DESIGN A COMMUNITY-OWNED SMART, STANDALONE HYBRID RENEWABLE ENERGY SYSTEM WITH POWER SHARING OPTION BETWEEN NEIGHBOURS

By

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A thesis submitted in conformity with the requirements for the degree of
Doctor of Philosophy

Victoria University Australia
Institute for Sustainable Industries & Liveable Cities

Abstract

Renewable energy sources are available without restrictions and are environmentally friendly. Due to their availability and topologic advantages, these renewable energy sources are believed as favourable power sources. Hybrid systems use more than two renewable energy sources, enhancing system efficiency and reliability. On the other hand, this system helps reduce the energy storage needs for stand-alone applications. With the advancements in renewable energy technologies, hybrid systems are becoming increasingly popular in isolated area power generation applications. Hybrid Renewable Energy Systems (HRES), including solar and wind energy, are an environmentally friendly, economical alternative for catering to the power needs of rural areas compared to traditional sources. However, these systems have certain drawbacks, as they are less reliable, and the power produced depends on climatic conditions. Proper sizing, battery backup, and a diesel generator as a standby source increase the reliability of hybrid systems. This project aims to design a community-owned, innovative, standalone hybrid renewable energy system with a power-sharing option between neighbours, comprised of PV panels, a wind turbine, battery storage, dump load, and a standby diesel generator. The PV, wind generator, and battery sizes are determined using interactive methods (Deficiency of Power Supply Probability DPSP) and analytical methods (HOMER, iHOGA). Smart controllers have been designed using artificial intelligence and MATLAB programming to achieve the overall control action. The recommended HRES would be able to cater to the load demand of the targeted community with minimum interruption throughout the year without grid power. Community power projects are now increasingly popular in Australia. One exciting application of standalone HRES is "community power." This type of system enables a community to cater to their power requirements without being dependent on grid power. It helps to reduce their greenhouse gas emission while providing control of the power generation in the hands of the locals. This also increases the job opportunities for the residents and strengthens the local economy. Renewable energy generation projects have been undertaken in Australia involving communities. However, they are primarily grid-connected systems. Not much work has been done so far here on standalone systems. This research can be presented as a guideline for this kind of project as it includes the most popular renewable techniques and steps to be undertaken for developing this kind of system.

All the glory to the Almighty

Aum Tryambakam yajaamahe sugandhim
pushtivardhanam |
Urvaarukamiva bandhanaan-mrityormuksheeya
maamritaat ||

We worship the three-eyed One, who is fragrant and who nourishes all.
Like the fruit falls off from the bondage of the stem, may we be liberated from death, from mortality.

To my Maa, the Divine Mother, my source, my power, my everything!

Jay Maa Kali
Om Namah Shivay

Table of Contents

Declaration of Originality

“I, Piyali Ganguly, declare that the PhD thesis entitled Design a Community-Owned Smart, Standalone Hybrid Renewable Energy System with Power Sharing Option between Neighbors is no more than 80,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work”.

I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University’s Higher Degree by Research Policy and Procedures.

Signature	Date
Piyali Ganguly	18/09/2023

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List of Figures

List of Tables

List of Nomenclature

AI: Artificial Intelligence

ANN: Artificial Neural Networks

BOM: Australia. Bureau of Meteorology

CRF: Capital Recovery

CRF: Capital Recovery Factor

CSA: Cuckoo Search Algorithm

DOC: Depth Of Charge

DPS: Deficiency of Power Supply

DPSP: Deficiency of Power Supply Probability

FIS: Fuzzy Inference System

FLC: Fuzzy Logic Controller

GA: Genetic Algorithm

GRHYSO: Grid-connected Renewable Hybrid Systems Optimization

HOMER: Hybrid Optimization Model of Electric Renewable Energy

HRES: Hybrid Renewable Energy System

iHOGA: Advanced Hybrid Optimization with Genetic Algorithms

LCC: Life Cycle Cost

LCE: Lavelized Cost of Energy

LOLH: Load Time Loss

LOLP: Load Loss Probability

LOLR: Loss of Load Risk

LPSP: Loss of power supply probability

MAPE: Mean Absolute Percentage Error

MAS: Multiagent-system

MF: Membership Functions

MOEA: Multi-Objective Evolutionary Algorithm

MOLP: Multi-Objective Linear Programming

MPPT: Maximum Power Point Tracker

NOCT: Nominal Cell Operating Temperature

NPC: Net Present Cost

NREL: National Institute of Renewable Energy

PI: Proportional Integral

PI: Proportional–Integral

PSO: Particle Swarm Optimization

PV: Photovoltaic
RES: Renewable Energy Systems
RES: Renewable Energy Systems
SOC: State Of Charge
SOV: State of Voltage
SPL: System Performance Level
TAC: Total Annual Cost
TMY: Typical Meteorological Year
TS: Takagi – Sugeno
TWh: Terawatt hours
YMY: Typical meteorological year

List of Publications

Book Chapters:

- Piyali, Kalam, Akhtar and Zayegh, Aladin **'Solar–wind hybrid renewable energy system: current status of research on configurations, control, and sizing methodologies'**, In Woodhead Publishing Series in Energy, Hybrid-Renewable Energy Systems in Microgrids, Woodhead Publishing, 2018, Pages 219-248, ISBN 9780081024935, https://doi.org/10.1016/B978-0-08-102493-5.00012-1.

- Piyali, Kalam, Akhtar and Zayegh, Aladin 'Utility-Scale Wind Turbines and Wind Farms – Chapter 13 entitled **- Chapter 13: Hybrid renewable energy systems: wind, solar, fuel cells and batteries.'** ISBN-13: 978-1-83953-099-9

Journal Publications:

- Piyali, Kalam, Akhtar and Zayegh, Aladin '**Fuzzy logic-based energy management system of stand-alone renewable energy system for a remote area power system'**, April 2019, Australian Journal of Electrical and Electronics Engineering 16(4):1-12 DOI: 10.1080/1448837X.2019.1588091

- Piyali, Kalam, Akhtar and Zayegh, Aladin **'Optimum Fuzzy Logic Control System Design using Cuckoo Search Algorithm for Pitch Control of a Wind Turbine' (2017)** ,Advances in Modelling and Analysis C, 72 (4). 266 - 280. ISSN 1240-4535

- Ganguly P., Kalam A., Zayegh A. (2019) **Modelling of an Optimum Fuzzy Logic Controller Using Genetic Algorithm**. In: Chattopadhyay S., Roy T., Sengupta S., Berger-Vachon C. (eds) Modelling and Simulation in Science, Technology and Engineering Mathematics. MS-17 2017. Advances in Intelligent Systems and Computing, vol 749. Springer, Cham

Conference Publications:

- P. Ganguly, C. Taluja, A. Kalam, A. Zayegh and P. Guha, "Research on Sizing Methodologies for Solar–wind Hybrid Energy System: A Review", in *Conference: International Conference on Green Energy For Environmental Sustainability (ICGEES 2020)*, Culicut, 2020.

- Piyali, Kalam, Akhtar and Zayegh, Aladin "Design a Control Mechanism for the Power Management of a Standalone Renewable Energy System," 2019 International Conference on Power Electronics, Control and Automation (ICPECA), New Delhi, India, 2019, pp. 1-6.

