of-n system. Figure 7.3 shows the series, parallel and series/parallel configuration of 4.5kW Wind/Solar micro-generation system. 1-out-of-n: F system and n-out-of-n: G system is a series system and n-out-of-n: F system and 1-out-of-n: G system is a parallel system. The series and parallel systems are widely used in both industrial and military systems. For example, if a minimum of 4 cylinders are firing where it may be possible to drive a V8 engine. However, the automobile cannot be driven, if less than four cylinders fire. In this case the functioning of engine behaves as 4-out-of-8: G system [7.7].

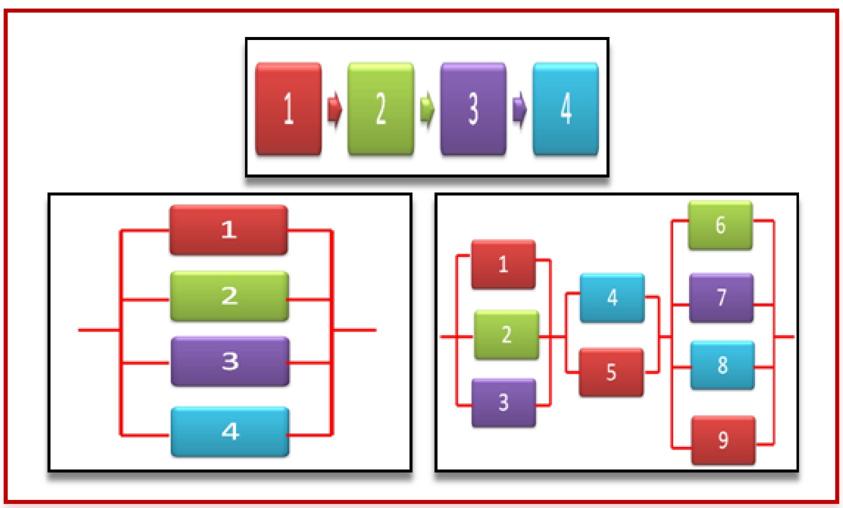

Figure 7.3 Series, Parallel and Series/Parallel System Configuration of 4.5kW Wind/Solar micro-generation system [7.7]

7.5 Evaluation and Results of k-out-of-n System with Exponential Distributions for Hydrogen Energy and Fuel Cell Power Generation System and 4.5kW WIND/SOLAR micro-generation System using MATLAB Simulation

The Figures 7.4(a & b) show the flow chart used to calculate failure rates of the components in a sub-system for Hydrogen Energy and Fuel Cell Power Generation System, n=11 & k=7 and for Wind/Solar 4.5kW micro-generation system, n=6 and k=3.

