School of Science, Engineering and Technology

ABERTAY UNIVERSITY

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An Iterative Analytical Design Framework for the optimal designing of an Off-grid renewable energy based hybrid smart micro-grid

(A case study in a remote area - Jordan)

By

Mohanad Halawani

December, 2015

"In the name of God, the Most Gracious, the Most Merciful"

"Knowledge is only a little that is communicated to you, (O men!)"

An Iterative Analytical Design Framework for the optimal designing of an Off-grid renewable energy based hybrid smart micro-grid

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Mohanad Halawani

Thesis Submitted in Fulfilment of Requirements for the Degree of Doctor of Philosophy in Electrical Engineering

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DEDICATION

This work is first dedicated to the memory of my father, ***Mohammad Saleem Halawani****, who has been my life-model for hard work; he instilled in me the confidence to achieve my dreams.*

And I dedicate my PhD;

To my mother

To my soul-mate; my wife

To my lovely sons (Saleem and Waseem)

To my sisters

To my brothers

And to my family.

ACKNOWLEDGMENT

I owe my sincere gratitude and earnest thankfulness to my supervisors; **Dr. Suheyl Ozveren** and **Dr. Daniel Gilmour** for their patience and kind support throughout my research. This dissertation would not have been possible without their academic and technical guidance. I would like to thank them for every effort they have given for improving the quality of my dissertation.

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It is a great pleasure also to thank everyone who has lent a helping hand in developing this dissertation successfully either directly or indirectly.

DECLARATION

I, Mohanad Halawani, hereby declare that I am the author of this thesis, and unless otherwise stated, all references cited have been consulted by me. The work, of which the thesis is a record, has been carried out by me, and it has not been previously accepted for a higher degree. This work has been carried out under the supervision of Dr. Suheyl Ozveren and Dr. Daniel Gilmour.

Signed …………………….. Date …………………

Mohanad Halawani

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CERTIFICATION

I certify that this is a true and accurate version of the thesis approved by the examiners, and that all relevant ordinance regulations have been fulfilled

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List of abbreviations

AC	Alternating current
AD	Anaerobic Digestion
ADF	Analytical Design Framework
CB	Circuit Breaker
CHP	Combined Heat Power
CO_2	Carbon Dioxide
DC	Direct current
DCF	Discounted Cash Flows
DG	Diesel Generator
FC	Fuel Cell
G	Grid
GHG	Green House Gases
GP	Generated Power
H_2	Hydrogen
H_2O_2	Hydrogen Peroxide
HOGA	Hybrid Optimization by Genetic Algorithms
HPS	Hybrid Power System
$Hybrid_2$	Hybrid Optimization Model for Electrical Renewable
HOMER	Hybrid Power System
IADF	Iterative Analytical Design Framework
IHPS	Isolated Hybrid Power System
IPS	Isolated Power System
IR	Incident Irradiance
LCF	Linear Cost Function
LP	Linear Programming
µG	Micro-grid
MPPT	Maximum Power Point Tracking
NC, NO	Normally Close, Normally Open
O_2	Oxygen
OGREH-SµG	Off-grid renewable energy based hybrid smart µ-grids
RES	Renewable Energy Source
SDO	Simulink Design Optimisation
PEM	Proton Exchange Membrane
PV	Photovoltaic
VR	Voltage Regulator
WTG	Wind Turbine Generator

Thesis outline chart

Part 1

- **Chapter 1**: Aims and objectives with general overview for the electrical sector, and isolated power systems.
- **Chapter 2**: Literature review for couplings, feeding modes, and hybrid power systems. Also presents a description and analysis of the technologies used within the thesis.
- **Chapter 3**: Research and design requirements describing in detail the requirements to achieve the aims and objectives which contribute the success, showing the problem stated and the motivation, as well as the limitation of this research.

Part 2

- **Chapter 4**: Describes the methodology of this research, such as simulations, survey, and experiments, it also shows the potential of the new control system.
- **Chapter 5**: This chapter presents the case study (Bayir-Jordan), where all the required data is presented, such as load and climate information.

Part 3

- **Chapter 6**: Shows the results from simulations, experiments, and analytical techniques.
- **Chapter 7**: Presents a discussion of the analytical techniques and the results presented in the previous chapter with more details and analysis, and the conclusion for this thesis that presents the achievement and the outcomes of this thesis. Recommendations are proposed for further work.

Reference

Appendix

Abstract

Creative ways of utilising renewable energy sources in electricity generation especially in remote areas and particularly in countries depending on imported energy, while increasing energy security and reducing cost of such isolated off-grid systems, is becoming an urgently needed necessity for the effective strategic planning of Energy Systems. The aim of this research project was to design and implement a new decision support framework for the optimal design of hybrid micro grids considering different types of different technologies, where the design objective is to minimize the total cost of the hybrid micro grid while at the same time satisfying the required electric demand.

Results of a comprehensive literature review, of existing analytical, decision support tools and literature on HPS, has identified the gaps and the necessary conceptual parts of an analytical decision support framework. As a result this research proposes and reports an Iterative Analytical Design Framework (IADF) and its implementation for the optimal design of an Off-grid renewable energy based hybrid smart micro-grid (OGREH-SµG) with intra and inter-grid (µG2µG & µG2G) synchronization capabilities and a novel storage technique.

The modelling design and simulations were based on simulations conducted using HOMER Energy and MatLab/SIMULINK, Energy Planning and Design software platforms. The design, experimental proof of concept, verification and simulation of a new storage concept incorporating Hydrogen Peroxide (H_2O_2) fuel cell is also reported. The implementation of the smart components consisting Raspberry Pi that is devised and programmed for the semi-smart energy management framework (a novel control strategy, including synchronization capabilities) of the OGREH-SµG are also detailed and reported. The hybrid µG was designed and implemented as a case study for the Bayir/Jordan area.

This research has provided an alternative decision support tool to solve Renewable Energy Integration for the optimal number, type and size of components to configure the hybrid µG. In addition this research has formulated and reported a linear cost function to mathematically verify computer based simulations and fine tune the solutions in the iterative framework and concluded that such solutions converge to a correct optimal approximation when considering the properties of the problem. As a result of this investigation it has been demonstrated that, the implemented and reported OGREH-SµG design incorporates wind and sun powered generation complemented with batteries, two fuel cell units and a diesel generator is a unique approach to Utilizing indigenous renewable energy with a capability of being able to synchronize with other µ-grids is the most effective and optimal way of electrifying developing countries with fewer resources in a sustainable way, with minimum impact on the environment while also achieving reductions in GHG. The dissertation concludes with suggested extensions to this work in the future.

List of key output

Work presented	Title	Name of international journal / conference
Conference paper	A Hybrid Power System for remote areas in Jordan	IEEE, UPEC 2015 conference preceding
Conference paper	Design and optimization of a new hybrid power system with multi storage system for remote areas in Jordan	Research student conference 2014 at Abertay University
Poster	Integrating Hybrid Renewable Energy from several resources as Solar, Wind and Thermal energy	Research student conference 2013 at Abertay University
Poster	Independent Hybrid Power System with Multi-storage	Energy Technology Partnership (ETP) 2015
Poster	Isolated Power system	Energy Technology Partnership (ETP) 2014
Presentation	Renewable Energy and Hybrid Power System	At University of St. Andrews, 2015
Presentation	Intelligent Hybrid Power System and long-term storage system	At University of St. Andrews, 2014
Article paper	Hybrid Power System for Jordanian Houses to Reduce the electrical bill in efficient way	Under final preparation
Article paper	Smart Grid in the Future and the Flexible Power Grid for Operation and Control with multi-storage	Under final preparation

Part 1

CHAPTER 1

INTRODUCTION

1.1 The originality of the research with the Aims and Objectives

Stand-alone power systems, for remote area power supplies, are described as independent power networks with generation and load that is not connected to the public electricity network because, as such connections for small demands with long transmission or distribution lines would be prohibitively expensive. Normally, the generation in these systems are near the end user and they have one voltage level. These systems are called off-grid or Isolated Power Systems (IPSs).

Creative ways of utilising renewable energy sources in electricity generation especially in remote areas and particularly in countries or regions depending on imported energy, while increasing energy security and reducing cost of such isolated off-grid systems, is becoming an urgently needed necessity for the effective strategic planning of Energy Systems. However, renewable energy is by its nature intermittent and variable yet an independent power system (IPS) has to supply grid level quality of service. One of the ways of providing continuity of service is to have an independent hybrid system (IHPS or off grid networks) with only a Diesel Generator (DG) as power generator. However, the costs of fuel are very high due to the extra cost of transport to remote areas therefore the use of DG has to be minimised. DG usage can be minimised by having appropriate automated storage and energy and demand management systems based on smart controllers to manage the generation, demand and the storage in an attempt to match the demand to available energy.

Therefore, ideally in such remote areas IHPS should contain dispatchable and non-dispatchable generators and energy storage elements with appropriate control systems. IHPS can thus take advantage of the complementary nature in profile of the renewable energy sources and ensure continuous and reliable power production.

1.1.1 The originality of this research

This thesis presents the following as the main contributions to knowledge:

- An IADF that provides a framework for the primary design methodology that can be undertaken to achieve the design aims derived from the requirement analysis; i.e.
  - to help the design engineer to outline the system requirements,
  - to indicate the information that needs to be collected to plan and design IHPS,
  - to provide an iterative process with evolutionary modification of models and simulations
- A streamlined energy management system that this thesis has referred to as an “intelligent supervisory switching controller system” was devised and implemented with a Raspberry Pi with two main types of smart controllers;
  - Central Controller which is a supervisory switching controller to schedule all electrical power generation (RESs, storage, and DG) and load sharing, responsible for monitoring the available power through the components controller.

  - Demand Controller for demand management utilising an adaptive tariff and automatic switching system as well as informing voluntary changes in the consumption patterns of the end users. This novel strategy enhances and optimizes µG by handling difficulties as they arise.
- A novel storage system (H_2O_2 as long term storage system) utilising a mixture of available renewable energy with:
  - combustion engine (as standby power) and
  - other storage system (for short and long term storage).
- Monitoring the sustainability of power availability from micro-grids to enable synchronisation with each other.
  - Covers any power deficit in any µG to maintain the available power at accepted levels, by providing power from the nearest µG.
  - Allows control of more than power system parameters to provide more reliable power.
- Formulation of the objective function (LCF) to model the optimal system to:
  - Optimize the cost of the µG components for the designing system
  - Helps initialize the setup for HOMER simulations and also to minimize the number of iterations.
  - Verify HOMER simulations.

1.1.2 Aims

The aim of this research project was to design and implement an Iterative Analytical Design Framework (IADF) for the optimal Off-grid renewable energy based hybrid smart micro-grid (OGREH-SµG) with:

1. Intra and inter-grid (µG2µG & µG2G) synchronization capabilities and a
2. Appropriate storage technique with an
3. Appropriate Energy and demand management scheme.

In this thesis will be reported:

- The description and the details of the IADF implementation and design of an OGREH-SµG, as a case study
  - **Implementation of different µ-grid designs:** for access to electricity in off grid/remote areas by investigating potential renewable energy sources (RES) based hybrid power system (HPS) with different types of storage systems and trying different smart generation and demand management strategies to control and regulate the system to cater for intermittent generation due to RES.
  - **Optimising the technical resilience of the µG's operational stability and reliability:** of the different generation and RES mixes and µG configurations, in order to increase the system robustness for different ranges of operating conditions.
  - **Evaluating the economic feasibility** of the HPS resulting from the above.
- Review and evaluate existing and potential RES technologies with special emphasis on storage technologies to derive and adopt models for the various techno-economic analysis and simulation studies to be used in the IADF. As well as the description and experimental and simulation details of the investigations for an appropriate (uncomplicated and safe) storage mechanism.

- The design and implementation of the intelligent supervisory switching controllers with the associated complementary adaptive tariff designs along with the results of the simulations demonstrating the increase in the resilience of the µ-grid's operational sustainability and reliability are reported in detail.

1.1.3 Objectives

1.1.3.1 Research objectives

- Literature review of the Off-Grid/Independent Hybrid power Systems and the planning and simulation tools used in power systems for their design, optimisation, operational plan and analysis to identify the gaps and to choose the suitable tools for devising and implementing the IADF.
- Review and evaluate existing and potential RES technologies with special emphasis on storage technologies to derive and adopt models for the various techno-economic analysis and simulation studies to be used in the IADF.
- Research an appropriate control and synchronisation technique for adoption and implementation in the system.
- Research an appropriate low (simple and uncomplicated) technology storage technique.
- Research an appropriate case study including the available data – a remote area Bayir/Jordan.
- Research appropriate generation and demand management approaches that can be used in micro grids to devise intelligent supervisory switching controller, scheduling and demand management algorithms that can be implemented in a microcontroller.

1.1.3.2 Implementation objectives

- Implementing the IADF through simulation software (HOMER and MatLab/Simulink) according to the information collected from the literature review, RES and storage technologies. Moreover, research synchronisation techniques to implement a simulation for new intra and inter-grid synchronising capability.
- Implementing analytical and mathematical evaluation for analysis with special emphasis on technical feasibility through dynamic equations and formula. Application of economical analysis, such as payback, cash flow, and life cycle cost to study the economic feasibility between the available systems in the literature review. The techno-economic feasibility will allow tracking observed information and embrace the performance examination of independent HPS. In addition, efficient social and ecological advantages, assessments and calculation of the aforementioned expenses are carried out by building a linear cost function.
- Find the actual behaviour of the end-users through a survey, in order to inform the adaptive management design.
- Design the intelligent supervisory switching controller system through hardware implementation by using microcontroller (Raspberry – PI).
- Proof the concept of H_2O_2 to be the future storage (as it is uncomplicated and safe to store), through practical laboratory work and simulation.

1.2 The rational

Results of a comprehensive literature review, of existing analytical, decision support tools and literature on HPS, has identified the gaps and the necessary conceptual parts of an analytical decision support framework mentioned above. A detailed design for the framework and the modelling investigations for the constituent parts were undertaken. As a result this research proposes and reports an Iterative Analytical Design Framework (IADF) and its implementation for the optimal design of an Off-grid renewable energy based hybrid smart µ-grid (OGREH-SµG) with intra and inter-grid (µG2µG & µG2G) synchronization capabilities and a novel storage technique.

Such a framework would be a beneficial as; there are huge numbers of remote areas that face difficulties in access to electricity because of technical, political and financial reasons mainly in developing and underdeveloped countries, where some of these remote areas use fossil fuels as the only source of energy. The reliance of economy on conventional generation and the unfavourable environment impacts of using this generation have re-established enthusiasm for renewable sources and movement toward building a more sustainable society.

Power generation in remote areas in Jordan depends on diesel fuel which it is very costly for these areas. Sometimes there are more difficulties in delivering fuel to these areas, and they have to stay in the blackout. This research takes a remote area of Jordan as a case study, but optimistically this research will bring benefit for all remote areas around the world. The research will only discuss the available renewable energy in this region. In these areas, there is no option to have distributed generation or grid connection. Solar radiation and wind are accessible in this region and numerous areas around the world. These systems reduce the cost of power by reducing transmission and distribution losses through distributed configuration of such micro-grids near the demand centres, and thus displace or reduce the use of fossil fuels, contributing to the sustainability of the energy systems (social benefits such as, having access to a reliable, good quality power supply).

1.3 Organisation of the research and thesis

The thesis recognises the importance of electricity and responds to the challenge of supplying electricity to remote areas. Isolated Power Systems (IPSs) could electrify these areas by using renewable energy as a generation power, supported by a reserve system to produce a completely integrated HPS, which is a cheap way to supply energy. Moreover, the issues to be considered in this research are as follows:

- Integrating µG able to work off-grid or on-grid by using RES as generation sources supported with storage and standby power systems. The stand by system could be a diesel generator (DG), CHP unit or the national grid itself.
- Economic feasibility within the µG.
- Control & sustainability of micro–grid with intermittent and variable wind and solar power, and the fluctuation of the load.
- Synchronisation of micro grids with each other and/or main national grid.
- Efficient and economical way of storing electricity.
- Generation optimization according to the location, the magnitude of the HPS and different storage types in order to equalize the load variations by matching the generation with the demand load.

- Intelligent supervisory switching controller giving the ability to control generation and load sharing, and allow voluntary load control by the consumer.

This research will develop the theoretical concept of isolated HPSs for remote areas. These systems will be helpful to electrify rural areas under standardized system concept.

1.4 Background

1.4.1 The significance of electrical power

Discoveries in electricity have changed human society, making a quantum leap between the eighteenth century and up to 21^{st} century. Hundreds of years ago, humanity would never have predicted that lives would be made easier through technology. In the modern day, people around the world cannot carry out their lives without modern technology. Humans have increased their dependence on electrical energy. Life styles have changed rapidly and electricity has become a main requirement for basic life. It is the main key for all modern technology and without it present life would be impossible. Electricity is the driving power for industries, agriculture revolution, economy, and the information technology revolution (Kaldellis 2002).

Electricity was essential in the development of mobile phones, computers, and the internet, heating systems, televisions, and light bulbs, nearly everything in the home would be completely different without it (Kaldellis 2002). This is not only making society more intelligent and healthy, but nowadays electricity is the main source for success in industrial, commercial and agricultural sectors. All these sectors are important for the economy on national and international scales. The development of electricity has impacted mostly on communications, as it has been improved tremendously, with a huge impact in people's lives. From electrically powered communication gadgets, to computers and smart devices, humans in the world can communicate with each other irrespective of distance. As long as there is power to operate a phone or internet, there will be no problem with long-distance communication (Al Bawaba 2012).

From corporate jobs to construction, all of these need electricity to operate their equipment, from white-collared workers who require electricity to power their offices and communication equipment in order to finish their daily tasks, to the blue-collared workers who require electricity to operate their machines. Consequently, their work is suffering when there is a shortage in electricity; they cannot provide the complete services that were promised to their clients (Al Bawaba 2012, FRAME 2003).

Transportation is mainly operated by fossil fuel with some designed to operate by electricity, such as trains and electrical vehicles, because it is more environmentally friendly. However, all transportation needs to be controlled and require electrical power to operate the control system (FRAME 2003). The food industry requires electricity in industrial food factories, which requires power to operate their machines. Electricity is needed in the home for heating and cooling systems. Also, by using white goods life is made much easier (FRAME 2003).

Electrical power should follow two rules; firstly, the power system should be safe for operators and facilities, and secondly, the system should supply a reliable power source that provides power in the required place and time (Golombek et al. 2013, Al Bawaba 2012, FRAME 2003).

Electrical energy may be in the form of light or thermal energy, kinetic energy and static energy, and it is possible to convert it to any desired form. Electricity is easy to operate and to control, and compared to other types of energy it is cheaper. Electricity is preferable to other power sources due to its flexibility of use and transfer (FRAME 2003).

1.4.2 Generation of electrical energy

The manufacture of electrical energy is similar to any fabrication, as it requires raw materials. This raw material can be any form of natural energy from five sources. First; the heat from the sun's radiation is converted into steam and uses a steam turbine to produce electricity. Another method is by using the direct sun light through solar panels. Secondly; wind, where the kinetic energy of the wind moves the turbine blades leading to the movement of an actuator shaft to produce electricity. Thirdly; using the kinetic energy of water (from high level to low level) to move a turbine shaft. Fourthly; using fuel in a combustion engine. The fuel could be in a solid form such as coal or biomass, or liquid form such as fossil fuel, bio diesel and bio ethanol, or gas form such as natural gas or bio-methane. Finally, nuclear energy works by producing steam energy, with the raw materials being Uranium or any fissionable materials (EIA 2005, World Bank 2004, Landau et al. 2002).

1.4.3 Access to electrical energy in the world

Almost 70% of the world's population uses electricity, which has a major impact on the daily life of individuals (Reddy et al. 2012). According to international records, the world population reached 7 billion in 2012, which puts more demands on electricity (Ying and Ruo 2012). The dramatic growth in population will increase the challenge for the decision-makers to provide an adequate supply of energy (Ying and Ruo 2012). Research has been carried out to establish the percentage of the world population that does not have access to electricity. The research concluded that a quarter of the world’s population have no access to electricity (Ahuja and Tatsutani 2009, Gronewold 2009, Birol 2002). This equates to 1.6 billion people who have no access to electricity, and this may increase to 2 billion in 2025 (Ahuja and Tatsutani 2009, Saghir 2002), where other authors argue that the number will decrease in 2030 as shown in Figure 1.1.

In order to ensure continuous access to electricity; transmission and distribution, lines are needed. Transmission lines have a very high capital and running costs to be efficient. Mainly in the third world (developing) countries, it is difficult to transmit electricity to some locations and indeed is impractical because of the high cost of transmission lines. In such circumstances, a stand-alone system is the cheapest and the fastest solution (Gronewold 2009), as described in the next section. Everyone has the right to have access to electricity; and the isolating power system (IPS) is able to solve many problems, such as access to electricity, environment and it allows the usage of renewable energy.

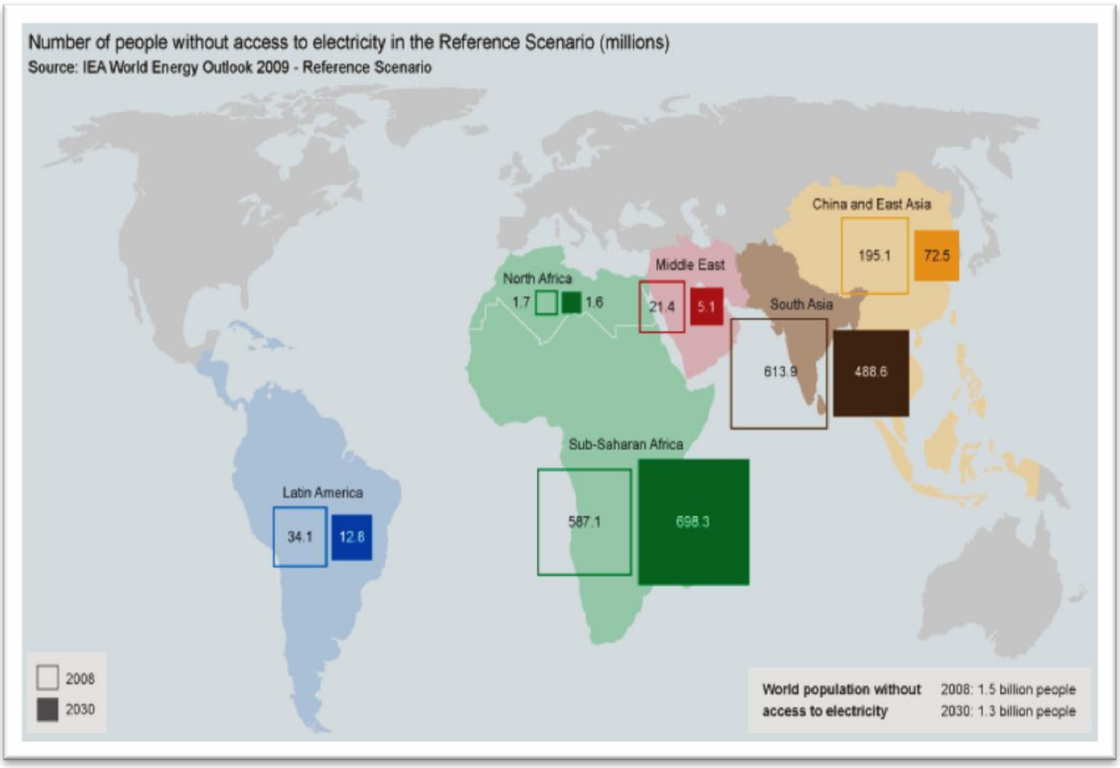


Figure 1.1: Access to electricity in the world (Lenrosen 2012).

1.5 Stand-alone power system

A stand-alone power system, for remote area power supply, is described as an independent power station that is not connected to the public electricity network because it is significantly cost prohibitive, and these systems are often preferred for remote areas. Normally, the generation powers of these systems are near the end user and it has one voltage level. These systems are called off-grid or Isolated Power Systems (IPSs).

IPSs are mainly used in small, largely isolated, and difficult to access places, or microwave/Radio repeater stations (Croci et al. 2012). IPSs are considered the most proficient way for powering a wide range of applications with reliable electrical power similar to the public electricity network. However, to have efficient and successful IPS it should avoid all the obstacles of connecting this area with the public electricity network; mainly the capital and running costs of this alternative power.

Furthermore, electrifying remote areas through DGs as a generation power has reasonable capital cost, but it has recently become a very high running costs option due to escalating fuel costs and the high cost for transport to remote areas.

As the cost of connecting these areas with national grid is high, and the running cost of having a diesel IPS is worst case scenario; reduction of the running cost is an alternative solution. Mitigating dependence on the conventional power supply and initiating the use of renewable energy as a source was reported previously (Daniel and AmmasaiGounden 2004, Duryea et al. 2001). Indeed, micro-renewable generation with control system and storage systems are often used together to electrify the autonomous areas. Renewable energy is available in any part of the world, and for the countries that lack access to electricity, renewable-IPS is the solution, where power can be generated from the sun, wind, and water energy in satisfactory levels.

1.5.1 Renewable Energy Source

Renewable energy source (RES) converts the power of natural resources (wind, sun radiation, water, etc.) from any type of energy (Kinetic energy, potential energy, heat energy, etc.) into electrical energy. The renewable sources can quickly replenish themselves and can be used repeatedly, thus supplying infinite energy resources. Moreover, these types of energy are available over the world therefore can be of great use for areas that lack access to electricity. RESs have the capability to shape the baselines for IPSs as the main generation power (Stover 2011, Keshav and Rosenber 2010).

The typical operation of the existing power systems are based on burning charcoal, crude oil or fossil fuel. The main disadvantage related to the use of these fuels is that these resources are non-renewable and can be depleted. This most definitely will have a negative impact on the world. However, renewable energy sources are emerging and are in the process of development (Hirst 2013).

Renewable sources can be converted to three distinct forms; electricity, heat and as fuel for combustion engines (REN21 2010). A water turbine is an example of a RES, where the power of water in the energy reservoir at a higher-level, flows into a narrow canal, guarded by a gate, to reach turbine blades. The kinetic energy is transferred into electrical power. A wind turbine is similar but in this case the power of wind moves the blades (REN21 2014, Koutroulis 2006). Solar power is another popular form of the RESs, where sun radiation is converted into electricity by a process called the photovoltaic effect (according to that the panel is called PV panel), one of its applications is water heating (Green Et al. 2011, Luque and Hegedus 2011, Atwater and Polman 2010).

Furthermore, RESs are used as a product of converting waste and harvested residues to bio-gas by using anaerobic digestion (AD), or converting waste to bio-fuel or bio-diesel by yeast technology to produce bioethanol fermentation in three steps; liquefaction, fermentation, and distillation. Thereafter, the biological fuel can be used in a combined heat power (CHP) unit to produce electricity and heat (REN21 2012, Leone 2011, Walker et al. 2010, Akunna et al. 2007).

Indeed, RESs have many advantages compared to the traditional fossil fuel-powered systems:

- RES technologies are indeed clean. They have very low environmental impacts with the only impact during manufacturing and decommissioning (there will be waste when they are no longer used). Therefore, Mellit et al. (2008) reported that in total RESs have less emission of greenhouse gases (GHG).
- Alternative energy cannot be exhausted. On the other hand, existing sources of energy, such as fossil fuel are limited and will deplete in the near future (REN21 2012).
- As the RESs will never run out, its price is fixed or at least new technologies will be responsible to reduce the capital cost of RES, where the running costs of 70% of RES are negligible. In contrast, fossil fuels prices have dramatically increased in the last few years as compared to the seventies and eighties from the last century (Stover 2011). Despite the recent decline in oil prices (ECB 2014), the general price trend has been a cumulative increase (Banks et al. 2015).

According to the advantages outlined, using RESs electric generation for stand-alone systems in remote areas has many economic advantages compared to using the existing public electricity network or DG (Battke et al. 2013). It would be difficult to connect a remote area due to the high capital and running expenses. On the other hand, IPSs that are based on fossil fuel as a source of energy, such as diesel generators, have many problems of maintenance, fuel transport and supplying spare parts. All of this will increase the operating cost and make the system inefficient (Martinot and Reiche 2000).

However, RESs have disadvantages, such as intermittent and fluctuating power. This limitation can be minimized by having standby power generation (Ortjohann 2003). Indeed, a back-up system is required when the system is using RES to ensure steady power production and to accommodate the fluctuating power (Daniel and AmmasaiGounden 2004, Duryea et al. 2001). This is explained in the next section.

1.5.2 Backup systems and batteries (storage systems)

In order to have continuous power supply, a backup system is important to bridge the gap between supply and consumption. In storage systems, electricity is stored when the production from RESs exceeds the required load, and when the demand load increases and generation is insufficient to absorb that, the storage power is released to support the systems. In other words the storage systems is used to overpass the time lag between generation and demand load, this is due to the variable and fluctuating RES power generation, and/or changes in dispatching load (Reske 2010, Daniel and AmmasaiGounden 2004, Duryea et al. 2001).

All types of electrical storage systems are conversion processes of electrical energy to another form of energy. In order to convert stored energy back to electricity during deficit periods, three processes are involved; charging, storing and discharging, each has different characteristics. The efficiency level of storage processes can relate to the storage term (short, medium and long term) (O’Donnell and Adamson 2012, Guerrero et al. 2009, Lasseter et al. 2002).

The robustness of the storage systems in off-grid or on-grid is critical in creating the ability to bridge the gap between generations and load to improve the efficiency (Battke et al. 2013, Droste-Franke 2013). This can reduce the need for stand-by systems, such as a CHP unit or DG. This supports energy production by maintaining the required voltage and frequency at the same level with a fast response in the consumed areas (IEA & Energy Research Institute 2011). Some renewable energy systems are unable to provide continuous electrical power, according to that storage provide power allowance during deficit periods. In order to increase the access to electricity; there is a need to improve the power system stability, flexibility, reliability and resilience (IEA 2014a, IEA 2014b, Paksoy 2013, IEA 2012, IEA 2011, Rasler 2011, IEA 2010).

In the case of off-grid and using RESs as power supply, it will have a condition where the storage system is fully exhausted. Therefore, in this instance (off-grid with RESs as the only generation, and storage system is totally exhausted), the off-grid will have a blackout unless the system has a second backup, and the definition for it will be standby system, and it should be able to cover the whole demand such as DG, gas turbines or CHP unit using bio-fuel, bio-gas and bio-mass, these three types will be connected automatically in some circumstances.

1.5.3 Hybrid Power System (HPS)

According to the previous introduction, HPSs are designed to generate power for independent μ-grids or remote areas. The generation power is predominately produced from renewable sources; but at the same time backup systems exist, and the whole unit is isolated from the public electricity network (Croci et al. 2012). Moreover, generation sources, storage systems and isolated load, are known as a HPS and it is useful in remote areas. HPSs contain more than one source of power generation, such as wind turbines, photovoltaic (PV), micro-hydro and/or fossil fuel generators, where different generation affect the systems and the methodology used. HPSs could be designed for small or large scale purposes (Duryea et al. 2001).

According to Daniel and AmmasaiGounden (2004) HPSs can be used to provide power in remote areas for both developed and developing countries in order to save the expansion costs of the national grid to these areas. Also, the cost of diesel transport is very high. Using renewable energy to generate power will reduce the cost (Duryea et al. 2001) and these sources are considered clean energy sources.

HPSs have to deal with the variation in power generation and demand load in short term thus different energy management structures are required. These structures vary with location and the size of the HPS according to the financially optimal design (Voutetakis et al. 2009).

1.6 Outline

This dissertation consists of three parts; the first part contains three chapters, the second part contains two chapters and the third part contains two chapters, references and appendices. The chapters are described as below:

Chapter 1 provides an introduction to the thesis, presents the need for the research and the aims and objectives.

Chapter 2 presents the literature review where it describes feeding mode and the different types of couplings (Bus-bar connection) that were used in previous studies. Furthermore, this chapter discusses different designs of hybrid power systems and presents their advantages and disadvantages in order to find out the most suitable hybrid power system for a remote area in Jordan. This chapter will act as a guide for the most efficient design that enables difficulties to be overcome that the other systems face.

Chapter 3 describes what this research is about; research and design requirements are described in details, the requirement to achieve the aims and objectives which contribute to its success, stating the problem and the motivation. At the end the limitations of this research are covered.

Chapter 4 describes the methodology for carrying out this research, by collecting data from authoritative and reliable sources, and the implementation of IADF. Followed by HOMER simulation and MatLab /Simulink in order to optimize the size and mixture of the system components and the synchronization between the generation and other systems or/and the grid. Creating a linear cost function and optimize by developing linear program using SCILAB simulation to compare with HOMER results. This will show the most achievable control system to organize the generation sizes and mixture between system equipment.

Chapter 5 presents the case study, where information was collected about climate, sun, wind, and load in remote areas in Jordan in order to proceed to the hybrid system design.

Chapter 6 shows all the results from the simulations, experiment and the evaluation.

Chapter 7 presents the discussion and conclusion of this study. Some recommendations have been proposed for future work. The pros and cons are pointed out in order to leap to the next stage for real implementation.

References are at the end of this thesis.

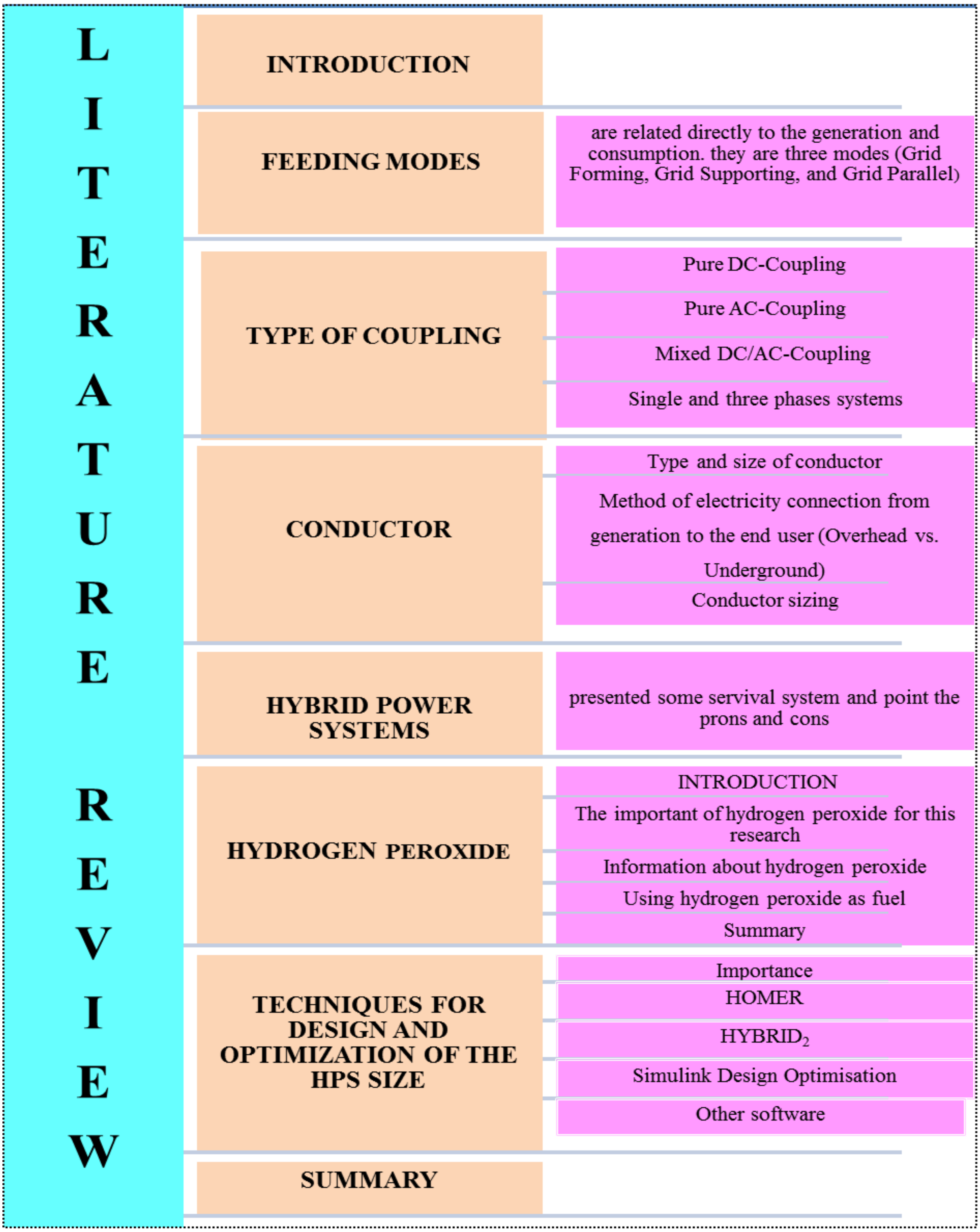
1.7 Summary

One of the most important inventions in the last century is electricity generation. Nowadays, almost 70% of the world's population have electricity which has a major impact on the daily life of everyone in the world. Basically, electricity is important for inventions and without it life will retard back to the 18^{th} century. Everyone has the right to have electricity; hence an isolated power system (IPS) is able to solve many problems such as access to electricity, environment and the ability to use renewable energy for those living in remote areas.

Based on the importance of electricity and the difficulties encountered in remote areas; IPS could be the solution using renewable energy supported by backup system to produce a completely successful hybrid power system, which is a cheap way to supply energy.

CHAPTER 2

LITERATURE REVIEW



2.1 Introduction

One of the most important advancements in recent centuries is electricity. However, some remote areas remain to be electrified and most electrical utilities are investigating the cheapest way to supply all areas with power. Due to the enormous distance and the meagre consumption of electricity in these areas, the concept of stand-alone systems is appealing. In order to design a stand-alone system, certain criteria have to be taken into consideration. Firstly, the most important criterion is to choose a suitable power supply, from either renewable resources depending on the location and the topography, or conventional resources depending on the availability of the raw materials as shown in Figure 2.1. Secondly, it is important to determine the type and the demand load for the area under study. Thirdly, a methodology must be determined to find the right size of hybrid power system. Lastly, the system must be chosen based on the availability of the raw materials, such as wind, sun rays and fossil fuels.

According to these variables, stand-alone systems have different feeding modes and coupling, and consequently this will present different designs. The need for resource poor developing countries to develop effective energy policy and management strategies, to meet their population's energy needs with minimal impact on the environment and reduce greenhouse gas emissions, is widely recognised. This chapter will discuss the three different feeding modes and the three different connection designs and their operating principles presenting the advantages and disadvantages of each design. Moreover, this chapter will discuss the different types of energy sources (individual or combined) and several types of storage in order to present different types of hybrid power systems. This will establish the most suitable and optimal system with minimal disadvantages and obstacles under particular circumstances.

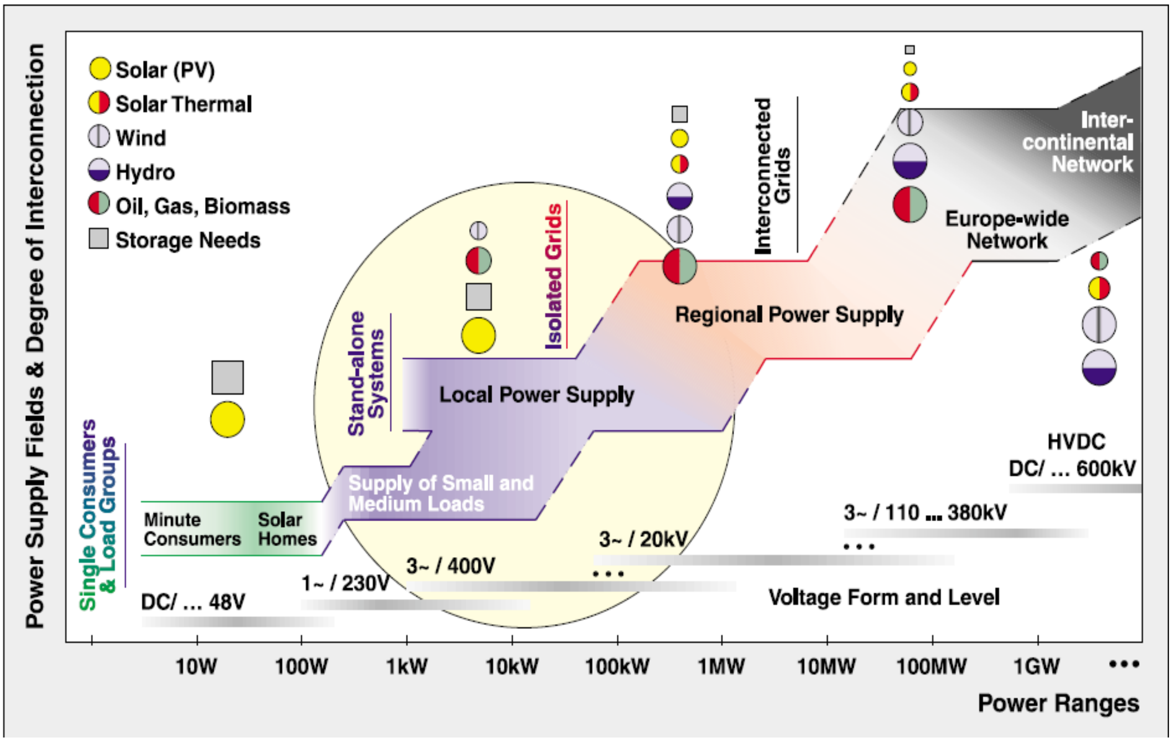


Figure 2.1: Classification of electrification technology with renewable energy (Kleinkauf et al. 2001).

There are three types of systems that provide service in stand-alone systems (off-grid) (World Bank 1996, Foley 1995). These include; Home Solar systems, Water pumps, and Mini-grid/Micro-grid:

- Home Solar System: this system normally includes a photovoltaic panel (PV), a battery and a charge controller, where small loads represent lights and DC appliances. This system is not connected to a national grid. According to the latest records, more than 500,000 of these systems have been installed in rural areas in developing countries (Kammer 1999, Kapadia 1999, Loois and Bernard 1999, Cabrall et al. 1998, Cabraal et al. 1996).

- Water pump: this pump is typically located in areas very remote from the public grid. In the past it was operated by utilising a windmill, and now it is operated by diesel generator or PV .
- Mini-grid and Micro-grid: for villages and remote areas far away from existing electrical grid. Mini and Micro-grid is electrically powered by fossil fuel (diesel generator), and/or the available renewable energy source in that site (ESMAP 2000).

The types of isolated power systems and the availability of their raw sources were described. The next section will explain the feeding modes.

2.2 Feeding Modes (The Category of Power Unit)

Feeding modes are related directly to the generation and consumption of the power system, and can be distinguished by their function. This includes: grid forming unit (controllable generators and uncontrollable loads), grid supporting unit (controllable generators and loads), and the grid parallel unit (uncontrollable generators and loads) (Strauss and Engler 2003, Lewis and Yang 1997). These are discussed in further detail below.

1. Grid Forming Unit is controlling the generation power by increasing and decreasing the power according to the required load. This control is achieved by balancing the voltage and frequency of generation systems according to the loads, which are managed by either a master generator or a set of battery banks.
2. Grid Supporting Unit: in this type the load consumes a predefined amount of power and generation power (GP) is generating the same amount, this unit

generates the same amount of power as it consumes. Therefore, the GP equals the consumed power. This is suitable where the active and reactive power is constant, such as in a communication tower.

3. Grid Parallel Unit: In this type of unit, the load and generation cannot be controlled and the maximum GP is a limitation. In this mode the GP is mainly renewable energy which means uncontrollable generation.

Comparison between the Three Feeding Modes: in the three types of power units all modes depend upon the GP and the energy demand. Under different situations GP and demand energy will be controllable or uncontrollable. The service power provided by the Mini or Micro-Grid contains one or more renewable energy sources in the GP, thus the GP is uncontrollable. Therefore, mini or micro-grid systems better suits small communities or domestic purposes, which mean that the load is also uncontrollable. The feeding unit in this thesis will be a grid parallel unit.

Another important aspect of independent systems is the type of coupling needed, which is discussed in the next section.

2.3 Type of Coupling

The previous section described the feeding unit as relying on production and consumption. The type of coupling required depends on the technological configuration of the GP and the load.

2.3.1 Pure DC-Coupling

In this type of coupling, the generating power units are connected directly to a DC-bus where the generation produces either DC or AC power required for an AC/DC converter (Figure 2.2). The battery is connected directly to the DC-bus and protected by a controller during the charging and discharging mode. The demand load should be DC, and in order to supply AC load an inverter is required. Generally, the pure DC-bus is only provided to pure DC load such as in communication towers (Fabbri et al. 2010).

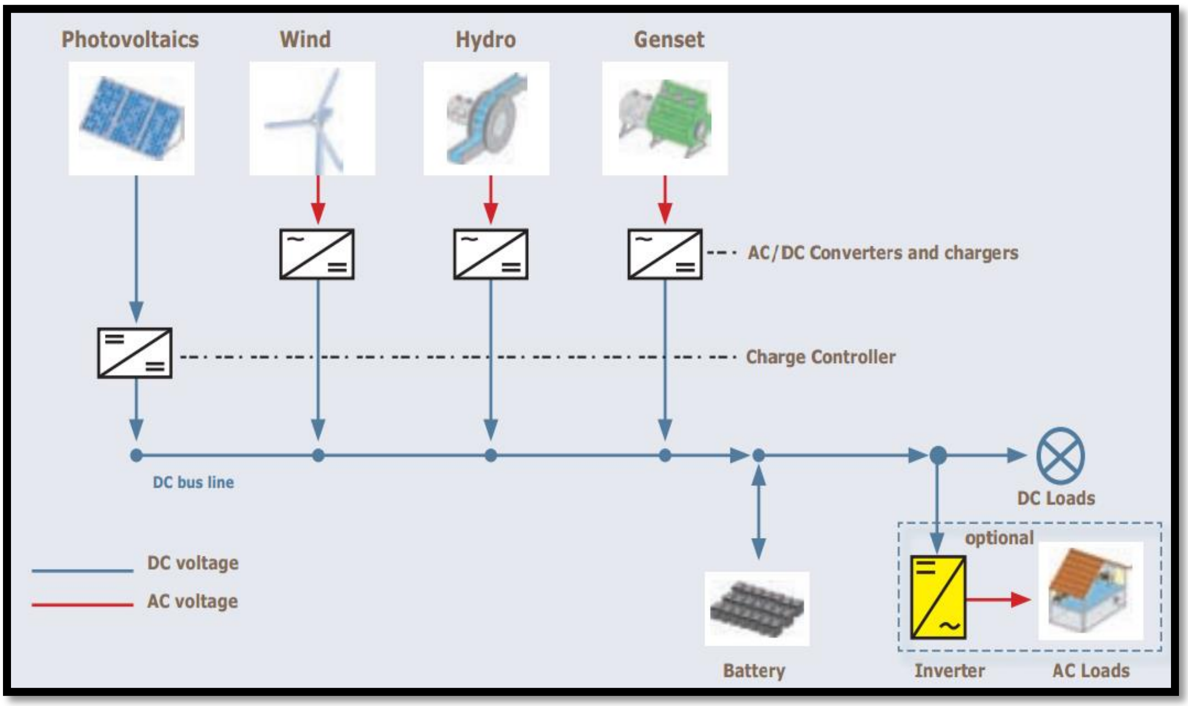


Figure 2.2: The structure of the Pure DC-coupling HPS (Wiemann and Lecoque 2006).

2.3.1.1 Operating principle

Croci et al. (2012) reported that the voltage of the DC-bus line is controlled by battery's voltages. In order to stabilize and maintain constant voltage, a DC to DC converter could be used in the DC generation. For AC generation, it is compulsory to have a rectifier to convert the power from AC to DC. Renewable resources and combustion engines generate electricity, which is converted to DC power (Figure

2.2). The batteries are connected to the DC-bus line to store the extra power which is fed back into the system in deficiency cases.

2.3.1.2 Advantages and Disadvantages of pure DC-coupling

The main advantages of the pure DC-coupling are:

- Enabling the system to use renewable energy (Croci et al. 2012).
- Using the battery as storage system is easier because it does not require a converter, but only a controller (Zhang et al. 2011).
- From the infrastructure side, supplying power using DC is cheaper in comparison to AC as three-phase requires four lines, but DC requires two lines only. Also, the use of a rectifier is cheaper than using an inverter (Zhang et al. 2011).
- Usually, fluctuations in generation power, when renewable sources are used, affect the system frequency. However, with DC-coupling there is no need for frequency or phase angle.
- This system is simple to design and fast to implement.

Disadvantages of pure DC-coupling:

- If the demand load is AC power, a DC/AC converter is required (Fabbri et al. 2010).
- According to Croci et al. (2012), this type of coupling is suitable for one specific DC load, similar to that used in telecommunication centers in minor islands or places far away from the electric grid.
- Designing the isolated power system using pure DC-coupling for remote areas is impossible where most of the end users are house holders and all

electrical equipment in houses is AC power. This requires a DC/AC converter for every house, which is more expensive for the end user.

All the advantages and disadvantages are compared with other types in Table 2.1 (page 37).

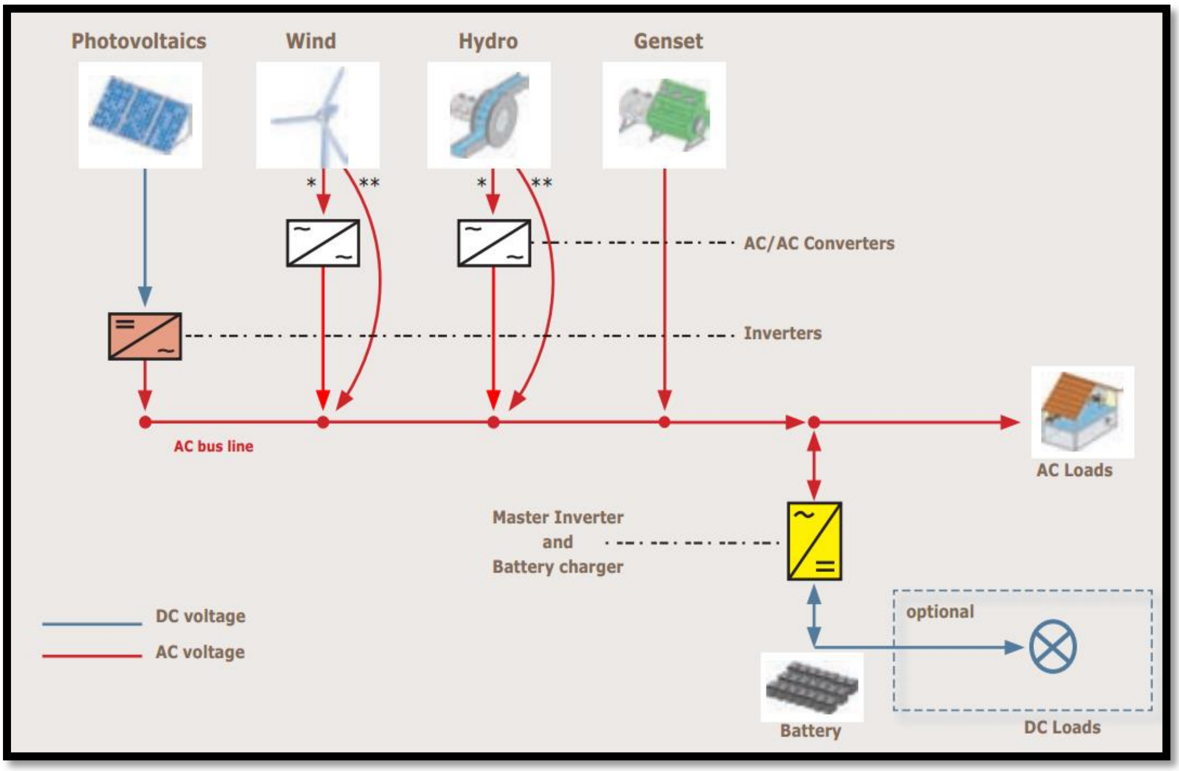


Figure 2.3: Structure of the Pure AC-coupling HPS (Wiemann and Lecoque 2006). The electrical generation units are connected to an AC-bus as illustrated by the symbol (**). For more stability the generation might be connected through an AC/AC converter (*).

2.3.2 Pure AC-Coupling

The structure of pure AC-bus is shown in Figure 2.3, and further explained in section 2.3.2.1. Basically, the electrical generation units are connected to an AC-bus. For more stability the generation might be connected through an AC/AC converter. Where DC generation units are connected to the AC-bus through an inverter, the battery bank should have two way converters to allow the power to charge and discharge.

Mtshali (2011) reported that pure AC-coupling is effective for isolated power systems, when the demand load is near the generation sources because this reduces the cost and power losses.

2.3.2.1 Operating Principle

Pure AC-coupling could be single or three-phase depending on the energy demand. The only difference is that in the three-phase type there are three inverters for the DC generation and three converters for the battery bank for each phase between DC and AC. One of the converters is the master and the other two are the slaves when the system is using the same batteries (Mtshali 2011). Moreover, a control system is required when the system is using AC-coupling. There are many control algorithms that can be used, such as active, frequency (for active power control), and reactive control systems such as voltage (reactive power control) (Meinhard et al. 2004).

The operating principle of pure AC-Coupling is uncomplicated and similar to that of pure DC-Coupling. If the generation power is AC, it will be connected directly to the grid, while DC generation (such as PV) requires a DC/AC converter (inverter). As shown in Figure 2.3, all power generators are connected to the AC-bus and the demand load is linked directly to the AC-bus. In a scenario where the generated power is higher than demand load, the extra power is stored in batteries through the bidirectional converter (two way inverter), where the converter controls the charging capacity for the batteries, and if DC loads exists it can be connected with the batteries after the converter. On the other hand, if the generated power is less than the required load then the system is dependent on the battery to supply the shortage in power. The bidirectional converter is required because the system requires a two-way converter to operate depending on the status of the batteries. To describe that simply, if the batteries are charged from the system, the bidirectional converter works as an AC/DC rectifier (converter), and when the battery reaches the discharging point, the bidirectional converter works as a DC/AC inverter.

2.3.2.2 Advantages and Disadvantages of pure AC-coupling

The main advantages of the pure AC-coupling are:

- The storage system is simple to implement by using a bidirectional converter to charge or discharge batteries (Zhang et al. 2011).
- Single or three phase power can be supplied by such systems depending on the load (Schmid et al. 2001).
- Uncomplicated and efficient configuration and operational matter to add a DG or CHP unit as a standby system (Meinhard et al. 2004).
- It is simple to design, operate, and configure such systems that can utilise many different types of traditional or renewable sources of energy.

However, the pure AC-coupling has disadvantages:

- For some designs it is difficult to use diesel generator to charge the batteries; because the diesel generator is connected directly to the load through a circuit breaker and at the same time the renewable sources are connected to the AC-bus through another circuit breaker. Furthermore, for safety, both breakers cannot be connected at the same time.
- For every DC generation source, a converter is required, as well as for power storage, which increases the cost of the system.

- This type of system has limitations of having varying storage because most of the storage systems require DC power and the releasing power is in DC format. Therefore every system requires a bidirectional converter, and in order to increase the size of storage the converter needs to be expanded.
- The storage capacity depends on the size of the inverter.

All the advantages and disadvantages are compared in Table 2.1 on page 37.

2.3.3 Mixed DC/AC-Coupling

In comparison to the last two types of connections, DC/AC coupling is slightly different. Usually, this type is good for stand-alone systems which depend on renewable energy, whereby DC or AC power is generated. These systems contain DC-coupling and AC-coupling, known as mixed DC/AC systems, and the structure is shown in Figure 2.4. Gupta et al. (2012) reported that HPS with mixed DC/AC coupling integrate the renewable sources in order to produce generation sources with maximum reliable performance and the best economic cost. By collecting information for HPS, it is important to arrange the components, where in mixed DC/AC-coupling the size of the system should be calculated because it is important for work implementation, optimization, and life cycle cost (Javadi et al. 2011).

The mixed DC/AC coupling can feed the AC load in two ways. The first is directly through AC-coupling, and the second is by DC-coupling through the inverter (Figure 2.4). In some cases, the battery bank and the DC renewable resources are connected to the DC coupling, while the AC resources are connected to the AC-bus, and the DC-bus is connected to the AC-bus through a bidirectional converter.

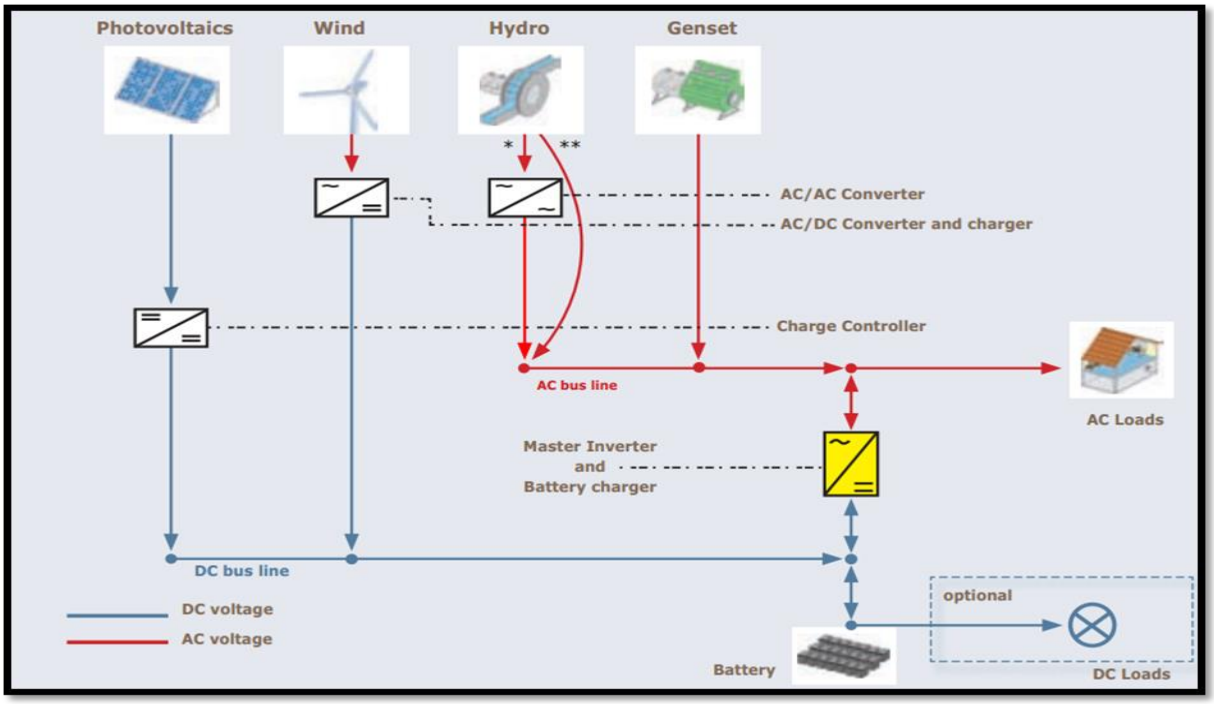


Figure 2.4: Structure of mixed DC/AC-coupling HPS (Wiemann and Lecoque 2006).

2.3.3.1 Operating Principle

In this system the generation power is produced from different types of renewable energy sources. The DC power sources are connected directly to DC-bus, and some AC power sources such as wind can be connected to the AC-bus or to the DC-bus if it has a built-in AC/DC converter. The power generation sources are connected to the AC-bus and feed the AC load directly. If the remainder is not enough then the DC power is converted to AC to feed the load. However, if the power from the AC-bus is sufficient the DC power charges the battery. When the AC power is more than enough, the extra power converted to DC power and stored. The battery bank feeds the system when the power generation is insufficient. In this system, the power generators are designed to have the ability to charge the batteries while they supply power to the load. The AC power generator can be connected directly to the AC-bus or connected through an AC/AC converter to stabilize the coupling (Gupta et al. 2012).

2.3.3.2 Advantages and Disadvantages

The main advantages of the mixed DC/AC-coupling are:

- This system is able to reduce the effect of the fluctuating generation by converting the DC power where the battery stabilizes the power and converts it to AC to feed the load.
- It can supply DC load and/or AC load at the same time where the AC load could be single or three phases.

However, the mixed DC/AC-coupling has disadvantages:

- The feeding for the load from DC generation depends on the size of the bidirectional converter (inverter). The storage sizes from AC generation depend on the size of the bidirectional converter between the DC-bus and AC-bus.
- In case of any problem with the bidirectional converter, the DC generation cannot feed the AC load, and the extra power in the AC-bus cannot be stored unless there is a standby converter.

All the advantages and disadvantages are compared in Table 2.1 (page 37).

2.3.4 Single and three phases systems

The actual demand load determines the shape of single or three phases. As shown in Figure 2.5, the AC generation could be single phase or three-phase and it feeds the load directly. DC generation supplies the power to the load through inverter in the single phase case, which is different in the three-phase scenario. For example, in the case of PV three separate inverters with three equal sets of PV units are required, every PV unit with the inverter feeding one phase (Strauss and Engler 2003). The scenario is different with the battery. In the case of the single phase, the battery requires a bidirectional converter to charge and discharge the power. One of the converters should be the master and the other two are the slaves to control the charging/ discharging power equally in every phase. These allow the power sources to match the load. The single phase system can be expanded to three phases easily (Strauss and Engler 2003, Schmid et al. 2001).

The layout of the electrical power grid for the isolated area is important. This includes the location of generation and end user, and the need for a single phase or three-phase system. In the case of three-phase configuration, the load in each phase should be balanced with the other two phases as much as possible in order to minimize voltage drop between the phases. Load imbalance between the phases can lead to over-heating and failure of the generator (Strauss and Engler 2003).

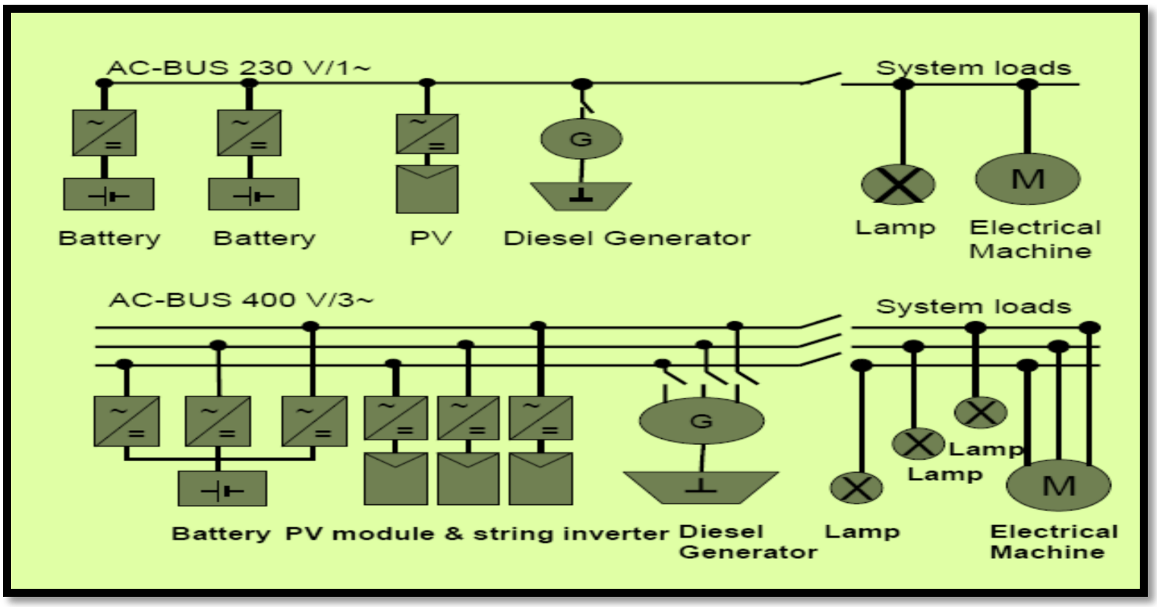


Figure 2.5: Structure of single and three-phase in HPS (Schmid et al. 2001).

2.3.5 Comparison between the three types of coupling

There are many configurations for the hybrid power systems as discussed previously. In order to choose the optimal configuration, the designer must determine which system offers better reliability than the others according to the generation type and the mode of the load with superior efficiency. This is because the system is designed to optimize the generation sources with the demand load by minimising energy loses and fully utilizing the generation. The economics of any choice is often the dominant factor, but, from the point of view of application, the generation sources and demand load are the main factors responsible for determining the system topology, where the type of load is responsible for determining whether the configuration is single or three-phase.

Gabler and Wiemken (1998) introduced AC/DC bus in North America using solar panels, whereas high generation of DC power requires a DC-bus which is cheaper. On the other hand, AC-bus was introduced in Europe where the DC connection is needed only for the battery, with a bidirectional converter. Gabler and Wiemken also reported that the performance level of all configurations are quite close, and that adding more converters between the components will lead to additional losses. The system with a DC connection required about 2.6% more power than the mixed AC/DC connection, whereas the AC connection required 12% more power than the mixed AC/DC connection. Moreover, the authors stated that in storage systems like batteries there are some losses, and according to the simulation and the period of simulation, more than 12-13% of losses in the full load come from inverters and rectifiers. These losses might change if the simulation period was changed as the author explained.

Thus, any system with AC/DC connection offers more compelling advantages than either AC connection or DC connection. This system can easily satisfy any AC loads directly, unlike a system with DC connection. On the other hand, the AC/DC connection can satisfy the storage system mainly if the storage is a battery or even supply the DC load, unlike any system with just AC connection.

All the differences between the coupling systems are summarized in Table 2.1 below.

Table 2.1: Comparison between types of coupling systems

Criteria	IPS Pure DC-coupling	IPS Pure AC-coupling		IPS with mixed DC/AC coupling	
		Single phase	Three phases	Single phase	Three phases
The ability to use renewable resources	Yes	Yes		Yes	
Use converter for storage system	No need	Yes		No need according to the converter between the AC and DC-Bus	
Type of load	DC	AC / single phase	AC/ single or three phases	DC and AC / single phase	DC and AC/ single or three phases
Use DC-bus to reduce the difference in frequency	Yes	No		Yes	
The use of DG or CHP in the system and ability to charge batteries	Difficult to use DG or CHP	Can use DG or CHP, but difficult to charge the batteries		Can use DG or CHP, and it charges the batteries	
Storage methodologies and quantity	Able to expand under conditions	Limited		Able to expand	
Size of the inverter between DC-bus and AC-bus determines the power sources	Only one coupling (DC)	Only one coupling (AC)		Yes it required	

Capital cost	Cheapest	Cheap	Medium	Medium but overall is acceptable	
Running cost	Cheapest	Cheap	Medium	Medium	
Sun rays affect the system	Not necessarily	Not necessarily		Not necessarily	
Wind speed affects the system	Not necessarily	Not necessarily		Not necessarily	
Environmentally friendly	Partly	Partly	To some extent	Partly	To some extent
Supports sustainable development	If the generation and load are DC	If the generation and load are AC		Yes	
The storage capacity depends on the size of the batteries	Yes	The size of battery and the inverter		Yes	
Maintenance cost	Cheapest	Cheap	Medium	Medium	Expensive
Stable system for long term	It depends (Medium)	It depends (Medium)		Reasonable	Yes
Energy losses	Medium	Highest		Lowest	

Once the type of load and its nature are determined, the choice of conductor can then be made. The next section describes this in details.

2.4 Conductor

The type and size of the conductor, and the way of joining the generation to the demand load should provide minimum cost and high efficiency.

2.4.1 Type of conductor

For electrical distribution and bus bars, the most frequently used materials for conductors are copper, copper covered with steel, and aluminium. Copper is the most commonly used conductor and has a high conductivity for electricity and heat. The physical characteristics of copper including high melting point, high resistance to corrosion and ability to easily bend and shape explains the widespread use of copper as a conductor. Copper conductors can be found in many different forms. Copper-covered steel contains copper and steel where the conductivity and resistance to corrosion is the same as in the copper conductor. The main difference is the higher strength because of using the steel. There are different ways to produce this type of conductor by; (1) melting the steel surrounding the copper, (2) electroplating the steel around the copper, (3) melting the copper and steel together until they bond to each other.

Aluminium is widely used as a conductor due to being the cheapest of the common conductive materials. However, aluminium conductivity is two-thirds less than that of copper because of the former higher resistance. From a different angle, aluminium conductor has a higher tensile strength than copper conductor (Fink and Beaty 2013).

Coating of the conductor

Bare copper can be oxidised at room temperature, and with increasing temperature, the reaction rate increases. Copper oxide has poor conductivity that can affect the reliability of connections. This problem is solved by coating the copper. Many types of coatings can be used. Tinned copper is usually used in places where the temperature does not exceed 150°C. It showed good corrosion resistance with low cost. Silver coated copper is usually used for higher temperatures up to 200°C but it has poor corrosion resistance with high cost, however, silver coated copper has very high conductivity and it is required in sensitive areas due to its stable conductivity with fluctuating heat. Finally, nickel coated copper is usually used for higher temperatures up to 260°C. Nickel coated copper has good corrosion resistance with medium cost (Fink and Beaty 2013).

2.4.2 Method of electrical connections from generation to the end user (Overhead vs. Underground) (Dugan et al. 2000).

The distribution lines between the generation control unit and consumer can be through an overhead conductor using poles or through underground conductor using sleeves or tunnels. Comparing underground distribution with overhead distribution shows that underground distribution seems to be a good choice for many reasons:

- In conventional distribution (overhead conductor), poles must be installed to carry the cables, which are considered one of the most costly items. Underground cabling eliminates this step, only requiring a trench or small tunnel to be dug.
- Underground distribution is less susceptible to weather changes, which increase the lifespan of the conductors due to less contact with wind, ice and trees, and also presents less danger to humans compared with the overhead cables.
- Underground cables experience less wear (less corrosion), unlike the cable on poles (overhead) which require replacement.
- Using underground cables is less disruptive than overhead lines which require cutting down all high trees in the lines' way. This is very costly if the lines run through forests. In addition, regular maintenance is required to trim vegetation near the lines.
- Underground lines have less environment effects and less visual impact.

However, using underground distribution has some disadvantages compared to overhead distribution:

- It is very costly to repair any underground distribution.
- Finding underground faults requires special equipment to detect the exact location and special equipment to fix the fault.
- Increasing the capacity of the distribution cable (such as increasing demand load in the future) is very difficult as it needs upgrading the size of the underground conductor.
- Making new joint connections for new customers requires special equipment and materials (water proof connections) and special training, unless the electrical utility has limited new consumers and this runs counter to intuition (load growth).
- The cost of infrastructure of the underground distribution will increase in rocky grounds.
- In arable grounds, construction will need to ensure that the roots of trees are far away from the underground cable. In addition, it should be far away from ponds where cables might need watersheds (to separates water flowing from the cables).
- Underground cable can easily be damaged during other construction projects such as digging to build new houses or water lines.

Ultimately, the economic feasibility aids to identify the way of power distribution, where underground distribution requires costly reliable insulation compared to using the overhead. The areas selected for this study are rural areas; increasing demand load in the near future requires upgrading of the conductors, which is costly in the underground option. Such areas already have overhead distribution which is the most common, cheap and easier to upgrade method.

2.4.3 Conductor sizing

The size of the conductor is one of the most important factors for the mini and micro-grid according to the huge cost of these conductors. The smaller the conductors, the cheaper they are, and for the end user the exact size or bigger is better for electrification. Reducing the size of the conductor can lead to potential losses such as drop in voltage due to the resistance increment which is directly proportional to the increase in the conductor temperature. Moreover, drop in voltage can lead to poor quality of the energy and voltage fluctuation. Reducing the conductor size, can lead to power losses in the form of thermal energy, leading to declination of voltage. Therefore, calculating the cost of transmission lines is one of the most important steps that must be considered carefully, taking into account the expected increase in electricity demand in the near future (Fink and Beaty 2013).

2.5 Hybrid Power Systems

As electrification of remote areas becomes an important subject, HPSs play a key role in improving the electrical power systems. In this thesis, HPSs are isolated from the national grid. They combine electrical resources and storage systems to offer better reliability. The wide use of IHPSs has given the ability for all stand-alone systems to become HPSs by combining renewable energy resources, with or without conventional energy, and adding to it a storage system, mainly a battery (Muselli et al. 2000). However, these systems should be synchronized with each other. Storage is important to power the appliances and loads when there is insufficient power from renewable energy (during times such as overcast weather for solar or calm weather for wind or during a calm night). The most popular storage system is the battery, where the batteries with the inverters are responsible for stabilizing the system frequency and voltage. Continuous charge and discharge for the batteries can affect their performance, and to reduce the impact efficient charge with low current and minimum self-discharge is required. Beverngen (2002) explains in his report that in remote areas worldwide the most common electrification system used is the diesel isolated power system, but now many systems are able to play an important role. The next sections will discuss and compare some of these systems with the diesel isolated system, considering the renewable energies which offer the best possibility for electrification in developing countries.

2.5.1 PV-battery isolated hybrid power system

A PV-battery IHPS can feed the demand load through two sources: the solar panels and batteries. The solar panels nowadays are the fastest growing technology in the electrical generation sector, and it is important to have a controller with the batteries in order to control the charging and discharging status to extend the batteries' lifetime (Xiong et al. 2011). The main configuration for this system is divided into two parts: the producer and the consumer. The producer parts are the solar panels, which should be bigger than the demand load and in some situations double the size of the load, batteries which should be operating for at least 24 hours alone, and the converter which should be bigger than the load. The consumer parts are the loads, distribution system and the controller (Lee et al. 2012, Becherif and Ayad 2010).

Figure 2.6 describes the PV-Battery IHPS. This style is based on solar panels and battery bank that are connected to the DC-coupling on one side, and the DC-coupling is connected to the AC-coupling through a DC/AC converter (Xiong et al. 2011). However, Benaouadj et al. (2012) report that if the load is DC, there will be no need for the inverter and the load will be connected to the same side of the PV and battery. According to Xiong et al. (2011), the two-way converter in this style is not required as the electrical flow is one directional from the DC-bus to the AC-bus. On the other hand Esram and Chapman (2007) reported that an optimised power system required the controller to have an access to the maximum output power from PV, and this can be achieved by Maximum Power Point Tracking (MPPT) system.

In this IHPS mode, whatever the style is, the size of the solar panels and batteries is dependent on the load size and the climatic nature, in addition to the sun's rays. The climatic nature must consider a huge package of recorded climate from 1 year to three years with daily sun radiation and daily clearness. Moreover, the implementation of a PV-battery IHPS has been very difficult in the past due to the high cost of the solar panels.

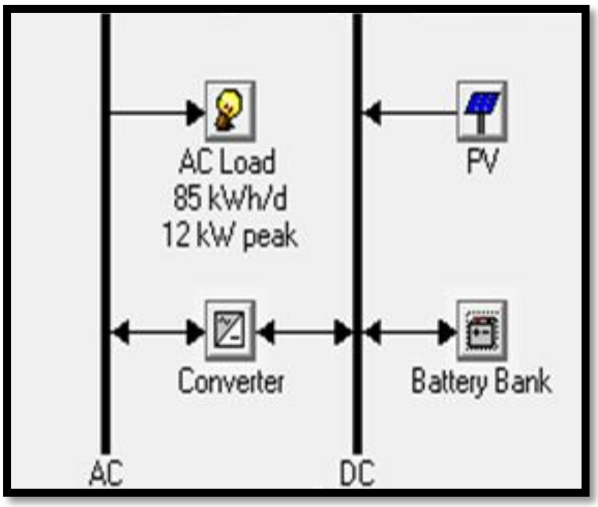


Figure 2.6: Structure of PV-battery IHPS.

2.5.1.1 Operating Principle

The basic components of PV-Battery IHPS which will be discussed in the following:

- Photovoltaic panel (PV) ● Battery bank ● Battery charge controller
- Inverter ● DC-bus and AC-bus ● Demand load

Photovoltaic panel

Recently, many new technologies have made the solar cell available in the market with variation in cost, efficiency and lifespan. The main characteristic of the PV cell is demonstrated in the current-voltage curve. To understand the mechanism of the PV cell operation knowledge of the internal configuration of the PV cell is required. In simple words, the operation of the solar panel works by converting the power of the sun's radiation into electrical power and this process is called the "Photovoltaic Phenomena".

Solar cells are semiconductor panels with the ability to convert sunlight into DC power. Solar cell made from semiconductor material usually comprise of two layers; the first one positive, and the other negative. Figure 2.7 shows the solar cell construction and its internal configuration to produce the electricity. When light hits the cell, some photons enter inside the cell and are absorbed by the atoms, and this process releases electrons from the negative layer, the free electrons can flow through a closed circuit and return to the positive layer. This flow of the free electrons produces electricity (Matthew et al. 2014, Schmid 2002).

Internally PV is made from p-n junction, which has equivalent electronic devices (Diode). The principle operation of the PV cell is similar to the principle operation of the diode; Figure 2.8 shows the equivalent diagram followed by the mathematical equivalent equation (2.1) (Matthew et al. 2014).

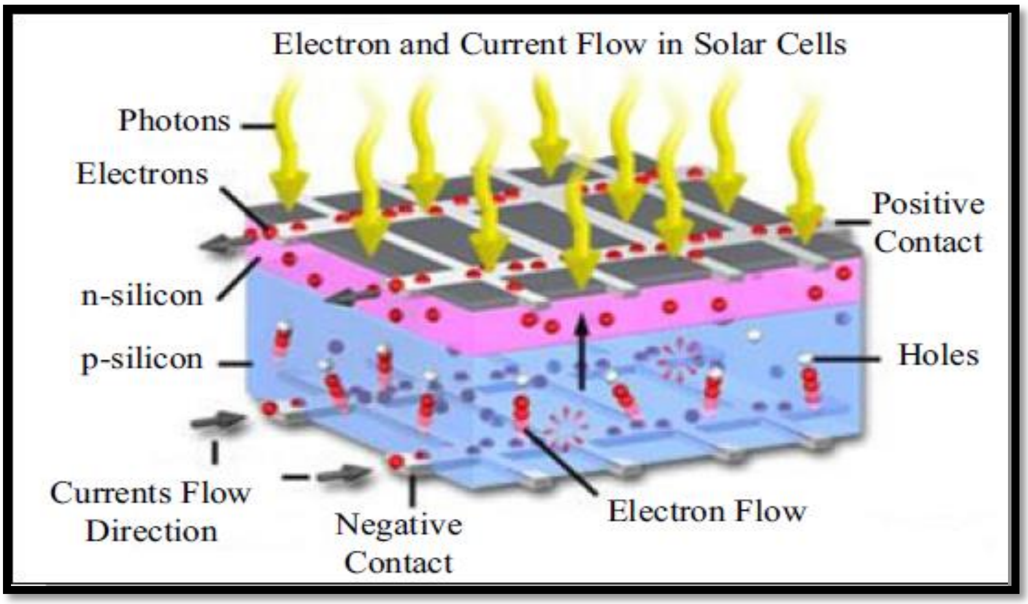


Figure 2.7: Photovoltaic internal configuration (Matthew et al. 2014).

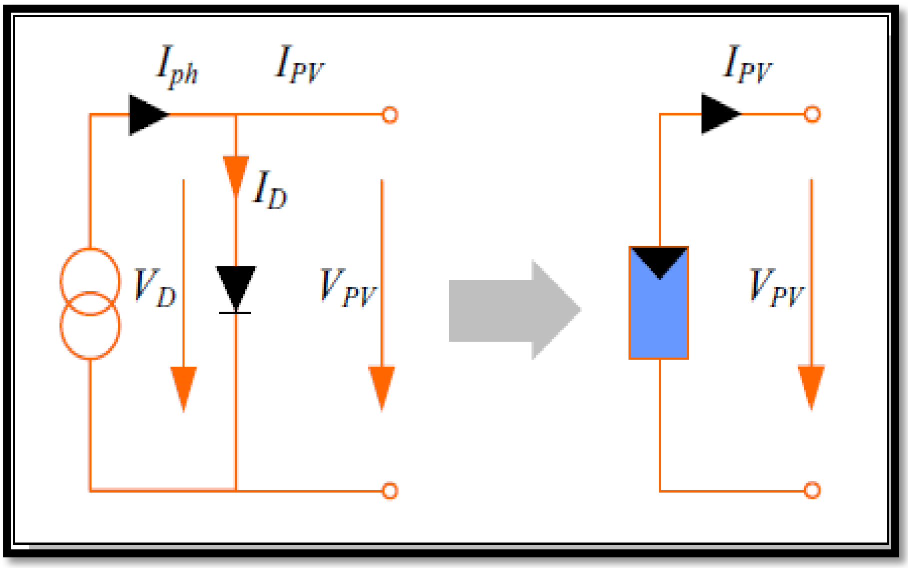


Figure 2.8: Photovoltaic cell equivalent diagram (Matthew et al. 2014).

$$I_{PV} = I_{ph} - I_D = I_{ph} - I_0 \times (e^{\frac{qV}{kT}} - 1) \tag{2.1}$$

Where

I_{PV} = PV current, A

I_{ph} = Photocurrent, A

I_D = Diode current, A

I_0 = Dark current, A

q = Elementary charge (magnitude of the electron), e = 1.6×10^{-19}AC

V = Output voltage, V

k = Boltzmann constant, 8.65×10^{-5}eV/K

T = Diode temperature, K

The solar cell produces current and voltage, but the amount of produced power depends on the cell type, load and insulation. The equivalent equation (2.1) can represent the I-V characteristic for the PV cell, when the terminals of solar panel, the plus and the negative, are short-circuited (that means the resistance of the load is zero), leading to zero output voltage. According to equation 2.1 and from the previous data, V_{load} = zero, there will be no current in the diode side I_D = zero, so the flow of the current will be from photocurrent to the load. To summarize that, R_{load} = zero, V_{load} = zero and $I_{PV} = I_{ph} = I_{sc}$, so the cell will generate the maximum current when the radiation flows to zero resistant load. The maximum current for the PV cell at the point with the value I_{PV} max refers to short-circuit and it is called I_{sc}. From another side, when the load is infinitely or very large load (such as open circuit), the output current I_{load} = zero, meaning all the current from the photocurrent flows through the diode. According to equation 2.1, I_{pv} = zero, by looking to the equation 2.2 which is derived from equation 2.1 shows the maximum voltage for the PV cell is in the case open-circuit V_{PV} max = V_{oc} (Lee et al. 2012, Schmid 2002).

$$V_{oc} = \frac{kT}{q} \cdot \ln\left(\frac{I_{ph}}{I_0} + 1\right) \quad (2.2)$$

Figure 2.9 shows the characteristic relation between the I_{sc} and V_{oc} for PV panel. The current has a maximum value at the short-circuit point. The voltage at this point is zero and thus means zero power. The situation is reversed at open-circuit point, and again the output, in between short-circuit point and open-circuit point will be value for the output power. However, it is important to have the maximum output power from the cell (increase the efficiency of PV), this process is called maximum power point (MPP). In order to have maximum power, the right resistant load should be applied, and as the load is fluctuating, this problem can be solved by using the right controller like the maximum power point tracker (MPPT) which keeps the load resistance at a high point in order to keep maximum power. The same figure shows the whole relationship between the current-voltage curves from the zero load to infinite load, with the harmonious MPP point. Moreover, the inverter or the batteries charger controller can act as MPPT controller (Lee et al. 2012, Schmid 2002).

$$\begin{pmatrix} V_{mPP} \approx (0.75 \rightarrow 0.9)V_{oc} \\ I_{mPP} \approx (0.85 \rightarrow 0.95)I_{sc} \end{pmatrix}$$

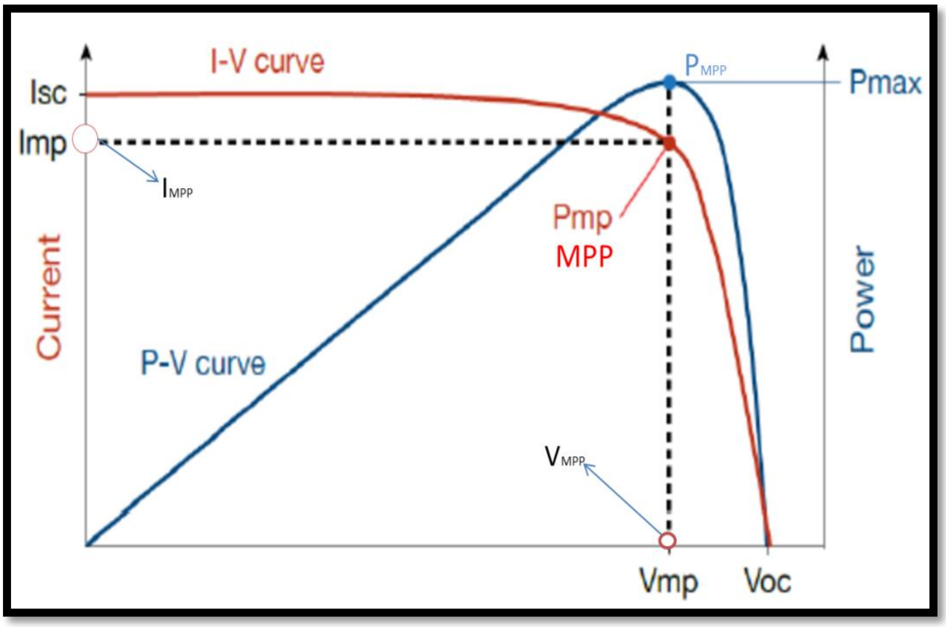


Figure 2.9: Current-voltage curve and P-V curve for solar cell with (MPP) (Lee et al. 2012).

In general, the solar cells mainly contain a group of PV panels connected together in series and parallel in order to generate the desired voltage and current to the loads. For having additive voltage, the cells must be connected in series; connecting the cells in parallel increases the current. The solar panels usually contain modules called arrays, where one module is compiled from several cells to match the desired voltage and current.

From another view, for solar panels there is a relationship between the current and voltage and this relationship is affected by the radiation and the temperature. The maximum power point (MPP) will change with different radiation levels (while maintaining the stability of all other variables) as shown in Figure 2.10. on the other hand, maintaining the radiation constant, and changing the temperature level shows no effect on the generated current, as described in Figure 2.11, where it roughly generates constant current in different temperatures (0, 25, 50, 75 and 100 °C), where the voltage is reduced synchronously with the increasing temperature (Schmid 2002). The most important parameters for the solar cell are MPP, fill factor (FF), and the efficiency of the cell (η). FF is a parameter used to represent the quality of the solar panel by determining the maximum output power from the solar panel (equation 2.3 describes FF). In other words, FF is the maximum of the I-V curve to a rectangle to have maximum power from PV, which measures the largest rectangle for the I-V curve. The maximum output power is described in equation 2.4. The efficiency (η) is defined by equation 2.5 which describes the ratio of the output energy to the input solar radiation (Schmid 2002).

$$FF = \frac{V_{mPP} \cdot I_{mPP}}{V_{oc} \cdot I_{sc}} \qquad (2.3)$$

$$P_{MPP} = V_{mPP} \cdot I_{mPP} = V_{oc} \cdot I_{sc} \cdot FF \quad (2.4)$$

$$\eta = \frac{V_{oc} \cdot I_{sc} \cdot FF}{P_{in}} \quad (2.5)$$

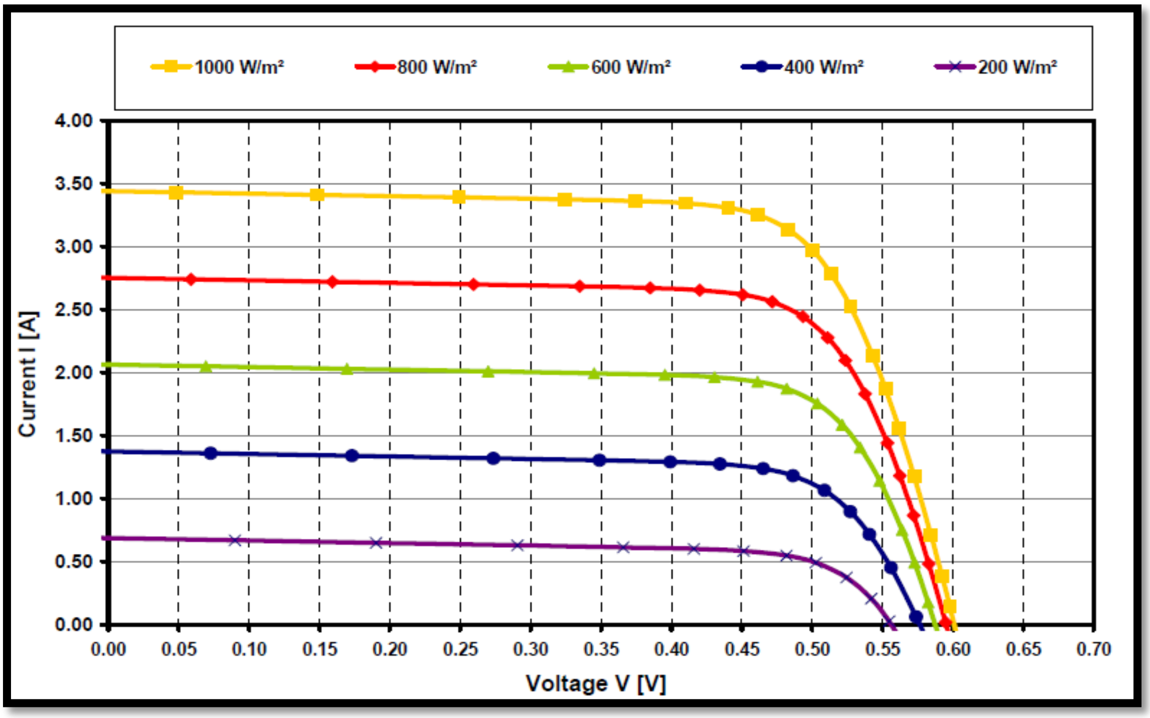


Figure 2.10: The effect of radiance on I-V characteristic curve (Schmid 2002).