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- P. Ganguly, A. Kalam and A. Zayegh, **"Optimum standalone hybrid renewable energy system design using HOMER for a small community of Portland, Victoria,"** *2017 Australasian Universities Power Engineering Conference (AUPEC)*, Melbourne, VIC, 2017, pp. 1-6. doi: 10.1109/AUPEC.2017.8282486

- P. Ganguly, A. Kalam and A. Zayegh, **"Design an optimum standalone hybrid renewable energy system for a small town at Portland, Victoria using iHOGA,"** *2017 Australasian Universities Power Engineering Conference (AUPEC)*, Melbourne, VIC, 2017, pp. 1-6. doi: 10.1109/AUPEC.2017.8282487

- Piyali Ganguly, Akhtar Kalam, Aladin Zayegh, **'SHORT TERM LOAD FORECASTING USING FUZZY LOGIC'** May 2017, International Conference on Research in Education and Science (ICRES), May 18 - 21, 2017 Ephesus-Kusadasi/Turkey

- Piyali Ganguly, Akhtar Kalam, Aladin Zayegh, ,**'OPTIMUM SIZING OF STANDALONE PV/WIND POWER GENERATING SYSTEM WITH STORAGE'** May 2017 , Piyali Ganguly, Akhtar Kalam, Aladin Zayegh, International Conference on Research in Education and Science (ICRES), May 18 - 21, 2017 Ephesus-Kusadasi/Turkey

Award and recognition

- Receiver of the Madsen Medal for the Best AJEE Paper in 2019 from Engineers Australia

THESIS OVERVIEW

CHAPTER

1

1.1 Introduction
1.2 Aims of the Project
1.3 Contribution to Knowledge
1.4 Statement of Significance
1.5 Methodology and Conceptual Framework
1.6 Summery

Chapter 1. Thesis Overview

1.1 Introduction

The global demand for electricity is rising. At present the major part of worldwide energy demand is met utilising the traditional energy sources, like coal natural gas etc. The advantages of conventional energy sources are that they are cost effective, easy to produce and use. However, the conventional sources have drawbacks. The major issue is with the conventional sources is that they are limited resources hence depletable. Another big concern related to these sources is there environmental impact. In contrast renewable energy is environment friendly and acquired from natural resources that are not exhausted while being used, for example wind or solar power. Hence, the renewable energy systems (RES) are being broadly accepted as an alternate to standard traditional energy sources due to the exhaustion of natural resources and their substantial environmental impact. Renewable systems can be of two categories, Grid connected and standalone. While grid connected systems are independent distributed power system which are connected to an electricity transmission and distribution system or grid. The standalone RES are independent of grid power. In types of RES, the operational capacity is calculated to match the demand. One of the expanding uses of standalone RES is in fuelling the remote areas where grid power is considerably expensive due to transport costs.

1.2 Aim of the project

1.3 *The research aims to design a community owned smart, standalone, hybrid RES including solar panels and wind turbines as renewable generators, battery storage. This system also includes a back-up diesel with power sharing option in-between the neighbours*.

Here the term ‘Neighbours’ represents the members of the participating households of the community project. This standalone HRES is a community microgrid, a standalone power system to power the targeted community.

The suggested system can be represented in the pictographic diagram which is presented below in Fig 1.1. The figure shows a prototype of the proposed system including ten households. The community is involving of ten households independently installed with solar panels and a in-house small battery back-up. Apart from that, a central battery bank is incorporated as storage device accompanied by a wind turbine and a standby diesel generator and also a dump load. The designed power management strategy for the d HRES can be described as follows:

- Each household will be using the power generated by the in-house solar generators first.
- In case there is any excess generation, the power that is excess, will be stored into the battery bank of each household till it reaches its maximum depth of charge (DOC). Once that stage reached, the excess energy will be stored into the central battery bank until it reaches its maximum DOC.
- When both in-house and central battery bank reaches their maximum DOC and there is an excess generation from solar panels or wind turbine, the excess energy will be sent to dump load.
- If at any stage, the power produced by the solar panels is less than the load requirement or at the night time when there is no solar generation, the battery bank of that household will be responsible for catering the load demand of the household. The battery bank will continue to do so till it reaches its minimum DOC.
- In the even the battery bank reaches the minimum DOC specified it will stop discharging and will get disconnected from the load. At this stage the excess load demand will be fulfilled by the central battery bank.
- The central battery bank is responsible for supplying the load demands till it reaches its own minimum DOC. In worst weather conditions, when the power produced by the renewable energy sources are significantly low, the central battery bank might reach its minimum DOC while catering the load demand for a longer time. In that situation, it will get disconnected from the load demand. At this stage, the diesel generator will get switched on and will continue to supply the load demand.
- The power produced by the wind turbine would be utilised for charging the central battery bank.
- A smart central controller would be responsible for the overall power management of the system.

Thus, the designed system would be able to supply the load demand with minimum interruption.

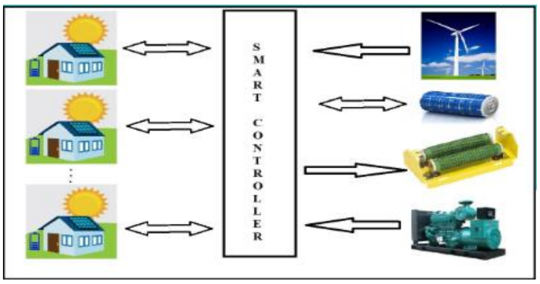


Fig. 1.1 The schematic diagram of the proposed HRES including ten households individually installed solar panels and battery bank, wind turbine, central battery bank , diesel generator dump load and a central controller.

When there is excess generation from the inhouse solar panels and the inhouse battery bank obtains its maximum state of charge (SOC) the excess generation from inhouse battery bank is stored in the central battery bank. The excess energy can be later used by any other household which is the core of the concept of power sharing. This way the community members can share the excess energy of each other which will reduce the requirement of storage for this standalone application. This is a very interesting concept and it can be a game changer in future in the field of renewable energy for communities.

Community ownership and sponsoring of renewable energy projects are common in several European countries and promptly developing in the USA. However it is a comparatively new concept in Australia. Community owned renewable projects creates social, political, environmental economic and technological benefits by Fig 1.2 represents the Motivators and benefits of community energy [110].

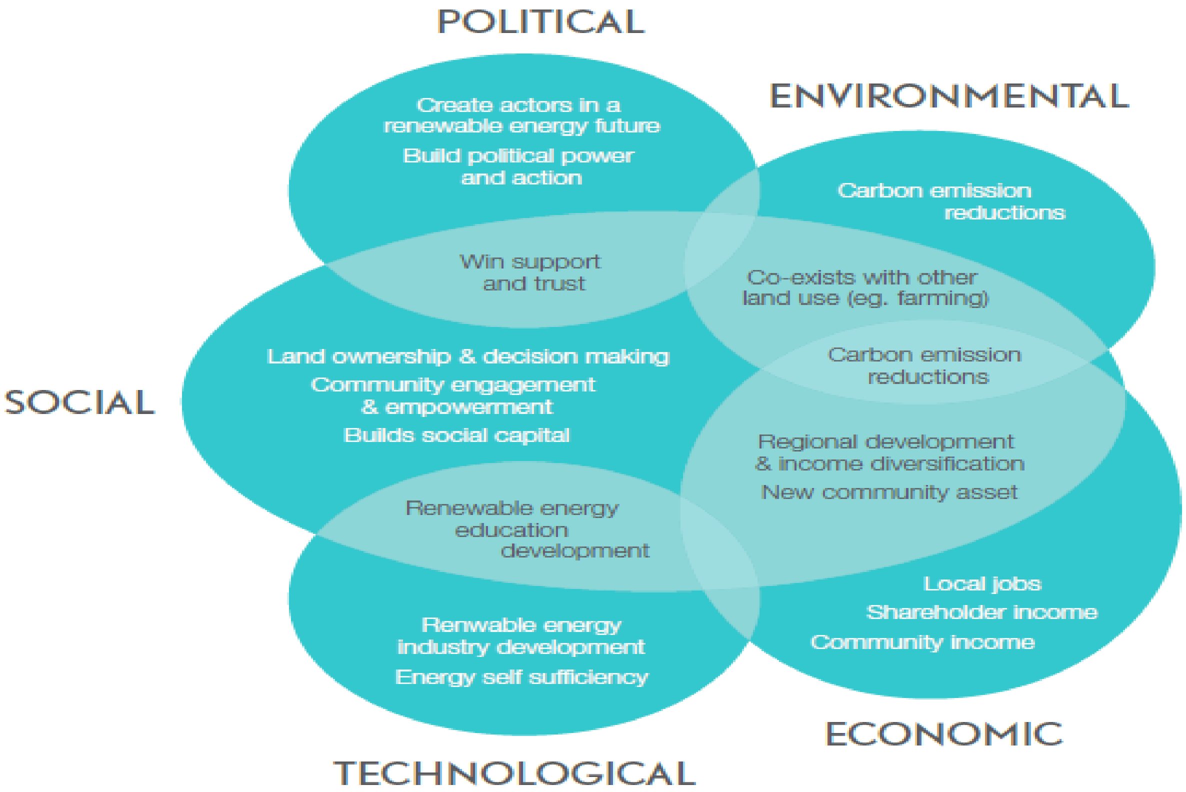


Fig 1.2 Motivators and benefits of community power sharing [110]