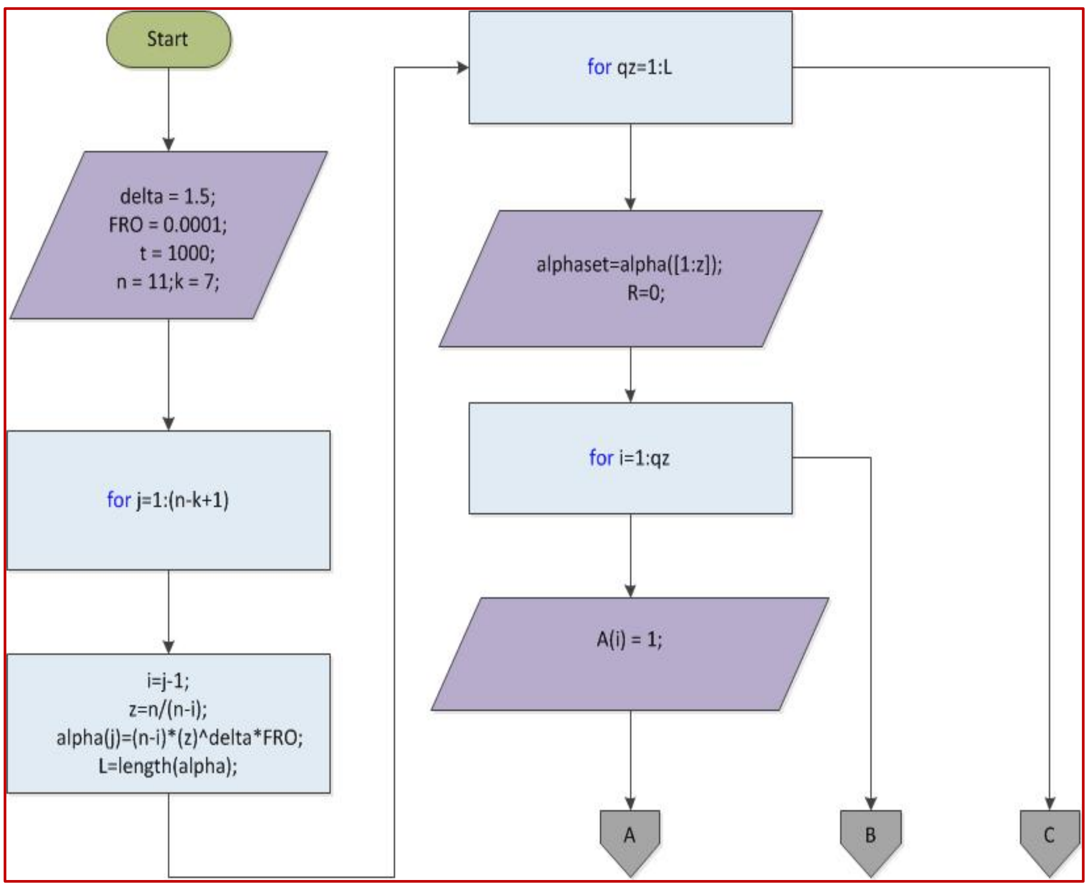

Figure 7.4a Flow chart for Reliability evaluation of Hydrogen Energy and Fuel Cell Power Generation System

The evaluation of k-out-of-n system with exponential distributions for Wind/Solar 4.5kW micro-generation system is done by using MATLAB simulation. The MATLAB simulation results with probability of state and cumulative success are shown in Tables 7.1 and 7.2. The reliability of Hydrogen Energy and Fuel Cell Power Generation System is 99.16% and the reliability of Wind/Solar 4.5kW micro-generation system is 99.41 % [7.5].