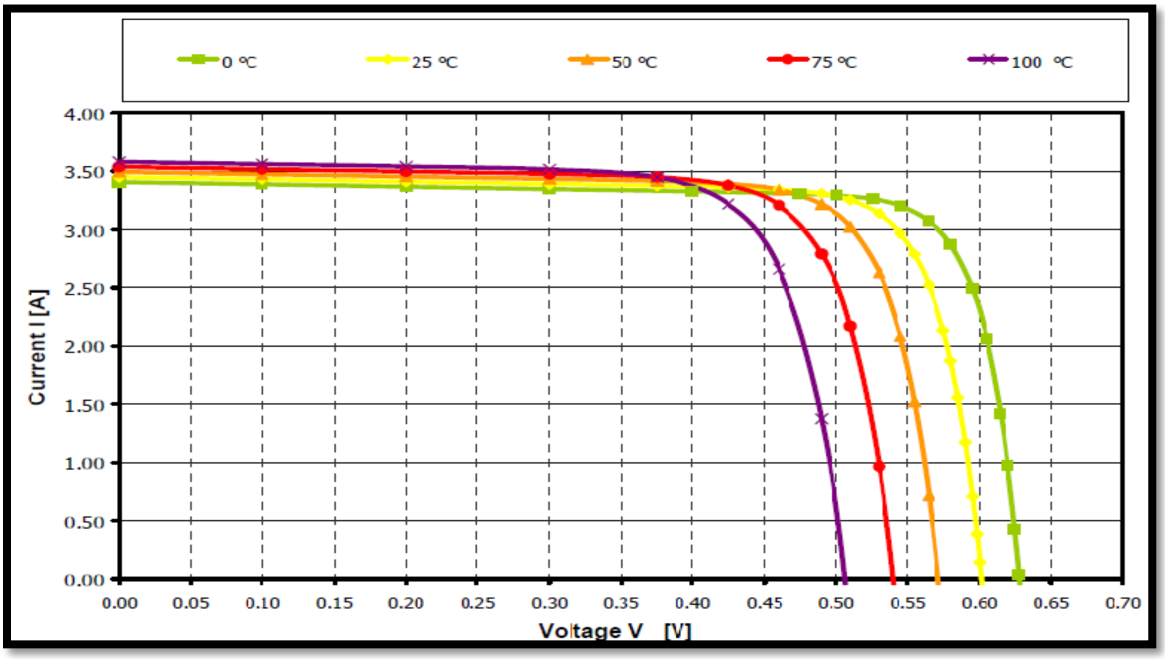


Figure 2.11: The effect of temperature on I-V characteristic curve (Schmid 2002).

A photovoltaic generator is a complete collection of solar cells, connections and protection parts. This section presents the mathematical equations for the whole panel and PV generator. The calculations are presented below from equation 2.6 to 2.10 under standard conditions (Hansen et al. 2000).

$$V_{OC}^{P} = V_{OC} \times N_{SC} \quad (2.6)$$

$$I_{SC}^{P} = I_{SC} \times N_{PC} \quad (2.7)$$

$$P_{max}^{P} = P_{max} \times N_{SC} \times N_{PC} \quad (2.8)$$

$$P_{max}^{P} = G(t) \times A \times P \times \eta \quad (2.9)$$

$$P_{max}^{PV\,Gen} = P_{max}^{P} \times N_{P} \quad (2.10)$$

Where

V_{OC}^{P} = open circuit voltage for 1 PV panel, V

V_{OC} = open circuit voltage for 1 PV cell, V

I_{SC}^{P} = short circuit voltage for 1 PV panel, A

I_{SC} = short circuit voltage for 1 PV cell, A

P_{max}^{P} = maximum power for 1 PV panel, W

P_{max} = maximum power for 1 PV panel, W

$G(t)$ = hourly irradiance, KWh/m^2

A = the surface area, m^2

P = the PV penetration level factor

η = the efficiency of PV panel

$P_{max}^{PV\,Gen}$ = maximum power generated from all PV panels, W

N_{SC} = number of series cells in 1 PV panel

N_{PC}= number of parallel cells in 1 PV panel

N_{P} = number PV panels

Battery

A solar generator converts radiation from the sun directly to DC electrical energy via PV cells. The sun does not shine continuously at any location on earth and therefore solar generators supply intrinsically variable power. To guarantee reliable and continual electrical power, storage is needed. Accumulators or batteries will store the excess energy in order to consume it when required at a later time and allow power to be drawn at any point during the day (Dalton et al. 2009, Dalton et al. 2008, Schmid 2002).

Several types of batteries exist such as liquid lead-acid, nickel-iron (Ni-Fe), nickel-cadmium (NiCad), sodium-sulphur (Na-S), and alkaline. There are two principal types of batteries; starting and deep-cycle and both are either sealed or vented.

- Starting batteries are used to provide high initial torque required to run DGs. This type of battery uses thin plates in order to maximize the surface area which gives very high current. However, this type is not used as a storage system in hybrid power systems. It mainly is used for starting diesel generators during blackout conditions.
- Deep cycle batteries are suitable for use with inverters. The plates in this type of battery are thicker than the starting battery with a smaller surface area, and because the plates are thicker and denser, they increase the life cycle during the state of charge or the depth of discharge.

Lead acid batteries are the most commonly used due to the availability and low cost. Lead acid batteries use electrochemical storage. In general, batteries consist of 2V-cell or more. Each cell contains an anode and cathode immersed in an electrolyte of sulphuric acid, which is often diluted by distilled water, that discharge the power of a chemical reaction between the plates and the solution to produce free electrons, the reversal of this chemical reaction occurs when the battery is charged.

Depth of discharge (DoD) and state of charge (SoC) are opposite to each other in the operation mode. The thicknesses of the plates determine the maximum depth of discharge. A fully discharged battery means the depth of discharge reached 100%. It is generally recommended not to allow depth of discharge to reach more than 80% in order to keep a reasonable lifetime of the battery. Beyond this percentage the battery could suffer damage. In simple words, DoD is the amount that the battery can discharge in one cycle before it requires charging again (Schmid 2002).

The second important parameter is the state of charge (SoC), and this indicates the amount of charge that is available to reach the full capacity of the battery. A fully charged battery means that the SoC is 100%, and a fully discharged battery mean the SoC is 0%. It is important to determine the battery SoC at any time during operation hour. Determining the SoC regularly makes the system easier to control. In addition, in an isolated power system it is very important to choose the required battery capacity in order to have higher reliability of the energy with lower cost (Kleinkauf et al. 2001).

Based on the previous paragraph it is important to calculate the right size and the rate of discharge, where the capability and batteries voltage are usually mentioned by the manufacturer. Moreover, battery efficiency, capacity and ambient temperature are important parameters to calculate the battery size. Capacity is the amount of energy that can be stored in the battery, measured by Amp-hour (Ah), to increase the storage capacity by slowing the rate of charge and discharge. The ambient temperature must be within the normal range to keep the battery efficiency high, it is usually about 25°C. If the ambient temperature increases, the battery life time will decrease. The efficiency of the battery is calculated from the following equation (Lee et al. 2012, Schmid 2002, Kleinkauf et al. 2001).

$$\boldsymbol{\eta_B = \frac{E_{out}}{E_{in}}} \qquad (2.11)$$

Where

$\boldsymbol{\eta_B}$ = battery efficiency, %

$\boldsymbol{E_{out}}$ = the output energy, Ah

$\boldsymbol{E_{in}}$ = the input energy, Ah

To have an efficient system the batteries should be large enough to operate the system in the case of a lack of electricity supply that could be 24 hours or more. Moreover, to have a reliable system, the storage should be of sufficient energy to operate the loads at moments of cloudy days or calm nights; the appliances will be powered from the batteries. To calculate the battery capacity, demand load and the battery backup usage time are required as follows: (Lee et al. 2012, Deshmukh and Deshmukh 2008, Habib et al. 1999).

$$\text{Battery Capacity} = \frac{E_d \times A}{\eta_B \times DoD \times V_n} \qquad (2.12)$$

Where

$\boldsymbol{\eta_B}$ = battery efficiency,%

E_d = energy consumption per day, W

A = number of days of autonomy (as wish to cover), days

DoD = depth of discharge, %

V_n = nominal voltage, V

Schmid (2002) pointed that the battery capacity can be affected by low and high temperature. The nominal capacities are mostly measured at 20 °C. In cold weather temperature will significantly affect and slow the chemical reaction inside the battery. In extreme high temperatures or warm weather, the life time of the battery will be reduced, and corrosion velocity of the rods inside the battery will increase, along with accelerating the self-discharge as shown in Figure 2.12. For these reasons the battery should be placed in a sheltered place, away from low and high temperature.

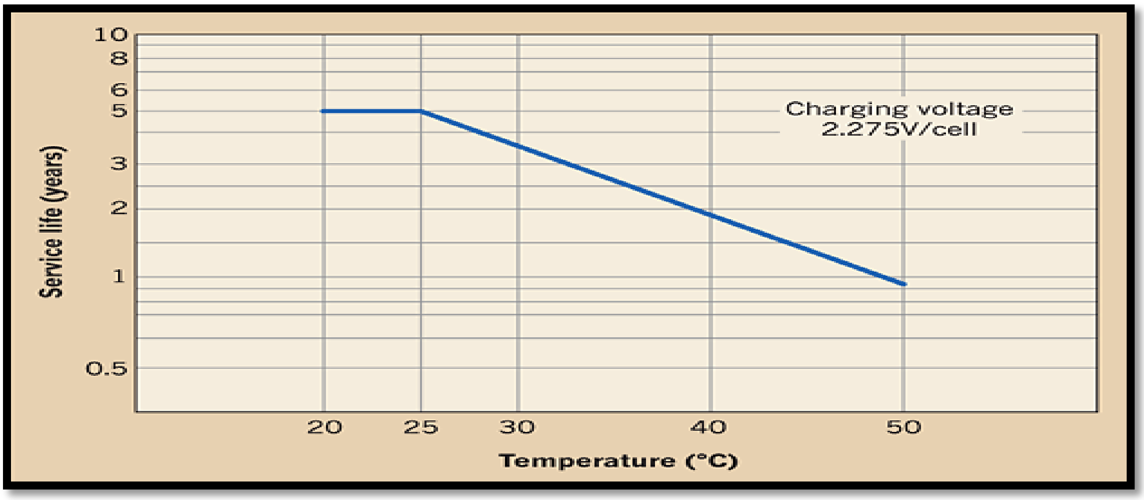


Figure 2.12: The effect of temperature on battery service life (Michael 2012).

Batteries are an important element of a PV-battery hybrid power system. The batteries are necessary for all fluctuating systems because of the nature of renewable energy and demand load. Thus, in sunshine hours, the PV generator is feeding the load, while the extra power is stored in the battery. On the other hand, during the night or cloudy day where the solar irradiation is low, the energy is supplied to the load directly from the battery. The mathematical steps of charging and discharging the battery are presented in the equations by Ani (2013), Abdolrahimi and Karegar (2012), Lal et al. (2011), and Linden and Reddy (2002). The size of batteries is important for stand-alone systems, where the designer usually expands the size of batteries in order to have more time to recover power. Once the required battery capacity is calculated and the rate of discharge is linked with temperature, the battery's size can be calculated as mentioned in equation 2.13.

$$\text{Battery size} = \frac{\text{Battery capacity}}{\text{rate of discahrge} \times \text{present temperature}} \quad (2.13)$$

$$E_{B\,min} = (1 - DoD_{max}) \times \text{Battery capacity} \quad (2.14)$$

$$SoC_{min} \cong 1 - \frac{DoD_{max}}{100} \quad (2.15)$$

$$E_B = E_{B\,old} + E_{charge} \quad (2.16)$$

Where

$\mathbf{E_{B\,min}}$= minimum energy in the battery, KWh

$\mathbf{SoC_{min}}$ = minimum state of charge, %

$\mathbf{DoD_{max}}$ = maximum depth of discharge, %

$\mathbf{E_B}$ = battery energy, KWh

$\mathbf{E_{B\,old}}$ = energy of battery before charging, KWh

$\mathbf{E_{charge}}$ = charging energy, KWh

DoD = depth of discharge,

Battery charging controller

The charge controller has two main tasks to protect battery, prevent the battery from exceeding the charge point or full discharge point by reducing overcharging and deep discharging during short power period. Therefore, the charge controller aims to achieve a suitable monitoring for charging and discharging. Furthermore, there are many types such as advance charge controllers where it is possible to monitor all battery features and show the stage of charge. In some hybrid power systems, the battery charge controller can be the management system for the hybrid power system. Systems such as these will be able to control the whole system and swap to a back-up system when the battery reaches the discharge limit. The most important characteristic of the battery is its lifetime because it represents a substantial capital investment and replacement cost compared to the whole system, and it is important to consider the potential to reduce the repeated replacement of the battery over the lifetime of the whole system. This can be undertaken by preventing overcharging. A controller can simply sense that batteries are fully charged and stop the flow of energy to the batteries. The mathematical model of the charge controller is presented in the equations by Schmela (2005) and Gabriele (2001).

The mathematical modelling of the battery charge controller is presented below. The charge controller manages the flow of energy from the energy source to the load or battery or from battery to load by monitoring battery voltage and keeping it in the acceptance values, between the maximum and minimum voltages values. The modelling of the controller is presented in equation 2.17 (Ani 2013, RETScreen International 2003, Manwell et al. 1998).

$$E_{out} = E_{in} \times \eta_{ch} \qquad (2.17)$$

Where

$\boldsymbol{\eta_{ch}}$ = charger controller efficiency, %

$\mathbf{E_{out}}$ = energy output from the charger controller, KWh

$\mathbf{E_{in}}$ = energy input to charger controller, KWh

Inverter

Since the generation source in this hybrid power is PV generation and it only generates direct current voltage (DC) electricity, as well as the battery, which also delivers DC. Few consumers operate directly with DC voltage. Furthermore, most commercial devices need an alternating current (AC) voltage for their operation. Therefore, a distinctive power element is required. These elements are commonly called “inverters” because they reverse or invert the polarity of the source from DC power to AC power with the required frequency rhythm. Inverters are often applied to either PV systems or batteries. The efficiency depends on the type of the inverter and often it is above 80%, as shown in Figure 2.13. High conversion efficiency is important for the system to be economic. Consequently, high conversion efficiency is not only required for nominal power range, but also under partial load conditions to keep the system economical to operate.

Inverters are ordinarily just single phase for small power system. The three phase inverter is more costly, which is utilised to serve higher power and unequal demand load. For the DC/AC bus framework with renewable generation and a storage system such as battery, it is prescribed to choose a single phase inverter to cover the small loads operation. In the case of stand-alone applications, the yield waveform from the inverters becomes more important. The deviation from the perfect sinusoidal voltage is regularly depicted as aggregate harmonic mutilation. For efficient and stable power supply, this harmonic distortion of the yield voltage ought to be less than 5%, which relates with the nature of the power electrical system mainly when these loads are computers or other electronic devices (Manwell et al. 1994).

There are three forms of the inverter waveforms output; square wave, modified sine wave or sine wave. These shapes are evidence of the quality and expense of the inverter. Square wave and semi square inverters compared to (50-60) Hz sine wave produces more harmonic distortion; however these are less expensive than sine wave inverters. Square wave and semi square inverters can be utilised suitably for dump loads, for example water heaters, heat radiator or tungsten lamps. On the other hand, modified sine wave or semi sine wave inverters generate waves between square waves and sine waves are more closely described as multiple-step square waveform that nearly approximates an immaculate sine wave. This type is used with most household equipment efficiently. Nonetheless, some delicate electronic gadgets may require a sine wave inverter. This type can create usable power and cost more than alternate types of inverters (Liu et al. 2011b, Yu, Song and Kwasinski 2011).

Another essential component for stand-alone applications, the capability to produce and to consume reactive power, should be specified for the user. Often motors are loads that require reactive power. Inverters produce different reactive power according to the inverter type and load type as well. For this situation, adequate power is characterized by kilo-volt-amperes (kVA) rather than kilo-watts (kW).

In isolated power systems, inverters often consist of electronic high frequency switching and capacitors. Xiong et al. (2011) support this and suggest that six switches for a bi-directional converter with ultra-capacitor will increase the life time of the batteries and the inverter. A periodic train is used in this case to control the switching of transistors in order that the DC source is engaged and disengaged in like manner. After that a transformer is used to amplify the magnitude to the specified voltage range in order to filter it to the required frequency. In typical operation, an inverter will cut out once it has reached the maximum power. Inverters are planned in the way that they can deal with power surges for a constrained duration, keeping in mind that the end goal is to reduce the hot spot in the switches and transformer. Ordinarily, this type of inverter is weak for starting the induction motors because it operates in over-supply capacity for a period of time.

The genuine power fed into the grid can be evaluated by knowing the actual generated power, and the efficiency of the inverter. The mathematical model for the inverter is presented in equation 2.18 (RETScreen International 2003, Manwell et al. 1998). In this type of hybrid power scheme, the PV panel and battery bank are connected directly to the DC-bus while the demand load is connected to the AC-bus, considering that the accrual power in the AC-bus comes through the inverter.

$$\mathbf{E_{inv} = E_{gen} \times \eta_{inv}} \tag{2.18}$$

Where

$\boldsymbol{\eta_{inv}}$ = Inverter efficiency, %

E_{gen} = energy generated from renewable and battery, KWh

E_{inv} = energy output from inverter, KWh

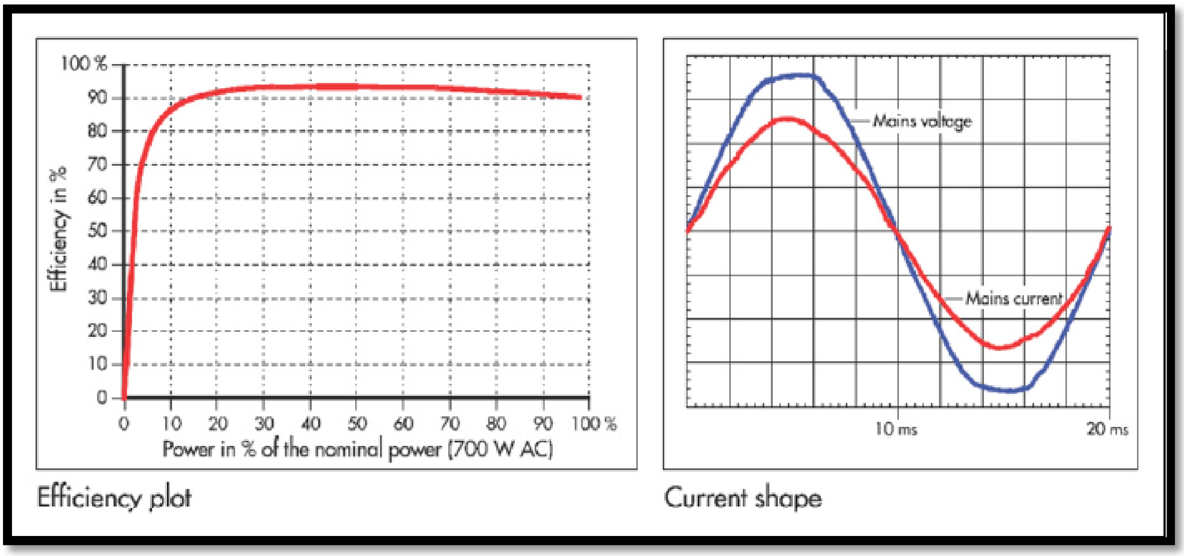


Figure 2.13: Inverter efficiency curve and current, voltage form for inverter (Sunny Boy 2011).

Demand load

This section will present the normal end-uses to which power can be put to and the limitations that a small scale isolated power system may impose, such as the type and size of end-uses. Load profiles portray power demand based upon time. Load profile estimation would set the generation capacity according to the power consumed by the end-user. And also the type of load (single phase or three phases) determines the type of the isolated mini grid. This will precede the guidelines to evaluating potential end-user demand load so that a mini-grid can be suitably estimated for the required load. This step is basic to the achievement of isolated power system in light of the fact that the adopted system has a huge effect on capital cost. Unnecessarily, oversized isolated power systems increase the capital cost that the utility or the community have to cover. On the other hand; undersized isolated power system will lead to end-user dissatisfaction and disappointment with the power quality.

A more reliable methodology to evaluate demand load is to overview the household appliances and survey end-users in a neighbourhood or in areas having similar demographic attributes with homogeneous economic features. This would help to evaluate the average demand load per end-user and additionally their load growth.

Typical PV-battery hybrid power system approach

The operating principle of a PV-battery hybrid power system, the solar panels generate the required power for the load where solar radiation can be measured in watt per square meter (W/m^2). If the generated power is greater than the required load, the excess power is immediately transferred to the battery to store it. On the other hand, if the solar panels provide less power than the load required, the batteries will release additional power to overcome this deficit (Belhadj 2010).

In order to design a PV-battery hybrid power system with the specific goal of knowing that this power generation is one of the solitary frameworks, it is essential to realize that the production energy at the ground level from sunlight at the peak (zenith) relies on distance to the sun and consequently on the time of the year. The system designer must know the four types and designs of PV collectors (fixed, dual-axis tracking, single-axis tracking: polar mount, and horizontal mount) in order to maximise the generation power, because every type has its pros and cons, and the cost are variable (Lee et al. 2012).

There are two critical points the designer needs to contemplate when planning, designing and calculating the size of the system. The first point is when the PV cell generates greater power than required and the batteries are fully charged. In this case, the controller must disconnect the PV from the grid. The electrification power for the end user will be totally dependent on the battery bank, in order to protect the solar panels. The second point is when both the PV generator and the battery are unable to cover all the required loads. Problems such as power deficit must be avoided during the design stage.

There are a huge number of hybrid power system designs and configurations which are frequently focused on experience based on trial and error. Observing and monitoring studies can identify issues, design corrections and even adjustments after installation. This may not be practical, particularly in remote areas in third world countries.

2.5.1.2 Economical aspects of PV and Battery in IHPS

The main consideration in all engineers and designers choices and decisions is financial aspects; therefore, the economics of any design must be considered to ensure the venture demonstrates a satisfactory return.

The financial model is focused around the utilization of ordinary life cycle costing. This incorporates yearly cash flow, the present estimation of framework expenses (capital cost), yearly running cost, and replacement cost. Also, this economic examination has been intended to consider a side-by-side correlation or to compare the financial matters of a hybrid power system with the existing one, such as a diesel isolated power system or grid connection.

Capital cost

To understand the economic side, it is important to know that cash flow is a yearly analysis to find the real figures for incomes and expenses (disbursements). The disbursements are divided into three main categories: capital costs, running cost (fuel expenses, operation and upkeep cost), and replacement costs.

Capital cost is the introductory funding for the hybrid power system including component costs, supply costs, establishment costs, custom duties, delivery costs, and perhaps the expense of installing a distribution network to the end users. Hence for this system the capital cost is given as an equation (2.19) (Manwell et al. 1998, Yaron et al. 1994, Stoecker 1989).

The capital cost of the venture incorporates factors such as:

- Outline planning and design, which can be placed under construction cost.
- Land securing, this can be placed under construction cost.
- Cost of the components.
- Cost of delivering the components, which can be placed under the cost of the components.
- Cost of distribution lines and poles including grounding, insulators and lightning protection.

$$C_{Cap} = C_{PV} + C_{Batt} + C_{inv} + C_{cont} + C_{bus} + C_{line} + C_{inst} \tag{2.19}$$

$$C_{inst} = C_{PV,inst} + C_{Batt,inst} + C_{inv,cont,inst} + C_{bus,line,inst} + C_{cons} \tag{2.20}$$

Where:

$\mathbf{C_{Cap}}$ = the capital cost for the system, currency

$\mathbf{C_{PV}}$ = the capital cost for the PV including delivery, currency

$\mathbf{C_{Batt}}$ = the capital cost for the batteries including delivery, currency

$\mathbf{C_{inv}}$ = the capital cost for the inverter including delivery, currency

$\mathbf{C_{cont}}$ = the capital cost for the controller including delivery, currency

$\mathbf{C_{bus}}$ = capital cost for the (AC & DC) bus including delivery, currency

$\mathbf{C_{line}}$ = capital cost for the distribution line including delivery, currency

$\mathbf{C_{inst}}$ = the total installation cost for the system, currency

$\mathbf{C_{PV,inst}}$ = the installation cost for the PV, currency

$\mathbf{C_{Batt,inst}}$ = the installation cost for the batteries, currency

$\mathbf{C_{inv,cont,inst}}$ = installation cost for the inverter & controller, currency

$\mathbf{C_{bus,line,inst}}$ = installation cost for bus bares and lines, currency

$\mathbf{C_{cons}}$ = the total cost of construction, currency

Running cost

Under the running cost section, there are many types of expenses such as regular maintenance expenses over the year (from cleaning the devices to adding distilled water for some devices such as batteries), and fuel cost over the year for generation using fuel such as diesel, hydrogen or bio-fuel. Hence the running cost is given as equation 2.21 (Manwell et al. 1998, Yaron et al. 1994).

$$C_{Run} = C_{PV,run} + C_{Batt,run} + C_{inv,chr,cont,run} + C_{bus.line,run} + C_{fuel} + C_{loss} \quad (2.21)$$

$$C_{fuel} = C_{fuel/L} \times F_{cons} \times H_{year} \quad (2.22)$$

Where:

$\mathbf{C_{Run}}$ = the running cost for the system, currency

$\mathbf{C_{PV,run}}$ = the running cost for the PV including cleaning, currency

$C_{Batt,run}$ = the running cost for the batteries, currency

$C_{inv,chr,cont,run}$ = the running cost for the inverter, charger and controller, currency

$C_{busline,run}$ =running cost for the (AC&DC) bus and the distributing line, currency

C_{loss} = the cost the losing energy in every devices, currency

C_{fuel} = the annual cost for the using fuel, currency

$C_{fuel/L}$ = the cost of the using fuel per one litter, currency/L

F_{cons} = fuel consumption rate per hour, L/h

H_{year} = number of hours the generator is operating per year, h

It is worth mentioning that the cost of the fuel in this system is zero based on the fact that there is no generation with fuel, only PV panels and the radiation from the sun is free. Once any other generation is added to the system, the capital cost and running cost of this generation must be added to the general cost.

Replacement cost

Substitution expenses are marginally more confusing in that they include normal money instalments but are not genuinely yearly. In the system life time there are some principle components that need to be replaced. These are parts but not necessarily a replacement of the whole device. Replacement of components is intended to maintain the overall life span of the system. All the equations for the replacement cost are presented as follow (Manwell et al. 1998, Yaron et al. 1994).

$$C_{rep,PV} = C_{PV,part} \times P_{fact} \qquad (2.23)$$

$$C_{rep,Batt} = C_{Batt,part} \times P_{fact} \qquad (2.24)$$

$$C_{rep,inv.cont} = C_{inv,cont,part} \times P_{fact} \qquad (2.25)$$

$$C_{rep,Bus,line} = C_{Bus,line,part} \times P_{fact} \quad (2.26)$$

$$P_{fact} = F \times \left[\frac{1}{(1+i)^n}\right] \quad (2.27)$$

$$i = \frac{i_f - f}{1+f} \quad (2.28)$$

Where

$\mathbf{C_{rep,pv}}$ = the replacement cost for PV, currency

$\mathbf{C_{PV,part}}$ = the cost of consumed part of PV, currency

$\mathbf{C_{rep,Batt}}$ = the replacement cost for battery, currency

$\mathbf{C_{Batt,part}}$ = the cost of consumed part of battery, currency

$\mathbf{C_{rep,inv,cont}}$ = replacement cost for inverter & controller, currency

$\mathbf{C_{inv,cont,part}}$ = consumed part cost of (inverter, controller), currency

$\mathbf{C_{rep,Bus,line}}$ = the replacement cost for bus and lines, currency

$\mathbf{C_{Bus,line,part}}$ = cost of consumed part of (bus bare, lines), currency

$\mathbf{P_{fact}}$ = present factor, %

F = future money, currency

n = component life time, year

i = the real interest rate, %

$\mathbf{i_f}$ = estimated interest rate, %

$\boldsymbol{f}$ = inflation rate, %

Present worth

To calculate the value of the system in the present, it is required to know the present worth factor (PWF) as mentioned in equation 2.29. The present worth of the system can be found by applying the PWF in the required year to total annual running cost as mentioned in equation 2.30 (Manwell et al. 1998, Yaron et al. 1994).

$$\mathrm{PWF} = \mathrm{A} \times \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \quad (2.29)$$

$$\mathrm{C_{Run,PW}} = \mathrm{C_{Run}} \times \mathrm{PWF} \quad (2.30)$$

$$\mathrm{C_{Sal,PW}} = \mathrm{C_{Sal}} \times \mathrm{PWF} \quad (2.31)$$

Where

PWF = present worth factor, %

A = annual cost (yearly money), currency

i = the real interest rate, %

$\boldsymbol{n}$ = System life time, year

$\mathbf{C_{Run,PW}}$ = present worth for running cost, currency

$\mathbf{C_{Run}}$ = total running cost, currency

$\mathbf{C_{Sal}}$ = salvage value, currency

$\mathbf{C_{Sal,PW}}$ = present worth for salvage value, currency

Life cycle cost

All the previous calculations are a preamble to define the life cycle cost. Life cycle cost is a tool to compare the system with other systems in order to evaluate the best system by energy and profit, as shown in equation 2.32 (Manwell et al. 1998, Yaron et al. 1994). For this system the life cycle cost is shown in Figure 2.14 compared with the existing system (diesel isolated power system), where it shows that the life cycle cost of the diesel over twenty years is much cheaper than using a PV-battery hybrid power system.

$$\text{Life Cycle Cost} = \mathrm{C_{Cap}} + \mathrm{C_{Run.PW}} + \mathrm{C_{rep.PW}} + \mathrm{C_{Sal,PW}} \quad (2.32)$$

Where

$\mathbf{C_{Cap}}$ = total capital cost for the system, currency

$\mathbf{C_{Run,PW}}$ = present worth for running cost, currency

$\mathbf{C_{rep,PW}}$ = present worth for replacement cost, currency

$\mathbf{C_{Sal,PW}}$ = present worth for salvage value, currency

Net present value (NPV)

Net present value (NPV) for any project is calculated by summing the running cost, replacement cost and subtracting the initial capital cost, as given by equation 2.33 (Manwell et al. 1998, Yaron et al. 1994, Stoecker 1989).

$$\mathrm{NPV} = \left(-\mathrm{C_{Cap}}\right) + \mathrm{C_{Run,PW}} + \mathrm{C_{rep,PW}} \qquad (2.33)$$

Cost of energy (COE)

Cost of energy is the cost of the total energy that is produced from the system during the system life time, as given by equation 2.34 (Manwell et al. 1998, Yaron et al. 1994).

$$\mathrm{COE} = \frac{\text{Life cycle cost}}{\mathrm{E_{gen}} \times \text{system life time}} \qquad (2.34)$$

Where

$\mathbf{E_{gen}}$ = energy generated per year, kWh/year

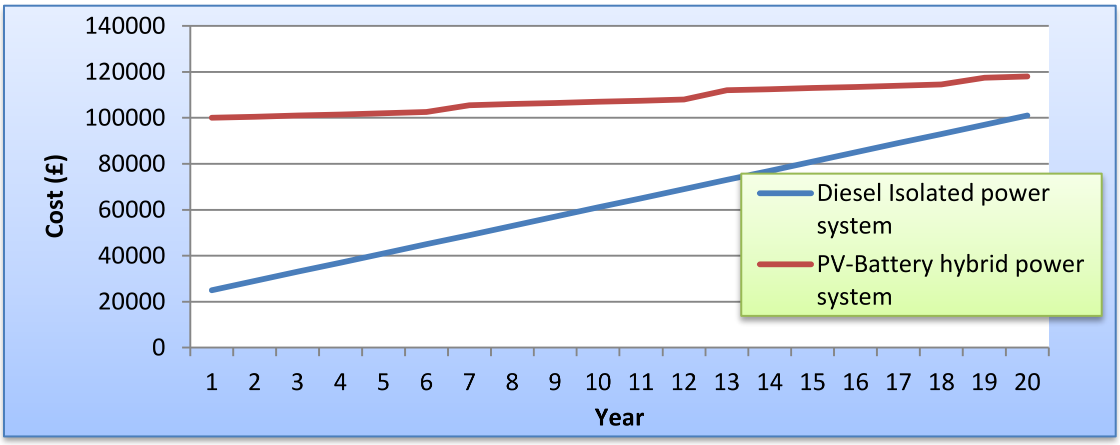


Figure 2.14: The life cycle cost for PV-battery hybrid power system compared to diesel isolated power system.

2.5.1.3 Advantages and disadvantages

The main advantages of the PV-battery hybrid system are:

- The use of a storage system is available by using batteries.
- This system requires basic configuration and simple design from the power sources, through storage, ending with the end user load (Lee et al. 2012).
- It can supply power to DC or AC loads (Lee et al. 2012, Xiong et al. 2011, Belhadj 2010).
- In the PV-battery hybrid system, it is not difficult to include and utilise various sources as a standby framework (Meinhard et al. 2004).
- system is reliant on the sun oriented power as the only energy source for the grid, it is accessible and available to install in order to introduce power for long life time solar panel, with very low running cost (it only requires cleaning dust from the panel) (Lee et al. 2012, Belhadj 2010).
- The PV-battery hybrid system is suitable for remote areas and for householders as well or any place that has experiences adequate solar radiation (Xiong et al. 2011).
- The PV-battery hybrid system, from an environmental standpoint is an environment friendly system excluding the manufacturing of the PV (Xiong et al. 2011). It generates clean energy and thus supports sustainable development. Moreover, there is no production of greenhouses gases during operation, and it may be eligible for some environmental subsidies or carbon reduction credits (Belhadj 2010).
- PV is noiseless generation.

Notwithstanding, the weaknesses for this system are specified underneath:

- If the system is receiving extra power and the batteries are full charged, the solar panel must be switched off to protect itself from damage.
- The redundancy power from the PV-battery hybrid system is low due to its complete dependency and reliance on solar radiation (there is no power from PV during the night or on a cloudy day). Electricity for PV-battery hybrid systems can be affected by weather and the geographical location (seasonal variation) and production of electricity during peak period can be affected by the daily demand (Belhadj 2010). Research by Staffhorst (2007) found that after recoding and calculating the generated energy from a 10MW solar panel, the author found that 90% of the energy production is from March to October.
- The power from solar panels, the battery bank or both must not exceed the inverter's rated power (Strauss and Engler 2003).
- The PV-battery hybrid system is insufficient for long term power generation. Numerous source can be added to support the system (Xie et al. 2010).
- The system requires full evaluation and assessment before installation. No less than one year of study and information accumulation about sun irradiation is required keeping in mind the end goal to plan and design an efficient power system (Nian and Behera 2012).
- The batteries' life time is very low (4 to 6 years) compared with the whole system life time of 20 years. Also the batteries are recognized as short term storage (Lee et al. 2012).
- The capital cost for the solar panel is very expensive. As the efficiency of solar panel power generation increases and manufacturing costs, the use of

PV panel will be more common even without feed in tariffs or financial support mechanisms.

- The storage capacity limit for the PV-battery hybrid system depends on the size of the batteries, moreover, during the deficit period relies upon battery capacity (Jimenez-Fernandez 2011).

Table 2.2 summarizes the preferences and weaknesses of this system at the end of section 2.5.3, and compares this system with convergent systems in sections 2.5.2 and 2.5.3.

2.5.2 Wind Turbine Generator (WTG)-battery hybrid systems

A wind turbine generator (WTG)-battery hybrid is another type of renewable hybrid power system that resembles the previous system to some extent. However, this system is using a different technology. Instead of using PV power, wind is used to supply energy. Wind is one of the most common renewable sources and the quickest developing renewable energy sources. Wind energy has shown a dramatic increase and is still growing in areas where wind resources are strong enough and stable enough to be attractive to exploit (Eroglu et al. 2009, Kwasinski and Krein 2007). The wind turbine generator is a standout amongst the most viable renewable energy innovations, and it is viewed as the basic stand-alone system (Sheng-Yang et al. 2011).

The WTG is considered to be one of the environmentally friendly forms of energy generation (Bevrani et al. 2010). WTG-battery hybrid system is deemed to be suitable for remote areas as it has low running costs and maintenance requirements (Ming-Shun et al. 2009, Ronan and Mark 2006). Others said that WTG is an alternative power for the old generation processes that depend on fossil fuel (Sheng-Yang et al. 2011). WTG represents the dramatic revolution in research and many studies demonstrate that the efficiency and productivity of wind energy is improved, and day to day there is a progress in WTG innovation (Carpentiero et al. 2010).

WTG depends on wind speed to create power. There are extensive regular varieties of WTG for power generation types, shapes, and models. Wind velocity fluctuates as a rule; it is exceptionally hard to foresee precisely the output power from wind sources. Any electrical system can assimilate seasonal variations, but for the WTG the acceptable limit of aggregate power is greater than a quarter of the total electrical system limit. In light of the irregular behaviour of this power source, batteries for the WTG stand-alone system remain an important and critical part of the system in order to keep the balance and parity of the system (Bowen et al. 2001). Charging batteries in the WTG-batteries hybrid system is performed in numerous ways; steady voltage charging, constant current charging, and trickle charging (Kuo-Yuan et al. 2010, Sung-Yeul et al. 2008).

Figure 2.15 shows the main configurations for a wind-battery hybrid power system. This system, according to some researchers, is suitable for use in a micro-grid or in a stand-alone system (Vasquez et al. 2011, Majumder et al. 2010, Mehrizi-Sani and Iravani 2010). Power generation for remote areas require high power efficiency productivity, where the WTG-battery system is viewed as a feasible option. Added to the efficiency and proficiency of this system, the WTG-battery system is best to supply remote regions with electrical power due to its simplicity and straightforwardness, minimal running cost, and diminished requirement for maintenance (Ming-Shun et al. 2009, Ronan and Mark 2006).

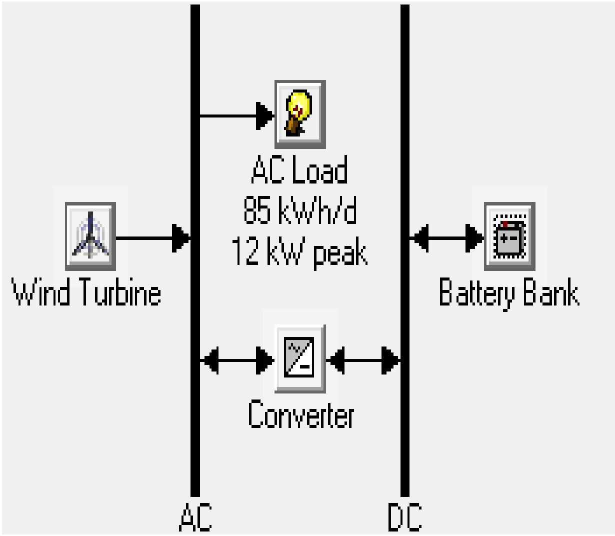


Figure 2.15: The structure of WTG-battery hybrid power system.

2.5.2.1 Operating Principle

The basic components of WTG-battery hybrid power system are as follows:

- Wind Turbine Generator (WTG) ● Battery bank ● Battery charge controller
- Converter ● DC-bus and AC-bus ● Demand load

Wind turbine

Wind is uninterrupted movement of barometrical air masses and is identified by its speed and its direction. These qualities are the consequence of the sun powered warming of diverse parts of the world's surface. Regardless of the way and the direction the air in the atmosphere is moving, the most important factor is the horizontal movement that can be used to generate electrical power. Wind power originates as a consequence of its movement. If all this movement is exploited, the generated power will be exceptional. According to the world meteorology organization only 1% around the world has access to convert wind speed into power in all its forms.

There are a large number of researchers supporting the fact that the best possible utilization of wind energy can resolve, in a manner, the world's energy issues. Nowadays there are limited numbers of countries that are using the wind power capacity available to them. Figure 2.16 shows globally the growth of wind power generation in the last 20 years, with almost 15% yearly development rate (Delphi 2014, Daltonet et al. 2009, Dalton et al. 2008).

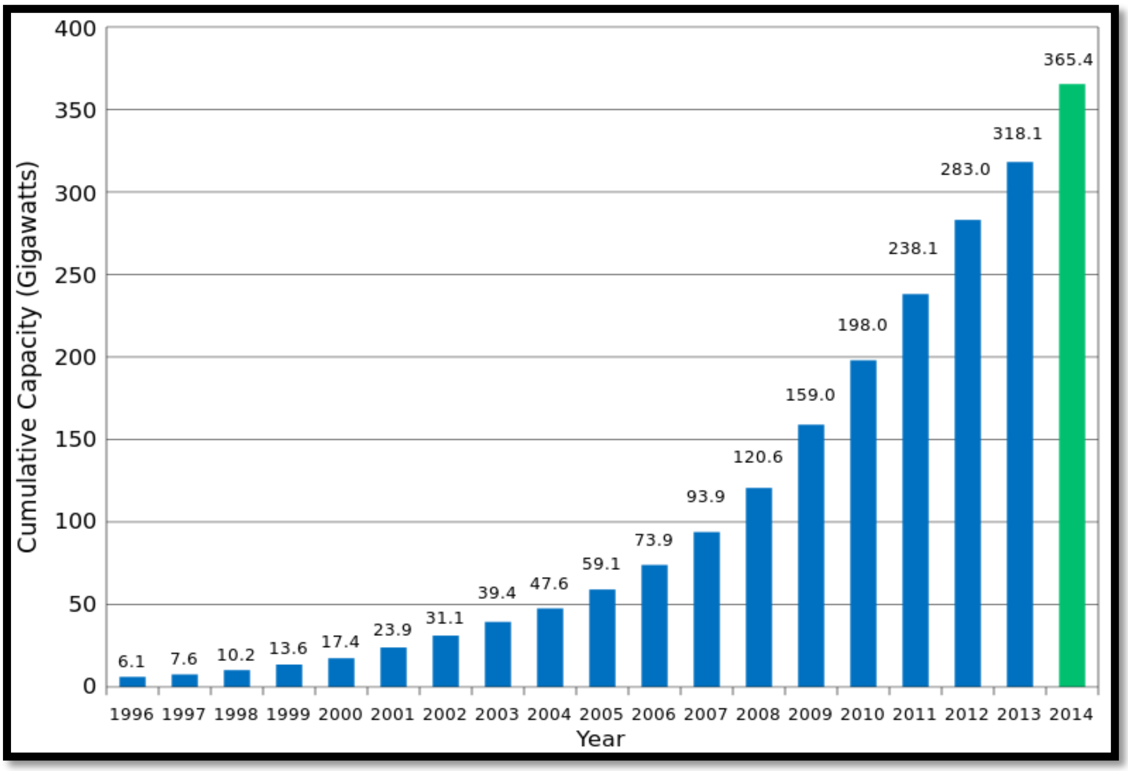


Figure 2.16: Worldwide wind power capacity in the last 20 years (Delphi 2014).

Despite its potential, wind energy can fluctuate easily. Wind speed cannot be anticipated and it is unlikely for it to be in constant operation. Without a doubt, the wide utilization of wind power and its proficient use is going to enhance the worldwide fossil fuel power offset without over-burdening the environment with hazardous gases.

Wind power has been used for centuries. The Egyptians were using wind power to propel ships and boats along the Nile as early as 5000 B.C. In China wind power has been used to pump water for agriculture by simple design windmills up to 2100 years ago. Europe also used windmills in the past for agriculture and manufacturing. Recently the utilization of nuclear energy alongside the low costs of the fossil fuel, together constrained the enthusiasm to exploit wind energy. Nowadays, high levels of emissions from fossil fuel sources have driven environmental targets and polices, and developed countries have started investing in creating energy from environmentally friendly resources. Also, the dramatic increases in fossil fuel based energy crises, consequently, have driven increased enthusiasm to create and innovate into alternative energy sources.

The mechanism that is used to harness the wind energy into electrical power is called the turbine. Wind turbines are utilized to produce power from wind kinetic energy, which is related to the wind speed and density. The wind kinetic energy moves the blades of the wind turbine according to the special design of the blades, which are connected to gear box through a shaft. The gear box is connected to the generator, the gear box will increase the rotational speed and the generator will convert the kinetic energy to electrical energy. To improve and enhance the generated energy the turbine is installed at the top of a tower (Liu et al. 2011a, Dalton et al. 2009, Fesli et al. 2009, Dalton et al. 2008, Gätin 2007, Park et al. 2004).

The main parts of a wind turbine are: blades, hub, tower and nacelle (contains shaft, gearbox and the electric generator) as mentioned in Figure 2.17. The blades are specially designed to catch the wind speed, and because the wind flows through the blades, thus flow will allow the blades to twist. The hub will spin according to the blades. The hub is connected to a gear box inside the nacelle, which contains the gear box and the generator. The gear box increases the speed from low speed to high speed. Normally it increases the speed from (30-60) rpm to (1200-1500) rpm, which is required to generate electricity. The electromagnet generators require high speed to generate (50-60) cycle AC. The tower is normally designed for three purposes; first, to enhance the efficiency of the wind turbine by installing it in the top of the tower to face the wind without obstacles, and by lifting the blades to a higher elevation the designer can increase the size of the blades for a better result where the blades will operate safely. Second, the tower contains all the power cables from the generator to the grid connection. Finally, in some designs the tower is designed to have the ability to allow the nacelle to rotate at the top. The gear between the tower and nacelle is controlled by controller and motor. The controller senses the wind direction and gives the motor an order to adjust position to keep the blades facing into the wind as a result of continuous change of the wind direction (Adejumobi et al. 2011, Gätin 2007).

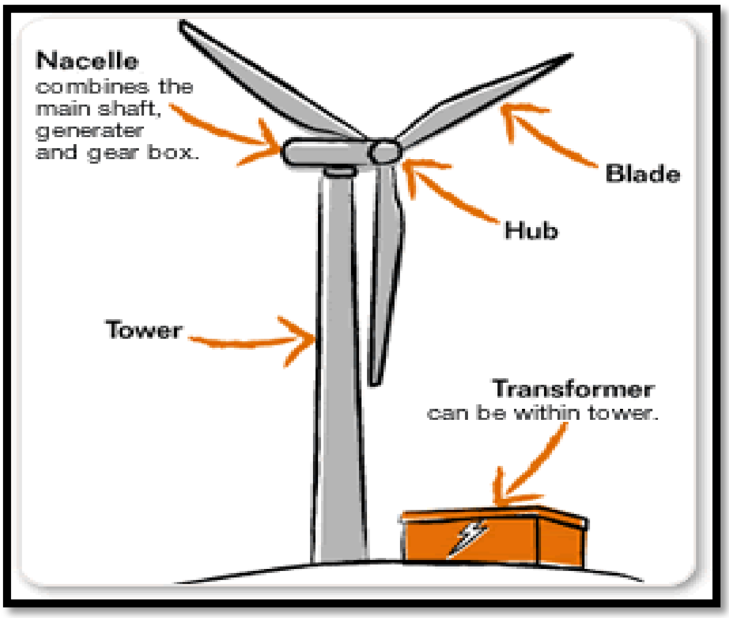


Figure 2.17: Wind turbine configuration (Renewable Global Energy 2013).

There are different sorts of advanced wind turbines, which are characterized by two primary classes: horizontal and vertical, as show in Figure 2.18 (Themes 2012).

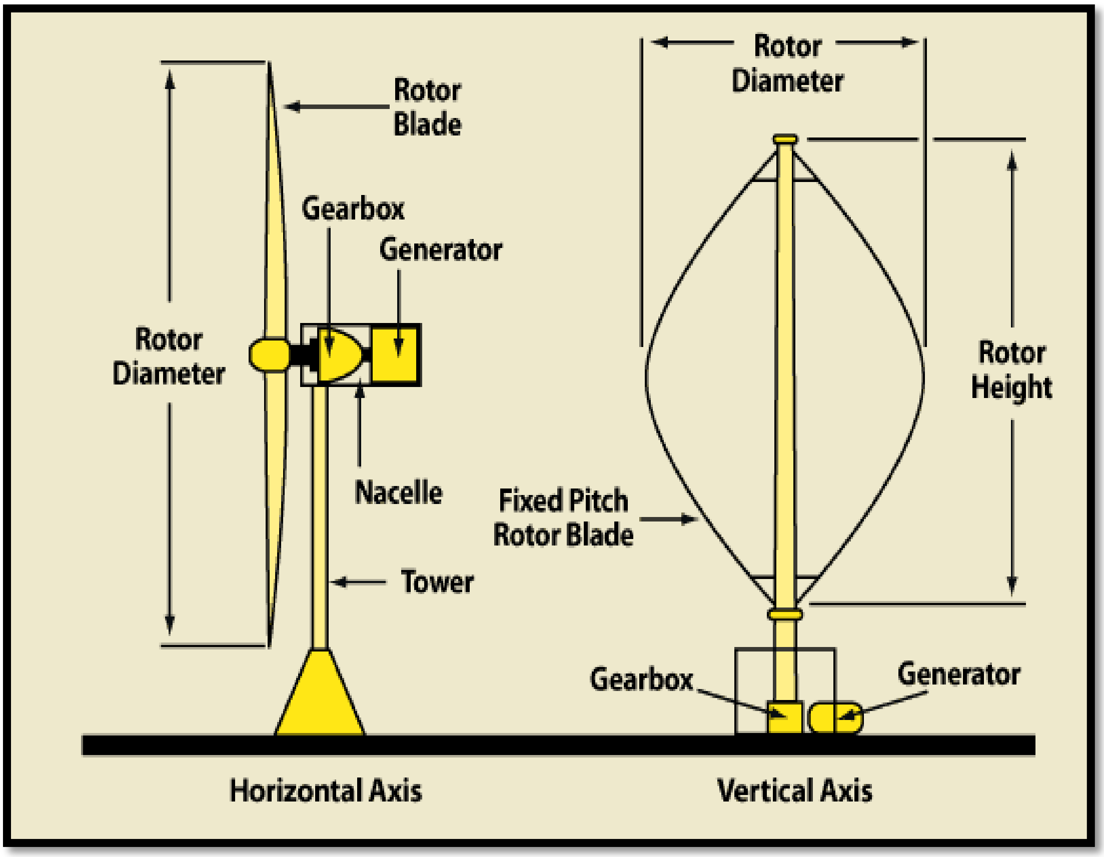


Figure 2.18: Horizontal and vertical wind turbine (Themes 2012).

Again it is important to report that the horizontal wind turbine requires reallocating its position according to the wind direction. This is not required by the vertical wind turbine, because its design can accept the wind from any direction. The rotating velocity of a wind turbine depends on air movement optimized parameters and its blades size. The most important thing for the wind turbine is connecting it to the grid, because the generated power must have the same grid frequency.

The electrical power that can be generated from wind can be calculated with the following equations (Lin et al. 2011, Shushu et al. 2011, Deshmukh and Deshmukh 2008, Park et al. 2004, Pecen et al. 2000, Mukund 1999).

$$P_W = \frac{1}{2} \times \rho \times A \times v^3 \times C_P \tag{2.35}$$

$$A = \pi \times r^2 \tag{2.36}$$

$$\rho = \frac{P}{R \times T} \tag{2.37}$$

$$C_P = \frac{\left(1 + \frac{v_0}{v}\right) \times \left(1 - \left(\frac{v_0}{v}\right)^2\right)}{2} \tag{2.38}$$

Where

P_W = the kinetic power in the air, W

ρ = Air density, Kg/m^3

A = Swept area by the blades, m^2

v = wind speed, m/s

C_P = power coefficient, %

r = blade length, m

P = air pressure, Pascal (Pa)

R = gas constant or known as molar, Joule/ (kelvin× mole) (J/mol K)

T = absolute temperature, Kelvin (K)

v = Upstream wind velocities, m/s

v_0 = Downstream wind velocities, m/s

To understand the mechanism behind the wind turbine power generation or the relation between wind speed and output power, a wind turbine power curve is needed to describe this. A general characteristic wind power curve is shown in Figure 2.19. In this curve there are three important stages: cut-in, rated output speed and cut-out.

Cut-in speed is normally caused due to low wind speed, which is not enough to turn the wind turbine blades which mean it will never provide the thrust to reach the threshold speed required to generate electrical power. Rated output wind speed is the point when the wind speed increments pass the cut-in speed. The power will increase as the wind speed increases until a point where power will be steady. Depending upon the turbine type, the wind turbine reaches the maximum capacity level for generating the maximum electrical power output up to the maximum specified speed, after that the internal mechanism operates to keep the wind turbine within the operational limits. At a point where the wind speed is high, the configuration of the turbine is fixed to this maximum electrical power level and there is no further increase in power. This is carried out in different ways accordingly to the turbine design but in general with large turbines, it is carried out by altering the blade angles in order to keep the force at a steady level. Cut-out speed is described as the wind speed increase over the rated speed, where eventually there is a danger of harm to the rotor. Therefore, an automated stopping mechanism is utilized to bring the rotor to a halt. In some types a braking system is used to reduce the speed to the rated one in order to keep the wind turbine in operation mode. In general, if the wind speed is either below the cut-in speed or over the cut-out speed the turbine will generate zero electrical power. Notably, if the speed is maintained between the cut-in and cut-out, accessible power is over the base edge (threshold) and at the same time the turbine health is kept up without any damage. Figure 2.19, shows that the generated power areas (rated speed) are divided into three different regions. Since Region I comprises of low wind speeds and is underneath the evaluated turbine control, the turbine is run at the most favourable level to collect all the available electrical power. Region III comprises of high wind speeds and is at the maximum possible turbine power. The turbine in this area, whatever the wind speed, generates power at the same level and produces constant power within this area. Region II is a dynamic area mostly involved with keeping acceptable rotor torque and clamour low (EMD-international 2010).

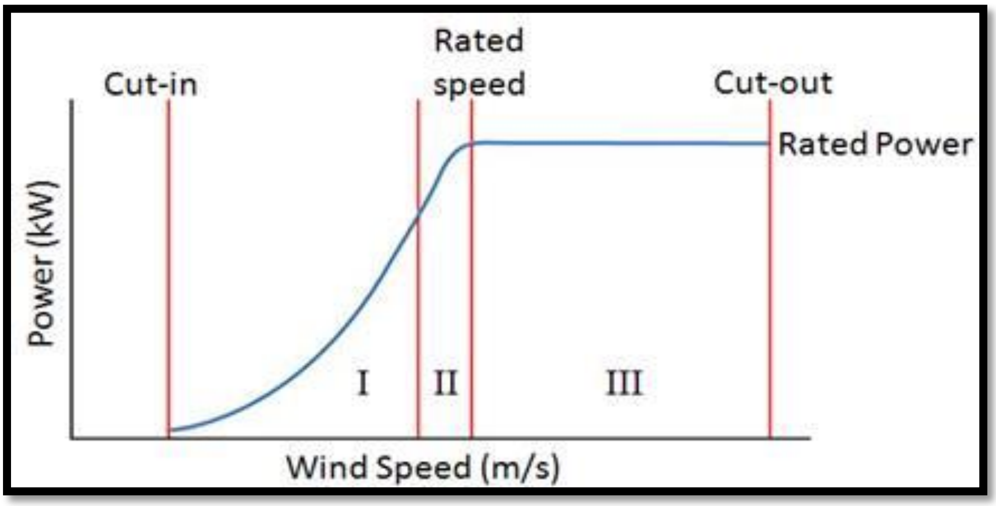


Figure 2.19: Wind turbine power curve (EMD-international 2010).

Typical wind-battery hybrid power system approach

The main power for the wind-battery hybrid system comes from two sources: a wind generator and a battery bank as shown in Figure 2.15 above. The wind speed determines the generated power as explained previously, and thereafter the mechanical power (kinetic energy) is converted to electrical power. The WTG utilises renewable energy that is clean and environment friendly. This system produces AC single phase electricity that is connected directly to the AC-bus through a circuit breaker for safety reasons. The production power depends on the type of wind turbine used and its size, and the system designer must know the average wind speed during the year in order to choose the suitable type, size and speed of turbines (Zhu et al. 2012, Zhu et al. 2011).

As explained, as long as the power produced exceeds the required load, the excess power will be stored in the battery bank through bidirectional converter. If the wind speed goes down and the WTG is not producing enough power, the batteries will compensate for this shortage. In case the wind is under the cut-in speed or over the cut-off speed, the wind turbine controller will stop the blades to protect the rotor, and power is not produced. In this case the system controller will disconnect the circuit breaker in order to save the wind generator from reverse power, and all dependence will be on batteries.

In this system there are two critical points the designer needs to contemplate when planning, designing and calculating the size of the system. First, if the WTG electrical power is greater than the demand load and at the same time the batteries are fully charged, the controller must disconnect the WTG from the grid. The electrical power for the end user will be totally dependent on the battery bank, in order to protect the WTG from dangerous affects. The second critical point is, if both the WTG and the battery are not able to cover all the obliged loads. Issues, for example, power deficiency, must be analysed and evaluated during the configuration stage.

2.5.2.2 Economical aspects of WTG and battery in IHPS

The main consideration for all engineers and designer choices and decisions is financial aspects; therefore, they should consider the economics of any design to ensure the venture demonstrates a satisfactory return. The economic considerations for this system are similar to the previous system; just one change is the replacement cost of PV with the cost of WTG in all equations. Replacing the capital cost and the running cost of WTG will define the initial life cycle cost. For this system the life cycle cost is shown in Figure 2.20 compared with a fully diesel fuelled isolated power system, where it shows the capital cost for a WTG-battery HPS higher than a diesel isolated power system. Also the graph shows the running cost for the WTG-battery HPS is almost steady with just a slight increase, where the diesel IPS has a dramatic increase year after year. The WTG-battery HPS is thus cheaper after 17 years. This graph implies that if there are any technologies to reduce the capital cost of this HPS or if there any ways to reduce the size of the system in order to reduce the capital cost, the HPS will be cheaper than the diesel system sooner than 17 years.

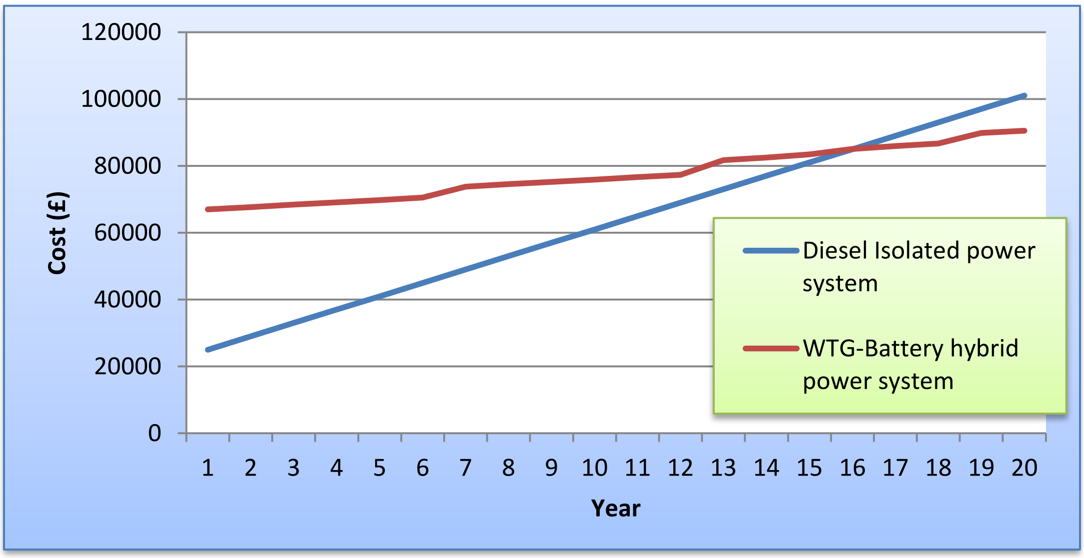


Figure 2.20: The life cycle cost for a WTG-battery hybrid power system compared to a diesel isolated power system.

2.5.2.3 Advantages and disadvantages

The main advantages of the WTG-battery hybrid system are:

- It is dependent on wind speed as the only power source for the grid; and the wind is free and available all the time, it has very low running cost because the system does not require fossil fuel or traditional fuel (Zhu et al. 2012).

- The wind-battery hybrid system is to some extent an environment friendly system but the WTG produces noise (Ronan and Mark 2006). It uses clean energy and supports sustainable development objectives and there are no emissions generated during its operation (Belhadj 2010).
- Relatively low maintenance cost for the wind-battery hybrid power system (Ming-Shun et al. 2009, Ronan and Mark 2006).
- The lifetime for wind turbines is long with some manufacturers claiming a lifetime up to 30 years.

The weaknesses for this system are specified underneath:

- The redundancy of the WTG-battery hybrid power system is low due to its complete dependence on wind speed; no wind means there will be no power because the wind does not blow year round or even at the rated speed at all times (Niankun et al. 2011).
- The system requires full assessment and evaluation before installation with at least one year of study and data collection about wind speed in order to design the system (Niankun et al. 2011).

Table 2.2 summarizes the preferences and weaknesses of this system at the end of section 2.5.3, and compares this system with convergent systems in sections 2.5.1 and 2.5.3.

2.5.3 PV-wind-battery hybrid power systems

A PV-wind-battery hybrid power system is another type of renewable hybrid power system that resembles the previous two systems to some extent. However, this system can feed the demand load through three sources: solar panels, wind turbines and batteries. This system is using the same technology of the previous two. The main configuration for this system is divided into two parts: the producer and the consumer. The producer part is divided into three sections: generation, control and storage. The generation section contains the solar panel generator and wind turbine generator. The question of which system is better, the wind turbine generator or solar panel generator, isn't as straightforward as expressing which innovation is better. Both have their advantages and disadvantages. Which engineering is best depends on the application and the area of the framework. For example, for large scale power generation, wind turbines are the most logical arrangement. Large scale wind turbines are proficient and powerful, and can be introduced in a mixture of areas, even offshore, relatively rapidly. Unlike early turbines, current turbines are essentially noiseless and the biggest turbine can produce electrical power in megawatts enough to power more than 2,000 houses. On the other hand solar panels have fixed parts, which mean less maintenance and less noise. Solar provides predictable power and wind turbine provide effective and efficient power; therefore, solar panel and wind turbine can complement each other.

Figure 2.21 describes the PV-wind-battery hybrid power system. This style is based on wind turbine connected directly to AC-bus. Solar panels and the battery bank are connected to the DC-coupling, and the DC-coupling is connected to the AC-coupling through a DC/AC converter. However, this system is esteemed to be more suitable and relevant for remote areas as it has low running costs and maintenance (Ming-Shun et al. 2009, Ronan and Mark 2006).

2.5.3.1 Operating Principle

The basic components of PV-wind-battery hybrid power system are as following:

- Photovoltaic panel (PV) ● Wind turbine (WTG) ● Battery Bank
- Converter ● Battery charge controller ● DC-bus and AC-bus ● Demand load

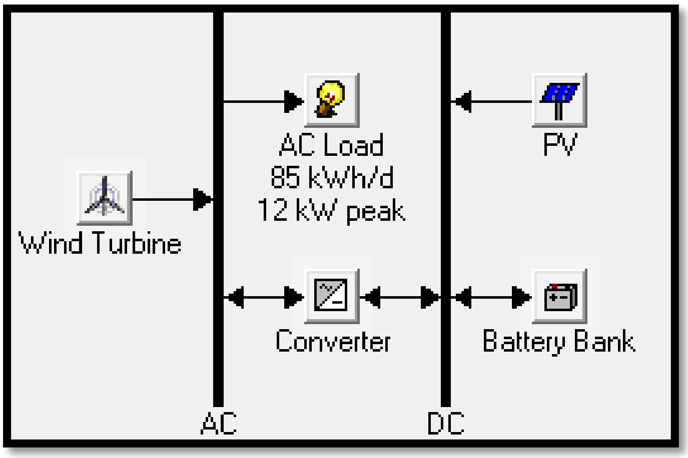


Figure 2.21: Structure of PV-wind-battery hybrid power system.

To describe the operating principle of this system, the solar panels generate some of the required power for the load, whereas the wind turbine generates most of the required power. If the generated power is greater than the required load, the excess power is immediately transferred to the battery to store it from the solar panel, unless there is more power to store from the wind turbine. The idea behind that is to reduce the converter operation time in order to increase the efficiency. On the other hand if the wind generates less power than required, the solar panels at working times provide power when the system has power deficiency, and if the power is still less or it is not in the working time of the solar, the batteries in this situation will release additional power to overcome this deficit.

2.5.3.2 Economical aspects of PV, WTG and battery in IHPS

The economic side for this system is similar to the previous systems; just the cost of wind turbine and solar panels will be added to all equations. For this system the life cycle cost is shown in Figure 2.22 compared with a diesel isolated power system, where it shows the capital cost for a PV-wind-battery hybrid power system is higher than a diesel isolated power system. Also the graph shows the running cost for the PV-Wind-Battery hybrid power system is almost steady with just a slight increase, where the diesel isolated power system has a dramatic increase year after year, and thus the hybrid power system is cheaper after 16 years. This graph can be changed according to the diesel fuel prices, which can be volatile, as shown over the last 10 years, with the fossil fuel prices fluctuating upwards. Also the advancement of technology and innovation can reduce the capital cost of this hybrid system or even reduce the running cost.

For the diesel isolated power system the main problem that makes the system expensive after a certain amount of time is the running cost, and there are only two ways to reduce the running cost: first by reducing the cost of the diesel fuel (and this is very difficult), and second by finding alternative fuels to replace the diesel. These alternative fuels should be cheaper to reduce the running cost.

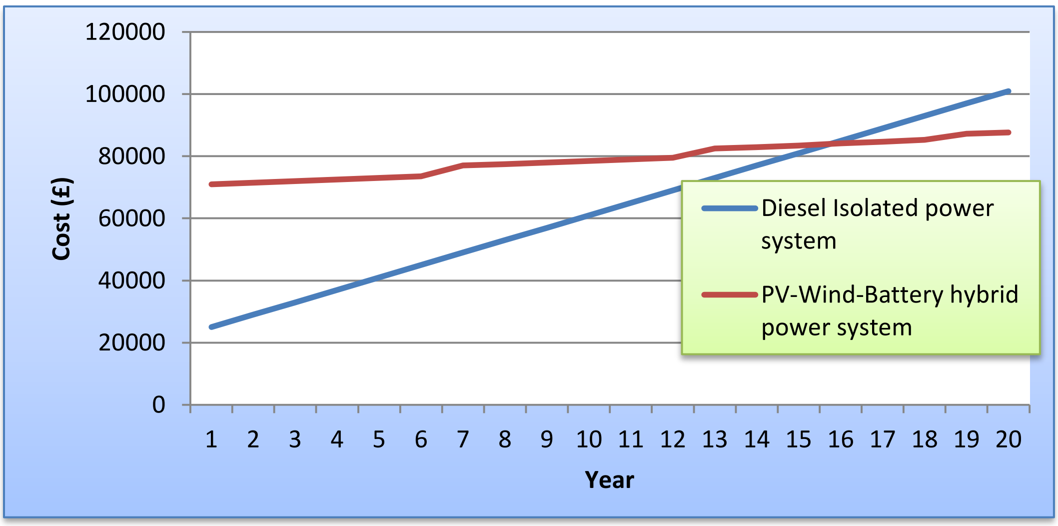


Figure 2.22: The life cycle cost for PV-wind-battery hybrid power system compare to a diesel isolated power system.

2.5.3.3 Advantages and disadvantages

The main advantages of the PV-wind-battery hybrid system are:

- The redundancy of the PV-wind-battery hybrid power system is high due to its complete dependence on wind speed, sun radiation or both (Niankun et al. 2011).
- Relatively low maintenance cost for the PV-wind-battery hybrid power system (Ming-Shun et al. 2009, Ronan and Mark 2006).

The weaknesses for this system are specified underneath:

- In the first phase, power from solar panels, battery bank or both must not exceed the inverter's power. In the second phase, the stored power from wind turbine must not exceed the rated power for the inverter as well (Strauss and Engler 2003).

The next section summarizes the preferences and weaknesses of the previous systems in order to have a clear comparison. Also at the end of section 2.5.6 Table 2.3 compares this system with the other systems in 2.5.4, 2.5.5 and 2.5.6.

Comparison between the PV, Wind and PV-Wind HPS

According to Table 2.2 and Figure 2.23, PV HPS is the most expensive system and the lowest with realistic power, where the running cost it almost steady. However, the PV-wind HPS provides the most accurate and realistic power with steady running cost, and the system after 16 years will be the cheapest according to the life cycle cost. It will even be cheaper than the diesel IPS after this time. Diesel IPS shows a very cheap initial cost compared to PV-wind HPS and it shows more accurate power than the HPS. On the other hand, the diesel IPS has dramatically increased running costs according to fuel consumption, and running cost could increase more depending on diesel prices and transport costs.

Table 2.2 Comparison between PV, Wind and PV-Wind HPS

Criteria	PV-Battery HPS	WTG-Battery HPS	PV-WTG-Battery HPS	Reference
The ability to use renewable resources	Yes	Yes	Yes	(Meinhard et al. 2004)
Use converter for storage system	No need	Yes	Yes	(Lee et al. 2012)
Type of load	DC or AC	DC or AC	DC or AC	(Lee et al. 2012)
In case of overpower the sources will switch off	Yes	Yes	Not necessarily	(Belhadj 2010)
Limitations for having storage methodologies and quantity	Possible to expand but expensive	Possible to expand but expensive	Possible to expand but expensive	(Meinhard et al. 2004)
Size of the inverter between DC-bus and AC-bus determines the power sources	Yes	Not necessarily only the amount of storage	Not necessarily only the amount of storage from wind or the supply from PV	(Strauss and Engler 2003)
Sun rays affect the system	Yes	No	Modest	(Belhadj 2010, Nian and Behera 2012)
Wind speed affect the system	No	Yes	Modest	(Nian and Behera 2012, Niankun et al. 2011)
Environmentally friendly	Yes	Reasonable (produces noise)	Reasonable (produces noise)	(Xiong et al. 2011, Ronan and Mark 2006)
Supports sustainable development	Yes	Yes	Yes	(Belhadj 2010)

Storage lifetime is short	Yes	Yes	Yes	(Lee et al. 2012)
The storage capacity depends on the size of the batteries	Yes	Yes	Yes	(Jimenez-Fernandez 2011)
Maintenance cost	Lowest	Low	Low	(Lee et al. 2012, Belhadj 2010)
Cheap running cost	Yes	Yes	Yes	(Lee et al. 2012, Zhu et al. 2012, Belhadj 2010)
Capital cost	Highest	High	In between	(Lee et al. 2012, Zhu et al. 2012, Belhadj 2010)
Stable system for long term	Reasonable	Reasonable	Reasonable	(Xie et al. 2010)
Energy losses	Medium if over powered or cloudy	Medium if over powered or over wind speed	Reasonable	(Belhadj 2010)
Accurate and realistic power	Lowest	Reasonable	High	(Xie et al. 2010)
Spread between the IPS	Low	Medium	High	(Xie et al. 2010)

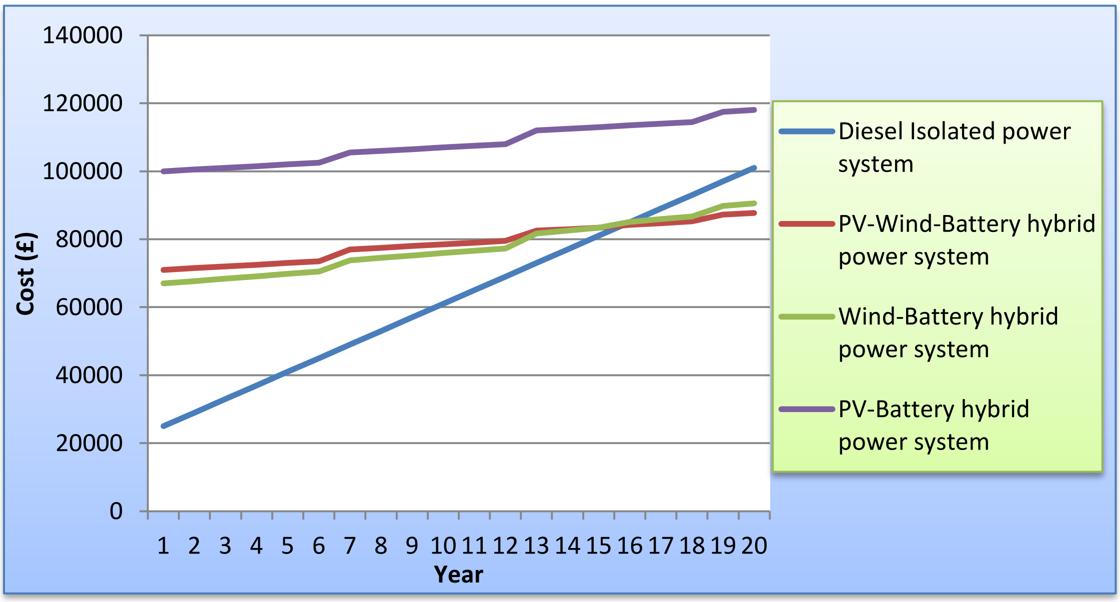


Figure 2.23: Comparison of the life cycle cost for PV, wind and PV-wind HPS with the diesel IPS.

2.5.4 PV-wind-battery-hydrogen hybrid systems

Again this renewable hybrid power system is very similar to the PV-wind-battery HPS. This system is utilizing distinctive innovation (a hydrogen stockpiling system) for energy storage. This new innovation, when compared to a battery storage system, is economically beneficial and environmentally safe. This system is modest and straightforward in method for growing power storage, while it is extremely costly in the case of batteries (Bajpai et al. 2010).

The main power for this HPS comes from four sources to feed the load: two as main sources: (PV and wind turbine), and two storage systems as backup power: battery bank and a fuel cell (FC). Both backup system store the extra power and release the power in deficit cases (Jimenez-Fernandez 2011). The main configuration of this system is mentioned in Figure 2.24, where it is similar to the system in section 2.5.3 plus the FC and electrolyser.

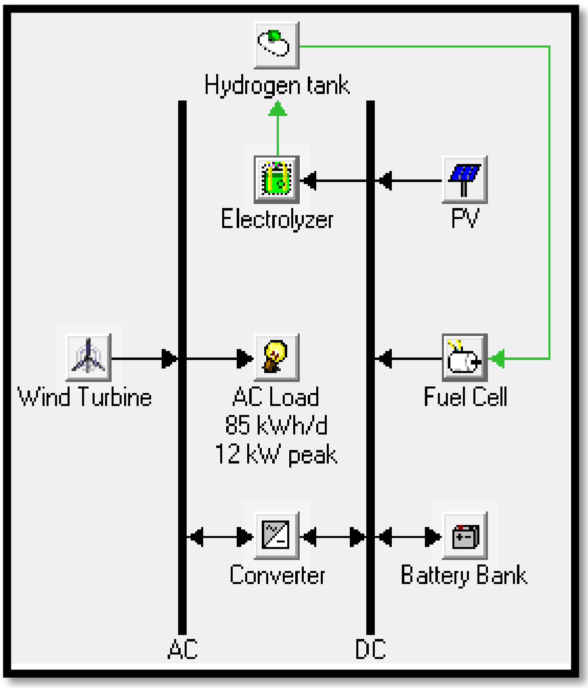


Figure 2.24: The Structure of PV-wind-battery-fuel cell HPS.

2.5.4.1 Operating Principle

The basic components of PV-wind-battery-hydrogen hybrid power system are as follows:

- Photovoltaic panel (PV) ● Wind turbine (WTG) ● Battery Bank
- Converter ● Battery charge controller ● Electrolyser ● Hydrogen tank
- Fuel cell (FC) ● DC-bus and AC-bus ● Demand load

Electrolyser

Electrolysis is a process of breaking down water into oxygen and hydrogen by passing an electric current through the polymer screen as shown in Figure 2.25. In other words, electrolysis is a chemical process, when the current passes through an anode and a cathode installed in water. Hydrogen, oxygen and heat are generated as expressed by equation 2.39. At the point when the cell works beneath the reversible voltage, no water break-down happens. When the voltage is operating between the reversible voltage and thermos-neutral voltage the electrolysis does not break down the water. Extra power is required to break down the water because the process needs to exceed the endothermic point. If the voltage stays at the endothermic point, extra temperature must be dispersed by an exothermic reaction for better operating. The principle parts of the electrolyser are the negative pole (cathode), positive pole (anode) and separator. For good results the cathode should be corrosion safe in the electrolyte, be a great electrical conductor with reliable construction. It ought to catalyse the oxygen advancement as successfully as could be expected under the circumstances. Both positive and negative poles are differentiated from one another by a diaphragm or a film membrane. By using the Faraday equation, the amount of hydrogen production can be calculated by referring to equation 2.40 (Fabbri et al. 2010, Veziroglu and Sahin 2008).

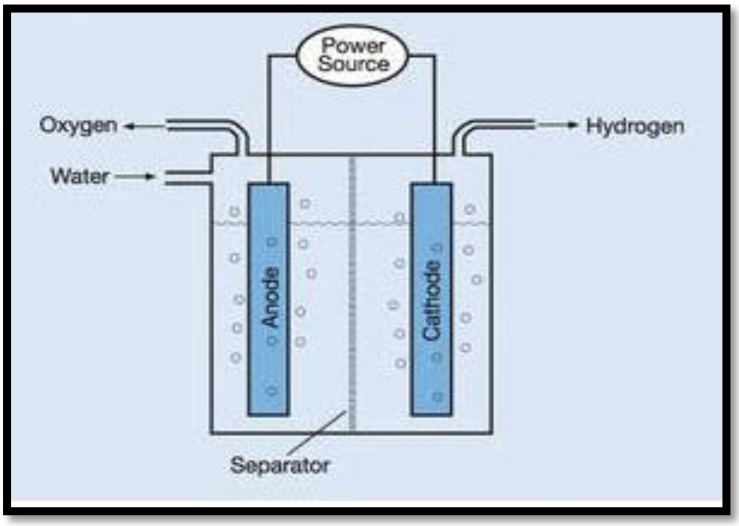


Figure 2.25: Electrolyser configuration model (ThyssenKrupp Uhde Chlorine Engineers 2010).

$$\mathbf{H_2O + Electrical\ current \rightarrow H_2 + (\frac{1}{2}O_2)} \quad (2.39)$$

$$H_{ele} = \frac{(P_{ele} \times 3600)}{(2 \times v_{ele} \times F)} \quad (2.40)$$

Where

$\mathbf{H}_{ele}$ = Hydrogen production from electrolyser per hour, mole/h

$\mathbf{P}_{ele}$= Electrolyser input power, W

$\mathbf{V}_{ele}$= Electrolyser input voltage, V

3600 = One hour in seconds, s

F = Faraday constant, “9.64853399×10^4, coulombs/faraday” (C mol^{-1})

There are many ways to calculate the efficiency of the electrolyser. The most common one is explained in equation 2.41. Efficiency of the electrolyser can be characterized as "the energy that preferably could be recouped by re-oxidation of the hydrogen in order to produce water (heat estimation from hydrogen), divided by the total input power to the electrolyser" as mentioned in equation 2.42.

$$\eta_{ele} = \frac{E_{out}}{E_{in}} \quad (2.41)$$

$$\eta_{ele} = \frac{\text{heating estimation from hydrogen}}{E_{in}} \quad (2.42)$$

Where

η_{ele} = Electrolyser efficiency, %

$\mathbf{E}_{out}$= Total output energy, W

$\mathbf{E}_{in}$= Total input energy, W

Hydrogen tank (storage)

In order to overcome every day energy deficits between accessibility and demand load, hydrogen needs to be stored as a gas or a liquid in order to be used when needed. Hydrogen is a very light element, with a very low density. This implies that a little amount of hydrogen occupies a substantial volume. Presently, storing hydrogen at 700 bars for normal utilization requires special materials that can sustain the pressure. However, compressing hydrogen is an exceptionally complex, hazardous and costly methodology. To expand hydrogen's gravimetric density, hydrogen can be stored as a liquid, converting it from gas. After converting it from gas, the hydrogen has to be stored until the system is required. Bajpai et al. (2010) expressed that hydrogen could be stored through three different procedures: first, liquefaction, which requires very high safety factors, second, as metal hydrides, which can be stored in amounts as small as one kilogram, and third, as high-pressure compression, which is less intricate than the other two methodologies but it needs space and safety.

Fuel cell (FC)

The key component of a hydrogen stockpiling system is comprised of an electrolyser unit to break down water into hydrogen by using electrical power during off-peak periods. This electrical energy is then stored as chemical energy. The hydrogen is stored until it is converted again to electrical energy during on-peak, or in high demand load, with this process converting the hydrogen into electrical power through a fuel cell unit. The fuel cell device electrochemically generates electrical power by using hydrogen. The FC can be used in many configurations and operating with different power ranges and characteristics. A Proton Exchange Membrane (PEM) fuel cell unit has been most widely investigated innovation to reverse the electrolyser operation, however solid oxide fuel cell (SOFC) and alkaline fuel cell (AFC) technologies can likewise be generators by converting hydrogen into energy. PEM fuel cells present a suitable choice compared to other FC types (Khan and Iqbal 2005a). Other types of fuel cells currently under development include Direct Methanol Fuel Cell (DMFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC).

One of the foremost concerns with respect to a hydrogen system is the entire cycle of productivity and efficiency. The losses are deep-rooted in this type of process of converting energy to stored hydrogen and re-converting it again to power. Losses are estimated in the range of 55 – 80 % energy (Fabbri et al. 2010, Khan and Iqbal 2005a). In order to increase the efficiency of the whole hydrogen system (from electrolyser to fuel cell), if the waste energy (heat) can be utilized, the efficiency can reach 85-90 %. The principles of fuel cell power generation can be described as positive and negative pole isolated from each other by a membrane. Hydrogen fuel feeds directly into the anode side while the cathode is fed by air or pure oxygen. The chemical process is expressed in equation 2.43. The fuel cell produces power through a simple electrochemical process as long as it is supplied with the chemical fuel, however, the fuel cell is different from a combustion engine in the way by which energy is converted. In a combustion engine the fuel is converted to heat energy, and then heat energy is converted to kinetic energy, which will generate electrical power. Each converted level will have energy losses. In contrast, fuel cell generated power is through a simple process as explained previously in equation 2.43. Fuel cell generated electricity will occur as long as it is fed by hydrogen as shown in Figure 2.26 (Fabbri et al. 2010, Veziroglu and Sahin 2008).

$$\mathbf{H_2} + \left(\frac{\mathbf{1}}{\mathbf{2}}\mathbf{O_2}\right) \rightarrow \mathbf{H_2O} + \textbf{Electrical DC Power} \qquad (2.43)$$

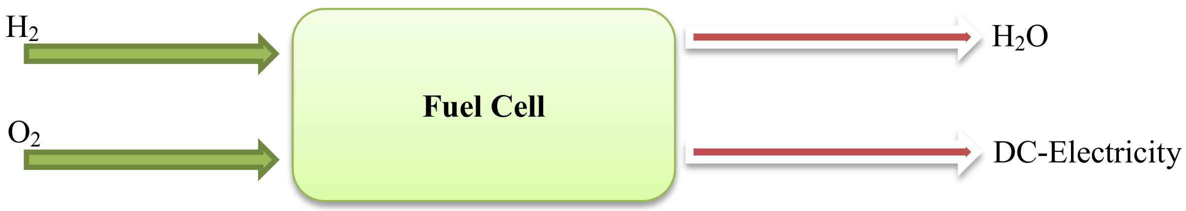


Figure 2.26: Fuel cell configuration.

In this section different FC types will be compared. The reaction product for AFCs, phosphoric acid fuel cells (PAFC) and PEMFCs is water, and the catalyst for these types is platinum. The cell components are carbon based, where the product is water plus CO_2 for SOFCs and MCFCs. In PEMFC the reaction operates from room temperature to 80°C. In this reaction hydrogen is the fuel, and the hydrogen ion travels to the oxygen side. The electrical efficiency for this type is 40-60%. In PAFCs the reaction operates from 160°C to 220°C. In this reaction hydrogen is the fuel and the hydrogen ion travels to the oxygen side. The electrical efficiency for this type is 50-55%. For AFCs, the reaction operates from room temperature to 90°C, in this reaction hydrogen is the fuel and the hydroxide (OH^-) travels to the hydrogen side. The electrical efficiency for this type is 60-70%. For MCFCs, the reaction operates from 620°C to 660°C. In this reaction hydrogen plus carbon monoxide (CO) are the fuels. The required element from air is not the oxygen like the last three types, it is carbon dioxide (CO_2), and the carbonate ion (CO_3^{-2}) travels to the hydrogen and CO side, and the catalyst for this type is Nickel. Note that the cell components are stainless steel based. The electrical efficiency for this type is 65%. For SOFCs, the reaction operates from 800°C to 1000°C. In this reaction hydrogen plus carbon monoxide (CO) plus methane (CH_4) are the fuel. Oxygen is required for this reaction, and the oxide (O^-) travels to the fuel side, and the catalyst for this type is Perovskites (ceramic). Note that the cell components are ceramic based, the electrical efficiency for this type is 60-65% (El-Sharkh et al. 2004).

The most commonly used fuel cell, the PEM fuel cell, contains a module where two rods, cathode and anode, are separated by a file membrane. This file contains special material that permits ions to stream but not electrons. As demonstrated in Figure 2.27, hydrogen gas is fed to the anode and oxygen gas to the next rod cathode. At the anode rod, a catalyst is used to accelerate the splitting. This causes the hydrogen to split into two parts; electrons and hydrogen ions. The film membrane as explained previously allows only the hydrogen ion to pass through to the cathode. While the oppositely charged electrons (negatively charged) transferred from an outer circuit to the cathode. Charged electrons exchanged from the fuel will go through the outer circuit (to constitute a DC electric current) and carry out their function before they reflect their effect at the cathode i.e. the hydrogen ions and the electrons join with oxygen to form water (El-Sharkh et al. 2004, Haile 2003).

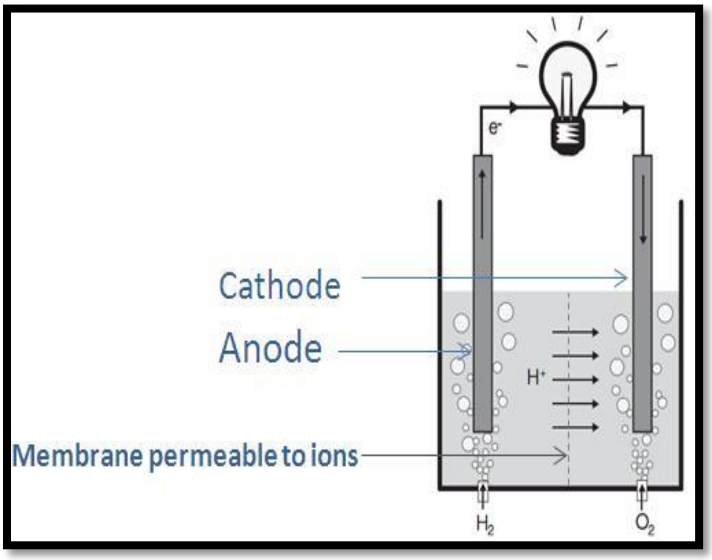


Figure 2.27: Working principle of PEM fuel cell (Haile 2003).

The selection of fuel cells depends on the energy component proficiency. The hypothetical efficiency of the fuel cell is mentioned in equation 2.44. This equation provides a theoretical value. According to this the efficiency from it is high and can reach 80%. There are four types of losses affecting the efficiency of the fuel cell. Three of them are mentioned in Figure 2.26, where the fourth is not demonstrated as a rule because of unused fuel. To calculate the real efficiency for the FC it is important to understand the types of losses that contribute to reducing the efficiency:

- **Activation loss,** also known as kinetic loss because of rate of the charge exchange responses occurring at the surface of the terminal rods. In simple words the losses are caused by the reaction.

- **Ohmic losses,** also known as resistive loss because of the imperviousness to the stream of electrons through the cathode materials. The current density is relative to the combined effect of the ionic and electrolyte conduction.
- **Mass transport losses,** also known as concentration losses, are due to the dispersion due to the change in centralization of the reactants at the surface of the rods as the reactants are spent.
- **Fuel crossover and inside current flows**: On a basic level, the electrolyte ought to transfer just ionic particles. Sometimes while using the fuel, the electrons transfer through the membrane and this fuel disseminating the electron conduction brings noteworthy losses.

The effectiveness of fuel usage is represented by the proportion of the fuel being used for the electrochemical response, inside a fuel cell. It is the proportion of the fuel utilized by the cell to create the electric current versus the aggregate fuel given to the power module (Haile 2003).

$$\eta_{FC} = \frac{E_{out}}{\text{heating estimation from hydrogen}} \tag{2.44}$$

Figure 2.28 below shows the I-V power curve, which demonstrates that the power is increasing while the current is increasing until the maximum power. Then after that suddenly the power is decreasing while the current is increasing. Before the maximum power the relation between power and current is direct correlation relationship, and after is reverse fit. The figure also shows the ability of the fuel cell to operate under the maximum power, and when the current is above the maximum power, both voltage and power fall (Haile 2003).

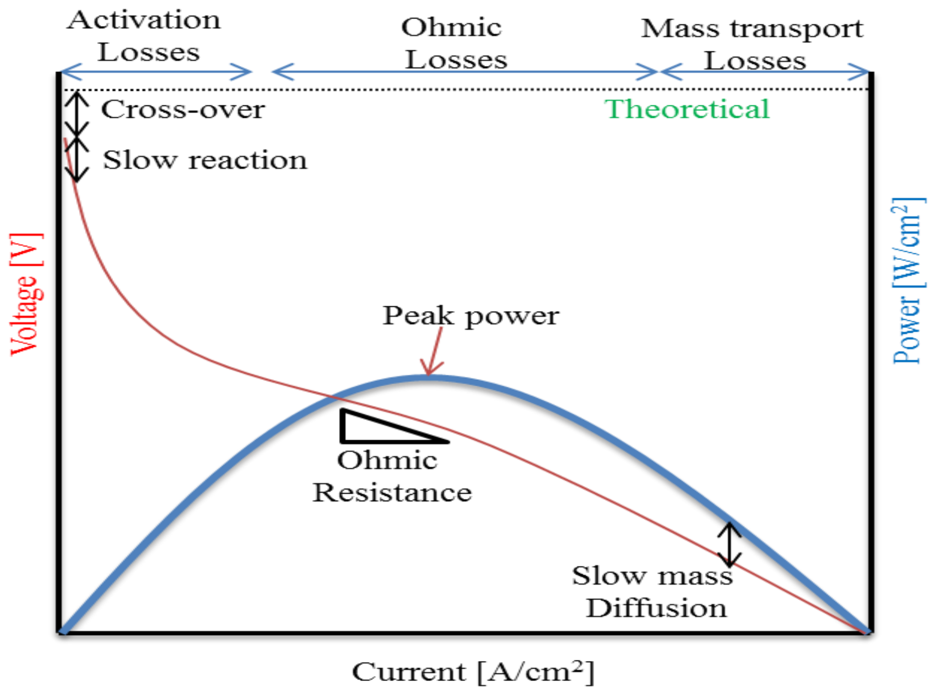


Figure 2.28: I-V power curve of a fuel cell and the individual losses (Haile 2003).