1.3 Contribution to Knowledge

The main areas where this study has contributed significantly to existing knowledge, can be summarised as follows:

A. **Community power** is not very common research area currently in Australia. Specially community power network with power sharing option among neighbours is a new area to explore. Not much research been registered in literature in this field, especially on standalone applications. This study will investigate the technical aspects of community power network and design a standalone HRES with power sharing options among the neighbours for a small community of Portland, Australia.

B. This study explored the option of community power by incorporating load sharing options between the community members. Excess energy generated by one member of the community is stored in the central battery bank which can be utilised by any other community member when they require, which allows the members of the community to share the load demand with other members. This concept is fairy new to Australia as a standalone application and can be a game changer in future in the area of renewable energy.

C. While conducting the feasibility study, a methodology of load forecasting using fuzzy logic has been investigated. This methodology has been accepted as a paper in an international conference (ICRES-2017).

D. During this project, various techniques has been investigated to optimally size the system components of HRES. They can be stated below:

a. A technique to optimally size the components of the HRES has been investigated which considers the Deficiency of Power Supply Probability (DPSP) criteria used in optimum sizing of the sources. It also considers the minimization of system cost ensuring reliable and economic, load supply for the hybrid, standalone system. This work has been accepted as a paper in an international conference (ICRES-2017).

b. During this project , another optimization tool has been explored called iHOGA, a comprehensive procedure to optimally size the components of a HRES that was designed for a small settlement situated in Portland, has been investigated using a software called iHOGA. The selected optimum system configuration was obtained after analysing the different solutions obtained. This work has been accepted as a paper at an international conference (AUPEC-2017).

c. This project also explored the optimally designed configuration of a standalone RES with battery storage using the tool HOMER for a relatively small community situated in Portland. It has been accepted as a paper in an international conference (AUPEC-2017).

E. The power flow management in HRES is crucial to make sure the constant energy flow between system apparatuses. This is also necessary to enhance the operating life of the HRES and to confirm the standard of energy flow. This study will explore the opportunities of utilizing AI techniques in this area.

Initially a controller was designed in MATLAB/SIMULINK environment to manage the power flow between the load, sources, storage, dump load and backup generators. This has been published in an international conference (ICPECA) .

A fuzzy logic controller was designed for power flow management between the load, sources, storage, dump load and a back-up generator with a centralised hybrid power generating system for the targeted community. In this work, the centralised power generating source considered is consists of solar panels, wind generators and storage battery along with dump load and back-up generator. This work has been published in a journal (Engineers Australia) .

In the next step, the project designed a fuzzy logic controller (FLC) with distributed energy sources. This is a new area and not much reported in literature till date.

F. This project is also investigating the options to improve the performance of the FLC by tuning the parameters. During this project, the options for optimally tuning the FLC has been explored using AI techniques like Genetic Algorithm (GA) and Cuckoo Search Algorithm (CSA). During this project, a FLC has been optimally tuned using GA to control the level of the liquid of a tank. This work has been accepted as a paper at an AMSE conference and published in the proceedings by Springer.

G. One major contribution of this project is to design an **optimum fuzzy logic controller (FLC) system to harvest maximum power from a wind turbine with the help of Cuckoo Search Algorithm (CSA) This is a maiden work in this field**.

CSA is comparatively new optimisation technique and has not been used previously in controlling the wind turbine to extract maximum power. During this work, utilising CSA helped in optimisation the pre-processor parameters of the FLC system that was used for the pitch control of a wind turbine to harvest maximum power from the wind. This work has been published at AMSE journal.

1.4 Statement of Significance

The understanding of the need to inhibit the weather changes and of the critical increment in the expenditures of traditional sources of energy have motivated many nations to provide innovative energy strategies promoting the use of renewable energy systems. They have many advantages over the conventional sources apart from the environmental benefits. One very important benefit of the HRES is they can generate power for isolated areas where the grid extension is substantially expensive. Hence, the standalone HRES which are independent of grid connection are increasingly popular in electrifying the remote areas and military applications. One interesting application of standalone HRES is community power. This concept enables a community to generate their own power requirements without being dependant on grid power and helps the community to reduce their greenhouse gas emission. This also increases the job opportunities for the residents and strengthens the local economy.

However, RES has some significant drawbacks due to their dependency on climatic conditions, and their high capital cost. Hence, before considering the HRES for community power projects, one must consider the following facts:

- Normally the lifespan of these kind of systems are approximately 25 years. While designing some standalone HRES one should study the increasing load requirement in modern life. Therefore, a load forecasting of aimed community of upcoming 25 years is vital for the proposed system to work successfully for its entire life span.

- Optimal sizing of the sources and storage devices of such systems is extremely important to avoid failure to meet the load requirement and increased establishment cost, specially, for standalone applications.

- When designing HRES, the designer has to consider the situation that the dynamic interface between load demand and the HRES can cause critical stability and power quality challenges [2]. Therefore, the development of power flow management strategies for HRES is vital to ensure the continuous energy flow between system components. This is also essential to improve the operating lifespan of the components of HRES and to ensure the quality and reliability of the energy flow.

This study is significant in many ways. It has considered all above stated aspects for designing standalone HRES for a locality situated in Portland, Victoria, Australia. The significance of the study can be summarised as follows:

- This study investigated the **methodology for designing the components of the HRES** that best suits the aimed community and its location. Different **size-optimisation methods** have been investigated in this study for the components of the HRES and the best suited system configuration for the targeted community was selected.

- The study successfully **designed a smart controller which will control the power flow** between the load, sources means solar and wind generators and storage devices. Different methodology, especially artificial intelligence, have been investigated to improve the performance of the proposed controller so that it can perform satisfactorily under different supply-demand conditions.

- **This study also investigated the control strategies for the wind turbines to extract the maximum power using Artificial Intelligence (AI) techniques. This is discussed in chapter 5.**

- The **performance of the system was analysed** once the design is complete ensuring that the system can perform as desired under various weather and load-demand conditions.
- Once the system is designed and the performance is tested**, the financial aspects of community power** was investigated, deciding the cost of energy, ongoing charges for the members of the community. This is important to make sure that the load sharing model can be sustainable for the target community.

The most important feature of the study is that it explores the option of community power, which is not a well-known concept in Australia till now, specially the standalone application. This study investigated the option of sharing load between the members of the community who participated in this project. They can store their excess generation from their PV panels and store in the central battery bank for any other community member to use. Which helps to reduce the wastage of excess power generated by sharing them between the members of the community. This project actually can empower a community by providing the member to take control of their power generation, involving the community members can be beneficial for them socially and economically to as it increases job opportunities for the community members.

Another fact is when the community members are involving themselves into this kind of project and they invest in this kind of project it significantly reduces the requirement of external funding, which actually increases the feasibility of establishing this kind of project.

Hence this project is very significant as per the present global condition where researchers are looking forward to replacing the conventional power sources wherever possible. This project brought the most popular technologies available in the field of RES under one umbrella. This work has a significant importance as this project can work as a technical handbook for any community willing to consider standalone RES with power sharing options between neighbours. This project would be able to help and encourage people to consider renewable energy, which might bring a great impact to the society and mankind.