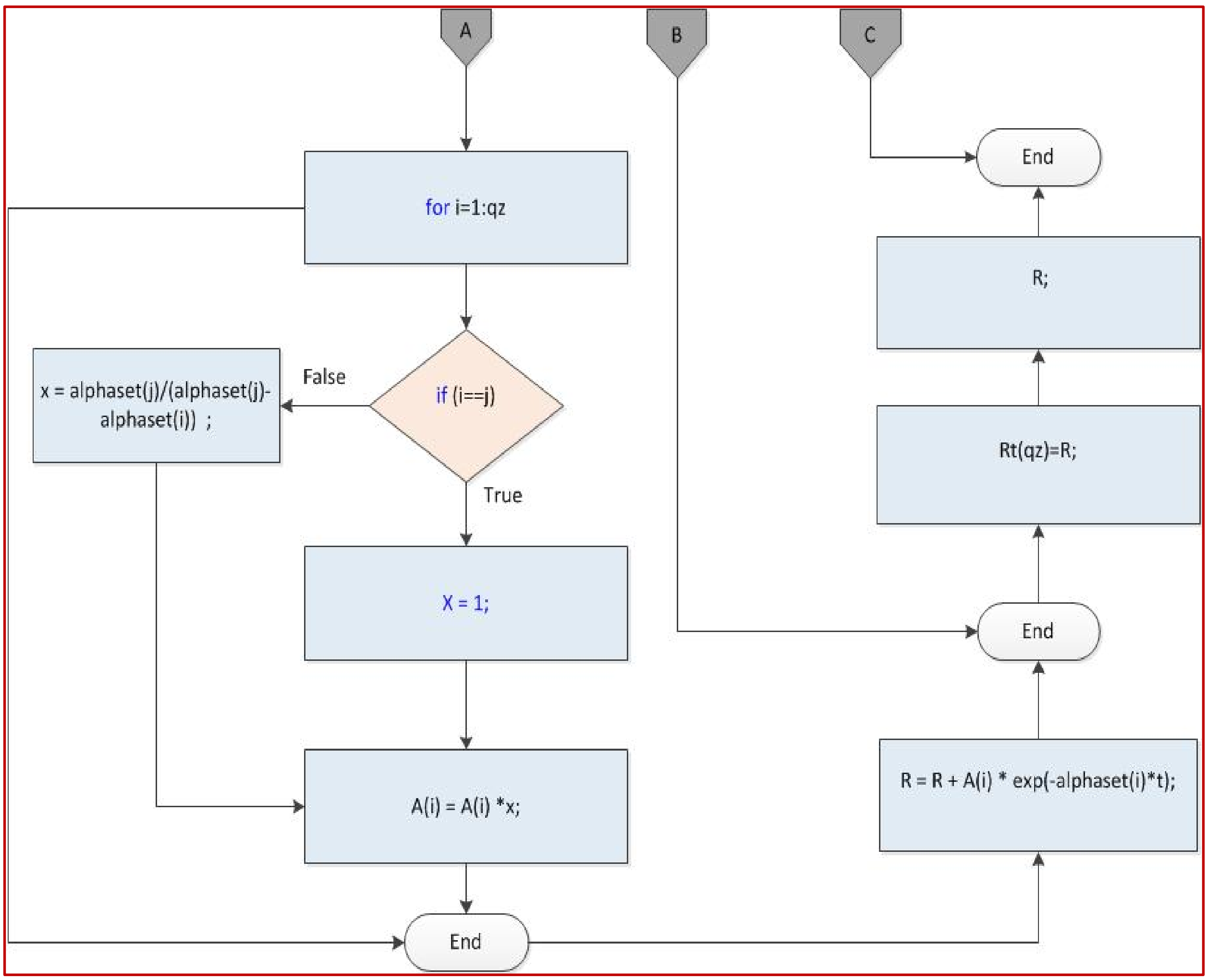

Figure 7.4b Flow chart for Reliability evaluation of Hydrogen Energy and Fuel Cell Power Generation System

Table 7.1 MATLAB Simulation Results of Hydrogen Energy and Fuel Cell Power Generation System

S. No	Probability of state	Cumulative success
1	0.332871083698080	0.332871083698080
2	0.356502302057339	0.689373385755419
3	0.199650739556302	0.889024125311721
4	0.078296699439221	0.967320824750942
5	0.024318900304678	0.991639725055620

Table 7.2 MATLAB Simulation Results of Wind/Solar 4.5kW micro-generation system

S. No	Probability of state	Cumulative success
1	0.548811636094026	0.548811636094026
2	0.320035767673904	0.868847403767930
3	0.101540811162206	0.970388214930136
4	0.023762664337905	0.994150879268041

7.6 Summary

In this chapter, the importance of LSS for Hydrogen Energy and Fuel Cell Power Generation System and 4.5kW Wind/Solar micro-generation system is emphasized. The limitation of other models of LSS like CE model, TRF model and stochastic reward approach are discussed. K-out-of-n system with exponential distributions is evaluated and the results are generated using MATLAB simulation for Case 2 when alpha which means failure rate is distinct. Further the special cases of 'k-out-of-n system' like series, parallel and series/parallel are discussed. To analyse systems with several k-out-of-n load sharing subsystems or modules it is straight forward to apply method proposed in this paper since this method can solve 'k-out-of-n systems' in short time [7.5-7.6].

Based upon the research, it is found that the reliability of a Hydrogen Energy and Fuel Cell Power Generation System is 99.16% and 4.5kW Wind/Solar micro-generation system is 99.41%. This chapter will help reliability engineers to accurately model the LSS that may arise in many practical situations.

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Chapter 8

Summary and Future Work

This thesis has worked on the idea of H_2 optimization, Fuel Cell as a back-up power for National Broadband Network (NBN) in Australia, and Hybrid System inclusive of renewable energy to reduce CO_2 emissions in Australia. It began with an introduction of natural greenhouse effect, man-made greenhouse effect, deforestation and enormous amount of greenhouse gasses emitted to the atmosphere by burning of fossil fuels. Then, the thesis mentioned that the energy consumption will continue to increase 2% per year which means energy consumption will be doubled every 35 years. The H_2 production facilities, fueling stations are very low in Australia compared with US and also the bibliometric analysis of US and Australia were presented in Chapter 1. The benefit of switching from fossil fuels to Hydrogen Energy, Fuel Cell technology and Hybrid Systems inclusive of renewable energy to reduce the impact of 'global warming' was also discussed in Chapter 1.

The thesis presented a number of research efforts related to the problems of conventional energy, the benefits of renewable energy and back-up power for NBN in Australia in Chapter 2. The Hydrogen Energy, H_2 production pathways, H_2 safety, barriers of Hydrogen Energy and Fuel Cells applications on electrical distributing system and its commercial viability in Australia was addressed in the same Chapter. The hybrid systems inclusive of renewable energy to reduce CO_2

emissions were discussed in Chapter 2. Finally, simulation and reliability analysis for H_2 Energy, Fuel Cell technology and Hybrid System inclusive of renewable energy was also highlighted in Chapter 2.