The PEM fuel cell is suitable as a reinforcement framework. It works as a backup system to provide power when the system needs it or when the battery bank is low (Khan and Iqbal 2005a). It is therefore important to calculate the amount of the required hydrogen for the required power in the process or the output power from this amount of hydrogen. Equation 2.45 demonstrates the methodology (Fabbri et al. 2010, Veziroglu and Sahin 2008).

$$P_{FC} = \frac{(2 \times H_{FC} \times v_{FC} \times F)}{3600} \tag{2.45}$$

Where

P_{FC}= Fuel cell output power, W

H_{FC} = the required hydrogen for fuel cell per hour, mole/h

V_{FC}= Fuel cell output voltage, V

3600 = One hour in seconds, s

F = Faraday constant, "9.64853399 × 10^4, coulombs/faraday" (C mol^{-1})

Bajpai et al. (2010) examined three scenarios for hybrid systems in order to find the most suitable one for size and cost. In the first case the hybrid system is connected to battery bank storage as the only storage system. The second scenario is when the hybrid system is connected to a supplementary source and storage (complete FC unit from electrolyser to FC) as the only storage and backup system. The third scenario is the hybrid power system has both storage battery bank and FC unit. The confirmation appears to demonstrate that the third situation is the most suitable one in light of the fact that it needs fewer units of batteries and FCs, and as a general guideline this means less cost and size. Likewise Banos (2011) revealed that the FC unit will work as a second source of power when the system requires extra power to cover the deficit in energy as backup power, while batteries supply power instantly to cover any deficiency. It should also be noted that the batteries are highly efficient compared to the FC unit. On the other hand, batteries are more expensive, and by consolidating both batteries and FC units the system will be stronger and more stable (Vosen and Keller 1999). Nonetheless, batteries can store energy as distributed or off-grid storage but for short-term storage, where FCs can store power for longer than batteries (medium to long term storage) with large amounts of energy (Corsini et al. 2009). In addition, according to research, installing FC units to any hybrid system will give the system more stability and increase the reliability of providing electricity and reducing its maintenance (such as replacing the batteries) (Zrvas et al. 2008, Fabbri et al. 2010). At the point when the FC unit is coupled with a renewable energy source or any innovation related with low carbon energy technology, hydrogen as an energy source or as storage system has the potential to be considered environmental friendly and can possibly decrease the emissions by reducing GHG.

Basically PEM fuel cells need hydrogen as a fuel in order to produce electricity. And since the electrolyser is producing hydrogen on over power period, the PEM fuel cell can use this hydrogen from the storage when the system required extra electricity to cover the deficit power; this type is circulating process as shown in Figure 2.29, or the PEMFC can use external source of hydrogen.

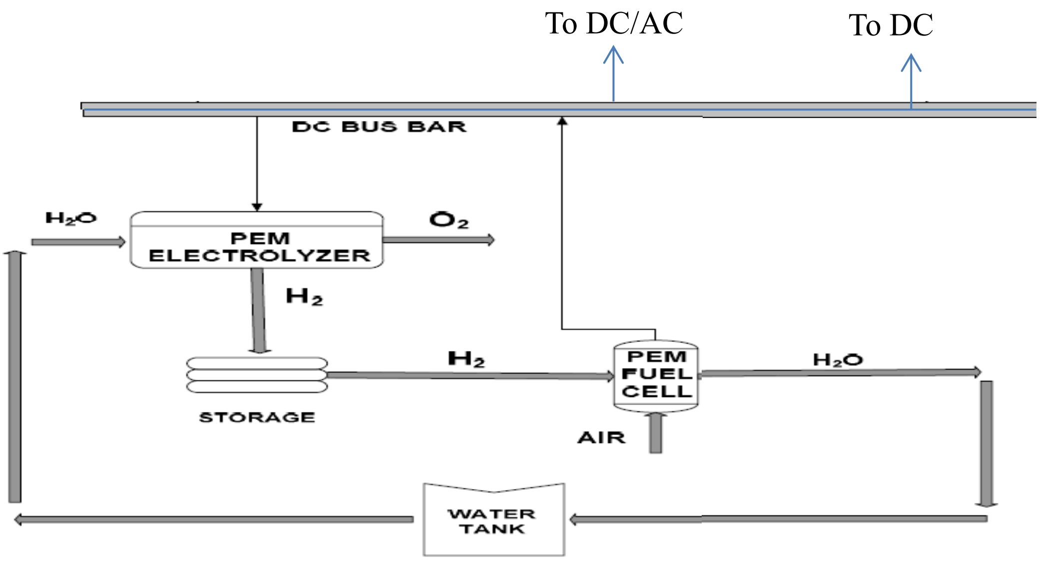


Figure 2.29: PEM Fuel Cell unit circulating Schematic diagram in HPS (Behling 2013).

Typical PV-wind-battery-hydrogen hybrid power system approach

According to Figure 2.24, the power is produced from renewable sources (PV, and wind turbine). PV panels supply power to the DC-bus in order to supply directly DC load or AC load through a DC/AC converter. A wind turbine is connected directly to the AC-bus. The second power source for this system comes from two sources: a battery bank and a fuel cell. Basically power is produced by solar radiation and wind speed which generate power by conversion to electrical power as explained previously. If the produced power is more than the consumption loads, the extra power is stored in the battery bank, and as soon as the batteries are fully charged, the controller will send a signal to the electrolyser in order to start producing hydrogen. From the other side, if the main power source goes down and is not producing enough power, first, the batteries will compensate this shortage (in this case the backup power will be depending on batteries). Second, if the power from the batteries is still not enough or the batteries are fully discharge the PEM fuel cell will start to operate in order to supply power to the DC coupling, as a second backup system, where it is converted to AC power through bidirectional converter to the required AC load (Tai-Sik and Sung-Yeul 2012).

This system has two critical points the designer needs to contemplate when planning, designing and calculating the size of the system. First, if the main resources powers are generating electrical power more than required and the batteries are already completely full charged and the hydrogen tank is full, the controller must disconnect one or more of the main power source from the grid. At this point the electrification power for the end user will be totally dependent on participation between part of the main sources and backup power (batteries and FC). The second point is if both the main sources and backup power are not ready to cover all the obliged loads, the deficit is higher than generated and backup power. Such issues, for instance, power insufficiency must be analysed and evaluated during the configuration stage.

2.5.4.2 Economical aspects of PV, WTG, battery and H_2 in IHPS

The financial side for this system is similar to the previous systems; simply the expense of electrolyser, hydrogen storage tank and FC will be added to all equations. For this system the life cycle cost is demonstrated in Figure 2.30 compared with a diesel isolated power system showing the capital cost for PV-Wind-Battery-hydrogen hybrid power system is higher than a diesel isolated power system, and the running expense for the hybrid system is almost steady, whereas the diesel isolated power system has a dramatic increase over time. This suggests that this hybrid power system provides a cheaper total cost after 15 years. This diagram can be changed as indicated by the diesel fuel cost where these cost are unsteady, with the fossil fuel prices climbing over the last 10 years. Additionally the innovation and advancement of technology can decrease the capital expense of this hybrid system or even diminish the running costs over time.

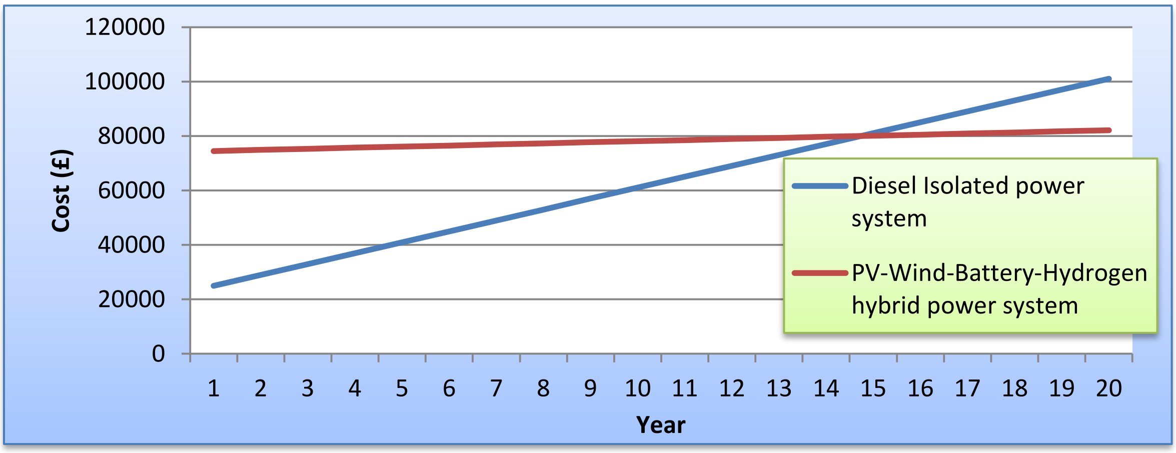


Figure 2.30: The life cycle cost for PV-WTG-battery-hydrogen hybrid power system compare to a diesel isolated power system.

2.5.4.3 Advantages and disadvantages

The main advantages of the PV-wind-battery-hydrogen hybrid system are:

- The storage system is available in two types, and the storage is not considered as a weakness anymore.
- Both power sources and both storage have very low running costs because there are no uses for fossil fuel or traditional fuels and low maintenance expenses (Zhu et al. 2012, Fabbri et al. 2010, Zrvas et al. 2008). According to

Niankun et al (2011) the redundancy of this hybrid power system is high due to its complete dependence on two different sources, and both sources together are suitable for remote areas.

- Using the FC unit is supporting the storage system for the long term with clean and silent operation (due to its chemical reaction with no moving parts), and the capacity of the FC is based on the fuel availability, with excellent reliability.
- The lifetime for the FC unit it is from 18 to 22 years.

Notwithstanding, the weaknesses for this system are specified underneath:

- There are limits to storage of hydrogen, and it requires general safety procedures. Additionally, the FC unit has low power density compared with batteries and combustion engine.

Table 2.3 summarizes the preferences and weaknesses of this system at the end of section 2.5.6, and compares this system with convergent systems at section 2.5.3, 2.5.5 and 2.5.6.

2.5.5 PV-wind-diesel generator (DG)-battery hybrid systems

The application of this system is dependent on diesel generator (DG) for providing ceaseless power supply (Rudell et al. 1993, Dettmer 1990). Again this hybrid power system is very similar to the system in section 2.5.3 where the only difference is this system is an extra diesel generator (DG) in order to provide continuous power as a backup power system. In this system, the PV panels are connected to the DC-bus with the batteries and the DC-bus connected with the AC-bus through bidirectional converter. The WTG is directly connected to the AC-bus, and the DG is connected directly to the AC-bus as seen in Figure 2.31.

The diesel generator functions as the reinforcement power on account of any electrical power insufficiency. Such a circumstance would be if the obliged load is more than the conveyed power. For this situation the DG supplies the power deficit (Whei-Min et al. 2011). Additionally, the DG in this system may be used to charge the batteries if the generated power is more than is required (Carpentiero et al. 2010). As per Notton et al. (1996), the DG is joined straightforwardly to the AC-bus and it must have the capacity to cover the whole obliged burden. As it were, the electrical power which is generated from the DG must surpass the greatest burden (maximum load).

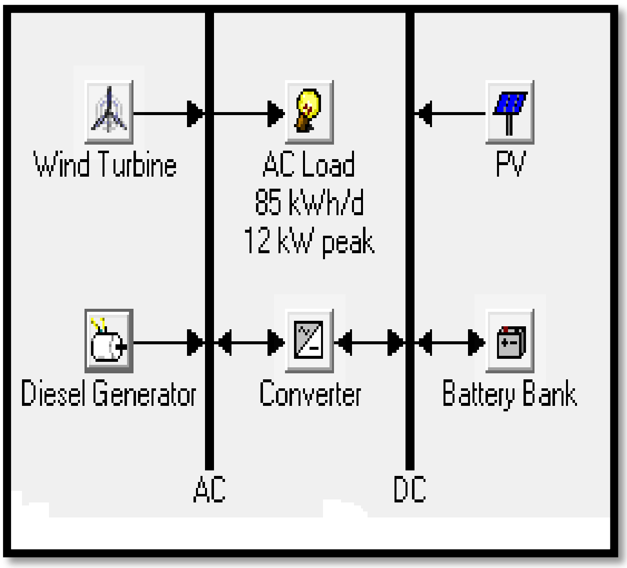


Figure 2.31: The Structure of PV-WTG-DG-battery HPS.

2.5.5.1 Operating Principle

The basic components of PV-wind-DG-battery hybrid power system are as follow:

- Photovoltaic panel (PV) ● Wind turbine (WTG) ● Diesel generator (DG)
- Converter ● Battery Bank ● Battery charge controller

- DC-bus and AC-bus
- Demand load

Diesel generator (DG)

There are two types of DG and it can be sorted by number of poles which sets by yearly working hour, for 400 yearly working hours or less 2-poles is recommended, outside this range overall 4-poles is the best (Roger and Messenger 2004).

A DG is fossil fuel combustion engine comprised of an engine and an alternator. A backup diesel generator can be associated with the HPS to supply electric power to crest burdens, which cannot be ensured by HPS if a consistent power supply is required or if there a deficit with the renewable energy to supply the load (Shaahid and Elhadidy 2004). A diesel generator can be part of any power system under one of the three considerations. First, if the power system depends highly on renewable energy, the DG will be a backup system and not necessarily operate every day. Second, the DC is producing the main power and will operate frequently. Third, DG has a portion of supply to meet by renewable energy; the DG will generally work every now and then. DG is utilized as an important part of the HPS for many reasons: to generate electrical power when PV and WTG generate insufficient power and also to support the batteries to a satisfactory level. The rate of diesel generation should be sufficient to accomplish these tasks. Ideal sizing for a DG requires cautious consideration of elements such as every day loads and regular burden changes and the annual growth rate for electrical load. Considerations of the possible integration and reliable operation restrictions of diesel and the penetration level of alternative power will help to identify the required capacity of the backup generator. The rate of diesel generation is measured by taking into account the crest load and/or normal burden values on a yearly base and taking into account the safety and extra limits for future growth, the DG will for the most part be larger than usual. The reasons for this are that the electrical loads in remote communities are usually described as being very fluctuating, with the crest load can be as high as the normal load. The working hours for the DG depend on the amount of power from the wind turbine and PV. Also the DG capacity must take into account weather conditions.

In general, most DG utilized as a part of HPS use synchronous alternators straightforwardly connected to a consistent diesel engine as explained in the last paragraph. The working rate is guided by regularized flow of fuel in the combustion area, which affects the engine speed and thus affects the frequency of the output voltage (the speed is controlled by the engine's governor to manage and estimate the required mechanical power second by second). Normally there are three categories affecting the operation of DG. First, the expense for running DG is represented by fuel utilization. Second, DG maintenance relies on the working hour and the working capacity. Finally, frequent operation affects the DG and increases the replacement of mechanical parts. Subsequently, for reducing running expenses, researchers indicate that once the DG is signalled to start, it ought to run for a shorter period of time. The manufacturers set this to no less than 15-25 minutes per operation. Another way to reduce running expenses is by not letting the DG operate underneath 50% of the full rated power and in some cases not less than 40% (Leuchter et al. 2007).

A DG ought to be chosen to cover the load during the deficit period or during the peak load so the rate of DG is measured by monitoring the load details, and further particulars can be estimated. The ideal choice for the rate of DG is that the power from DG with the power from different sources should supply enough power to cover the required load at any time. There is research that explains that the best methodology for large loads is to utilize various DG units of different sizes in order to optimize the power from every generator to get the maximum power productivity from every unit (Baalbergen et al. 2009, Leuchter et al. 2007).

Diesel generator fuel consumption and efficiency

Fuel is injected into a DG cylinder through an injector. DG consumes fuel whether there is load or no load, and this consumption depends on the type and the internal design of the combustion machine. Fuel consumption is high during the engine starting or at low load power compared with full load consumption. As the consumption depends on load and gyration, subsequently, DG is in general demonstrated by positive relation between speed and load as the main parameters affecting the fuel consumption, any increase in whichever or both will increase the fuel consumption. There are some engines with fixed speed in order to protect the electrical side which makes the consumption depend only on load rate. For DG used as a backup system, it is important to know its efficiency as it characterizes the generator. Many researchers reported that the efficiency of DG fluctuates from 20% to 37% at full load (Baalbergen et al. 2009). Equation 2.46 expressed the fuel efficiency for DG (Ibrahim 2002, Heywood 1988). According to Baalbergen et al. (2009) and Leuchter et al. (2008) fuel consumption can be calculated according to the equation 2.47 to 2.50.

$$\eta_{DG} = \frac{P_{GEN}}{Q_{LV} \times f_c} \tag{2.46}$$

Where

$\boldsymbol{\eta_{DG}}$= diesel generator efficiency, %

$\mathbf{P_{GEN}}$ = the generated power, KWh

$\mathbf{Q_{LV}}$= the lowest value for heating the fuel, KWh/L

$\mathbf{f}_{\boldsymbol{c}}$ = the rated fuel consumption, L/h

$$f_{c-relative}(t) = \frac{1}{4} + \frac{3}{4}\, P_{relative}(t) \tag{2.47}$$

$$P_{relative}(t) = \frac{P_{output}(t)}{P_{rated}} \tag{2.48}$$

$$f_c(t) = \mathbf{f_c} \times f_{c-relative}(t) \tag{2.49}$$

$$f_{c-daily} = \frac{1}{T}\int_0^T f_c(t)dt = \frac{\mathbf{f_c}}{T}\int_0^T \left(\frac{1}{4} + \frac{3}{4}\frac{P_{output}(t)}{P_{rated}}\right) dt \tag{2.50}$$

Where

$\mathbf{f_{c-relative}(t)}$ **=** relative fuel consumption at any time, L/t

$\mathbf{\frac{1}{4}}$ = genset-specific constants by empirical factor,

$\mathbf{\frac{3}{4}}$ = genset-specific constants by empirical factor,

$\mathbf{P_{relative}(t)}$ **=** relative power at any time, KWh

$\mathbf{P_{output}(t)}$ = output power at any time, KWh

$\mathbf{P_{rated}}$ = DG rated power, KW

$\mathbf{f_c(t)}$= the rated fuel consumption at any time, L/h

$\mathbf{f}_{\boldsymbol{c}}$ = the rated fuel consumption, L/h

$\mathbf{f_{c-daily}}$= fuel consumption per day, L/day

T = number of working hours, h

dt= time interval, s

t = at any time, h

Diesel generator lifetime

As indicated by the maker data, utilizing DG with standard maintenance for standby or non-stop operation will lead the DG to work for the lifetime of the system. A major-overhaul is unavoidable to maintain the lifetime of DG. The overhaul depends on the working hours, however, it is usually needed between 15000 to 80000 working hours. There are some elements that have unfavourable impacts on the DG working lifetime are demonstrated below (Bleijs et al. 1993):

- Very low load operation, usually less than 40% of the full load. This causes incomplete burning of diesel and will increase the erosion inside the cylinder due to the existence of sulphur which has not been fully combusted. This will weaken the DG rendering and causing running problems, which will decrease the lifetime and increase the running cost.
- Frequent starts have negative consequences for DG upkeep as well as causing erosion every single time the DG starts that may lead to an inability to start the engine and consequently, will affect the reliability and quality of HPS.
- Starting temperature is important, as the DG should be warmed and kept running for a few minutes without load. Starting the engine at low temperature can cause wear as the lubricant viscosity is very high, and because of high viscosity, the lubricant system will be slow to supply oil to the sensitive areas such as piston, crankshaft and bearings.
- Ignoring maintenance, particularly disregarding the changing of the grease oil, filters (oil filters and fuel filters) and oil-channels as suggested in the manual can dramatically decrease the DG lifetime. Contamination of the

greasing oil with other substances during operation can change the lubricant oil properties, which can cause problems for the DG.

DGs in HPSs are normally combustion engines. The AC frequency is kept up by the governor which modifies and controls the amount of fuel that will flow to the combustion chamber in order to keep the speed basically steady at the required level. However, to calculate the electrical power supplied by DG relies on the demand load, as mentioned in equation 2.51 (Manwell et al. 1998, RETScreen International 2003).

$$P_{GEN} = P_{DG\_cap} \times \eta_{DG} \quad (2.51)$$

Where

η_{DG} = diesel generator efficiency, %

P_{GEN} = the generated power, KWh

P_{DG_cap} = the capacity of DG, KWh

Typical PV-wind-DG-battery hybrid power system approach

According to Figure 2.31, the main source of power is produced from renewable sources (PV, and wind turbine). PV panels supply power to the DC-bus in order to supply the DC load directly or AC load through a DC/AC converter. The wind turbine is connected directly to the AC-bus. The second power source for this system comes from the battery bank and DG. Basically, power production is similar to the previous system. Again if power production is higher than the consumption, the exceeding power is stored in the battery bank, and as soon as the batteries are fully charged, the controller will shut down one of the renewable energy to save the HPS (Markvar, 2000). From the other side, if there are power deficits where the power production is not enough, there will be two scenarios: first, the batteries will compensate this shortage; second, if the system still suffering from power deficit, the DG will start to operate in order to supply power to the AC coupling as a second backup system where it is converted to DC to store the extra power in batteries for increasing the efficiency of DG (Carpentiero et al. 2010).

2.5.5.2 Economical aspects of PV, WTG, DG and battery in IHPS

The financial side for this system is like the system in section 2.5.3; simply the expense of diesel generator (DG) will be added to all equations. For this system the life cycle cost is demonstrated in Figure 2.32 compared with a diesel isolated power system to imply that the venture demonstrates a satisfactory return. The capital cost for a PV-wind-DG-battery hybrid power system is higher than a diesel isolated power system, additionally the graph shows the running cost for the hybrid system is almost steady, with just a slight increase, where the diesel isolated power system has a dramatic increase over a seemingly endless timeframe, and this suggests that this HPS is cheaper after 20 years. This diagram, as with the previous systems, can be changed according to the diesel fuel cost where this cost is unsteady. Additionally, innovation can diminish the capital cost as well.

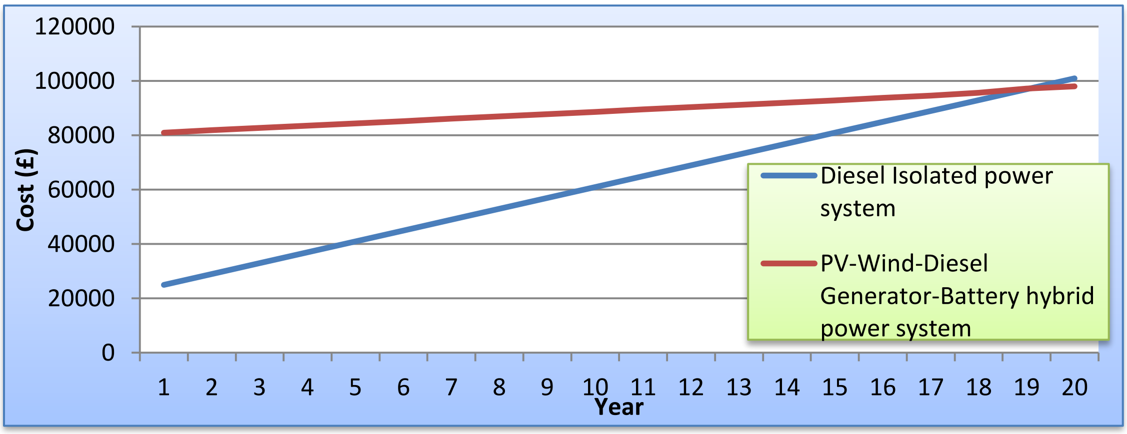


Figure 2.32: The life cycle cost for PV-WTG-DG-Battery HPS compare to diesel Isolated power system.

2.5.5.3 Advantages and disadvantages

The main advantages of the PV-wind-DG-battery hybrid system are:

- The redundancy of any hybrid power system is high if the system relies on two or more different sources as power supply.
- Ignoring DG or considering the running hours for DG is zero, the system has reasonable maintenance costs.

Notwithstanding, the weaknesses for this system are specified underneath:

- DG backup system has very high running cost because it depends on fossil fuels. According to Niankun et al. (2011)
- DG requires an overhaul between 15000 to 80000 working hours (Bleijs et al. 1993).
- According to the utilization of DG, this system is not environmental friendly regards to noise and the greenhouse gases that are produced during the combustion process (Ying-Yi and Ruo-Chen 2012, Xiong et al. 2011, Ronan and Mark 2006).

Table 2.3 summarizes the preferences and weaknesses of this system at the end of section 2.5.6, and compares this system with convergent systems at section 2.5.3, 2.5.4 and 2.5.6.

2.5.6 PV-wind-DG-battery-hydrogen hybrid systems

In this system, the diesel generator (DG) is considered as third stage of backup. The configuration of this HPS is very similar to the HPS in section 2.5.4 where the only difference is that this system has an extra diesel generator (DG) in order to utilize it to provide continuous power to balance the power deficit. In this system, the PV panels are connected to the DC-bus with the batteries and FC unit, where the WTG and DG are connected directly to the AC-bus, and the DC-bus connected with the AC-bus through bidirectional converter, as seen in Figure 2.33.

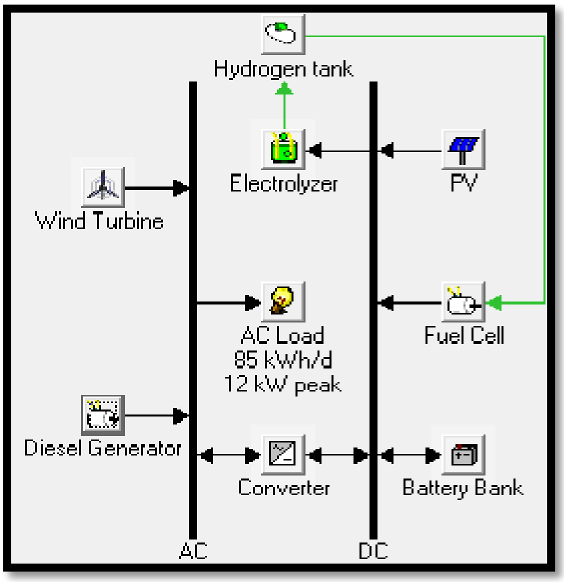


Figure 2.33: The Structure of PV-WTG-DG-battery-hydrogen HPS.

2.5.6.1 Operating Principle

The basic components of PV-wind-DG-battery-hydrogen HPS are as follow:

- Photovoltaic panel (PV) ● Wind turbine (WTG) ● (DG) ● Battery Bank
- Converter ● Battery charge controller ● Electrolyser ● Hydrogen tank
- Fuel cell (FC) ● DC-bus and AC-bus ● Demand load

As per Figure 2.33, the primary source of power is created from PV, and wind turbine. PV panels are connected directly to the DC-bus in order to supply directly DC load or AC load through a DC/AC converter. On the other hand, wind turbine is connected directly to the AC-bus. The secondary power source for this system comes from different sources: a battery bank and a FC unit. The DG is a final addition.

Fundamentally, power creation in this system is similar to the previous HPSs. Again if power production is higher than the utilization, the exceeding power is stored in the battery bank and/or the electrolyser, and as soon as the batteries are fully charged and hydrogen tank as well, the controller will shut down one of the renewable energy sources for safety reasons (Markvar 2000). On the contrary, if there is a power deficit where the generated power is not enough to cover the demand load, there will be three actions that will occur. To begin with, the batteries will compensate for this shortage. Second, if the system still experiencing power shortfall as the batteries are completely depleted or can only supply some of the power, the FC will begin to generate power, in order to compensate the shortage of power to the DC coupling as a second backup system, converting to AC power to provide the demand load. Finally, if after operating both backup systems the HPS is still experiencing power shortfall the DG will begin generate AC power. If the DG generates more than the required power, the extra will be converted to DC power in order to store it in batteries and/or as a H_2 fuel. Storing the excess power will keep the DG operating at full load which will increase the efficiency of DG (Carpentiero et al. 2010).

Studies have discussed the DG in hybrid system using one renewable source with DG such as PV-DG-battery and WTG-DG-battery. In this case the DG is operating most of the time, also there are examples where the DG is connected with more than one renewable sources such as; PV-WTG-DG-battery, PV-WTG-DG-H_2 and PV-WTG-DG-battery-H_2. The PV-WTG-DG-battery-H_2 is found to provide more reliability and sustainability for HPS (Markvar 2000, Habib et al. 1999). Zhang et al. (2011) has noted that the system that combines renewable sources, storage systems and DG will have long-term provision of continuous electrical power.

2.5.6.2 Economical aspects of PV, WTG, DG, battery and H_2 in IHPS

As previously stated the financial side of proposed systems is important. For this system it is like the system in section 2.5.4 - essentially the cost of the diesel generator (DG) will be added to all comparisons. For this system the life cycle cost is shown in Figure 2.34 compared with a diesel isolated power system to identify if the venture demonstrates an agreeable return. The figure shows the capital cost for PV-wind-DG-battery-hydrogen HPS as higher than a diesel IPS. Furthermore the diagram demonstrates the running expense for this HPS is steadier. If the system was able to sell the abundance of electrical power, the life cycle cost will decrease. From the another side, the diesel isolated power system has a dramatic increase in life cycle cost due to the high running cost over time, and this suggests that this HPS will have a cheaper total cost after 17 years. This diagram, as with the previous systems, can be changed based on the diesel fuel cost where due to volatile fuel costs; In addition innovation can diminish the capital costs too.

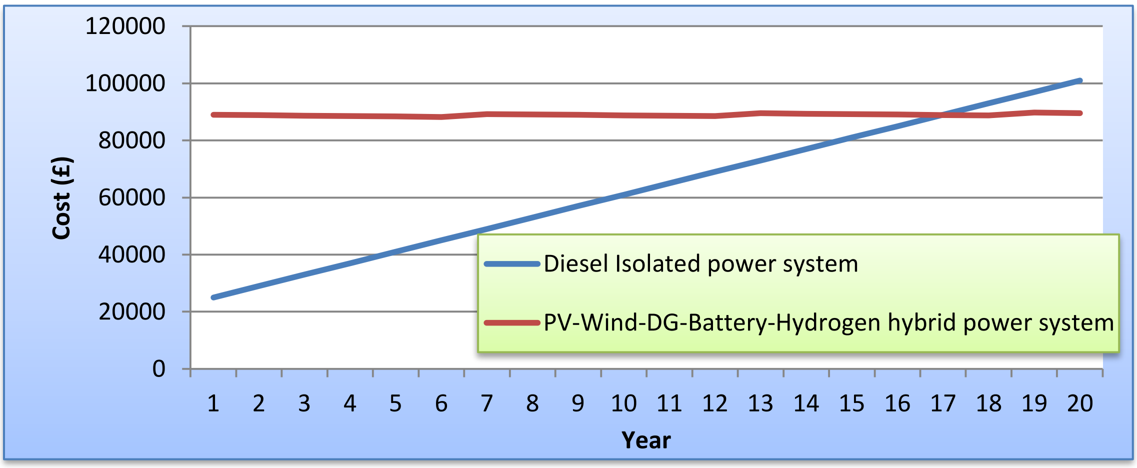


Figure 2.34: The life cycle cost for PV-WTG-DG-battery-hydrogen HPS compare to a diesel isolated power system.

Table 2.3 summarizes the preferences and weaknesses of this system at the end of this section, and compares this system with convergent systems at section 2.5.3, 2.5.4 and 2.5.4.

Comparison between the PV-wind-batteries, PV-wind-batteries-FC, PV-wind-DG-batteries and PV-wind-DG-batteries-FC HPSs

According Table 2.3 and Figure 2.35, that PV-wind-DG-batteries-FC HPS is the most expensive system with the highest capital cost and the highest with realistic power, where the running cost it almost unsteady according to the use of diesel fuel in emergency cases. However, the PV-wind-batteries-FC HPS is giving modest accurate and realistic power with steady running cost and the system after 15 years will be the cheapest according to the life cycle cost. It will even be cheaper than the diesel IPS. PV-wind-DG-batteries HPS shows as high realistic power, but also the running cost is unsteady due to the use of diesel fuel, moreover, the storage system is not efficient. The diesel IPS shows a very cheap capital cost compared to the previous HPSs and it shows accurate power. On the other hand, taking a look to the life cost of diesel IPS shows a dramatic increase, and after 20 years it becomes the most expensive system, due to the high running cost due to the costs of fossil fuels (diesel). Running expense could therefore increase depending on the diesel costs (where it has shown dramatic increase in the last few years) and its transport.

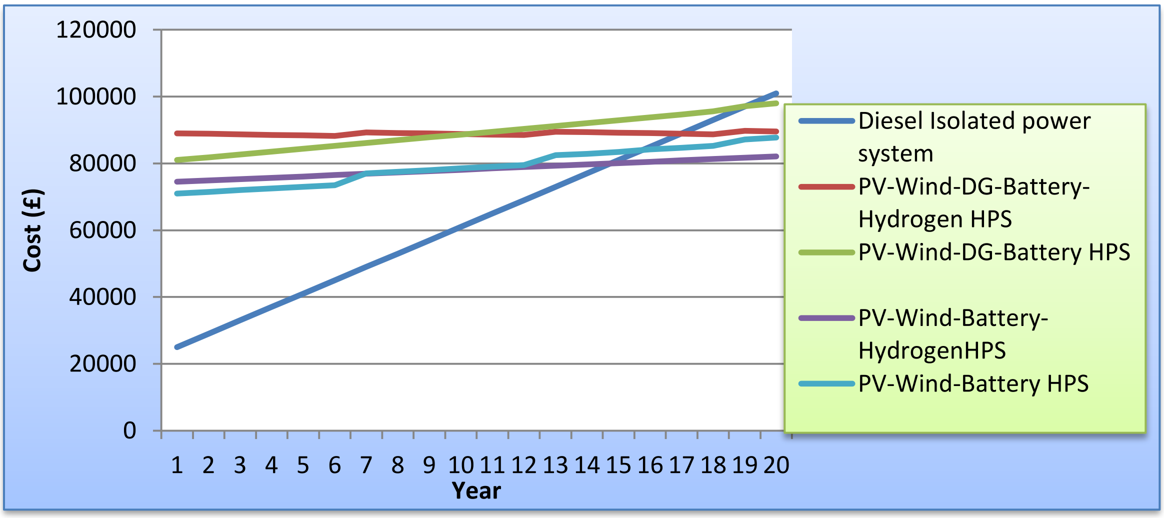


Figure 2.35: Comparison of the life cycle cost for HPS in section 2.5.3, 2.5.4, 2.5.5 and 2.5.6 with a diesel IPS.

Table 2.3 Comparison between section 2.5.3, 2.5.4, 2.5.5 and 2.5.6 HPSs

Criteria	PV-WTG-Battery HPS	PV-WTG-Battery-Hydrogen HPS	PV-WTG-DG-Battery HPS	PV-WTG-DG-Battery-Hydrogen HPS	Reference
The ability to use renewable resources	Yes	Yes	Yes	Yes	(Meinhard et al. 2004, Croci et al. 2012)
use converter for storage system	Yes	Yes	Yes	Yes	(Lee et al. 2012)
Type of load	DC or AC	DC or AC	DC or AC	DC or AC	(Lee et al. 2012)
In case of overpower the sources will switched off	Not necessarily	Little prospect	Not necessarily	Little prospect	(Belhadj 2010)
Limitations for having storage methodologies and quantity	Yes, able for expand but very expensive	Able to expand but expensive	Yes, able to expand but very expensive	Able to expand but expensive	(Meinhard et al. 2004)
Size of the inverter between DC-bus and AC-bus determines the power sources	Not necessarily only the amount of storage from wind or the supply from PV, batteries	Not necessarily only the amount of storage from wind or the supply from PV, batteries, FC	Not necessarily only the amount of storage from wind, DG or the supply from PV, batteries	Not necessarily only the amount of storage from wind, DG or the supply from PV, batteries, FC	(Strauss and Engler 2003)
Sun rays affect the system	Modest	Modest	Modest	Modest	(Belhadj 2010, Nian and Behera 2012, Zhu et al. 2012)
Wind speed affects the system	Modest	Modest	Modest	Modest	(Nian and Behera 2012, Niankun et al. 2011, Zhu et al. 2012)

Environmentally friendly	Reasonable (produces noise)	Reasonable (produces noise)	No (produces noise and GHG)	No (produces noise and GHG)	(Ying-Yi and Ruo-Chen 2012, Xiong et al. 2011, Ronan and Mark 2006)
Supports sustainable development	Yes	Yes	To some extent	To some extent	(Belhadj 2010, Ronan and Mark 2006)
Storage lifetime is short	Yes	No	Yes	No	(Lee et al. 2012)
The storage capacity depend on the size of the batteries	Yes	No	Yes	No	(Jimenez-Fernandez 2011)
Maintenance cost	Lowest	Low	Highest	High	(Lee et al. 2012, Belhadj 2010)
Cheap running cost	Lowest	Low	Highest	High	(Lee et al. 2012, Zhu et al. 2012, Belhadj 2010)
Capital cost	Lowest	Low	High	Highest	(Lee et al. 2012, Zhu et al. 2012, Belhadj 2010)
Stable system for long term	Reasonable (45%)	Good (60%)	Good (70%)	Very good (80%)	(Xie et al. 2010, Niankun et al. 2011)
Energy losses	Reasonable	Reasonable (lowest)	Reasonable	Reasonable (lowest)	(Belhadj 2010)
Continuous power supply	Average (50%)	Good (60%)	High (80%)	Highest (90%)	(Croci et al. 2012)
Continuous power increase the running cost	No	No	Yes	Yes	(Zrvas et al. 2008)
Accurate and realistic power	Modest	Between modest and high	high	Highest	Xie et al.) (2010
Spread between the IPS	High	Low	Highest	Low	(Xie et al. 2010)

Next section (hydrogen peroxide) is added as it will be used in this thesis as storage. Full explanation about hydrogen peroxide from manufacturing to its use as fuel will be discussed.

2.6 Hydrogen peroxide

2.6.1 Introduction

Hydrogen Peroxide (H_2O_2) is a simple compound oxygen and hydrogen, which is basically water with an additional oxygen atom. Hydrogen peroxide is a colourless or almost pale blue, odourless liquid and slightly more viscous than water (Inoue et al. 2013, Fu et al. 2010, Sheldon 2008). H_2O_2 has chemical oxidizing properties and it is used as strong bleach or cleaning agent where the capacities of hydrogen peroxide as an oxidizing agent is stronger than highly reactive oxygen species. Hydrogen peroxide is green chemistry and environmental friendly (in low concentration) due to the direct supply of hydrogen and oxygen elements. Hydrogen peroxide will be used as a storage system in this thesis because of its characteristics that are described below. Extra power is stored using batteries or hydrogen, (by an electrolyser where water is split to produce hydrogen and oxygen). The hydrogen is stored in order to use as fuel in the fuel cell when required.

Hydrogen and oxygen can be also used to manufacture hydrogen peroxide which can be stored for a long period. This section will explain the way of producing hydrogen peroxide from the oxygen and hydrogen, as indicated later in section 2.8.3.3. The method of using hydrogen peroxide as fuel to produce electricity and the way of its storage will be discussed.

2.6.2 Information about hydrogen peroxide

Louis in 1818 was the first one who described hydrogen peroxide (Jones & Clark 1999) where it was produced by nitric acid. Later, an advanced process replaced the old process using hydrochloric acid, and to precipitate the barium sulphate, sulphuric acid is added. This process was later used after the discovery of hydrogen peroxide until the last century (Jones & Clark 1999). Nowadays, there are many modern ways to produce hydrogen peroxide and one of these will be discussed later in this section as it will be the cheapest way for this project (Fu et al. 2010).

Moreover, hydrogen peroxide is unstable if the concentration is more than 70% according to traces of transition metal salt, which can decompose hydrogen peroxide (David 2003, Richard 1894).

2.6.2.1 Structure

Hydrogen peroxide is an acid called hydroperoxic acid, where the structure of hydrogen peroxide has a single bond between the two oxygen elements O−O with a high barrier approximately 29.45 kJ/mol, and every oxygen element is connected with hydrogen element in a twisted way with an angle of 90° as shown in Figure 2.36.

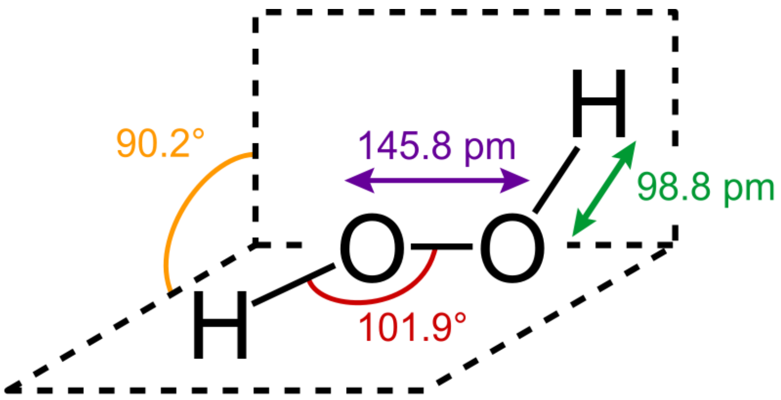


Figure 2.36: H_2O_2 Structure (SVG 2010).

2.6.2.2 Physical properties for hydrogen peroxide

Pure hydrogen peroxide differs from water. It has a molar mass of 34.0147 g/mol, a density of 1.135 g/cm^3 at 20°C if at 30% concentration, but if it is pure the density is 1.45 g/cm^3 at 20 °C. Melting point is -0.43 °C, boiling point is 150.2 °C. For solubility, hydrogen peroxide is soluble in alcohol but insoluble in petroleum and it is miscible in water. Hydrogen peroxide is slightly more viscous than water, approximately 1.245 cP at 20 °C. H_2O_2 specific heat capacity is 1.267J/g K as a gas and about 2.619 J/g K as a liquid. H_2O_2 pH is 4.5 to 6.2 depending on the concentration as mentioned in Table 2.4. The classification of hydrogen peroxide according to the EU is "Oxidant, Corrosive and Harmful" (Fu et al. 2010; Inoue et al. 2013; Technologies for a clean environment 2008).

Table 2.4 Comparison between hydrogen peroxide concentration at different pH values

Concentration (%)	0	10	20	30	40	50	60	70	80	90	100
pH at 25 °C	7	5.3	4.9	4.7	4.6	4.5	4.5	4.5	4.6	4.9	6.2

2.6.2.3 Manufacture hydrogen peroxide

In ancient times, hydrogen peroxide was obtained in enormous quantities by hydrolysis of chemical compounds, the most famous ones are ammonium peroxydisulfate $(NH_4)_2S_2O_8$, and ammonium bisulfate NH_4HSO_4, as shown in the next equation (Jones & Clark 1999).

$$(NH_4)2S_2O_8 + 2\ H_2O \rightarrow H_2O_2 + 2NH_4HSO_4$$

Nowadays, cost is the most important parameter to manufacture anything. Hydrogen peroxide is manufactured in huge quantities, using an economical process called AQ ("Anthraquinone process"). This process, developed in 1939, is still the leading method to deliver hydrogen peroxide economically. The AQ process is a circulating process consists of two part "autoxidation and hydrogenation". This first part consists of a 2-alkyl anthrahydroquinone, such as isopropanol ($CH_3CH(OH)CH_3$)" or (2-alkyl-9, -10 dihydroxyanthracene ($C_{16}H_{12}(OH)_2$), and when any of these compounds is oxidized, it will produce hydrogen peroxide and 2-alkyl anthraquinone, such as acetone (CH_3COCH_3) or 2 ethylanthraquinone ($C_{16}H_{12}O_2$), and by adding hydrogen to composite output it is called the hydrogenation and it will take the process back to the first component. However, in the second part adding hydrogen alone will not react without a catalyst, such as metal, and for acetone it requires palladium (Pd) as catalyst. The two parts of AQ process repeat as a cycle as shown in Figure 2.37. To simplify AQ process, hydrogen and oxygen are producing hydrogen peroxide and the components stay the same, as the process repeats itself (circulating process) (Ye 2011, Jose et al. 2006, Lunsford 2003, Lee et al. 1999, Iball and Mackay 1962).

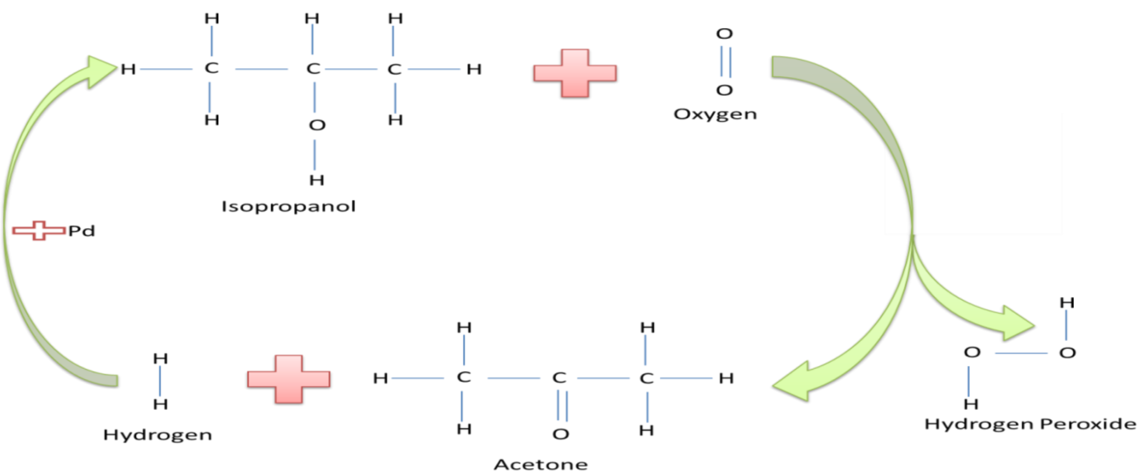


Figure 2.37: H_2O_2 production by AQ process.

There are two steps that should be added to the AQ process, first, filtration. This step is important to evacuate all the catalyst in order to be used again. Also it is not desirable to have hydrogen peroxide with palladium. The second step is to extract the hydrogen peroxide by adding water as it should be in aqueous form. Then it is concentrated to the required level and stored. These steps are explained in Figure 2.38. The AQ process is considered inherently an environmental friendly process (Campos-Martin et al. 2006).

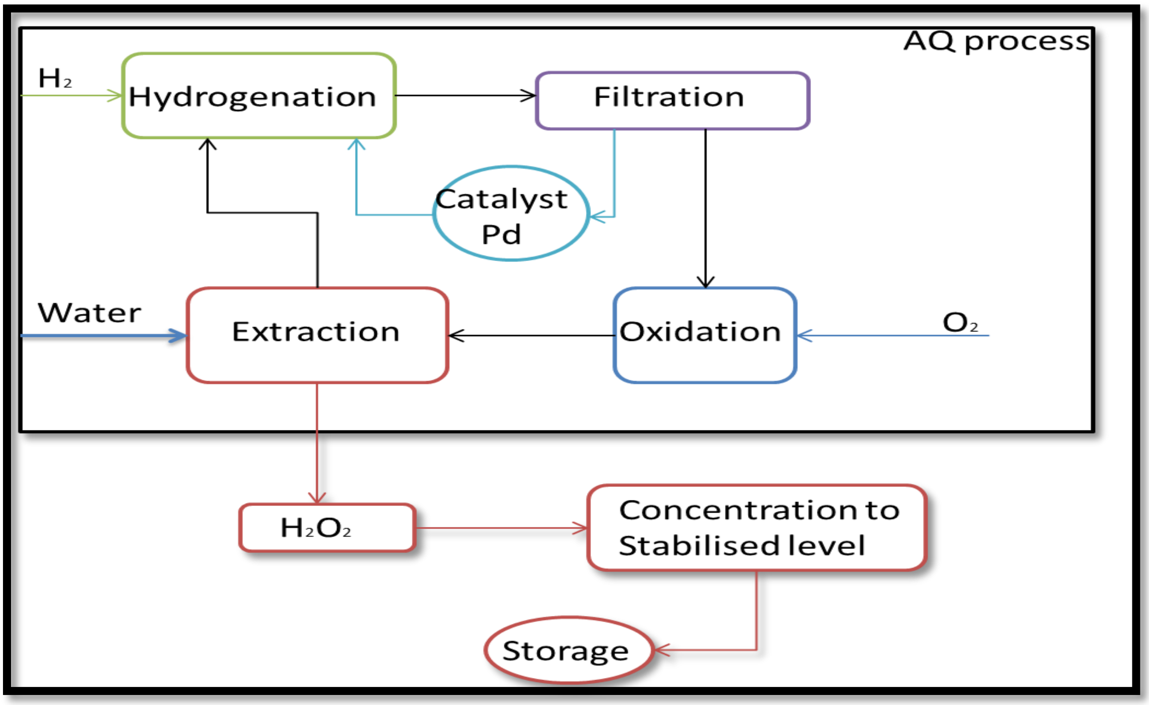


Figure 2.38: AQ Manufacturing process.

2.6.3 Hydrogen peroxide as fuel

Hydrogen peroxide (H_2O_2) has been broadly used as an oxidant. Notwithstanding, H_2O_2 can also be used as fuel (Wolf 1963). H_2O_2 is considered as an energy storage system like batteries which can store energy in chemical form. On the other hand, H_2O_2 has the same issue that H_2 has, existence in nature; H_2O_2 does not exist normally like fossil fuel, it should be manufactured as explained before.

Hydrogen peroxide has been utilized as rocket fuel at high concentration, and it can be used as Mono-propellant or bi-propellant (Hill 2001). Likewise it can be utilized in an automobile, and it can be stored in liquid form. It can be considered as a storage and energy production system, and when it is used to provide power, it produces water and oxygen as a process associated with the power production, making the whole process environmentally friendly to generate clean energy, similar to H_2.

Nonetheless, the similarity between hydrogen and hydrogen peroxide is only in producing power, as hydrogen peroxide can be stored at room temperature in liquid form, is easy to transport, and can be stored for long time (unlike hydrogen).

Recently, the feasibility for H_2O_2 to be used as a fuel for a specialised fuel cell by decomposing it has been realised. This new method of using hydrogen peroxide to generate electrical power could essentially reduce the cost of manufacturing H_2O_2, and increase the opportunity of manufacturing it from RES (Lehmann and Stenner 2004). Previous studies into hydrogen peroxide fuel cells used H_2O_2 with a metal (aluminium) electrode. Nowadays, H_2O_2 fuel cells based on H_2/ H_2O_2 or sodium borohydride ($NaBH_4$)/ H_2O_2 increase the efficiency to 60% compare to the normal hydrogen fuel cell 40% as shown in Figure 2.39 (George 2006).

2.6.4 Summary

Hydrogen peroxide (H_2O_2) is an oxidant, manufactured in many ways, with the cheapest being the AQ process. H_2O_2 is considered as a clean fuel and decomposing it will produce energy. H_2O_2 can be used as a fuel in a fuel cell to generate DC electrical power. Using H_2O_2 instead of H_2 in a fuel cell increases the efficiency from 40% to 60%, and it can operate at room temperature.

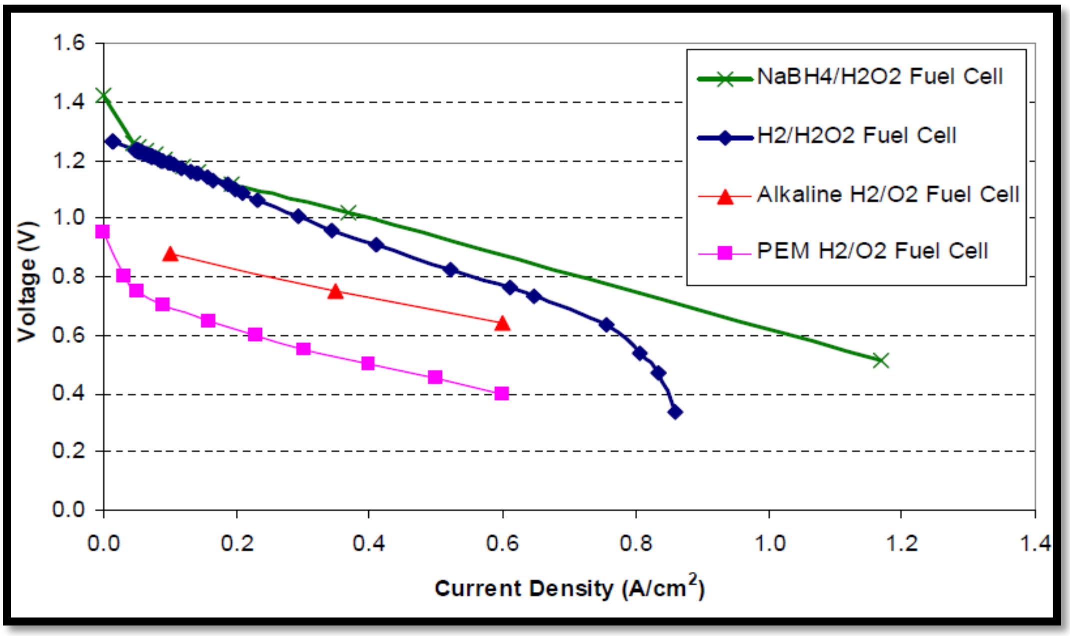


Figure 2.39: performance comparison (George 2006).

2.7 The importance of optimal sizing

To plan and design a hybrid system it is important to figure out the right size by using many different methods (Banos 2011). Any system is designed according to calculating the daily demand load but also by measuring sun radiation and wind speed year-round. In addition to the previous point, the following points are considered important in the success of the hybrid system:

- The size of the bi-directional converter is enough to supply the AC load in the community network.
- The battery's depth of discharge and its lifetime. This point is important as well for the capital and running cost.
- How long the storage systems have the capacity to supply power for during power deficit.
- The required power for a water heater if there are no alternative options.

The issue of deciding the ideal sizes of diverse components in HPS is a research area that has not been regularly studied, and the system utilises different resources which complicates this. It is demonstrated that the optimal size of the system components will lead to minimum capital and running expenses and the payback period is lower with higher net return. To understand the importance of the optimal size for HPS, a discussion of the under and oversized scenarios is presented below.

2.7.1 The scenario of an oversized IHPS

To design a HPS, the designer must take account of two main criteria. Firstly, the output power must be continuous and reliable. Secondly, the whole life cost of the system must be minimised, which implies minimum capital and running cost and an early payback period. In an oversized scenario, the designer in this case focuses on generating continuous reliable power without taking into consideration the economic side. The main advantages for an oversized system will be a supply of continuous reliable power, and if the backup system is DG, it will reduce the fuel and maintenance costs. On the other hand, in this case there are two critical points to be noted. The first point is that the capital cost of the system will be very high and in some cases there will be no payback in the system lifetime. The second point is that the power losses are always increasing in an oversized HPS due to the generated power producing more than the demand load, and when the storage system is totally full, in this case, the controller must disconnect one or more generators from the grid, or send the extra power to dump load. In both cases the electrical power is wasted. In summary, the capital cost will be high and the running cost will be low with more clean energy production.

2.7.2 The scenario of an undersized IHPS

In this case the generated power will cover the average demand load. If the load is below average, the extra power will be stored, and if the load is above average, the storage power will compensate for the power deficit, and in some cases the combustion generator will need to operate frequently or for long periods. The main advantage for undersized systems is the low capital cost. However there are many disadvantages. The output power for the HPS is fluctuating and unreliable. Also the undersized system depends on the backup power, such as a combustion engine, and this will increase the running cost. The payback period is therefore very long. Finally, from the environmental viewpoint, the system produces greenhouse gases and noise. In summary, the capital cost will be low and the running cost will be very high while the system is not environmentally friendly or reliable.

2.7.3 The scenario of the exact sized IHPS

In this scenario the production power will provide 10-20% more than the average demand load. The storage capacity is larger in this scenario to absorb the extra power and to support and compensate the power deficit in peak periods. The main advantage of this system is average capital and running costs with acceptable power generation. Also the system, to some extent, is environmental friendly. On the other there are many critical points that must be considered. First, the storage system has limitations and when the storage system is totally full, the losses will increase. Secondly, the system does not address the population growth, if there any increases in population, an additional generation source will need to be added. Finally, because the generated power and demand load is fluctuating, it is difficult to predict, and it can affect the sustainability of the system. In summary, the capital and running costs are average with almost reliable electrical power and nearly clean power.

2.7.4 Innovative scenario – Flexible/optimal sized IHPS

This system is similar to the previous system with some modifications to reduce the disadvantages to a minimum. In this scenario the production power will provide 20-35% above the average load. The storage will be able to absorb all the excess power and compensate for power deficits in peak periods in order to provide steady power. The load will be controlled in order to stop the fluctuating and the unpredictable loads. Moreover, in this scenario the production power and demand load will be kept balanced by adjusting both at the same time. The main advantage of this system is reducing the dependency on the combustion engine as a stand-by to a minimum, meaning less running costs and more clean energy. On the other hand the capital cost of this system is slightly higher and the payback period is longer. The capital cost is the only real disadvantage, whereas there are numerous advantages:

- Guarantee consistent electrical power with effective operation in the HPS.
- Reduced fuel and maintenance costs of the DG, therefore resulting in substantially decreased running costs.
- Noteworthy decrease in greenhouses gases.
- Clean energy is provided and the system is quieter.

2.8 Designing and optimization techniques for sizing IHPS

All the designed HPSs depend on meteorological information compiled over at least one year (Koutroulis et al. 2006, Yang and Lu 2004). The first basic method used for sizing a HPS relies on upon meteorological information, and knowing the precise load throughout the day. Additionally, the rate of each renewable source utilized and its type is used to calculate the generation power. The storage capacity relies upon load measuring, as storage must be of a sufficient average rate for an entire day (Wang and Nehrir 2008). Increasing the number of variables to enhance the estimation will raise the complication of optimizing the system size increasing the time and effort needed. Along these lines it is imperative to discover a durable strategy to choose the ideal HPS rapidly and precisely. Yang et al. (2008) mentioned the optimizing techniques such as, probabilistic approach that exhibits the random estimation of size based on convolution method and the main demerit of this approach is that, dynamic variable cannot be optimized. Another technique is the graphic construction technique. This technique is based on monthly consideration of meteorological data, and the main barrier for this technique is that only two parameters are incorporated every time. The third technique is the iterative technique. This method is dependent on iteration; adding more generation sources so that the production power is equal the demand load for a period by mixing the sources several times. The main issue with this method is that its time and effort consuming and sometimes provides unpredictable solutions. The final technique is artificial intelligence, that includes different approaches such as, genetic algorithms or fuzzy logic, which have shown themselves to be appropriate to instances of non-direct systems. These approaches are able to handle all the parameters with linear and non-linear systems carefully, and also this technique is used in most software simulations.

There are various approaches to designing a HPS, each with varying levels of confidence that a powerful system will be designed. These approaches can fluctuate from hand calculations utilizing general guidelines to complex software produced for the power generation sector.

The basic configuration for the HPS is multifaceted, and as more components are added, the complexity increases. Computer software tools are used to assess the implementation of a HPS, including complex ones. These tools utilise simulation of the ideal set-up by comparing the implementation of several systems from their power generation reliability to costs. Bernal-Agustin and Dufo-Lopez (2009) added that in addition to the different methods there are many simulation programs, such as HOMER, $HYBRID_2$, and HOGA. According to Castaneda et al. (2012), in order to compare between the simulation programs, the same hybrid system under similar circumstances should be used.

Subsequently, to enhance the execution of HPS optimization, numerous studies have been directed to lessening the simulation time and the quantity of utilized variables. Among them, Celik (2003) built up a predictive algorithm that requires monthly estimations of meteorological data. This process empowered the simulation tool to use less time to estimate the optimal HPS as there is no need for hourly information, as these simulations are able to presents a techno–economic assessment. The following sections contain a brief depiction of the more well-known software.

2.8.1 HOMER software

Hybrid Optimization Model for Electrical Renewable (HOMER) is a software program that has been created by the National Renewable Energy Laboratory

(NREL) to advance renewable isolated power systems. HOMER is an optimization software utilizing hourly load and specified resources (such as, wind speed and solar rays for the whole year) with appraisal of the environmental information for renewable sources. It also includes individual capital and running cost of the system components in order to calculate the economic payback and life cycle cost of systems. HOMER simulation is sorted hourly as explained before and it is quick and thorough, taking account of different arrangements of power generators, storage systems, and load alternatives. HOMER is viewed as the king of HPS simulation (Ackerman 2005, Lundsager et al. 2001). It has been utilized broadly as a part of past studies of renewable energy in isolated power systems (Zoulias and Lymberopoulos 2007, Khan and Iqbal 2005b), and in many renewable sources approval tests as well (Rodolfo and Jose 2005).

According to Bernal-Agustin and Dufo-Lopez (2009) and Castaneda et al. (2012) that HOMER simulation is the most commonly used software to design HPSs. The simulation is publically available and free to install and chooses the cheapest system with the most probable match between demand load and generation power.

The steps followed by HOMER in its analysis include first an analysis of all load types from electrical, thermal and hydrogen. Then, the system will check the capability of generation sources to produce electrical power, thermal energy and hydrogen. After that, HOMER chooses the storage system mode if the power is in or out and at what level the generation is fulfilling the demand load or if there is a need to use fossil fuel (or other types of generation) to cover electrical load. Following this, the dynamic performance of all the components is added to calculate all the financial calculation along with the project lifetime. HOMER then iterates through these steps in order to re-size the system. After re-sizing all components the simulation adds the sensitivity analysis, if the designer requires it, by repeating all the steps with new amended parameters and so on. The results of reasonable systems will be order ranked according to the cheapest capital cost. Using HOMER simulation always results in a system that contains the biggest size of the renewable source and the smallest storage system (Barley and Winn 1996).

Nonetheless, the software has some barriers. It does not empower the designer to choose the suitable parts for a HPS and the calculations and computations are not attainable or obvious to the user.

2.8.2 SDO Software

Simulink Design Optimisation (SDO) is software that comes as a part of MatLab. Simulink is used not just for HPS but can be used for electrical, mechanical or even electronic circuits. Simulink programming can indeed perform the enhancement of HPS with the assistance of the designer to arrange the changes and upload them. The advanced use of SDO for the HPS is to seek estimates of the dynamic parameters that pertain to HPS voltage and frequency, in order to study the ability to keep it between specific limits, or the action that should be taken after a particular situation. This kind of simulation requires a progression of tasks to optimize the system. Most importantly is choosing the advanced parameters for the design. For this situation, the estimated power for every component should be added along with all the other parameters from capacity to numbers of every device in the system. After that, according to the parameters and the shape of the system, it is important to keep changing the characterized parameters, and to keep in mind that these parameters limits are characterized as well. At the same time SDO utilises one of two techniques: Latyn Hypercube and Genetic Algorithm (Castaneda et al. 2012).

The software has some barriers. First, SDO is not able to add the capital or running cost of every part of the system during the simulation. The SDO designs the system without taking account of the economic side and mostly results need economic evaluation. Second the software is not free (Castaneda et al. 2012).

2.9 Summary

The variously discussed HPSs so far are semi-complicated in design, and their design can be different from place to place to maximise the utilization of RES, where it is affected by many factors such as load, weather and geography of the place. The type of load (DC or AC) determines the type of coupling, and the amount of load. Many methods are available to calculate and optimize the size of HPS, whereby every method focuses on a certain part of the system. In this chapter most of the pros and cons have been examined for every system. HPSs were represented in comparison with other systems as well as the costs involved to improve the system with minimum economic impact.

The standards for the outline of HPSs ought to be that they are protected, satisfactory, expandable, and effective. Protected system can be accomplished by guaranteeing that the system components are planned in compliance with the electrical codes or norms being used in the country, because in remote areas and for the purpose of reducing the cost some safety standards may be compromised. Indiscriminately complying with these measures makes some components superfluous, more costly and less available to rural populaces. HPSs that are appropriate provide electrical power that covers the required level of productivity and administration quality. Expandable HPS refer to the ability of the system to accept more loads, and this will be outlined in the design stage where the cost is minimised for providing the expansion at a certain level. An effective HPS is a system that produces enough electrical power with the minimum cost where the end-users are satisfied.

Using renewable energy as generation power has many benefits, such as, reducing the cost of fuel, reducing the fuel transportation expense and reducing GHG. The micro-grid is comprised of RES and conventional generation both with a storage system, which is known as HPS. The designer always tries to create a HPS providing enough power all day and every day to provide a superior performance, adaptability of arrangement and ecological benefits contrasted with the single conventional generation. Additionally, HPS offers less fuel use which implies less maintenance expenses of the fossil fuel generator, and this can result in enhancement of the productivity of operation and diminish the operating time.

Using renewable energy has some risks regarding power sustainability and quality, where it depends on daily, geographic, and climatologic matters. Likewise, HPS has a very high capital cost. According to the difficulties of predicting renewable sources and the total dependence on climate, combining generation is the solution for an amazing alternative for producing electrical generation.

The main hypothetical investigation of HPSs is the accessibility of models, which can be utilized to study and understand the conduct of HPS and the environmental side as well. Therefore, it gives the ability to study the renewable energy closely, the type of coupling and the converter behaviour. Also, it is important to monitor the storage system, the requirement to store energy or if the system requires energy from the storage or the reserve system. Moreover, this research is looking for unlimited expandability of energy by adding new technology that will be able to absorb all the extra energy. However, the HPS can expand in other ways, by connecting more remote areas with each other under special design.

2.9.1 Research contribution

Originally, off-grid systems have been designed to overcome the difficulties that accompany transmission lines, with regards to the high capital and running costs of installing transmission lines to supply far away areas. Consequently, overseeing and monitoring the stream of power is fundamental to guarantee the stability of power supply. Monitoring provides the ability to enhance and optimize HPSs by handling the difficulties that arise without issue, improving utilization. Utilising a mixture of renewable energy with a combustion engine is a good choice for Jordanian remote areas with the base of short and long term storage system. However, all the required data has been analysed with a full consideration of the environmental impact.

The expectation of this thesis is to achieve a new philosophy OGREH-SμG by implementation of intelligent supervisory switching controller framework, to control and manage the generation from one side and demand from the other side, implanting demand management strategy with complementary adaptive tariff. In this wayit will achieve more gains in the electrical sector particularly in Jordan. It will likewise prevail as a model for other remote areas, and it can affect the whole electrical sector if they adopt the new framework, which will encourage development in areas without electricity. An advanced load dispatching strategy is at the core of

OGREH-SμG; this strategy works by controlling the demand to meet the power generation. It controls and manages the main drawback of renewable power generation; i.e. power fluctuation, by making the rates of power production and consumption closer.

This thesis has presented the following as the main contribution to knowledge as detailed in section 1.1:

- IADF (iterative analytical design framework) provides a framework for the primary design methodology that can be undertaken to achieve the design aims derived from the requirement analysis.
- A streamlined energy management system that this thesis has referred to as an "intelligent supervisory switching controller system" was devised and implemented with a Raspberry Pi microcontroller with two main types of smart controllers.
- Novel storage system utilising a mixture of available renewable energy with:
- Monitoring the sustainability of power availability from micro-grids synchronisation with each other.
- Formulation of the objective function (LCF) to model the optimal system in order to.

To expand upon the findings of IHPSs, this bespoke system (OGREH-SμG) is designed for Bayir area as a particular task; however, the available resources and sizing approaches vary significantly. There are socio-economic and political issues to devising sustainable systems. Installing reasonable IHPSs or HPSs including technical and economical feasibility should meet the requirements of the end-users, and solve all the issues such as load growth, charging tariff and subsidy settings. The implementation of these systems is also dependent on the institutional quality.

2.9.2 Functionality overview of HPS - The functional capability of HPS

In standalone power systems, the required load can be functioned and adjusted by a HPS or IPS controller. In any case, unclear technology or complicated systems will have a huge effect on the system operation, and it makes the system unclear, which will always tend to have a poorer performance. Rather, performance generally relies upon the complete cycle; the availability of RES advancements, the size of generation and storage, also the HPS construction modelling and the followed control methodology. Most of the effectiveness of electrical power from HPSs, and the possibility of payback are intensely influenced by the correct implementation of the design in accordance with the standards project. However, fluctuating output power is the main distinguishing feature of HPSs.

2.9.3 Summarized analysis

Solar power is in abundance on the global surface and up to now it has not been used much in electrical generation. A small amount more utilization of this power could be used for the betterment of the population around the world with sufficient power to cover their demand load. Solar panels are utilized to convert sun radiation into electricity, where solar panels are useful for small to medium loads. On the other hand, wind turbines can be used where there is wind availability and it is used widely in many countries for medium to big loads. Integrating solar panels with wind turbines will increase the reliability and sustainability for the power system, and to some extent they are environmental friendly during the operation time. However, the main disadvantages for both combined systems are: they require storage systems and they both generate fluctuating power due to daily and seasonal variation.

HPS has a brilliant prospect in the market sector in light of the fact that numerous abodes in developing and underdeveloped countries need access to electrical power; and because many of these areas are rural, it is difficult to have grid connection, and the remoteness of the location is an obstacle to supply the areas with fossil fuels because of the extra cost of the fuel. HPS could be one of the best alternatives power generation for electrifying these remote areas.

Software such as HOMER can be most effective for choosing an optimal HPS by going through all conceivable combinations of components. However, it may take considerable computation time. A pre-estimation for these HPSs can save money, effort and time, and it shows the big picture of the future for required implementation in the territory. Moreover, joining RES in HPS with backup combustion engines will promote the electrical production from RES. A pre-estimation for HPS will economize money and time, and can draw the outline of HPS that is required to be installed in the future for remote areas.

This research is presents a particular supervisory controlling system for HPS, which is a new idea for vast control frameworks intended to overcome the issues with current configuration approaches and enhance financial matters and consistent quality of HPS. The work concentrates on a few specific issues in the supervisory control and design system.

Chapter 3

Research and modelling requirements

3.1 Introduction

HPSs are usually used to electrify remote locations with each HPS comprised of more than two power production technologies where power is distributed to the end-user through an autonomous micro or mini grid. Consequently, electrifying remote areas is usually carried out by using RESs with a standby or backup system. This interactive system is a practical innovative arrangement which gives excellent and dependable power for end-users where a nearby HPS can provide the end-user with the same reliability and power quality as the national grid. Additionally, with proper planning, theoretically HPSs can be joined to the public grid or IHPSs. In underdeveloped countries where the national public grid cannot meet the demand with frequent blackouts, HPSs can provide more reliable and stable electricity to remote locations than the national grid.

3.2 IHPS design specification

Before implementing HPSs or IHPSs, the research process must involve the following steps:

- Problem identification by thorough literature research.
- Formulation of suitable methodology to study the gaps identified in the literature.
- Selection of an area for the case study.
- Preparation of a geotechnical report.
- Ethnographic field studies.
- Evaluation of the results.
- Design implementation.

- Determination of designing problem, possible solutions using simulation tools, and design validation by:
    1- Designing and modelling power generation.
    2- Evaluating the design under empirical conditions.
    3- Analysing the issues that may arise.

3.3 Information required for implementing IADF

In order to plan, design and implement a proper HPS the following points must be taken into consideration:

- Permission of the authorised utility.
- Studying the electrical power use, choices and limitations forced on the consumer by the supplier and evaluating the expenses of electrical power. In addition, determining average loads and maximum expected loads.
- An initial feasibility study should evaluate the expenses, proposed utilization style and alternative options.
- Mapping and determining the location of power generation and storage components, and the distance between these and the load demand. For system distribution, mapping individual houses needs to be conducted to include distance and loads in the calculation.
- Surveying the configuration load per individual user to study the expected peak load, heavy loads and their operating hours.
- Estimation of the economic cost between underground and overhead distribution lines.
- Calculation of the level of service and maximum power.

- Calculation of HPS installation and infrastructure costs.
- Preparation of safety requirements.
- Installation of all wires, cables, and distribution boards.

3.4 IHPS general implementation problems

HPS installation cost is the primary problem for small communities particularly when RES are taken into consideration. Therefore, utilization of HPSs for providing electrical power is difficult unless the expenses are extensively reduced.

3.5 Motivation and Justification

Remote locations may lack electricity supply due to technical, political and financial reasons where some of such areas use fossil fuels as the only source of energy. Reliance on conventional power generation, along with the depletion of fossil fuels and the negative environmental impacts of using this generation method should increase our enthusiasm to establish renewable sources to build a sustainable society. Combining the latest technologies with various electrical generation methods can provide a strong and strategic power supply in contrast to simply utilizing one generation method. Mixing RES with conventional generation has ensured the minimum expenses for remote areas, where the surplus power from each generation can compensate the power deficit in another generation. RES requires zero fuel thus minimum running costs. However, RES is considered a non-dispatchable generation relying on accessibility to the raw-sources. Conventional generation, on the other hand is considered a dispatchable generation which can supply power at any time. Mixing these generation sources together is promising to profit from regular changes in sun and wind. A storage system adds strength to HPSs by storing the existing energy to utilise during power deficiency and to counterbalance the changes in status of renewable sources. Electrical power in Jordanian remote areas is generated by DG, which are very costly and difficult to deliver diesel fuel to such areas.

In order to evaluate the suitability of an independent system to an area, the capital and running costs and the quality of power generation should be considered. RESs have very high capital costs compared to DG; on the other hand the running costs of DG are even higher. DGs, with sufficient fuel, can supply very high quality and reliable electric power while RESs provide lower power quality as they are affected by daily climate or environmental changes. Accordingly, an independent system which is totally dependent on diesel generators is able to provide power on demand. However, in some areas the capability of operating DGs does not generally coordinate with the accessibility to diesel fuel or even its availability in this remote area. From the environmental side, DG is controversial as it generates greenhouse gases with very high running costs. On the other hand, when the system is totally dependent on RESs, a storage system is required to improve power reliability. The quality of the system depends on the size and capacity of the generation and storage systems, which need to be bigger than a normal combustion engine thus increasing the cost. The storage system here is liable to high exertion due to unexpected demand or power, where bigger generation can lead to overcharges while low available power (high demand) leads to fast deep discharges, which can collapse the storage system and necessitate a replacement. Since DG and RES have some disadvantages, combining both systems may be beneficial. In this case the RES provides the main power, the storage system is the reserve power, and DG is the last resort as a standby power generator. This system may be considered an alternative power solution to off-grid areas with minimum running costs and low environmental impacts. This research will focus on a remote area in Jordan as a case study; however the findings might be beneficial to any remote or rural areas having difficulties with grid connection, using the combined RESs, conventional generation and storage systems. The success of this project will allow Jordan to be the leader in its region and the first country in the Middle East to utilise RES to generate electricity for remote areas. This combination is considered a flexible independent power system as it can:

- Adapt many types of power sources and sizes
- Adapt with the fluctuating demand
- Expand the system components when required.

3.6 General limitation in electrical sector

The most significant issue concerning RESs uptake in the energy business is its high capital cost, which makes the generated power from these sources excessively costly. The present and future business perspective of the innovation is that it is for marginal applications, and not for general uses. Nevertheless, climate variation is another issue that can affect electrical power generation. Regarding the environment, RESs produce some GHG during the manufacturing stage as fossil fuels are the main source of energy production; however, it is remarkable that the GHG emissions from manufacturing RESs components is lower than the generated power from fossil fuels (Mellit et al. 2008). There are issues confronting remotes areas in the electrical power sector such as increasing economic growth and demand load growth (demand energy) which are described below.

3.6.1 Demand load growth and economic growth

One of the major difficulties in electrifying remote areas is to keep the growth of the demand load steady while protecting it through sensible and dependable electrical supplies. Most energy demand figures for developed or developing countries show a dramatic increase in energy consumption year after year, and sometimes the energy demand growth is quicker than economic growth. Consequently, any methodology needs to recognize various options taking into account ecological attainability without hindrance to the economic growth.

3.6.2 Population growth and energy access

Overall, 1.6 billion people have no access to electricity, whereas others believe the number will increase to 2 billion in 2025 with more unequal access to energy (Saghir, 2002; Ahuja and Tatsutani, 2009). According to the International record; the world population reached 7 billion in 2012, these numbers will put more demands on electrical generation as it will increase the challenge for the decision-makers to provide the required energy for isolated communities (Ying and Ruo, 2012).

3.6.3 Sustainability and quality of service

The energy sustainability and quality for conventional generation is high for the countries which have easy access to the raw materials required for power generation. However, these raw materials are unstable and rare in extensive parts of the world. Low power quality in the electrical sector forces not just extra expenses on the current generation; it also adversely influences business development. Enhancing access to electricity, general sustainability and quality of power generation with the right administration is an imperative test confronting remote areas, as depending on fossil fuels for generating power is often difficult, and the sustainability and reliability of generating this power from RES is low.

3.6.4 Security of supply

While the electrical sector often relies on fossil fuels to generate power, increment in economic growth will expand the demand for fossil fuels. High worldwide fossil fuel costs make the electrical energy unreliable and insecure. Jordan is a fossil fuel consumer mainly in the electrical energy sector. It imports fossil fuels from neighbouring countries whereby fuel price fluctuation makes this sector vulnerable. A project is required to broaden the electrical sector base in the national grid or independent systems in order to decrease incidents of power losses. Likewise, this necessary project should have the capability to manage energy disruptions which may arise from circumstances beyond human control, such as fossil fuel irregularity or depletion. In addition, affordable and reasonable raw materials prices are important for electrical sector reliability and energy security. However, expanding the electrical access and the significance of reliable and secure power are reasons for advanced development to prevent power deficit.

3.6.5 The system efficiency

Electrical power efficiency is very important for the energy sector and to enhance the utilisation effectiveness more cooperation from the private sector is required. The general arrangement of electrical energy need to be adjusted to attain maximum power efficiency through active polices to include a wider section of the private sector to participate in investment. End-users require acceptable power efficiency. However, when the demand load is growing, environmental issues must be taken in account. There is likewise a necessity to enhance the energy efficiency by utilizing conventional power sources.

3.6.6 Environmental and health considerations

99.4% of Jordanian electricity is generated from fossil fuel[1]. Direct environmental and health effects are associated with using the fuels to generate electricity where GHG is generated, and indirectly by dealing with waste after-using the fuel. Environmental and health impacts are considered as external costs and are usually ignored in the utility's calculations (ecosystems), where air pollution is not even mentioned. Therefore, alternative generation options need to be incorporated which have minimal environmental and health effects. Jordan has a good exposure to sun radiation where it is usually utilised in heating water for domestic purposes. In addition, high altitude and open areas have steady wind speed in summer and strong wind in winter. These sources are considered environmentally friendly as it generates very low GHG. Improving these renewable sources requires consideration of environmental and social expenses along with economic feasibility.

3.7 Barriers to implementing IHPS in Jordan

There are some barriers facing the implementation of IHPS in remote areas of Jordan, mainly because it depends on collecting data for more than three years, while the time scale allocated for this research is relatively short; data was collected from

[1] http://geography.about.com/library/cia/blcjordan.htm

governmental and authorized website databases. This data was introduced and calibrated by human beings and it may be inaccurate or the real numbers may be mistakenly changed. Furthermore, most data collected was dependant on weather and end-users demand load in Jordanian remote areas, whereas the climate is changeable over many years (data is inaccurate for long terms). The following are some of the key barriers recognized by this research:

3.7.1 Legislative, current feed-in tariff:

Generally, the legitimacy of electrical power sectors is fragile, with a large number of outstanding laws to be drafted. There is effectively neither a regulation for rural power nor a regular tariff (electrical levy rate per kWh) to protect independent areas from electrical utilities charges which can be randomly high. Poor preparation associated with weak decision-making on the short term puts the end-users in an unacceptable position.

Up to now, no policies are available to protect the utilisation of renewable energy in Jordanian utilities although the Ministry of Power has advanced RESs in the national grid and in other independent applications. Current RESs regulations are deficient and inadequate to supply any advancement in Jordanian renewable energy (where ebb and flow is the followed renewable energy strategy).

Feed-in tariff (advanced payment policy to improve the investment in renewable energy) is also important to support the utilisation of renewable energy. Such a tariff is lacking in Jordanian polices meant to protect renewable investments. The basic tariff setting is also missing, which is the amount the electrical utility should pay in return for providing unstable electrical power from RESs. This is mainly because

RESs do not respond in a desired manner as per required by the load demand, that makes it undesirable for Jordanian electrical utilities. Setting prices for RESs should have the capacity to meet top demands, particularly wind turbine and solar panel which can provide very high power in Jordan and can be predicted.

Some areas In Jordan have independent power systems (diesel isolated power system), where the electrical utility charges for the price of kWh plus the cost of diesel transport to the region. Furthermore, utilizing RESs in off-grid has begun as the old systems depend on the availability of diesel. On the other hand, off-grid systems have economic and technical advantages over the public grid extension, and the huge spending in the national grid. Yet the off-grid areas currently utilizing diesel IPS should be prepared to utilise RESs.

In conclusion, regulations should be an instrument supporting sustainable and cost-effective projects, rather than burdening the end-users by increasing the administrative cost.

3.7.2 Financial, economical, and banking system:

Funding RESs projects in Jordan is risky as they represent a new technology with rapid development. Awareness about renewable energy is not very common leading to overestimating the costs or inability to provide funds that would permit improvement opportunities. Moreover, it is difficult for electrical utilities to cooperate with other sectors to find creative solutions for problems such as handling the lack of fossil fuel and its unpredictable prices. Added to that, there is an absence of business organizations and infrastructure to utilise renewable power.

The banking system in Jordan is weak and deals only with short term investments with very high premium rates and interests. There are minor financial establishments in the rural range supplying funds for short terms with very high interest up to 30% annually. RESs require very high capital costs which might be considered an obstacle for funding and utilising renewable energy with poor economic conditions.

Lacking investments to develop the energy sector in Jordanian rural areas can lead to problems in developing education and health in particular. Thus, advancement of rural electrical power needs governmental funds at different levels. In spite of the fact that most of the rural areas have independent power systems operated by diesel generators the main issue is to keep the fossil fuel supply or to find alternative power sources.

3.7.3 Technical constraints

Lacking familiarity with the accessible technologies and their expenses and implementations is one of the main issues. In Jordan, absence of institutions capability to arrange, design, execute and maintain RESs are another obstacle with a deficiency of providing technology at moderate costs. Communication between decision-makers and other sectors in order to plan, implement and operate such projects is missing. In addition, absence of authoritative information about renewable energy sources with a lack of technical improvement, absence of cooperation between partners, makes it difficult to develop comprehensive renewable energy policies.

Planning does not sufficiently hold the view of wide decisions and choices when investigating the minimum cost for new energy capability. In Jordan, there is no selfgoverning authority to formulate a regulation and standards in electrical power sector, where the utilities viewpoint is commercial, instead of considering the socio-economic perspective.

3.7.4 Lack of information constraint

The success of independent system depends on the information available about modern efficient technologies. The lack of specialised socio-economic information on renewable energy and its innovations, in developing countries, hinders the utilization of renewable energy. Knowledge of diverse renewable energy choices, expenses and advantages are weak where advertising and marketing of renewable products hardly exist. This shows risks involving cross-subsidies between consumer and power production.

The end-users may have insufficient knowledge to make informed choices as most utilities provide little information about the type of fuels that are used or the GHG produced during the power generation. Because renewable technologies are relatively new, most end-users have insufficient knowledge about this technology. Consumers are unlikely to be aware that these intermittent technologies can be highly reliable when combined with other options. Furthermore, consumer's increased demand on energy as a result of more electrical equipment complicates the load prediction or even exceeds the maximum power production. Developed and modern life increases the expectation of the consumer and adds more challenges on the independent electrical systems.

Part 2

Chapter 4

Methodology

4.1 Research methodology

This section explains and details the methodology undertaken to conduct the research for planning, designing developing and implementing an IADF for an OGREH-SμG. This consists of a four stage methodology corresponding to the Research and data collection, Information Architecture and analytical process design (Figure 4.1a).

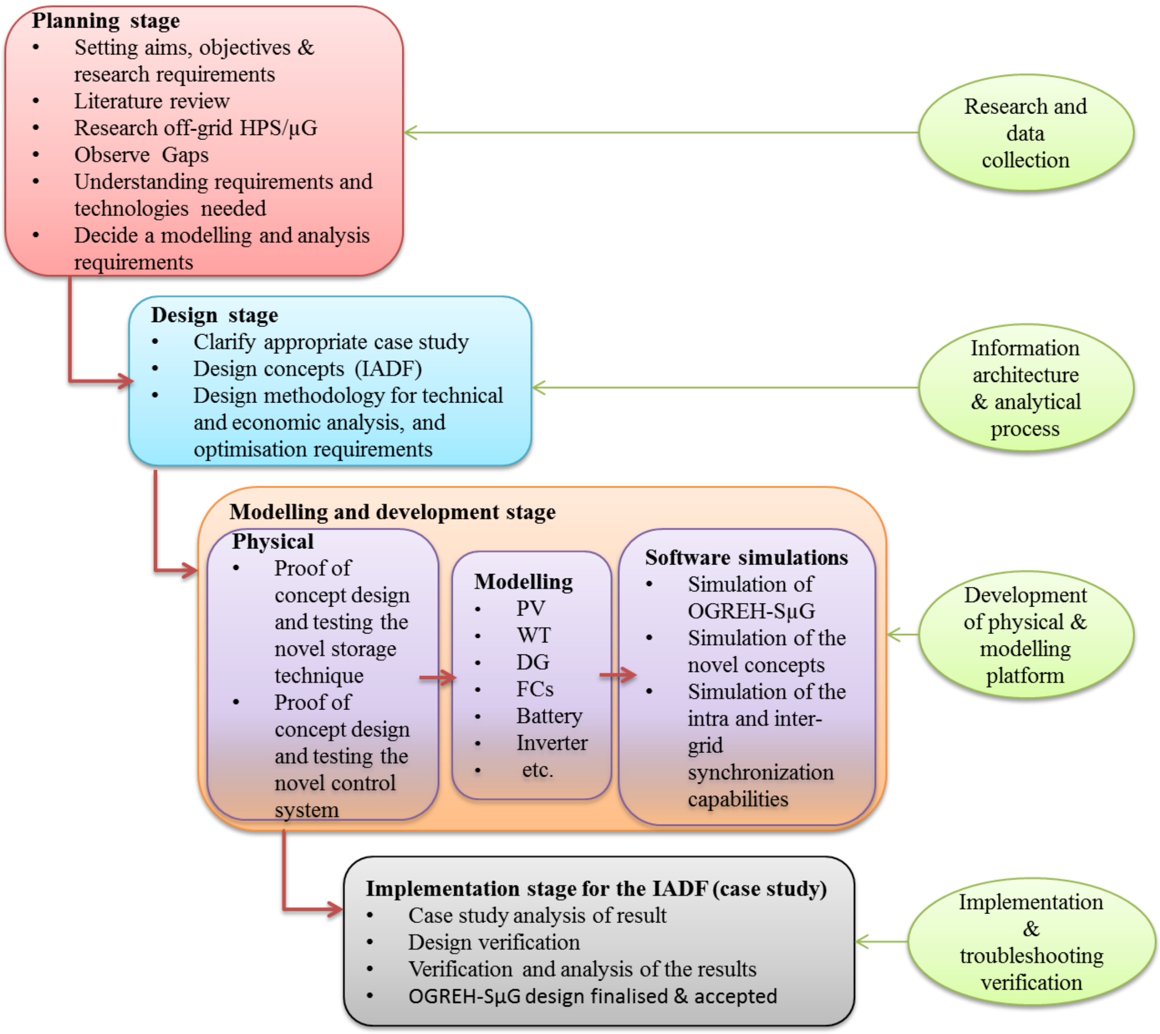


Figure 4.1a: Figure 4.1a: Research methodology used to design and implement an IADF with case study implementation.

4.1.1 Planning stage

The planning stage is collecting all the required details necessary to put together an OGREH-SµG, i.e. Generator sets, RES, and storage. Research for the requirements of HPS & OGREH-SµG and understanding the constraints. These requirements derived for the preliminary search were then categorised into related topics and keywords and new searches were conducted on Data based containing journal articles, academic books and annual reports, whereby the most recent studies were used to construct this contextual analysis in light of the most progressive data and up dated information for the case study. Analysing the most recent studies for observation and derivation of the gaps in the existing knowledge as well as the capability and the functionality in the area of current planning and design methodologies, frameworks for the design of HPS.

Analyse and comparison of the available design, configuration and capabilities of HPS as well as the analysis and simulation used as reported in the literature. This exercise was then used to inform the research process undertaken in the design stage as explained in the next section.

4.1.2 Design stage

At this stage the gaps in the available knowledge for the planning and design of HPS was identified resulting in the need for an IADF for OGREH-SµG becoming evident. With the basic requirements for an IADF clarified.

The following design process for choosing and configuring

- The software platforms
- The modelling required for

- Software
- Hardware

- Also the associated algorithms for these platforms
  - Bus configuration and synchronisation
    - Voltage,
    - Frequency and
    - Phase angle
  - Economic generation dispatch
  - Demand management through adaptive control

These processes were identified and undertaken for the next stage.

This stage also included the design of the information architecture for better performance and usability, in order to create the initial primary design methodology, the project followed and incremental iterative process. Where the problems arise they were resolved with validated design solutions on micro examples and case study data, in order to achieve the design aims. This stage explained in detail in section 4.2.

4.1.3 Modelling and development stage

Development stage in this thesis divided in two parallel implementation processes;

- **Hardware**
  - **Experimental** a series of proof of the novel concept by experimental setups and testing of the H_2O_2 generation by AQ process for a novel storage mechanism.
  - **Microcontroller (Raspberry – Pi)**
- **Software**
  - **Modelling**, researching and devising the models for the component parts of IHPS testing and improving the component models, in order to choose appropriate models for OGREH-SμG.

- **Software simulation**, researching and evaluating the appropriate simulation tools for designing IHPS and supplementing these with appropriate algorithms for the hardware platforms that form part of the IADF for OGREH-SμG. In this stage the new concepts are tested and calibrated by simulating it in the specified software platforms and testing the devised algorithms.

The purpose here is to resolve the design issues for the IADF for OGREM-SμG before the implementation phase. Development stage is explained in greater detail in section 4.3

4.1.4 Implementation stage

At this final stage all the main design issues that came in the development phase are resolved, and all the component parts of the IADF are tested with subsets of the case study data and results are analysed to verify that the design objectives are achieved and the results can be verified. This process involved verification that the component parts i.e. the Simulink and HOMER simulations and the controller algorithms were able to facilitate calculations and analysis that would results in acceptable quality for the supply service i.e. voltage and frequency within the given design requirements. The framework includes economic feasibility calculations as in addition to the technical analysis and simulation stages for the design of the OGREH-SμG according to the design requirements set at the beginning of the design process before the final design is finalised and accepted. The implementation stage is explained in greater detail in chapters 5 and 6 in the context of associated aims, objectives and outcomes.

4.2 Iterative Analytical Design Framework (IADF)

As explained in previous sections the extensive literature review undertaken was used to determine and evaluate the gaps and the requirements of the design (planning and analysis) for IHPS. IADF provides a framework for the primary design methodology that can be undertaken to achieve the design aims derived from the requirement analysis for the IHPS and can be described in the flow chart in Figure 4.1b. The most significant feature of the framework is that it facilitates an evolutionary iterative approach to the design process.

Research type depends on the philosophy of the research. Based on the definitions of three paradigms of the research type and method, for this PhD thesis can be classified as mixed quantitative and qualitative method research. This research presents different types of information as explained in appendix L.

The IADF defines the software and analytical simulation platforms and the process whereby the initial primary designs and operational assumptions are generated and tested. Working within such a framework facilitates review of the prototype models and OGREH-SμG configuration against the design requirements and the technical and economic simulation and analysis results. Based on this feedback the modifications can be undertaken to reanalyse and simulate the new configurations and complementary variables. IADF methodology is expanded and further detailed in Figure 4.2.