1.5 Methodology and Conceptual Framework

The project has been developed within the following phases and chapters.

a. Feasibility study

The first step of this project will be the feasibility study of the selected location. Before installation and operation, the feasibility study of the hybrid energy system is routinely performed. The feasibility analysis comprising of the study of the climatic condition of the aimed site, accessibility of renewable energy sources and evaluation of its prospective load and load demand of the application site. The pre-feasibility study helps in finding out what kind of HRES would be the best solution for the target.

The basic constraint of renewable energy sources is these systems are dependent on meteorological conditions like solar irradiation, average hourly wind speed etc. So, it is very important to investigate the possibilities of establishing some RES at a location before taking any further step. The feasibility study will consider the annual average solar irradiation of that location, daily average wind speed, available at the area etc. The purpose of this research is to ensure that once established, the renewable energy sources will be able to deliver their best performance. This is crucial as improper meteorological conditions may result in an inability to generate desired energy from the renewable energy sources. For example, at a very low wind speed (say,2m/s) a wind turbine would not be able to generate any power. If the area is covered with shade of trees, solar panels will not be able to work properly. So, it is very important to ensure that the selected location is appropriate for establishing a standalone RES.

Load forecasting is a very important step for this project. The expected lifespan of the project would be 25 years. While designing such system, one need consider that the demand for energy is constantly increasing in modern life with the development of cutting-edge technologies. So, if the design is based on the present average daily load consumption, it might not be able to fulfill the increasing load demand of that community after ten years. Considering that, load forecasting of the target community needs to be conducted, ensuring the reliable demand-supply

.

b. Optimum Sizing

The next step is to precisely evaluate the size of individual component that can cost-effectively satisfy the load demand. The HRES under consideration consists of solar generators, wind generators, battery storage, dump load and a standby diesel generator. For selecting a combination of hybrid system which is optimum to meet the load requirement, one must carry out an evaluation based on power reliability criteria and system life-cycle cost. The optimum combination for the hybrid system can make the best balance between power reliability and system cost. Hence this phase concentrates on studying numerous optimisation techniques and finding the optimum system configuration for the targeted community

This study has investigated three different optimisation algorithms/ tools that are currently being used in research / industry. They can be described as follows:

1. A model has been proposed to optimise of the capacity of various components of standalone, hybrid power generating system including solar wind generators and battery bank. The suggested model considers the Deficiency of Power Supply Probability (DPSP) criteria for optimum sizing of the sources. This also considers the minimization of system cost ensuring reliable and economic, load supply for the hybrid, standalone system. A case study has been conducted to optimally size the components of one standalone system which is designed to supply a community located in Portland, Victoria, Australia.

2. During this research study was conducted to determine the optimal configuration of standalone renewable energy system with battery storage using the software called HOMER for a small locality based in Portland, Victoria. To attain that, a pre-feasibility study was conducted. Sensitivity analysis was conducted for numerous hourly wind speed values, solar irradiation data, scaled yearly average load demand and yearly capacity shortage. Numerous renewable energy sources alongside energy storage devices and their usage with respect to expenditure and performance were investigated. The different results were analysed, and the optimum system is chosen. The properties of the optimally selected system are studied and analysed.

3. This study also investigated a detailed approach to optimally sizing the components of a hybrid renewable energy system for a small town based in Portland, Victoria, Australia, using the software iHOGA. Analysing the different solutions, the optimum system is selected. The characteristics of the selected system are investigated.

c. Design of the control mechanism for the HRES

Once the optimum sizes or the sources and storages are selected, in the next step was the development of a smart central controller. The controller should be responsible for managing the power flow among the various components of the HRES, such as the sources, load demand, storage, dump load and diesel generator. This controller should be able to ensure the load sharing between the members. During this work, a smart controller would be designed which will be able to decide when to charge or when to discharge the batteries (the central or in-house), or send excess power to dump load or when to start the diesel generator etc. The controller should be performed efficiently under constantly changing supply -demand condition. Artificial intelligence techniques such as Fuzzy logic, Cuckoo Search Algorithm have been investigated to improve the overall control mechanism.

As mentioned before, a smart FLC has been designed during this project to achieve the overall power management of a standalone HRES with centralised sources. The proposed intelligent energy management systems are designed aiming to minimize the cost of operation and the impact on the environment while substantially improving the economic and technical performance of the system supplying power. The HRES considered here is the combination of the photovoltaic (PV) array, wind turbine, battery storage, dump load and a standby diesel generator. The proposed FLC ensures the reliable power management between generators , storage, and load. The simulation results evidently clarifies that the designed controller presented high level of performance under different load and generation conditions. In the next part of the design a Fuzzy logic controller was designed for distributed energy sources.

Apart from the designing the controller for power flow management, some control mechanism has been developed for the optimum performance of the wind turbine during this study. Wind energy has the prospective for becoming the major contributor in the world's energy future. The main concern with wind generation is that the wind is an intermittent resource, so the efficiency and control of wind generator are highly important. Pitch angle control of wind turbines is a very common measures for altering the aerodynamic torque of the wind turbine in the circumstances where the wind speed exceeds the rated speed. The mentioned work is a maiden one, which developed a methodology to design an optimised FLC system utilising Cuckoo Search Algorithm (CSA) resulting an enhanced performance of wind turbine and maximise the energy captured.

d. Performance Assessment

For selecting of the precise component of an HRES and accurate projection of its energy production, it is very important to get their performance analysis done under different operating conditions. When the predicted power generation from each components is significantly precise enough, the designed combination will cater the load demand at the minimum expenditure.

Hence, after the control strategies are determined, the system model was developed using MATLAB /SIMULINK to check the performance of the system, which helped to understand if the system controller is working as desired under various demand-supply conditions.

Following the verification and simulation of the system, the second part is associated to develop and implement a testbed for the designed control system representing loads and local generation units such as wind turbine, solar panels. This was created using relevant hardware to test the control mechanism.

e. Financial aspects of community power

This is an important step for designing a microgrid with community involvement. In the designed HRES there will be an option for the community members to save their excess power generation into a central battery bank. When the in-house battery reaches its minimum DOC, and load demand of a household is greater than that the power generated by the in-house solar panels the central battery will be responsible for supplying the load demand allowing the members to share their excess power with their neighbours. With this kind of power sharing options, a proper financial model needs to be established. The financial model can be developed based on multiple factors such as total system cost, government policies on renewable energies, financial contribution of the community members or getting financial support from financial institutions etc. However, to achieve all these it is very important to understand the establishment cost, cost of energy of the designed system. This section will discuss numerous costs associated with the designed system so that one can set up the financial model based on that.

1.6 Summary

Hybrid Renewable Energy System (HRES) including of solar and wind generators, is eco-environmentally friendly, cost-economical option for powering the countryside areas contrasted to conventional sources. However, the systems have a major drawback due to their dependency on climatic conditions. Hence for standalone applications it is very crucial to incorporate storage systems. However due to high expense of storage systems the incorporation of storage increases system cost. Where oversizing of storage system components can cause additional cost, under sizing of the system components decreases the reliability of power supply. Incorporation of storage devises and renewable sources makes the power management more complicated. This research work presents a detailed methodology to design a standalone hybrid renewable energy system for a small community located at Portland Victoria. The system is comprising of solar / wind generators, battery storage, a standby diesel generator and a dump load. This study investigates various methodologies for optimally sizing the various components of the hybrid renewable energy system. One of them is by using interactive method (Using Deficiency of Power Supply Probability, DPSP). Two other analytical methods also have been investigated which use the tools called HOMER and iHOGA they are two software tools that are internationally recognized. A smart controller has been designed using Fuzzy Logic to achieve overall control action among the system components.