In Chapter 3 during laboratory experimentation, the total number of bottles of H_2 generated from 3.1 liters of rain H_2O and the numbers of hours taken to generate one bottle of H_2 storage tank were examined and presented. During laboratory experimentation the H_2 generator was continued to run 3 times to generate H_2 from VRLA batteries (48V, 120A) and the results were presented in Chapter 3. The work mainly focused to produce H_2 on-site by rain H_2O and to run both (T-1000 PEM Fuel Cell power generation system and EL100 H_2 generator) simultaneously together for long run capabilities (8 hours) at desired load of 1kW and also the trouble shooting of H_2 generator were presented in Chapter 3. Satisfactory and unsatisfactory results obtained during laboratory experimentation were highlighted in Chapter 3 and a few important results are presented in this section.

- A completely off-grid stand-alone solution can be reliably deployed combining Solar and H_2 (satisfactory result).
- Industry claims a H_2 purity of 99.95%. Yes, this is correct (satisfactory result).
- Over-long charge time (unsatisfactory result) and
- Automatic switching off of process before completion of the charging and due to over pressure (unsatisfactory result).

In Chapter 4, the working principle of T-1000 PEM Fuel Cell and the description of the system installed were presented. Trouble- shooting of T-1000 PEM Fuel Cell and also the reasons why telecommunication sites today rely on VRLA batteries were discussed in the same Chapter. T-1000 PEM Fuel Cell and the excellent interface with the other devices like EL100 H_2 generator, batteries, H_2 storage tank, load and measuring units were pointed out in Chapter 4. The most important results obtained from Chapter 4 during laboratory experimentation were, the system setup produced at the same time it consumed H_2 and unsatisfactory behavior to meet the required 8 hours of back-up power for telecommunications site for the desired load of 1kW and how long it will take to produce enough H_2 to run 1.2kW T-1000 PEM Fuel Cell for 1, 4 and 8 hours were presented in Chapter 4.

In Chapter 5, the Australian Government's clean energy future or clean environment plan, the introduction of the Direct Action Plan, repel of the carbon tax or emissions trading scheme and the trouble-shooting of 3kW VAWT were presented. The guidelines for implementing 4.5kW Wind/Solar micro-generation system at Power Systems Research laboratory, its monitoring and data transmission were discussed in the same Chapter.

The results of energy produced by 4.5kW Wind/Solar micro-generation, energy consumed by Building D, Level 5, Footscray Park Campus and a 3 Bedroom Hall Kitchen (BHK) residence in Melbourne were examined and presented in Chapter 5. The techo-economic performance of 4.5kW Wind/Solar micro-generation system in Victoria, Australia, the system configuration, the system costs, capacity shortage and carbon emissions of the system for five selected suburbs in Victoria were analyzed and discussed in Chapter 6. In terms of economic consideration for 4.5kW Wind/Solar micro-generation, grid connected system for both 9.6kW converter size and 4.5kW converter size, it was found that the Cost of Energy (COE) increases rapidly as the capacity shortage is reduced and was presented in Chapter 6. Finally, the Chapter 6 concludes that the capacity shortage has to be met from grid, batteries or diesel generators and the simulation results were presented.

In chapter 7, the importance of Load Sharing System (LSS) for Hydrogen Energy, Fuel Cell Power Generation System and 4.5kW Wind/Solar micro-generation were presented. The special cases of 'k-out-of-n system' and the limitations of other models like CE model, TRF model and stochastic reward approach were presented in the same Chapter. And also by using MATLAB simulation, 'k-out-of-n system' with exponential distributions is evaluated and the results were presented in Chapter 7.

8.1 Future Work

The implementation of renewable energy to reduce carbon consumption and Fuel Cell as a back-up power for Australian NBN: experimentation, simulation, optimization and reliability analysis can be further extended as highlighted in this section.

- To verify the behaviour, reliability and long run capabilities, safety signals and automatic switching 'OFF' process of **EL100 H_2 generator with 30 bar** when called upon for back-up power in telecommunication sites like NBN may be an idea for future work.

- To monitor how much bottles of H_2 is generated, how long it will take to generate one bottle of H_2 tank of capacity 150 liters and the H_2O consumed between the maximum and the minimum liquid level of the **EL100 H_2 generator with 30 bar** can be one area of further work to the current work.