Overall view of IADF methodology

This section further describes and details the methodology of the investigations that was undertaken to achieve the aim and the associated objectives and outcomes that resulted in an Iterative Analytical Design Framework (IADF) for the optimal designing of an Off-grid renewable energy based hybrid smart µ-grid (OGREH-SµG) with intra and inter-grid (µG2µG & µG2G) synchronization capabilities and a novel storage technique.

The IADF as devised helps the design engineer outline the system requirements, information that needs to be collected to plan and design IHPS. The collection and organisation of primary data such as, load, sun radiation and wind speed is included in the methodology and constitutes the initial design phase following the requirements analysis which is then followed by the technical modelling of the generation and network bus configuration necessary to meet the demand profile within the standard technical constraints for IHPS. This is then followed by the technical analysis and simulations technically feasible configurations are then analysed and simulated for taking into the account the capital and running cost and lifetime for every component to determine the economic feasibility. The process is iterative and evolutionary with the modification of the model and simulation parameters and variables as well as the connection configuration until an optimum design is achieved, that is a system that meets the demand within the technical operational constraints at minimum cost for the lifetime of the system.

The critical initial design stage is to be able to create a realistic load profile for the remote area for which the IHPS is going to be designed. For the case study used in this investigation a load survey was conducted, load for every house and electricity utilisation over a period of time (3 years for the present investigation – the load survey was part of an earlier MSc investigation). The resultant load profiles comprises of

1. Identify the different user (load) categories
2. For each category above daily, weekly, monthly (seasonal) and annual variations

The profiles for each category was estimated

1. By identifying and assigning a consumption profile for different devices surveyed to be connected for each user (load) category.
2. By assigning usage behaviour (time of use over 24 hours/ for typical week day and typical weekend/ for winter and summer) for each device.
3. Combining step 1 and step 2 for each user (load) category.

Once the above profiles are created they can then be used to drive the design and the simulation process.

The strategy used in IADF for the optimal designing of an OGREH-SμG with intra and inter-grid (μG2μG & μG2G) synchronization capabilities and a novel storage technique is a general technique and can be utilized as a generic IHPS design process. Such a framework can also be used for

1. Operational planning purposes for different contingencies
2. Expansion planning scenarios involving several (OGREH-SμG)
3. Fuel and maintenance planning.

The overview of IADF is based on 6 step iterative evolutionary approach where the iterations are triggered with the technical and economic analysis. The overview of the chart in Figure 4.1b is explained below

- Box 4.1b1 shows the secondary and primary data and information collection stage for identifying the climatic conditions in the case study area, in order to understand the historical framework as explained in detail in section 4.3.1.

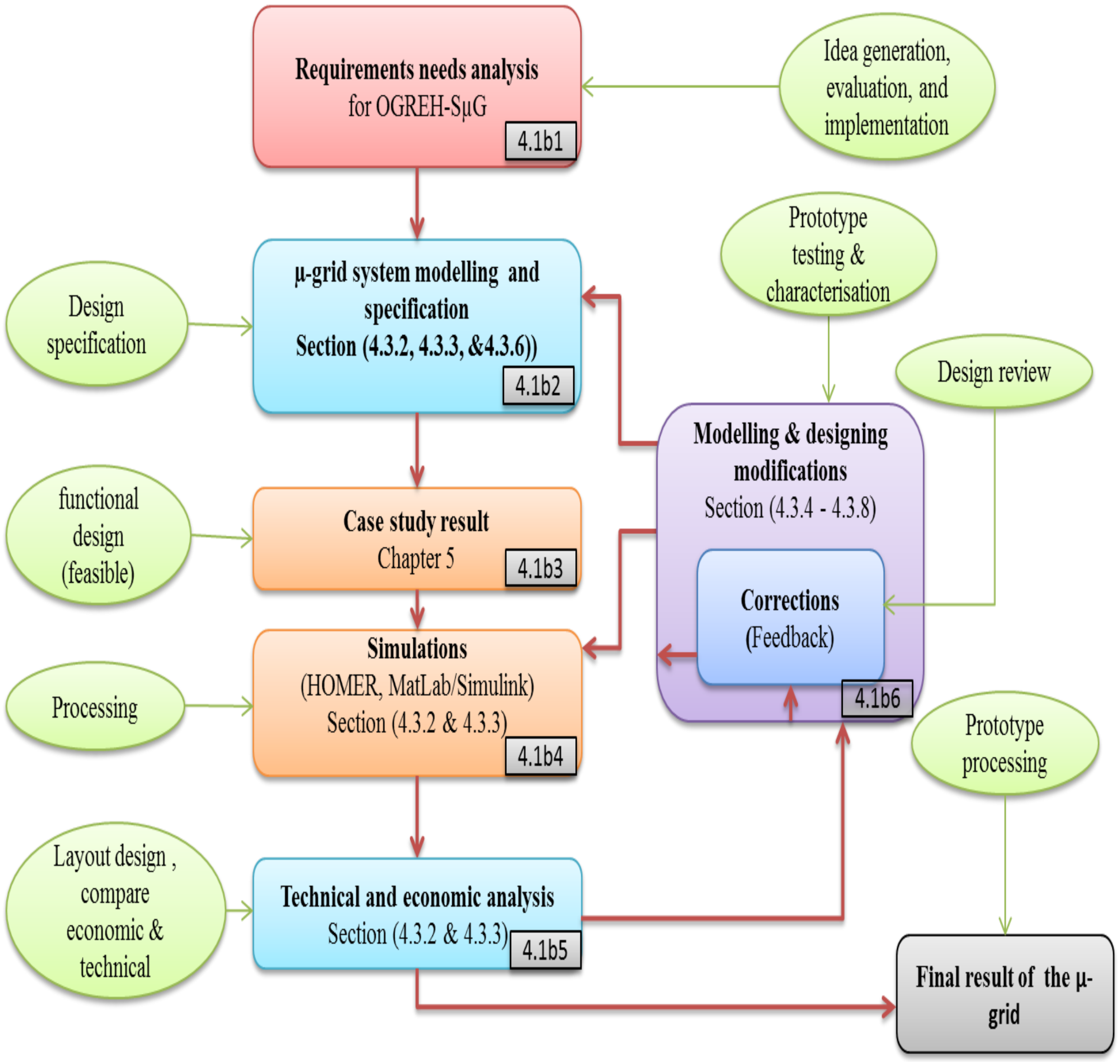


Figure 4.1b: High level (Summary) Overview of IADF.

- Box 4.1b2 describes the modelling and the specification stage an essential part for designing IHPS as explained in chapter 2, an essential part of this modelling stage was to mathematical formulation of the objective function to optimize the cost of the IHPS components as detailed in section 4.3.6.
- Box 4.1b3 signifies the stage where the primary data and information necessary to run the case study. These data are average sun rays, wind speed, and to know and measure hourly, daily and monthly average demand load for the case study, in order to understand the meteorological information (in

order to select the appropriate RES) and the demand (to help select the optimal size of generating units). This box is explained in great detail in chapter 5.

- Box 4.1b4 signifies the stage where simulation tools chosen for designing IHPS i.e. HOMER and MatLab/Simulink software tools which were used to simulate off-grid systems to study the dynamic behaviour and the economical feasibility as described in sections (4.3.2 and 4.3.3) and the models derived for these simulators are used to analyse and simulate the initial design assumptions and configurations of the IHPS.
- Box 4.1b5 evaluates technical and economical ability of the system to survive a range of load and contingency conditions. Technical analysis and simulation (Box 4.1b4) is conducted to achieve the optimal set points and configurations so that the voltage, frequency and line loadings are within the required operational boundaries and this technical analysis is complemented with the economic analysis (feedback as described in sections (4.3.2 and 4.3.3)) to ensure an optimal (lowest cost within the operational constraints) solution.
- Box 4.1b6 represents the process whereby;
    - Technical performance issues related i.e. generator/bus configuration, arise during the analysis simulation.
    - Economic performance issues in terms of the analysed and simulated design achieving lowest cost can be resolved.

At this stage the performance is improved by the incremental and evolutionary changes to parameters and the variables of the models used in the analysis and the simulations.

The inner corrections box represents the process where incremental changes are made to the models to improve performance and the outer box represents the design changes trialled for larger improvements after the limits are reached with the correction phase. The driver for this process is to meet the design requirements at minimum cost. The details of this process are explained in sections (4.3.4 - 4.3.8). Both loops are iterative and evolutionary until the design solution µG is finalised and accepted.

4.3 Details of IADF methodology implementation

The evolutionary approach in the primary IADF is explained in detail. The IADF methodology, based on 8 steps to utilise and evaluate the IHPS for this study to design an optimal system (OGREH-SµG) is shown in Figure 4.2 (The Detailed IADF) flow chart.

Due to the complexity of the IADF this detailed chart is initially explained briefly below for an overall view of the IADF and the iterative processes involved. This is followed by a detailed explanation of each block and processes within these boxes are detailed in the sections indicated in the chart:

- Box 1 indicates the secondary and primary data and information collection stage for identifying the climatic conditions in the case study area, in order to understand the historical framework as summarised in section 4.3.1, and explained in great detail in chapter 5.

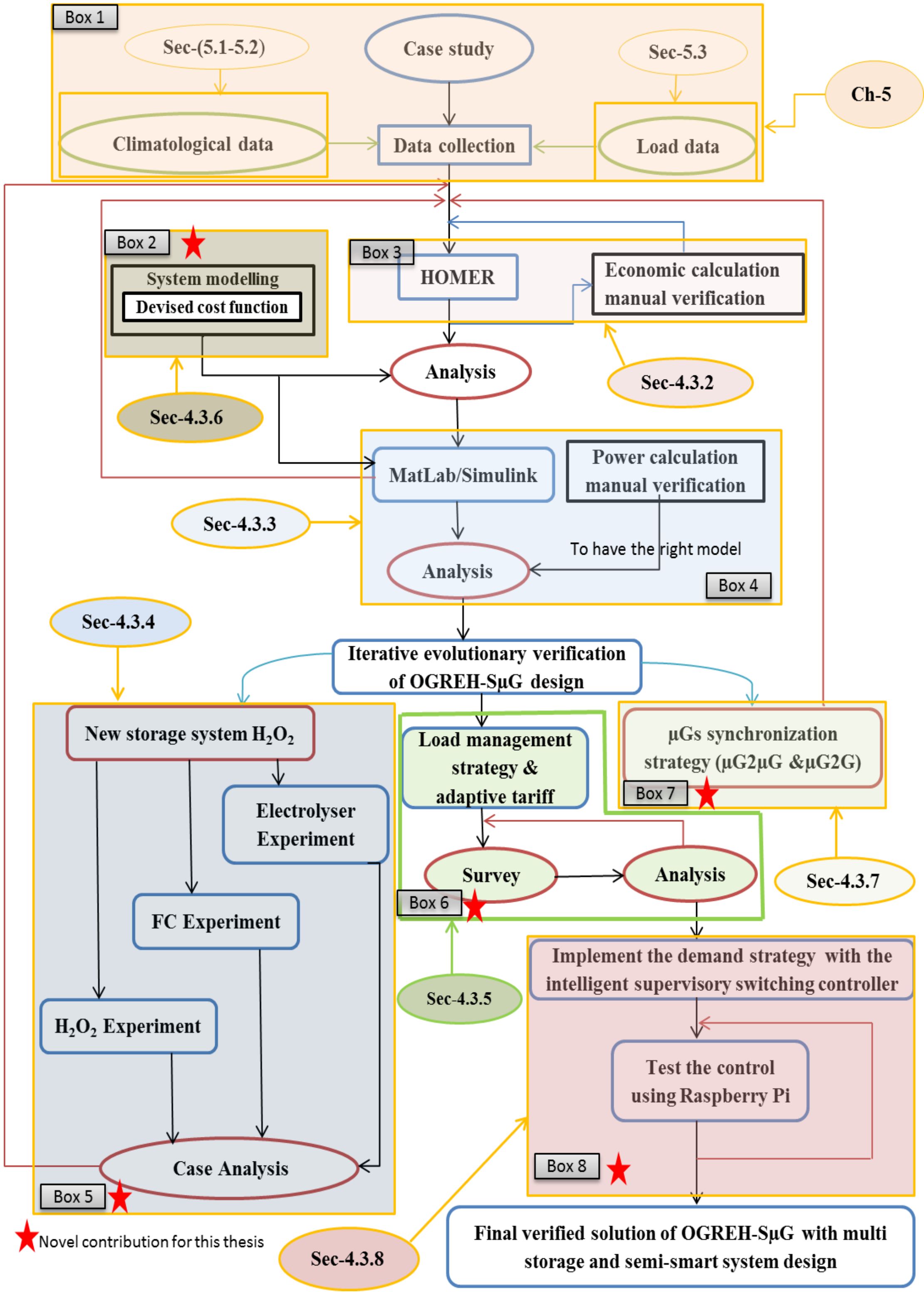


Figure 4.2: The Detailed IADF.

- Box 2 describes the modelling and the specification stage an essential part for designing IHPS as explained in chapter 2. An essential part of this modelling stage was the mathematical formulation of the objective function to optimize the cost of the IHPS components as detailed in section 4.3.6. As well as the detailed simulation components models for RES (PV and WTG), storage (battery and FCs), and DG, as detailed in section (4.3.2, 4.3.3).

- Box 3 signifies the stage where HOMER simulation tool was used to optimize the validity of the simulated system for the generators (RES, DG, and storage) mix chosen from three perspectives; the sizing of the generation, meeting demand at minimum cost as explained in section 4.3.2. This information is useful in deciding to precede the next analytical stage described below.
- Box 4 demonstrates the MatLab/Simulink software tool, in order to show the sustainability and reliability of the simulated system by studying the dynamic behaviour. The benefit of this simulation is to characterize voltage, current, and frequency in every cycle to insure harmonious operation as described in section 4.3.3.
- Box 5. Before this stage the initial simulation was undertaken for battery and H_2-FC as the only reserve power. This shows the experimental part to test the novel storage system. The lab analysis was taken to increase the system durability and reliability which depends on available power to resist any change over long term of operation, as detailed in section 4.3.4. After that lab work the results were applied as a feedback to HOMER and MatLab/Simulink simulation tools.
- Box 6 demonstrates the survey which was carried out to understand the behaviour of the consumer, and the effectiveness of installing smart systems

to control their consumption and assessing the effects of their addition upon some electrical properties, of importance for electrical controlling success, of the two ways to control demand loads, as explained in section 3.4.5.

- Box 7 shows intra and inter-grid (μG2μG & μG2G) synchronization capabilities as explained in section 4.3.7. (Studies simulated in Simulink).
- Box 8 presents a micro controller (Raspberry Pi) to control the OGREH-SμG. A Raspberry Pi device will be installed as a controller for demand management, so that the demand is controlled to be no more than the available power (in terms of generated and stored power) at any time, and control the GPs. Raspberry Pi is used due to its cheapness and ease of control. As explained in section 4.3.8.

4.3.1 Data collection

As in (Figure 4.1b, box 4.1b3) and in (Figure 4.2, box 1), the accessibility and sizing of PV and wind turbine at a specific location are decided by the climatological situation. For each particular site, climatologic conditions, including sun rays, ambient temperature profiles, and wind speed, has to be compiled for having maximum sustained power from renewable resources. An investigation for the qualities and circumstance of sun rays and wind speed at a particular place ought to be carried out at initial design stage. To implement sustainable design, long term climate information has to be collected. For this preset investigation 3 years of data was collected.

Many researchers use long-term analysis for climate data, such as Mahmoudi et al. (2008) used long term data for analysis of the Arabian Gulf. Also Dihrab and Sopian

(2010) reports PV-Wind-HPS for Iraq after analysis of climatological data. Shakya et al. (2005) reported a HPS (wind turbine and solar panels) for Australia. El- Hadidy and Shahid (2000) examine the potential of renewable energy in independent systems, depending on Dhahran meteorological station for climate analysis. Data collection in this research was based on both primary and secondary data collection, as described below.

4.3.1.1 Secondary Data, information and knowledge collection

The secondary data and information for related topics and keywords were acquired from journal articles, academic books and annual reports. Review and auditing for secondary data was carried out to identify the used system in every study; similar systems were chosen, in order to find the most suitable system for Jordan. According to the limited studies in the Middle East, the research was focused on studies done in different places with fairly close climatic conditions. Such studies can be useful for designing a hybrid system in Jordan, as a case study for this thesis to validate the conceptual IADF devised whereby the most recent studies were used to construct this contextual analysis in light of the most recent data and up dated information for the case study. Meanwhile, previous studies also were utilised in order to understand the historical framework and the gaps in these studies. All these studies are summarised and explained in chapter 2.

The ideas acquired from the literature review has assisted in establishing the gaps in the existing design approaches and form a foundation for the concept of IADF. This kind of research is required for further studies regardless of the fact that the cases are empirical, practical or theoretical. Therefore, the importance and the beneficial value of having a case study as described in chapter 5.

4.3.1.2 Primary Data collection

The target behind primary data is to analyse and predicts the weather in Jordan in order to identify average sun rays, wind speed, and to know and measure hourly, daily and monthly average demand load to the identified remote area. Moreover, the Meteorological information which related to the chosen RESs in the Jordanian remote area HPS as a part of generation power are imperative for the management of that framework. The meteorological information that was widely available was the ambient temperature, wind speed, and sun radiation at the chosen location.

The sources of information were searched in more than one source; mainly the raw data that has been acquired is sourced from three different sources for verification cross checking and averaging purposes as explained in detail section (5.1-5.3). The collected data covers a period of the last three years (2012-2014)[2].

Data analysis

Continuous investigation in renewable generators is a process from both the planning and operational perspectives. By understanding and analysing the required parameters of the renewable generation, it is conceivable to calibrate the performance of the generation power, such as climatological conditions, generation capacitance, and demand load conditions (average, peak load). SPSS, Scilab, and Microsoft Excel methods were used to analyse and characterise the collected data. These types of analysis make high credibility for the simulations utilizing these analysed data, by composing systems comparisons or modelling mathematical statements for new proportional circuit to fit with IHPS. Moreover, the finishing of

[2] The collected data has a major challenge, which is updated these data, regard to that the data for 2015 was not available.

the tables processing (for climatological conditions, generation capacitance, and demand load conditions) have been carried out by Scilab and Microsoft Excel. SPSS and Microsoft Excel have been undertaken to analyse the survey data.

4.3.1.3 Choosing the Feeding Modes (Power Unit Category)

Feeding modes are related directly to the generation and consumption of the power system explained in the literature review section 2.2. All modes depend upon the GP and the energy demand. Under different situations GP and demand energy will be controllable or uncontrollable. As indicated by this thesis, the service power provided by the OGREH-SμG contains one or more renewable energy source in the GP, meaning the GP is uncontrollable. This system is for a small community or domestic properties, which means that the load will also be uncontrollable. The feeding mode unit for OGREH-SμG will be a grid parallel unit.

Another important aspect of independent systems is the type of coupling needed, which will be discussed in the next section.

4.3.1.4 Type of coupling/bus

There are many configurations for the hybrid power systems as detailed in literature review section 2.3. In order to choose the right configuration, the designer must determine which system offers better reliability than the others according to the generation type and the mode of the load. The efficiency of the chosen type should be better than the other types. This is because the system is designed to optimize both the generation sources with the demand load by minimising energy loses and fully utilizing the generation. The economics of any choice is often the dominant factor, however, from the point of view of application, the generation sources and demand load are factors mainly responsible for determining the system topology, and the type of load is responsible for determining whether the configuration is single or 3- phase. Refer to Table 2.1, which explains the advantages and disadvantages between the types of coupling. Mixed AC/DC-bus with the configuration of three-phase was chosen for OGREH-SµG due the more compelling advantages that matched the topology of the system in the chosen area.

4.3.2 Simulation using HOMER Software

Figure 4.1b, box (4.1b4, 4.1b6)) and in (Figure 4.2, box 3), demonstrates the place of the HOMER (or similar) simulation platforms functionality in the IDAF framework. This is mainly to evaluate the two critical dimensions of Technical and economic feasibility and optimality of the design configuration under consideration, at each iteration (feedback and correction) until a final configuration is accepted based on a predetermined optimality based on the design specifications (Ketjoy et al. 2003).

The simulation platform called HOMER (Hybrid Optimization Models for Energy Resources) was created for this reason. HOMER was designed by the National Renewable Energy Laboratory (NREL) in 1992.

4.3.2.1 Introduction

HOMER is a simulation tool for both grids connected and off-grid systems, and can simulate a range of fossil fuel and RES based generators as well as storage technologies. The simulations conducted show the technical and economic feasibility of the various combinations and outputs of the generation mix to satisfy a set of demand (load) profiles and operational constraint.

Technically, the results demonstrate the ability of the generated power in the system to match the demand under various scenarios. The technical and economic output of the simulations can then be used to compare the simulated design with other possible alternatives or aspects of technical and economic design requirements.

The economic analysis yields net present value, life cycle cost, and payback period values for the design. HOMER only required inputs from the database per every area as explained in the previous section (data collection), to offer exceedingly precise results.

4.3.2.2 Use of HOMER for Sizing the Micro-Grids systems

HOMER is a sizing measuring tool for the generation power based on balancing load and generation mix. Optimally, the results are useful for examination of the system or to compare it with other systems. This simulation tool can offer precise results given a meteorological database included the data for the chosen area.

HOMER offers a realistic interface that is basic and straightforward; also it shows all input and output graphically in order to simplify understanding. It is enhancement and sensitivity investigation calculations permit the designer to assess the financial and practical sides of an expansive number of conventional power or alternatives (renewable energy) and to record differences between them both technically and economically. The concurrent technical and economic analysis shows the technical feasibility and economic status of a range of solutions and economic sensitivity analysis helps to find optimal solutions that satisfy all design criteria including contingencies.

HOMER is a technical and economic analysis simulation platform that can simulate IHPS configuration steps and calculate the results of 3 significant analytical processes listed below:

- “Simulation: simulate the power system for a year with adjustable time parameters from 1 minute up to 60 minutes, in order to balance and consider the operational generation mix with the demands, including storage system and/or grid connection with their mode (such as, Battery: charge or discharge, Grid: as generator or as storage). This simulation allows the designer to determine feasible configurations i.e. generated power under specific conditions to meet the demand. It can estimate the economical feasibility for the system over its life time (capital cost, running cost, and fuel cost…etc.).
- Optimization: in this step the tool analyses every conceivable combination of components in a single run, and after that it simulates the entire possible configuration, where theses configurations are sorted as a list according to the optimal choice by using the cheapest life cycle cost.
- Sensitivity analysis: in this step the tool gives the designer a chance to set a number of input variables for every single parameter, on the grounds that variables are unable to be controlled in all components, where there is no ability to know the significance of a specific variable or choice without running hundreds or a great many simulations and looking at the outcomes. HOMER repeats the optimisation step for every single sensitive variable.

4.3.2.3 Access for real sizing of systems

This thesis aims to design IADF for OGREH-SμG with a generation mix that could consist of conventional generation, such as DG and CHP unit and/or RESs, such as

PV, wind turbine, and hydro power, probably complemented by a storage system. Therefore the simulation and analysis platforms in the framework have to cater for these types of generation.

Lambert et al. (2005) and Lilienthal et al. (2004) reported the followed suggestions that are helpful for electrical sector. These suggestions were used to glean overall IADF for designing OGREH-SµG;

- Expand the independent power system quality and sustainability studies. The simulation is able to show whether the generation can match the demand, and will indicate if the system requires a change in the generation and storage mix or capacity in order to increase the power reliability.
- Fuel planning and utilization. There are elements which help to save fuel or to reduce the using of fuel, by maximising the use of storage and RES.
- Decreasing greenhouse gases emissions by maximising utilisation of RES.

4.3.2.4 Discussion

The planning and design of a micro-grid can be time demanding option, because of the vast number of configuration choices and the uncertainty of the variables for example, demand/load growth and future fuel cost. The main critical variable is the intermittency and the variability of RES, and hence fluctuating generated power that has to satisfy a load/demand that is variable but mostly with a predictable cyclical (daily, weekly, monthly, seasonal, and annual) pattern.

The devised IADF for OGREH-SμG utilising simulation platforms such as HOMER is intended to overcome these difficulties (Lambert et al. 2005, Lilienthal et al. 2004).

HOMER has the ability to allow the designer to choose the type of coupling bus configuration for the designed system depending on configuration of generation power and demand/load as design requirements. Also there are various ways of modelling loads such as hydrogen load, two types of thermal loads, and two electrical loads (primary load and deferrable load) that can be used in these simulations. After all the required generation and load information has been input along with the rest of the design constraints the simulations can be undertaken.

4.3.2.5 Modelling OGREH-SμG using HOMER

Figure 4.3 shows the schematic diagram of the final model of the chosen system, where the components are chosen to optimize the system. The design represents the "Grid Parallel Unit" containing mixed DC/AC–coupling. The components in the AC-bus are DG and WT as AC power generation, where the set of the DG is hardly operated as it is meant to be the standby generator. The second part is the load with all houses presented as one load. The bidirectional converter is joining the AC-bus with its counterpart the DC-bus, which demonstrates the ability of the power to travel from the AC side to the DC side and vice versa. The components in the DC-bus are PV, H_2-FC, and H_2O_2-FC as DC generation, battery bank. H_2-FC, and H_2O_2-FC are the reserve power for the system. The extra power is stored in the battery bank or used to electrolyze the water. The electrolyser stores the H_2 and O_2 in tanks and part of it is converted to H_2O_2 through the AQ process in order to use H_2 and H_2O_2 as fuel for the FC to cover the deficit in power.

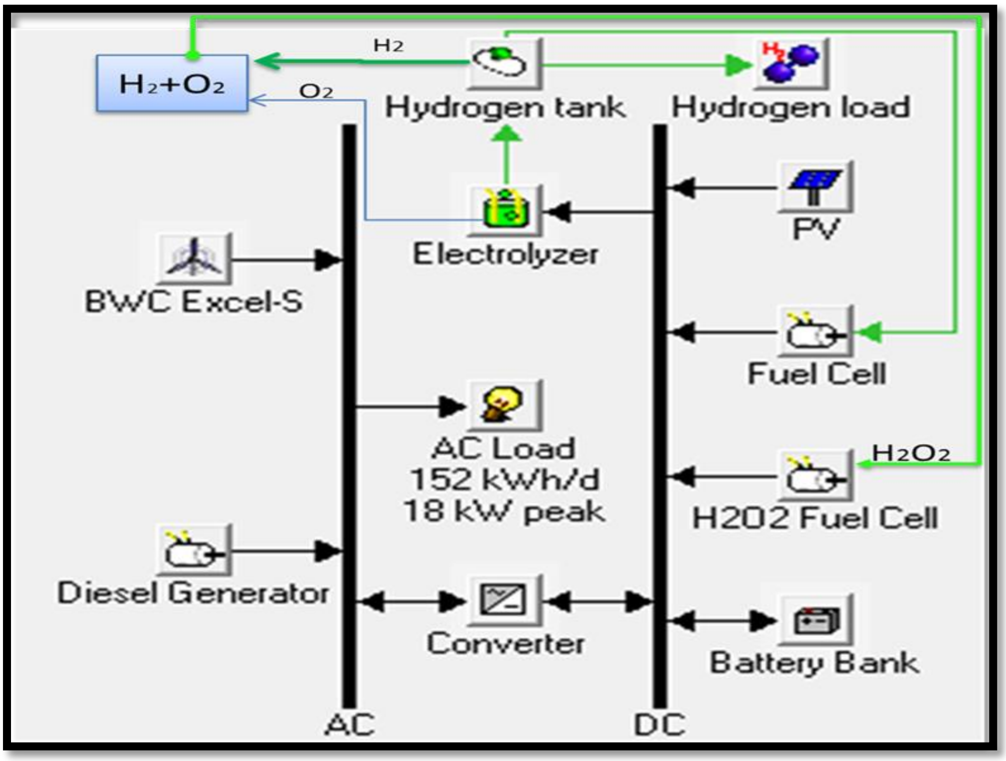


Figure 4.3: The schematic diagram of OGREH-SμG by HOMER.

4.3.3 Simulation using MatLab/Simulink Software

Figure 4.1b, box (4.1b4, 4.1b6)) and Figure 4.2, box (4) represents the stage of IADF where initial design set up is technically analysed, which has already passed the HOMER simulation stage. In MATLAB, μG will be analysed in terms of synchronization and bus configuration to match the operational criteria such as frequency and voltage constraints.

4.3.3.1 Introduction

This stage is about the dynamic simulation of micro-grids at specific operational discrete points within the operational range using MatLab/Simulink Software to demonstrate the operational feasibility of the generation mix and bus configuration in meeting the demand. It is part of the iterative process where if the input generation mix, configuration of grid components for voltage and frequency control as well as synchronisation does not prove to be viable i.e. it cannot match demand within the operational voltage and frequency constraints of the generation mix, configuration of the IHPS and components are resized and reconfigured for improving the system performance. This is verified again by HOMER simulation before coming back to this step for a repeat technical analysis as described above.

The operational behaviour (frequency and I-V characteristics) of IHPS is simulated under various operational points for load-sharing between the generators to verify that the voltage and frequency will be within the operational design constraints. The stage is necessary as the HOMER like simulators used in section 4.3.2 of the framework simulation only check that the power balance is satisfied and evaluate the economic cost of the generation mix. The only significant difference between the two simulations reported in the literature is that Power balance and economic evaluation are automated (calculated over a time period driven by the demand profile) whereas analytical simulations reported were (due to computational burden) conducted individually over several discrete operational points on these demand profiles for different contingent generation mixes. In the present investigations simulations were automated to be driven by the demand profile where it is devised as a load controller model in MatLab/Simulink.

4.3.3.2 Use of MatLab/Simulink for calculating and measure the voltage and the frequency of the system

This part details the technique to help choose IHPS components and verify that the given generation mix to match the demand will result in acceptable voltage and frequency supplied. MatLab/Simulink simulation aims to simplify and improve the IHPS for all demand requirements as indicated by the demand profile. The cyclic nature of the demand profile makes it easier to characterize voltage, current, and frequency for every demand profile cycle to ensure that the voltage and frequency constrains are satisfied throughout the year and for contingency situation.

Key calculations in these simulations are listed below:

- Voltage and current at output of every generation and at the input and at the output of every other device, such as inverters, in order to compare the V-I characteristic in the whole demand cycle.
- Frequency.
- Active and reactive power flow calculated as follows
    - Calculate the generated power individually.
    - Calculate the duration of every generated power.
    - Calculate the supply mismatch difference between the demand load and available power (generated and stored power).
- The required power in every demand cycle.
- The existing power and compare it with the storage power
- The synchronising between the power generations

4.3.3.3 Discussion

Initialisation Stage: For the analytical simulation stages initially modelling of the individual IHPS components were undertaken, this was then followed by the simulation of these individual components for verification of these models by comparing these with published results, thus a library of models were created and verified. This stage has to be repeated if the library does not contain a model of the RES or some other components that needs to be modelled in other studies, therefore this is the part of the framework where it is not generic and might have to be customised for different users.

Simulation stage: After the modelling library is created the micro grid that passed the HOMER demand matching and economic evaluation feasibility stage can now be modelled using the models from the model library.

The MatLab/Simulink simulations were driven by the demand function summated with constant loads representing the demand required for cooling, control and the electrolyser (storage). The main components which have been simulated are explained in more detail with their devised models in the next section.

4.3.3.4 Modelling OGREH-SµG using MatLab/Simulink

The final generation mix that has been as the most optimal in the HOMER simulation stage has been modelled in MatLab/Simulink tool, where the components are chosen to optimize the system, the schematic diagram Figure 4.9. Also the design represents the "Grid Parallel Unit" as explained in section 4.3.1.3, contain three-phase mixed DC/AC–coupling as detailed in section 4.3.1.4. Next part will present the modified models individually for the chosen system.

4.3.3.4.1 PV model

The Simulink model for PV is implemented as shown in Figure 4.4, where the main components of this model is the solar cell (Figure 4.4 a); the first step is to connect the solar cells in series and in parallel to achieve the required voltage and current (Figure 4.4 b and c). Every cell contains:

- "+" terminal signifying the positive electrical voltage,
- "-" terminal signifying the negative electrical voltage, and
- "IR" terminal signifying the incident irradiance input.

Figure 4.4 e represents the IR input signal. IR is modelled by modifying a sine wave by using a switch with 2 constant values and a clock to represent the IR variation (Figure 4.4 f is represents the IR input signal). This input model also required "S-PS converter (Simulink signal to physical signal converter)" because the sun radiation model is a Simulink signal and the solar cell system is a physical signal.

The PV model was designed using a physical signal. The solar cells are connected in series and in parallel to achieve the required voltage and current. As the model has a physical signal it requires a "solver configuration" to solve the parameters. Also the model required a "PS-S converter" as this also has to be carried out as a reverse process to convert the Physical signal to Simulink signal to demonstrate the outputs.

4.3.3.4.2 Wind turbine model

The Simulink model for WTG is built as shown in Figure 4.5 a (there are two wind turbines modelled in the case study (Figure 4.5 c)). The WTGs modelled have induction generators. The WTG model implemented contains:

- Input stage (Figure 4.5 b). The wind input is important for this model, regards to that a sum model to join the generate step function with the generate sine wave to represent the fluctuating in wind speed
- Model Figure 4.5 c, and explained in detail in Figure (4.5 d and 4.5 e).
- Output Stage Figure 4.5f. (voltage, current, power, and frequency)
- Protection system model as shown in Figure 4.5 g. This protection system is connected directly with the WTG "Trip", which applies the logical design (logical model, dynamic reading from the WTG, and delay/step delay) to decide the operational status of the WTG. The wind protection model

contains AC current and voltage unbalance, AC over and under voltage, and AC over current, also protection from over and under speed.

In the WTG model, both wind turbines contain three terminals for 3-Phase AC power "A, B, and C", also connected to three-phase V-I measurement to show individual outputs, then they are connected to each other through port connection to join the system. Both WTG can show individual outputs as everyone has "m" (which represents Simulink signal for every WTG) and it can show 19 outputs (I_{abc}, V_{abc}, and power). Multi-meter is used as a measurement parameter for the voltage and the current for both WTGs at the same time, to one power system block. Send signal and receive signal are used in this model to reduce the wire connection as much as possible. Phase frequency model is used to generate the frequency according to the input signal.

4.3.3.4.3 Hydrogen fuel cell model

Simulink model for H_2-FC is built as shown in Figure 4.6 a, where the main component of this model is the "fuel cell stack" (Figure 4.6 b). The FC contains three outputs;

- "+" terminal signifying the positive electrical voltage,
- "-"terminal signifying the negative electrical voltage, and
- "m" terminal signifying the FC stack model output (it represent 12 output Simulink signals for the FC), part of this output is shown in Figure 4.6 c. These outputs are utilising and consumption of O_2 and $H_{2,}$ voltage, current, efficiency, and flow rate.

The input for the FC model is the fuel flow rate (Figure 4.6 d). To have the right flow that is needed the flow rate selector, which is modelled by having a flow regulator signal (Figure 4.6 e) that depends on the current of the FC modified by a MatLab function followed by limit upper and lower model. This step determines the fuel consumption according to the FC current, and a sin wave to generate a signal to represent the amount of stored H_2. Both flow signals are connected to the FC input through a selector operated by a special model to select which signal goes through. The selector output is connected to maximum and minimum value limiter model. This is then connected as the input to the FC model as the input fuel flow rate.

In this model there is also a mechanism to output the values calculated by the model called the "bus selector" in Figure 4.6 c. Two "bus selectors" were chosen for display purposes:

- First "bus selector" is showing fuel flow rate, utilising and consumption of O_2 and H_2, and the FC efficiency.
- Second "bus selector" is showing FC current and voltage.

To regulate the FC output DC voltage, a chopper model (buck converter) is used. Scopes, voltage and current measurements are used to represent the output of the model at the output of the chopper.

4.3.3.4.4 Hydrogen peroxide fuel cell model

The Simulink model for H_2O_2-FC is built as shown in Figure 4.7 a. This model is similar to the H_2-FC model with two different details; the size of the FC, and the fuel flow rate.

For the fuel flow rate there are three parts:

1. fuel regulator which is similar to the regulator in H_2-FC model, which determines the fuel consumption
2. special selector model to select which signal goes through the selector switch,
3. and finally the H_2O_2 storage model (Figure 4.7 f), using a sin wave to generate a signal to represent the amount of the stored H_2O_2, and a signal

from the regulator to represent the amount of H_2O_2 that is remaining. It also shows a fluctuation model to represent the availability of H_2 to produce H_2O_2 through the AQ process and the concentration of H_2O_2. All these signals (Figure 4.7 e, d, and f) represent the fluctuation in the H_2O_2 flow rate and the changes in the H_2O_2 concentration. The represented flow rate model is realistic and affective as it is highly accurate without the complexities of more sophisticated modelling.

4.3.3.4.5 Battery model

The Simulink model for the battery bank was built as shown in Figure 4.8a, where the model's main components are presented as follow:

- "Generic battery model" as shown in Figure 4.8b and explained in (Figure 4.8c). The generic battery model contains 3 outputs as described below;
    - "+" terminal signifying the positive electrical voltage,
    - "-"terminal signifying the negative electrical voltage, and
    - "m" terminal signifying the battery model output (it represent 3 output Simulink signals for the battery (voltage, current, and state of charge)). Voltage and state of charge are shown in Figure 4.8f.
- Controlled current source as shown in Figure 4.8d, in order to control the battery charging mode.
- Chopper model (buck converter) as shown in Figure 4.8e, to regulate the battery output DC voltage.
- Scopes, voltage and current measurements are used to represent the output of the model at the output of the chopper. In this model there is a "bus selector" to represent the calculated outputs Simulink signals for the battery.

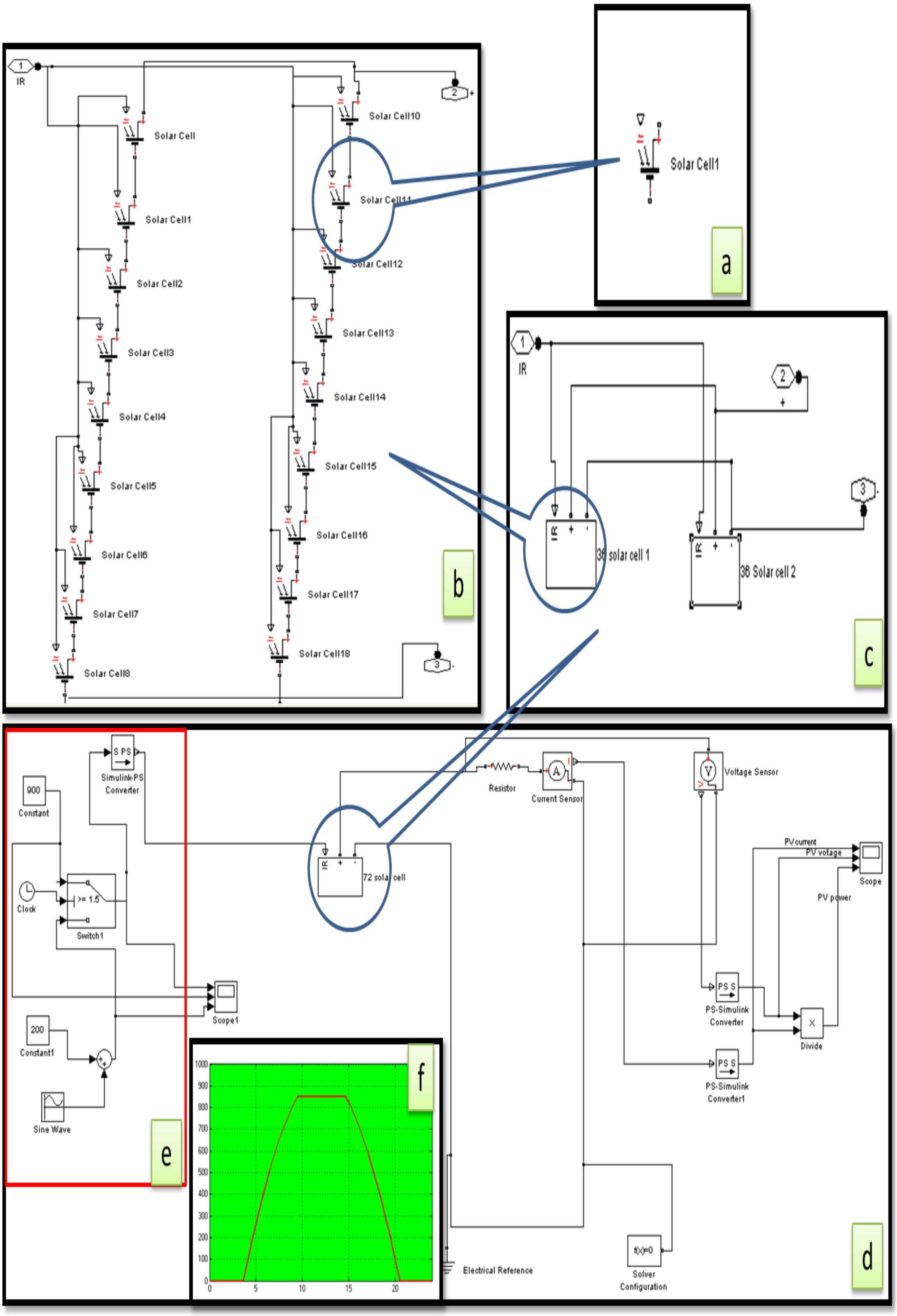


Figure 4.4: PV model by Simulink.

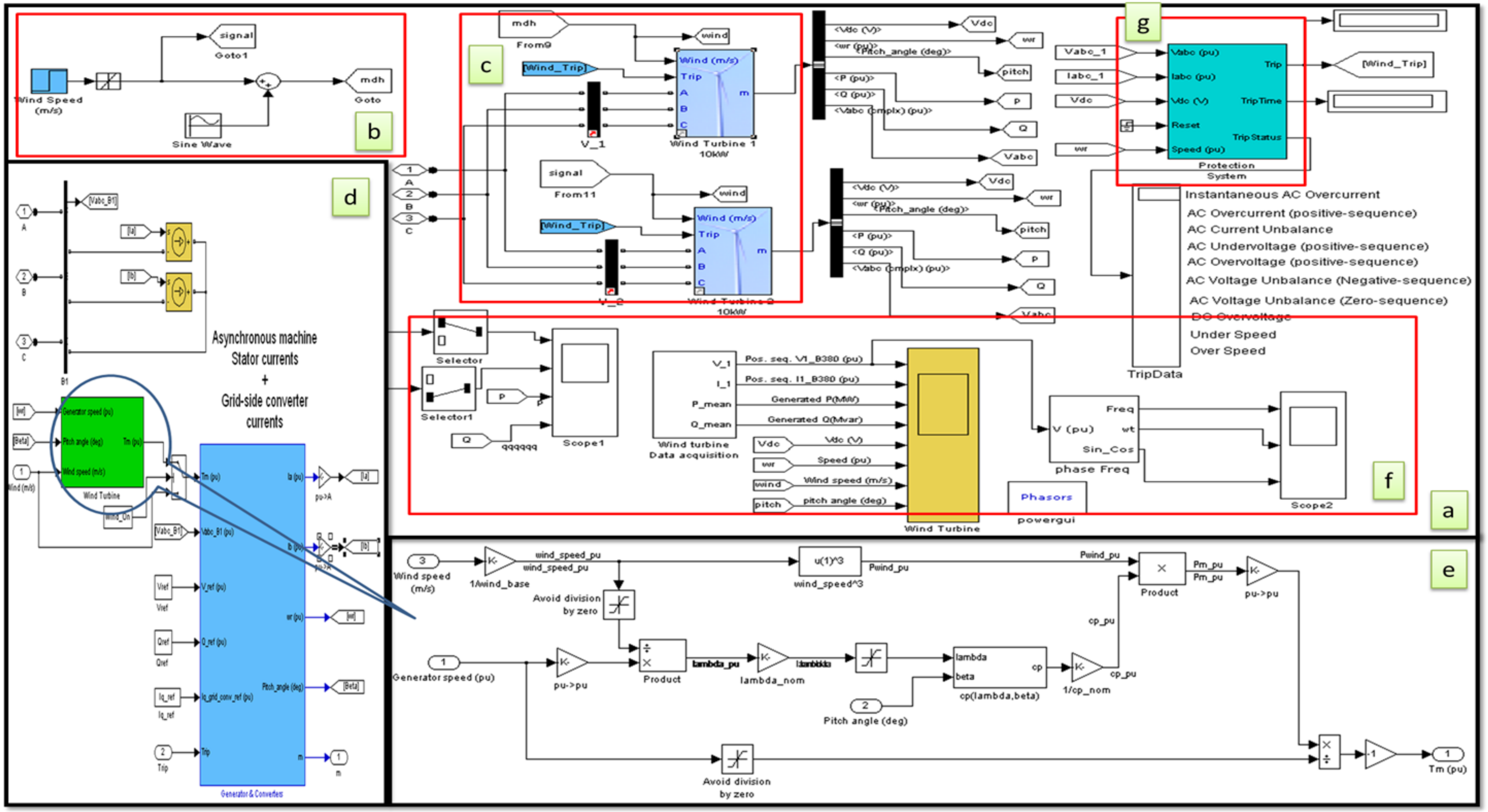


Figure 4.5: WTG model by Simulink.

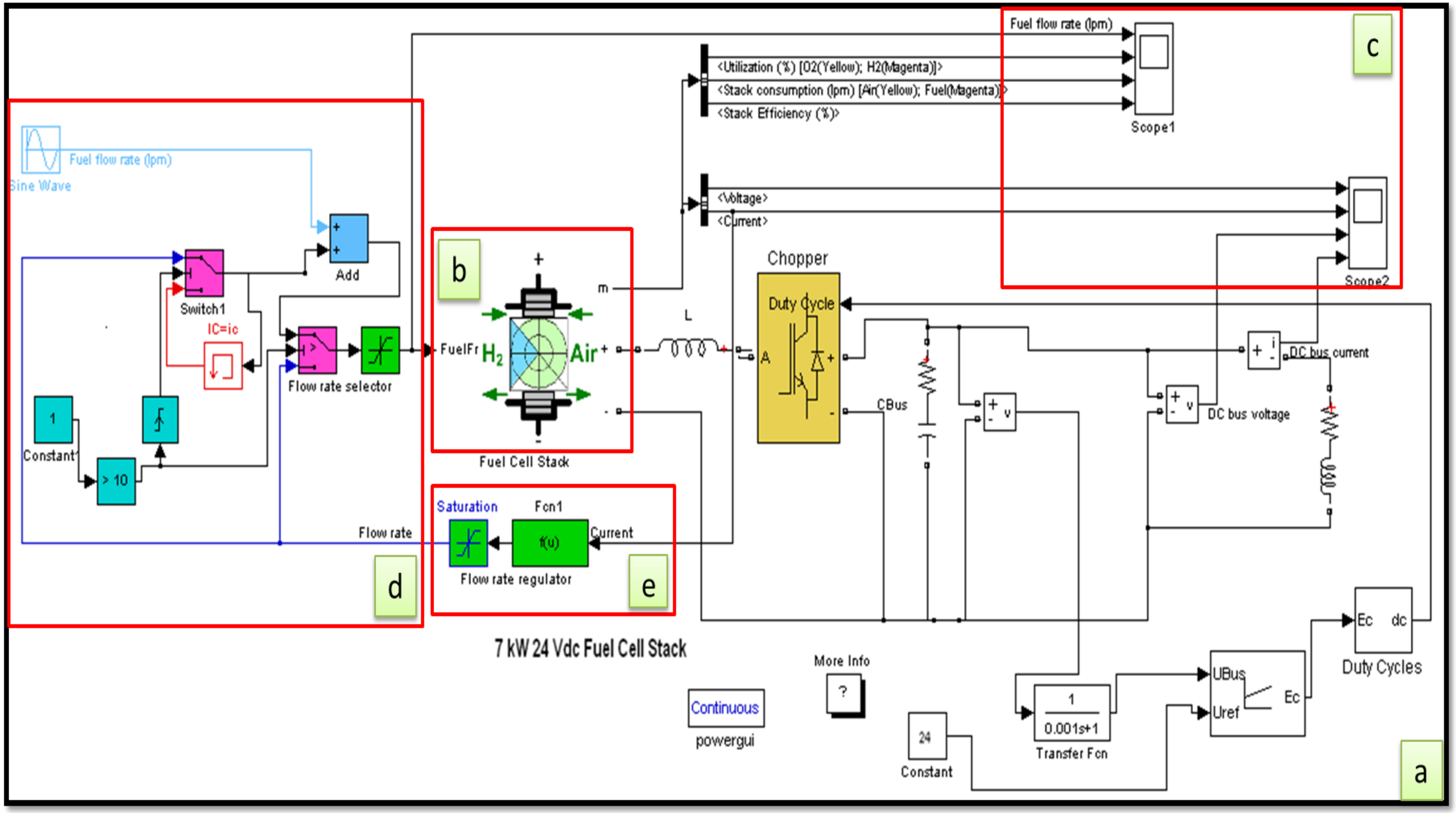


Figure 4.6: Hydrogen FC model by Simulink.

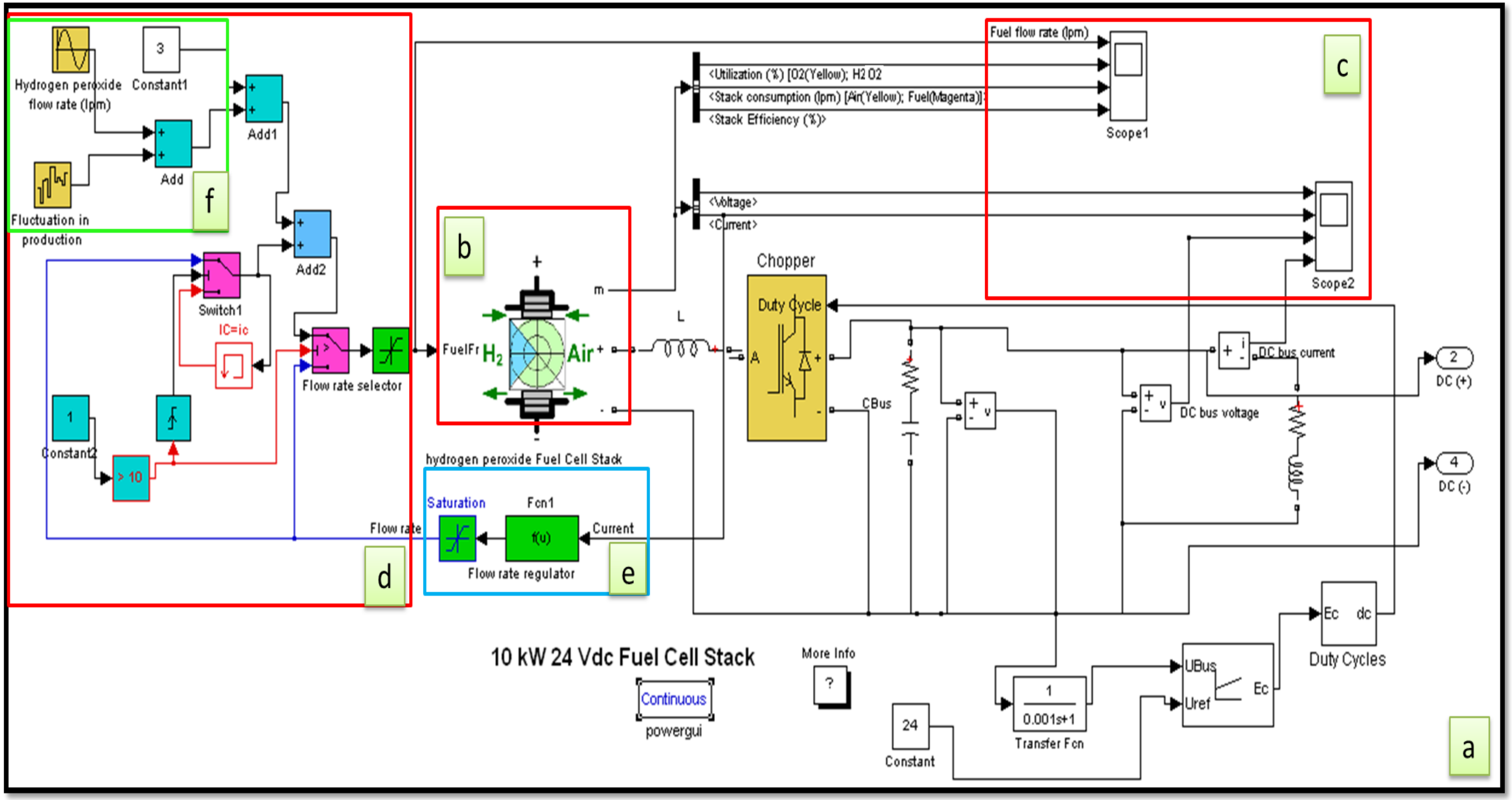


Figure 4.7: Hydrogen peroxide FC model by Simulink.

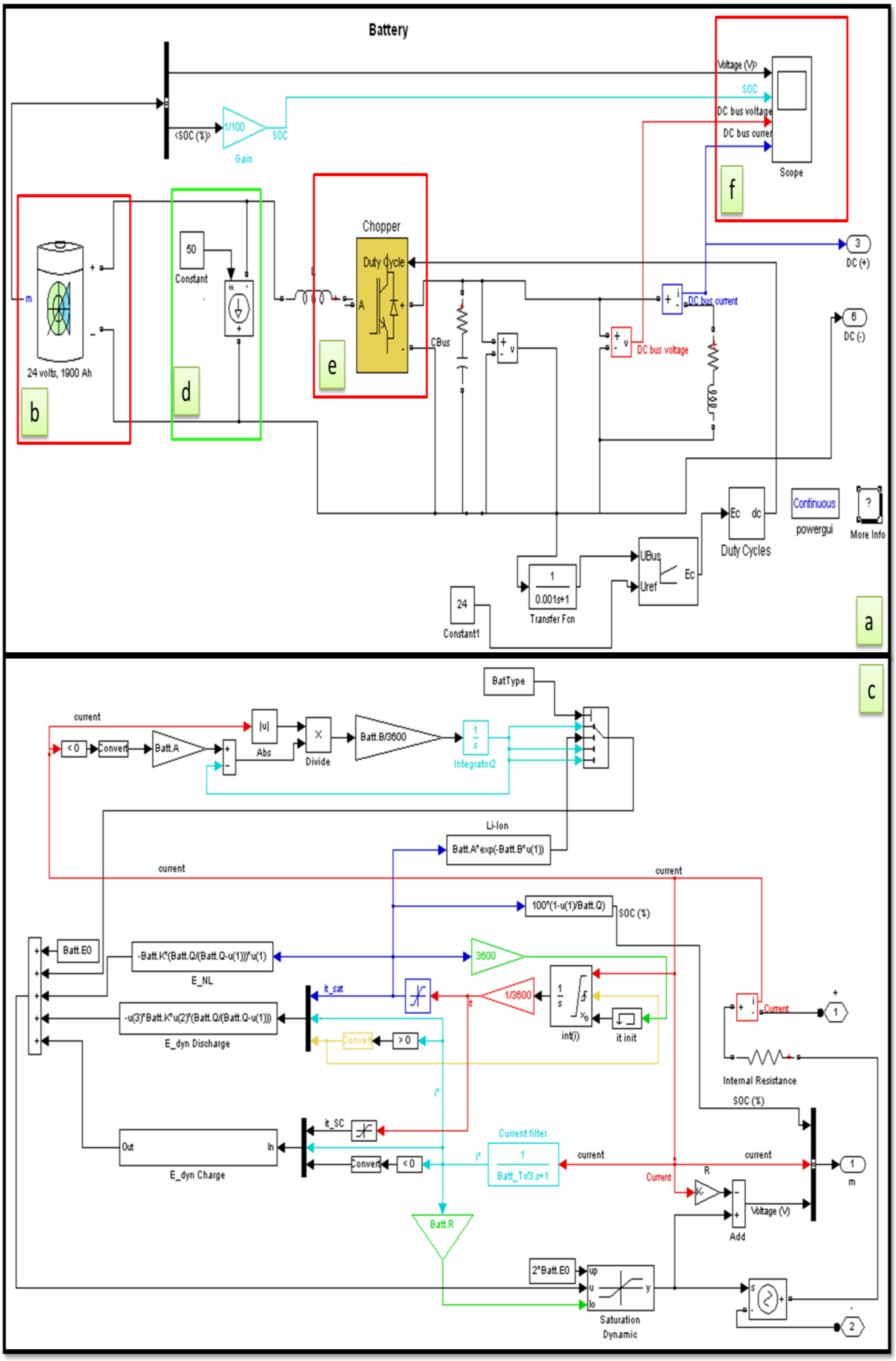


Figure 4.8: Battery bank model by Simulink.

4.3.3.4.6 Diesel generator model

Simulink model for DG is built as shown in Figure 4.9 b, which represents the whole OGREH-SμG model that was designed and simulated within the IADF. The DG in OGREH-SμG model of is implemented as a three-phase source which contains three terminals for AC power “A, B, and C”. This model is shown as a part of the system connected directly to the AC-bus before the rectifier as shown in the same Figure.

4.3.3.4.7 Bi-directional converter model

Simulink model for bi-directional converter model is built as mention in Figure 4.9d. Rectifier model and inverter model “power electronic devices” are used to represent the bi-directional converter. Rectifier model is used to demonstrate the flow of AC power from WTG and DG to the load and/or converted as stored power. Inverter model (insulated-gate bipolar transistor) is used to demonstrate the flow of power from DC-bus (PV and reserve system) and AC-bus (WTG and DG) as it is converted and regulated to AC. The used inverter model contains a gate input in order to regulate the voltage to the required level, and it needs a “voltage regulator model” to operate the gate as is demonstrated in Figure 4.9e. This model uses a discrete signal to generate a sin-cos signal to have a transformation according to reference voltage then to send it to PI controller. After that the signal is transmitted to a discrete generator to generate pulses to the inverter gate using logic models.

4.3.3.4.8 OGREH-SμG model

Simulink model for OGREH-SμG model is built as shown in Figure 4.9 a; this model contains the follow components:

- DG (Figure 4.9b) connected directly to the 3-phase AC.

- WTG models are connected directly the 3-phase AC with DG as an input for the rectifier model.
- Bidirectional converter model (Figure 4.9d) contains;
    1. Rectifier model, the input is AC power and the output is DC power "+,-", where the DC-bus is connected directly.
    2. Inverter model, the input is DC power "+,-", and pulse signal from the voltage regulator, and the output is connected to the demand through filters and measurements units.
- DC-bus (Figure 4.9c) contains PV, Battery, and both FCs. Both DC-bus and the rectifier output are connected to the inverter model input.
- LC filter is used to reduce the harmonic which is generated from both converters. then the system is connected to the end-use load
- V-I measurement model, is used to connect the load to the end-user. The output is used for the following,
    1. used to calculate and show the required measurements and also,
    2. used to modify signal (reference signal) to generate pulses through voltage regulator model and discrete pulses model to adjust the inverter gate.

The simulated OGREH-SμG was designed by using software tools, such as HOMER initially to obtain a feasible minimum cost solution and then simulated in MatLab/Simulink and with LCF simulations in order to further iteratively optimise the design under operational constraints criteria within the IADF. The interface for iterative feedback and the presentation of the final output within the framework have been undertaken by Microsoft Excel, HOMER, and MatLab (some results has been exported from Mat/lab to Excel by using protocol code as described in appendix J) for a more effective visual presentation.

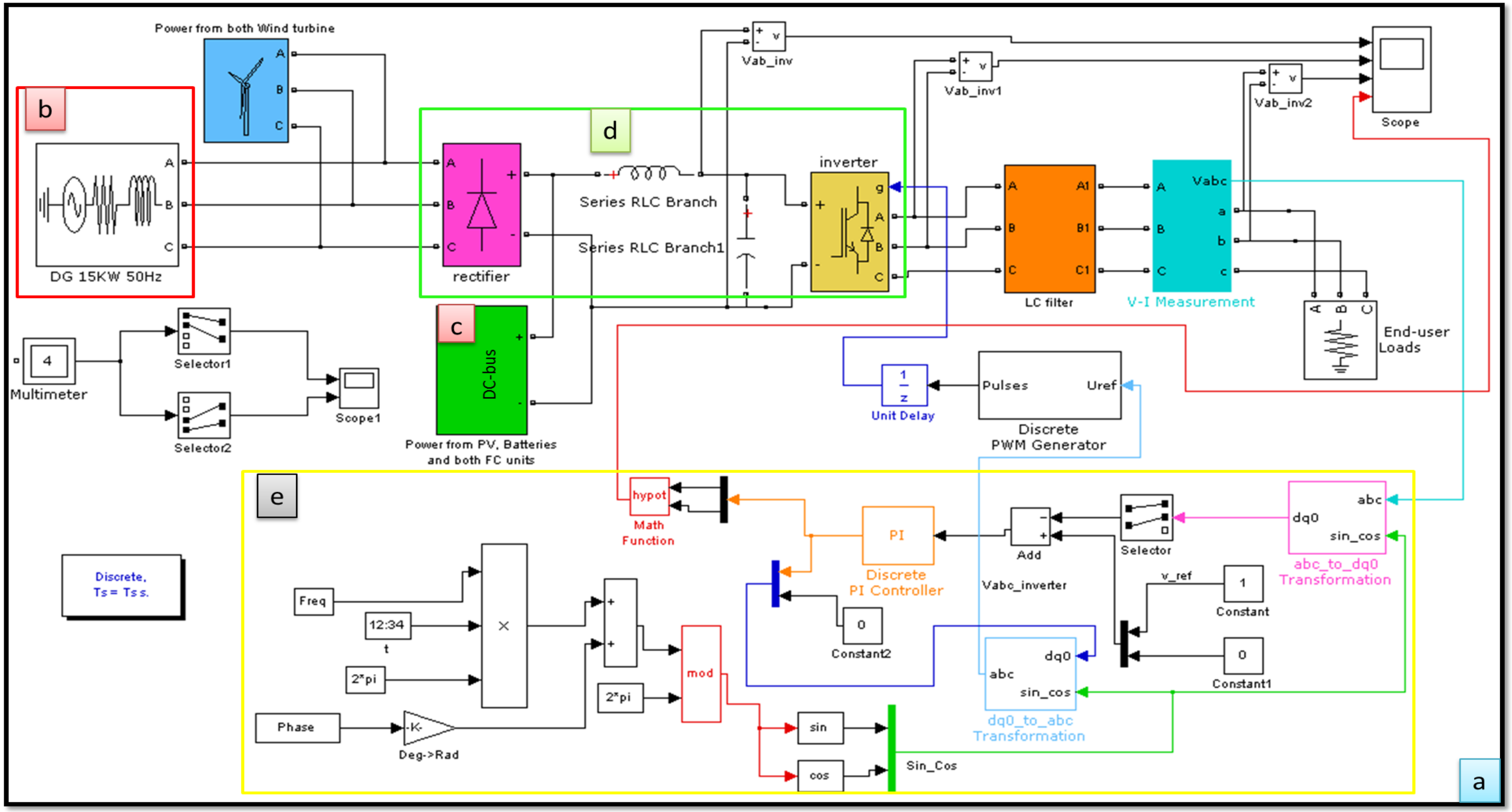


Figure 4.9: OGREH-SµG model by Simulink.

4.3.4 Proof of concept Investigations for H_2O_2, Fuel Cell, and Electrolyser (Practical Laboratory work)

Electrical storage has to play important and pivotal part in the future Power Grids especially with IHPS, as in other off grid applications storage might be a good operational practice but is not a must as there is a grid connection and the grid can be used as backup power. However it is also a requirement as good operational practice to mitigate against the intermittency and variability of the RES.

The main problem of storing electrical power is that presently it cannot be stored in the same form (stored directly – except in capacitors and superconductors) in large quantities for long duration applications. It requires conversion to another form in order to store it. This process can be expensive, with a short storage lifetime, or huge losses accompany such processes with power converted to another form and converted back to electrical power, when needed.

4.3.4.1 Introduction

The investigative work undertaken is shown in (Figure 4.1b, box 4.1b5) and in (Figure 4.2, box 5), has been undertaken to investigate a potentially novel storage approach to the problem of intermittency and variability of RES and introduce flexibility (lifetime efficiency, lifetime costs, and operational flexibility such as long storage, charging times, and losses) to the design of OGREH-SμG.

The objective of these experiments was to evaluate the usability of the diverse storage techniques by investigating,

1. amount of H_2 which can be converted from excess electrical power from the RES,
2. the amount of recoverable waste heat that can be used

    a. from the electrolyser generated during the conversion period,
    b. from the fuel cell
3. the efficiency of the fuel cell to generate power and
4. to test the effect of heat on the concentrate of H_2O_2 in long term storage.

4.3.4.2 Electrolyser

4.3.4.2.1 Electrolyser experimental setup

Hoffman apparatus was used to carry out the investigations with the electrolysis of water, in this lab analysis. The approach utilized here was a simple well known way to electrolyse into hydrogen and oxygen (Fabbri et al. 2010)

The objectives of this stage were

a. to investigate if there was a difference between the actual hydrogen production from electrolyser per hour and theoretical calculations that can be conducted using Faraday equation, and
b. to study if it was possible to recover waste heat from the process. In other words, will the hydrogen production be affected by the heat recovery/exchange process.

4.3.4.2.2 Electrolyser apparatus

1. Hoffman apparatus (code WJ.607, Jaytec, UK).
2. Two carbon electrodes (code WJ.609, Jaytec, UK).
3. Safety clamp (code WJ.610, Jaytec, UK).
4. Two crocodile clips 4mm plug (code EC1030, Mindsets, UK).
5. Bench power supply unit was used (1-13V) AC and DC (8.5A) (code F4G85458, UNILAB, Philip harris, UK).
6. Banana cables 4mm, 30cm (code 220091-01, Rojo, UK).
7. Digital multi-meter (code 37772, harbor Freight tools, UK).

8. Stopwatch (ACCUSPLIT Pro Survivor - A601X Stopwatch, Clock, Extra Large Display code 220091-01, Rojo, UK).
9. Water.
10. Thermometer Dual Scale (initial, UK).

4.3.4.2.3 Experimental Conditions

The procedure for the investigations described above was undertaken as follows;

1. Analysis in a lab with ambient temperature (21-26 °C) for 2 hours daily for five days (from 04:00 to 06:00 Pm);
2. Repeat the experiment three times for every voltage over a period of days, in order to have sufficient data to statistically verify the results.

4.3.4.2.4 The Experimental Procedure and Design

As shown in Figure 4.10.

1. The safety clamp bind with stand, then
2. the Hoffman apparatus linked with the clamp.
3. The two carbon electrodes installed inside the Hoffman,
4. the Hoffman filled with water, and
5. then the bottom end of the carbon rods connected by crocodile clips,
6. the clips connected by wires to the power supply and multi-meter.

Stage 1

After all equipment was connected the operation was started at 20V DC to 26V and the current from (1-6A) as this is the output of the RES sources that are connected to the DC bus as shown in Figure 4.3. The voltage and current were increased in increments of (1 V - 1A) and held at that voltage for ten minutes, when measuring the current (ampere) was also monitored to record the actual power that is delivered to the carbon electrodes inside Hoffman. In this set up;

- the cathode releases hydrogen and ● the anode oxygen.

Theoretically double the volume of H_2 is developed than O_2. Then the amount of released O_2 and H_2 were measured verifying the electrolysis process.

Stage 2

In this stage experiments were carried out to note the effect of water temperature on the Electrolysis process, the experimental set up is similar, however, he water was cooled from 45C° down to 25C° with decrements of 10C° then down to 10C° with decrements of 5C°, and then the same measurements as described in Stage 1 were undertaken and the O_2 and H_2 productions recorded.

4.3.4.2.5 Results captured and analysis

The outcomes from this test were captured in content records in a particular configuration in Excel file. The typical document configuration of this lab work is indicated in Appendix F. After that all measurement was demonstrated and analysed as it shown in the same appendix. The final results are presented and explained in results chapter.

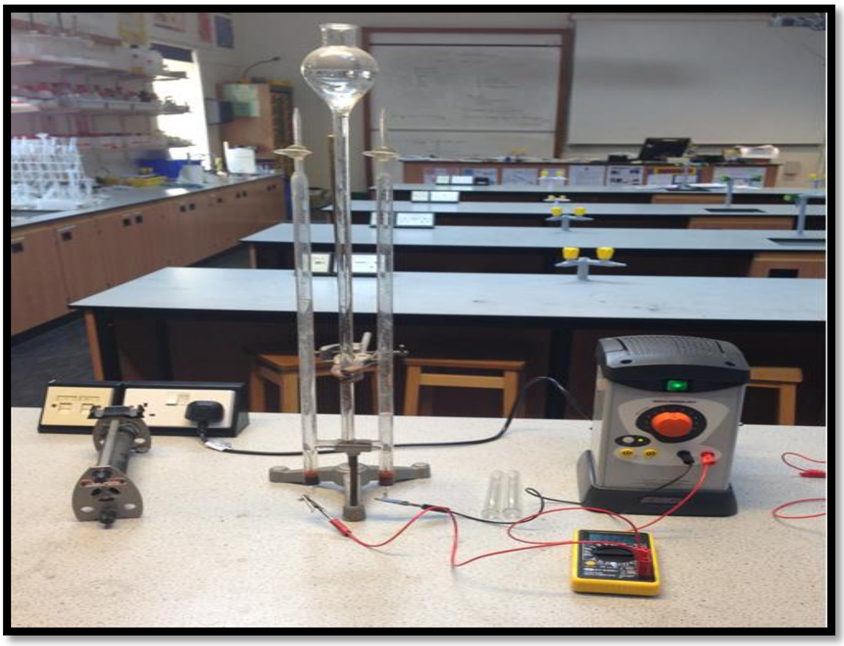


Figure 4.10: Electrolysis by Hoffman.

4.3.4.3 Fuel cell

4.3.4.3.1 Fuel cell experimental setup

The lab work was utilized here, to electrolyse the water into hydrogen and oxygen, both should be stored, and then both hydrogen and oxygen fed to a fuel cell to produce electrical power.

The objectives introduced in this stage were

a. to measure the difference between the electrolyser input power and the output power from fuel cell, that will guide to the calculate the electrical efficiency between input and output,
b. to study if it was possible to recover waste heat from the process in other words, will the hydrogen production be affected by the heat recovery/exchange process.

4.3.4.3.2 Fuel cell apparatus

1. Hydro-Genius package (code complete, heliocentris, Germany). It contain:
    a. Solar module.
    b. Motor. (Figure 4.11).
        I. Two plug terminal positive and negative.
        II. Motor stand.
        III. Propeller.
        IV. Electrical motor (0.2-3 V, 10-125 mA).
    c. Lamp 120W bulb.
    d. Gas volume measurement set, tubes and tubing for hydrogen and oxygen.
    e. Electrolyser kit. (Figure 4.12).

I. Electrolyser (160mm×130mm×210mm; 1.6-2.5V; 0-1,000 mA).
II. Two tip jack terminal positive and negative terminals.
III. Two half-cell (oxygen and hydrogen) generation.
IV. Two gas separator (oxygen and hydrogen).
V. Two scrubbers (oxygen and hydrogen).
VI. Protective diode

f. Fuel cell kit. (Figure 4.13).

I. Fuel cell (160mm ×130mm ×70mm; 0.4-1.0 V; maximum 2,000 mA).
II. Two tip jack terminal positive and negative terminals.

2. Bench power supply unit was used (1-13V) AC and DC (8.5A) (code F4G85458, UNILAB, Philip harris, UK).
3. 12 Banana cables 4mm, 30cm (code 220091-01, Rojo, UK).
4. 4 Digital multi-meter (code 37772, harbor Freight tools, UK).
5. 2 Digital Joule-meter and wattmeter (code 082.605, UNILAB, UK).
6. Stopwatch (ACCUSPLIT Pro Survivor - A601X Stopwatch, Clock, Extra Large Display code 220091-01, Rojo, UK).
7. Water.
8. IR Infrared Digital Temperature Gun Thermometer Laser Point (-50~900 °C) Non-Contact (code GM900, INFRARED, China).

4.3.4.3.3 Experimental Conditions

The procedure for the investigations described above was undertaken as follows;

1. Analysis in a lab with ambient temperature (21-26 °C) for 1 hour daily for ten days (from 04:00 to 05:00 Pm);
2. the model was fixed position horizontally,

3. the experiment has been repeated five times for every voltage and temperature over a period of days, in order to have sufficient data to statistically verify the results.

4.3.4.3.4 Procedure and design

1. preparing the motor as shown in Figure 4.11,
    a. place 4 supports to the indicated corners in the motor stand base,
    b. then fix the motor to the base by the screws and insure the shaft is inserted throw the hole,
    c. then the cable clamps are places in the indicated place in order to fix the motor lead.
    d. The final step is to fit the propeller to the axle and make sure it is firmly held without being loose, taking into account the propeller is free from the base and able to turn.

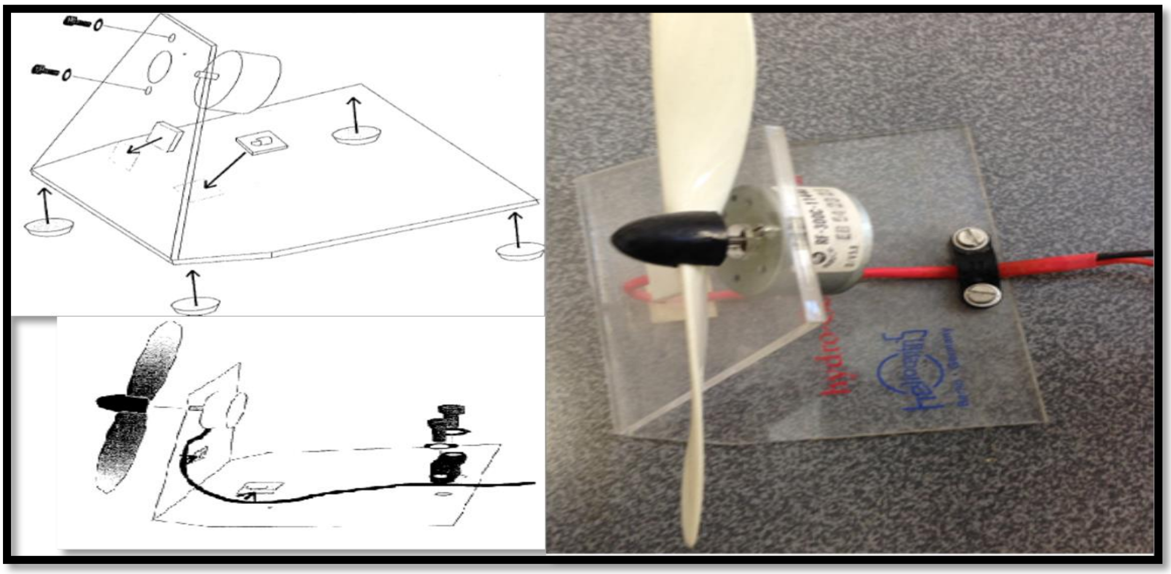


Figure 4.11: Electrical motor used for cooling.

2. prepare the electrolyser as explained in Figure 4.12
    a. both oxygen and hydrogen scrubber are prepared by place the gas containers (test tubes) inside the allocated holder, then

b. insert the two small rubber tubes which have two holes inside both tubes, then
c. insert the laboratory tubing inside the rubber to make gas–washing containers, and connect the input gas with the big rubber for the main electrolyser, and before closing the big rubber,
d. put some water inside the electrolyser until the mark.
e. It is important to connect the diode between the two tip jacks,
f. the other holes in the gas-washing containers will be tubing to the fuel cell, the hydrogen and oxygen container to the FC input.

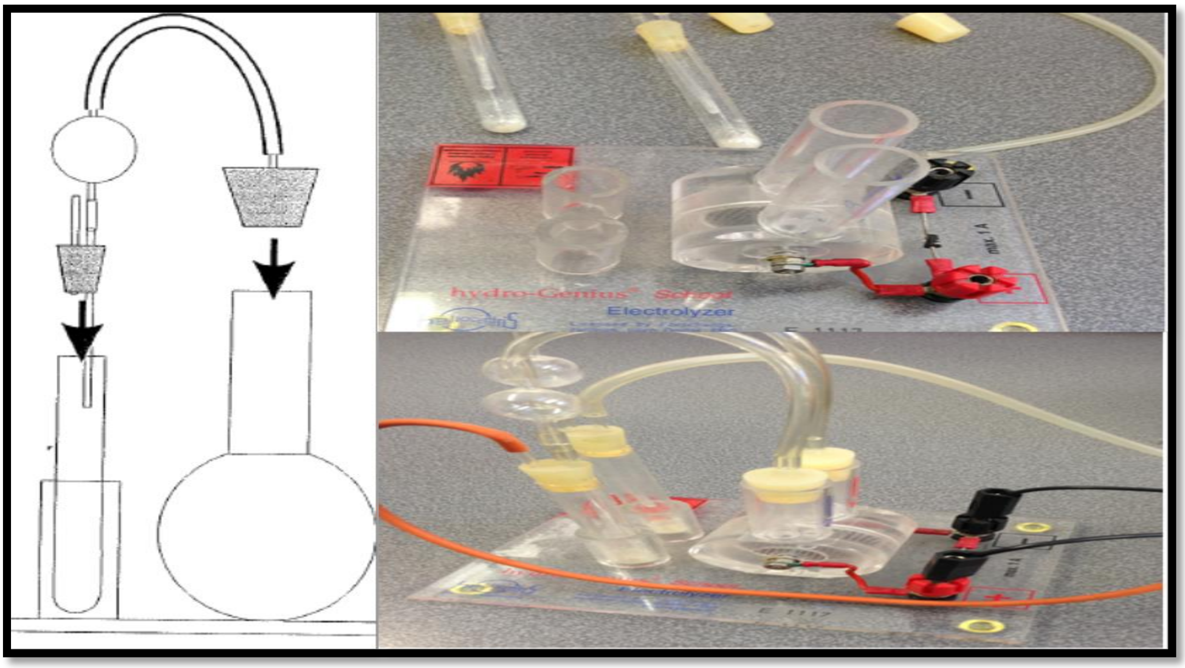


Figure 4.12: Hydro-Genius electrolysis with hydrogen and oxygen storage.

3. preparing the fuel cell as shown in Figure 4.13,

   a. place the shell of the fuel cell in the plate by screwing the plot, and before full threaded the plot to make sure the direction of the shell is correct, then
   b. install the shell wires with the tip jacks taking into account the same collar red with res tip jack and the black wire the same, after
   c. insert the tubing in the located places.

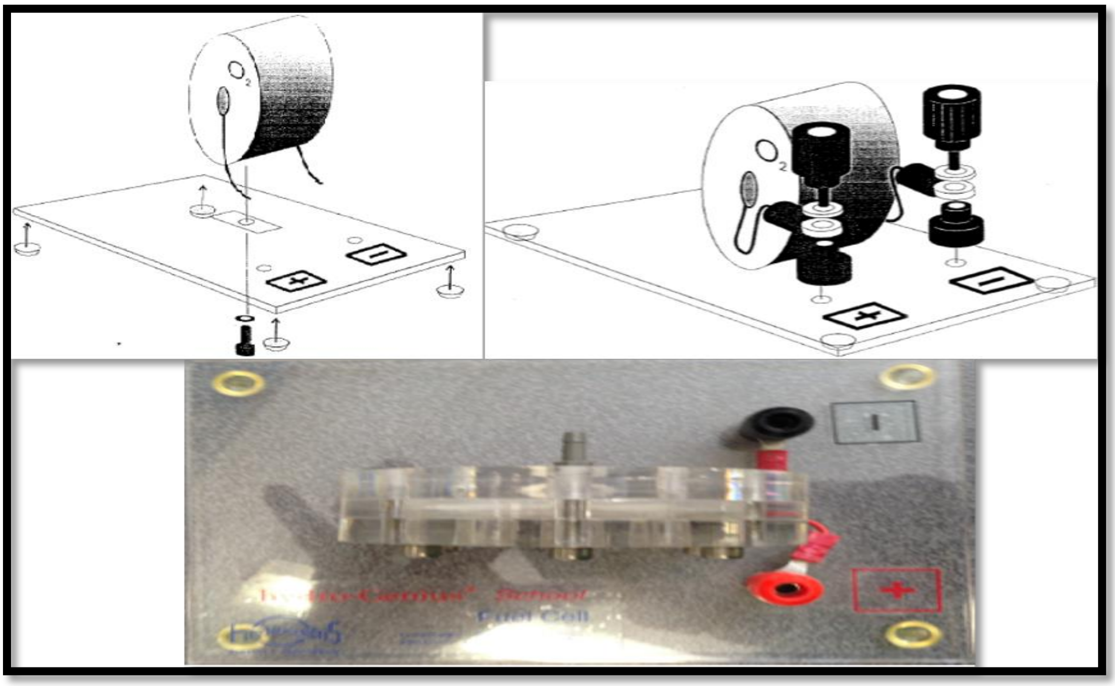


Figure 4.13: Hydro-Genius fuel cell.

Connect the measurement equipment

After all equipment was connected the electrolyser has connect both hydrogen and oxygen tubing to the fuel cell as shown in Figure 4.14,

1. and the water is full to the mark,
2. the power supply is connected to the digital Joule-meter and wattmeter to the supply side, and
3. from the output of the digital Joule-meter is connected respectively to the multi-meter which in current position then to the electrolyser and is connected parallel to another multi- meter in volt position (Figure 4.15).
4. FC tip jacks (output) are connected to the second digital Joule-meter and wattmeter in the supply side where both multi-meter are connected respectively an parallel to the supply side to measure volt and current, the load side is connect to the lamps (Figure 4.16).

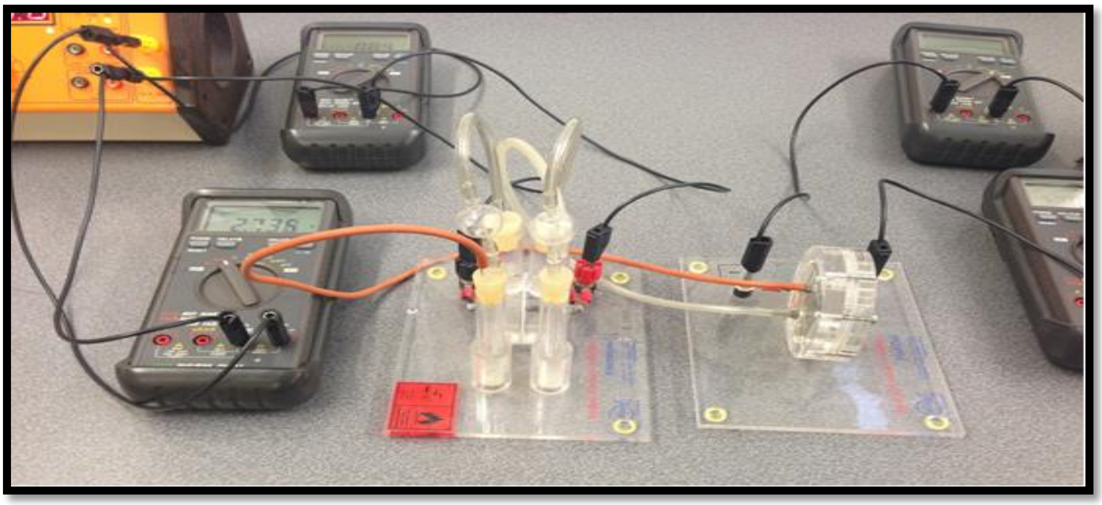


Figure 4.14: Hydro-Genius fuel cell and electrolyser with the connections.

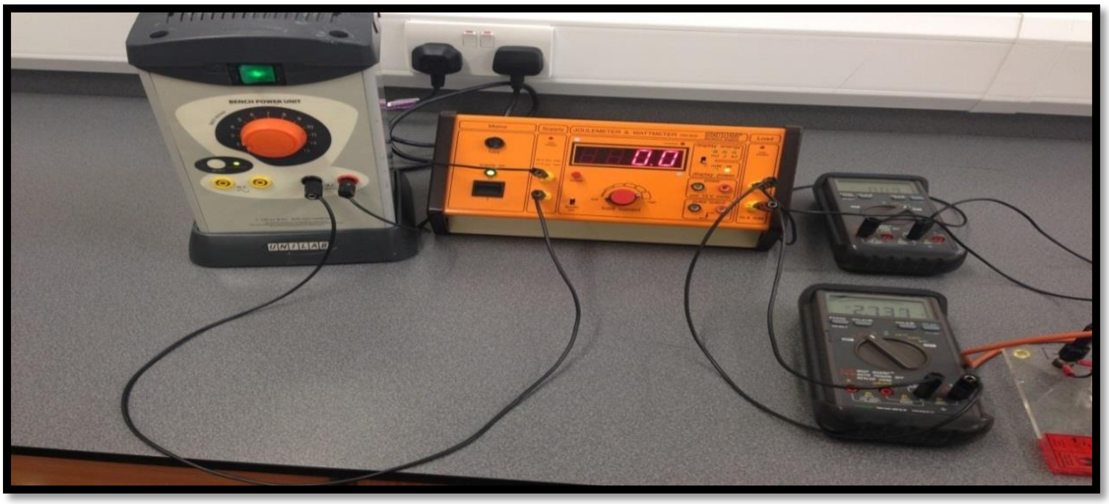


Figure 4.15: Digital Joule-meter and wattmeter with electrolyser connections.

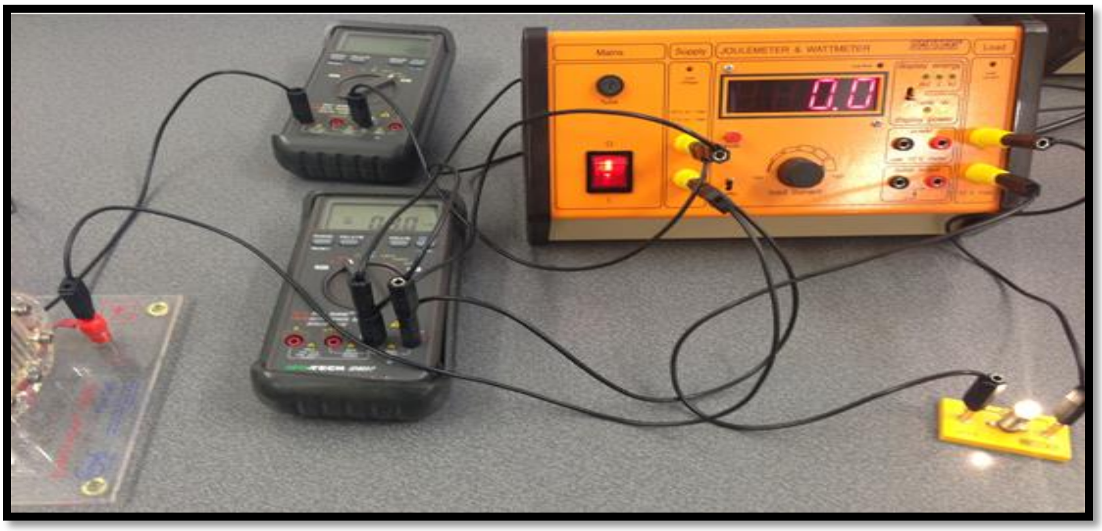


Figure 4.16: Digital Joule-meter, wattmeter with Fuel cell and load connections.

Stage 1

After all equipment was connected the operation was by started at 20V Dc up to 26V DC. The voltage was increased in increments of 1 V and held at that voltage for 5 minutes.

a. Turning on the power supply and if the readings are obviously in the first two multi-meters and on the first wattmeter at the same time the operating of the electrolyser can be heard, after a while the FC will generate power (lamp will turn on), the test is set for 5 minutes then the power supply is turned off,
b. the fuel cell still generating power until the stored hydrogen is finished, and it is important to take the wattmeter readings when the fuel cell is stopped, because it will give the actual efficiency,
c. Undertaken the reading from the multi-meters (current and the voltage) during the test.

The process explained as, the current is passed through the electrolyser. The cathode releases hydrogen and the anode oxygen and it is stored inside the gas-washing container, and when the FC starts it takes the stored hydrogen and oxygen to generate DC power. Then all meters readings are measured and recorded.

Stage 2

In this stage the investigation is carried out for the possibility to recover waste heat from the FC process. This stage of the experiment was carried out following the previous stage process, but to cool down the fuel cell the motor was added. The propeller is facing the FC and the motor is connected to external power supply. The measurements techniques were similar to the previous stage. The results obtained were compared at the same voltage before and after the addition of cooling motor, to check the effect on the electrical generation. Moreover, the measurement of FC temperature is carried out using the infrared digital temperature gun through the operation.

4.3.4.3.5 Results captured and analysis

The outcomes from this test were captured in content records in a particular configuration in Excel file. The typical document configurations of this experiment are indicated in Appendix G. After that all measurement was demonstrated and analysed as explained in the same appendix. The final results are presented and explained in results chapter.

4.3.4.4 Storing H_2O_2 for long term

4.3.4.4.1 Storing H_2O_2 for long term setup

Storing hydrogen peroxide in different concentrations was carried out to study the effect of climatic variation on storing hydrogen peroxide mainly in hot weather countries. The approaches utilized here were simple ways to store H_2O_2 in normal and hot weather for long periods.

The objective of this stage was

- to investigate if there was a difference between the concentration of H_2O_2 at the beginning of the experiment and after a long period of time.

4.3.4.4.2 Storing H_2O_2 experiment apparatus

1. 20× 150mm white plastic bottle (code HDPE 601999, model: PE-150S Pharhome, China).
2. Hydrogen peroxide 3% (Mckesson, USA).

3. RC heating plate laboratory use (code CB162, Stuart, UK).
4. Beaker Squat Form with Graduations and Spout, 400ml (code FB-33113, DWT Code: 11524, FISHER BRAND, Singapore).
5. Hydrogen Peroxide test strips QUANTOFIX 1000, Colour reaction white → brown (code 91333, MACHEREY-NAGEL, Germany).
6. Oven (code N30C, Philips Harris Ltd, UK).
7. Thermometer Dual Scale (initial, UK).
8. Magnesium dioxide (Vishnupriya Chemicals Private Limited, UK).
9. Test tube (Pyrex, UK).
10. Gas syringe (code 406036607, Interchangeable WEBER SCIENTIFC, England).
11. Rubber stopper with hole (code CE-STOP03A, Home Science tools, UK).
12. Laboratory and vacuum tubing (code E-3603, Vijay Engineering Corporation, UK).

4.3.4.4.3 Experimental Conditions

The procedure for the investigations described above was undertaken as follows;

1. Analysis in a lab with two set of ambient temperature for 5 months;
    a. the first (15-26 °C) and b. the second (38-40 °C).
2. All the beginning test for this experiment, undertaken in two days for preparation then stored for 5 months, and
3. after five months the test is carried out over one day.