The system has been simulated using MATLAB/ SIMULINK programming and the results shows desired performance. Hence this methodology can be successfully implemented to design a standalone hybrid renewable energy system for any location for given load profile and climatic conditions.

CHAPTER

2

Chapter 2. Literature Review

2.0 Introduction

A significant amount of literature is available in different fields of renewable energy. Extensive amount of literature has been considered during this project. Based on the literature survey conducted on numerous fields of renewable energy systems, two book chapters and nine conference papers have been published [183] [184]. The publications have detailed the intense literature review that has been done to understand the current status of research on the various fields related to renewable energy systems. This is vast and wide ranged starting from feasibility study. Literatures on optimum sizing, development of control mechanism, Artificial Intelligence in the field of renewable energy systems etc.

The references have been provided in the relevant chapters. Some part of that intense study that has been considered for this project can be represented in following sections.

2.1Feasibility study and load forecasting

Before any HRES is installed and start operating, the feasibility study of the aimed location of HRES is customarily conducted. This investigation needs to includes the study of the climatic condition of the proposed location, making sure that there is significant availability of renewable energy sources and assessment of its potential load and load requirement of the aimed site [7].

A crucial factor that determines the obtainability and greatness of solar and wind energy production of a specific site is the climatic condition of that location. Numerous climatic factors, for example, solar radiation, air temperature, average wind speed are variable factors. Hence to utilize the solar and wind resources in best possible way it is important to analyze the characteristics of factors like solar radiation and wind conditions. This should be conducted at the very first stage [185] The feasibility of setting up a hybrid renewable energy system with solar and wind generators depends on the potential of solar radiation and wind energy potential of the targeted location. Hence appropriate weather data collection is important for designing a hybrid renewable energy system.

This study assists in discovering out the potentials to develop a Hybrid Renewable Energy Systems (HRES) for any location. Hence to understand the current studies conducted on feasibility study, intense literature has been explored.

To determine the best realistic solution, one would need the site-to-site basis weather data [7]. Many Research has been done analysing solar and wind energy sources and multiple examines on finding the prospects of making use of solar and wind energy resources in many territories or countries have been testified in the literature [22-26]. Once the feasibility study confirms the prospects of establishing a HRES of the target location, the next step of the project would be the load forecasting. Load forecasting is the method of predicting the electrical load demand. Load forecasting is an integral and central process in the planning and operation of electrical energy management system [111]. Various studies have been conducted by researchers to improve the accuracy of the load forecasting [112-118, 186-187]. Traditional models for load forecasting can be generally classified as time series models or regression models [186]. In a time, series model, the prior load was used to estimate future load demand. However, this estimation method is extremely difficult to master, and a vast amount of data is necessary to create a thorough forecasting system. The regression model is the second most common approach for forecasting short-term load [187]. The database is partitioned into smaller chunks using this strategy. A regression model for each component, such as a specific season or day of the week, can be developed. The estimated parameter values are easily interpretable, however this method has the drawback of requiring a large database, which may include obsolete historical data.

2.2 Optimum Sizing

Conducting optimum sizing method is crucial to utilize the RES proficiently and economically. The optimum sizing of the components of HRES can safeguard the minimal investment with the maximum employment of the system apparatuses so that the HRES can be utilised at the optimal conditions in in connection to investment and system power reliability obligations. An optimum combination of the hybrid system is the one that can make the best negotiation between power reliability and system cost. Therefore, for selecting an optimum combination of modules for a hybrid system for maximum reliability, the assessment must be carried out based on power reliability and system life-cycle cost. A significant number of studies have been reported in the literature suggesting various optimum sizing methods for the components of the HRES [119-122].

Fig 2.1 present implicit criteria/methodology commonly utilized for optimum sizing of HRES [185].

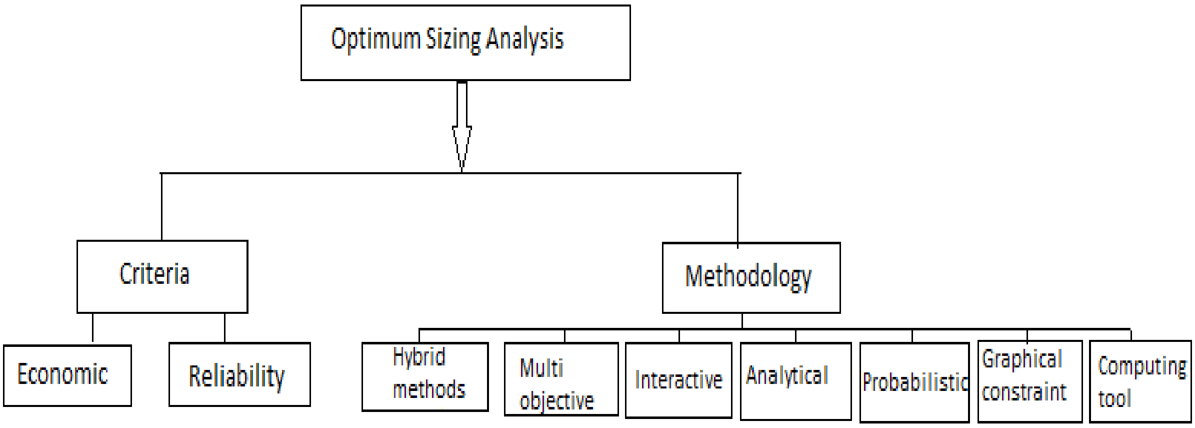


Fig. 2.1 Optimum sizing criteria/ methodology of solar wind HRES.

This study designs a standalone HRES for a small community located in Portland Victoria. The standalone systems have a major disadvantage.

In case of insufficient generation from the renewable resources, there would be no back up from the grid. Hence incorporation of storage device will be mandatory for uninterrupted power supply. However, one needs to remember that the storage is expensive hence oversizing of storage devices can lead to higher system cost. One also needs to keep in mind that bigger the storage is , bigger the sizes of the generators will be required to charge them.

If the systems are oversized, during peak generation time, if there is excess energy, the grid actually works as an infinite storage for the grid connected systems. But the standalone system doesn't have that facility, hence the excess generations are either stored in storage devices for future use or they are sent to some dump loads in most common cases. This will lead to waste of energy.

Considering these factors, it is very important to size the system components of a standalone HRES optimally so that the designed system can meet the load demand and without causing higher system cost. Optimum sizing is a balancing between system power supply reliability and system cost. So this is a very vital step for designing a HRES, specially a standalone system where no backup is available from the grid.

This study explored various methodologies for optimum sizing the components of the HRES. Study has been conducted to learn and implement different methodologies to optimally size the components of HRES to supply the load demand without compromising the reliability of power supply with minimum system costs. Three different methodologies of optimum sizing have been used in this study which can optimally size the components of the standalone HRES. They are based on tools like HOMER and iHOGA and also using DPSP criteria.

Intense literature survey has been conducted on the different criteria of optimum sizing, numerous literature and studies has been considered in this study [14] [67-116, 188, 189]. According to some study, the optimum hybrid system configuration can be chosen by minimising the cost per kilowatt-hour (kWh) [188]. Some researchers looked into employing a genetic algorithm to optimise hybrid renewable energy systems, as well as appropriate operation strategies to fulfil various load demands [189]. Optimisation research has also been carried out utilising a software called Hybrid Optimization Model for Electric Renewables (HOMER)[190-191]. The study that has been conducted on the sizing methodologies will be discussed in detail with relevant references in Chapter 6.

2.3 **Dynamic Modelling**

A standalone solar wind HRES is comprising of PV and wind generators, battery bank, inverter, controller, and other accessory devices and cables. The PV panels and wind turbines are the power generators which supply the load demand. When there is enough generation from the solar and wind generators, the excess power from the renewable sources will be used to charge the battery bank until it reaches its maximum state of charge (SOC) after the load requirement is satisfied. When the energy generated by the sources are less than the load demand, the battery will start to discharge and supply the load demand to compensate the deficient power generation from the PV array and wind turbine to meet the load demand until it reaches its minimum SOC.