- A further comparison will be from Valve Regulated Lead Acid (VRLA) batteries of 48V, 120A how much H_2 can be produced from **EL100 H_2 generator with 30 bar**. The aim of testing of **EL100 H_2 generator with 30 bar** and M-FIELB H_2 Fuel Cell and its integration into telecommunications site for back-up power solution when both are working together simultaneously is to show how this work can be extended.

- The purpose to present Figure 8.1 is to show how this work can be extended to produce H_2 directly from solar energy bypassing the batteries. In Chapter 3 Figure 3.8, the electricity produced by solar panels was fed to VRLA batteries (48V, 120A) via a solar charge controller and then the energy from batteries were consumed by EL100 H_2 generator to generate H_2. The purpose of monitoring, "How long it will take to produce enough H_2 to run 1kW M-FIELD H_2 Fuel Cell for 1, 4 and 8 hours" and to examine **EL100 H_2 generator with 30 bar** and M-FIELD H_2 Fuel Cell as shown in Figures 8.2 and 8.3 is to show how this work can be extended for long run capabilities since the required back-up power for telecommunications by regulation is 8 hours for the desired load of 1kW.

- The energy produced by 4.5kW Wind/Solar micro-generation system, and energy consumed by the Building D, Level 5, Footscray Park Campus and a 3 BHK residence in Melbourne is examined for one month can be one area of further work (to examine 3 to 6 months) to the current work. 'k-out-of-n system' with exponential distributions is using

MATLAB simulation for Case 2. Similarly, Cases 1 and 3 can be analyzed for future work.

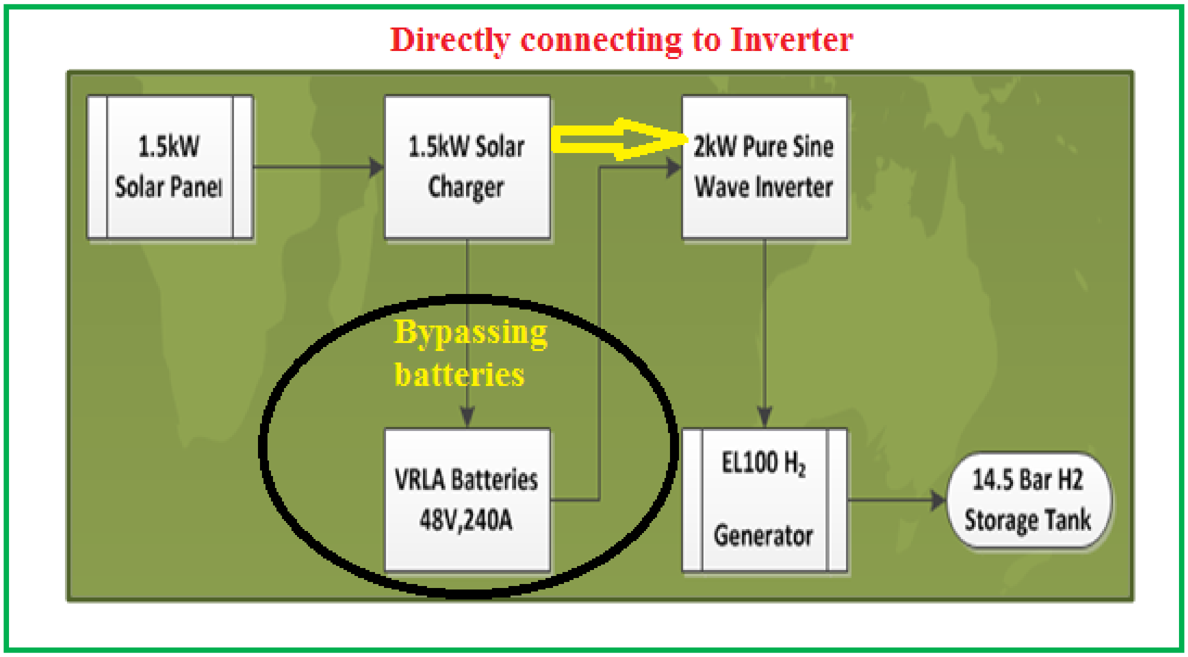

Figure 8.1 Block diagram of H_2 generation from Solar Energy bypassing batteries

Figure 8.2 Photo of M-FIELD H_2 Fuel Cell Back Door “Water In” Port.

Figure 8.3 M-FIELD H_2 Fuel Cell at Power Systems Research Laboratory, Victoria University