4.3.4.4.4 The Experimental Procedure and Design

Prepare the hydrogen peroxide concentration,

1. by pouring 400ml of H_2O_2 solution in the beaker, and

2. put the beaker in the heating plate and set the heater at 80 °C to allow the water to evaporate, and increase the concentration of the H_2O_2, and to reduce the solution volume to the follows concentrations:
   - 400ml in the beaker contain 3% as set from the manufacture.
   - When the solution in the beaker becomes 80ml the concentration is 15%.
   - When the solution in the beaker becomes 60ml the concentration is 20%.
   - When the solution in the beaker becomes 40ml the concentration is 30%.
   - When the solution in the beaker becomes 30ml the concentration is 40%.
   - When the solution in the beaker becomes 24ml the concentration is 50%.

Prepare the sample of H_2O_2,

1. 5 concentration samples have been prepared and tested by the strips test and by the chemical test; (the chemical test will be reported later at the end of this experiment).
2. After both test are finished and the concentration is the right one, the solution in every single sample is poured in to 4 plastic bottles, two with lead and two without, and
3. put one with lead and one without in group A and the rest in group B, and so on for every concentration sample, until there are two groups and every group have 5 bottle with lead with all concentrations (15-50%) and 5 without lead with 5 concentrations as well.

Group A has been stored in the fume cupboard in the lab as shown in Figure 4.17. **Group B** has been stored inside oven, the oven has been set at 40 °C (to present the weather in hot countries) as shown in Figure 4.18. The oven has been tested for two days before starting the experiment.

Figure 4.17: Group A.

Figure 4.18: group B.

Experiment performance and testing stage

1. Every few days a check-up is carried out to make sure that everything is ok, such as the oven temperature and the bottle conditions.
2. Every week there were tests for the samples using strips test and a chemical test.

3. After five months, a strips test and chemical test undertaken for every single bottle in order to find any change in the concentrations after long period of storage.

The chemical test (Song et al., 2010; Hasan et al., 1999; Kong et al., 1998):

- inserting the first side of the tubing inside the gas syringe, and
- the other side of the tubing is inserted inside the rubber stopper,
- the rubber will close the test tube after putting 1ml of H_2O_2 solution with Magnesium dioxide. Both together will have reaction and oxygen is released as a result of this reaction, and
- the released O_2 is driven through the tubing to the gas syringe which will represents the change measured after the reaction (volume of gas in ml),
- as the oxygen is arrived to the cylinder it will push the inside syringe outside, and after the reaction is finished and no more oxygen is released,
- measuring of the volume of O_2 in the Gas syringe is carried out,
- then by using chemical equations, calculate the concentration of H_2O_2 inside each bottle. The calculation used is reported below.

Calculations (Song et al., 2010; Hasan et al., 1999; Kong et al., 1998):

- Standard atomic weight for hydrogen is 1.0079 g/mol.
- Standard atomic weight for Oxygen is 15.9994 g/mol.
- Standard atomic weight for hydrogen peroxide is containing two atoms of hydrogen and two atoms of oxygen and that equal 34.0146 g/mol.
- Oxygen density is 1.429g/L.
- Hydrogen peroxide density is 1.13g/L.

I. By measuring the volume of the produced oxygen in ml and as the standard STP (standard temperature and pressure) are 22.4L/1 mol.

II. Calculate the mole of the produces oxygen = measuring in L / 22.47.

III. $2H_2O_2 \rightarrow 2H_2O + O_2$

IV. So every mole of oxygen is equal 2 moles of hydrogen peroxide per ml.

V. Calculate molarity = moles / volume in L.

VI. Calculate Mass (g) or concentration (g/L) = molarity × Standard atomic weight for H_2O_2

VII. Calculate Volume = mass/ hydrogen peroxide density

VIII. Finally the concentration in percentage = volume × 100%

According to that Table 4.1 clarifies the percentages with the molarity and mass with the amount of the produced oxygen. However this method is considered the best method to calculate the concentration of hydrogen peroxide.

4.3.4.4.5 Results captured and analysis

- Report the average volume of produced O_2 from the reaction as magnesium dioxide is only a catalyst, which means that all the H_2O_2 will react.
- Formula mass and density for hydrogen peroxide is important for the calculation.
- Report the molar ratio and discuss whether it is affected by storing H_2O_2 for 5 months.
- There were some poor results, and after investigation, some particular sources of error were recognized which might have influenced the results. These sources have been fixed by repeating the concentration test and the calculation.

The outcomes from this test were captured in content records in a particular configuration in an Excel file. The typical document configuration of this lab work is indicated in Appendix H. The final results are presented in the results chapter.

Table 4.1 the relation between the concentration and molarity and the volume of the oxygen

hydrogen peroxide percentage	hydrogen peroxide volume (L)	hydrogen peroxide Mass in the solution (g)	hydrogen peroxide molarity in the solution	hydrogen peroxide mole in 1ml	produced oxygen in mole per 1ml	produced oxygen volume (ml)
10%	0.1	113	3.32210286	0.0033221	0.0016611	37.20755
15%	0.15	169.5	4.98315429	0.00498315	0.0024916	55.81133
20%	0.2	226	6.64420572	0.00664421	0.0033221	74.4151
30%	0.3	339	9.96630859	0.00996631	0.0049832	111.6227
40%	0.4	452	13.2884114	0.01328841	0.0066442	148.8302
50%	0.5	565	16.6105143	0.01661051	0.0083053	186.0378

4.3.4.5 Discussion

Accordingly, this thesis shows an advanced and optimizes versatile technique for HPS. The proposed study began by investigating outline and assessment parameters of individual systems. The HPSs comprise of sun powered photovoltaic, wind turbine, and DG, also for the storage system H_2 as a part of fuel cell and batteries.

- The systems were designed and simulated by using HOMER software for modelling the system and MatLab/Simulink programming to test and verify I-V carve and to check if there is synchronizing between the generations which will allow the characteristics of the output power to be studied.

- From the other side the experiments are curried out to support the system by understanding the benefits from the system equipment which generate heat, in other words the ability to recover waste heat.
- Finding another way to store H_2, as it is difficult to store H_2 in huge amounts, H_2O_2 was the answer, and according to that the third experiment was carried out to find the effect on the H_2O_2 characteristic over a long period of time.
- Finally, a demand management strategy is curried out to find a suitable way to control and manage the fluctuation of both generation power and demand.

4.3.5 Questionnaire (Survey)

This section in Figure 4.1b is mentioned in box 4.1b5 and in Figure 4.2 is mentioned in box 6.

4.3.5.1 User requirements

The literature reported difficulties of installing smart grid, such as breaking the barrier of privacy. The end-users play an important part in the utility operation and effectiveness of the IHPS, where the consumer acceptance to demand management strategy without breaking their privacy is necessary. Therefore understanding the behaviour of consumers and attitude of engineers responsible for planning and operation of the electricity utilities in remote areas is important for designing adaptive tariffs and operational constraints. For this, a survey of a sample of end users and the technicians was conducted.

4.3.5.2 Questionnaire details

Ethical approval was granted for the research from the ethics committee at University of Abertay Dundee. Ethical opinion was sought from Jordan for this survey and the reply indicated that no ethical approval was required under these terms in Jordan.

This survey sought to find the actual behaviour of the end-user and the effectiveness of installing smart systems to control power consumption by identifying ways that end-users are happy to use, and assessing the effects of their addition upon some electrical properties. This was undertaken by personal interview survey of a sample of Jordanian;

- end-users (in remote areas) and
- qualified technicians and engineers in Jordanian electric utility/technical department.

The survey was first piloted to establish appropriateness. This was undertaken on a sample of five people.

The introduction invited the target groups to take part in this survey, and those who refused to participate were excluded. To guarantee anonymity and maximum confidentiality of all the respondents in the survey, no names or covered codes were implanted in any part of the survey and, so no personal details will be recorded or published.

This survey was divided into nine questions comprised of three sections: the first section described the electrical usage and behaviour, the second section was based on the ability and proficiency of changing the end-users behaviour. The third section was to evaluate the target response to control electrical bills by reducing the payment amount. The questions were introduced as follows:

- Question 1 asked about the monthly consumption of electrical power during the last year, where the annual average was calculated.

- Question 2 asked about the monthly payment, as it is not fixed compared to normal grid prices. Users in remote areas pay the same tariff as for the normal grid plus the diesel fuels cost and its transport. The consumers were also asked if they support the implementation of alternative energy sources.
- Question 3 asked about the understanding of the different charging tariff stages according to the Jordanian electrical utilities (Table 4.2).

Table 4.2 Jordanian electrical utility tariff

	Demand in KWh	Prices in fils	Prices in £
1	(1 - 150)	33	0.05
2	(151 - 300)	72	0.10
3	(301 - 500)	80	0.11
4	(501 - 600)	114	0.16
5	(601 - 750)	141	0.20
6	(751 - 1000)	168	0.24
7	(1more than 1000)	235	0.34

- Question 4 asked about high consumption equipment in each house, such as water heater, washing machine, and air conditioner, and if the consumer is able to specify the time they use such equipment.
- Question 5 was related to question 4 and asked if the user can change the time they use the high consumption equipment to specific hours during the day.
- Question 6 asked about the consumer acceptance to a smart grid which can control the time of equipment usage in each house depending on the available power. This question was asked on two occasions; before and after explanation of the smart grid and the way it works.

- Question 7 asked about the consumer acceptance of installing a minicomputer (Raspberry Pi) inside the house which can turn-on and off the heavy consuming equipment.
- Question 8 asked the consumer if they prefer to control their bill.
- Question 9 asked about changing the charging tariff protocol of the Jordanian electrical utilities to complementary adaptive tariff along with a demand management strategy as explained in section 4.3.5.3.

The responses were entered in SPSS software and data analysis was performed by a Chi-square test to localise differences between the responses of the surveyed groups (see Appendix I).

4.3.5.3 OGREH-SμG demand management and complementary adaptive tariff

The OGREH-SμG demand management and complementary adaptive tariff will allow a breakthrough to implement new methods to reduce non-critical demand mainly in “grid parallel unit” as in this type the generation power and demand are fluctuating.

The OGREH-SμG demand management and complementary adaptive tariff design is based on three main concepts:

1. Each residential unit contains two electrical panels where one cable is distributed to each unit and connected to two distribution panels; one panel is for the critical load (very important load, such as lights and fridge freezer units that need to be connected 24/7), and the second for non-critical load “Deferrable load” (serving load that can be shed automatically for short periods of time to match the demand with the available generation, switching-off equipment such as water heater,

laundry, and ironing). Installing both panels in a new house is not a problem, however existing houses require dividing the cables in the circuit breaker panel into two groups, then connecting the cables to the two panels (critical and non-critical panels). The main outcome of this process is that the controller can manage the demand load to meet the generation power as the latter is unpredictable.

2. Each residential unit has a Raspberry Pi as a minicomputer where the Raspberry pi is connected to each socket in the house (connected to each load individually using current sensors). The demands can be displayed on TV/ AV channel with red and green LED lights to indicate power deficit and excess respectively. The advantage of this process is that, the end-user can control the load in a cheap way according to the light indicator LEDs which allow switching-off high demand equipment in the case of power deficit, or using extra power at a lower tariff as explained in point 3.
3. A complementary charging adaptive tariff is set to replace the old charging tariff (Table 4.2). The new adaptive tariff is as follows:
    a. High tariff – in the case of power deficit; the controller alerts the consumer by a red LED display.
    b. Normal tariff – when the generation matches the demand; the controller does not show any signal (red and green LEDs are off).
    c. Low tariff – in the case of excess generation; the controller alerts the consumer by a green LED display.

4.3.6 The Linear Cost Function (LCF) for OGREH-SμG

This stage is shown in (Figure 4.1b, box 4.1b2) and in (Figure 4.2, box 2). The general aim of optimizing procedures is the calculation and estimations of the free variables of a function that maximise or minimize the value of the function (generally called the "**Objective Function**").

In this investigation a cost function was formulated as a linear equation of energy generation and storage units. This LCF will therefore calculate the cost of the OGREH-SμG generation and storage mix, subject to design constraints as shown in equation 4.1 and 4.2. The exhibited strategies in this part incorporate a linear relationship for *n* elements of *n* variables using mathematical model to minimize or maximize it. In OGREH-SμG case the LCF has to be minimised (the objective function is the cost of system with 8 free variables ($x_1$to x_8) as reported in the next section).

$$f(x_i) = \sum_{i=1}^{n} (C_i \times x_i) \qquad (4.1)$$

$$non\ negative\ varibles: \begin{cases} x_{i=1} \geq 0 \\ \quad : \\ x_n \geq 0 \end{cases} \qquad (4.2)$$

Where

$f(x_i)$ = Objective function (designed variable vector)

x_i = Variables

C_i = Cost of the x_i variable at reference value

n = Number of variables in the objective function

4.3.6.1 The importance of optimizing LCF for OGREH-SμG

The objective cost function in our investigation has been formulated as a linear equation with eight variables to be solved by the linear programming (LP) method in order to find the optimal mix for the energy generation at minimum cost within the operational and design constraints. The Linear equations are solved using the "Karmarkar's algorithm" in Scilab. "Karmarkar's algorithm" is called "Interior point methods" reported as LP algorithm solving, where the solution is without any boundary of any set, it resolves the problem through interior region and optimizes the solution through the iterative last step. This step is called "polynomial time[3]".

Equation (4.3) is the objective function formulated for designing minimum cost of OGREH-SμG with equations (4.4 to 4.14) representing the linear equality constraints, these constraints were devised and formulated based on the results of HOMER simulations (average optimal values) and industrial standard manuals as explained and referenced below.

$$minimize\ C = C_1 \times X_1 + C_2 \times X_2 + C_3 \times X_3 + C_4 \times X_4 + C_5 \times X_5 + C_6 \times X_6 + C_7 \times X_7 + C_8 \times X_8 \qquad (4.3)$$

Where

C = the total cost for the system.

C_1 = cost for 1 KW of solar panel £1400.

X_1 = size of the solar panel.

C_2 = cost for 1 KW of wind turbine £1000.

X_2 = size of the wind turbine.

[3] "Polynomial time is an algorithm solvable, where number of steps needed to finish the algorithm using some negative integer with complex input, this process is fast and most familiar mathematical operations".

C_3 = cost for 1 KW of Batteries £1800.

X_3 = size of the Batteries.

C_4 = cost for 1 KW of inverter £900.

X_4 = size of the inverter.

C_5 = cost for 1 KW of electrolyser £1200.

X_5 = size of the electrolyser.

C_6 = cost for 1 KW of hydrogen fuel cell£1750.

X_6 = size of the hydrogen fuel cell.

C_7 = cost for 1 KW of hydrogen peroxide fuel cell £1950.

X_7 = size of the hydrogen peroxide fuel cell.

C_8 = cost for 1 KW of diesel generator £3800.

X_8 = size of the diesel generator.

Subject to

$$X_1 + X_2 - 0.5X_3 \geq P_T \quad (4.4)$$

Equation (4.4): the full power from PV and WTG must cover the maximum demand and charge 50% of the battery rated power (the % are calculated as averages from HOMER simulation).

$$0.65X_2 + X_3 \geq P_n \quad (4.5)$$

Equation (4.5): 65% from the rated power of WTG with the full discharge from the battery must cover maximum demand at night (the % are calculated as averages from HOMER simulation).

$$-X_1 - 0.25X_3 + 0.9X_4 \geq n_s \tag{4.6}$$

Equation (4.6): the full power from PV and 25% of rated power from battery discharge with the inverter safety margin must not exceed 90% of the inverter rated power (the % are calculated as averages from HOMER simulation and from ABB[4]).

$$X_2 + 0.25X_3 + 0.35X_6 + 0.40X_7 \geq P_n \tag{4.7}$$

Equation (4.7): the full power from WTG, 25% of rated power from battery discharge, 35% of rated power from H_2FC and 40% of rated power from H_2O_2FC must match or to be greater than the maximum night load (the % are calculated as averages from HOMER simulation).

$$0.55X_1 + 0.45X_2 - 0.25X_3 - 0.25X_6 - 0.25X_7 \geq 0.25P_T \tag{4.8}$$

Equation (4.8): if the load is 25% of the maximum load, 55% of the PV rated power and 45% of the WTG rated power should match the demand with the ability to charge 25% rated power of the battery and 25% of the required H_2 and 25% of the required H_2O_2 (the % are calculated as averages from HOMER simulation).

$$0.4X_3 + 0.35X_6 + 0.35X_7 \geq 0.4P_n \tag{4.9}$$

Equation (4.9): in a calm night the 40% of battery rated power, 35% of rated power from H_2FC and 35% of rated power from H_2O_2FC must match 40% of that the maximum night load (the % are calculated as averages from HOMER simulation).

[4] https://library.e.abb.com/public/1c4234b4fa1cb5f4c12571e7004bed25/Voltage%20ratings%20of%20high%20power%20_%205SYA%202051NLay.pdf

$$-0.75X_3 + 0.9X_4 - 0.25X_6 - 0.25X_7 \geq 0.5n_s \tag{4.10}$$

Equation (4.10): the 75% of rated power from battery discharge, 25% of rated power from H_2FC, and 25% of rated power from H_2O_2FC with the inverter safety margin must not exceed 90% of the inverter rated power (ABB) (the % are calculated as averages from HOMER simulation).

$$X_1 - 0.05X_2 \geq 0 \tag{4.11}$$

Equation (4.11): the rated PV power should be greater than 5% of the WTG rated power (the % are calculated as averages from HOMER simulation).

$$X_5 - 0.1X_6 - 0.1X_7 \geq 0 \tag{4.12}$$

Equation (4.12): the rated power for electrolyser should be greater than 10% of rated power from H_2FC and 10% of rated power from H_2O_2FC (the % are calculated as averages from HOMER simulation).

$$0.95X_8 \geq P_T \tag{4.13}$$

Equation (4.13): the rated power for DG should be greater than the maximum load, as DG in OGREH-SμG is a standby generator (design requirement).

$$125X_1 + 15X_2 + 40X_3 + X_4 + 2X_5 + X_6 + X_7 + 4X_8 \geq 500 \tag{4.14}$$

Equation (4.14): according to the calculations and measurements of implementing OGREH-SμG for the case study, the area required for installation to implement this project is 500 m^2, and for the generation and storage; 125 m^2 is required to install 1 kW of PV, 15 m^2 is required to install 1 kW of WTG, 40 m^2 is required to install 1 kW of battery bank, 2 m^2 is required to install 1 kW of electrolyser, 1 m^2 is required to install 1 kW of H_2FC, 1 m^2 is required to install 1 kW of H_2O_2FC, and 4 m^2 is required to install 1 kW of DG (these were estimated from several manufacturer's catalogues as typical values.

Where

P_T = is the maximum load 15KW (according to the average from case study).

P_n = the load at night 12KW (according to the average from case study).

n_s = the inverter safety margin 0.5KW (ABB[5]).

All the equations, matrices, and optimisation are mentioned in detail in appendix E. The results of the optimisation are reported in Chapter 6 section 6.4. For LP purposes Scilab was used.

4.3.6.2 Linear cost function and its optimization summary

This cost function is used to model the optimal system, which was calculated from the HOMER simulations (that use GA for optimisation), in order to:

1. verify the HOMER solution, and
2. find the optimal size of the system component (energy generators, sources and storage) by linear programming using Karmarkar's algorithms. This facilitates a more transparent way for the design of OGREH-SμG as
    a. the cost components, and
    b. the constraints can be changed easily in a more transparent way to see the effect on the cost.

[5]https://library.e.abb.com/public/1c4234b4fa1cb5f4c12571e7004bed25/Voltage%20ratings%20of%20high%20power%20_%205SYA%202051NLay.pdf

Therefore, this approach is ideal for the iterative evolutionary design where HOMER simulation is an automated, quick and effective way of getting an optimal solution that can further be fine-tuned using the LCF with LP to try to achieve the optimum solution for the design, which is the core idea of IADF.

4.3.7 µ-grids synchronization Strategy

As in (Figure 4.1b, box 4.1b5) and in (Figure 4.2, box 7) this strategy is to connect more than one µG together in parallel with active power sharing control strategy. When one µG has extra power it will be transferred to the nearby µG. If any µG has a shortage of power it will not start the reserve power system and will import from the nearest available power. Every µG will be connected with other µG like an intra-grid (Figure 4.19). For example, if there is any shortage in µG 1 but there is technical connection problem between µG 1 & µG 2, and there is extra power from µG 2, then the power from µG 2 will transfer to µG 1 via µG 3. This is economically efficient active power sharing system when compared with systems operating on reserve power and over a wider geography can also mitigate the variability and intermittency of the renewable energy sources. This strategy is simulated in

1- HOMER and
2- MatLab/Simulink.

It was simulated as grid connection with limited available power and zero cost in HOMER, and normally simulated in Simulink, the simulation results are presented in Chapter 6.

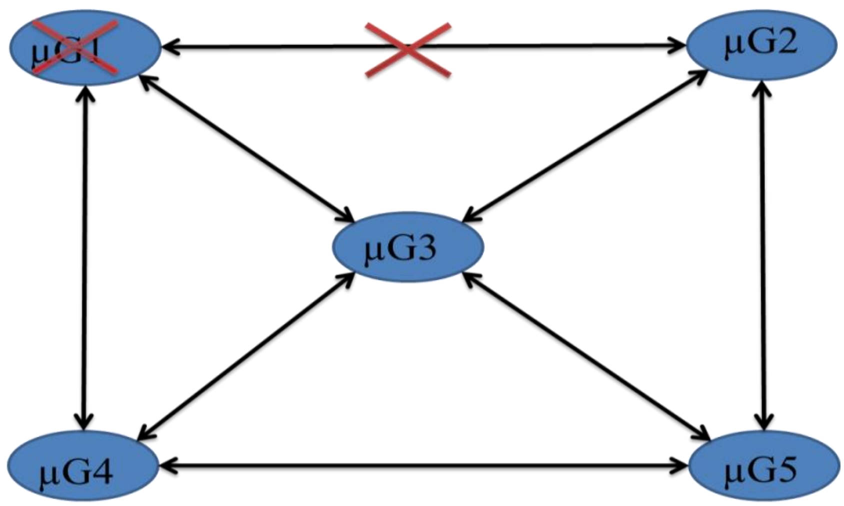


Figure 4.19: The µG synchronization Strategy.

The synchronization between the micro-grids will be through the AC lines, as explained by MacLeod et al. (2010); having DC connection between grids or micro-grids together is costly and will lead to high losses compared to an AC connection if the distance is less than 50Km. Therefore the µ-grid to µ-grid connections are simulated as AC connections.

The "synchronizing-relays" method was chosen as explained in Figures 4.20 and 4.21b. The voltage, phase angle and frequency parameters should be within acceptance range for smooth synchronisation. The configuration of a typical µG is shown in Figure 4.21a; generally every µG will have multiple generation sources as well as various storage schemes that require synchronisation. For a µ-grid to µ-grids operation, µ-grids will receive reference voltage, phase-angle and frequency from either the master-µG or the previous slave- µG.

As shown in Figure 4.21 the Bayir µG is the master-µG and the others are the slaves. It is important in the synchronizing mode to have a reference µG (Bayir)/ "forming grid" that the other µ-grids can synchronize to or with each other.

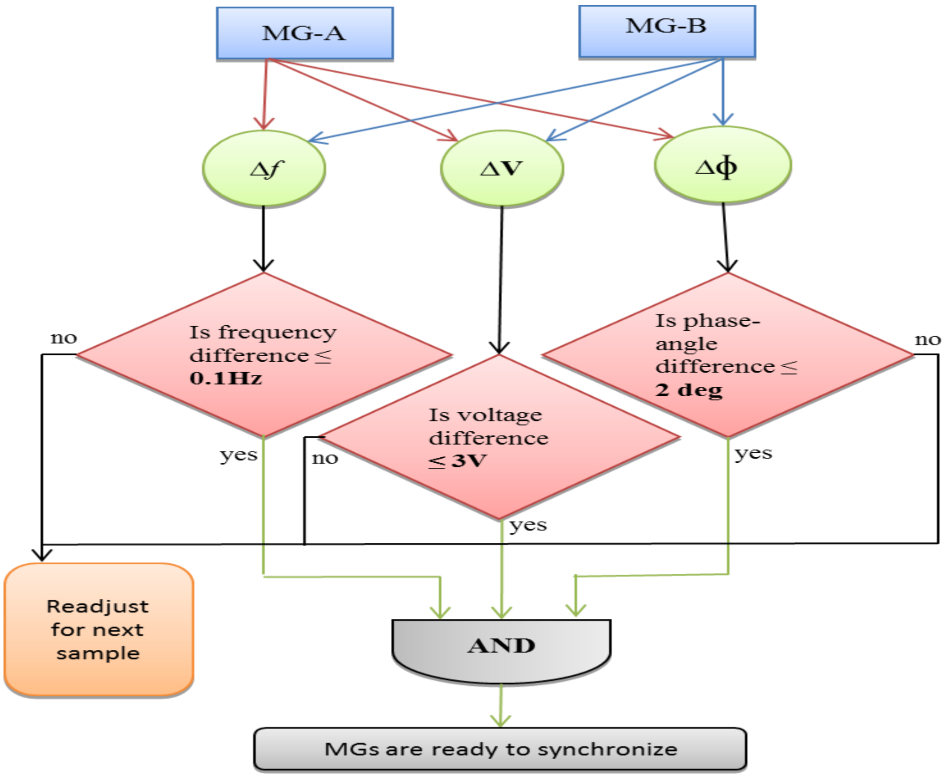


Figure 4.20: Flowchart for the synchronizing-relays.

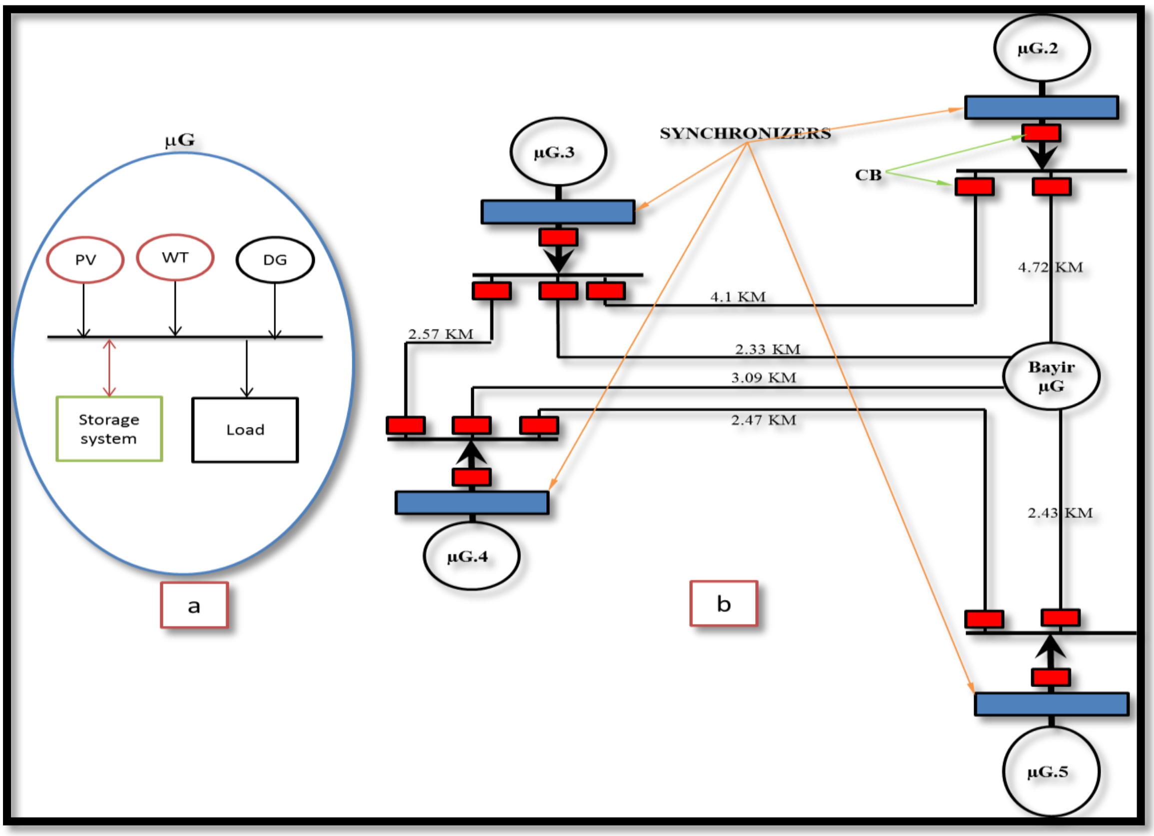


Figure 4.21: Schematic μ-grids synchronizing diagram.

The Simulink configuration model of the system synchronization is built as shown in Figure 4.22a; the Bayir-μG represents the OGREH-SμG and the synchronizing μ-grids nearby “from the μG.2 to μG.5”, also each μG contains (generations, storage and demand) but operates as slaves.

Accordingly, Bayir Circuit Breaker (CB) is always closed (Normally Closed-NC) and the other μ-grid-CBs are open (Normally Open–NO) depending on synchronizing mode. According to the μ-grids synchronizing model each μG is connected to RLC load to represent loses in this μG. In the Simulink Model measurements (results of the simulation calculations) for the frequency, voltage, and phase-angle has to be extracted and used as input for the synchronization box in Figure 4.22a and explained in detail in Figure 4.22b, that contains the voltage regulator (VR) to match voltage (line to line), variable frequency drive to match frequency (by switching frequency), and phase angle to synchronise as presented in Simulink model (Figure 4.22b).

Each synchronizer has three receiving signals from the master grid (a, b, and c as generation lines) to measure (voltage, phase angle, and frequency) as the synchronizer requires reference parameters. According to these parameters the synchronizer will carry out to match the μG parameters with the Bayir-μG parameters. The synchronizing model unit contains set “synchronizing-relays” model. The model implemented contains two set of inputs;

- 3-phase inputs from the reference μG (Figure 4.22b, Bayir-μG), and
- 3-phase input from synchronized μG (Figure 4.22b, μG), where both inputs are connected to current and voltage measurements to present the following;
    1. Current

2. Voltage
3. Frequency
4. Phase-angle

These parameters are subtracted and compared logically. Then the three parameters should be in the accepted level to allow the "and logic operator" to transmit a command signal to close the CB (Figure 4.22b, com). If any parameter is not in the accepted level a signal will be transmitted to the μG inverter (VR or variable frequency drive) to adjust the parameters. The modelling requires gains, constants, and selectors (switches to select the criterion through multi-inputs data) to model the μG elements. A limiter is used to keep the values within the actual ranges, and 3-phase V-I measurement to show individual outputs voltage and current. The model is using, sending and receiving signal to reduce the complexity of the grid to grid connections.

The main benefit of this system could be:

- The ability to reduce the cost of power
- Enhance the reliability as there multi reserve power systems
- Featuring higher robustness according to the high flexibility and reliability
- Sharing the available power between μ-grids, and load sharing management to properly managing and controlling the power flow
- An appropriate option for the future national grid configuration / distributed generation

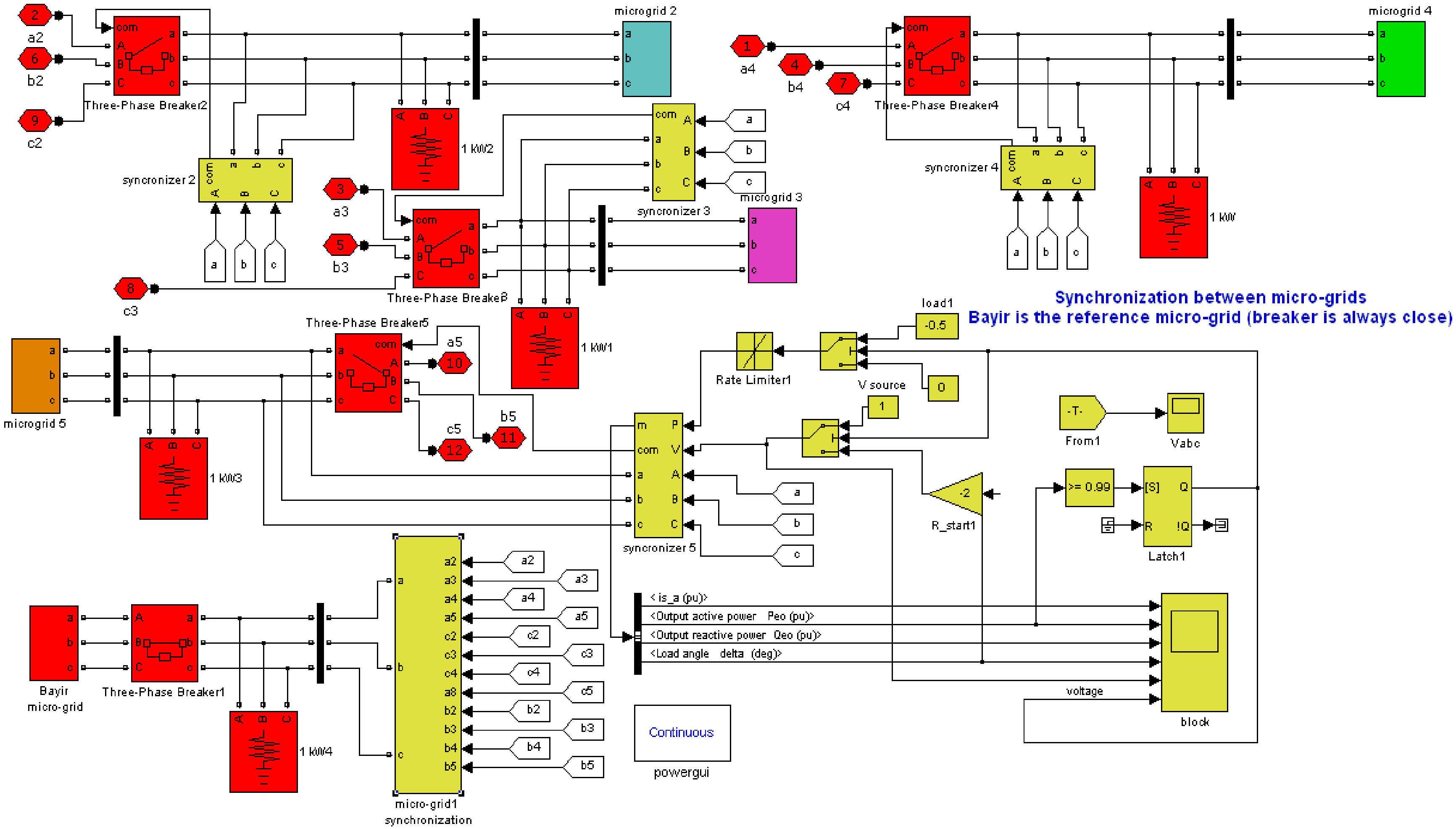


Figure 4.22a: Micro-grids synchronizing model by Simulink.

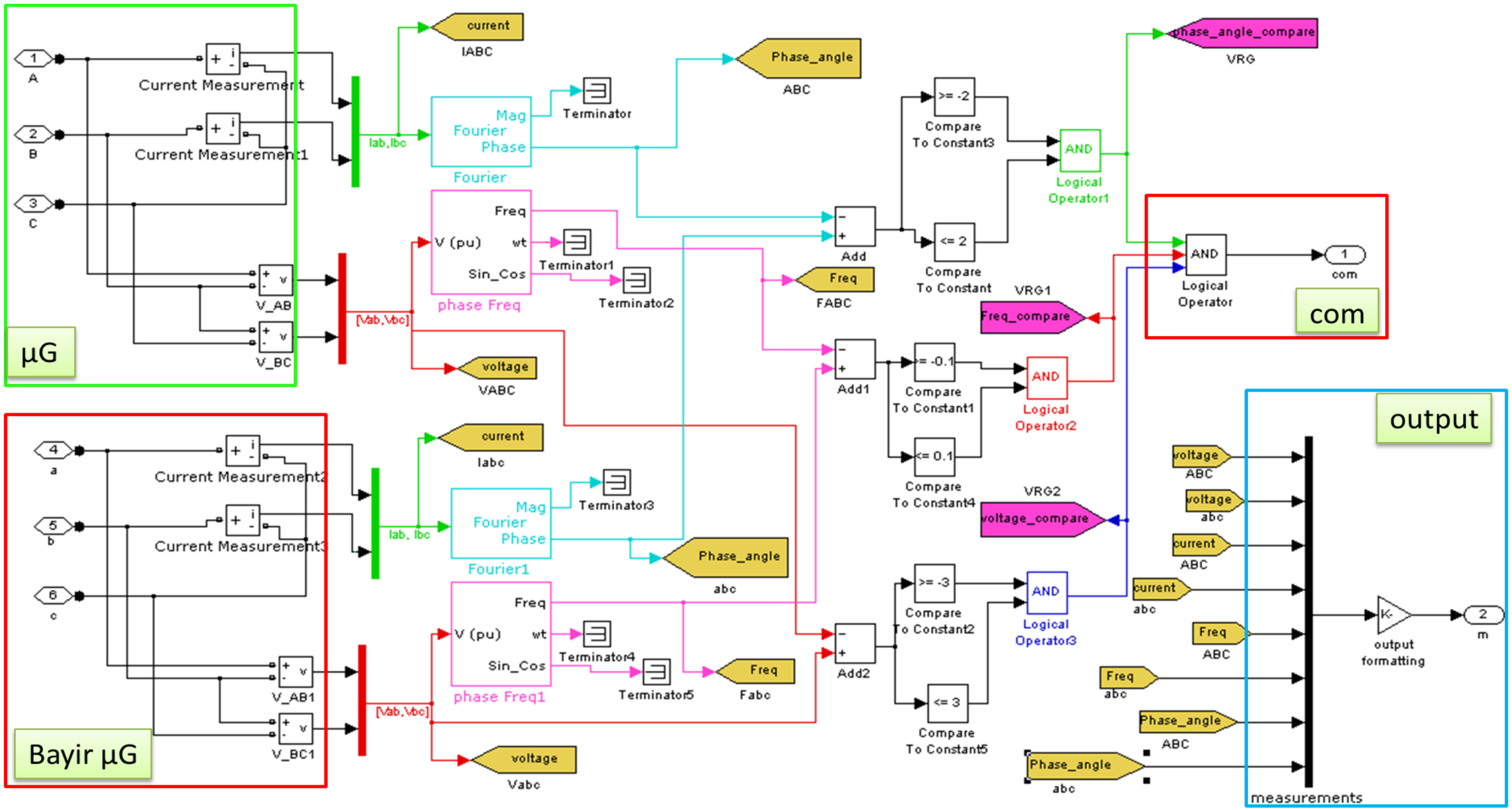


Figure 4.22b: Modelling the synchronizing-relays.

4.3.8 Testing and programing Raspberry Pi as intelligent supervisory switching controller

In this section we will explain part of the IADF as depicted in Figure 4.1b "Overview IADF Flow chart", box 5 and in Figure 4.2 "The Detailed IADF Flow chart", box 8. The Raspberry Pi is a small, cheap and low-power minicomputer made in the United Kingdom. Python programming language is used to manage the intelligent supervisory switching controller in the Raspberry Pi. Because of the low cost and small size (not much bigger than a credit card), Raspberry Pi is often connected to multiple sensors to fulfil tasks such as simple security systems using pressure mats and infrared sensors (Horan 2013).

This system is implemented to give the consumer the ability to control the consumption load by installing Raspberry Pi in every house to show the consumer a full picture about the system, and give the consumer the ability to automatically shed (reduce) the load when the main controller indicates power deficit and status of the system in the red (high tariff) operational model. The controller enables the consumer to monitor the status of the system through red (high tariff – power deficit), green (Low tariff – excess generation) and no signal (normal tariff generation matches demand).

This control scheme is implemented by installing a central control (Raspberry Pi microcontroller- BCM2835) for OGREH-SμG and a unit control (Raspberry Pi microcontrollers - BCM2835) for each residential unit, to control the power balance between generation, storage system and demand as "intelligent supervisory switching controller" as presented in sections (4.3.8.1 and 4.3.8.2). More details of the operation are given Chapter 6.

4.3.8.1 Management of load demand (inside the house)

The Raspberry Pi is connected to each socket through current sensors to monitor the consumer load; the Raspberry Pi is also connected to green and red LED display panel to indicate OGREH-SµG's status (power availability and charging tariff). Furthermore, in every consumer unit the raspberry pi is connected to the non-critical load panel through a relay (so that loads connected to this panel can be disconnected when required). This is explained in detail in OGREH-SµG demand management strategy and its effectiveness with complementary adaptive tariff (section 4.3.5.3).

Figure 4.23 shows the external connection for green and red LED displays and the connection of the non-critical load panel. Figure 4.24 shows the socket connections with the current sensors[6], in order to calculate the power individually and display the results for the consumer. The main advantage is to control load and display consumption with some advices about reducing load, (such as turn the light off in the bedroom as the TV is on in the living room). Also, the OGREH-SµG main controller will have the ability to predict the load and reduce it according to the power availability by shedding the non-critical load panel.

Summary

As explained briefly above, a Raspberry Pi is connected to sockets through current sensors, to record and monitor the power consumed in individual sockets. There are two types of circuits in the demand unit:

1. Critical Load: (Unit that need to be connected 24/7).

[6] ACS712 (low current sensor board)

2. Non-critical Load: (Serving load or Deferrable load) that can be shed for short periods of time when the energy status is indicated by red the load is shed automatically to match the demand to the available generation – this is explained in detail in the complimentary tariff section 4.3.5.3).

There is also further voluntary demand management by using green and red LEDs to indicate high or low cost tariff periods to influence consumer consumption behaviour. The main objective is to control load and display consumption with behavioural prompts for reducing demand to match generation.

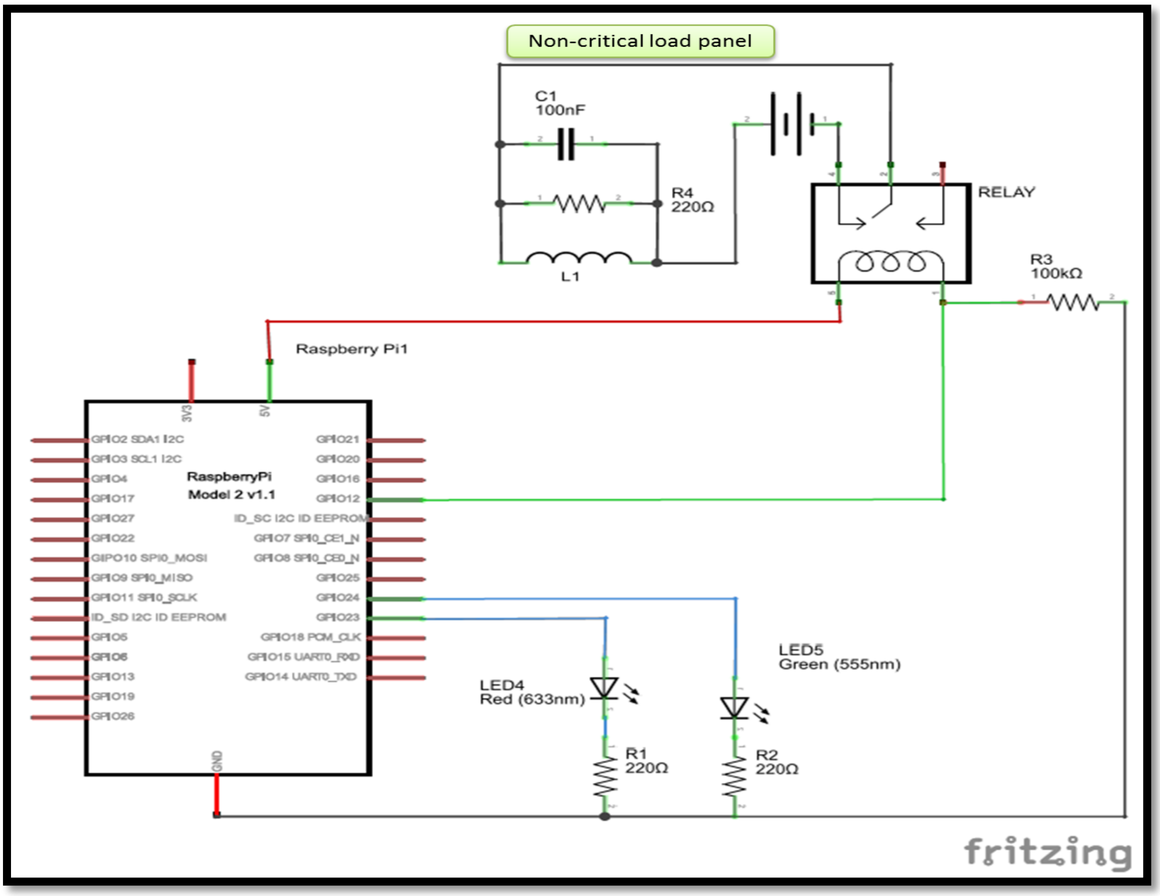


Figure 4.23: Schematic diagram for the LEDs and non-critical load panel[7].

[7] All the schematic diagrams in section 4.3.8.1 and 4.3.8.2 has been undertaken by Fritzing Fab.

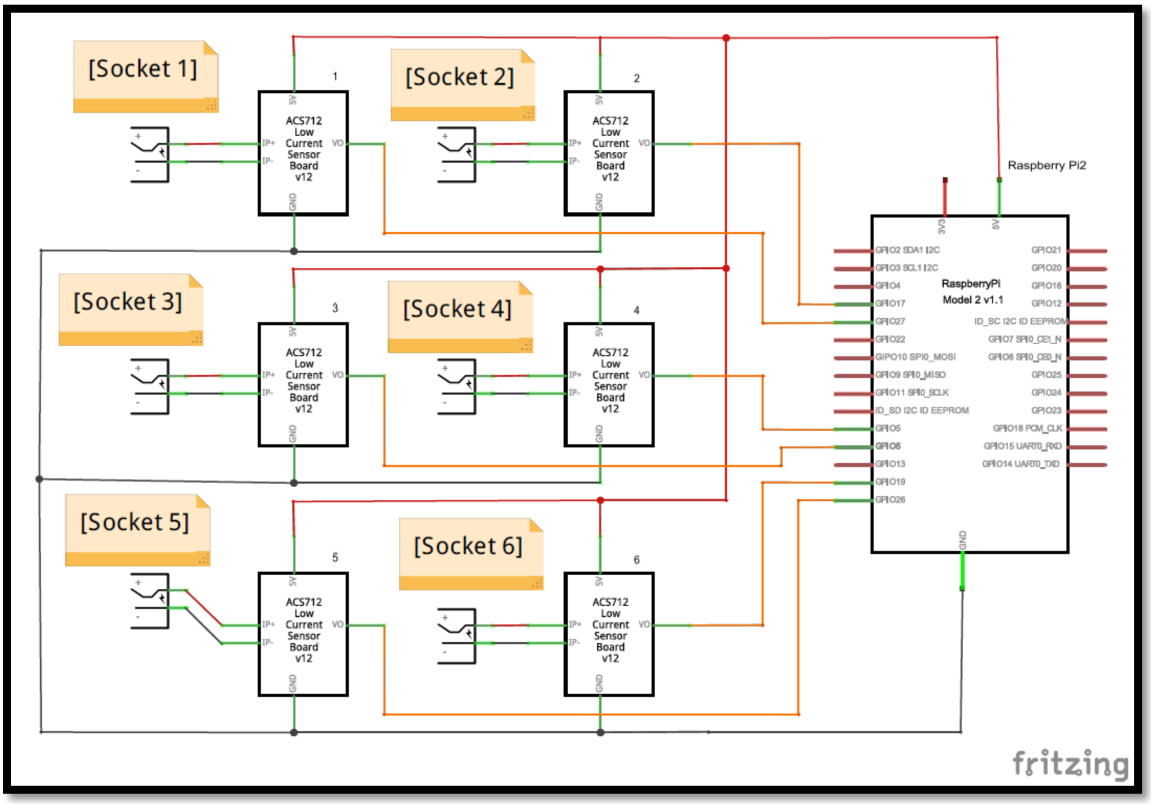


Figure 4.24: Schematic diagram for current sensor inside every socket[7].

4.3.8.2 Raspberry Pi for the central control (control and dispatch of generation and storage units)

The central controller has two main functions

1. To operate the PV panel to track the sun and ensure that the radiation is perpendicular to the sun throughout its daily course, hence optimising system performance. Figure 4.25 shows the schematic diagram for the tracking system using photo cell, light sensor[8], and temperature sensor[9] to collect information about sun direction to let the motor, which is adjusted to operate in one dimension, to follow the sun.

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[8] Lily Pad (light sensor)

[9] LM35 (temperature sensor)

2. To implement an intelligent supervisory switching controller for the OGREH-SμG in order to schedule all generation power (RESs, storage, and DG) and load, with sharing as shown in Figure 4.26. Each RES (PV and wind turbine) has a MPPT charge controller resource that optimises the charging of the batteries with these generation resources (Lee et al. 2012). The central controller is responsible for monitoring the available power in all generation resources through signals from individual controllers. The central controller transmits a command signal to the individual controller to decide which generation power should operate to provide power (as describe in detail in Figure 4.27). This control system will study the flow of power from the generation to the demand load and compare the difference between both, in order to store excess power or use the stored power, or to shed the non-critical load panel. The last option is to operate the DG.

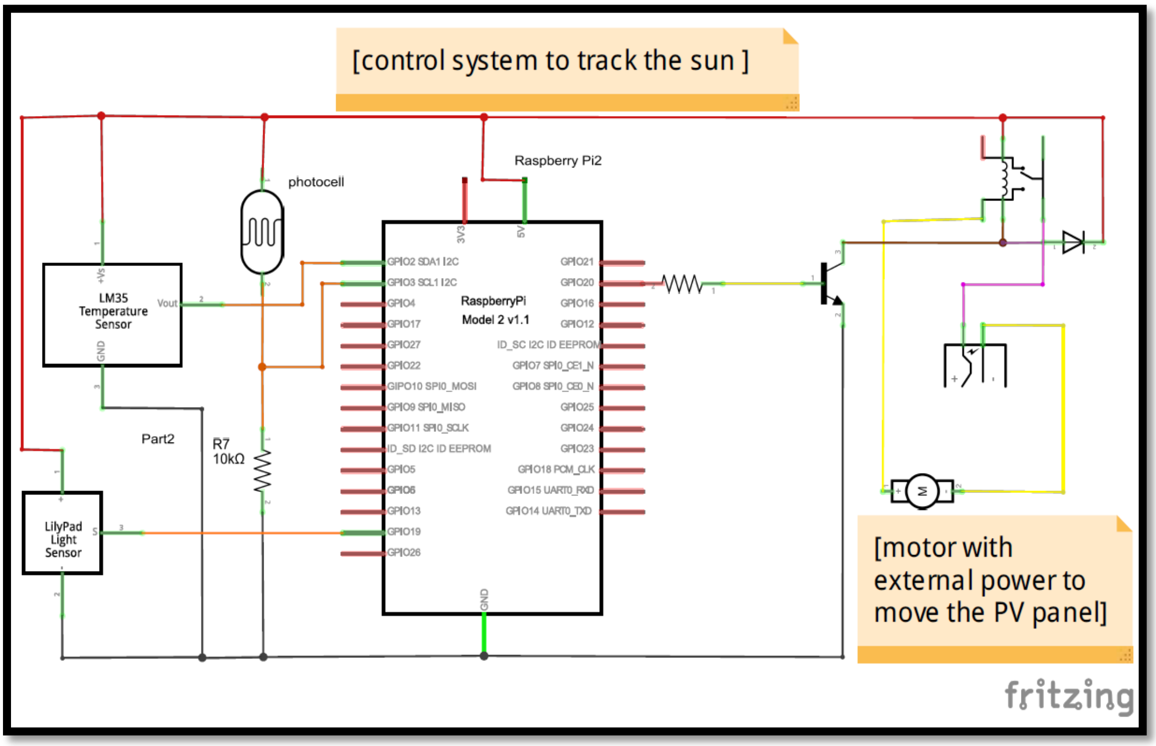

Figure 4.25: Schematic diagram for PV to track sun[7].

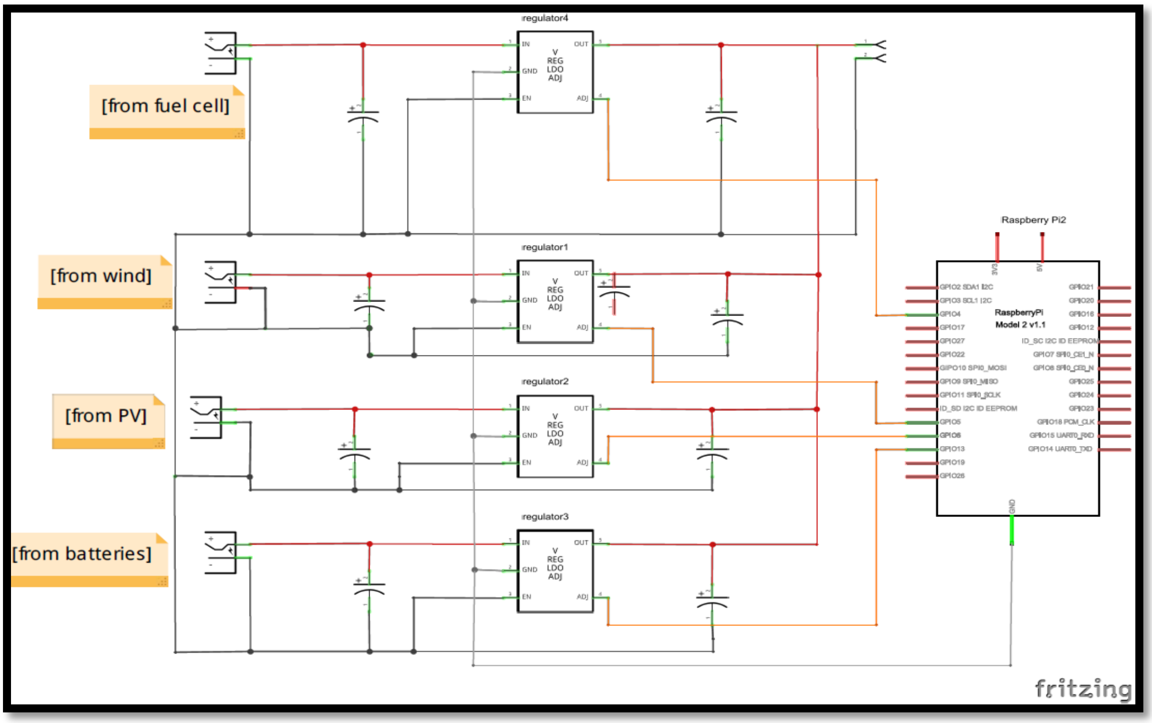

Figure 4.26: Schematic diagram for controlling OGREH-SμG generation[7].

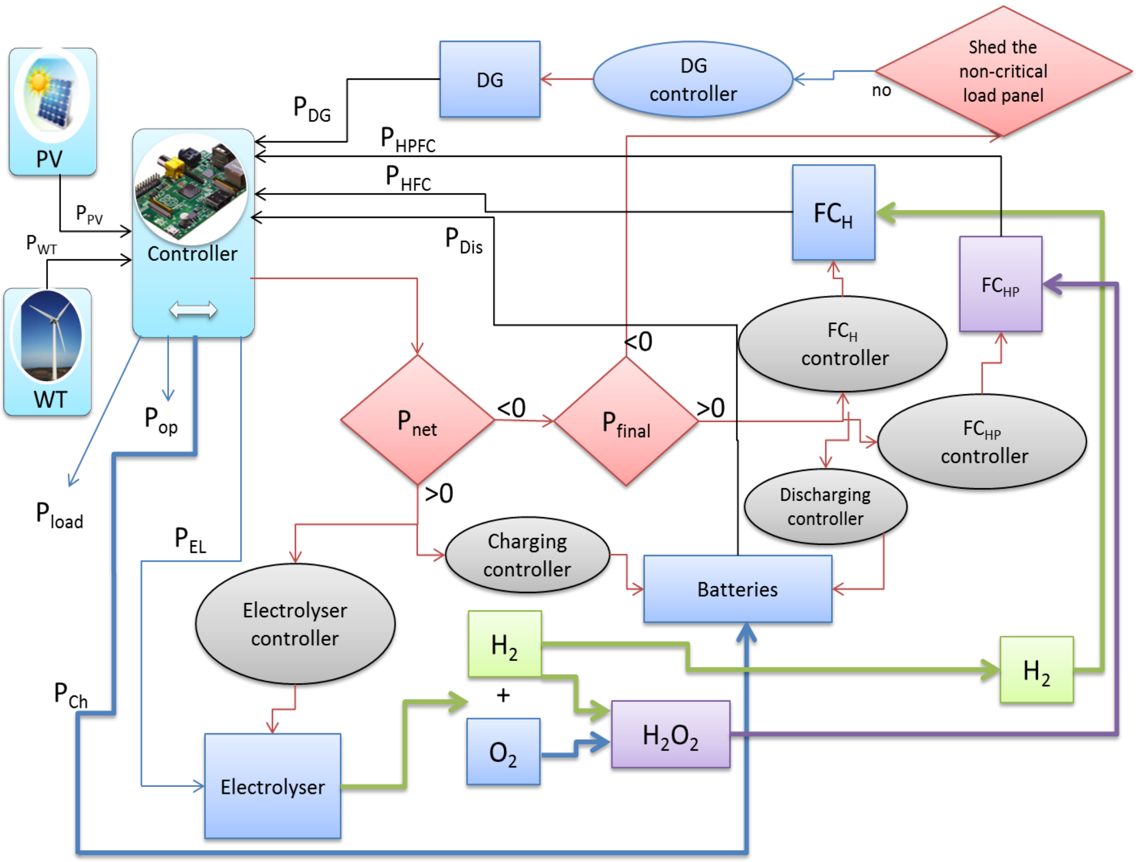

Figure 4.27: Block diagram of the controlling system of OGREH-SμG.

With regards to the second function which is controlling the OGREH-SµG; as shown in the block diagram Figure 4.27. The Figure shows the required controlling procedure in order to supervise, organize and manage the (generation and load sharing) of OGREH-SµG - based in Bayir remote area-Jordan. Where PV and WTG are the main sources, both FC and batteries are the secondary power (reserve power). Finally, the DG is the last chance for the system to keep running (standby power). The intelligent supervisory switching controller algorithm is shown in appendix M.

Wind turbine generator and PV are the main generation sources for the system. Equation 4.15 explains the relation between load and generation power:

$$\mathrm{P_{net}} = \mathrm{P_{PV}} + \mathrm{P_{WT}} - \mathrm{P_{load}} - \mathrm{P_{op}} \qquad (4.15)$$

Where P_{net} is the difference between the generation power and load power, P_{PV} is the power generated from sun, P_{WT} is the power generated from wind, P_{load} is the demand load, and P_{op} is the required power to operate the system. There are many cases where the controller can solve the fluctuation in P_{net}; the first, if $P_{net} = 0$ the situation remains as it is without any change. Second if $P_{net} > 0$ then the extra power passes to the batteries or to the electrolyser as in equation 4.16:

$$\mathrm{P_{PV}} + \mathrm{P_{WT}} = \mathrm{P_{load}} + \mathrm{P_{op}} + \mathrm{P_{Ch}} + \mathrm{P_{El}} \quad if\ P_{net} > 0 \qquad (4.16)$$

Where P_{EL} is the required power to electrolyse water in order to produce hydrogen and oxygen, P_{Ch} is the required power to charge the batteries. Last, if $P_{net} < 0$ then there is a need for extra power to cover the load as mentioned in equation 4.17:

$$P_{PV} + P_{WT} + P_{Dis} + P_{HFCl} + P_{HPFC} = P_{load} + P_{op} \quad if\ P_{net} < 0 \quad (4.17)$$

Where P_{HFC} is the power generated from the hydrogen fuel cell, P_{HPFC} is the power generated from the hydrogen peroxide fuel cell, and P_{Dis} is the power generated from batteries. The controller in this situation when $P_{net} < 0$ has two preferences depending on the P_{final} as mention in equation 4.18:

$$P_{final} = P_{net} + P_{HFC} + P_{HPFC} + P_{Dis} \qquad (4.18)$$

The first option, if $P_{final} \geq 0$ the controller will keep the situation as it is without any change (the power will be from PV and WTG plus both FCs and batteries). The second option, if $P_{final} < 0$ the controller can give a signal to all inside houses raspberry pi's to switch off the secondary panel (unnecessary load), and if still not enough and as a final stage the controller will send a signal to the DG controller to start DG to generate power. The advantage of switching off the unnecessary loads is to reduce the power demand, in order to reduce the operation hours of DG.

4.3.8.3 Summary

A micro controller (Raspberry Pi) is used to control the OGREH-SµG, with the control routines written in Python, are the novel features of the system to control the demand load and keep it under the umbrella of the available power. The novel control strategy implemented also includes a synchronization capability that facilitates µG2µG & µG2G connections. Moreover, it will give the controller the capability to predict the load and matching demand load with the available power.

4.4 Summary of this chapter

The optimal design of HPS is carried out by supplementing the systems capabilities with a multi storage system. The system's capability is further enhanced by an intelligent supervisory switching controller using microcontrollers to balance the generation, and synchronise µG2µG & µG2G. Such capabilities increase the robustness of the system by increasing its availability, reliability and sustainability.

LCF and economical calculation manual verification were undertaken to model the optimal system. OGREH-SµG was evaluated with the previous simulations (HOMER, MatLab/ Simulink to verify the economic and dynamic behaviour), and tested to achieve the outcomes reported in IADF for a remote area in Jordan as a case study. Then the data was presented in HOMER simulation for possible IHPSs solutions. The novel ideas and demand management strategy with complementary adaptive tariff are presented below:

1. IADF for OGREH-SµG.
2. LCF to model the optimal system
3. µG2µG synchronisation capability was tested by HOMER and Simulink.
4. Novel storage: H_2O_2 was tested by experiments to study its sustainability for long time storage, in addition to fuel cell and electrolyser.
5. OGREH-SµG demand management and complementary adaptive tariff as implemented by Raspberry Pi and tested in HOMER, was accepted by users and technicians through a survey.

Chapter 5

Case study – Bayir/Jordan

Jordan is chosen as a case study for the new IHPS design in this thesis.

Geographic criteria:

Jordan is a small country situated in the Middle East, bordered by Syria on the north, Saudi Arabia on the south, Saudi Arabia and Iraq on the east, and the occupied West Bank on the west. Jordan is located on the following geographic coordinates: 31 00 N, 36 00 E. It occupies an approximate total area of 96,188 square kilometres[10]; whereby land accounts for 91,971 sq. km, and water accounts for 329 sq. km.[11]

Climate criteria:

Basically, about 75% of Jordan shows desert climate with less than 200 mm^2 of rain per year. The west of Jordan has a hot Mediterranean climate with a dry summer, a cool wet winter, and two transitional seasons. Jordan has diverse terrain and landscapes relative to its small size. Based on geographic and climatic basis; Jordan can be divided into three main areas: the Jordan Valley, the Mountain Heights Plateau, and the Badia region in the east. Jordan has an example of two extreme heights in one country; the lowest point is the Dead Sea (about -408 m) and the highest point which is Jabal Ram about 1,734 m. Jordan is located in the solar belt and has very high percent of sun rays. Also Jordan has various topographic features

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[10] http://www.kinghussein.gov.jo/geo_env1.html

[11] http://geography.about.com/library/cia/blcjordan.htm

between mountains, valleys and deserts, which give different atmospheric pressures between different locations. This difference facilitates the flow of air and wind. Consequently, Bayir has wind and solar potential.

Scarcity of natural sources:

The most demanding environmental challenge Jordan faces nowadays is the scarcity of water. Jordan shares most of its surface water resources with its neighbouring countries, which has also exacerbated the problem. The current use of water already exceeds the renewable supply. Natural resources are also scarce in Jordan; phosphates, potash, and shale oil represent the main and only resources. Jordan imports fossil fuel for electricity generation where about 99.4% of electricity is generated from fossil fuel[12].

Electricity in Jordan:

Jordan is connected to one National electric grid, where electricity is generated by a diesel power plant, with considerably high environmental impacts (such as pollutant emissions and noise) and very high costs. Due to this, Jordan needs to integrate renewable energy sources (RES) in order to save energy by implementing sustainable programmes.

Jordan has nine main cities; Amman the capital, Al-Mafraq, Ma'an, Irbid, Al-Balqa, Al-Karak, Al-Tafilah, Al-zarqa and Aqaba. The remote areas in Jordan are located in the first three cities as marked in Figure 5.1 where Bayir is located in part 3. Figure 5.1 also shows of the distribution of electrical transmission lines in Jordan.

[12] http://geography.about.com/library/cia/blcjordan.htm

Area selection:

The case study for this thesis will be a remote area in Ma’an called Bayir which is geographically situated at 30∘761954□N latitude and 36∘679564□E longitude. Bayir was selected as a case study due to the following reasons:

1. Bayir represents one of the most remote areas in Jordan which is about 109.88 Km away from the nearest point of transmission line, where a stand-alone system dependent on a diesel generator is the only source of power.
2. This is one of the remote areas in Jordan confronted by inconsistent diesel supply due to distance and accessibility, especially during winter.
3. Bayer is surrounded by four smaller remote areas which also lack the access to electricity; all these remote areas are under Ma'an Governorate. The first remote area is located 4.72 Km to the north of Bayir, and the geographic location is 30∘807530□N latitude and 36∘692158□E longitude. The second remote area is located 2.43 Km to the south of Bayir, and the geographic location is 30∘741122□N latitude and 36∘670899□E longitude. The third remote area is located 2.33 Km to the north west of Bayir, and the geographic location is 30∘768153□N latitude and 36∘659791□E longitude. The fourth remote area is located 3.09 Km to the south west of Bayir, and the geographic location is 30∘756731□N latitude and 36∘649954□E longitude (Figure 5.2).

Data collection:

Relevant data was collected from Bayir and then averaged where applicable in order to design successful IHPS. Meteorological data were collected first for all Jordanian cities in order to decide the appropriate type of data required for this research. Table

5.1 shows the main meteorological data for Bayir, where only solar PV and wind turbine renewable technologies will be considered.

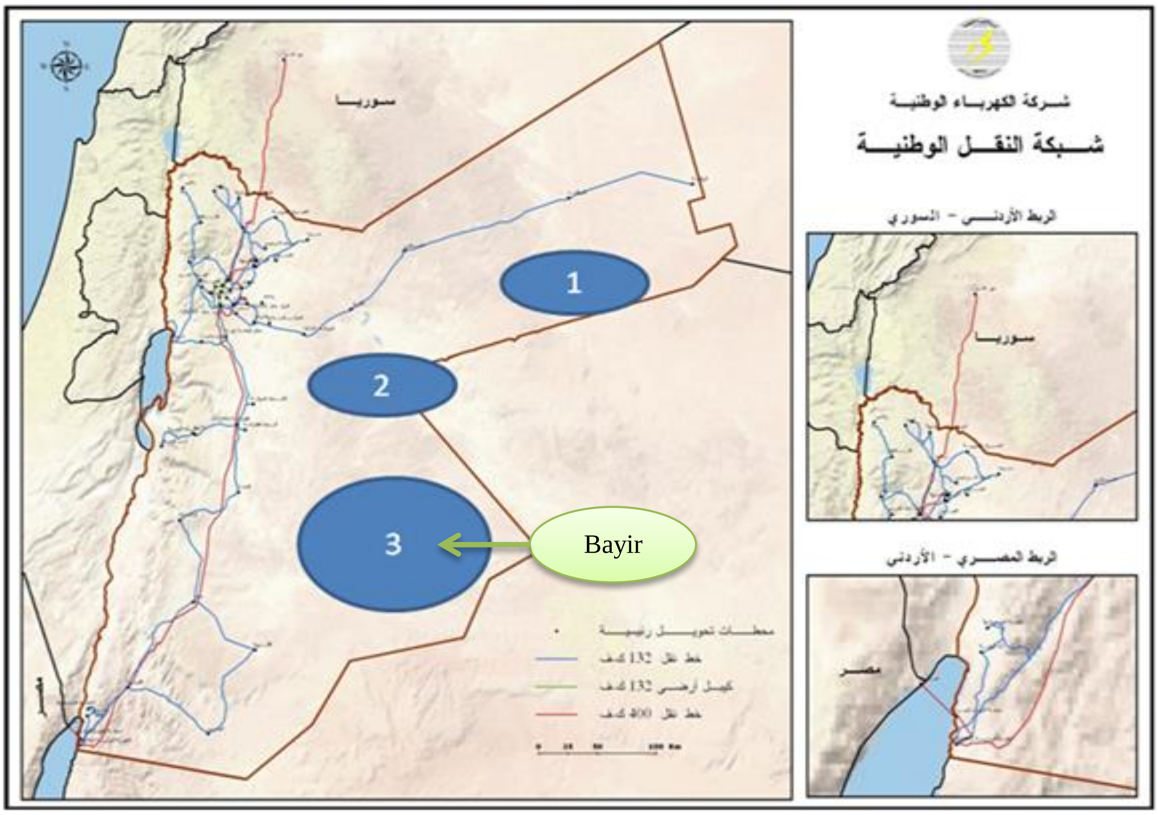

Figure 5.1: Electrical transmission lines in Jordan (NEPC 2015). Area 1 is part of Al-Mafraq city, area 2 is part of Amman city, and area 3 is part of Ma'an city.

Table 5.1 Meteorological data for Jordan during one year (2012)

Month	Temperature (C°)	Sun radiation (MJ/m2)	Wind speed (m/s)
January	4	12	18
February	5	18	18
March	11	21	12
April	17	26	8
May	21	31	6
June	29	35	12
July	31	36	11
August	35	36	11
September	32	33	11
October	24	27	18
November	14	16	21
December	3	9	23

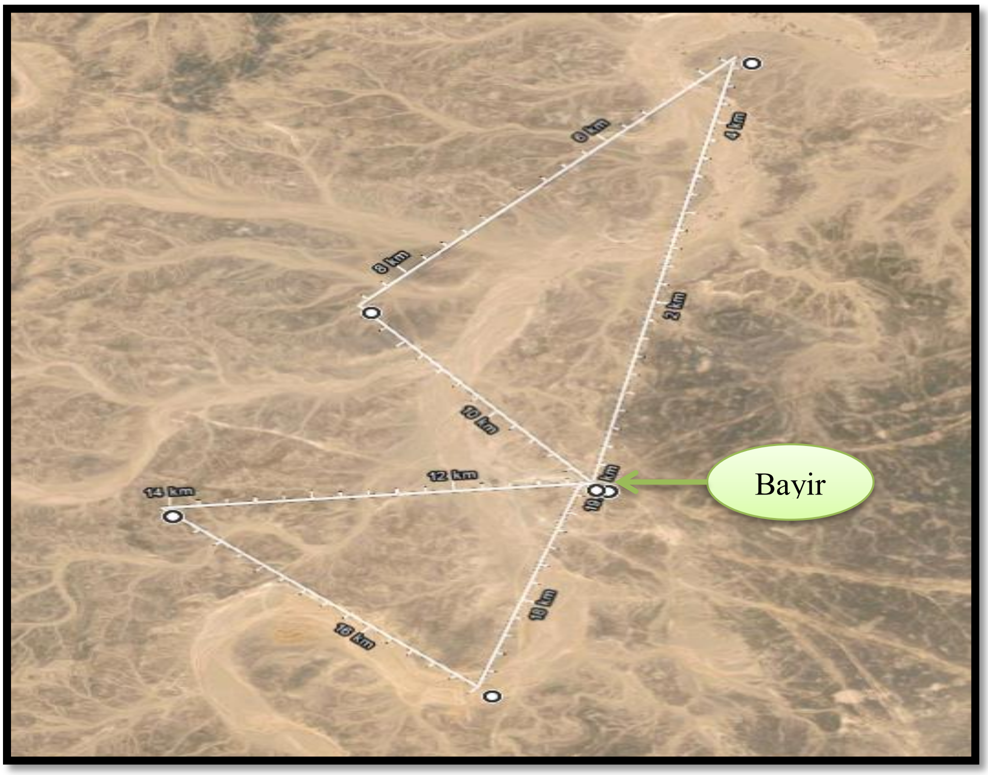

Figure 5.2: Bayir with the surrounding remote areas (Google earth 2014).

Specific power criteria for Bayir:

5.1 Wind speed

Wind speed data was collected and compared for three years (2012-2014) from two websites: the Arabia weather website[13] and Jordan weather forecast website[14] where the average speed was calculated. Table 5.2 shows the average monthly wind speed in meter per second for Bayir compared to the three cities. Table 5.2 shows that the wind speed during winter is higher than summer where the highest wind speed rate is recorded in January, November and December. Summer and spring months start from April to September. Wind profile in Bayir for the three years is shown in Figure

[13] http://www.arabiaweather.com/Jordan/map

[14] http://met.jometeo.gov.jo/jometeo/e_main

85.3, while Figure 5.4 shows the wind speed for one day in winter and one day in summer.

Table 5.2 Wind speed in Bayir for three years[15]

Wind speed (m/s)				
Month	**2012**	**2013**	**2014**	**average**
Jan	18	22	17	19
Feb	18	22	16	19
March	12	15	11	13
Apr	8	11	8	9
May	6	10	6	7
June	12	12	10	11
July	11	15	11	12
Aug	11	12	11	11
Sep	11	12	11	11
Oct	18	22	12	17
Nov	21	22	15	19
Dec	23	24	12	20

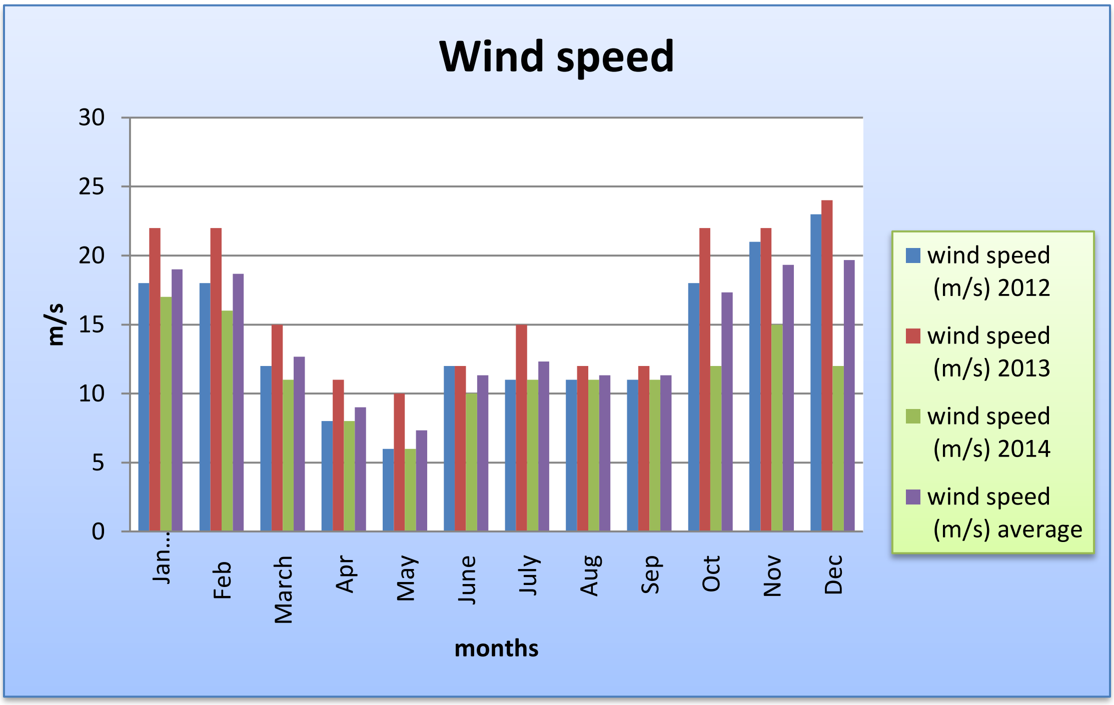

Figure 5.3: Wind speed in Bayir per year (2012-2014).

[15] http://www.arabiaweather.com/Jordan/map and http://met.jometeo.gov.jo/jometeo/e_main

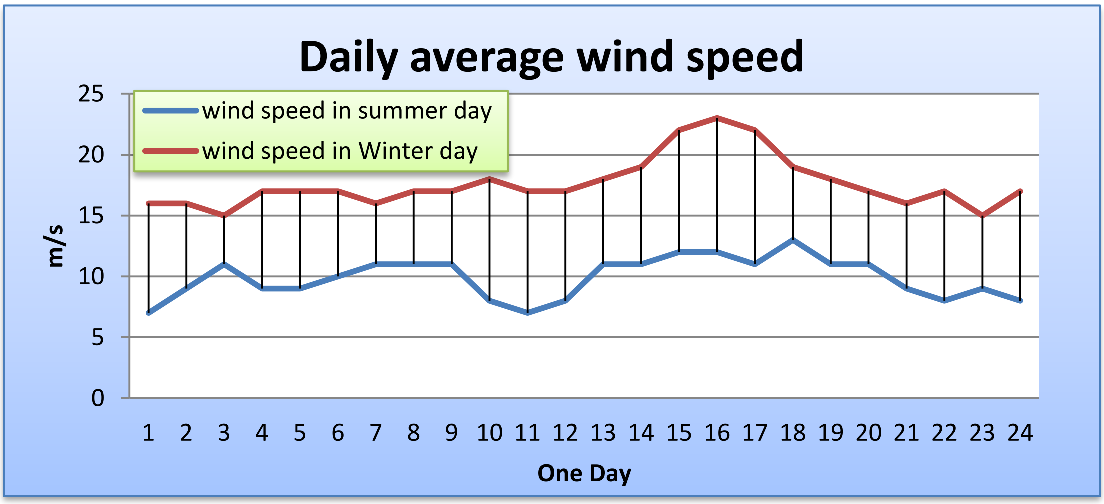

Figure 5.4: Wind speed in winter and summer day.

5.2 Daylight hours

Daylight hours were collected from the same websites for wind speed in addition to the Gaisma website[16]. All the Jordanian cities are located at the same longitude, so they have the same daylight.

Table 5.3 shows the average daylight and sun radiation per month. The highest daylight is recorded in June and the lowest in December and January while June is the sunniest month of the year where the solar energy is 7.95kWh/m^2/d compared to only 2.76kWh/m^2/d in December. These differences should be taken into account during designing and sizing the components of IHPS.

The daily percentage of sun radiation and daylight hours were compared between one winter and one summer day (Figure 5.5). Figure 5.6 shows the sun path diagram for Bayir with sunrise and sunset times per month over one year. In addition, the latitude and longitude of Bayir were entered in HOMER tool to compare the sun radiation data collected with HOMER database per year (Figure 5.7).

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[16] http://www.gaisma.com/en/location/maan.html

Table 5.3 Average daylight hours and daily sun radiation per month

	Month	Jan	Feb	March	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Daylight hours (hour/day)	**Bayir/ Jordan**	9	10	10	11	12	14	13	13	12	11	10	9
Daily sun radiation ($kWh/m^2/d$)		3.04	3.96	5.13	6.36	7.16	7.95	7.85	7.21	6.17	4.79	3.44	2.76

Figure (5.5) shows more daylight hours in a summer day compared to winter day. The highest sun radiation (100%) is recorded in summer day at 14:00 o'clock compared to (80%) at 12:00 o'clock midday in winter. The daylight starts and diminishes as the sun rises and sets respectively from zero%, increasing during the day then diminishing to zero% again.

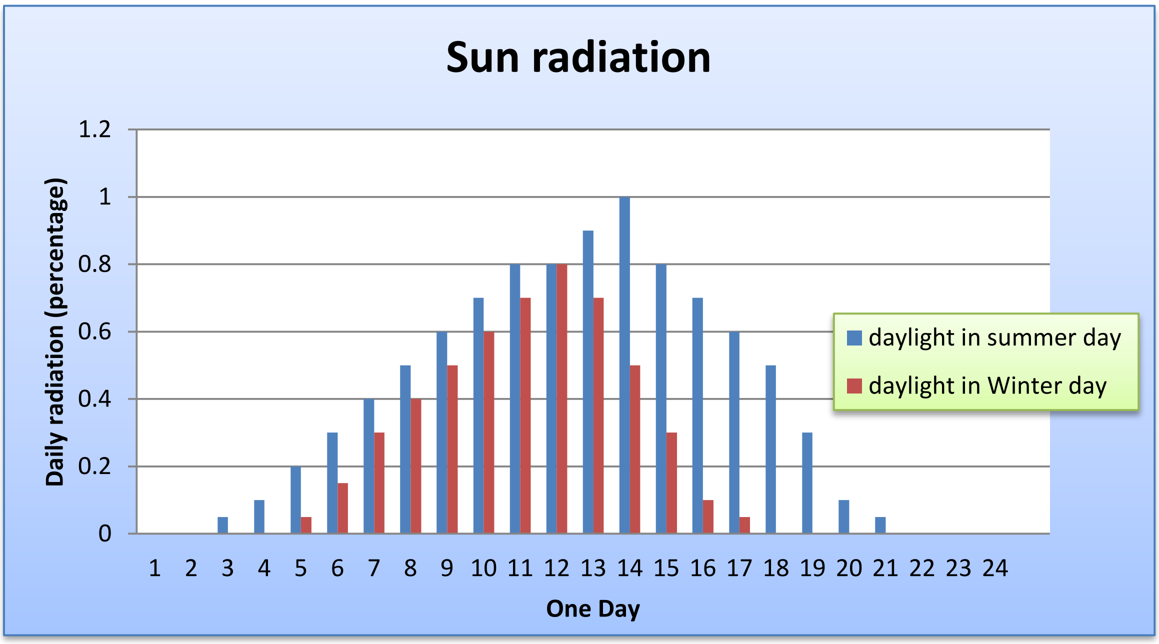

Figure 5.5: The daylight and percentage of sun radiation in a winter and summer day.

Figure 5.6 describes the sun radiation and light day hours per month during the year 2014. There is a noticeable shift in the sun path from the end of March until the end of October due to daylight saving time (summer timing).

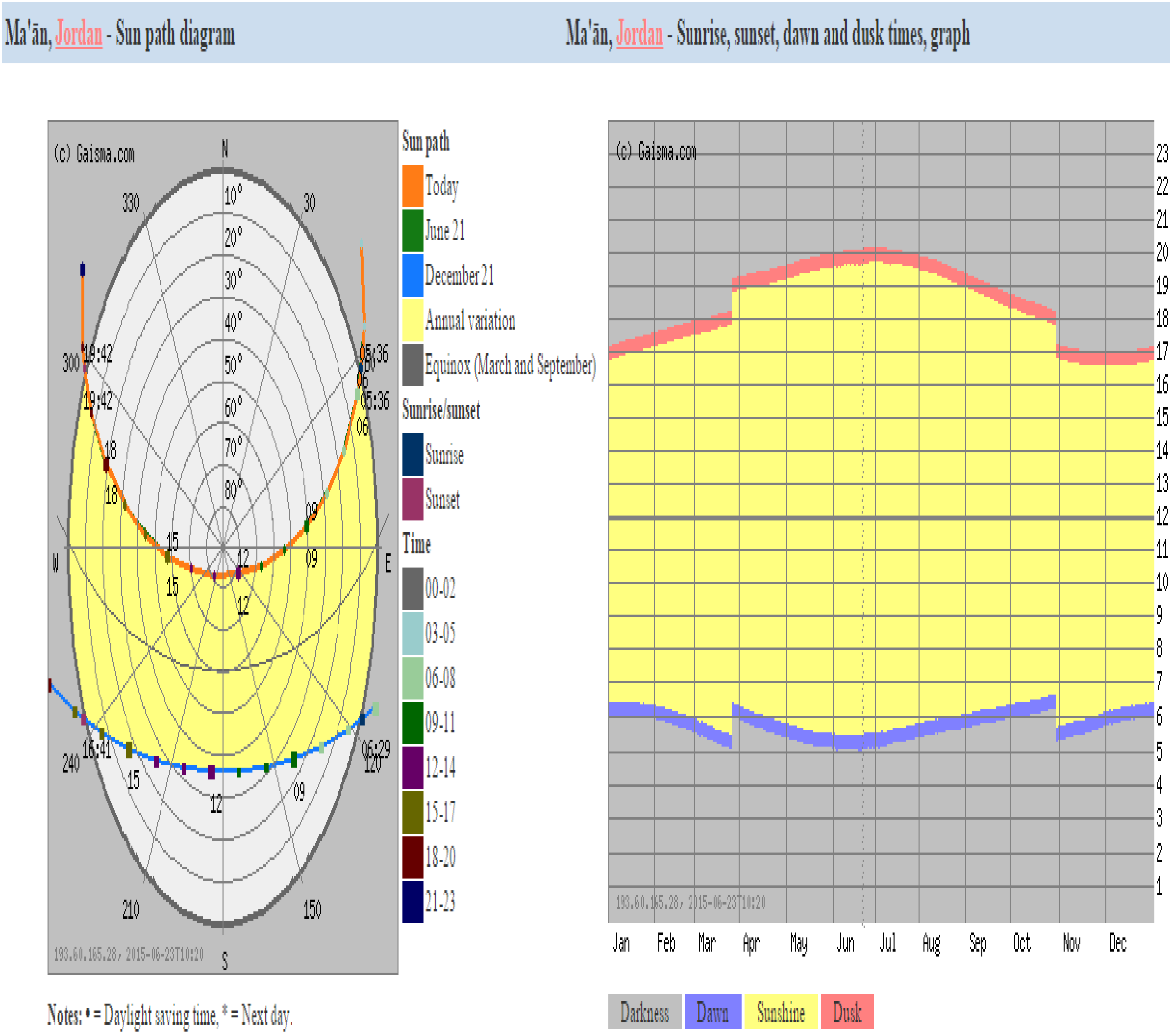

Figure 5.6: Sun path diagram for Bayir, showing sunrise (blue horizontal lines), and sunset (red horizontal lines) **(GAISMA 2015).**

Figure 5.7 shows the average daily sun radiation in kWh/m2/d for one year according to HOMER tool where June and July show the highest radiation.

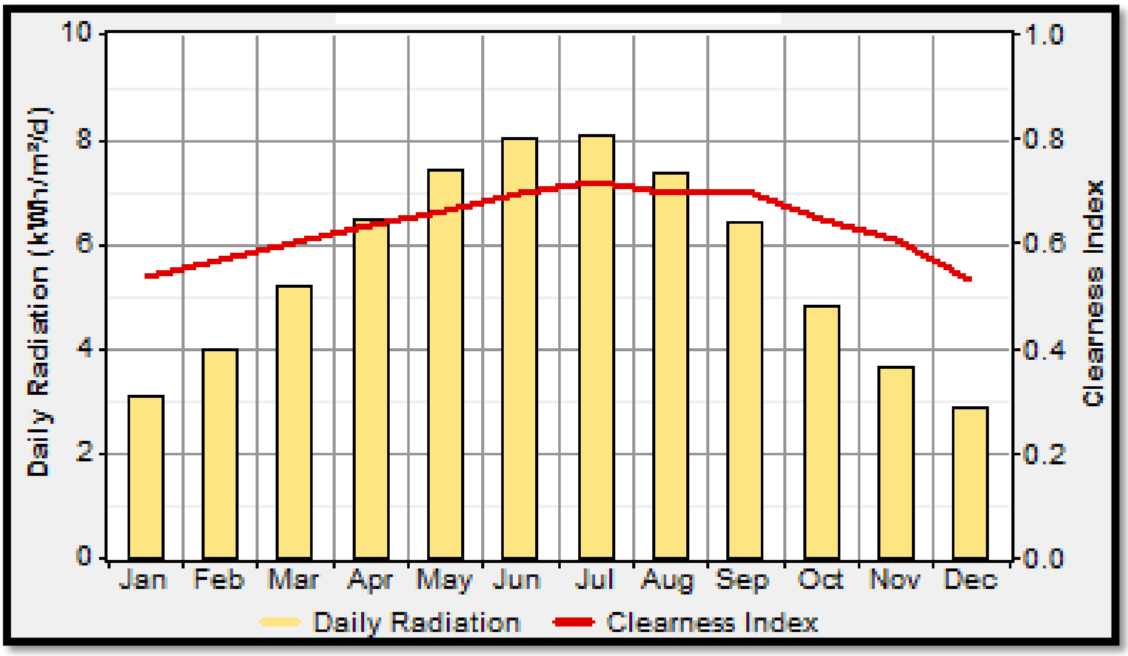

Figure 5.7: Sun radiation per year for Bayir as obtained from HOMER tool.

5.3 Load data

Load data was collected between the years (2012-2014) from three Jordanian utilities websites: The Jordanian Electrical Power Company, The National Electrical Power Company, and The Electrical Distribution Company. The load was manually calculated from the data to estimate the hourly average consumption per month during the years (2012-2014) (Table 5.4) which was then exported to HOMER simulation tool. The total consumed load was calculated to be 55480 kW per year.

Figure 5.8 shows the average monthly load for three years (2012, 2013, and 2014). The load fluctuates as a result of demand changes during each year. Minimum and maximum loads are shown in both Table 5.4 and Figure 5.8.