The successful design of HRES system is primarily defined by the performance of its individual components. Hence, it is very significant to model the individual components precisely at first stage to foretell the performance of the system. Once that is achieved, the performance of their combination can be evaluated in terms of meeting the demanding reliability. When the power output projection from the individual components is precise, the subsequent combination will be able to deliver the load demand at the minimum cost. Hence it is a vital step to get a proper mathematical model of each component of the HRES that plays a role is control mechanism or affects the overall control action. The standalone HRES under consideration is comprising of PV panels, wind turbines, battery storage diesel generator and dump load. Among all these system components, the diesel generator and dump load does not affect the system performance as their only action is to get a control action to start (for diesel generator) and once started just supply the load demand till it is turned off. The function of the dump load in considered system is just to receive excess generated power. Hence these two components do not directly impact the control action of the overall system. Hence their mathematical model is not vital or not necessary.

However, the PV generators, the wind turbine and battery bank are the important components that impacts the control of the overall system. The PV and wind generator's power output vary based on the climatic conditions like solar irradiation, wind speed. The output power from these two takes crucial role in overall control mechanism. Similarly, the battery SOC is a very important factor that plays a vital role in overall control action. Depending upon the in house battery SOC and the SOC of the central battery bank the controller decides the control action that needs to be taken. Hence, the mathematical modelling of the PV and wind generators and battery bank is a vital step in the design of the standalone HRES. Hence studies have been conducted to investigate the current methodologies or research that is present in literature currently to successfully model the system components of HRES. Researchers have explored various methodologies to model the different components of the HRES [128-143].

PV modules performance depends on their material, temperature and solar radiance on their surface. Numerous studies have been conducted on the influence of environmental factors on PV panels performance [40-49]. The effect of temperature on silicon photocell characteristics is discussed in [40]. A novel and simple model for predicting PV module performance for engineering applications based on the I–V curves of a photovoltaic (PV) module is presented in [44]. This model includes five factors to account for the complex relationship between PV module performance and solar-irradiance intensity and temperature.

To derivation of the mathematical model of a wind energy generator one needs to include the dynamics of wind turbine and modelling of the generator. As per the existing literature on the assessment of the wind energy systems not much studies have been conducted in this area. Studies has been reported on regional wind energy assessment [51], financial aspects of wind energy [52] and local wind energy guidelines [53]. Studies been reported in literature for modelling the wind energy systems [54-59]

Studies has been reported in literature on development of the behavioural model of battery [46] [60-69]. In their research Kim and Hong [46] studied the discharge performance of a flooded lead–acid battery cell. Their research was influenced by the works of Gu et al. [60], Ekdunge and Simonsson [61].

In their work, Ekdunge and Simonsson investigated the integration of mechanism of diffusion–precipitation in the kinetics reaction of the negative electrode. In [67] the remaining battery capacity of the battery is determined by computing an accumulated discharge value and is presented in steps on a display unit in a cheap, high precision accumulation type remaining battery capacity metre and technique. Detailed has been discussed in relevant chapter.

2.4 Design of the control mechanism

When designing these HRES, it is crucial to consider the dynamic interaction between load demand and the HRES. This interaction can lead to significant stability and power quality issues, which are not commonly encountered in traditional power systems. To ensure an uninterrupted power supply for the load demand, effective management of energy flow within the hybrid system becomes essential. As a result, the control technique plays a vital role in enhancing the system efficiency and optimizing energy generation for the entire plant. Numerous studies have been documented in literature focusing on the power management of hybrid power systems [85,123-127].

Many HRES uses the traditional approach to control the power supply to the load requirement as per the load demand. The conventional methodology uses power electronics-based DC–DC converter to harvest maximum energy from PV and wind generators and achieve the overall control of the HRES. Presently numerous advanced controlling techniques have been added to conventional control strategies that been reported in the literature which can be used to compensate the power fluctuations which is resulted by the inconsistency of the renewable energy resources which impacts the quality of power supply system.

Jonathan et al. [130] discussed a control technology for HRES in their work which tracks and takes control decisions based on the definite battery state of charge (SOC) which has significant advantages over the traditional methods. In their study Ottoson et al. [131] presented a methodology where they used a data logger and provided a comprehensive analysis of the energy production and performance of an HRES which consists of solar, wind generators and diesel plant. Another work presented by Nogaret et al. [125] discussed an expert control mechanism which is system-based for HRES. This technique is based on an advanced control system to achieve the optimal operation and supervision of a medium size HRES which comprising of wind and solar generators. In their work, Chedid et al. has shown a methodology by using CAD (Computer aided design) tool [121] to optimally design and control a HRES which includes wind solar generators. This methodology considers all environmental factors. Literature is available on using Linear programming techniques to reduce the cost of production while satisfying the load requirement. Researchers Pitrone and Pitrone [122] presented an expert system for controlling that incorporates Fuzzy Logic theory, Neural Network and programmable logical controller (PLC) that can help to supervise and control a distributed HRES online.

This study aims to design a hybrid renewable energy system for a small community located at Portland Victoria. This community consists of ten households. Each household consists of inhouse solar panels and a in house battery storage. There is also a central battery bank, wind turbine, dump load and diesel generator. The designed system will provide each household to share their excess energy with their neighbours by storing the excess energy to their inhouse battery bank first and they are storing the excess to the central battery bank once the inhouse battery bank reaches its maximum state of charge (SOC). The schematic diagram of the community is presented in Fig 2.2.

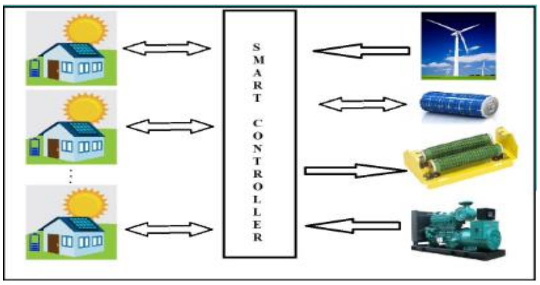


Fig. 2.2 The schematic diagram of the proposed HRES

Each household uses the power generated by the in-house panels first and stores any excess in inhouse battery for future use. Once that in-house battery reaches maximum SOC excess energy goes to central battery bank. Once the central battery bank reaches the maximum SOC the excess energy goes to dump load. The wind generation is utilized to charge the central battery bank and supply load demand when needed. When there is enough excess energy and both in house and central battery bank reaches their maximum SOC, any excess generation at this stage is sent to the dump load.

When load demand is more than power generated by the in house solar panels, in house battery bank starts supplying the deficiency till it reaches its minimum SOC. Once they reach minimum SOC the central battery bank starts discharging and supplying the load demand.

When both in house battery bank and central battery bank reach their minimum SOC, the diesel generator turns on to supply the load demand.

A huge number of literatures have been studied to understand the current research scenario on control mechanism of Hybrid Renewable Energy Systems. Study also been conducted to explore literature on application of Artificial Intelligence techniques in the area of control of hybrid renewable energy systems.[28][89][67-167]. In [28], the design is framed as an optimisation issue, with the goal of getting the system's configuration as well as a control approach that minimises both the total cost and pollution emissions over the installation's useful life. To control the energy flow in the HRES, research presented in [147] suggests a distributed EMS. Multiagent-system (MAS) technology is used to create this distributed controller. A HRES is viewed as a collection of different pieces that work together to achieve global coordination in this idea. A MAS is shown, as well as an explanation of the agent strategy for HES. More relevant studies have been discussed in the associated chapters.

However, the overall control mechanism of the system presented in this study is very complex as multiple stages are involved. Hence the design of the controller is very complicated. As these kinds of systems are not widely studied so far hence not many methodologies are available in literature to control these kinds of complex systems. Hence, during this study a Fuzzy Logic controller has been designed to achieve the desired control action. Fuzzy logic controller enables to feed the expert knowledge to feed as artificial intelligence to the controller to achieve the desired control power flow management. Not only that, incorporation of artificial intelligence in controller design keeps options for future development work for more complex systems.

This study also develops a control mechanism for pitch control of a wind turbine using Fuzzy Logic to harvest maximum power from the wind using Cuckoo Search Algorithm which was not reported in literature before. Most wind turbines on the market today use pitch control systems that use standard Proportional–Integral (PI) algorithms [152]. These control systems are engineered to operate at or near nominal wind speeds and power extraction levels. These mechanisms are popular because they have a good response for linear model systems and are easy to implement. Huge wind turbines, on the other hand, are very non-linear systems; consequently, non-linear control techniques would be necessary to extract maximum power from large wind turbines. The method discussed in this project is an advance artificial intelligence is capable of handling these nonlinear systems efficiently.

Control technique has a crucial part in improving the system efficiency and energy generation of a plant. Hence, the selection of appropriate control technique is important in system design process, to economically maximise the power availability from an HRES . Hence, the power flow management is very important in HRES to make sure the continuous energy flow between components of the system. This increases the operating life of the designed HRES and ensures the quality of energy flow.

2.5 Summary

From the literature survey it can be observed that hybrid renewable energy systems are the growing topic of interest for researchers around the world. Intense research been done and being conducted in numerous topics related to this field. However, there is a lot of scope for contributing to this growing industry and research. Hence this study acknowledges the contribution of the researchers in this area and concentrates to contribute to the knowledge.

FEASIBILITY STUDY FOR DESIGN AND TESTING OF HRES

CHAPTER

3

Chapter 3. Feasibility Study for Design and Testing of HRES

3.1Introduction:

The global requirement for electricity is rising. As per a recent report released by The U.S. Energy Information Administration called International Energy Outlook 2016 (IEO2016), the world energy demand is anticipated to grow by 48% between 2012 and 2040 [1]. From 2012 to 2014 the worldwide electricity consumption has increased by 5% [1]. A steady increase in electricity requirement is predicted due to growing economy in developing countries. The increasing populations and improvement in quality of living standard for many developing countries are the contributing factors to the increasing demand for energy resources. At this stage the major part of global energy necessity is provided by the conventional energy generators like coal natural gas . The advantages of conventional energy sources are that they are cost effective, easy to generate and use.

However, the conventional sources have serious drawbacks. The major issue is with the conventional sources is that they are limited and depletable. Apart from this the conventional sources also have significant environmental impact. They produce greenhouse gases that contributes to the global warming. Moreover, these emissions from these generators are causing various diseases like asthma, cancer etc. Alternatively, renewable energy is environment friendly and gained from natural resources that are infinite, i.e. wind or solar energy. Hence, the renewable energy systems (RES) are being broadly adapted as an replacement to the conventional energy sources due to the exhaustion of natural resources and their consequential ecological influence [2]. Renewable sources these days are recognized globaly as mainstream sources of energy [3].

3.1.1 Hybrid Renewable Energy Systems (HRES)

The surge of Renewable Energy Systems is attributed by several factors including the improving cost-affordability of renewable technologies, devoted policy initiatives, better access to financing, concerns about energy safety and the environment and rising requirement of energy in developing and emerging countries [4]. Fig 3.1 represents global renewable power capacity and annual growth rate, 2000-2015[5].

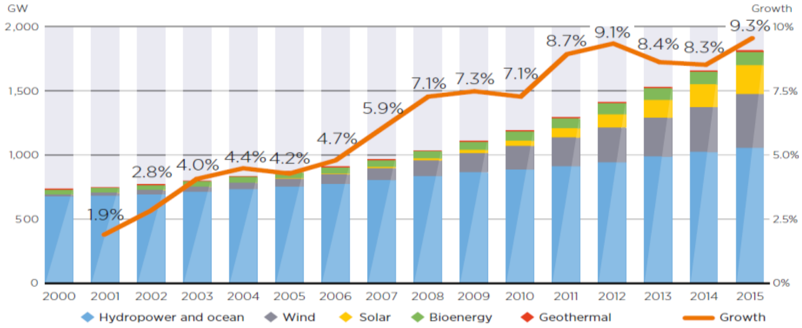


Fig 3.1. Renewable power capacity and annual growth rate, 2000-2015[5]

Among all the RES, the application of solar and wind energy system has become progressively popular due to integrated and environment friendly nature [6][7]. The field of solar–wind has achieved a remarkable growth for past two decades in its extensive use of standalone to utility interactive solar–wind systems [7][8]. Fig 3.2 represents the global capacity trends of solar and wind energy [9].

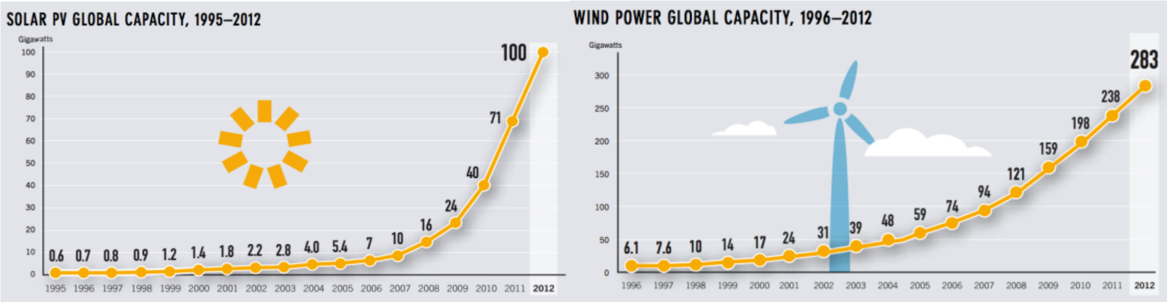
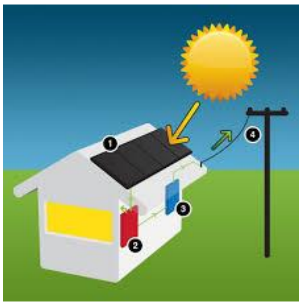


Fig. 3.2 Global capacity trend for PV and Wind energy generation. [9]

An estimated 23.5% of all electricity produced in 2015 was provided by the renewable energy sources –5660 terawatt hours (TWh). The global electricity generated by source, 2015 is represented in Fig 3.1[5]

RES can be used in two different modes, Grid-connected and standalone. Grid-connected systems are independent decentralized power system connected to the electricity transmission and distribution system or grid. These kinds of RES are appropriate for the applications which are close to the electricity grid. They allow to draw power from grid when the power produced by the RES is less than the load demand. Standalone RES are autonomous, not dependent on grid power. In the standalone applications of RES, the operational capacity of the generators and storage is designed to match the demand. One of the growing uses of standalone RES is in powering the remote areas where grid power is significantly expensive due to high transportation cost. Figs 3.3 A and B represent the grid connected and standalone RES [10][11].



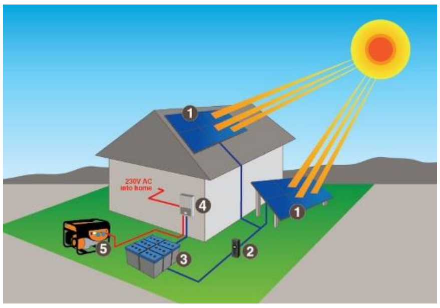


Fig 3.3A

Grid Connected system[10]

Fig 3.3B

Standalone system[11]

3.1.2 Grid connected systems

There are two t types of use of the grid-connected systems [12]. The first type is mostly for catering the local power demands and any excess power generation is sent to the grid. When there is deficiency of power supply from the RES due to unfair meteorological circumstances, the required load demand can be met by the grid.

The other type is utility scale RES. In this scenarios the decentralized stations are maintained by the utilities similar to the large electric power plants . The power generated by these systems is fed into the central power grid rather than serving the local power requirements. Few important features of grid connected systems are stated below [12].