Table 5.4 Average load for Bayir[17]

Hour\load (KW)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
00:00 - 01:00	4.02	3.90	4.13	4.04	3.90	4.11	4.03	5.00	4.03	4.19	3.93	4.07
01:00 - 02:00	3.98	3.87	4.05	3.94	3.83	4.05	3.95	5.00	3.96	3.89	3.94	3.94
02:00 - 03:00	3.89	3.69	3.89	3.82	3.78	3.84	3.82	7.00	3.86	3.94	3.70	3.83
03:00 - 04:00	3.85	3.71	3.89	3.86	3.75	3.87	3.84	5.00	3.74	3.86	3.78	3.76
04:00 - 05:00	3.85	3.80	3.84	3.89	3.70	3.84	3.85	5.50	3.94	3.92	3.71	3.88
05:00 - 06:00	4.25	4.18	4.39	4.27	4.15	4.36	4.24	5.00	4.40	4.28	4.12	4.34
06:00 - 07:00	4.92	4.81	4.80	4.94	4.67	4.82	4.80	5.50	4.84	4.88	4.70	4.82
07:00 - 08:00	6.58	6.56	6.80	5.72	6.57	6.86	6.84	8.00	6.88	6.70	6.67	6.86
08:00 - 09:00	6.93	6.83	7.25	5.97	6.97	7.27	7.01	7.36	7.05	7.06	6.86	7.11
09:00 - 10:00	6.87	6.82	7.04	6.05	6.95	7.08	7.08	7.36	7.18	7.11	6.85	7.09
10:00 - 11:00	6.76	6.74	7.25	6.10	6.80	7.01	6.87	7.39	7.09	6.97	6.85	6.95
11:00 - 12:00	7.14	6.93	7.33	6.08	6.88	7.54	7.17	7.25	7.27	7.19	6.87	7.04
12:00 - 13:00	6.80	6.86	7.30	6.06	6.83	6.97	6.90	7.41	7.13	7.04	7.06	6.82
13:00 - 14:00	6.99	6.90	7.37	6.33	6.83	7.06	6.99	7.41	7.19	7.25	6.84	7.07
14:00 - 15:00	6.82	6.82	7.18	6.02	6.70	7.24	6.90	7.26	7.08	7.09	6.77	6.93
15:00 - 16:00	8.29	7.74	8.38	6.02	8.07	8.12	8.10	8.57	8.12	8.20	8.14	8.47
16:00 - 17:00	8.65	8.73	9.09	7.09	8.86	9.00	9.01	9.37	9.08	9.02	8.77	8.80
17:00 - 18:00	9.94	9.50	10.03	7.65	9.65	9.66	9.57	10.13	10.03	9.51	9.41	9.42
18:00 - 19:00	10.44	10.41	10.78	9.05	10.25	10.57	10.75	11.50	10.55	10.44	10.94	10.41
19:00 - 20:00	9.67	9.26	9.58	7.45	9.39	9.64	9.52	9.83	9.52	9.47	9.48	9.50
20:00 - 21:00	6.88	6.65	6.93	5.74	6.64	6.78	6.86	6.85	6.89	6.67	6.61	6.71
21:00 - 22:00	5.74	5.82	5.96	4.97	5.78	5.91	5.90	6.07	5.93	5.87	5.76	5.96
22:00 - 23:00	5.44	5.29	5.46	4.48	5.44	5.58	5.25	6.00	5.42	5.39	5.40	5.36
23:00 - 00:00	5.05	5.00	5.27	4.21	5.11	5.14	5.12	5.32	5.23	5.15	5.05	5.16
Daily demand	153.73	150.80	157.98	133.74	151.49	156.33	154.34	171.08	156.39	155.09	152.18	154.27
Hourly average demand	6.41	6.28	6.58	5.57	6.31	6.51	6.43	7.13	6.52	6.46	6.34	6.43

In order to study the range of fluctuation, evaluating the load on daily basis is required. Figure 5.9 shows the average load of one day in summer and another one day in winter with the on-peak and off-peak periods. This type of data can guide the designer to study the maximum demand power, and determine the exact period to cover the required load.

[17] http://www.nepco.com.jo/

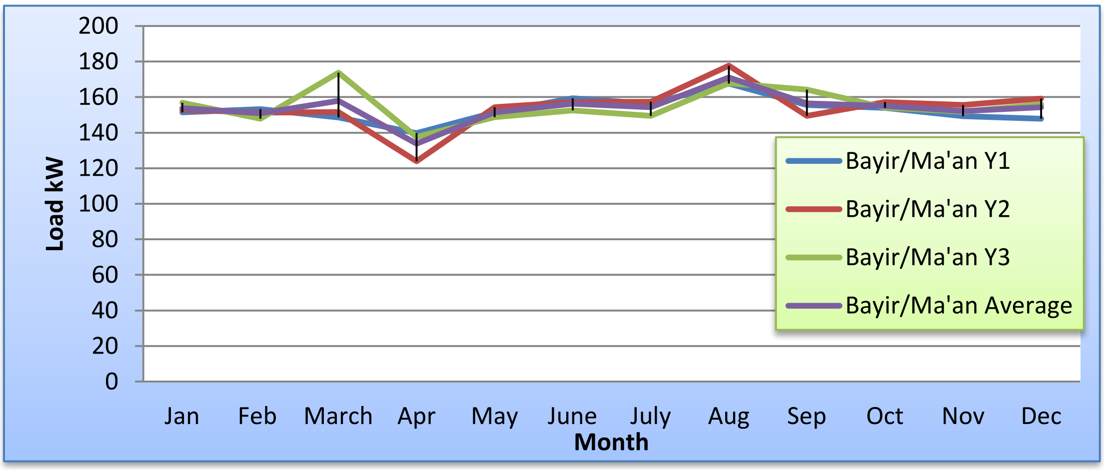

Figure 5.8: The average load for Bayir remote areas in three years. Y1; year 2012, Y2; year 2013, and Y3; year 2014.

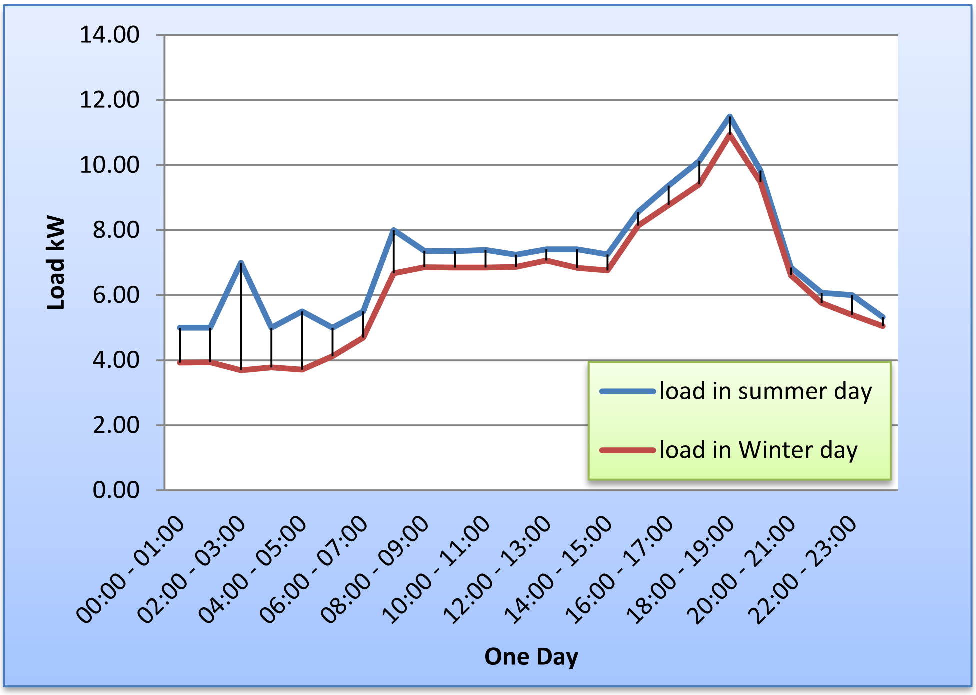

Figure 5.9: Average load in summer and winter day for Bayir remote areas, showing the on-peak and off-peak hours during the day.

Bayir has two on-peak hours which are; early morning in the summer as a result of using light and water pumps for making ablutions for Dawn prayer. In winter this peak is shifted due to time change. The second high peak is similar in both summer and winter at 06:00 pm, as it is the times most people finish their work between 04:00 and 08:00 pm, and may be start to use some electric facilities and devices.

5.4 Summary

A remote area was selected as a case study in Jordan to design IHPS. The temperature, wind and solar data as well as the demand were presented in this chapter.

This remote area is located in south east Jordan, and it is not connected to the public electric grid where a diesel isolated power system is operated as the only source of power. The location has the following characteristics as shown in this chapter's Figures and Tables: annual sun radiation is 25.083 MJ/m2/day which is equal to 6.967 kWh/m2/day annual average insolation, and annual average wind speed is 14.333 m/s.

The important data was presented numerically and graphically, which can help the designer to make decision or to export the data to simulation tools. The main important data was the demand load, which is the foundation of building any power system. These collected data will carry this study to the next stage, which is the design of the new IHPS for Bayir. The fluctuation between the collected data in both monthly and yearly scales will be considered in the design stages.

Part 3

Chapter 6

Results

6.1 Introduction

This chapter characterizes and evaluates the technical and economic feasibility of IHPS at Bayir remote area. These evaluations were attempted for PV-Wind-Hydrogen-Hydrogen Peroxide-Diesel-Batteries OGREH-SμG which was tested according to the data during the period of January, 2012 to December, 2014. Appendix A presents all the required data which were used as input data for the simulation (as HOMER input summary). The system performance was portrayed as daily, monthly, and yearly operation, the effectiveness and the losses of the system, for example, performance proportion, sun radiation and wind speed based part, salvage, capture individual losses and the whole system losses. Economically, the capital cost, Running cost, and replacement cost was added, in order to find the specific cost for the generated power, life cycle cost, and cash flow. The suggested IHPS along with its components are the results of a series of technical and economic analysis and simulation studies run with HOMER simulation.

6.2 HOMER simulation results

According to HOMER Energy software, the resultant optimal configuration that has given the best results is shown in Figure 4.3. The optimal results show that 268800 solutions have been simulated; few of these systems were feasible, in this thesis, the suggested OGREH-SμG is PV-Wind-Hydrogen-Hydrogen Peroxide-Diesel-Batteries Isolated Hybrid Power System, this system was chosen according to the 80 sensitivity analysis which added to the simulation to study all the circumstances which can affect the system.

6.2.1 Technical evaluation

Hour by hour simulation is carried out for the chosen system, part of this simulation is mentioned in Appendix B, and the rest of data will be presented in CD. Table 6.1 presents the yearly generated power per individual component, where the generated power from DG reduced from (55,480kWh/year to 3,304kWh/year). Figure 6.1 shows the monthly average power production, where it shows the requirement for DG is drastically reduced even though it is still needed during March, May, June, July, August, and September as a result of low wind speeds). However, in January, February, October, November, and December the DG is required to operate to cover 3.8% of the load as a result of high demand with minimum PV power production.

Table 6.1: Yearly HPS components energy production

Production	kWh/year	%
PV array	995	1.150
Wind turbines	65,272	75.417
Hydrogen Fuel Cell	375	0.433
Diesel Generator	3,304	3.818
H_2O_2 Fuel Cell	16,184	18.700
Batteries	417	0.482
Total	86,547	100.00

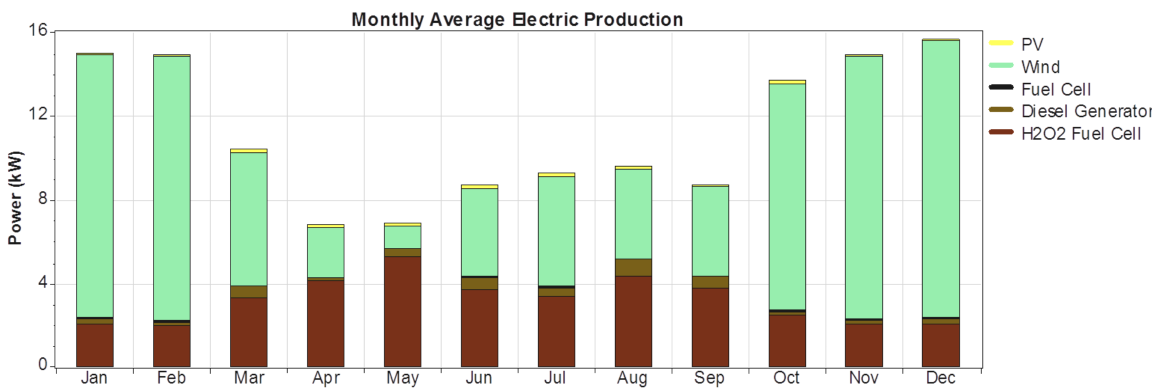

Figure 6.1: Monthly power production for the OGREH-SμG.

6.2.1.1 PV results and manual calculation

The rated PV capacity which has been chosen is 0.560 kW, the total production from it around the year is 995kWh/year. Figure 6.2 shows the monthly average power produced from PV panel, and it shows the highest production is from April to September, and the lowest months are January and December, and for more detailed daily average power production for the above stated months is shown in Figure 6.3, as it demonstrated the power reached 0.4 kW from April to September. Figure 6.4 and 6.5, respectively shows the PV power production along with solar incident in summer and winter day, as it indicates that the production in summer day (450W) is much higher than winter day (125W) for the same rate of PV panel.

Calculation of the number of series in one panel and number of panels

This calculation is with reference to the PV panel as described in section 2.5.1.1, to calculate the number of series cells in one panel, number of parallel cells in one panel, and the number of panels that is required to be used. These calculations are undertaken because it is required to calculate the series cells and the parallel panels in order to implement it in Simulink.

By using these equations with the preliminary data, as every solar cell individual has a voltage almost 0.66V at 25 °C for silicon solar type, and the voltage in DC-bus in the system is 24V.

Using equation 2.6: $24 = 0.66 \times N_{sc} \rightarrow N_{sc} = 36.3636 = 36$ series cell;

Using equation 2.7: $23.3 = 6 \times N_p \rightarrow N_p = 3.8889 = 4$ solar panel;

Using equation 2.8: $560 = 3.96 \times 36 \times N_{pc} \rightarrow N_{pc} = 3.92817 = 4$ parallel panels;

The final connection is 4 parallel panels and every panel contains 36 series cell. Also the connection can 4 panel 2 series connected parallel with 2 series, and that required having inside every panel 36 cells, two parallel circuits with 18 series cell.

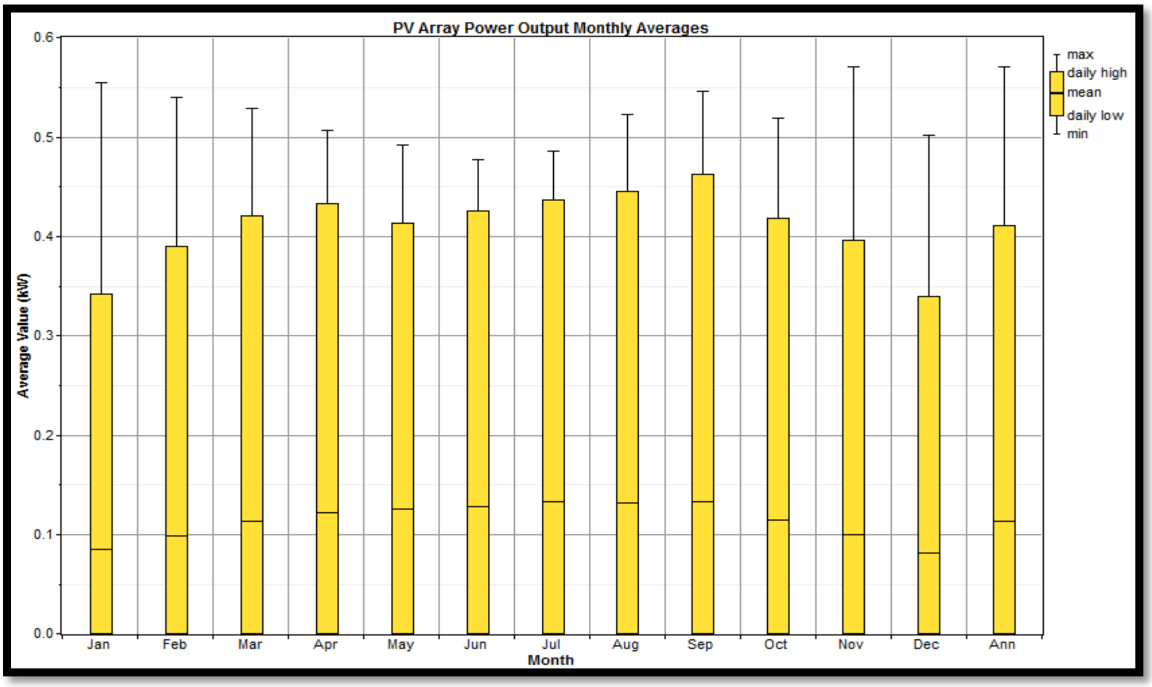

Figure 6.2: Monthly average PV power production.

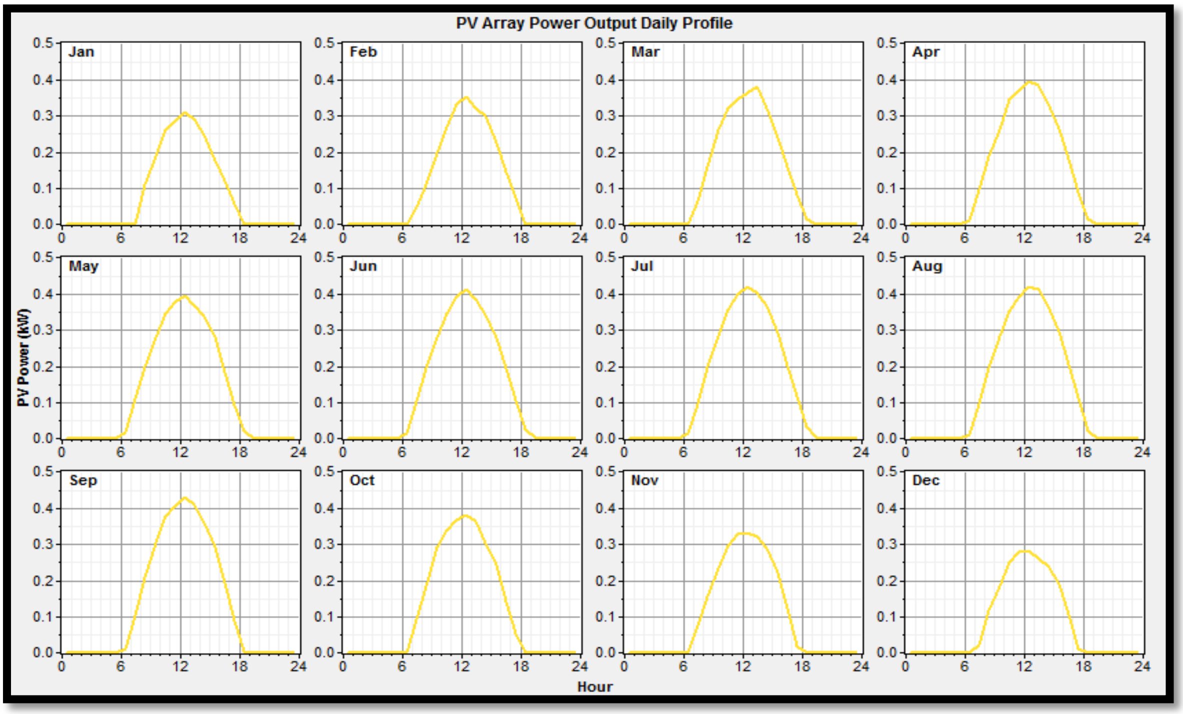

Figure 6.3: Daily PV power production in Monthly bases.

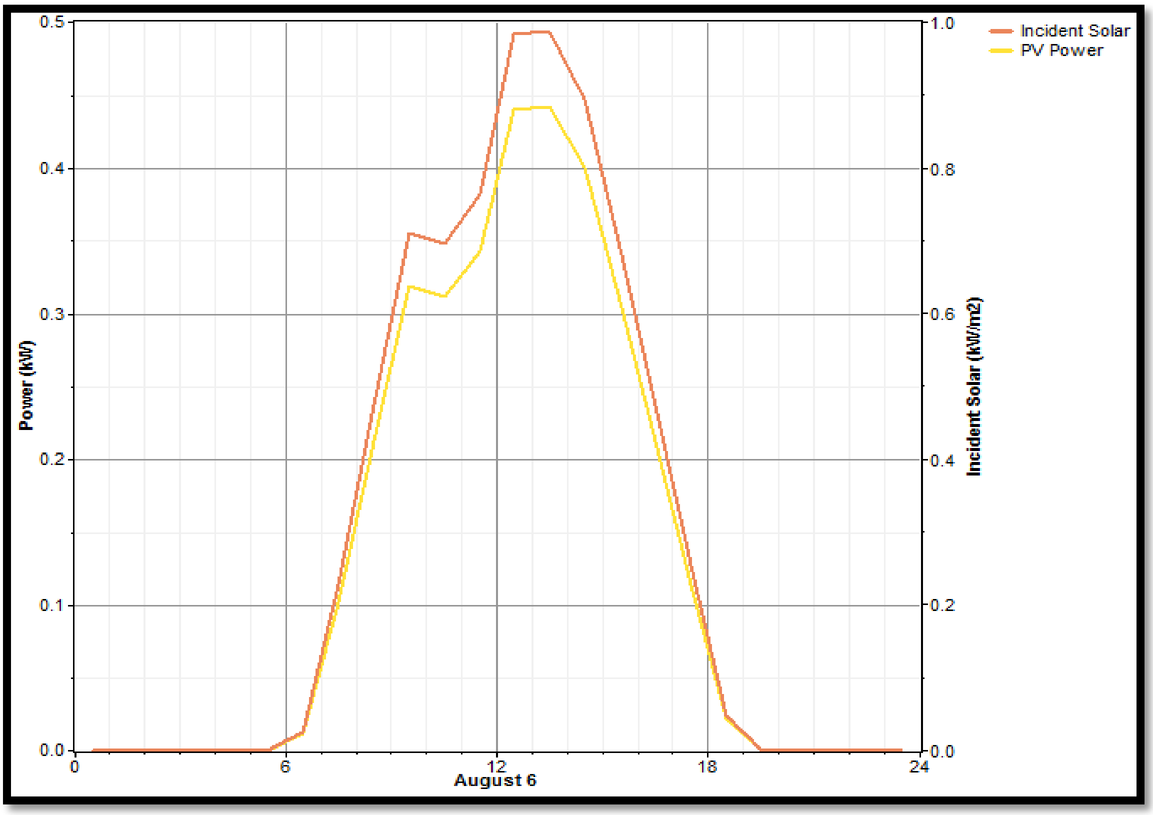

Figure 6.4: PV power production and solar incident in summer day.

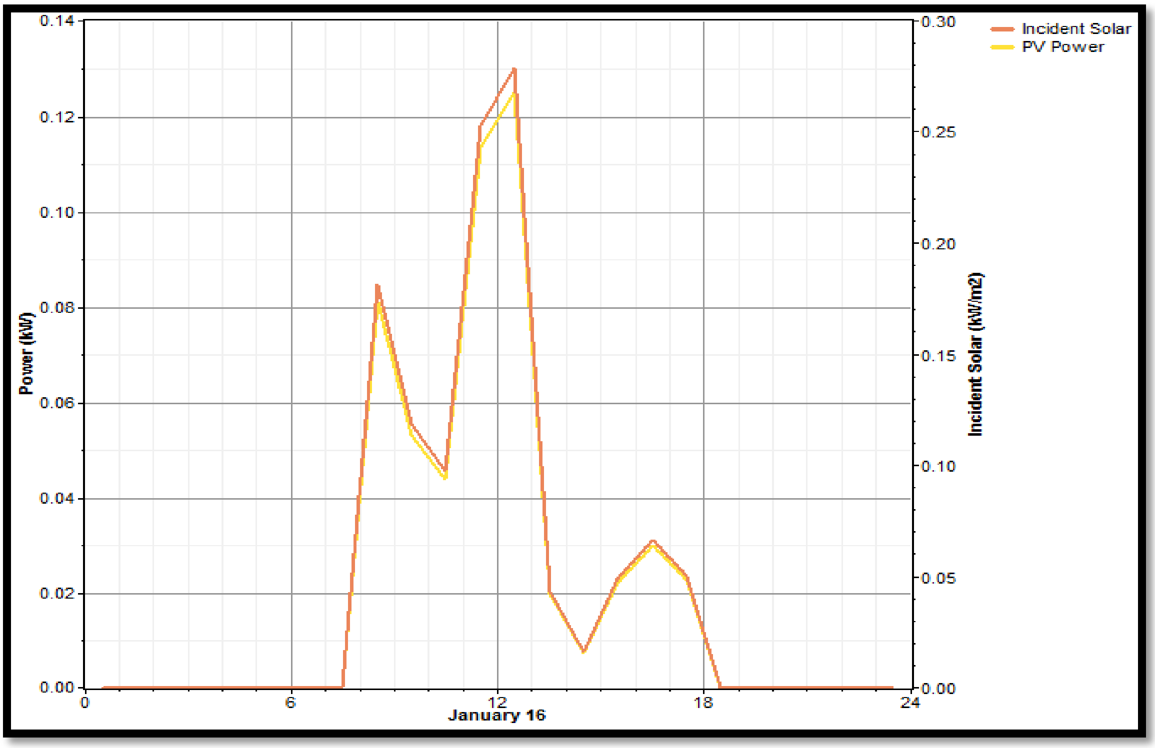

Figure 6.5: PV power production and solar incident in winter day.

6.2.1.2 Wind turbine results and manual calculation

The turbines chosen for the design are two turbines from BWC Excel-S with 10kW AC rated power (from energy wind power); this type was selected with regard to the wind speed range in this type which matches the case study area. The total production from both turbines around the year is 65,272kWh/year. Figure 6.6 shows the monthly average power produced from both wind turbines, as it demonstrate that the lowest production in month of May whereas the highest productions is from October to February, and for more detailed daily average power production for the above stated months is shown in Figure 6.7. Figure 6.8 and 6.9, respectively show the wind turbine power production and wind speed in summer and winter day, the power production in summer day (5kW) is much less than the production in winter day (22kW) for the same rated turbine.

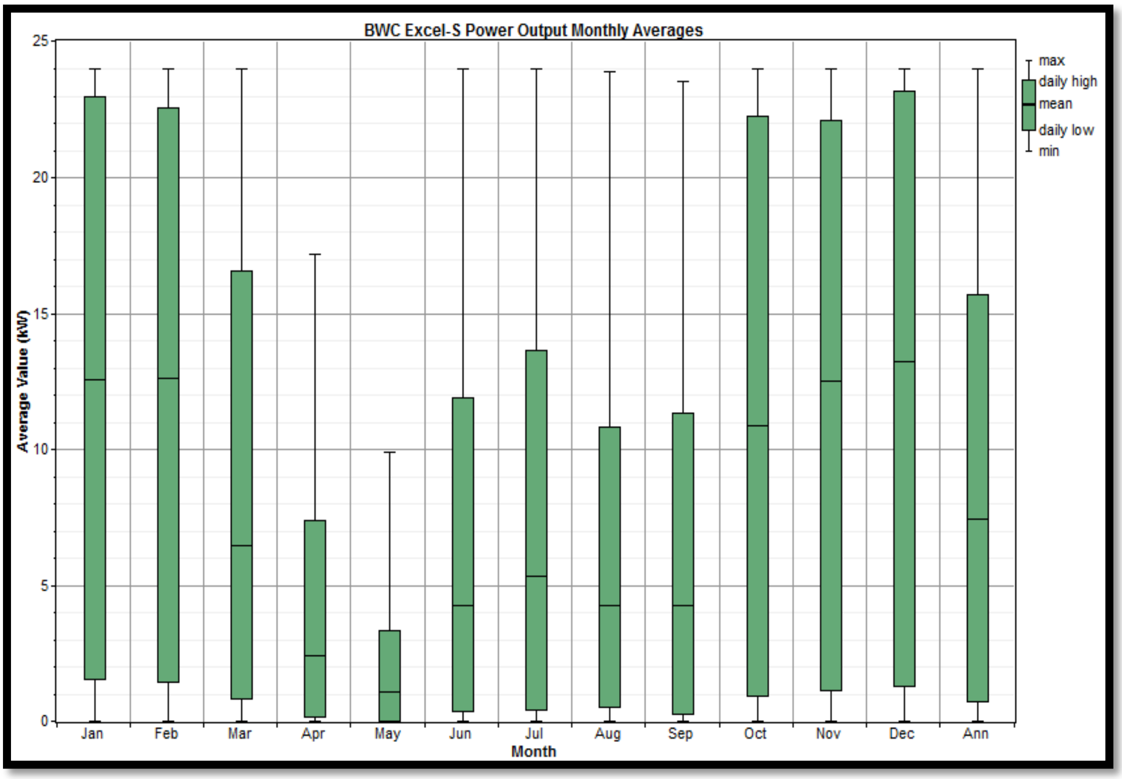

Figure 6.6: Monthly average wind turbines power production.

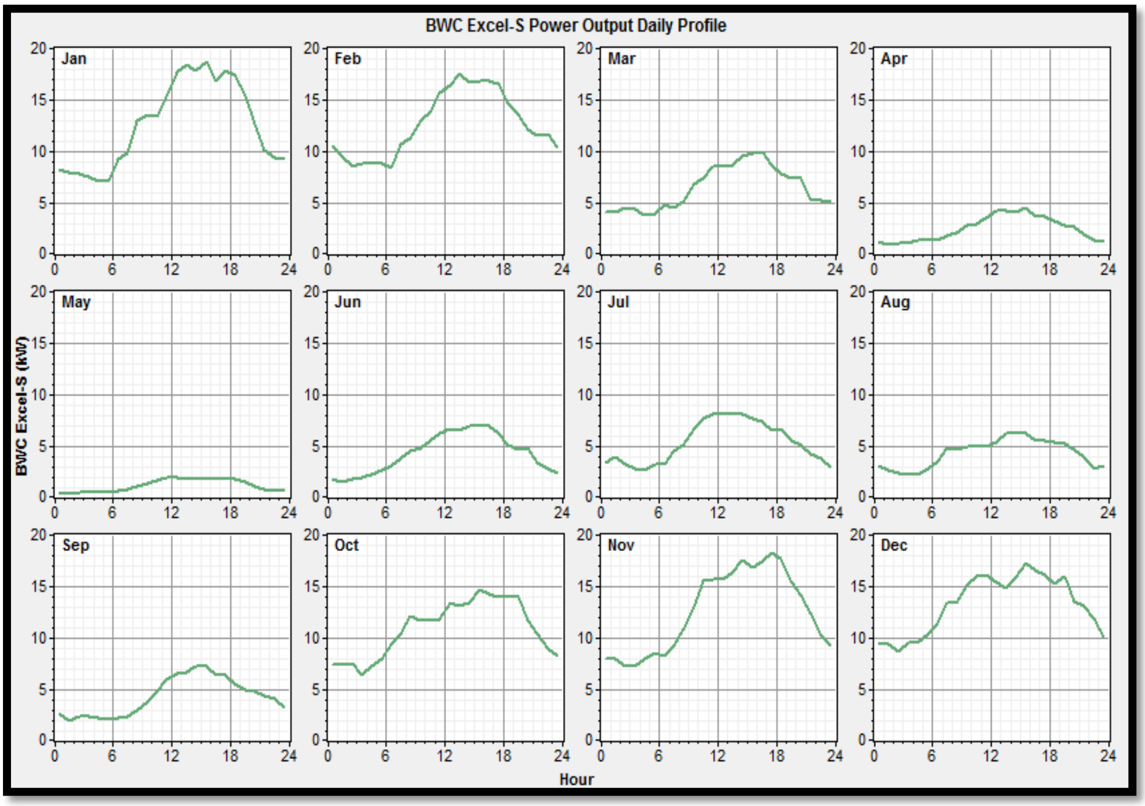

Figure 6.7: Daily wind turbines power production in Monthly bases.

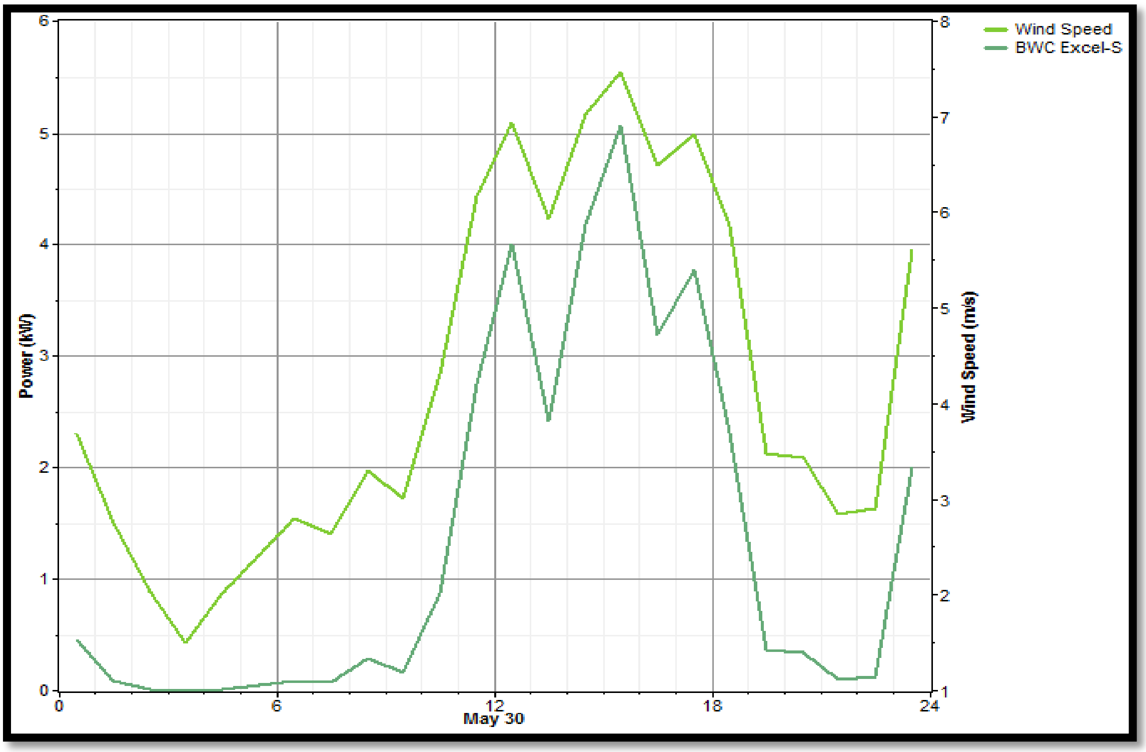

Figure 6.8: Wind turbine power production and wind speed in summer day.

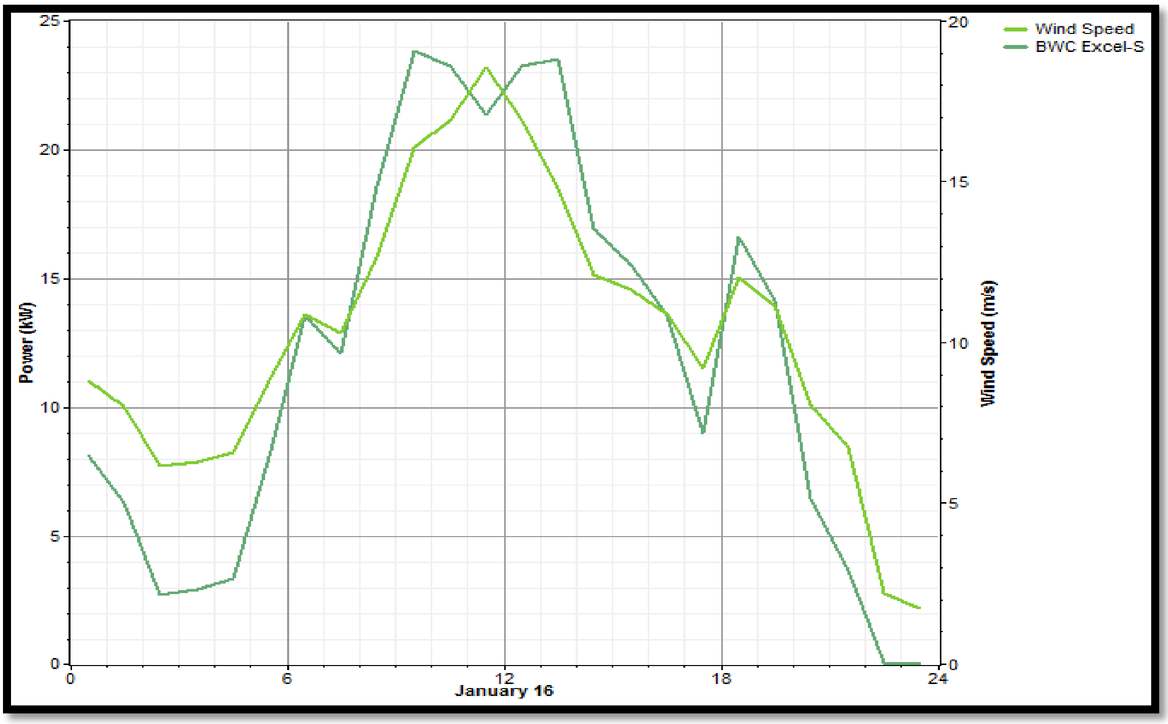

Figure 6.9: Wind turbine power production and wind speed in winter day.

Calculation for the wind power density

This calculation is with reference to wind turbine as described in section 2.5.2.1, to calculate the kinetic power in the air, power coefficient, and the swept area of the wind turbine blades. These calculations are undertaken because it is important to know if the wind has enough wind power density to move the blades.

By using these equations with the preliminary data, as the diameter for the wind turbine blades is 7m, and the air density is 1.226 kg/m^3 at standard temperature and pressure (288K, 760Hg).

Using equation 2.36: $A = \pi \times (3.5)^2 \rightarrow A = 38.465\ m^2$;

Using equation 2.38: $C_P = \frac{(1+0.227)\times(1-(0.227)^2)}{2} \rightarrow C_P = 0.58194$;

Using equation 2.35: $P_w = 0.5 \times 38.465 \times 0.58194 \times 1.22 \times (12.333)^3 \rightarrow P_w =$ 25614.16 W or it can be described as wind power density: 25.16kW per 38.465 m^2.

6.2.1.3 Electrolyser results, hydrogen storage, and manual calculation

The electrolyser chosen for the design is 3kW DC rated power and the hydrogen sorted tank is 1kg. The total consumption load around the year is 12,313kWh/year. Figure 6.10 show the relation between the electrolyser input power and the electrolyser output (hydrogen in kg). Figure 6.11 and 6.12, respectively show the electrolyser monthly output average where the highest production is from October to February, and the lowest months are April and May, and the monthly average stored hydrogen the available hydrogen (stored hydrogen) is demonstrated in the next figure. Moreover, part of the generated hydrogen is stored and the other part is converted to hydrogen peroxide as explained in section 2.8.3.3.

Calculation of the hydrogen production

This calculation is with reference to the Electrolyser as described in section 2.5.4.1, to calculate the expected power, with the preliminary data, such as the hydrogen atomic mass is 200.59amu/1 atom, 1 atomic mass unit 1.661×10^{-24} g/1amu, and Avogadro's number 6.022×10^{23} atoms/mol. multiplying the previous will give the gram per mole 200.64 g/mol. These calculations are undertaken because it is important to compare the manual calculation with HOMER results, and also it is important to implement a function for H_2 production rate in Simulink simulation.

Using equation 2.40, to calculate the hydrogen production by taking the half yearly input power as 2.5kW, and for the other 6 months input power as 1kW (these values regard to HOMER results): $H_{ele} = \frac{(2.50\times1000\times3600)}{(2\times24\times9.64853399\times10^{4})}$ = 1.9433mol/h in summer day, and for winter day $H_{ele} = \frac{(1\times1000\times3600)}{(2\times24\times9.64853399\times10^{4})}$ = 0.7773mol/h, and if 1mol of H_2 = 200.64g, then

1.9433mol/h = 389.9g/h = 9357.689g/day = 9.36kg/day = 280.8kg/month = 1684.8kg/6 months.

0.773mol/h = 155.95g/h = 3742.89g/day = 3.74kg/day = 112.2kg/month = 673.2kg/6 months.

The estimated production of hydrogen per year = 1684.8kg + 673.2kg = 2358kg/year.

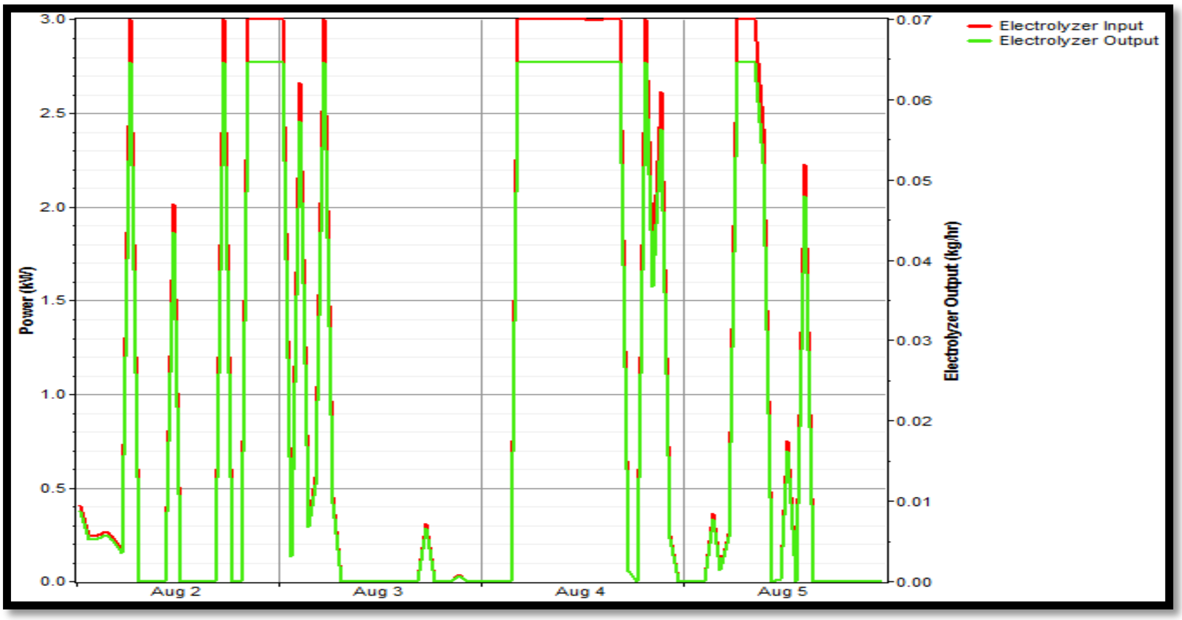

Figure 6.10: Electrolyser input power compare to the output hydrogen in kg.

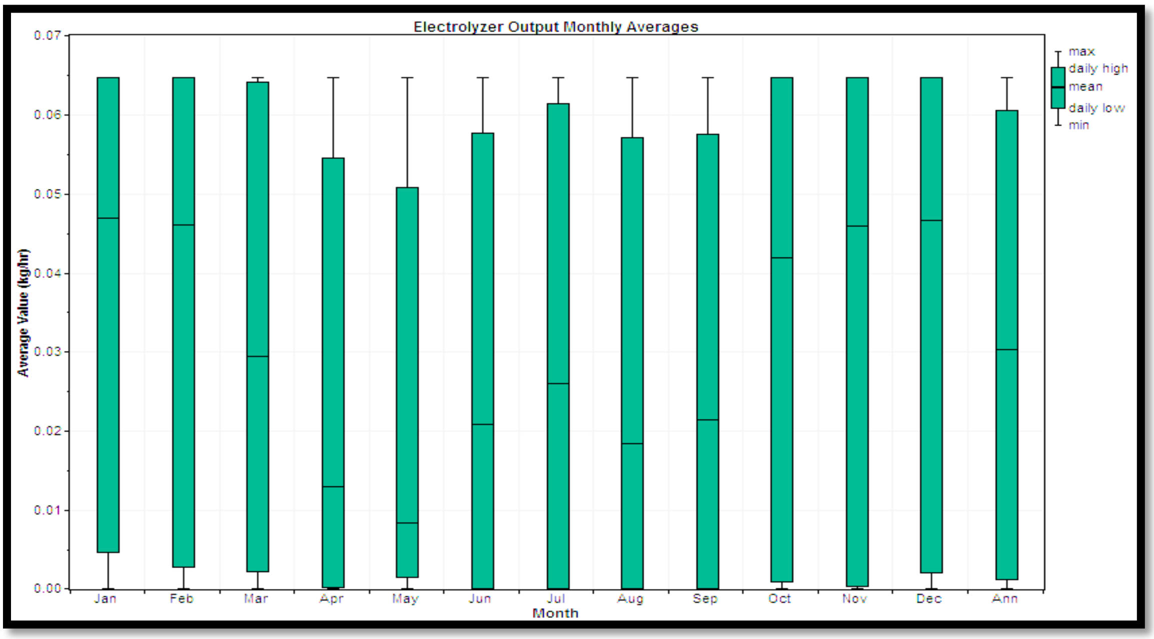

Figure 6.11: Electrolyser monthly average output hydrogen in kg.

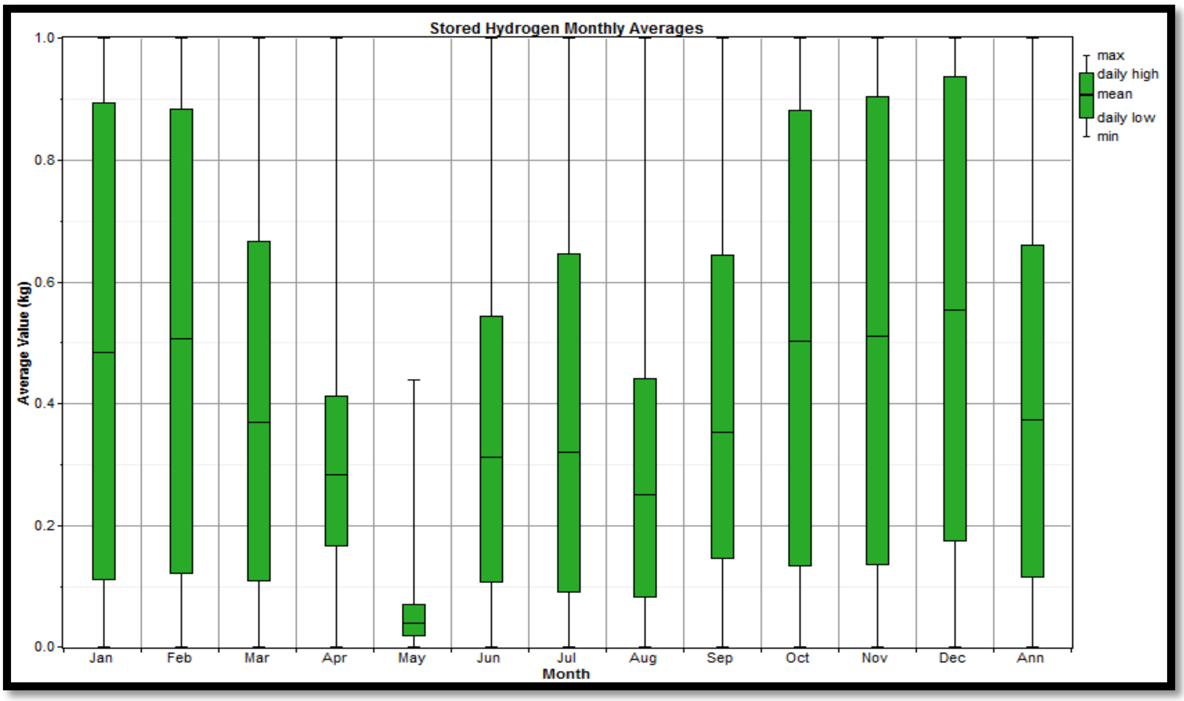

Figure 6.12: Monthly average stored hydrogen.

6.2.1.4 Hydrogen fuel cell results and manual calculation

The H_2-FC chosen for the design is 5kW DC rated power. The total production from this fuel cell around the year is 375kWh/year. Table 6.2 shows the operating details, such as fuel consumption, electrical production, and thermal production. Figure 6.13 shows the monthly average production from the fuel cell, and it shows the highest power production is in November followed by October and December to February, and the lowest month is May where the production is non-existent. Figure 6.14 and 6.15, respectively show the power production and the available hydrogen (stored hydrogen) in summer and winter days; the reason for showing a number of days rather than just one day was to illustrate the frequency of change in hydrogen FC power over time, the power production in summer day is 1 time every 4 days (the average production is 2.1kW), where the production in winter day is 4-5 times every 4 days (the average production is 1.5kW).

Table 6.2: Hydrogen fuel cell operating details

Quantity	Value	Units
Hydrogen consumption	189	kg/year
Specific fuel consumption	0.505	kg/kWh
Fuel energy input	6,308	kWh/year
Electrical production	375	kWh/year
Mean electrical output	1.57	kW
Min. electrical output	1.5	kW
Max. electrical output	2.38	kW
Thermal production	319	kWh/year
Mean thermal output	0.496	kW
Min. thermal output	0.487	kW
Max. thermal output	0.615	kW
Hours of operation	239	hour/year
Number of starts	239	starts/year

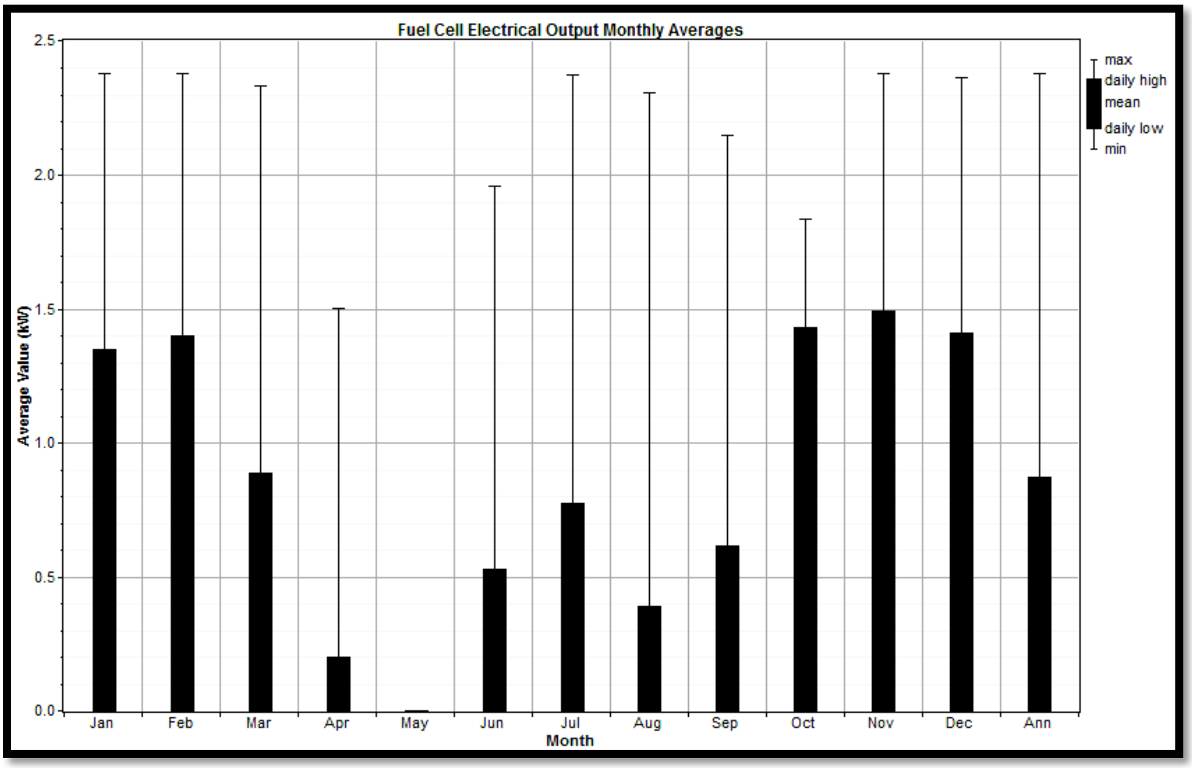

Figure 6.13: Monthly average hydrogen fuel cell power production.

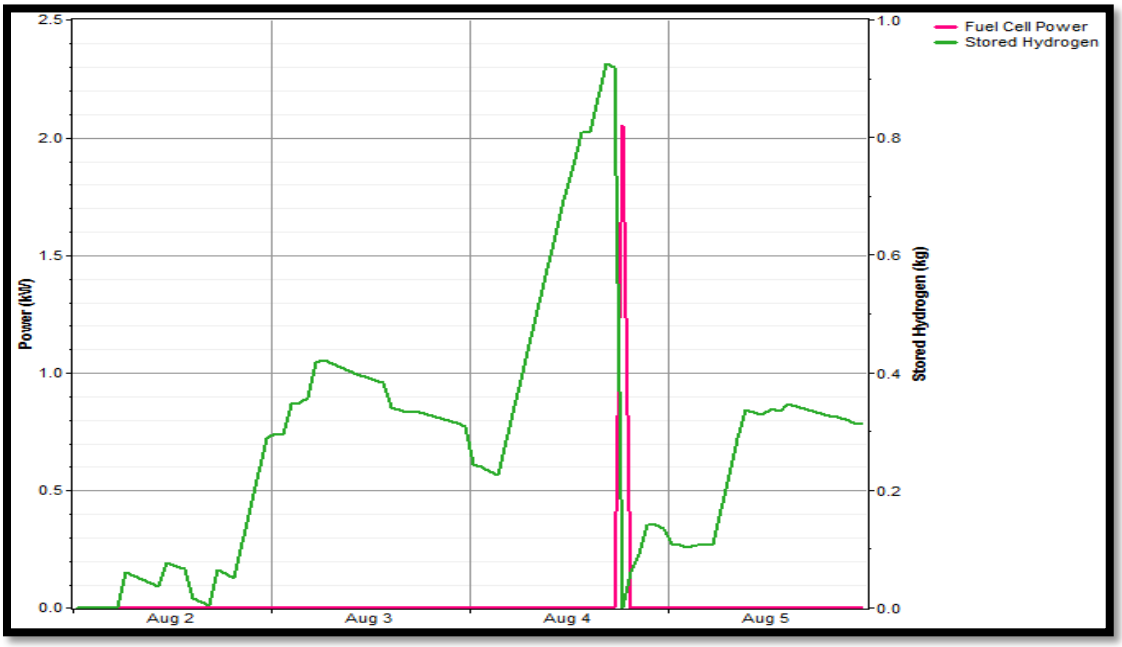

Figure 6.14: Hydrogen FC production and stored hydrogen in summer days.

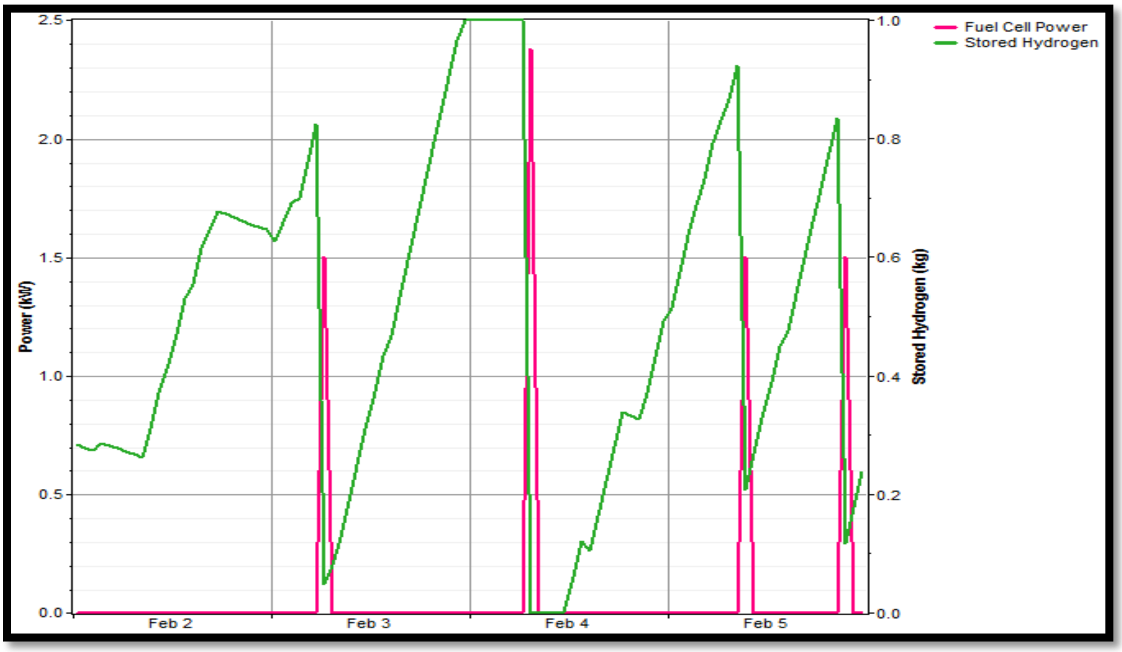

Figure 6.15: Hydrogen FC production and stored hydrogen in winter days.

Calculation for the actual FC generated power

This calculation is with reference to the fuel cell as described in section 2.5.4.1, to calculate the expected power, with the preliminary data, such as the hydrogen atomic mass is 200.59amu/1 atom, 1 atomic mass unit 1.661× 10^{-24} g/1amu, and Avogadro's number 6.022×10^{23} atoms/mol. multiplying the previous will give the gram per mole 200.64 g/mol. These calculations are undertaken because it is important to compare the manual calculation with HOMER results, and also it is important to implement a function for H_2–fuel flow rate in Simulink simulation.

According to HOMER the hydrogen consumption is 189kg per 239 hour, and 0.505kg per kWh. If 1mol of H_2 = 200.64g, then 505g = 2.51mol

Using equation 2.45: $P_{FC} = \frac{(2\times 2.51\times 24\times 9.64853399\times 10^{4})}{3600}$ = 3.2kWper working hour

The generated energy per year should be 3.2×239 (operating hour per year) = 764.8kW/year.

6.2.1.5 Hydrogen peroxide fuel cell results and manual calculation

The H_2O_2-FC chosen for the design is 10kW DC rated power. The total production from this fuel cell around the year is 16,184kWh/year. Table 6.3 shows the operating details, such as fuel consumption, electrical production, and thermal production. Figure 6.16 shows the monthly average production from the H_2O_2 fuel cell, and it shows the highest power is in the month of May, and the lowest months are February and November. Figure 6.17 presents a comparison between power production from H_2O_2 fuel cell and the production from wind turbine in the same period, to study the relation between the operations of H_2O_2 fuel cell according to the majority production power which is from wind turbines, as it shows the fuel cell mainly operate when the production power from wind turbine is low or not enough for the demand load, as a result of low wind speed.

As described previously (section 6.2.1.3), the total estimated hydrogen production per year is 2358 kg, 189 kg is used directly as fuel for the fuel cell, that means 2169 kg/year of hydrogen is converted to hydrogen peroxide, which equal to 24132.18L at hydrogen density (0.08988 g/L)

Table 6.3: Hydrogen peroxide fuel cell operating details

Quantity	Value	Units
Fuel consumption	12,284	L/year
Specific fuel consumption	0.759	L/kWh
Electrical production	16,184	kWh/year
Mean electrical output	4.29	kW
Min. electrical output	3	kW
Max. electrical output	10	kW
Thermal production	927	kWh/year
Mean thermal output	0.141	kW
Min. thermal output	0.123	kW
Max. thermal output	0.225	kW
Hours of operation	6,565	hour/year
Number of starts	927	starts/year

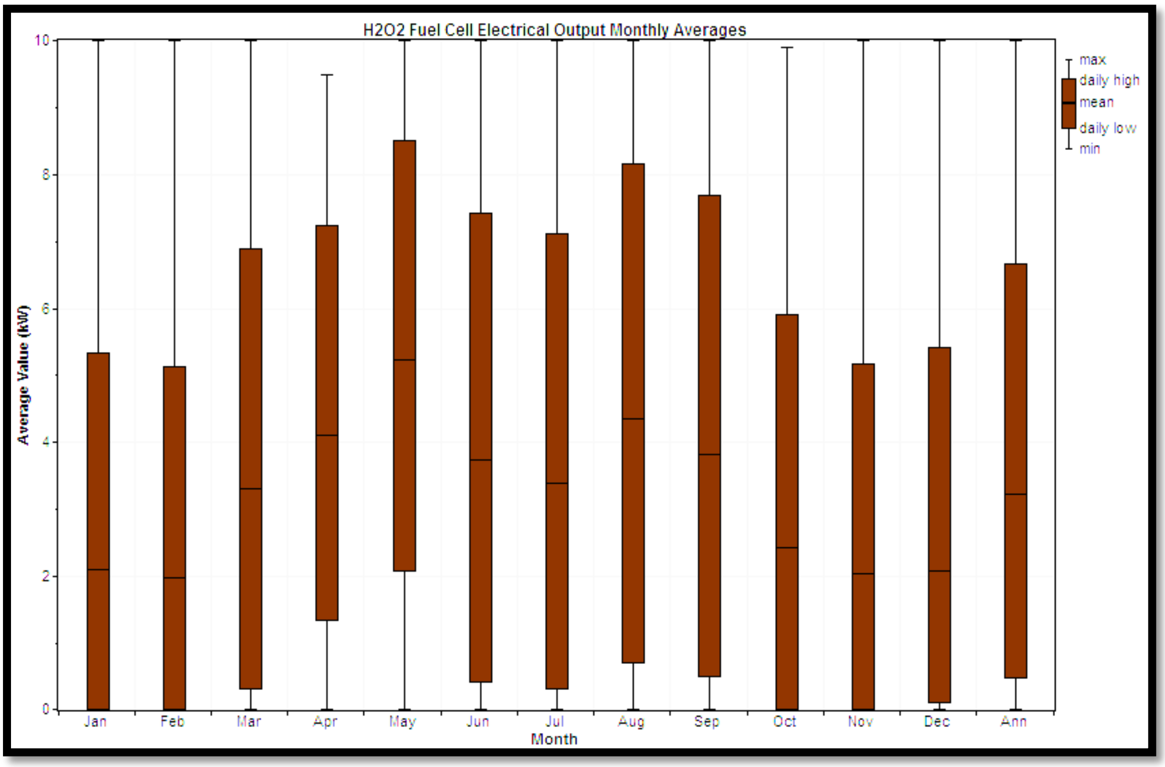

Figure 6.16: Monthly average hydrogen fuel cell power production.

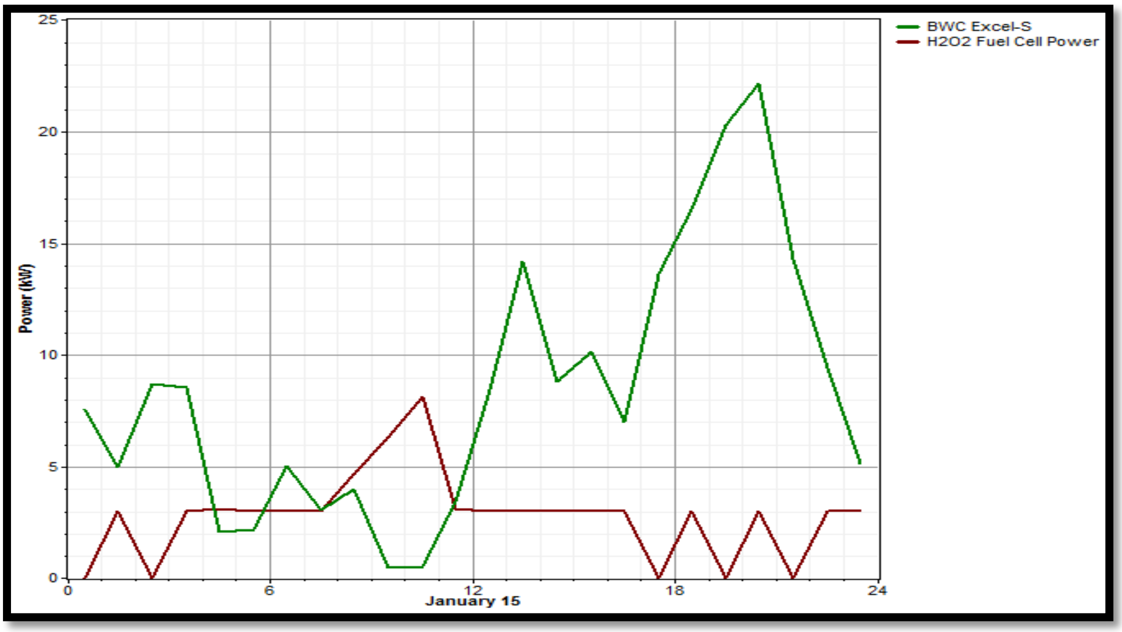

Figure 6.17: H_2O_2 FC production compared to wind turbine production.

6.2.1.6 Diesel generator (DG) and manual calculation

The DG chosen for the design as a final stage backup system. According to that the DG should cover the entire load. 15kW AC rated power is required to cover the entire load. The total production from this DG around the year is 3,304kWh/year. Table 6.4 shows the operating details, such as fuel consumption, electrical production, and thermal production. Figure 6.18 shows the monthly average production, and it shows that DG required to generate (3 to 4) kW in summer months, and in winter months it required to generate 2kW.

Calculation for diesel fuel consumption

This calculation is with reference to diesel generator as described in section 2.5.5.1, to calculate the expected diesel consumption for the operating hours in one year. These calculations are undertaken because it is important to compare the manual calculation with HOMER results.

According to HOMER the operation hours of DG is 732 hour/year and by dividing it by 2 as it is for 6 months, it will be 366 hour/6 months. Also the average generated power in summer months is 3.4 kW and 2.25 kW for winter months.

Using equation 2.47: $f_{c-relative}(h - summer) = \frac{1}{4} + \frac{3}{4}\, 3.4 = 2.8$ L/h and by multiplying it with working hours (366h) in 6 months it is equal to 1024.8 L/6 months in summer.

To calculate for winter hours: $f_{c-relative}(h - winter) = \frac{1}{4} + \frac{3}{4}\, 2.25 = 1.9375$ L/h, and to calculate that for 6 months × 366 = 709.125 L/6 months.

The consumed diesel fuel per year is equal the diesel consumption in winter months plus the diesel consumption in summer months: 1024.8 L/6 summer months + 709.125 L/6 winter months = 1733.925 L/year.

Table 6.4: Diesel Generator operating details

Quantity	Value	Units
Fuel consumption	1,704	L/year
Specific fuel consumption	0.516	L/kWh
Fuel energy input	16,772	kWh/year
Mean electrical efficiency	19.7	%
Electrical production	3,304	kWh/year
Mean electrical output	4.51	kW
Min. electrical output	4.5	kW
Max. electrical output	6.71	kW
Hours of operation	732	hour/year
Number of starts	389	starts/year
Operational life	20.5	year
Capacity factor	2.51	%
Fixed generation cost	4.11	$/hour
Marginal generation cost	0.3	$/kWh

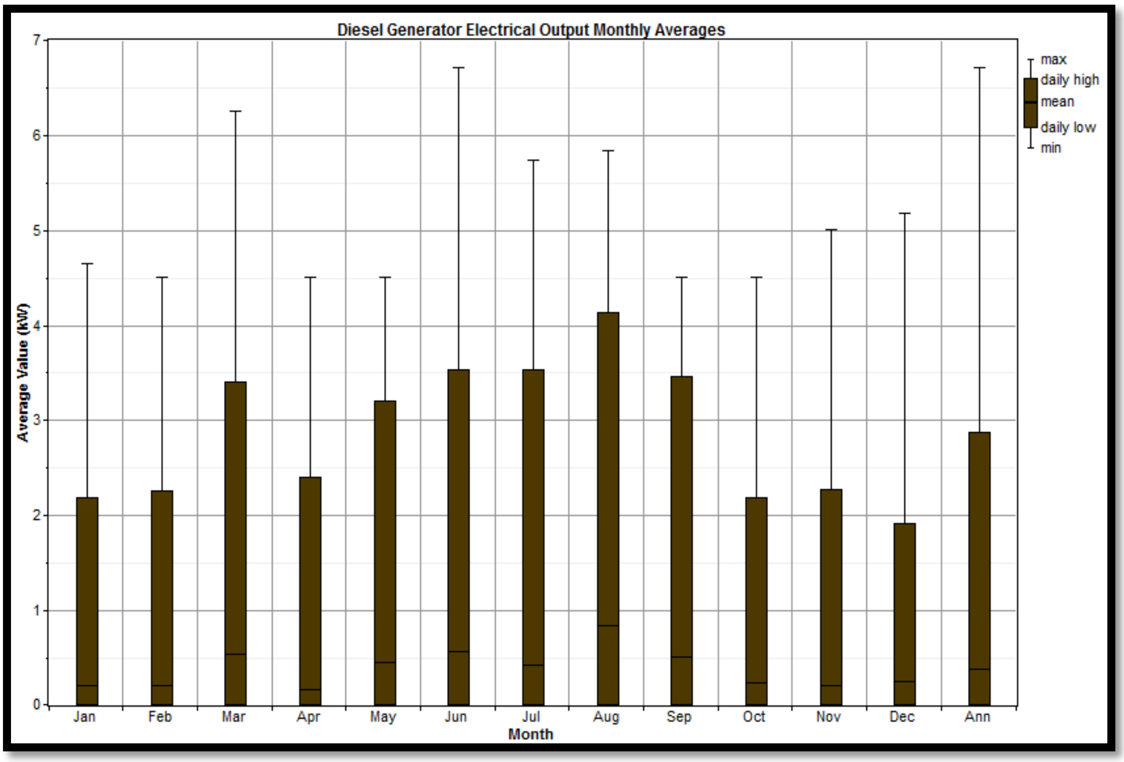

Figure 6.18: Monthly average DG power production.

6.2.1.7 Batteries results and manual calculation

The batteries chosen for the design are two sets of batteries every set contains two batteries in series, every battery is 12 V with nominal capacity of 1900 Ah (7.5 kWh). According to HOMER simulation the total batteries input energy is 524 kWh per year, and the nominal capacity is 15.2 kWh, where the usable nominal capacity is 9.12 kWh. Figure 6.19 shows the monthly average battery input power negative values indicate discharge status, and positive values indicate charging. The figure shows equality charging and discharging between the months and for more detailed daily average batteries state of charge for all months are shown in Figure 6.20. Figure 6.21 presents a comparison between batteries input power and batteries state of charge.

Calculation for the batteries capacity

This calculation is with reference to battery as described in section 2.5.1.1, to calculate the required battery capacity for the designed system. As the daily average load is 152 kWh, and the daily primary load is 23 kWh. The battery required covering the primary load for one day and it should be enough for 5 hours at full load, and the system voltage is 24 V. These calculations are undertaken because it is important to compare the manual calculation with HOMER results and it is necessary to select a set of batteries cover a specific load for a specific period.

Using equation 2.12: $\text{Battery Capacity for primary} = \frac{23000\times 1}{0.95\times 0.71\times 24}$ = 1420.8 Ah; and using the same equation to calculate $\text{Battery Capacity for whole load} = \frac{152000\times 0.2}{0.95\times 0.71\times 24}$ = 1877.9 Ah. According to the capacity for the chosen battery it should exceed the calculated one in order to operate as required. The best selection is two set of two series 1900 Ah, 12 V deep cycle GEL batteries which is designed to discharge to low energy level and it has the ability for quick charge. Figure 6.22 demonstrates the discharge current in part (A), part (B) shows the depth of discharge.

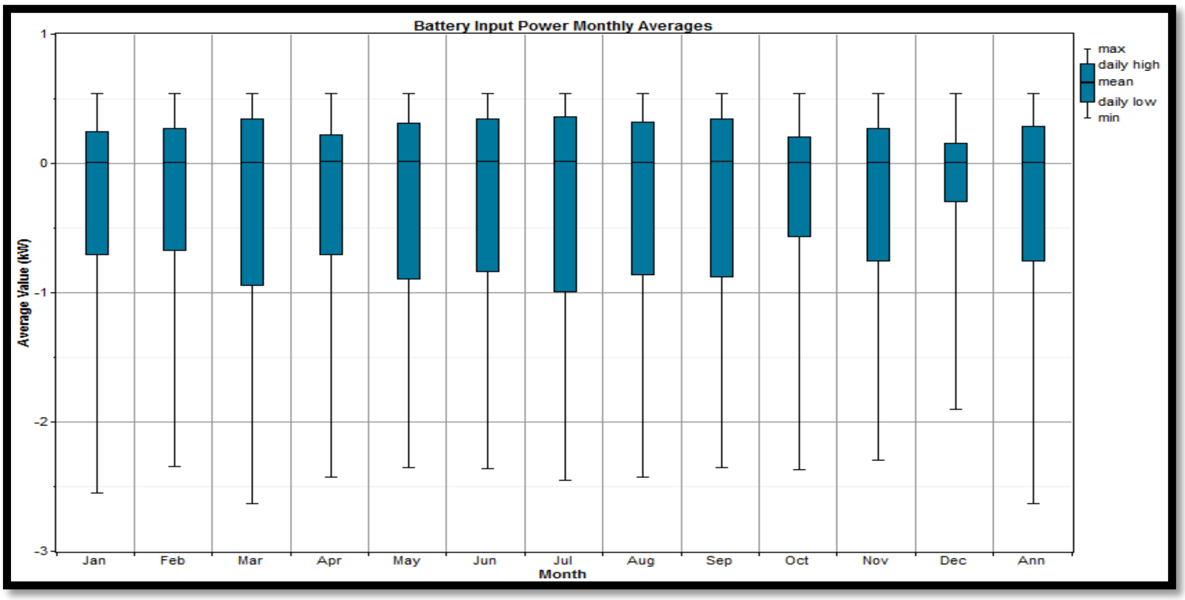

Figure 6.19: Monthly average battery input power.

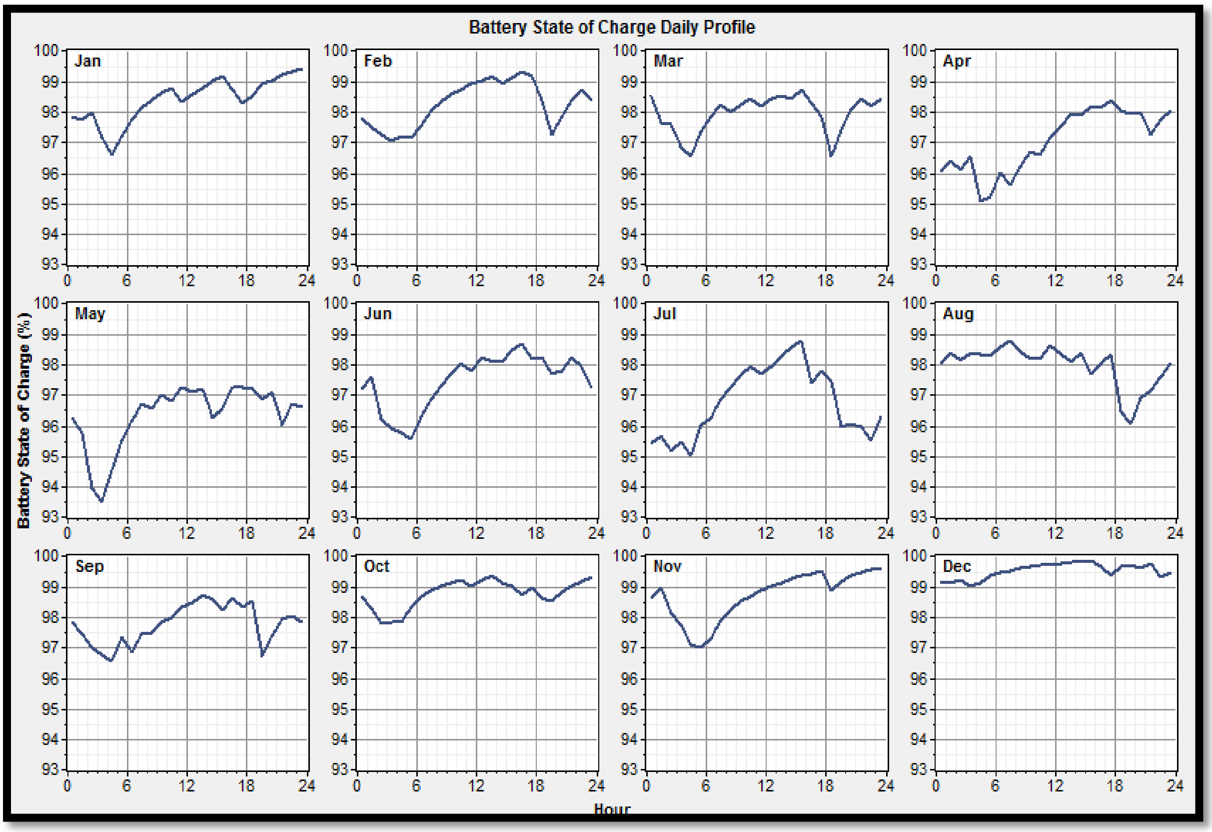

Figure 6.20: Daily battery state of charge in monthly bases.

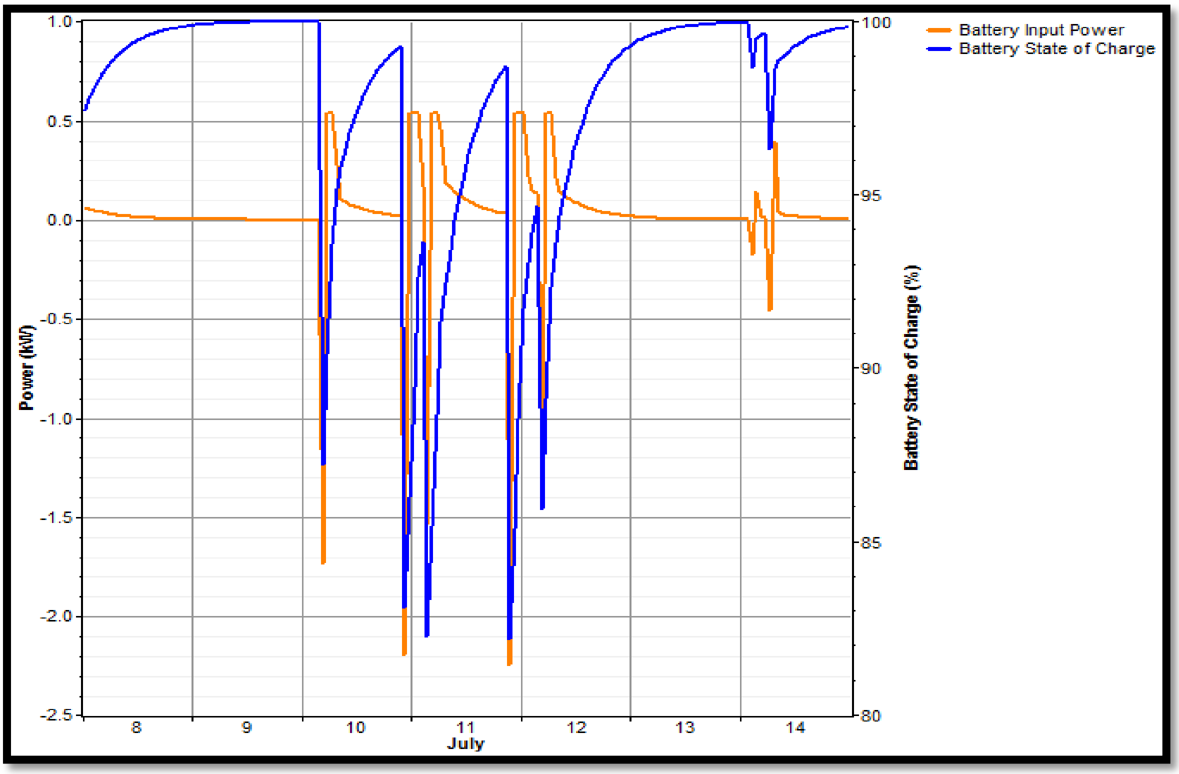

Figure 6.21: Battery input power compared to battery state of charge.

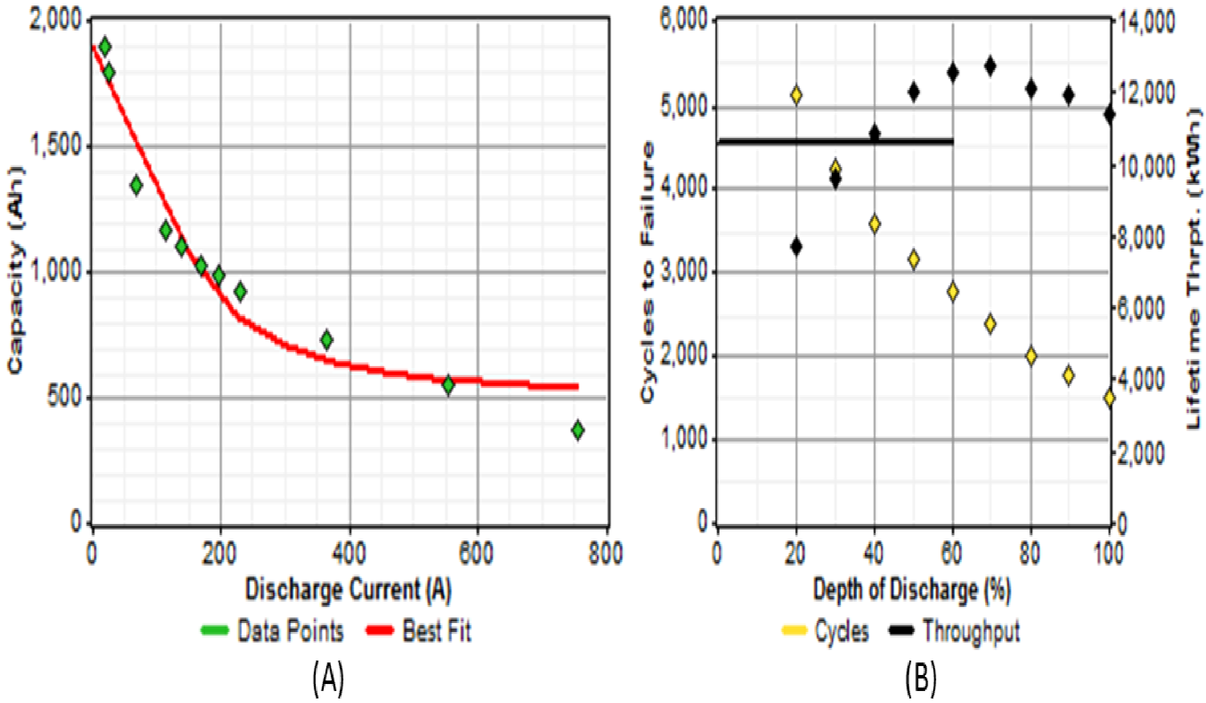

Figure 6.22: Battery details.

6.2.1.8 Bi-directional converter results

For an efficient system the inverter rating should be higher than the generated power, and the rectifier rating should be higher than power stored from wind turbine and DG, in other words to allow the bi-directional converter to operate safely, it should be higher than the produced power (Strauss and Engler 2003). Accordingly the chosen capacity of bi-directional converter is 10 KW. HOMER tool present the bi-directional converter as inverter and rectifier, Figure 6.23 shows the monthly average rectifier output and Figure 6.24 shows the monthly average inverter output. The results show opposite values, as the month of May show lowest rectifier production, and the highest inverter output, also October to February show high rectifier output and the lowest inverter output. Table 6.5 shows the bi-directional operating details, such as capacity, hour of operation, and input output power. Figure 6.25 presents a comparison between inverter input output power and rectifier input output power.

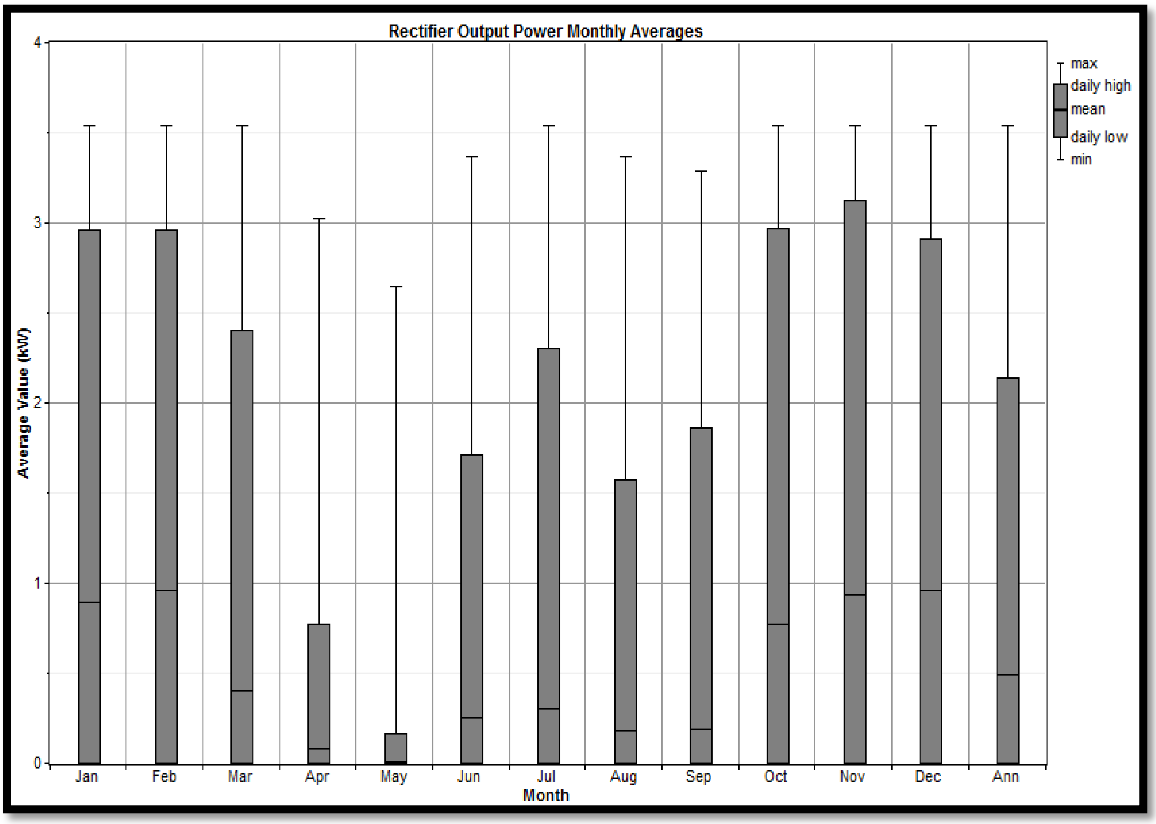

Figure 6.23: Monthly average rectifier output power.

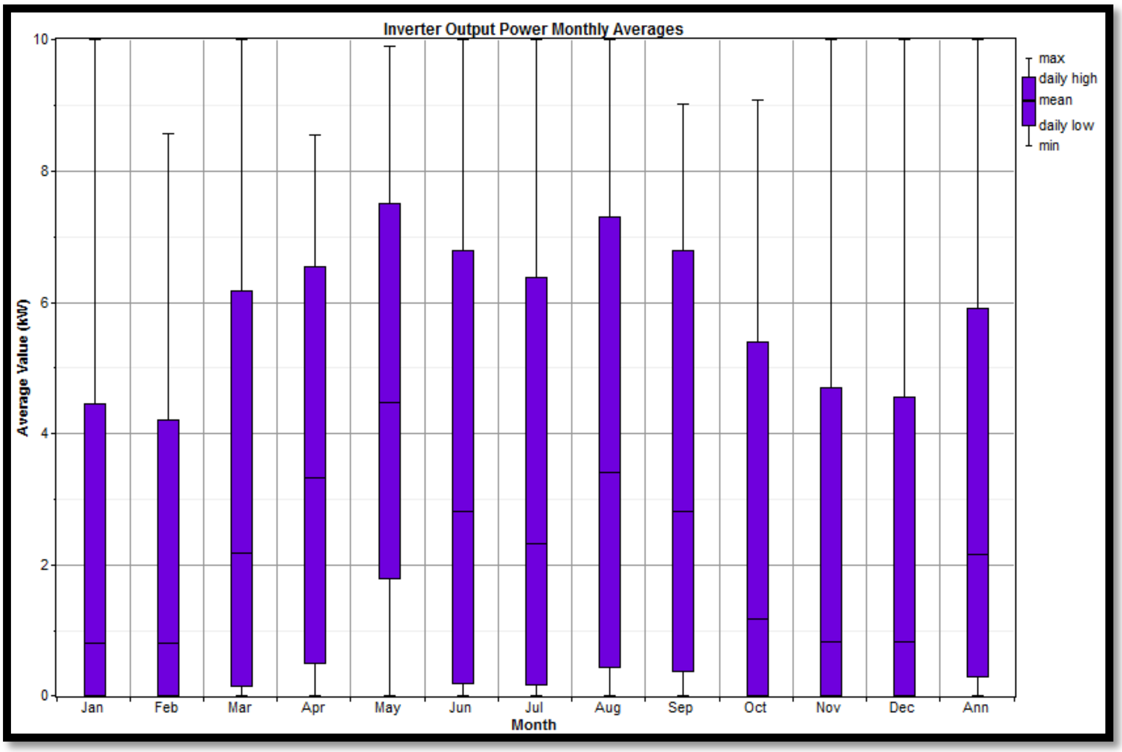

Figure 6.24: Monthly average inverter output power.

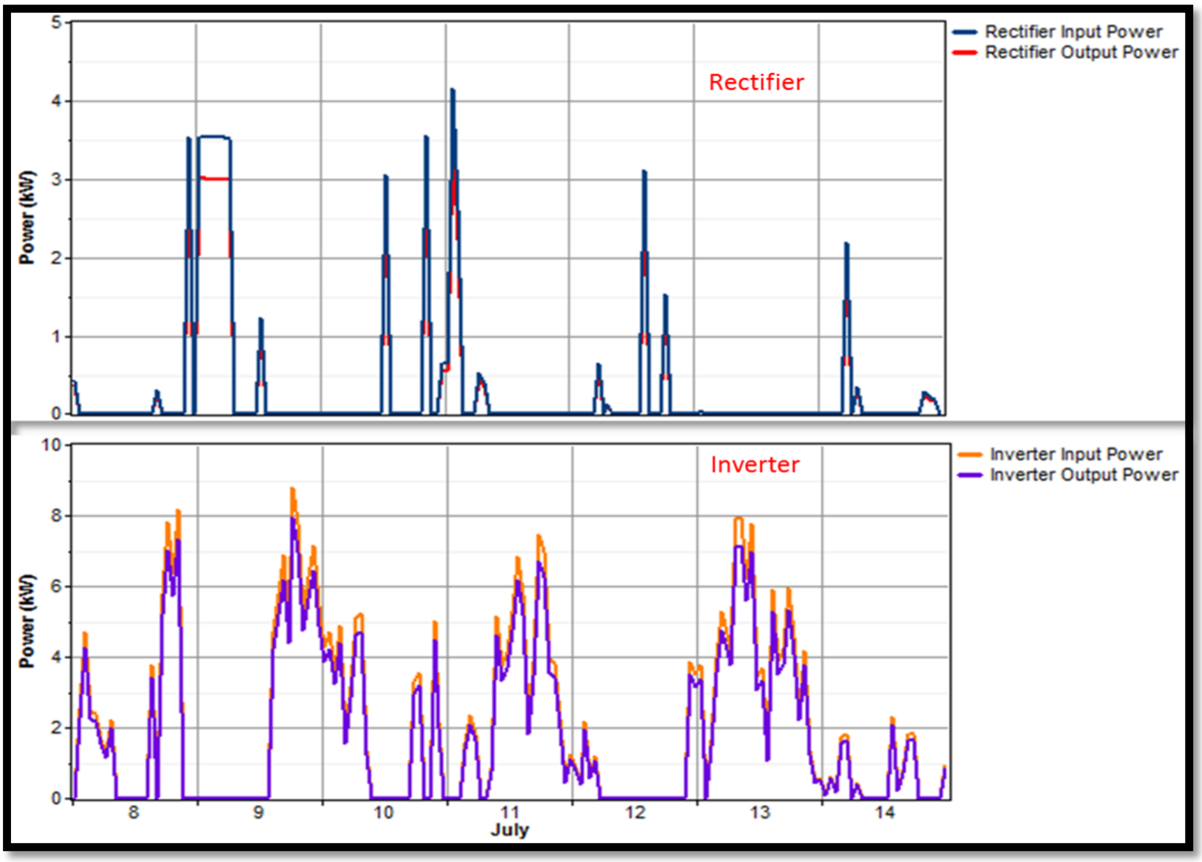

Figure 6.25: Rectifier and inverter output power input power.

Table 6.5: Bi-directional converter operating details

Quantity	Inverter	Rectifier	Units
Capacity	10	10	kW
Mean output	2.1	0.5	kW
Minimum output	0	0	kW
Maximum output	10	3.5	kW
Capacity factor	21.5	4.9	%
Hours of operation	4,892	2,520	hrs/year
Energy in	20,921	5,069	kWh/year
Energy out	18,829	4,309	kWh/year

6.2.1.9 Summary

Previous, yearly generated power per individual component is presented, by showing the monthly average power production, and showing when every individual component is operating, and is the reserve power system required. Moreover, appendix C presents the full report of the simulation by HOMER tool.

6.2.2 Economical evaluation

HOMER energy software also presents the economic feasibility for an individual system, in order to study and compare between the available systems to find the optimal generation mix, and to balance the load for the different load levels during the simulation period. The results of these simulations demonstrate technical and economical ability of the system to survive all load and contingency conditions (the interest rate is assumed as 10% in these calculations). Economical analysis, demonstrates the economic feasibility and the economic viability of the design assumptions on the sizes of the generation sources by calculating net present value, life cycle cost, and payback periods for each generation mix that matches the demand. Figure 6.26 and 6.27 demonstrate the cash flow and payback period which is 24 years for OGREH-SµG by the system components and the cash flow type respectively. Both figures show high capital cost of the system, and the only significant replacements that are necessary are in year 15 for converter and year 21 for the DG. Moreover, Table 6.6 explains the cost summary for the system according to the disbursements and components (as calculated with HOMER), and Figure 6.28 shows the net present value according to the cash flow summary which is explained in detail in appendix D.

To understand the economic feasibility, it is important to know that cash flow is a yearly analysis which is used to find the real values for incomes and expenses. The disbursements are divided into three main categories: capital costs, running cost (fuel expenses, operation and upkeep cost), and replacement costs. See (section 2.5.1.2), using the equation in that section to calculate the payback period and the life cycle cost. Table 6.7 (manual verification) shows the economic feasibility in 25 years and it shows the discounted cash flows (DCF), as the system future cash flows is discounted back to the present to conclude what a valuation economically, and Figure 6.29 show the life cycle cost compared with the existing system (Diesel IPS), however, with the economic assessment and generation mixture output results shown in, it will be seen that the system's life cycle costs will be lower than the fully Diesel fuelled IPS within 15 years.

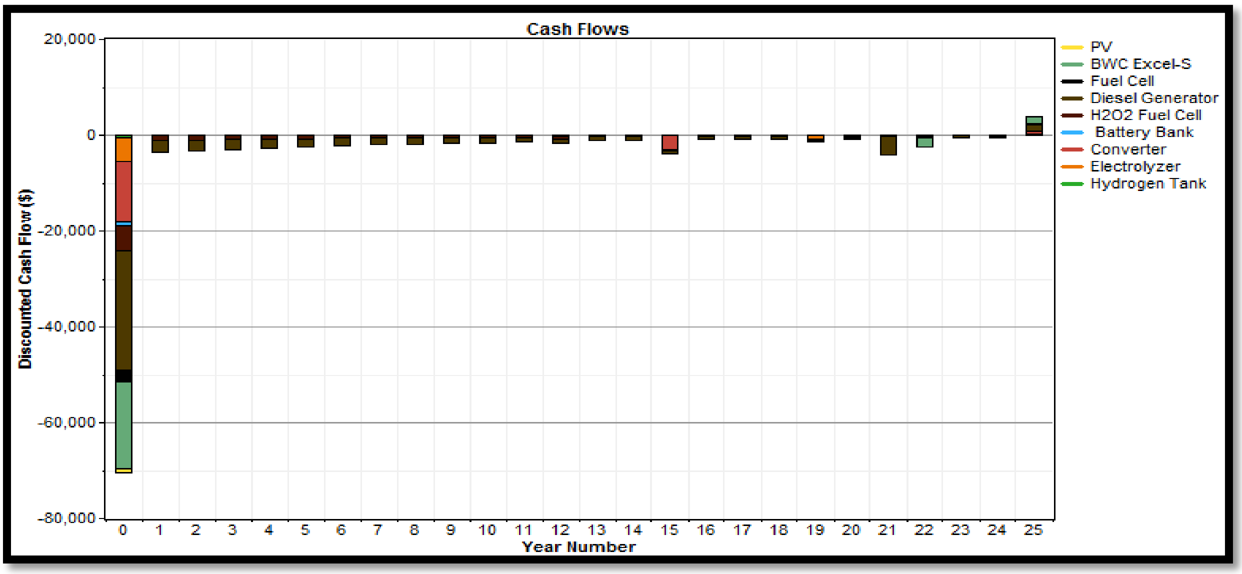

Figure 6.26: Cash flow according to the system component.

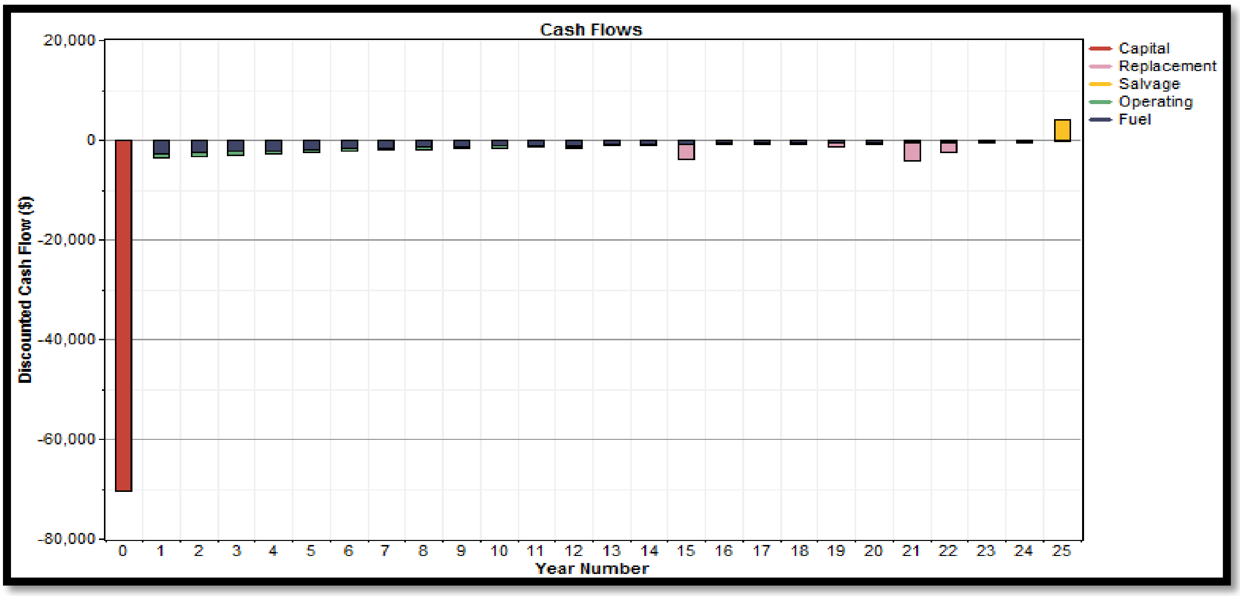

Figure 6.27: Cash flow according to the cash flow types.

Table 6.6: Cost summary (HOMER)						
Component	**Capital (£)**	**Replacement (£)**	**O&M (£)**	**Fuel (£)**	**Salvage (£)**	**Total (£)**
PV	-840	-125	-64	0	58	-970
BWC Excel-S	-18,000	-1,966	-91	0	1,275	-18,781
Fuel Cell	-2,500	0	0	0	223	-2,277
DG	-25,000	-3,546	-6,644	-18,566	1,800	-51,957
H_2O_2 Fuel Cell	-5,000	0	-596	-8,921	23	-14,493
Battery Bank	-1,000	-420	-18	0	85	-1,354
Converter	-12,475	-2,986	-1,135	0	384	-16,212
Electrolyser	-5,000	-818	-45	0	316	-5,547
Hydrogen Tank	-500	0	0	0	0	-500
System	-70,315	-9,860	-8,593	-27,487	4,163	-112,091

Table 6.7: Discounted cash flow (Manual verification)							
Years:		1-5	6-12	13-25			
Fuel Growth Rate:		10%	12%	15%	**Discount Rate:**		10%
Year	**Capital cost and replacement**	**Operating and Maintenance cost**	**Fuel cost**	**Fuel Growth**	**Fuel cost after growth**	**Flows**	**Value**
0	**-70,315**	0	0	10%	0	**-70,315**	**-£70,315**
1	0	**-1,027**	**-3,721**	10%	**-4,093**	**-4,748**	**-£4,316**
2	0	**-1,027**	**-3,721**	10%	**-4,093**	**-4,748**	**-£3,924**
3	0	**-1,027**	**-3,721**	10%	**-4,093**	**-4,748**	**-£3,567**
4	0	**-1,027**	**-3,721**	10%	**-4,093**	**-4,748**	**-£3,243**
5	0	**-1,027**	**-3,721**	10%	**-4,093**	**-4,748**	**-£2,948**
6	**-1,000**	**-1,027**	**-3,721**	12%	**-4,168**	**-5,748**	**-£3,245**
7	0	**-1,027**	**-3,721**	12%	**-4,168**	**-4,748**	**-£2,436**
8	0	**-1,027**	**-3,721**	12%	**-4,168**	**-4,748**	**-£2,215**
9	0	**-1,027**	**-3,721**	12%	**-4,168**	**-4,748**	**-£2,014**
10	0	**-1,027**	**-3,721**	12%	**-4,168**	**-4,748**	**-£1,831**
11	0	**-1,027**	**-3,721**	12%	**-4,168**	**-4,748**	**-£1,664**
12	**-1,000**	**-1,027**	**-3,721**	12%	**-4,168**	**-5,748**	**-£1,831**
13	0	**-1,027**	**-3,721**	15%	**-4,279**	**-4,748**	**-£1,375**
14	0	**-1,027**	**-3,721**	15%	**-4,279**	**-4,748**	**-£1,250**
15	**-12,475**	**-1,027**	**-3,721**	15%	**-4,279**	**-17,223**	**-£4,123**
16	0	**-1,027**	**-3,721**	15%	**-4,168**	**-4,748**	**-£1,033**
17	0	**-1,027**	**-3,721**	15%	**-4,279**	**-4,748**	**-£939**
18	**-1,000**	**-1,027**	**-3,721**	15%	**-4,279**	**-5,748**	**-£1,034**
19	**-25,000**	**-1,027**	**-3,721**	15%	**-4,279**	**-29,748**	**-£4,864**
20	**-5,840**	**-1,027**	**-3,721**	15%	**-4,279**	**-10,588**	**-£1,574**
21	0	**-1,027**	**-3,721**	15%	**-4,279**	**-4,748**	**-£642**
22	0	**-1,027**	**-3,721**	15%	**-4,279**	**-4,748**	**-£583**
23	**-16,000**	**-1,027**	**-3,721**	15%	**-4,279**	**-20,748**	**-£2,317**
24	**-1,000**	**-1,027**	**-3,721**	15%	**-4,279**	**-5,748**	**-£584**
25	46,591	**-897**	**-3,721**	15%	**-4,279**	41,973	£3,874
			Total				**-£119,994**

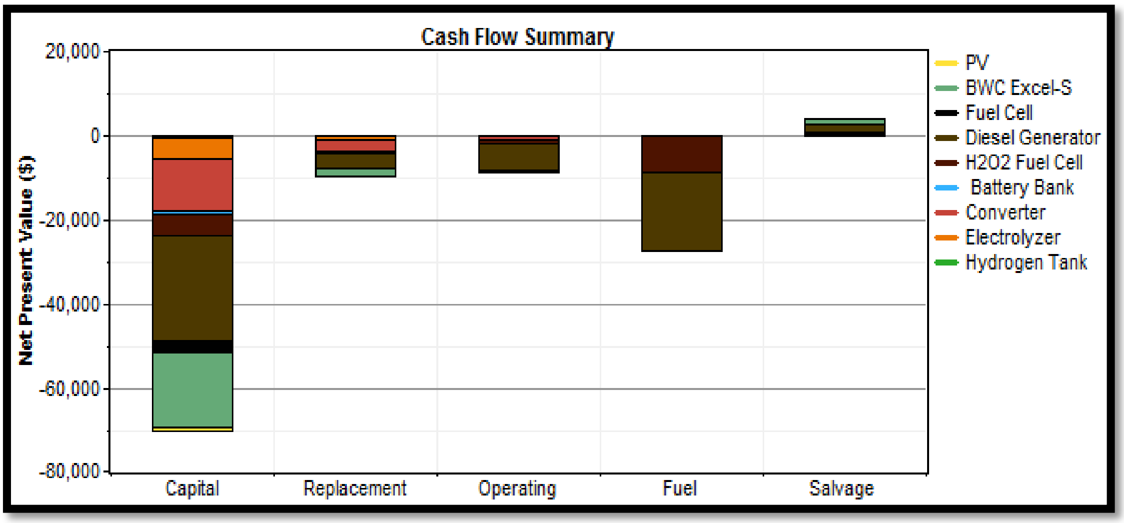

Figure 6.28: Net present value according to the cash flow summary.

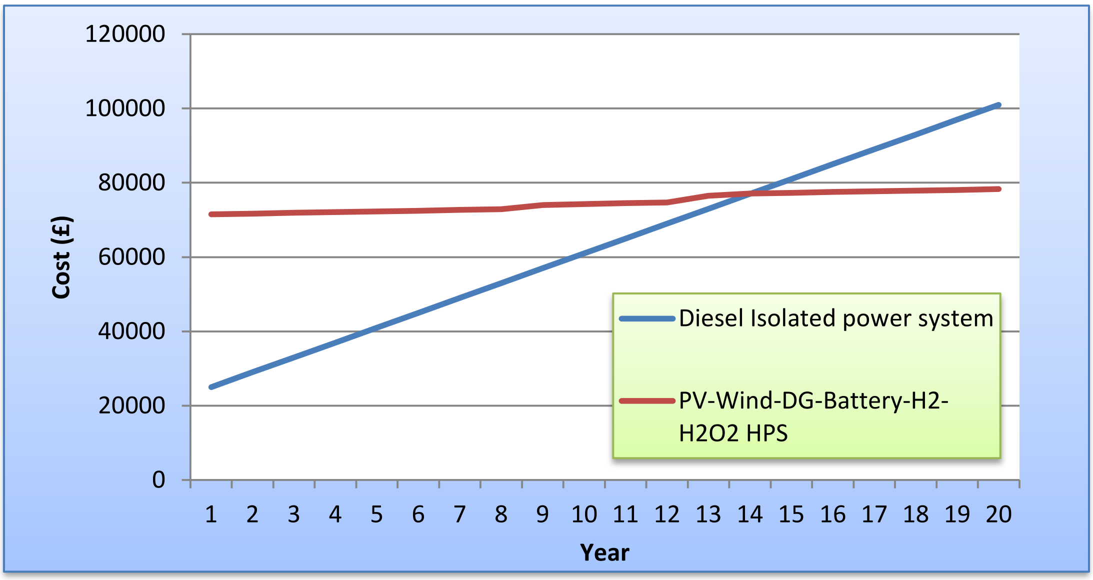

Figure 6.29: Compare the life cycle cost for chosen HPS with the Diesel IPS.

6.3 MatLab/Simulink simulation results

MatLab/Simulink simulation is undertaken as a supplement for HOMER simulation, in order to conduct for the technical analysis (dynamic behaviour, such as voltage and frequency) and viability of the design (different synchronizing modes). The HOMER Energy software PV-Wind-Hydrogen-Hydrogen Peroxide-Diesel-Batteries isolated hybrid power system with the recommended capacity is modelled in the

Simulink tool, Simulink can present in block diagrams with the proper selection and configuration parameters the optimal system configurations as simulated in HOMER. For the simulations in Simulink micro grid system components models have been developed and as explained in (section 4.3.3) some of these have been fine-tuned and modified from the model used in HOMER to achieve convergence with the main model in the Simulink simulation. The next section will detail the results obtained with the modified models.

6.3.1 Results of PV model

The Simulink model for PV used in the simulations was shown in Figure 4.4. Based on this model, measurements for the current, voltage, and power have been obtained as shown in Figure 6.30, as these results from these simulations are only for one solar panel.

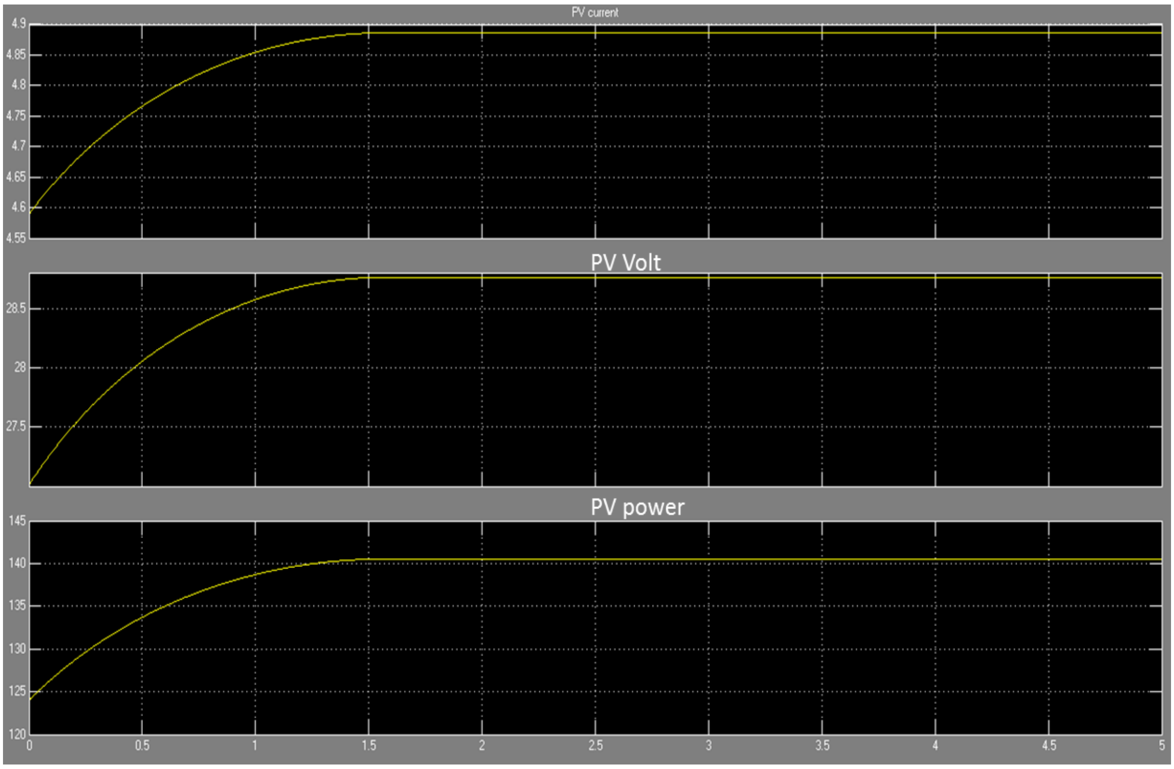

Figure 6.30: Simulation results for one solar panel.

6.3.2 Results of wind turbines model

The configuration of WTGs is shown in Figure 4.5; there are two WTG 10kW Permanent magnet synchronous generators, as this type of generators are simple structure with high efficiency. Figure 6.31 present the voltage and current for one WTG, and it shows fluctuation output as a result of fluctuating input (wind), where Figure 6.32 is presenting the wind curve, active power (P), and reactive power (Q), where reactive power shows slightly high according to the high harmonics caused by the inverters. Figure 6.33 shows WTG frequency with the ramp (wt) varying between 0 and 2*pi, synchronized on the zero-crossing, also it shows the vector sin (wt) and cos (wt), according to the frequency block parameters; the system can be used to synchronize on variable frequency sinusoidal signal, if the automatic gain control is enabled, the input is selected according to the input signal magnitude.

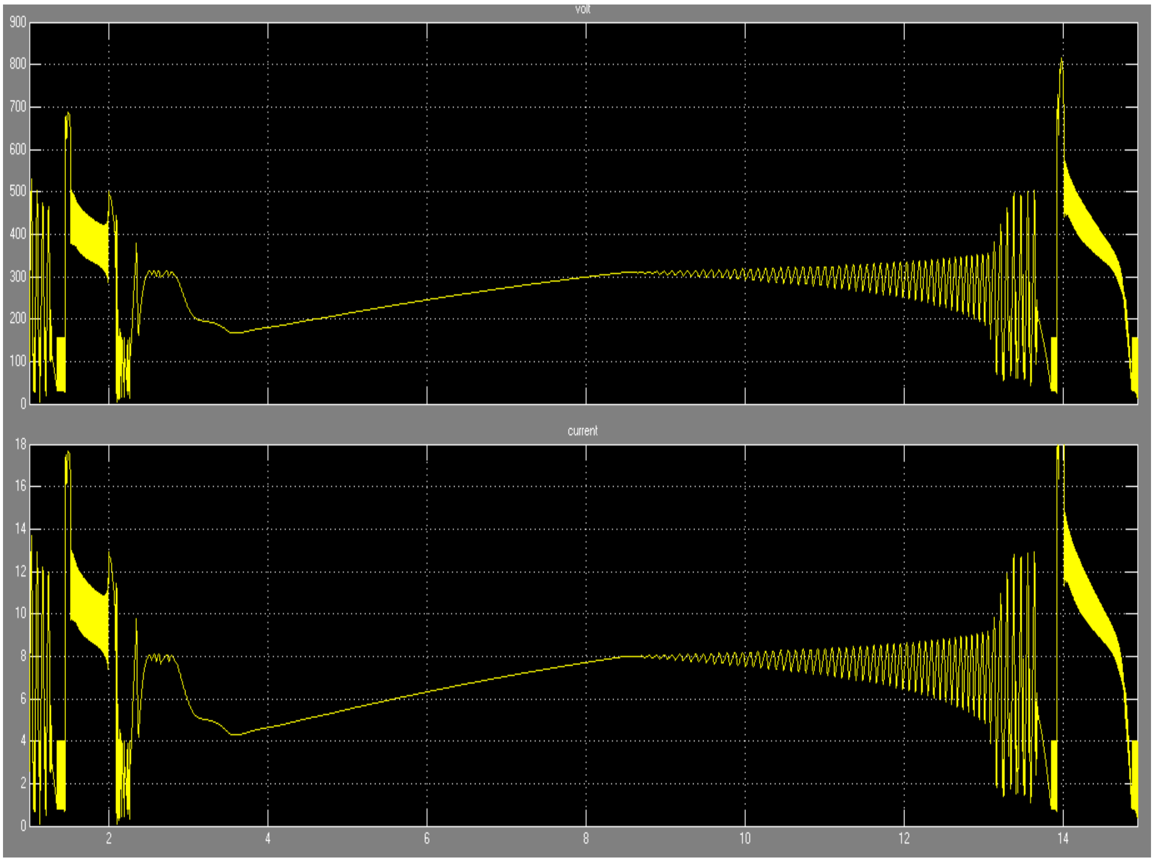

Figure 6.31: Simulation results volt and current for WTG.

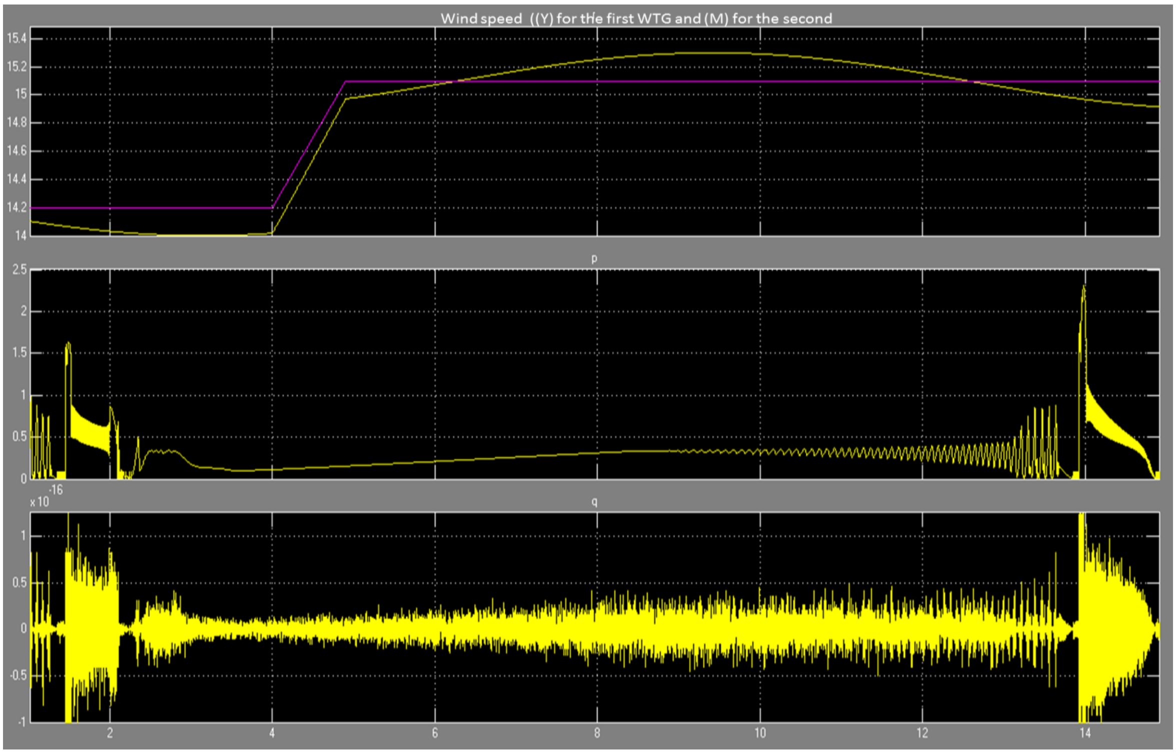

Figure 6.32: Simulation results wind speed active and reactive power for WTG.
((Y) Is the yellow line for the first turbine and (M) is magenta line for the second turbine)

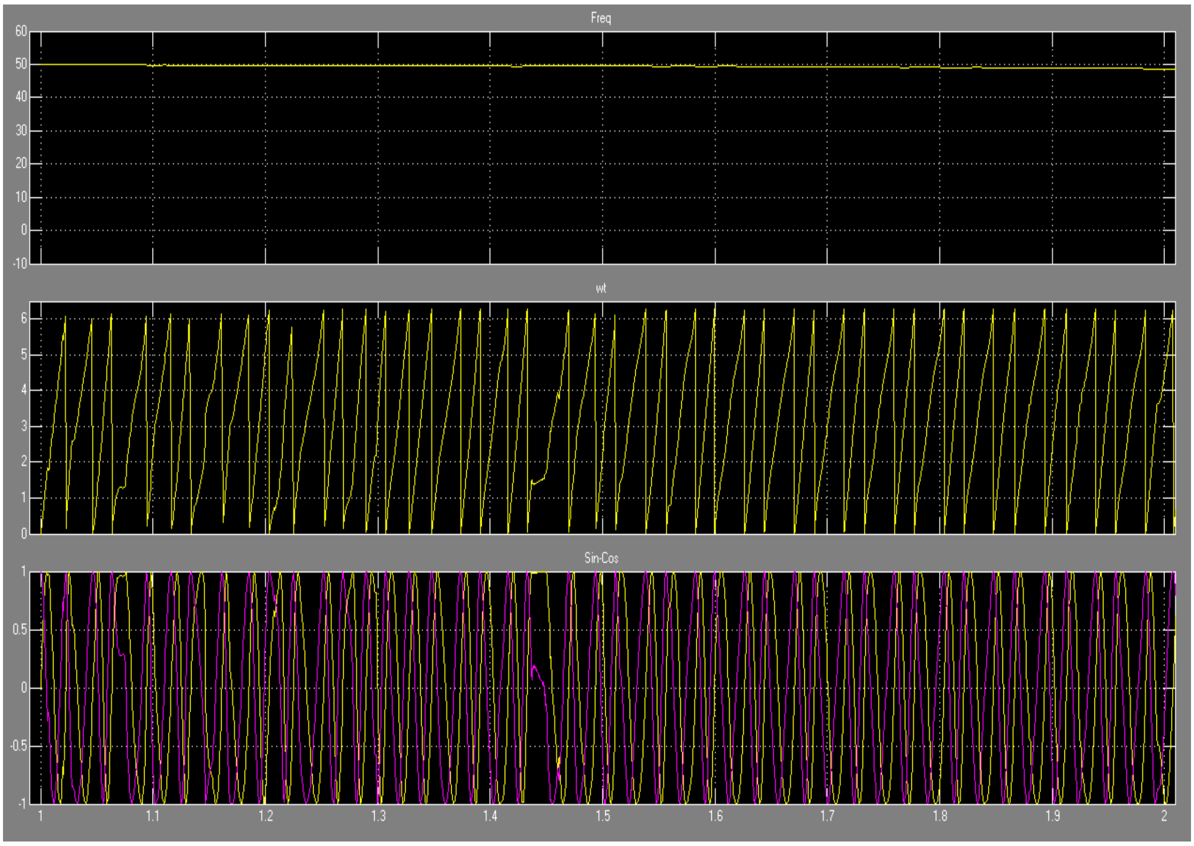

Figure 6.33: Simulation results frequency, wt, and sin (wt) cos (wt) for WTG.

6.3.3 Results of hydrogen fuel cell model

PEM-FC is the type of FC modelled and simulated the configuration of hydrogen FC is show in Figure 4.6, 5 kW 24 volt DC fuel cell stack. Figure 6.34 presents the voltage (it is about 28 V DC) and current (it is about 12A DC) for the FC and it shows volt and current for the DC-bus, where Figure 6.35 is presenting the flow rate, consumption and the stack efficiency. The flow rate is according to the flow rate selector, which allows the system to study the FC in all situations, for the efficiency it shows 50% as starting then it is 42% with steady flow, and in fluctuation flow it shows 35% as an average.

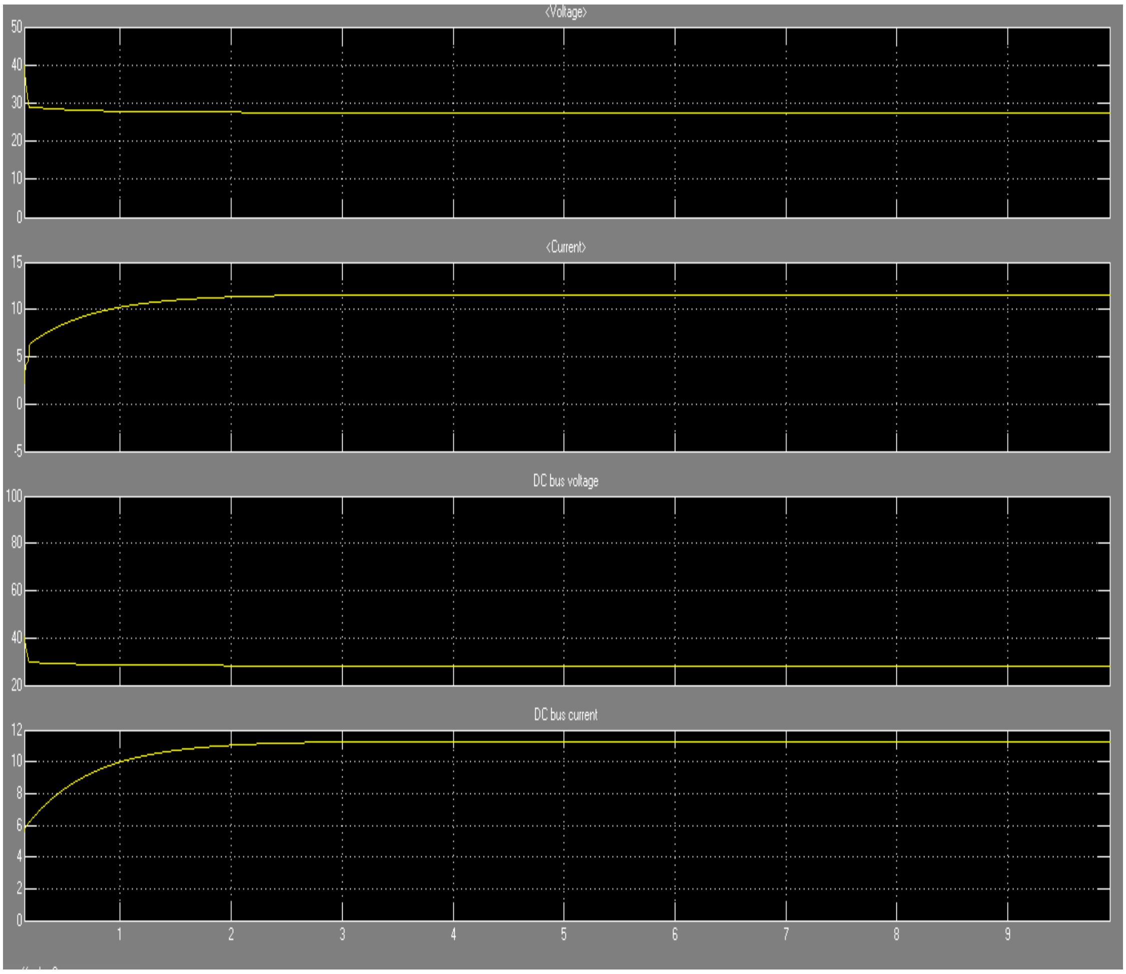

Figure 6.34: Simulation results volt and current for H-FC and DC-bus.

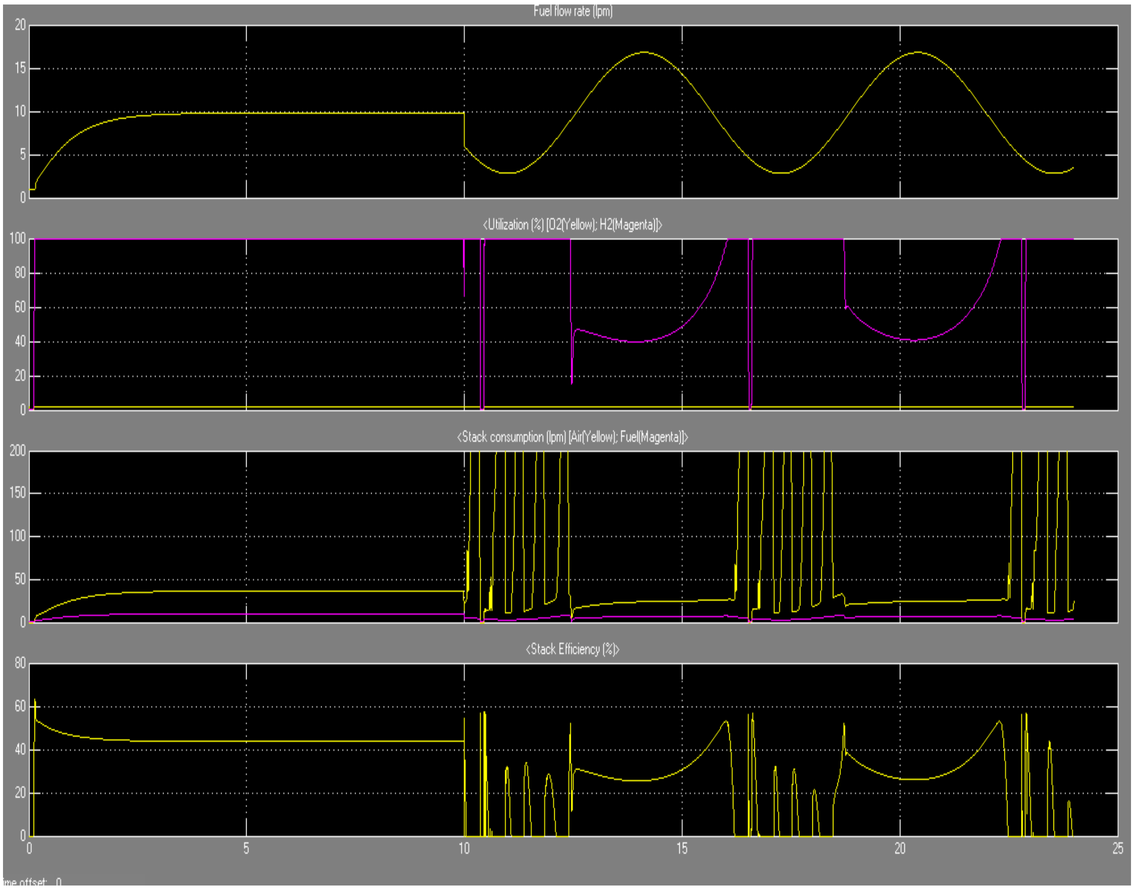

Figure 6.35: H_2FC simulation results fuel flow rate, consumption and efficiency.

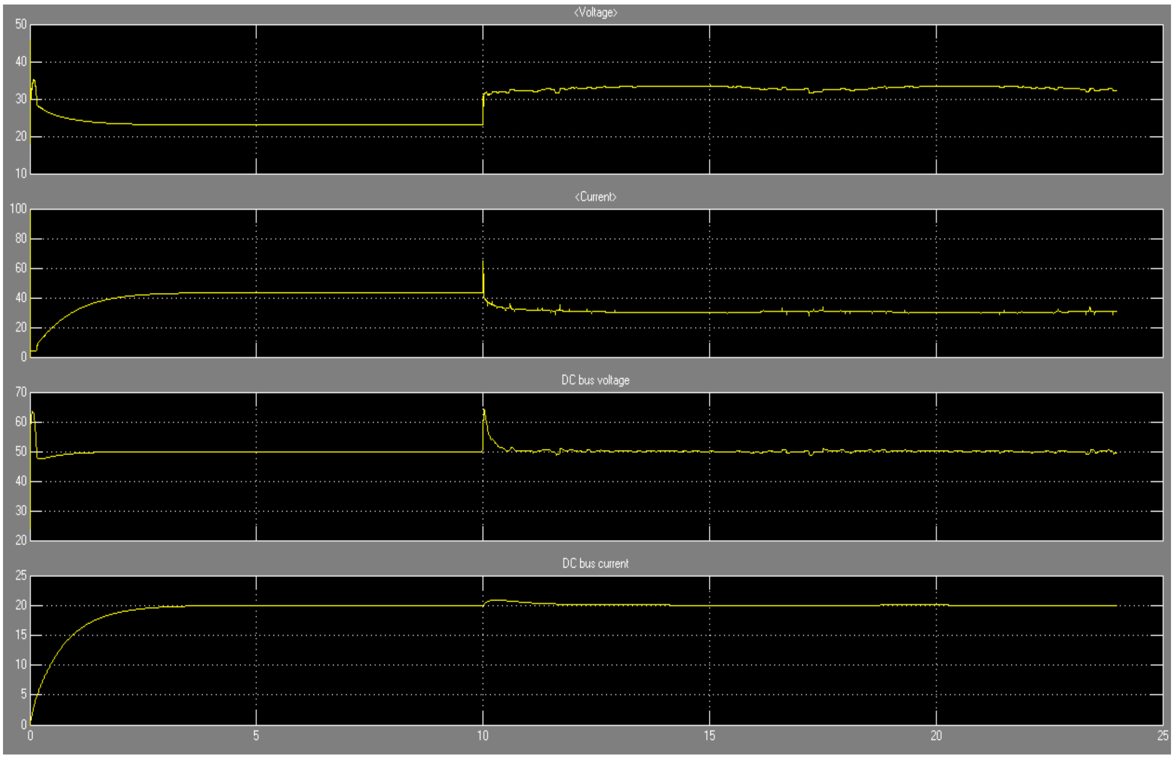

Figure 6.36: Simulation results volt and current for H_2O_2-FC and DC-bus.

6.3.4 Results of hydrogen peroxide fuel cell model

The configuration of hydrogen peroxide FC is show in Figure 4.7, 10 kW 24 volt DC fuel cell stack. Figure 6.36 shows the voltage and current for FC and the DC-bus, where Figure 6.37 is presenting the flow rate, consumption and the stack efficiency (average is 55%).

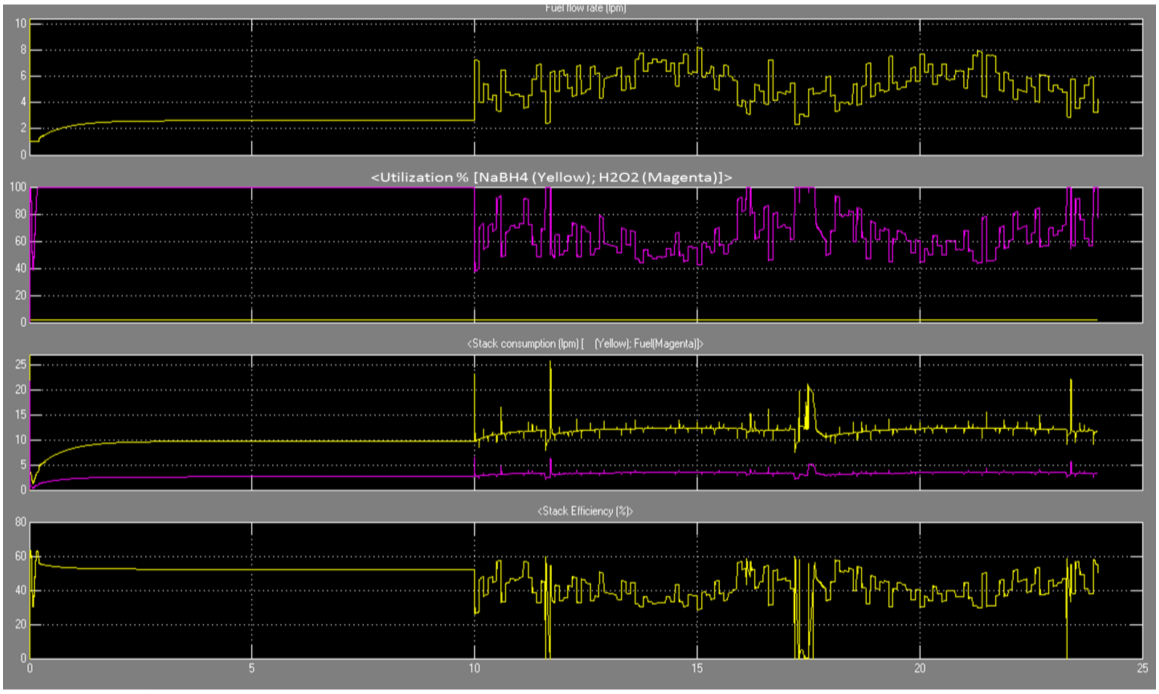

Figure 6.37: H_2O_2-FC simulation results fuel flow rate, consumption, and efficiency.

6.3.5 Results of Battery model

The batteries configuration is shown in Figure 4.8, the batteries are located inside the DC-bus block, and the batteries system require a charging controller in order to preserve the batteries for the rated lifetime. Figure 6.38 illustrates the battery's voltage (almost 24V DC ± 2V), state of charge (97%), and the DC-Bus voltage and current while it is in operation, the state of charge percent could be altered, as the designer can connect or disconnect the batteries from the system (the red circle shows the area that is magnified below for more clarification). Simulink converter has been used in the DC-bus as some types are used Simulink mode and some are used physical signal output.

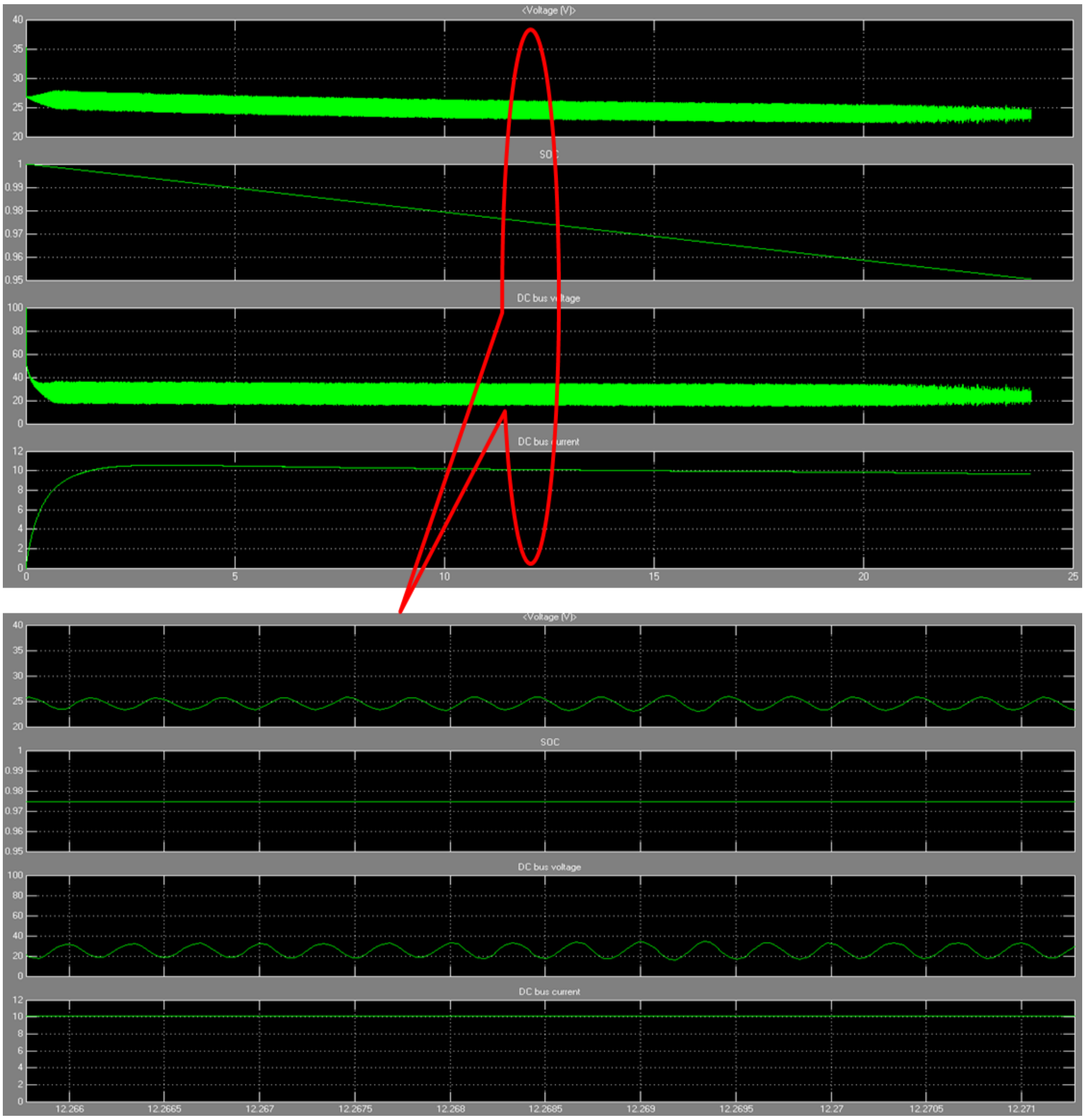

Figure 6.38: Voltage and state of charge of batteries.

6.3.6 Results of Diesel generator (DG) model

The DG configuration is shown in Figure 4.9; the DG is connected directly to the AC-bus before the rectifier as mentioned in the same Figure with 15 kW 50 Hz.

Figure 6.39 is presenting the DG voltage and current during the operating period. In this simulation the designer is switching on and off.

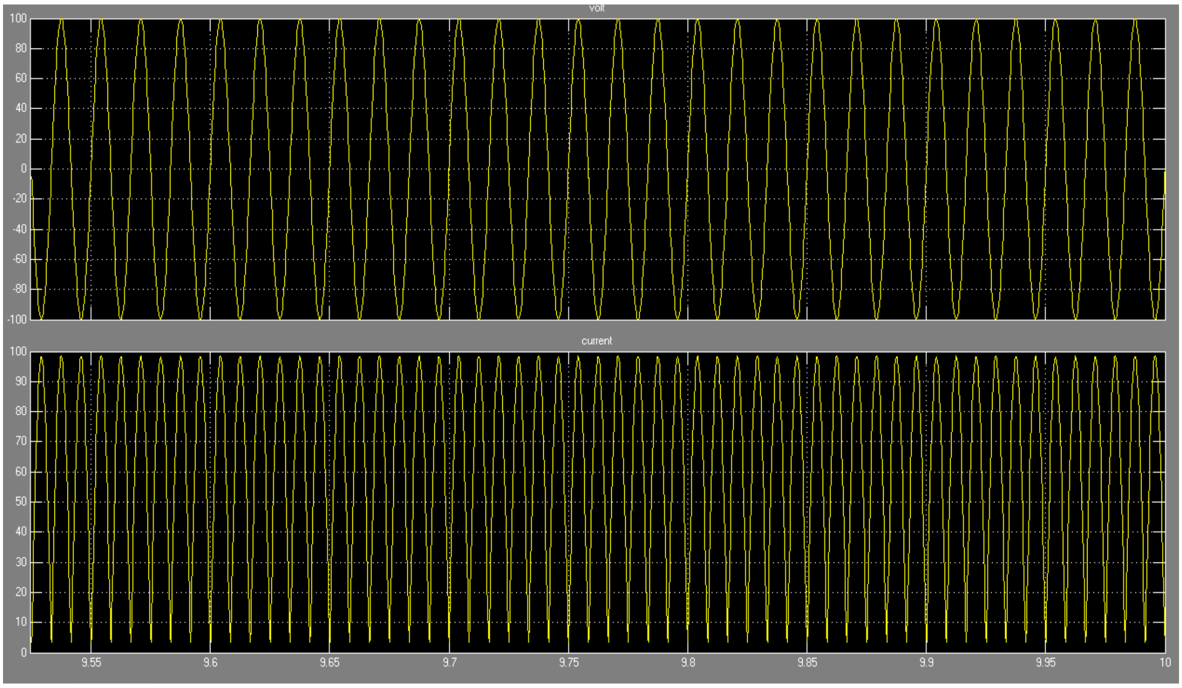

Figure 6.39: Voltage and Current of DG during the operating period.

6.3.7 Results of bi-directional converter model

The bi-directional converter is presented in Figure 4.9, an AC/DC/AC bi-directional converter is built, and its diagram and parameters are based on successful measurements, the designed converter is divided into rectifier and inverter, this design was made to proceed more efficiently with the simulation cases as it mentioned in Figure 6.40 where it shows the voltage and current in the AC-bus before the rectifier. The IHPS in this case shows more sustainability and reliability as well as providing a powerful technique that it might offer many advantages large supply with the variations in load, dynamic response, and the simplicity of this model to be implemented. Figure 6.41 is presenting the voltage and current responses at the instant of one diode during the transient state. Figure 6.42 is illustrates the DC-bus frequency (almost zero) with the ramp (wt equal to 3.6 rad), also it shows the vector sin (wt) and cos (wt), it shows that the frequency in the DC-bus is very small and almost zero.

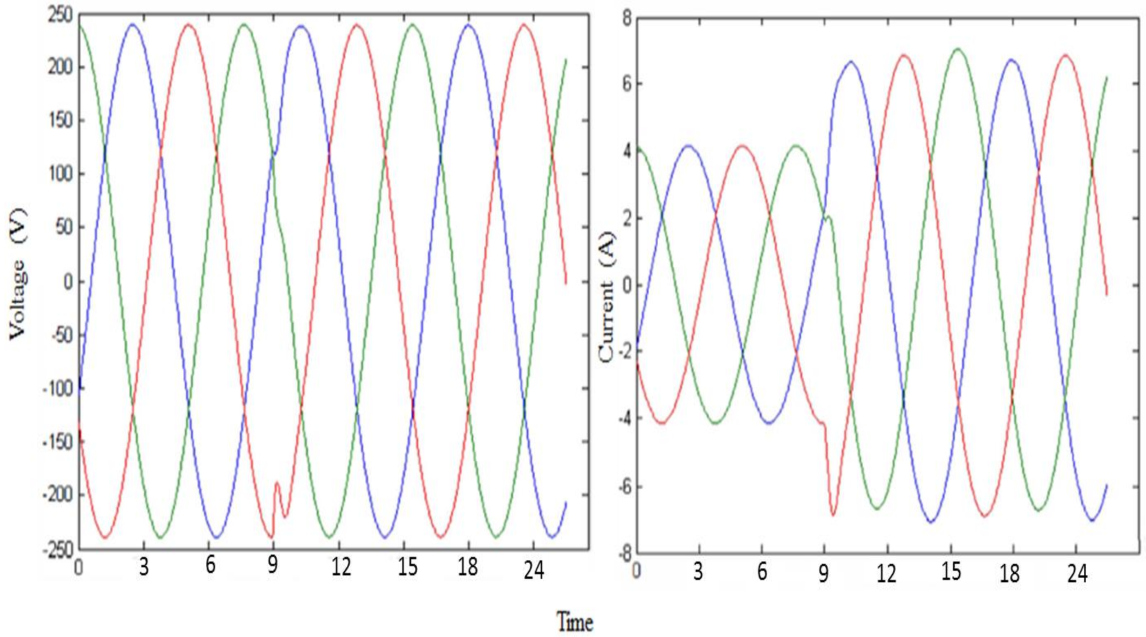

Figure 6.40: Voltage and Current response at the AC-bus before rectifier.

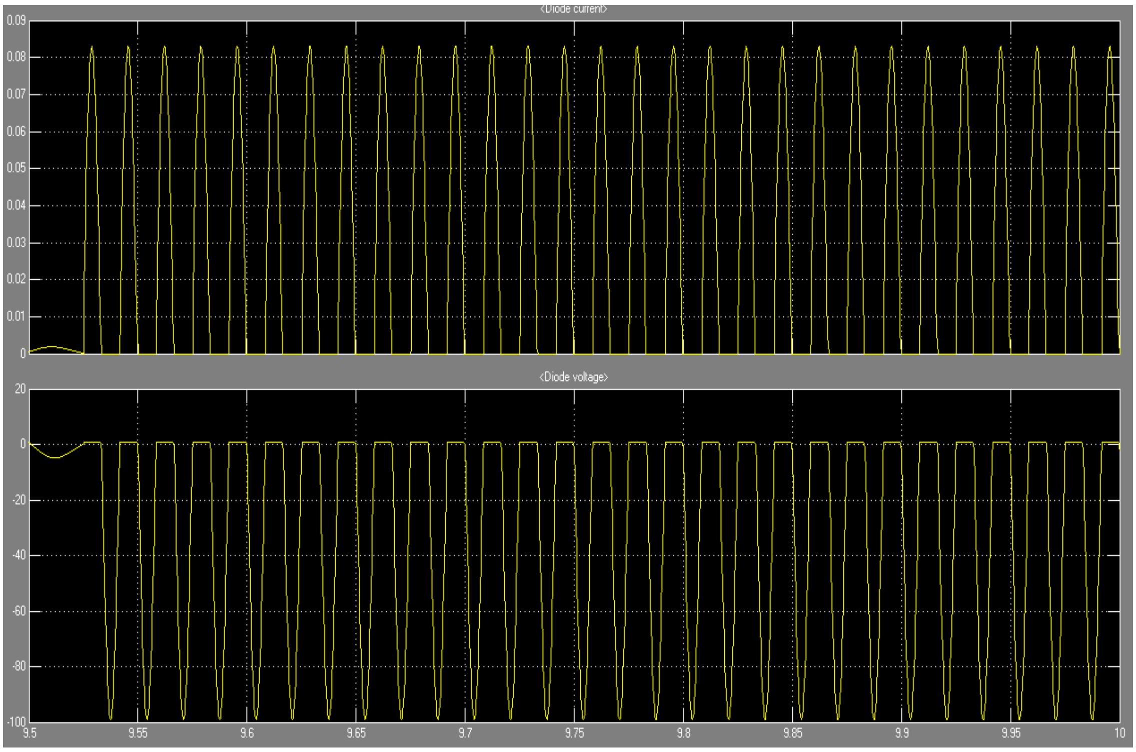

Figure 6.41: Voltage and Current of diode at instant period.

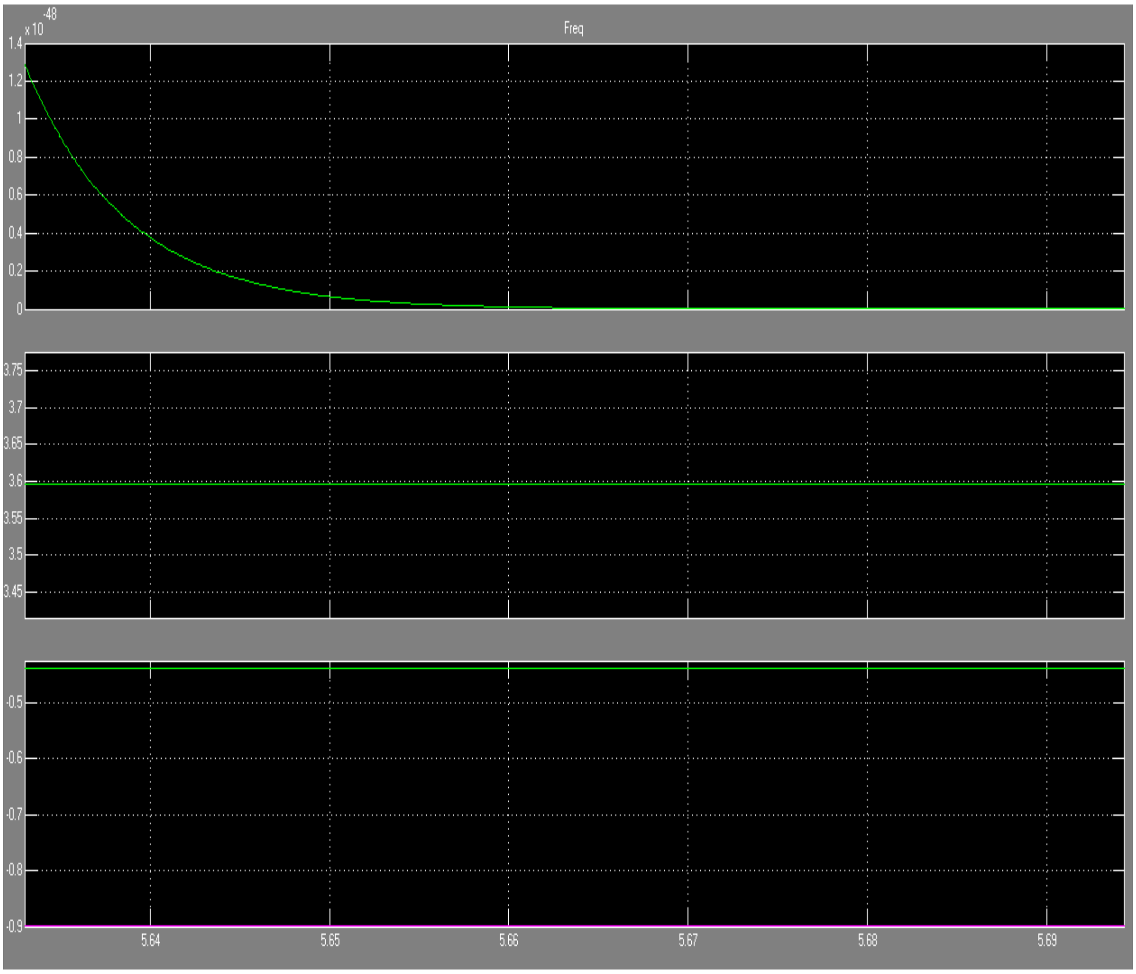

Figure 6.42: Simulation results frequency, wt, and sin (wt) cos (wt) for DC-bus.

6.3.8 Summary

This part simulates the supplement design from HOMER, in order to conduct for the technical analysis (dynamic behaviour, such as voltage and frequency) and viability of the design (different synchronizing modes). OGREH-SµG with the recommended capacity is modelled in the Simulink simulation, in order to present it in block diagrams with the proper selection and configuration parameters the optimal system configurations as simulated in HOMER. Under certain conditions the initial value can be assigned any value, even zero, to finish the simulation. The multi domain dynamic behaviour is simulated and the results viewed individually.

6.4 OGREH-SμG Linear Cost Function results

A LCF with eight variables has to be minimised, by implementing LCF in LP to minimise the cost of the system. In this design 8 variables were created, and according to the equation in section 4.3.6, Table 6.8 is presenting the optimal system according to the optimization function created by Scilab "Karmarkar's algorithm". The LP for OGREH-SμG LCF is presenting in appendix E.

Table 6.8: The minimum values of HPS by using optimised cost function

xopt	Components	Results	Final results	Unit
X1	PV	0.8293129	0.829	kW
X2	Wind turbine	15.500153	15.5	kW
X3	Batteries	2.0490814	2	set/group
X4	Bi-directional converter	5.1979063	5.2	kW
X5	Electrolyser	1.5058239	1.5	kW
X6	Hydrogen Fuel cell	3.2363959	3	kW
X7	Hydrogen peroxide FC	7.7435966	8	kW
X8	Diesel generator	15.958403	16	kW

6.5 Proof of concept Investigations for H_2O_2, FC, and Electrolyser results

As electrical storage in IHPS is playing an important and pivotal part to guarantee continuous power supply. According to that three experiments are prepared producing hydrogen (electrolyser), generated power by fuel cell, and hydrogen peroxide long time storage.

6.5.1 Electrolyser experiment and hydrogen production results

This experiment has been completed in two parts as explained in appendix F, where Table F.1 presents a comparison between the actual hydrogen productions from the electrolyser and using Faraday equation to calculate the production, moreover, volt current, and power are presented. Table F.2 presents the hydrogen production with different temperatures. According to the data in appendix F, there are slight differences between the measured hydrogen compared to that calculated as mentioned in Figure 6.42. Where Figure 6.43 is describing the effect of reducing the temperatures on the hydrogen production, as it shows that it is difficult to use the heat in a beneficial way as the hydrogen production is decreased when the temperature is reduced.

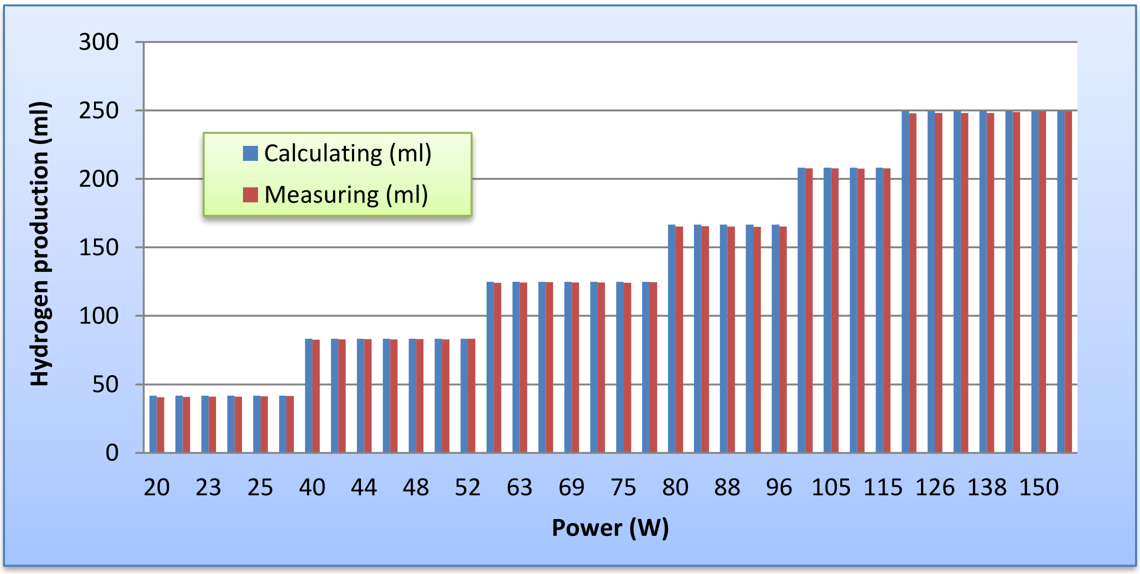

Figure 6.43: Hydrogen production with different temperatures.

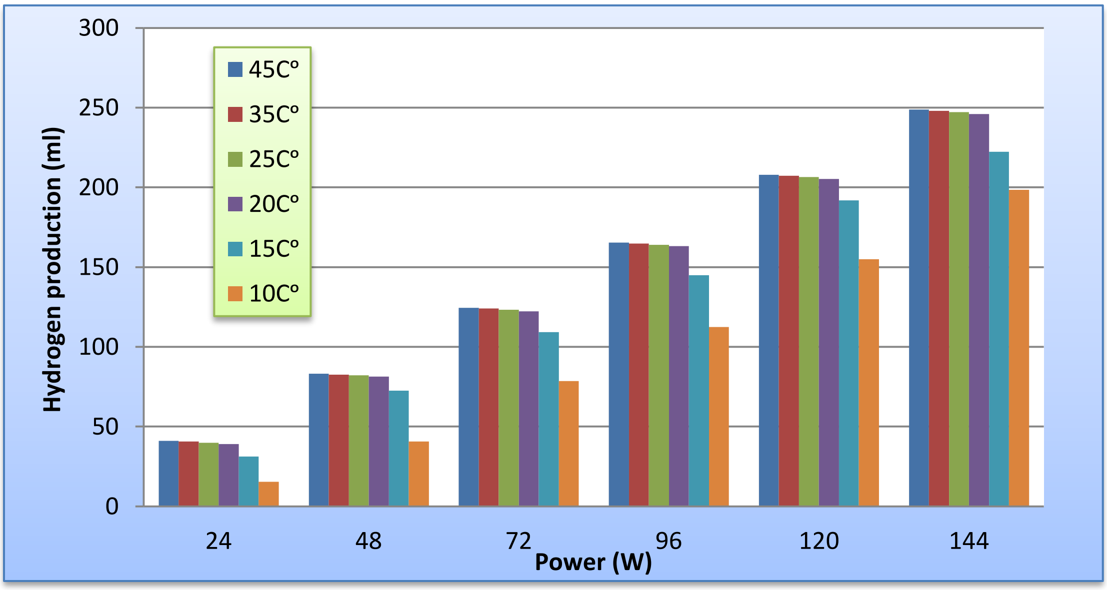

Figure 6.44: Hydrogen production with different temperatures.

6.5.2 Fuel cell experiment results

This experiment has been undertaken in two parts as reported in appendix G, where Table G.1 presents the input power before the electrolyser, output power after the fuel cell, and the efficiency between the input and output power, the operating temperatures are measured and presented in the same Table. Overall efficiency for the electrical power is (36.38 %). In Table G.2 presents the input power, output power, and efficiency for different temperatures. According to the data in appendix G, the efficiency is fluctuating from 35.5% to 37.5% as mentioned in Figure 6.45. For more explanation of the efficiency at the measured temperature refer to Figure 6.46. Figure 6.47 shows very slight differences between the output power from 45°C to 15°C, where the output is decreased when the temperature reached 10°C, and in this situation as it is recommended to use the heat in beneficial way.

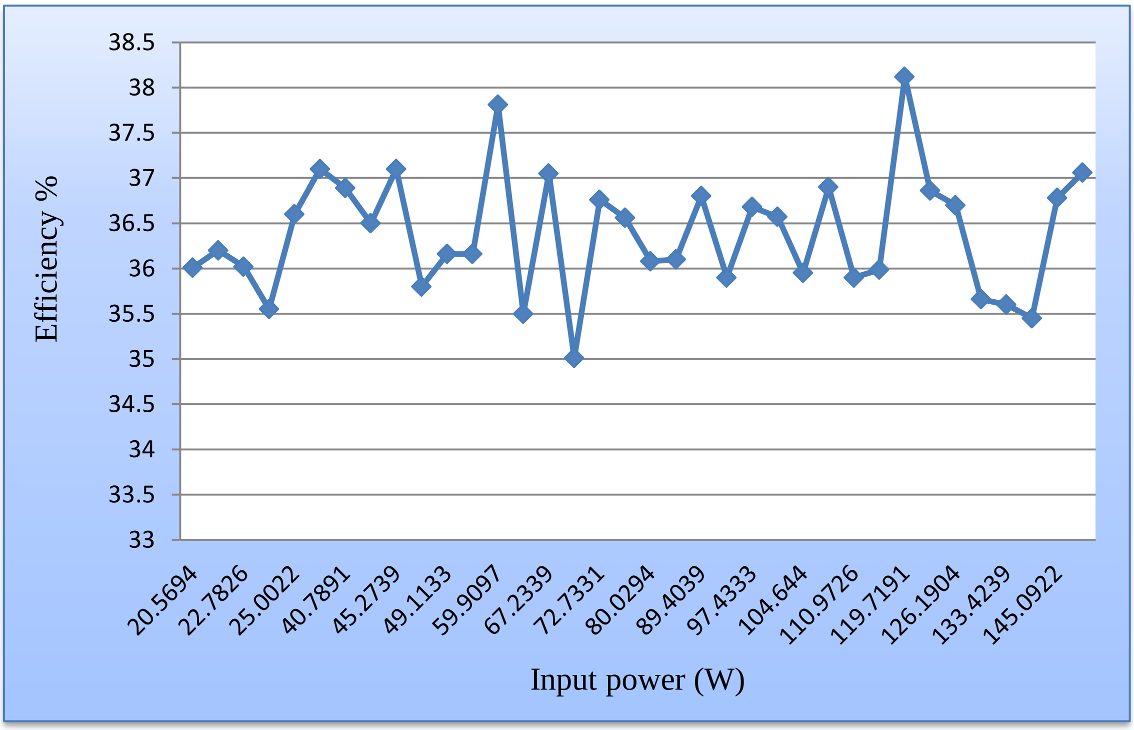

Figure 6.45: Fuel cell unit efficiency from electrical to electrical.

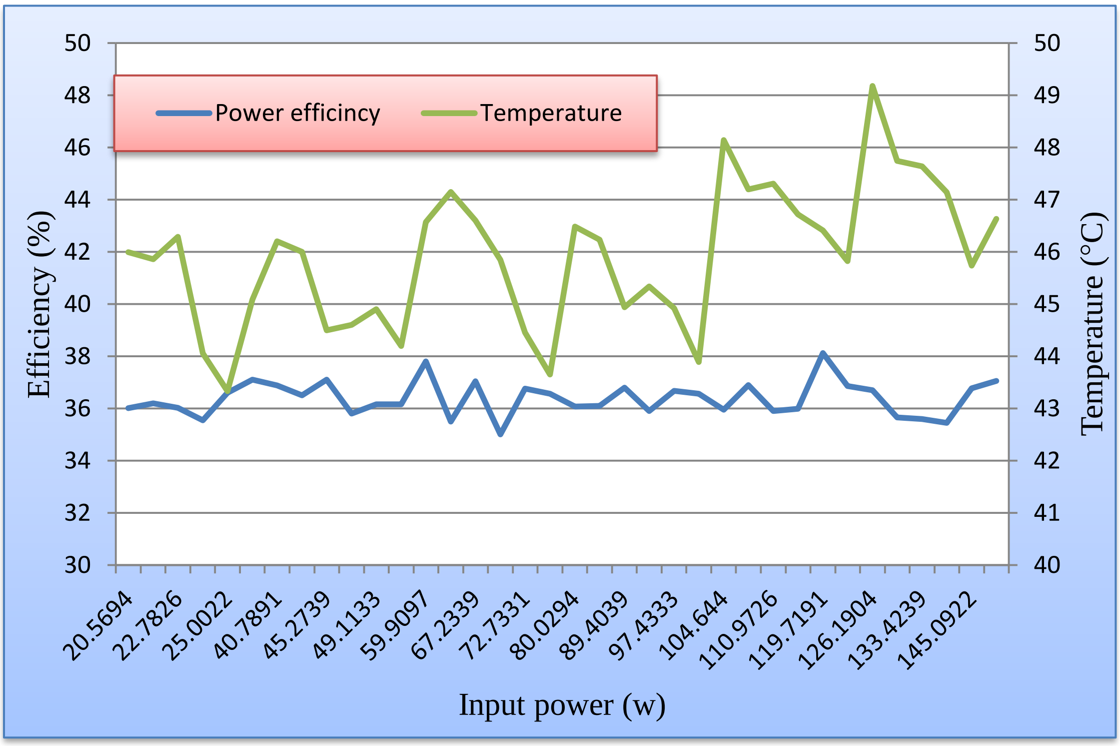

Figure 6.46: Fuel cell unit efficiency at the measured temperature.

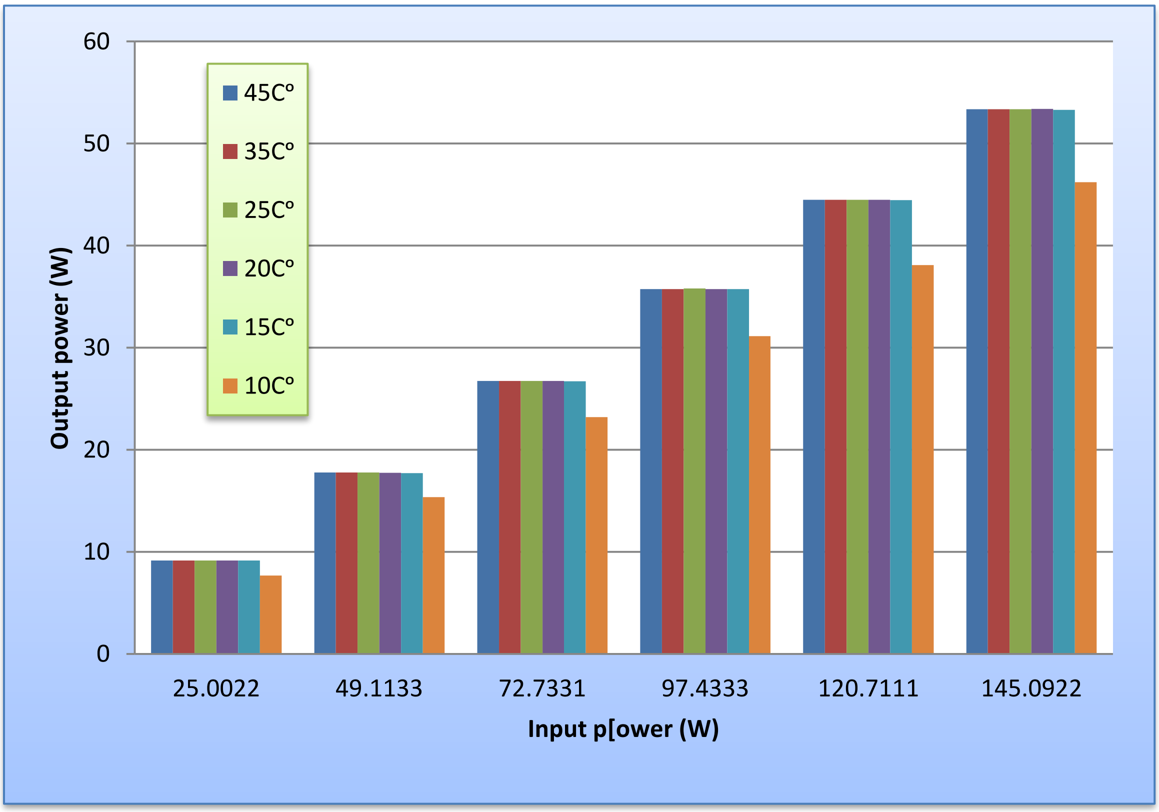

Figure 6.47: Output power with different temperatures.

6.5.3 Results of hydrogen peroxide storage

The readings and results from testing the hydrogen peroxide in a weekly basis are explained in appendix H, where Table H.1 presents the calculated concentration for hydrogen peroxide according to the released oxygen from the tested sample as reported in section 4.3.4.4.4. Table H.2 presents the oxygen production and the concentration of hydrogen peroxide on a weekly basis. According to the data in appendix H, the released oxygen for one sample (50% concentration with lead at room temperature) is presented in Figure 6.48 where it shows a reduction of only 5 ml of oxygen in 5 months compared to day one. Figure 6.49 demonstrates a comparison between the released oxygen for all samples after 5 months, where it shows a slight difference between the samples. The concentrations for H_2O_2 after 5 months are presented in Figure 6.50, and it shows that the long term storage of H_2O_2 is efficient as the concentration of it after 5 months is decreased but in acceptable ranges.

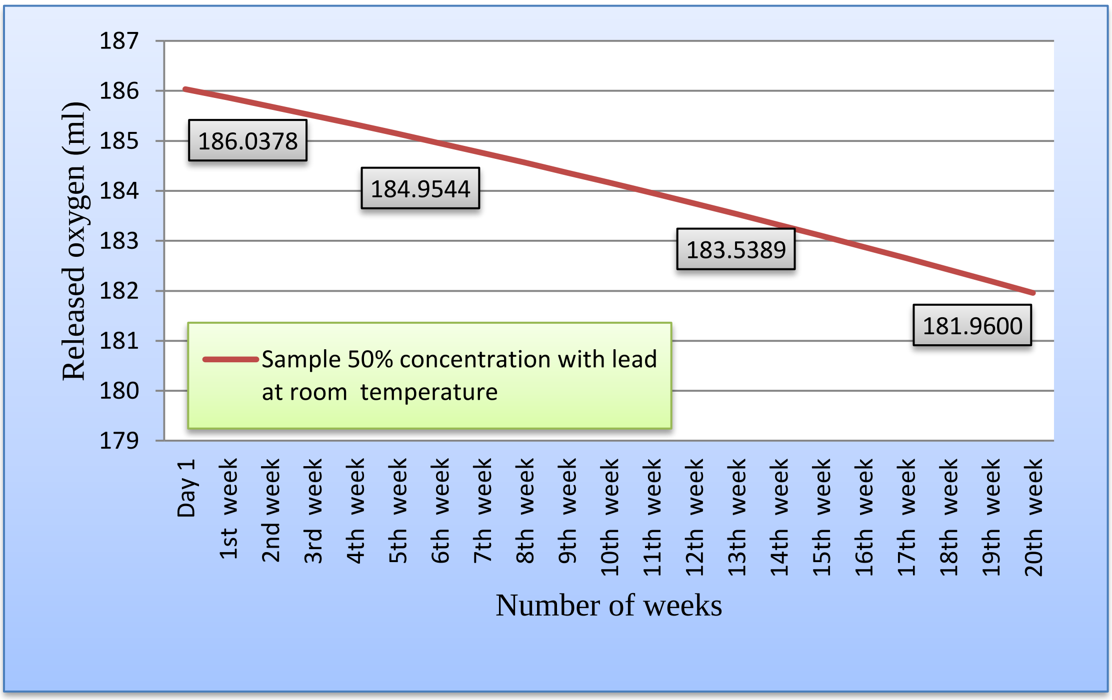

Figure 6.48: Released oxygen for one sample in weekly basis.

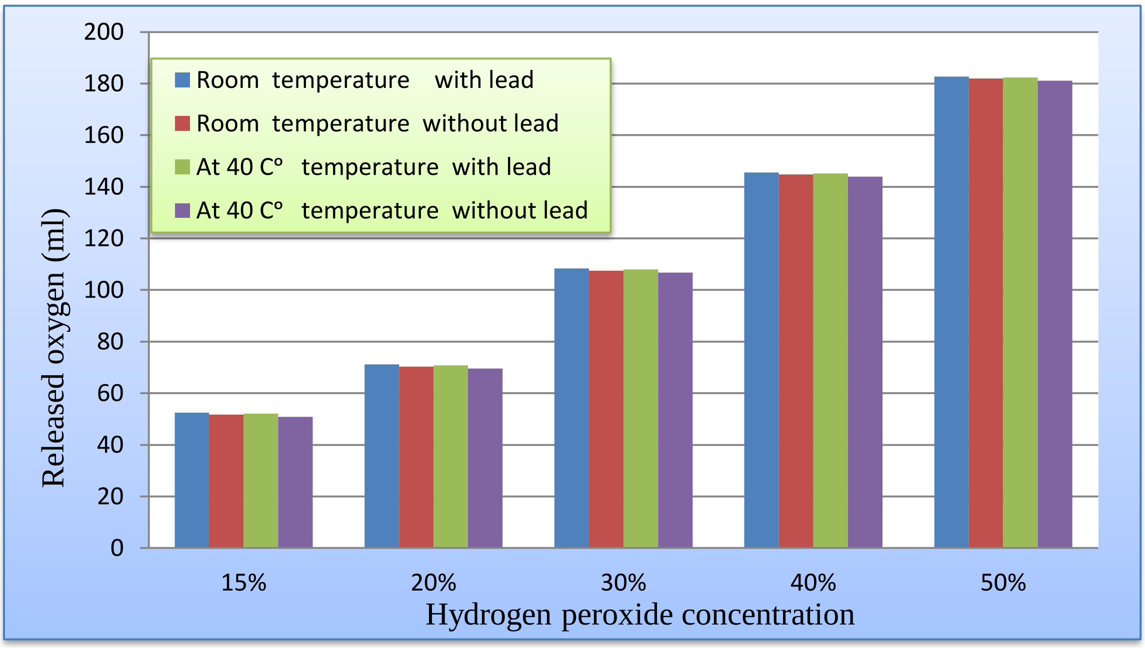

Figure 6.49: The comparison of released oxygen for all samples after 5 months.

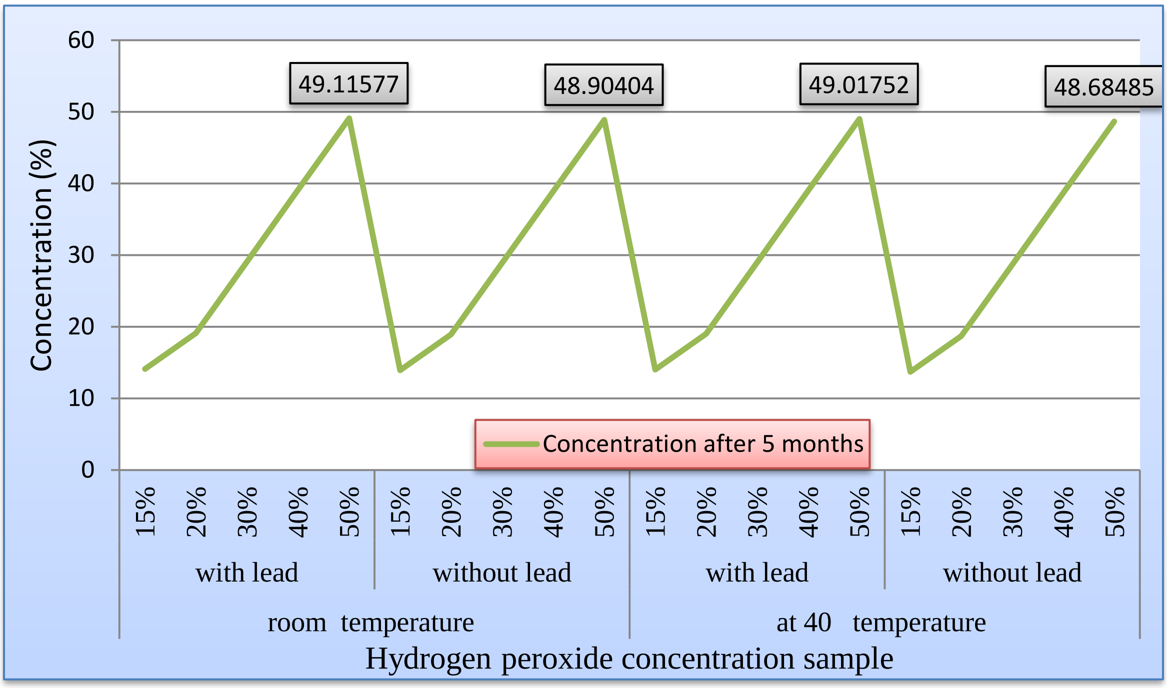

Figure 6.50: Hydrogen peroxide concentration after 5 months.

6.6 Questionnaire results

According to the results in appendix I, most end-users are in type 2 consumers (151-300 kW) and paying between £15 - £20. The objective of the demand management strategy implemented in the OGREH-SμG is to move the majority of the consumers from type 2 to type 1 (0-150 kW).

Figure 6.51 shows the types of heavy duty equipment used in residential units. Also the results indicate that the majority of those surveyed will change their behaviour of usage if this was possible with having the relevant information and facilities.

Responses for Question 6 demonstrated consumer preference for a smart grid, following a detailed explanation of a fully automated smart grid and its advantages, however, the main concerns on this was the issue of privacy, as a fully automated smart grid would mean the monitoring of private life style information, and controlling the end-user usage based on this information.

The responses given in the next part demonstrates that there would be more acceptance for a semi-automated internal controller as part of a system that did not monitor and record usage i.e. intrude on privacy – of the type proposed in our design.

The responses for next question indicate that 70.3% would like to control their electrical consumption whereas 3.6% would not, and the rest 26.1% were undecided.

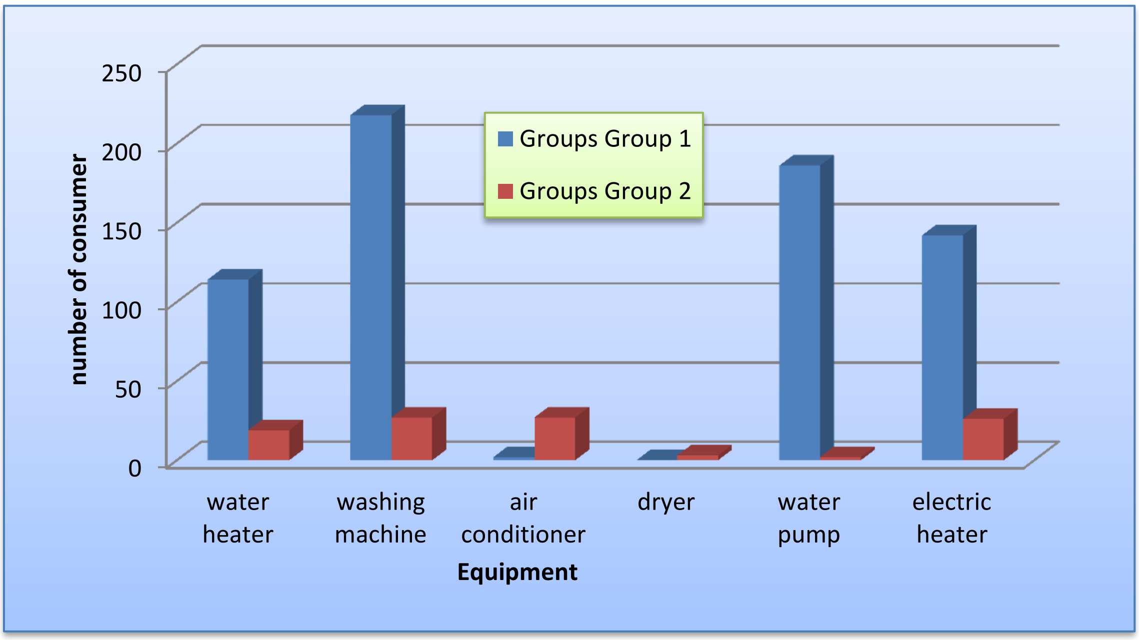

Figure 6.51: Heavy equipment usage in remote areas.

6.7 Results of testing the implementation of the demand management strategy and complementary adaptive tariff

Testing and optimisation of the demand management strategy and the design of the complementary adaptive tariff was conducted by HOMER simulations within the IADF, for these simulations the DG is forced off around the year except during the weekends in summer months. The optimised strategy and the tariffs are detailed in section 4.3.5.3.

The load in HOMER simulations is represented by two load icons, one is for critical load and the second is for the noncritical loads (a load that can be supplied any time during the day and could be deferred in time) the type of loads that were assumed in this category in our simulations is shown in Table 6.9, this can be changed based on the designers preferences or priorities.

Table 6.9: The average demand loads for a remote area house

Name of the load	power (W)	Quantity	used per day (Hour)	load per day KWh/day	load per month KWh/month
Fridge	172	1	11.5	1.98	59.34
Washing machine	275	1	0.35	0.10	2.89
Microwave	750	1	0.45	0.34	10.13
AC unit	2000	1	1.1	2.20	66.00
TV	40	1	5	0.20	6.00
Iron	1000	1	0.1	0.10	3.00
Computer	55	1	1	0.06	1.65
Satellite or DVD	25	1	3	0.08	2.25
low energy light	18	4	3.5	0.25	7.56
Standard light bulb	75	2	0.3	0.05	1.35
Hair dryer	1400	1	0.1	0.14	4.20
Water heater	1800	1	0.2	0.36	10.80
kettle	1000	1	0.45	0.45	13.50
	Total			6.29	188.66

The demand management strategy and the complementary adaptive tariffs approach adopted will reduce the optimisations loading constraints and will simplify the implementation of sensitivity analysis to compare simulations with and without load management and adaptive tariff is implemented for the design under consideration. The resultant optimal configuration utilising non-critical load shows a significant improvement in reducing the running cost mainly by reducing the operating hours for the DG.

Figure 6.52 shows the monthly average power production after using non-critical demand panel (deferrable load), where it is shown that the requirement for DG is drastically reduced. The DG is now only required to operate to match 0.2 % of the load even with critical operational constraints such as high demand and minimum PV generation. Hourly simulations are carried out for the system being designed; the results of these simulations are presented in this section however the detailed simulation outputs carried out are reported in the attached CD.

It can be seen that the generated power from DG is reduced to (3,304kWh/year) from (55,480kWh/year) in an ISP with only DG, and moreover the new management strategy and adaptive tariff reduces the DG to (284kWh/year) with a reduction of 91.5% from the system without the implementation of Demand managements and adaptive tariff.

The DG as explained in section 6.2.1.6 is chosen as a final stage backup system, accordingly the DG should be chosen with a rated capacity of15kW AC to supply the total load. Table 6.10 shows the operating details, such as fuel consumption, electrical production, and thermal production. Figure 6.53 shows the monthly average production.

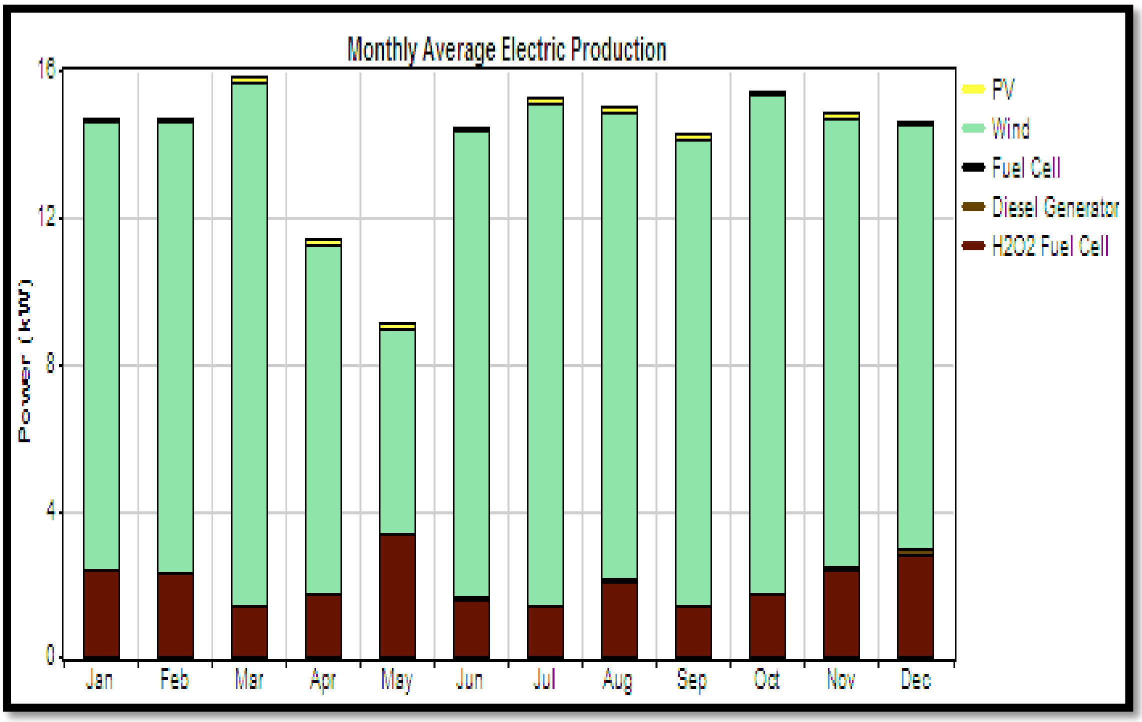

Figure 6.52: Monthly power production for HPS with deferrable load.

A real-time demand response is ability to handle the intermittency and variability of RESs. It is assumed that increasing number of non-critical load (deferrable loads); will be employed in the system demand response in the future with development of smart technologies for load consumption. In this thesis, the expected mismatch between demand and available power is reduced by shifting the consumer loads (non-critical load) to match with available generation in real-time. Hourly simulations are shown in each time step that the simulation minimizes the mismatch to match the load with the available RES and storage and back up available. The importance of real time control can be demonstrated by reducing the time step from 24 hours to 1 hour as in general, it is demonstrated that the mismatch converges to zero as the time steps get shorter (effect of continuous – real time - demand management and load sharing).

Table 6.10: Diesel Generator operating details with deferrable load

Quantity	Value	Units
Fuel consumption	131	L/year
Specific fuel consumption	0.461	L/kWh
Fuel energy input	1,289	kWh/year
Mean electrical efficiency	22	%
Electrical production	284	kWh/year
Mean electrical output	5.68	kW
Min. electrical output	4.5	kW
Max. electrical output	13.3	kW
Hours of operation	50	hour/year
Number of starts	39	starts/year
Operational life	300	year
Capacity factor	0.216	%
Fixed generation cost	4.11	$/hour
Marginal generation cost	0.3	$/kWh

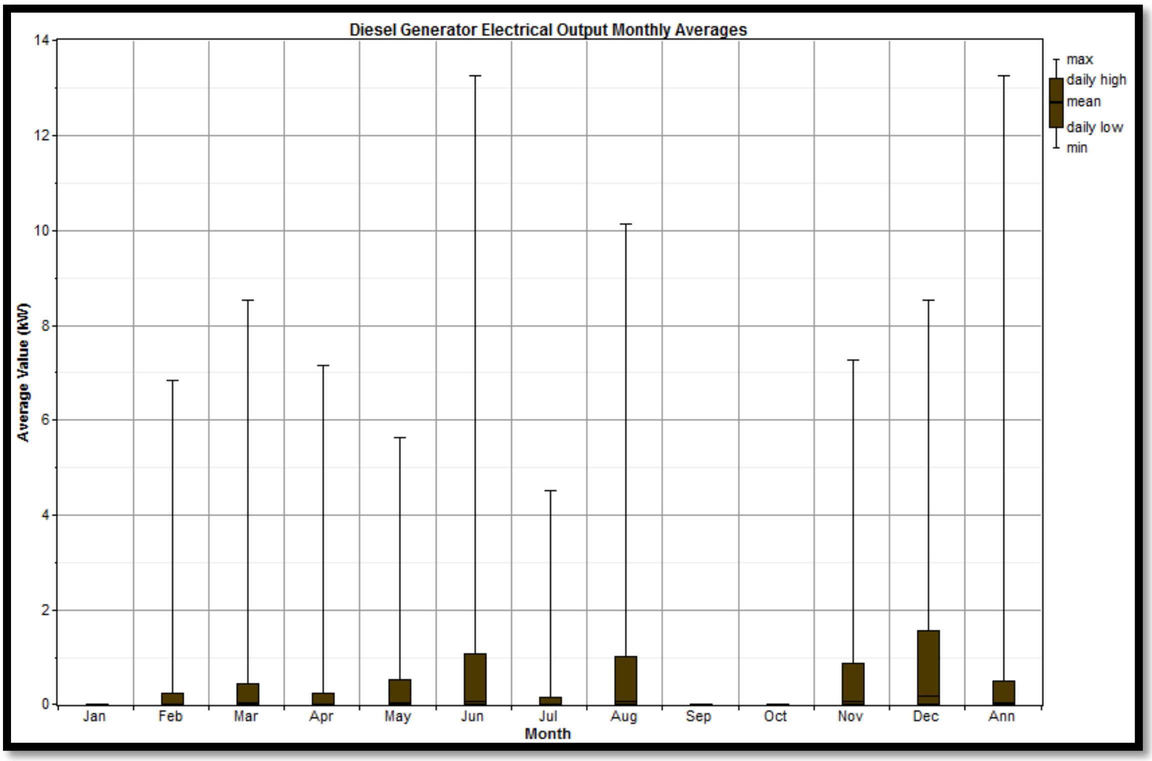

Figure 6.53: Monthly average DG power production with deferrable load.

6.8 Raspberry Pi implementation results

There are two types of microcontroller control (raspberry Pi) used as intelligent supervisory switching controller in this research work design of the OGREH-SµG;

1. Demand management strategy to control and manage the demand load inside the house.
2. Central controller
    a. to make a control system which operates PV panel to track the sun,
    b. to implementing an intelligent supervisory switching controller for the OGREH-SµG in order to schedule all generation power (RESs, storage, and DG) and load share it together.

6.8.1 Results of demand management strategy.

As explained in section 4.3.8.1, inside every house will be raspberry Pi to organize and control the demand load. Nevertheless, Figure 6.54 shows the power generation and actual demand load in a chosen day; also it shows the load after being controlled. As it shows when the demand load is higher than the generated power (as mentioned in the same figure between 18 to 21 P.M.) the controller will shed the unnecessary load as reported below. As the charging rate is changeable according to the power generated, the controller is indicating to the end-user by switching green and red LED on and off, the best time to use more power in low rate is indicated by the green LED (in this day it is from 1 to 11 A.M.), and the high rate of charge is indicated by the red LED (in this day it is from 17 to 22 P.M.), and the controller may switch the secondary panel off while the red LED is on. On the other hand the normal rate for charging is when both LED are off (in this day it is from 12 midday to 16 P.M. and 23 P.M. to 12 midnight).

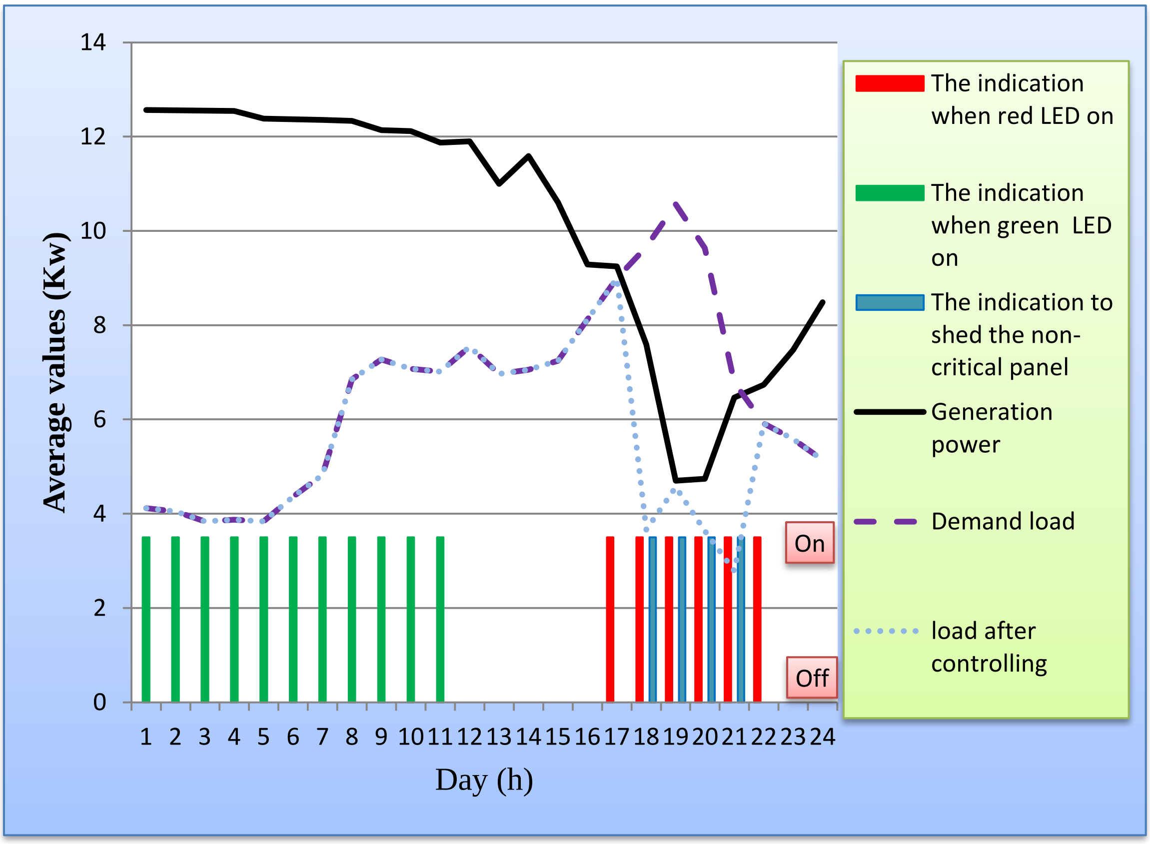

Figure 6.54: The indication of one day raspberry Pi controlling the load.

6.8.2 Results of the OGREH-SμG central controller for

As explained in section 4.3.8.2, the first part is to track the sun radiation as mentioned in Figure 6.55, the radiation is shown with the blue columns and the percentage is in the left axis. The response time for the tracking system is indicated with the red columns and the response time is indicated in the right axis, and if the response time is 5 minutes or less the indication shows 5 minutes.

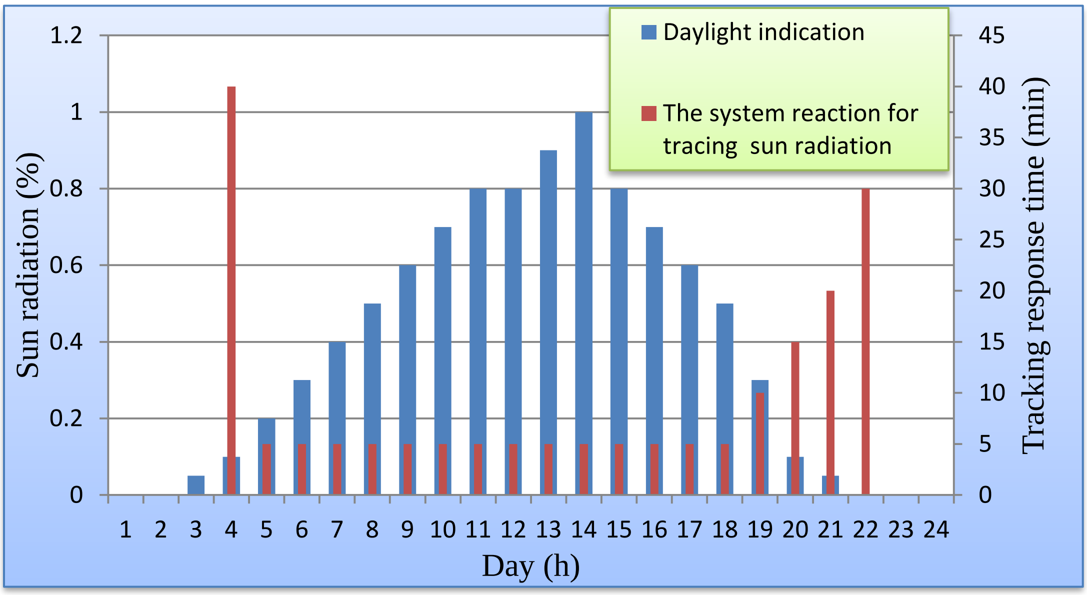

Figure 6.55: Sun radiation and tracking system responding time.

In this section the results of the implementation of the central controller is presented The data of load and generation power from WTG and PV presenting the generated load with the demand load in winter and summer respectively are derived from the previous simulations in Figures (6.56 and 6.57).

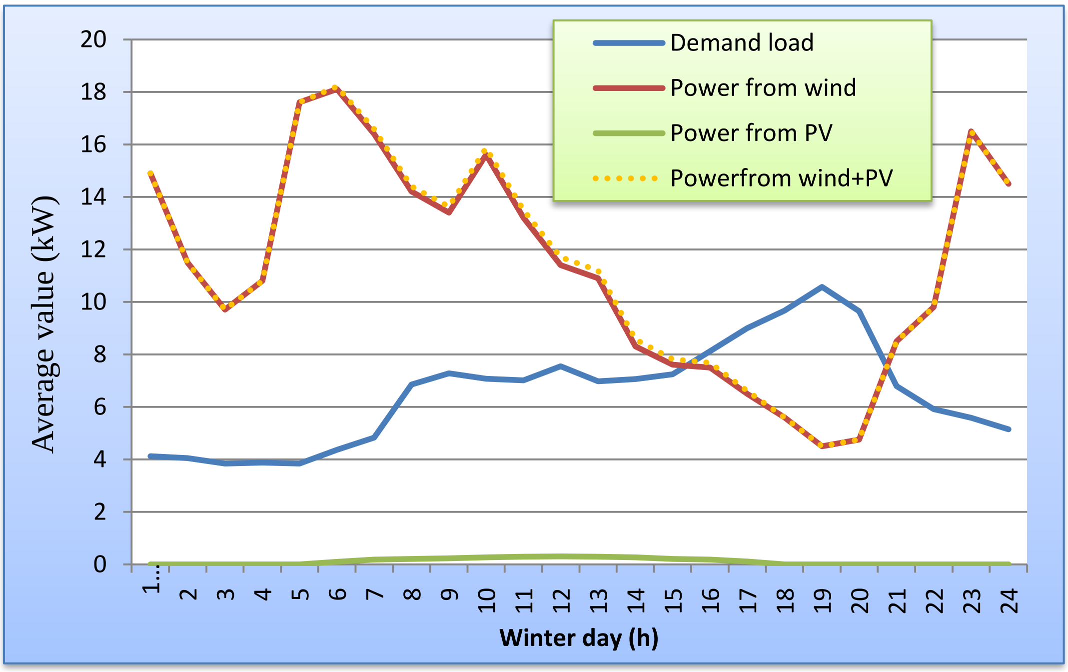

Figure 6.56: Power generation and demand load in winter day.

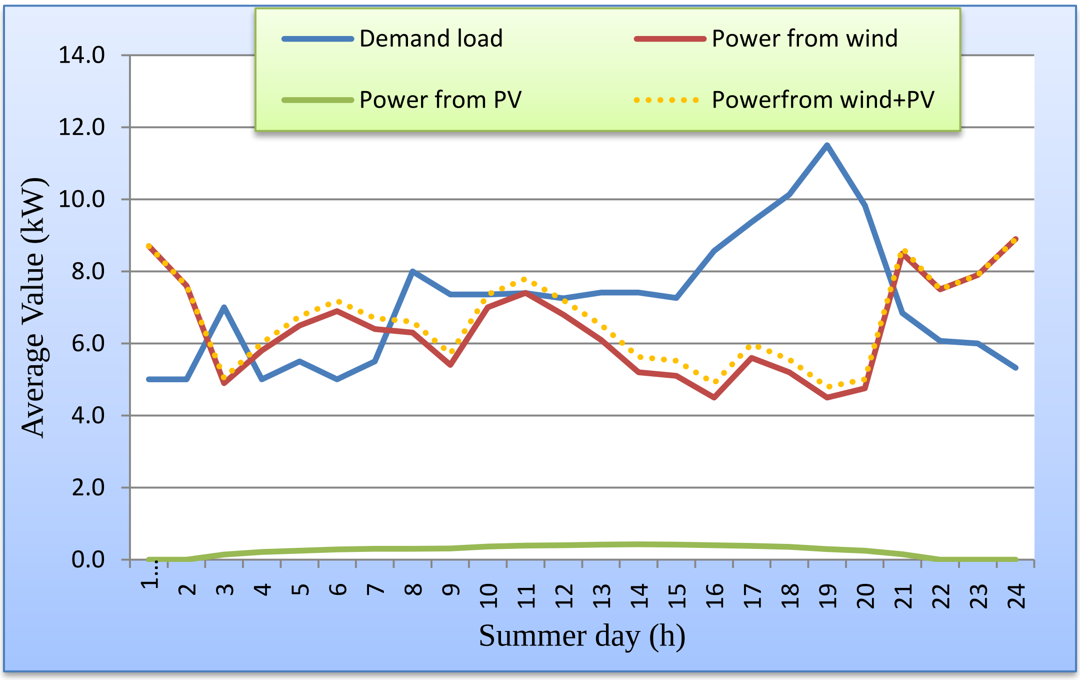

Figure 6.57: Power generation and demand load in summer day.

As explained in the Block diagram of the controlling system of OGREH-SµG (Figure 4.27), when $P_{net} > 0$, there is excess power, this power is available to charge the batteries and to generate H_2 and O_2. On the other hand, when $P_{net} < 0$, the renewable sources generate electrical power which is insufficient compared to demand load. Under this condition, both FC units and batteries start supplying the shortage in power, in some situations (such as summer scenario) the generated power with the reserve power is still insufficient compared to demand load, at this stage the controller will shed the non-critical load in order to reduce the demand, and when it is still not enough the standby power (DG) will operate to cover the deficit in power. Figures (6.58 and 6.59) show the power status of storing and using the stored power (reserve power) and it shows when the system requires the standby power to operate in winter and summer respectively.

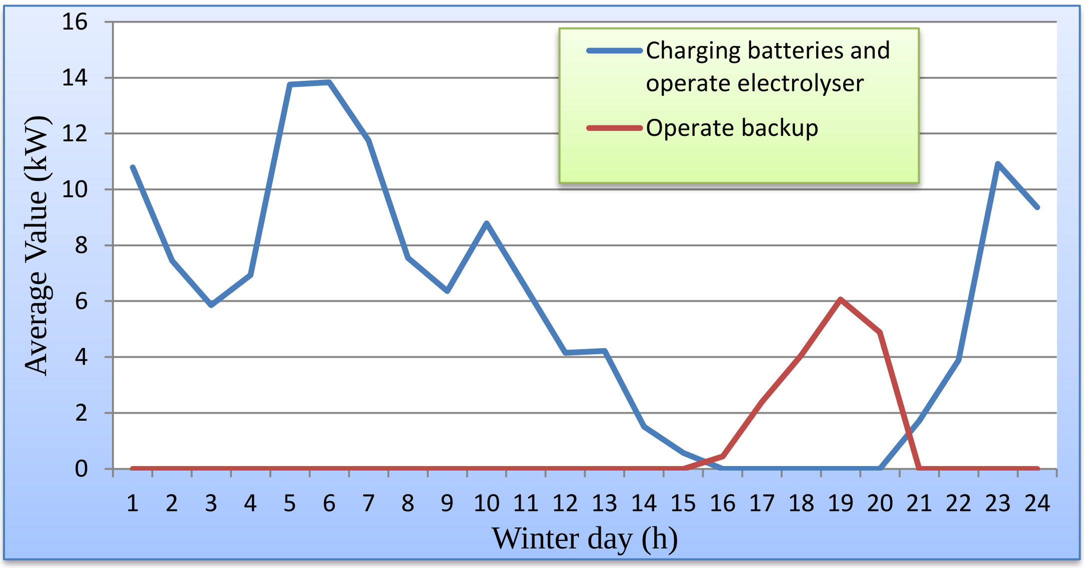

Figure 6.58: Power status of the operating the reserve and storing power in winter day scenario.

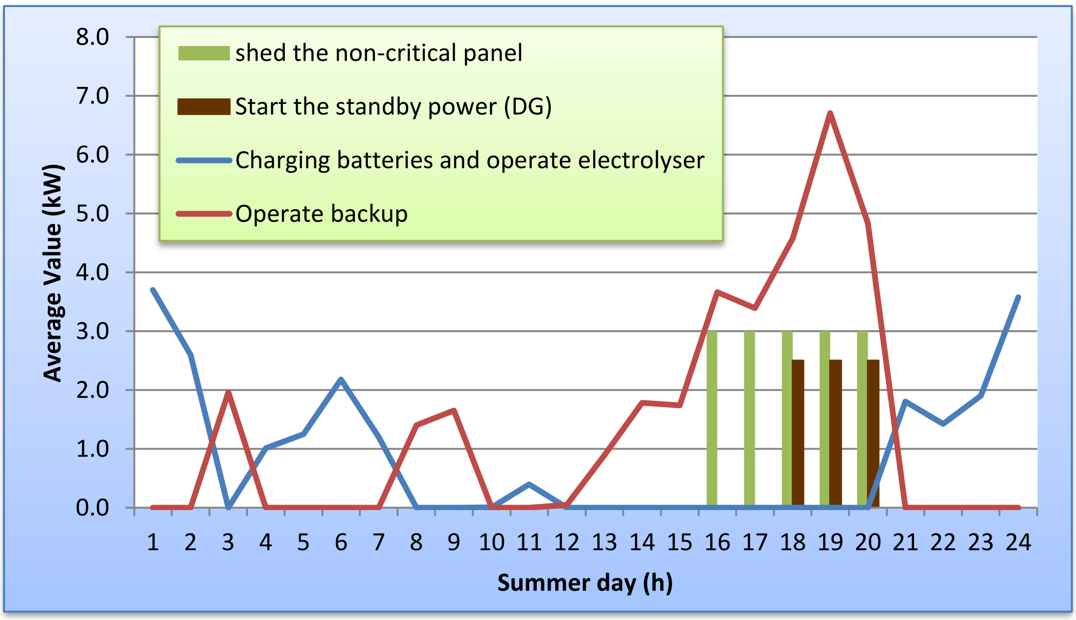

Figure 6.59: Power status of the operating the reserve, standby (DG, shed non-critical panel) and storing power in summer day scenario.

Figures (6.60-6.61) show the total delivered power from WTG, PV, and reserve power (batteries and both FC units) in winter and summer day respectively, and sometimes it shows the delivered power from the standby generator (DG) when required as is shown in the summer day.

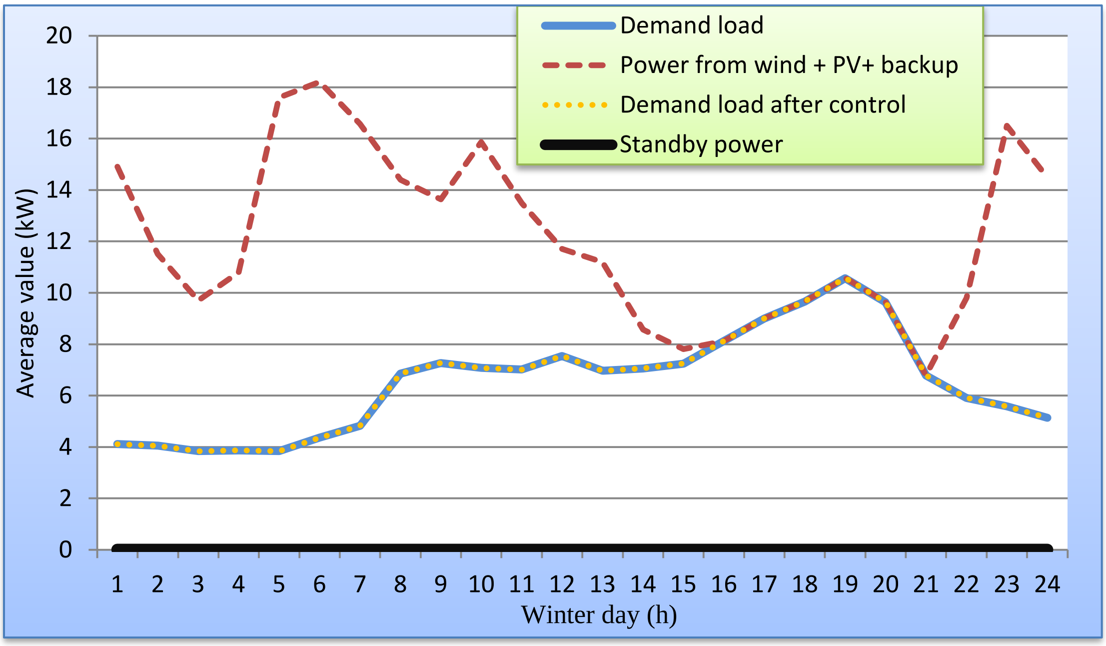

Figure 6.60: Total delivered power compared to expected load and actual load in winter day.

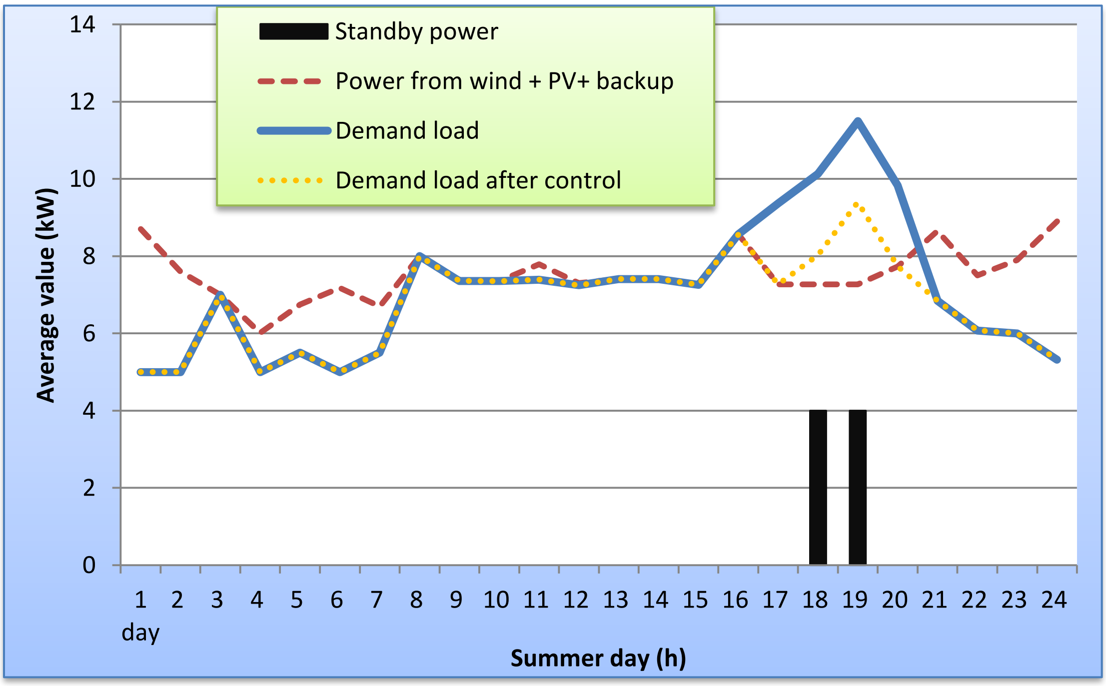

Figure 6.61: Total delivered power compared to expected load and actual load in summer day.

6.9 Results of testing µ-grids synchronization strategy

The “synchronizing relays” method was used and the flow chart is mention in Figure 4.20, the synchronizer required to set these parameters in acceptance range for smooth synchronizing. The µ-grids synchronization model is shown in figure 4.22a. Based on this model measuring for the Frequency, voltage, and phase-angle has been extracted as mention in Figures (6.62-6.63), where the synchronization process is depending on voltage regulator (VR) to match voltage (line to line), variable frequency drive to match frequency (by switching frequency), and have the same phase angle to synchronise smoothly.

Figure 6.62 presents the synchronizing parameters frequency and voltage, and it shows the green line is the reference µG and both red and blue totally synchronized with the master. The frequency shows a difference in the first few seconds, and before 8 seconds the level of frequencies were within accepted levels. For the voltage it is clear that the first 5 seconds shows a difference between the µ-grids voltage until later on the difference is reduced to accepted levels, mainly after 9 seconds.

Figure 6.63 is presenting the synchronizing parameters phase-angle, and it shows the phase-angle of the red µG joins the green phase-angle after1.22 seconds, where the blue took time to join the reference, after 8 second it starts joining the green line with accepted level and at 9 seconds it totally joins in Figure 6.63.

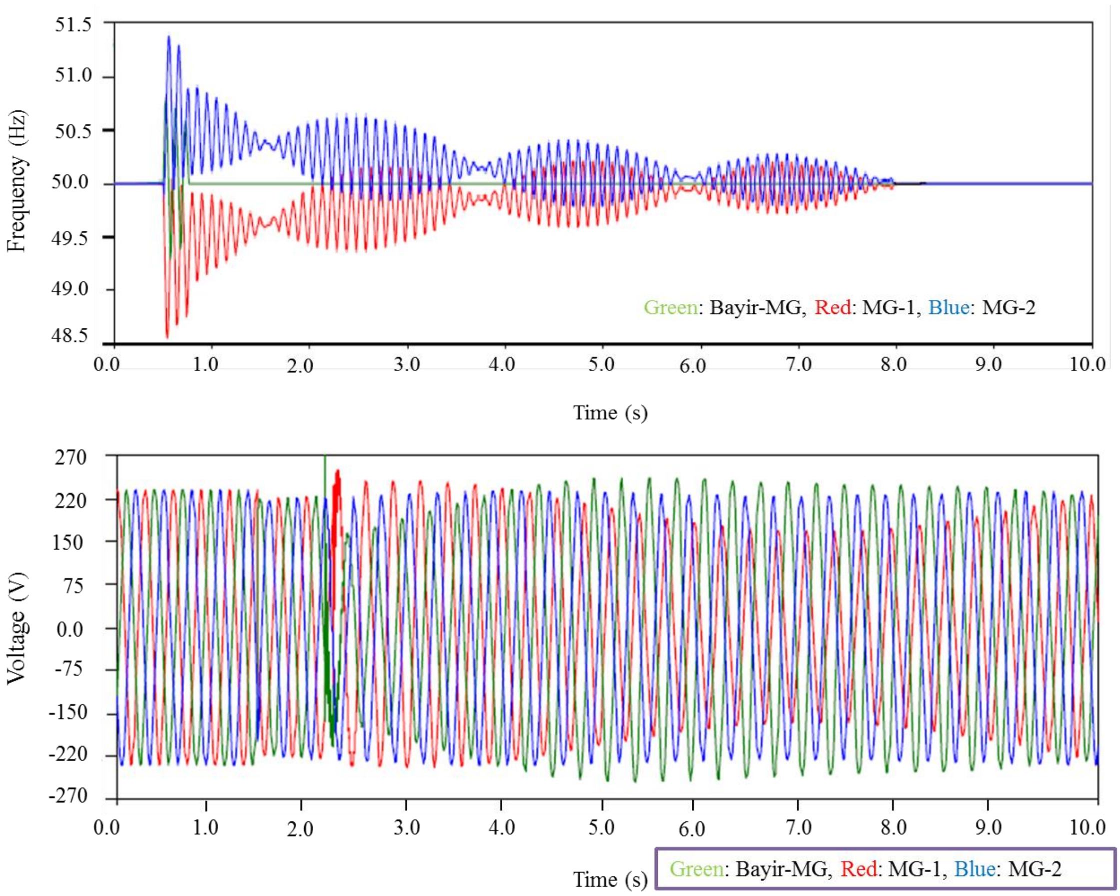

Figure 6.62: Simulation results frequency and volt for MGs synchronizing.

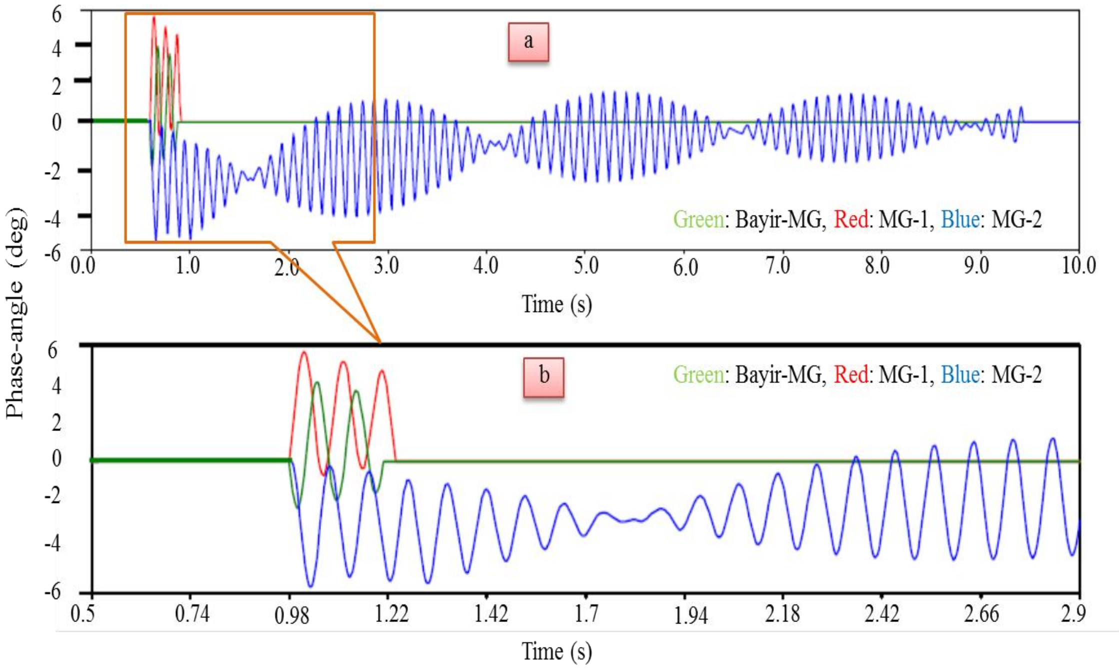

Figure 6.63: Simulation results phase-angle for MGs synchronizing.

6.10 Summary

In this chapter, the results of the HOMER and SIMULINK simulations conducted within the IADF for the OGREH-SμG design including the simulations for the intelligent supervisory switching controller as central controller and the load management strategy for the OGREH-SμG as well as the experimental results for Proof of concept Investigations for H_2O_2, FC, and Electrolyser were presented. The results show that central controller of the OGREH-SμG is able to synchronize the power resources and shed the non-critical load when the system requires. The WTG and PV are the main power generators. The electrolyser produces H_2 and O_2, as part of it will be converted to H_2O_2, and the batteries will be charged when the generated power is higher than the load demand. From the other side, both FC units and batteries operate to produce electrical power as reserve power, when the original generated power (WTG and PV) is less than the required load. The results demonstrate that both FCs and batteries generate power to cover the shortage if possible; if not the controller will shed the non-critical load, and if it still not enough DG operates to supply power to cover the power deficit, the extra power from the DG will be stored.

The results have been presented for both winter and summer average days. The results show that the operating OGREH-SμG with the ability to shed the non-critical load is more effective, in reducing the operating hours of the DG, and controlling the power flows between sources and matching the generation with the load in an optimal manner. The results are presented to demonstrate the effectiveness of using long term storage (H_2O_2) resulting in the overall increase of the efficiency of the system by reducing the operating hours of the DG.

The system effectiveness of the OGREH-SμG is further increased by adding semi-smart controllers at the residential units that indicate to the end-user the generation status (deficit – high tariff, generation matches demand – standard tariff, excess generation – low tariff). So that demand can be managed to match the generation automatically, by the demand controller or through changes in the behaviour of the consumers in response to generation status/tariff indicators by shedding the non-critical load (such as, water heater and washing machine) or voluntary increase and decrease in consumption, is a useful way that gives the consumer a wider view and responsibility to manage their demand.

Chapter 7

Discussion and Conclusion

7.1 Introduction

As mentioned in the introduction Stand-alone power systems, for remote areas power supply, are described as independent power networks with generation and load that is not connected to the public electricity network because, as such connections for small demands with long transmission or distribution lines would be prohibitively expensive. The ever increasing nature of oil prices, and limited resources necessitate creative ways of utilising renewable energy sources in electricity generation especially in remote areas and particularly in countries or regions depending on imported energy. While increasing energy security and reducing cost of such isolated off-grid systems, is becoming an urgently needed necessity for the effective strategic planning of Energy Systems. Therefore, ideally in such remote areas IHPS should contain dispatchable and non-dispatchable generators and energy storage elements with appropriate control systems. IHPS can thus take advantage of the complementary nature in profile of the renewable energy sources and ensure continuous and reliable power production.

Designing stable, flexible, and reliable IHPS for such remote areas was undertaken in this thesis in a trial to overcome the aforementioned issues. This was carried out by simulations in HOMER and Simulink, techno–economic assessments, and surveys to increase the robustness of the system. The unique IHPS design devised in this thesis can also be operated as a smart µG. Therefore with this purpose in mind and as explained in the aims and objectives section, the purpose of the study was to design and implement an Iterative Analytical Design Framework (IADF) for the optimal "Off-grid renewable energy based hybrid smart micro-grid (OGREH-SμG) with

1. intra and inter-grid (μG2μG & μG2G) synchronization capabilities and a
2. novel storage technique with an
3. Appropriate Energy and demand management scheme".

The flow chart (Figure 7.1) below summarises the order of analysing the IADF results in order to explain the strategy utilized to evaluate the OGREH-SμG. The methods used and the results obtained will be discussed in the following order:

- Comparison in different ways to find the optimal sizes and mixtures of the system component using HOMER and LCF-analysis (LCF) (section 7.2).
- Comparisons of the results of technical analysis and dynamic behaviour (voltage, current, and frequency) using HOMER and Matlab/Simulink with power calculation and manual verification (section 7.3).
- Comparisons between the economic feasibility using HOMER and economical calculation manual verification (section 7.4).
- Analysis of the "proof of concept investigations for H_2O_2, FC, and electrolyser" and its impact on the novel storage system (section 7.5).
- Interpretative analysis of the load management strategy and complementary adaptive tariff (section 7.6) through:
  - Acceptance of the concept by the end-user (using a survey questionnaire).
  - Implementation of the concept (using Raspberry Pi).
  - Testing OGREH-SμG with load management strategy and complementary adaptive tariff (using HOMER).
- Analysis of the intelligent supervisory switching controller as a central controller for OGREH-SμG (using Raspberry Pi) (section 7.7).
- Analysis of the μ-grids synchronization strategy (section 7.8).

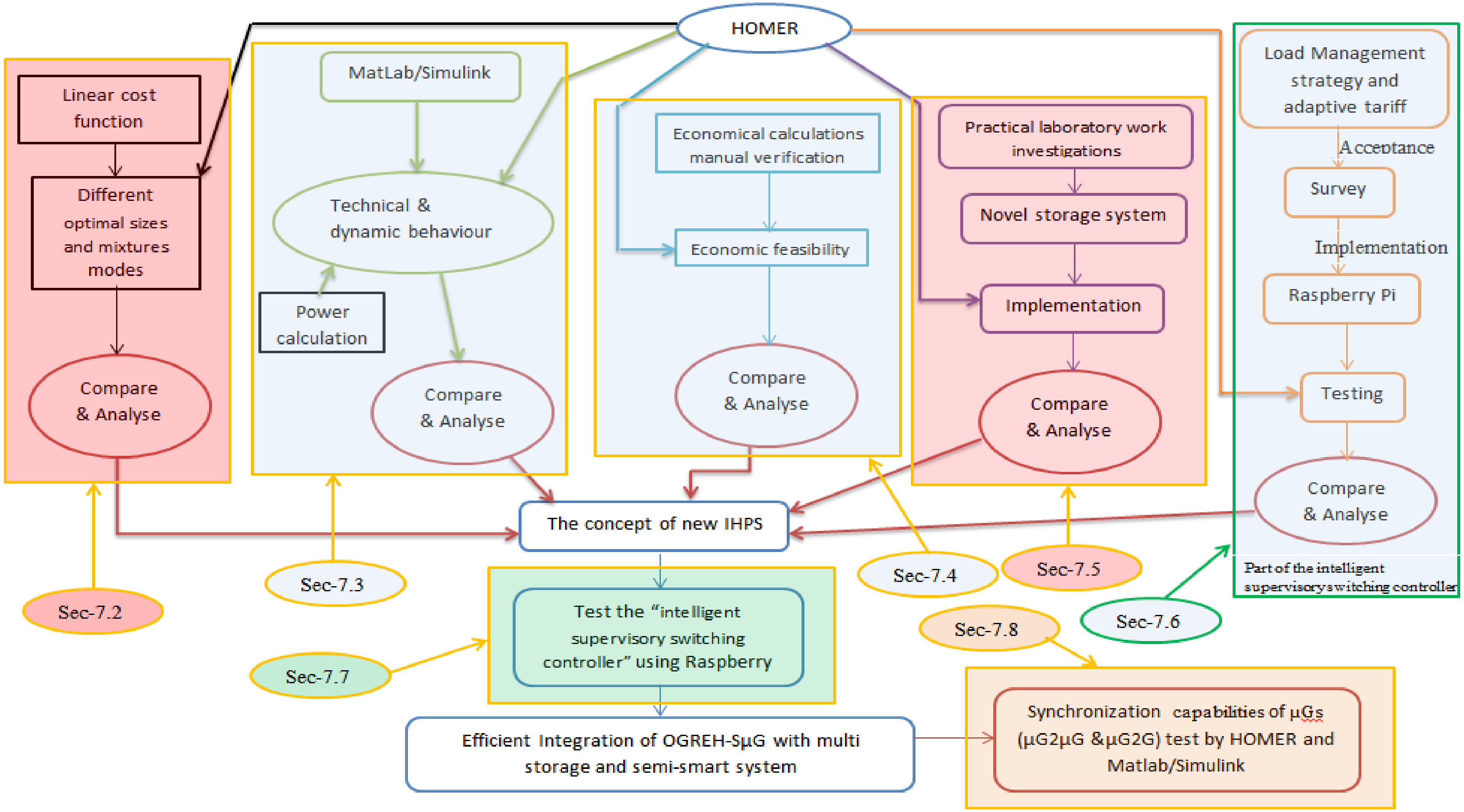

Figure 7.1: The OGREH-SμG design using IADF

7.2 Comparison of different sizes and mixtures of the IHPS configurations between HOMER and LCF

HOMER simulations demonstrated that many IHPS configurations were technically feasible; however some of these configurations were not economically feasible. The IHPS configurations selected from HOMER were subjected to sensitive parameters (explained below) to increase the robustness of the system. This demonstrated inconsiderable differences between the OGREH-SμG and the results from the optimized LCF. HOMER analysis revealed that the optimum system relied on the interplay between the imperative input variables, by probabilistic characterization of sensible scenarios according to the sensitivity parameters[18]. The system evaluation depends also on the techno-economic statement.

Sensitive analysis[18] characterises the IHPS design and it varies among the stakeholders undertaking the project. Each partner aims for IHPS with long-term cost investment funds. Clients (end-users), on the other hand, look for stable, reliable, and dependable power for their electrical equipment. In general, sensitive analysis is applied in order to maximise electrical power flexibility and to handle the difficulties that may arise (such as a calm and cloudy weather and high demand) by simulating the possible solutions in different scenarios. Sensitive analysis excludes impractical combinations by permitting some changes in the critical parameters to arrive at an optimal system. This analysis also selects an optimal system which is able to coexist with different variables, which explains the slight difference between the OGREH-SμG and the optimal LCF i.e. the parameters considered in HOMER simulation

[18] These sensitive analyses are: (i) components prices, (ii) higher and lower than the expected demand load, (iii) solar radiation average input, (iv) wind speed average input, (v) diesel prices and availability, (vi) annual interest rate, (vii) components lifetime.

(sensitive analysis) can change the capacity of the components to suit different parameters in order to increase the system sustainability.

The sensitive analyses parameters were added to repeat the simulation steps carried out in HOMER, which set the major changes in the IHPS design such as change in power reliability (by identifying losses of power at any stage which can lead to generation/ demand imbalance) thus optimizing the system with minimum cost. After adding these parameters the OGREH-SμG represented the cheapest system which was able to survive under the amended parameters, and can be controlled by ensuring the reliability of the operating IHPS with low failure rate (Kolhe et al. 2012, Liu et al. 2011a, Niankun et al. 2011, Carpentiero et al. 2010, Dalton et al. 2009, Dalton et al. 2008, Khan and Iqbal 2005b, Barley and Winn 1996).

Therefore, LCF was appropriate for the iterative evolutionary approach as a quick and effective way of getting an optimal solution that can further be fine-tuned using LP to achieve the optimum design, which is the core idea of our IADF.

According to the optimum solution, the PV generation has minimal input (560 w), which is considered very small compared to the WTG and can be removed. However, the hour to hour simulation shows that in summer days during June, July and August there is power deficit of about 0.5 Kw. This shortage cannot be covered by the primary power (WTG) or the reserve power (batteries and FCs) and the DG is required to operate to supply this deficit. Therefore to keep OGREH-SμG environmentally friendly within accepted levels with minimal GHG; the PV system is added to overcome this small deficit instead of starting the DG. This supports the green energy of the system.

In conclusion, most RESs run under very low operational costs as they do not depend on fuel compared to combustion engines, therefore they require less maintenance. Individual RES are not robust with low reliability and unpredictable resources. Combination of multiple RES together with reserve power may add robustness to the generation and resolve inconsistencies associated with using one RES. Although it is important to have such combinations, proper attention is needed in order to study and analyse the overall dynamic behaviour of the system. The section below outlines these technical issues in the isolated hybrid model and it also includes a comparison between HOMER simulation, Matlab/Simulink, and manual power calculation.

7.3 Dynamic-technical analysis using HOMER and Matlab/Simulink results (verified using manual power calculation)

Applying the concept of OGREH-SμG, via HOMER simulation alongside with Matlab/Simulink simulation demonstrated that PV- wind- H_2- H_2O_2- DG- batteries IHPS was the optimal model for the studied remote area (Bayir). Comparatively, the other IHPS configurations showed major changes during operation which was only appropriate during the morning and after midnight times. However, PV and WTG combinations were included in the system to meet the required loads as demonstrated in a previous work (Kirk 2004).

Technically, a mixed DC/AC-bus was selected to OGREH-SμG as a cheaper choice due to the phenomena of the physical situation:

- The demand is AC power,
- The PV and storage systems are DC-power.

The dynamic evaluation of OGREH-SμG energetic potential as a whole and individually showed sustainability in synchronization in addition to organized load sharing as the voltage and frequency levels were well regulated (Chapter 6). However, the reactive power and electrical harmonics were slightly elevated due to the use of AC-DC inverters and DC-AC converters. Mtshali (2011) reported that one of the disadvantages of implementing IHPS is the harmonics, which added complexity to the system and at the same time increased the power cost. The representative load in Simulink simulation was between maximum and average load (7.5 -15 kW). However, any increase in the load demand more than the maximum load may have an influence on the OGREH-SμG voltage level leading to increase in the current flow which causes inefficient IHPS. This can be addressed by performing classical algorithm method to design an intelligent dispatch load program (see appendix K). The work of Castaneda et al. (2012) suggested that any type of dispatch technique can manage the load demand and the available power. This dispatch can improve the automated reactive power controller by increasing the proper criteria (such as disconnecting loads to keep the system running). Thus any increase in the load is accompanied by increase in the current flow which affects the voltage level. The dispatch was designed in this thesis by calculating the total demand and the output power from each generation source, whereby if the power generation is not enough, the dispatch function will run.

Momentary fluctuations in renewable resources are best accompanied by fluctuations in voltage and frequency for the system to cope with as there is more available power compared to the required load. Adding multi-storage systems with load management strategy reduces the effect of fluctuation on the system. Storage systems can offset directly the power deficit while the load controller reduces the demand load to accepted levels. The maximum advantage of generating renewable power was met as 19.6% of the generated power was overlapped with the stored power to provide the required demand and support the system.

Both simulations (HOMER and Simulink) demonstrated similar generation efficiencies, with slightly different values. Simulink provided a detailed description of values in the model. Performing sensitive analysis with HOMER simulation added more robustness to the system. On the other hand, Simulink does not support sensitivity analysis therefore these assumptions were added manually. In addition, Simulink does not calculate the capital and running costs.

Power losses (from bi-directional converter, battery, and the other components) were calculated by measuring the electromotive force i.e. the potential difference between two ends; terminal voltage and resting stage) as demonstrated by the work of (Hyman 1986a, Hyman 1986b). The 15 kWh DG was selected to cover the maximum load and to handle the associated difficulties (no generation from RES and the reserve system is totally discharged) and HOMER calculated the DG running cost depending on the entered fuel curves (as fuel consumption is related to the load level).

One of the primary aims of this thesis was to reduce the dependency on diesel fuels by using indigenous renewable energy sources was achieved, as the power generation combination was satisfactory with the annual demand (Figures 6.1 and 6.52). Although the requirement for DG was drastically reduced, it was necessary during April and May (low wind speeds), October, November and December (high energy demand). Using RES with DG without using other storage systems reduced the fuel consumption by 45%, mainly with loads under 50% of the DG rated power. And with using storage systems (batteries and FCs) reduced the fuel consumption to 3.8%.

According to Jabian and Estoperez (2012), the system frequency, voltage and power generation are the most important parameters to set the technical feasibility for any IHPS. PV is a promising renewable energy for this remote area as it generated 995 kWh of electricity per year due to uniform sun radiation profile. Wind turbines generated 65,272 kWh of electricity per year which can efficiently provide power to the total load of 55,480 kWh per year with a reserve power of 10,787 kWh per year. The system frequency was approximately 50 Hertz with slight fluctuations where the power generation was higher than the load demand. However, it is reported that when the demand is greater than the power generation, the frequency is affected (Jabian and Estoperez, 2012). Figures (6.31 and 6.40) show that voltage and current have little vacillations at the time of exchange (in the AC-bus before the rectifier), then settle down directly after exchanging.

The total electrical energy supplied by the reserve power was 16,976 kWh per year, operating for 6565 hours of H_2O_2-FC with 927 numbers of starts, 239 operating hours of H_2-FC with 239 numbers of starts, and 417 kWh from batteries (as explained in sections 6.2.14, 6.2.1.5, and 6.2.1.7). This demonstrated a positive relationship between the production rate of both H_2 and H_2O_2 on the surplus power. However, for 732 hours the reserve power was unable to ensure the total deficit energy demand because the demands exceeded the available power from the generators and reserve systems. This was only assumed when there is insufficient stored power in batteries and insufficient stored hydrogen and hydrogen peroxide in the storage tanks to feed both FCs. The total power shortage after using the total reserve power was 3304 kWh per year before utilising the load management strategy and complementary adaptive tariff, and by implementing this strategy the shortage was 284 kWh per year. However, on some occasions, when the generators and reserve power were not enough to supply the system, the standby generator (DG) was required to operate to cover the power shortage. Using the new load management strategy and adaptive tariff reduced the standby generator working hours from (732 hour per year with 389 numbers of starts) to (50 hour per year with 39 numbers of starts). This is considered a significant reduction in the running cost mainly by reducing the operating hours for the DG. This was demonstrated in the work of Lee et al. (2012) as batteries can provide power for short term while DG provides power for long term in the case of power deficit. Fabbri et al. (2010) used FC and batteries to increase the sustainability of a stand-alone power system as they compensated the power deficit during the year. However, hydrogen was used in the aforementioned study as a medium term storage system for the primary RES and the batteries were used for the same purpose with high efficiency.

The power losses incurred here during the operation were minimal as follows:

1. Losses from batteries during charging (high SoC) and discharging (high current) in the form of heat power due to the chemical reaction (approx. 215kWh per year.)
2. Losses from the inverter were approximately 355kWh per year with the losses in electrolyser being approximately 566kWh per year.
3. Heat loss in the form of thermal energy associated with power generation by the hydrogen fuel cells was about 989kWh per year.

4. Other losses were in distribution cables, which were estimated to be 466kWh per year.

Therefore, the total energy lost during the operation of the OGREH-SμG was estimated to be 2,591 KWh per year. This demonstrates low losses in the performance ratio compared with the total power. Such losses are considered mainly technical (Van Voorden et al. 2005).

To characterize the power generation performance ratio; a theoretical approach of operating the PV and WTG with the maximum power was applied (as explained in sections 6.2.1.1 and 6.2.1.2). Sections (6.3.1 and 6.3.2) show that both generations provided power which was stable in the case of PV but fluctuating with steady frequency in the case of WTG. The difference between the theoretical power and the manually calculated power was defined according to the test condition (the size of the renewable energy generators and the demand) i.e. the theoretical approach used variable test conditions in both simulations (HOMER and Simulink), while for technical calculation manual verification only one test condition was used. This study showed that the optimal sizing of storage in the state of charge (SoC) was 97.8% between October and March, which was reduced to 94.6% due to low wind speed between April and September.

Technical calculations manual verifications were used because:

- Calculating the batteries capacity is important to verify the LCF results, and to implement the size in HOMER and Simulink Simulations.
- Calculating the number of solar cell series in each panel, and the number of PV panels and parallel panels according to the PV size from HOMER simulation is important to present the results in Simulink PV modelling.

- Calculating the wind power density is important to verify that the air power density is able to move the blades of the chosen wind turbine, with air power density of 25.16kW and the size of the chosen WTG is two set of 10kW.
- Calculating the produced H_2 from the electrolyser is important to model the flow rate function and to implement this in Simulink Simulations.
- Calculating the required H_2 to generate power is important to model the fuel rate function and to implement this in Simulink simulations as an input for the H_2-FC.
- Calculating the required H_2O_2 to generate power is important to model the fuel rate function and to implement this in Simulink simulations as an input for the H_2O_2-FC.
- Calculating the diesel fuel consumption is important to verify HOMER simulation which showed slightly different results (1704 L per year) compared to the manual power calculation (1733.925 L per year) This deference may be explained by the fact that the manual power calculation divided the operating hours in half between summer and winter.

In summary, both Simulations (HOMER and Simulink) showed that perturbations in voltage, frequency and power generation capacity, in the case of climate variations, resulted in fluctuations in power generation. However, the dynamic behaviour of the OGREH-SμG energetic potential was sustainable in synchronising and load sharing between generation sources. It is actually important to analyse the economic feasibility of the system by studying the disbursements such as the life cycle cost, payback and cash flow on a yearly basis which are used to find real values for incomes and expenses of OGREH-SμG. This includes a comparison between the results of economic analysis, as obtained from HOMER simulation, with the results from the manual economical calculations (section 7.4).

7.4 Economic feasibility using HOMER and manual calculations

This section will portray the economic analysis of OGREH-SµG compared to other configurations and the existing diesel IPS. Although the technical and dynamic analyses were beneficial to assess OGREH-SµG, the economic advantages of the system should be highlighted. The socio-economic and environmental improvements induced by providing electrical service for the remote area (Bayir) can be achieved by implementing HPS.

The initial cost (capital cost) according to HOMER analysis and manual calculations was similar considering that the initial cost was inserted into HOMER as input data (see appendix A). These are the costs incurred over buying the system components, construction and installation of distribution lines and AC-DC-bus systems. A similar economic approach was demonstrated in previous work (Manwell et al. 1998, Yaron et al. 1994).

Running costs are the costs incurred after implementing the system including the operating, maintenance and fuel costs. The manual calculations showed slightly higher running costs compared to those calculated by HOMER (section 6.2.2). This might be explained by the fact that HOMER does not consider fuel price growth, while this growth can be calculated using the manual calculation as in the work of Manwell et al. (1998) and Yaron et al. (1994).

With regard to replacement costs, the manual calculation showed higher values than those obtained from HOMER results (section 6.2.2). This is because HOMER calculates the actual working hours whereas the manual calculation considers the manufacture life-time (Manwell et al. 1998).

The difference in cash flow between HOMER analysis and the manual cash flow (Tables 6.6 and 6.7) was -£7,903 which can be explained by the difference in running and replacement costs as described above.

Life cycle cost (Figure 6.29) showed that OGREH-SµG was cheaper than the existing diesel IPS after 14 years and the payback system (section 6.2.2) was after 24 years. Although the initial cost of the diesel IPS was much cheaper than OGREH-SµG, the running cost of the former system was dramatically high; such findings were also demonstrated by others' work (Liu et al. 2011a, Markvart, 2000, Hybrid Sizing and Economic Comparison Workbook 1998-1999, Manwell et al. 1998). Ani (2013) reported that batteries are the most costly equipment for the HPS lifetime, and the cost of any HPS can be reduced by reducing the size of batteries. In OGREH-SµG system the optimization was conducted by modifying the minimum size of batteries using a storage system which was dependent on other types of storage (H_2 and H_2O_2).

The environmental evaluation showed that implementing OGREH-SµG can benefit the environmental energy quality by reducing working hours of the DG as compared to the existing system (sections 6.2.1.6 and 6.7). Furthermore, the OGREH-SµG has less environmental impacts, of which most during manufacturing and decommissioning, and sometimes during operation of standby generator. This is in agreement with the work of Dalton et al. (2008) and Mellit et al. (2008) as they reported that RESs showed less emission of GHG. Comparing the generated electrical power from DG and the OGREH-SµG demonstrated that OGREH-SµG produces less air pollution due to the implementation of electrical efficiency measurements (appendix C).

With regard to social benefits, HPS permitted the end-users in remote areas to utilize electrical equipment with a better quality of life. This may be similar to the situation where the end-users procure the electrical power from the public grid. Furthermore, there was significant fuel saving as most of the power was produced from sun and wind turbine, which are free and boundless.

The OGREH-SµG showed appropriate economic feasibility due to the low running cost which may be explained by the dramatic reduction in DG operation time to 50 hours per year. However, considering the economic, social and environmental aspects without calculating the heat losses; the DG generated 55,480 kWh per year for the case study area (Bayir). Testing the devised optimized system (OGREH-SµG), coupled with an intelligent supervisory switching controller was significantly cost-efficient as the DG generated only 284 kWh per year. This is in agreement with a previous work that reported adding RES to DG can reduce fuel consumption for better cost-effectiveness (Whei-Min et al. 2011, Beccali et al. 2008).

The cost–benefit analysis and life cycle cost show high payback which is considered a financial limitation. However, to overcome this novel intelligent switching controller and the synchronizing capability presented in this thesis add an economical effect to the system as mentioned in Appendix N. It shows that by calculating the cash flow of the five systems (µ-grids) and then dividing the total cost by individual systems the payback of each system becomes 9 years (Appendix N, Table N.4) as the storage and the standby generations are shared between the µ-grids. Appendix N shows the cash flow before and after adding the modification to the µG.

The previous two sections presented the techno–economic assessment for unique IHPS for remote areas. However, implementing OGREH-SμG was carried out by three storage systems, one of which was a novel hybrid storage system. It was therefore important to analyse the effect of the new storage system on the HPS. The section below outlines the practical laboratory work for investigating H_2O_2, FC, and Electrolyser to study the possibility to recover the heat wasted from the process, in addition to evaluating the long-term stability to store H_2O_2.

7.5 Analysis and impact of the practical laboratory work investigations on the novel storage system

The practical laboratory work was divided into three experiments:

1. The first experiment was carried out to study the possibility to recover the heat wasted from using the electrolyser. The results showed that such heat cannot be used in a favourable way (Figure 6.44) as hydrogen production decreased under reduced temperature. This is supported by the work of Saur (2008) who reported very low levels of the useful heat emitted from electrolyser.
2. The second experiment was carried out to study the possibility to recover the heat wasted from using the FC. The findings demonstrated that this heat can be useful (Figure 6.47) as the output power was steady although there was reduction in temperature. The operating temperature of the tested FC was 45°C and the electric output was steady or slightly reduced when the temperature was gradually reduced to 15°C, this difference in temperatures can be used to increase the concentration of H_2O_2. In addition to that, the FC

was able to provide electrical power combined with heat energy, with better cost-effectiveness. The work of Berndt (2004) demonstrated significant capital saving using the heat produced from the FC during operation; such as feeding and utilizing hot water tank instead of wasting the heat. In the same context, Bompard et al. (2008) and Saur (2008) reported that the heat emitted form FC can be used to supply the thermal load, or can be used in cogeneration application respectively, which increased the FC efficiency.

3. The third experiment was carried out to study the benefits of long term storage of H_2O_2 on its concentration. The results showed that H_2O_2 concentration was slightly decreased and that five months storage was efficient.

In general, hydrogen and H_2O_2 are not considered as essential sources of power and better described as secondary sources. Hydrogen and H_2O_2 require energy for production. In OGREH-SµG, H_2 and H_2O_2 were considered as medium and long term storage, respectively. Energy is stored in the chemical form, and both of hydrogen and H_2O_2 can be later utilized to generate power when required.

The OGREH-SµG was sustainable during the peak periods (afternoon and evening) and the sustainability was increased after implementing short, medium and long term storage systems. Moreover, increased evening demand loads caused a short period of DG operation (due to the mismatch in generation demand). The work of Khan and Iqbal (2005b) and Chedid and Rahman (1997) supported that any IHPS with optimal storage systems and enough capacity can reduce the initial cost of the system, and maintain the probability of supplying electrical power at any time.

In conclusion, OGREH-SμG contained three different types of storage which reduced the power cost (as the most appropriate economic solution was compared with other systems containing fewer storage types) by reducing or replacing the use of fossil fuel, as proposed by Bajpai et al. (2010). Such variations in storage systems added robustness to OGREH-SμG components by increasing the availability, reliability, and sustainability (Ma and Lu 2011, Abbey and Joos 2007, Denholm 2006, Van der Linden 2006, Bullough et al. 2004, Zhou et al. 2004).

The new type of storage 'H_2O_2' (long term storage) increased the reliability of the system because of the unlimited amount of storage for use in cases of power deficit. Bastien and Handler (2006) and Berndt (2004) concluded that H_2 is environmental-friendly and is expected to have a huge role in future economy. Accordingly, the novel storage system used in this study was the hydrogen peroxide (H_2O_2) produced by the AQ process. H_2O_2 might be the future energy storage as no safety measures are required at low concentration levels compared to hydrogen. It could be treated similar to water as it can be stored in low concentration for safety.

The hybrid power system in our design included wind and sun powered generation, complemented with batteries, DG, and two sets of fuel cell unit (H_2 and H_2O_2). The design and simulation of a new storage technology incorporating H_2O_2 fuel cell increased the FC efficiency from 35% to 65%. Moreover, the system required a smart energy management framework to schedule all generation power (RESs, storage, and DG) and load sharing. The next two sections present an intelligent supervisory switching controller system (central controller and load management control strategy with complementary adaptive tariff).

7.6 Interpretative analysis of the demand management strategy and complementary adaptive tariff

Applying the load management strategy and complementary adaptive tariff (using Raspberry Pi in each house) was presented in section 6.7. The load management strategy was used to reduce unnecessary load at peak demand periods or during supply power deficit. This guaranteed the system flexibility and increased its reliability along with cheaper prices for the end-user. Bayir's daily demand load is unsteady and by using this method for reducing actual demand load, significant improvement in the operating hours of DG and its characteristics such as reduction in the number of starts was achieved.

Rodolfo and Jose (2005) and Barley and Winn (1996) recommend having control strategies for the HPS according to the considered parameters and system configuration. Both studies used a dispatch strategy designed by genetic algorithms, Rodolfo and Jose (2005) designed a classical method[19] based on the available power in the worst conditions, while Barley and Winn (1996) presented the "Ideal Predictive Dispatch Strategy" based on assumed perfect prediction of load and wind speed. Tofighi and Kalantar (2011) presented an algorithm power management system to control the power flow between PV, batteries and demand which supports the demand management strategy as part of the intelligent supervisory switching controller used in this thesis.

The main aim was to reduce or replace dependency on diesel fuel. Dramatic reduction in DG operation hours was demonstrated after using the load management

[19] Classical method depends on three steps (load following strategy, cycle charging strategy, and combined strategy).

strategy to shift the load from on-peak to off-peak periods (sections 7.3, 7.4). This was the most economical way to run the DG as it works mostly in full load rather than half rated power, which decreased the running cost (as shown in HOMER simulation). The reduction in operation cost was expected as the DG is used to charge the batteries and in some occasions to electrolyze water (in case of power excess). After using the load management strategy, DG is switched-off to satisfy the required load with the available power from the main power source and storage. This approach showed the ability to provide the cheapest available power.

7.6.1 Load management strategy and complementary adaptive tariff acceptance (using survey)

Fluctuation in power generation and demand load causes many difficulties to control the system in cases of generation power decrease and demand load increase. In these modes, the power sharing dynamics shift to unstable regions especially if the reserve power cannot compensate the power deficit. This leads to more oscillation in the system which leads eventually to operate the DG. Controlling the load by load dispatch according to the available power will shed non-critical loads.

The results of the survey showed that 70.3% of the technicians thought that implementing this strategy can reduce and control the power flow during power deficit periods, and these strategies should be encouraged by utilities as it increases the system sustainability. The advantages of implementing this strategy (intelligent load management controller) include; increased robustness of the system with quicker dynamic response, cost-effectiveness which might guide the utilities to use this strategy in other places or in the national grid. The capabilities of this strategy emerge in power deficit situations, as its performance is improved (Tofighi and

Kalantar 2011) compared to old types of techniques (power controller). Such techniques reported increasing the capacity of the primary sources and using dump load in the case of extra power, and switching-off the dump load in power deficit cases (Senjyu et al. 2005).

7.6.2 Load management strategy with complementary adaptive tariff implementation (using raspberry Pi)

Raspberry Pi was used in order to evaluate the implementation of the management strategy and adaptive tariff (section 6.8.1 and Figure 6.54). Using Raspberry Pi for one day detected a difference between the available power and demand loads allowing the end-user to use the electrical power in a low rate tariff in the case of surplus power (green LED light). In case the available power was not different from the demand load no indications were given to the end user (both green and red LEDs turned-off) so the power was used in a normal rate tariff. However, in power deficit cases, Raspberry Pi alarmed the end-user to reduce the load which is within the high rate tariff (by switching-on the red LED) indicating that the demand load is still high where the non-critical panel is shed by the controller between 18:00- 21:00 pm. In conclusion, the load management strategy with complementary adaptive tariff was satisfactory under the given conditions, with the available practical data, and can be applied to OGREH-SµG.

7.6.3 Testing the load management strategy with complementary adaptive tariff (using HOMER)

Load management strategy and complementary adaptive tariff demonstrated the ability of the different strategies managing the HPS to provide more efficient power, and significantly reduce the running cost (by reducing the DG operating hours).

Moreover, the number of starts was reduced to 39 per year based on the inefficient power of DG to start-up. This approach allows the evaluation of non-critical load (deferrable load) to reduce the operational cost and provide sustainability to the OGREH-SµG. HOMER simulation showed that even with unpredictable generation and load, there was a possibility to reduce the running cost and provide continuous stable power based on the ability to shed non-critical load. The power prices provided from this system were substantially lower than those from the DG as demonstrated in section 6.7.

The results of the proposed OGREH-SµG were demonstrated in both cases (before and after applying the demand management strategy). After using this strategy to shed the non-critical panel, the system showed low overshoot, long settling time and reduced running cost (reduced dependence on DG) compared to the results before using the strategy. Moreover, the findings demonstrated the robustness of the proposed demand management strategy during worse scenarios. This novel strategy required an intelligent supervisory switching controller system that control, manage and organize the generations and load sharing. The section below presents an intelligent supervisory switching controller and details briefly but comprehensively the design and simulations performed.

7.7 Analysis of OGREH-SµG central controller (using Raspberry Pi)

In order to maximize power production from the available sources, IHPSs require an adapted control strategy to organize load sharing between sources. Raspberry Pi is based on a measuring protocol to organize communication between generators, reserve and standby power components. The priority of order of these sources is given based on the management strategy as any power system requires a controller to manage the load sharing between generation (Croci et al. 2012, Pourmousavi et al. 2010, Van Voorden et al. 2005). The advantage of using a central controller include managing variable sources (multi, primary and secondary sources) by calibrating and fixing the available power provided from each component, in order to share these loads between the sources after assessing the status of components (Tofighi and Kalantar, 2011). However, Van Voorden et al. (2005) added that an uncontrolled system leads to shortened component lifespan, mainly batteries.

The Raspberry Pi is easy to implement by minimizing the control complexity i.e. using direct measurements to achieve faster response and reduce system losses. In the first phase (PV panel operates to track the sun), the controller showed a good response time to track sun radiation in order to maximize the solar panel output power. In the second phase (implementing an intelligent supervisory switching controller for the OGREH-SμG), the controller showed the ability to shed non-critical loads, controlling the power flow between the sources with successful balance in generation and consumption. Accordingly, the aim was achieved by; reducing the operating hours of DG to the minimum with optimum performance of the OGREH-SμG, joining the storage power or shedding non-critical load. The available power levels of the OGREH-SμG were able to cover the required load with and without the load management strategy as tested under different conditions.

The controller has many assumptions which were implemented here in order to provide a wide range of OGREH-SμG management and control scenarios, these assumptions are presented below:

- The generated power is enough to supply the load

- The controller has enough measurements for the amount of stored power and the time required to be exhausted
- The controller decides how and when to deal with the excess power by charging batteries or electrolyzing water
- When the HPS requires the storage power, the controller decides the load sharing between the generation and stored power
- The controller decides the tariff rates according to the available power
- The controller controls the load management strategy in order to shed non-critical loads
- The controller is designed to deal with different issues that can arise in order to keep HPS operation steady even in abnormal conditions
- The controller manages the load at steady state and reduces load fluctuations
- The controller decides when to operate the DG and what to do with the excess power.

The single board computer (Raspberry Pi) was used as supervisory switching controller for smooth power flow between generation and demand in OGREH-SµG. This novel control strategy also included a synchronization capability that facilitates µG2µG & µG2G connection. The section below details briefly but comprehensively the design and simulations performed of synchronization capability.

7.8 Analysis of µ-grids synchronisation strategy

The concept of a smart-µG (fully automated) independent system which can utilize indigenous renewable energy sources with a capability to synchronize with the µG or between each other sources was used here.

The technology of "synchronizing relays" increases power capability by utilizing digital microprocessors automatically without human involvement. Some characteristics must be met such as line voltage, frequency and phase angle, in addition to assessing the voltage sequence during first usage. These parameters are required for smooth synchronization (Mazloomzadeh et al. 2012).

μ-grids synchronization strategy demonstrated ability to chase the available power between the μ-grids. Redundancies in the power from different μ-girds are considered an advantage because it can cover power deficit in other μ-grids to maintain acceptable power levels. Moreover, the controller in each system manages the available power according to the required load, and decides if the system should export or import the electrical power in cases of excess or power deficit. Synchronization of μ-grids showed the ability to control the system parameters to achieve reliable power (Mazloomzadeh et al. 2012). Moreover, the robustness of the system is increased due to the availability of three form of reserve power within each system (batteries, H_2-FC, and H_2O_2-FC), and a load management strategy to reduce the load and including two forms of standby power (available from the nearest μG, DG). This enhances the power quality and cost-efficiency as most of the generated power is used. μ-grids synchronization might be the future of national grids, as it provides a solution for the problems of centralized generation, and an inevitable solution especially in decentralized generation.

In cases where the generating source supplied the demand, the voltage and frequency was determined by the droop curve. On the other hand, when multiple generators served the same load, the generators were dispatched to avoid reactive power flow between generations to share the load according to their droop curve. In this design, the generations were inter-connected in the system and equipped to modify individual generation settings. The main achievements from µ-grids synchronization strategy are as follows;

- Reduction in the power cost (due to reduction in DG operating hours)
- Enhancement of the reliability of off-grid system as there are multi reserve and standby power systems
- Featuring higher robustness of the system due to the high flexibility and reliability
- Sharing the available power between µ-grids to properly manage and control the power flow
- Synchronization might be an appropriate option for the future national grid configuration/ distributed generation.

7.9 Main research findings

IPS 100% RES system requires huge capacity of storage system which is extremely costly. Hybridising these systems to provide continuous and reliable power requires some modifications such as storage and/or synchronisation with conventional generators or with the national grid. Synchronising these systems with conventional generation such as DG will increase the reliability and reduce the cost of the system. In this thesis, OGREH-SµG was considered as an alternative power supply for rural areas. DG in OGREH-SµG was used as a standby power generation, and was hardly operated due to the high efficiency of the system. The system was subjected to a number of factors which are presented with the outcomes below:

- Techno-economic assessment to devise and implement IADF. The choice between the available IHPSs and the existing system was subjected to dynamic and economic analysis in HOMER and MatLab/Simulink to design a unique OGREH-SµG that can generate sustainable power with minimum impact on the environment (reduction in GHG by utilising indigenous RES and a novel storage approach (H_2O_2-FC)).
- The appropriate type of OGREH-SµG is biogeographically-based and subject to the availability of resources. Using the devised IADF to design OGREH-SµG demonstrated that flexible IPHS platforms using non-dispatchable and dispatchable generation can be cost effective compared with fossil fuel based centralised power systems (using only fossil based fuels).
- The findings highlighted the importance of sensitive analysis to detect the effect of any change in the system performance. Including the amended parameters in the OGREH-SµG influenced the designer decision to choose the appropriate IHPS which can operate under these parameters by ensuring reliability with very low failure rates. The chosen OGREH-SµG system was compatible with different variables according to the sensitive analysis and this explains the slight difference between the chosen system and the mathematical calculation as in LCF analysis, based on the available data – for the case study (Bayir /Jordan).
- The design of OGREH-SµG contained three different types of storage (reserve power); batteries, H_2-FC and H_2O_2-FC. Moreover, H_2O_2 was a simple, uncomplicated and safe technology that can be stored providing cheap rate power compared to other technologies, and it was considered as a long-term storage as validated by practical experiment.

- The system has the ability to synchronize with other µ-grids with the following advantages;
    1. Reduction in cost
    2. Increasing the robustness of the power availability, where µG with power deficit can import available power from the nearest µG. On the other hand, µG can store the extra power in another µG, and both ways can lead to properly controlling and managing power flow
    3. It is an appropriate option for future national grid configuration.
- Load management strategy and complementary adaptive tariff were evaluated by adding non-critical load to HOMER simulation to control and schedule random fluctuation in demands to meet generation. The demand-generation control strategy tentative explanation derived to be accepted by the end-user and utility, as the survey demonstrated satisfactory results. A comprehensive review of load management strategy with complementary adaptive tariff is implemented through programing Raspberry Pi in order to allow the end-users to control the electrical bills by using indication lights. This is considered a fast and safe communication method between the end-user and the supply unit.

The designed OGREH-SµG is a complicated system comprised of multiple technologies. However, this combination can estimate the performance of all the components smoothly to meet demands under different conditions such as varying wind speed and random sun radiation. These types of generation limit the natural fluctuations to ensure stable and reliable power supply compared to conventional generation.

7.10 Recommended criteria to implement IADF for OGREH-SμG

This research utilises wind and solar energies as the primary sources for power generation. The modified technologies used here are summarized as follows:

- Modification of electrical storage system by increasing its capacity. This has improved the financial feasibility and reliability of the power system. There are no straightforward technologies for storing electrical power as it can be stored in different forms and then converted back to electrical power when required. Most IHPSs use batteries which are efficient but costly and/or FC which have long lifetime but are not efficient. OGREH-SμG includes a novel power storage system in the form of hydrogen peroxide (H_2O_2) which can increase the efficiency of the FC to 65%.The findings suggested that the three types of storage; short, medium, and long term are necessary to meet the required load for continuous power supply in Bayir.
- Modification of the controller by introducing a novel intelligent supervisory switching controller which is a central controller with load management strategy along with complementary adaptive tariff. The importance of implementing a smart control strategy can be summarised as follow; first the controller organizes load sharing between the sources with successful balance, and stores the excess power. Second, the controller shares the reserve power to cover shortage, as overseeing and monitoring the stream of power is fundamental to guarantee the sustainability of power supply. Third, the controller sheds the non-critical load to control load fluctuation to match power generation in power deficit cases. All together this helps to reduce the operating hours of DG unless there is an urgent need for the standby power. Finally, the benefits of voluntary demand

management, using green and red LED, can influence consumer consumption behaviour. Voluntary management can lead to harmony between the economic feasibility and end-users allowing them to control their electrical bill.

- Synchronizing the IHPS with conventional generation or national grid has provided sustainability and reliability to the system. Adding RES to conventional generation will significant reduce the life cycle cost compared to conventional generation alone. In Bayir remote area, it is impossible to connect its distribution network with the national grid due to the high cost of electrical power transmission lines. The findings of this thesis highlighted the importance of synchronizing µG with DG. To expand the findings of this thesis, the novel control strategy includes synchronization capability that facilitates power flow among µ-grids. µ-grids synchronisation provides redundant power which can cover power deficit in IHPS to maintain the available power at acceptable levels.

This research demonstrated the potential of OGREH-SµG to increase the penetration of hybrid systems in local and global energy markets. HOMER and MatLab/Simulink simulations are used to simulate the available RESs (as Jordan is privileged with many natural resources). The results from both simulations showed that an optimal system design can meet all demands by maintaining the prescribed values of frequency and voltage with reduced cost.

7.11 Conclusions

The purpose of this thesis was to design and implement an IADF for the optimal "OGREH-SµG with intra and inter-grid (µG2µG & µG2G) synchronization capabilities and a novel storage technique". In addition synchronisation capabilities, microcontroller based smart controllers along with a complementary adaptive tariff design were applied to increase the resilience of the µG's operational sustainability and reliability.

The results and the discussions we have shown that the aim of this research project to design and implement an Iterative Analytical Design Framework (IADF) for the optimal "Off-grid renewable energy based hybrid smart micro-grid (OGREH-SµG) with, synchronization capabilities, an appropriate storage technique as well as an Energy and demand management scheme" was achieved. In this approach the µ-grids, isolated from the national grid, have the capability of being operated as smart µ-grids with multi-mode synchronization capabilities. The major features of the design evaluated as a case study for the implementation of the IADF are summarized as follows:

- The designed system was PV-WT-Battery-H_2FC-H_2O_2FC-DG OGREH-SµG; where OGREH-SµG is a µG based on hybridization of different types of generation and storage, which is stable and cost-efficient. One of the primary outcomes of this feature was to reduce the dependency on diesel fuels by using indigenous RES.
- The OGREH-SµG system demonstrates high quality service (availability, sustainability and reliability) of the power supply to the end user. The different combinations of generation and storage increase the robustness during different operating conditions; the robustness can further be increased with implementing (µG2µG) synchronization capabilities.
- Implementation of this design for the case study demonstrated that the IADF is an effective design framework for optimum IHS (Renewable Energy

Hybrids) in general. OGREH-SµG design also demonstrated financial feasibility to meet the required electrical demand for Bayir. Mixing RESs with a conventional genset has assured it will be cost-effective with lowest life cycle cost (the life cycle cost shows high capital cost, very low annual cost, and after 14 years is cheaper than the existing diesel IPS) with stable power generation for rural areas. Combination of wind turbine, PV, and storage system in OGREH-SµG showed an effective and successful solution to the reliable off-grid supply issue and also facilitated further backup and load sharing with an embedded DG and ability to synchronise with the grid and or /neighbouring µ-grids.

As demonstrated in our case study Design and simulation results the DG in OGREH-SµG is used as a standby power generation, and it is hardly ever operated, because of the highly efficient performance of the system. OGREH-SµG as reported is considered the optimum alternative to off-grid power supply for electrification of rural areas.

An optimum system choice is subject to a number of evaluations/assessments and decision making steps, which are presented with their outcomes below:

- Techno-economic assessment: this can be implemented by using an IADF. Based on suitable tools, such as HOMER and MatLab/Simulink, to design IHPS that can generate power in a sustainable way and have minimum impact on the environment (reduction in GHG) by utilising indigenous RES and storage.
- Optimum generation mix: The appropriate type of IHPS is geography-based and subject to the availability of resources. Using the devised IADF to design

OGREH-SμG demonstrates that flexible IPHS platforms using non-dispatchable and dispatchable generation can provide cost effective solutions compared with fossil fuel based centralised power systems using only fossil based fuels.

- Sensitivity analysis: The findings highlighted the importance of sensitive analysis to detect the effect of any change in generation mix and operational variables and parameters on the system performance and cost. An iterative analytical framework as reported for the design of the OGREH-SμG in our case study demonstrated an influence on the designer decision to choose the appropriate IHPS which can operate under these parameters by ensuring the reliability of IHPS with very low failure rate. The chosen OGREH-SμG system was compatible with different operational variables according to the sensitive analysis and as demonstrated by the difference between the chosen system and the mathematical calculation as in LCF analysis for – case study remote area Bayir /Jordan.
- Appropriate storage approach: The reported design of OGREH-SμG contained three different types of storage (reserve power); batteries, H_2-FC and H_2O_2-FC. Moreover, H_2O_2 shows simple, uncomplicated, and safe technology can store and provide power cheaply compared to other technologies (storage mechanism), and it can facilitate long-term storage as validated through the practical lab experiments.
- Appropriate standby by reserve approach: Ability to synchronize with standby power (DG) and other μ-grids, this has two advantages;

1. The µG with power deficit can import available power form the nearest µG.
2. In the case of power excess with full storage, µG can store the extra power in another µG.

- Appropriate “intelligent supervisory switching controller” was evaluated by adding two controllers (central controller to schedule generation and Load management strategy and complementary adaptive tariffs): these were evaluated by adding deferrable load (non-critical–load) to HOMER simulation to control and schedule random fluctuation in demands to meet generation. The intelligent supervisory switching controller tentative explanation came to be accepted by the end-user and utility, as the survey demonstrated satisfaction. A comprehensive appraisal of load management strategy and complementary adaptive tariff was implemented by programing Raspberry Pi controller as demand controllers. This was to enable end-users to control demand in the case of generation and demand mismatch by corresponding tariff indication lights. This was considered a simple, fast and effective communication method between the end-user and the central control unit. The intelligent supervisory switching controller framework in OGREH-SµG promotes the energy sustainability in three ways:

1. Balancing between the generations and demand based on reserve power (multi-storage systems) and standby (DG).
2. Integrating the load management strategy with complementary adaptive tariff to control the demand by: fulfilling the critical load and allowing the end-users to control their bill.

3. Synchronizing between µ-grids (the available power from the nearest µG). It is apparent that a properly designed controller is able to receive advanced data which contributes to better sustainability. The implementation of IADF in OGREH-SµG demonstrated high robustness and satisfactory dynamic performance (voltage, current, and frequency). OGREH-SµG demonstrated improvement in operational efficiency and reduction in environmental impacts compared to the existing systems, by keeping the power generation and the demand load closer to each other (using auxiliary power or reducing the load).

The modelling design and simulations were conducted using MatLab/Simulink and HOMER simulation for planning. The simulation was performed by evaluating OGREH-SµG performance using practical loads and climate data for Bayir/ Jordan. Deferrable load was added to the simulation in order to assess the new load management strategy. In addition to technical and dynamic behaviour, economic feasibility was incorporated into this system using three different techniques, Payback, Life cycle cost, and Cash flow in order to optimize the system.

A new storage approach incorporating Hydrogen Peroxide (H_2O_2) fuel cell was designed, lab-tested and simulated. Simulation and experimentation with a single board computer (Raspberry Pi) was devised and programmed for the smart energy management framework to implement a novel control strategy, including intra and inter grid (µG2µG &µG2G) synchronization capabilities. In the thesis, comprehensively detailed design and simulations were presented.

The results and the discussion of the case study of a remote area, Bayir/Jordan, also demonstrate that IADF is an effective framework for designing IHPS/OGREH-SµG for remote areas. The results also demonstrated that appropriate generation and demand management approaches such as the ones have been reported that can be used in micro grids devise an intelligent supervisory switching controller, scheduling and demand management algorithms that can be implemented in a microcontroller.

The investigations demonstrated that the techno-economical analysis using tools such as HOMER and MatLab/Simulink is most effective within an IADF. We have also discussed how the system resilience and robustness can be increased by (μG2μG & μG2G) synchronisation. This study has discussed the results that can be obtained through LP optimised LCF that have been devised and has reported how this fits into the IADF framework facilitating efficient and robust design calculations. The results demonstrate that the IADF framework is enhanced by the efficiency, social and ecological advantages parameters included in the LFC reported. The techno-economic feasibility that can be undertaken by IADF will allow tracking of observed information and enable the performance evaluation of independent HPS. The results demonstrate that economic analysis for different scenarios despite high capital cost gives payback period between 9-14 years and this is comparable with systems reported in the literature. The results demonstrate that a well designed and implemented end-users survey is very effective to inform the adaptive management design. This can be seen in the 70% user satisfaction recorded. This chapter also shows that intelligent supervisory switching controller system, i.e. the central and demand management controllers as devised and reported (through hardware implementation by using microcontroller (Raspberry – PI)) are crucial in the design and operation of OGREH-SμG as it increases the reliability and availability of generation to match the critical demand.

This thesis has discussed the results of the proof of concept studies for H_2O_2 that can be used as future storage mechanism where we have concluded that it an uncomplicated and safe method to store – even for long term storage, through practical laboratory work and simulation.

Thesis Contributions

This thesis has presented the following as the main contribution to knowledge:

- IADF provides a framework for the primary design methodology that can be undertaken to achieve the design aims derived from the requirement analysis;
  - helps the design engineer to outline the system requirements,
  - information that needs to be collected to plan and design IHPS,
  - iterative process with evolutionary modification of models and simulations
- A streamlined energy management system that this thesis has referred to as an "intelligent supervisory switching controller system" was devised and implemented with a Raspberry Pi with two main types of smart controllers;
  - Central Controller which is a supervisory switching controller to schedule all electrical power generation (RESs, storage, and DG) and load sharing, responsible for monitoring the available power through the components controller, and to transmit a signal to the controller to operate and provide power or store power. Also the system operates PV panel to track the sun, and to allow synchronization with another μ-grids.

- Demand Controller for demand management utilising an associated adaptive tariff and automatic switching system as well as informing voluntary changes in the consumption patterns of the end users. The smart control system implements a novel load management strategy and adaptive tariff in order to enhance and optimize IHPS by handling the difficulties that arise.

- Novel storage system utilising a mixture of available renewable energy with:
  - combustion engine (as standby power) and
  - other storage system (with the base of short and long term storage system).
- Monitoring the sustainability of power availability from micro-grids synchronisation with each other.
  - It covers any power deficit in any μG to maintain the available power at accepted levels, by providing power from the nearest μG.
  - It shows ability to control more than power system parameters to enhance more reliable power.
- Formulation of the objective function (LCF) to model the optimal system to:
  - optimize the cost of the IHPS components for the designing OGREH-SμG, and
  - It helps to initialize the setup for HOMER simulations and also to minimize the number of iterations.
  - verify HOMER simulations.

To expand upon the findings of IHPSs, this bespoke system (OGREH-SμG) is designed for Bayir area as a particular task; however, the available resources and sizing approaches vary significantly. There are socio-economic and political issues to devise sustainable systems. Installing reasonable IHPSs or HPSs including technical and economical feasibility should meet the requirements of the end-users, and solve all the raised issues such as the load growth, charging tariff and subsidy settings. The implementation of these systems is also dependent on the institutional quality.

Creative ways of utilising RES to electrify remote areas which depends on imported energy, while increasing energy security and reducing cost of such isolated off-grid systems, is becoming an urgently needed necessity for effective strategic planning. Such an approach that is based on off-grids utilising indigenous RES will increase the reliability and sustainability of the energy infra-structures of the area while reducing the dependence on fossil fuels.

Decentralizing will encourage the usage of RESs, the generation will locate near the demand, and that will open the door widely for utilising micro or mini-grids.

Implementing the OGREH-SμG system in remote areas is important because it:

- Allows access to electricity in off-grid/remote areas
- Improves the robustness and resilience of the power system by increasing
    - Availability (through different modifications)
    - Reliability (through different technologies)and
    - Sustainability (through smart controller)
- Reduces the cost of power by
    - Reducing transmission and distribution losses through distributed configuration of micro grids
    - Displacing/reducing the use of fossil fuels
- Contributes to sustainability of energy systems and reduction in GHG.

- Monitors the sustainability of power availability from µ-grids synchronisation with each other.

For optimum operation, some factors have been addressed in the IADF and implemented in the OGREH-SµG design studies within this framework such as:

1. Using non-critical load (deferrable load) to control the fluctuations in load, mainly in on-peak period by shedding this load.
2. Expanding the controlling system by allowing the end-users to control their bill. An indoor controller allows end-users to facilitate the trade-off power to be used now or later.
3. Increasing the operational efficiency and reducing the environmental impact, by keeping the power generation and the demand load closer to each other (provision of the auxiliary electrical power or reduction of the load).
4. Having multi-types of storage (short, medium, and long term), which improve the sustainability, by adapting the temporary and long term peak-loads.

The satisfactory performance shown by results of the simulations demonstrates high robustness. The OGREH-SµG design incorporated a novel storage system, which increased the efficiency of the FC from 35% to 65%, and a novel smart control framework, which increased the effectiveness of IHPSs. Techno-economic analysis was performed to evaluate the efficiency of the chosen system in electrifying developing countries, having insufficient resources, considering sustainability with minimal impact on environment. Technically, the maximum advantage of generating renewable power was met, as the generated power was overlapped with 19.6% of the stored power to supply the required demand. Testing the load management strategy with the complementary adaptive tariff reduced the starting of DG to 39 times per year. The implementation of this strategy was through a single board computer (Raspberry Pi), which was easy to operate, and reduces power losses in the system.

Future Work

This section provides some possible recommendations for future research work that can enhance the IADF for the OGREH-SµG

- The central controller can be improved further to automatically synchronize µG to µG by monitoring generation and demand balances in the neighbouring µ-grids and coordination between the central controllers for load sharing.
- A load forecasting system can be integrated to the load monitoring system for predictive Energy and storage management, which can be used to handle the uncertainty and the stochastic factors.
- µgrids are typically not green-field – requiring further studies / analysis. Using simulation to validate controls ensures that the objectives will be met and significantly reduces risk (protection), power quality and commissioning time. Technical Feasibility Studies and Design: such a framework will be enhanced by dynamic simulation in addition to traditional transient analysis. This is required for µgrids due to low inertia and intermittent renewables.

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Appendices

Appendices (Appendix A to Appendix N is included in the attached File

The End

"And put they trust in Allah, and enough is Allah as a disposer of affairs."