- The functioning capacity of these kind of RES is determined by the supply sources. Unless the supply sources are available, this system would not function.

- As they are connected to the grid, these systems can be set up systems in relatively large-scale and enables these systems to run at high plant load factors which improves economic feasibility of the process.

- In grid connected RES the grid takes the role of a battery with an infinite storage capacity which has the capacity to compensate the seasonal load discrepancies resulting the overall efficiency of a grid-connected system better than the standalone system. These systems has almost unlimited storage capacity, hence, the excess generation can always be stored. This contributes to the further improvement the system efficiency as a result of result of reduction of excess generation when the demand is not at its peak.

- The cost involved in interfacing of these types of systems with the grid is incurred in adding to the initial system set up cost.

3.1.3 Standalone systems

Standalone RES are independent of the utility grid. Standalone RES are more appropriate for remote areas where extension of the grid is significantly complicated, and no other source of energy is available there. Standalone systems, comprising of the PV panels as generator along with storage, are profitable choice for applications which are away from the utility grid. Some applications that widely uses these kinds of systems would be the lighthouses and other remote stations, supplementary powering units for emergency services and military bases, and industrial services using delicate electronics devices [13]. However, standalone RES have some characteristic drawbacks such as low capacity factor, high battery costs and limited capacity to stock excess generation which contributes to the waste of the excess generation [14].

Some significant characteristics of standalone RES are as follows.

- In these kinds of RES, the operative capacity is designed to match the load demand.

- In this kind of RES the local load demand has the maximum priority.

- These systems are ideal for distant applications, where the system has low plant load factors.

- These kinds of systems are mostly built on technologies like PV, which are mostly seasonal.

- Due to unavailability of the utility grid, they need storage for the excess generation during off-peak demand stages, leading to extra cost for battery and storage. Otherwise the excess generation would be wasted.

The Grid connected and standalone RES have their own strengths and weaknesses. Hence the selection of grid connected or standalone RES for a specific application depends on numerous factors. Both systems primarily use renewable energy sources ensuing substantial reduction in the greenhouse gas emissions and climatic change. The standalone RES are favoured applications where the grid accessibility is an issue. These kinds of RES are suitable to supply power to hilly areas and distant communities.

Other major factors the affects the selection of grid connected or standalone RES are the viability and load factors. In case of grid connected RES the excess power can be sent to the grid. Hence, the grid connected RES are not influenced by the low load factor that is a typical characteristics of rural power situation. As the grid performs as an unlimited storage, it enables uninterrupted operation of the system also disregards any extra costs on storage.
However, the grid extension is extremely expensive in remote areas. In situations like that, the standalone RES are inevitable. Hence, before considering RES, it is important to study the pros and cons under which standalone or grid connected RES might be feasible for any application.

The changeable nature wind and solar applications and their strong dependency on climatological changes are their main disadvantages. As a result, the differences of production from the solar and wind energy generator might not align with the load demand time distribution. This limitation affects the energy performance of the RES and reduces the batteries life. The autonomous use of either PV or wind generators may cause significant over-sizing, making the design less cost-effective. Due to seasonal dissimilarities neither the PV nor wind generators can deliver uninterrupted power supply for standalone applications.

This problem can be overcome by incorporating more than one types of renewable generators in an appropriate combination, where one sources weakness can be overcame by other one’s strength. Integration of multiple types of renewable generators improves the efficiency of the system and increases the reliability of the energy supply. This also helps to reduces the requirement of storage with respect to the RES comprising of only one type of renewable generator. As the PV and wind generators have complementary characteristics, for certain sites, the RES including both PV and wind with storage better options due to high reliability. RES comprising of more than one types of renewable sources and/

or storage are called Hybrid Renewable Energy Systems (HRES). HRES may include both renewable non-renewable sources.

HRES those contains wind and solar generators as main resources can function in two modes. They are simultaneous and sequential. When they operate in simultaneous mode, both the solar and wind energy sources generate energy simultaneously whereas in sequential mode the sources generate energy alternatively. The speciality of HRES are that they incorporate more than one types of renewable generators and uses their operating characteristics efficiently which assists the HRES to achieve higher efficiencies than a RES containing a single type of generator. HRES can perform in both grid- connected or stand-alone mode.

The basic elements of a PV/wind HRES can be presented as is Fig 3.4 [15]. The PV and solar generators and the storages are connected to the AC/DC bus via the converters. As per the network requirement that AC/DC bus may be connected to another AC/DC bus via converters. In the case of grid-connected systems that AC/DC bus may be connected to the power grid or it can be connected to the load for standalone applications.

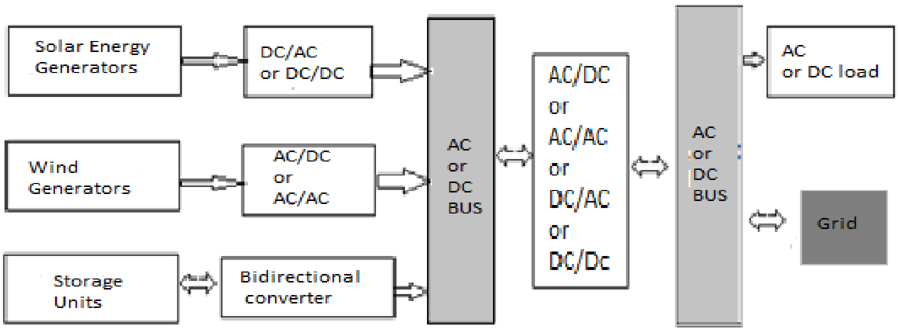


Fig 3.4 The basic elements of a PV/wind HRES [15]

The design process of HRES more complex with respect to the RES with single type of source. The complication arises due to numerous factors, i.e. the uncertain nature of the of renewable energy generations, load requirement, nonlinear features of the components, multiple parameters and variables are to be taken cared of to design the HRES optimally. Moreover, the optimum configuration and optimum control strategy of HRES are inter-reliant. This turns the design and analysis process of HRES more complicated [16].

Appropriate sizing of the components of HRES is very important as oversizing or under sizing may increase the set-up cost or incapacity to cater the load requirement. Studies have been conducted to optimally design the system components of HRES and improve the performance, reliability and accuracy of prediction of the power generation of HRES to increase their acceptancy as alternative power sources. [17].

The advantage of the grid-connected systems is that the excess generation can be sent to grid and in case of insufficient generation the excess requirement can be supplied by the grid. As the standalone system does not have that facility, the design of standalone HRES for any application becomes more complicated. Hence, few considerations need to be made while designing the standalone HRES. They are discussed below:

- Before setting up any RES for any location, it is important to ensure that the targeted location has the availability of the required renewable resources. As an example, to set up a standalone HRES with PV and battery storage for an application, one needs to make sure that the average solar irradiation of the targeted location is good enough for produce required amount of power. Otherwise system efficiency will be poor. Likewise, to consider wind power, one must confirm that the targeted location has good enough average wind speed as every wind turbine has a cut in wind speed below which they don't start producing. It also have a upper speed limit which it can gain without damaging the system, called Cut out speed. For example, wind turbine named IEA_15MW_240_RWT has a cut in speed of 3m/s and cut out speed of 25m/s. the safe performance of the turbine will be achieved during the wind speed of 3m/s-25m/s. Once the turbine reaches 25m/s it must shut down to avoid any damage to the system. So, if the average wind speed of that location is less that the required speed the wind generators will not be able to produce required energy. Similarly in case of PV systems it is important to make sure that the solar panels does not exceed the rated voltage to avoid damage of the panels. This investigation of availability of resources are called Feasibility Study.

- If the potential location has the availability of more than one types of renewable resources, the initial part of the design would be the selection of most relevant renewable technology or technologies so that the selected system could be cost effective and more reliable.

- The operational period of these systems are approximately 25 years. The power need is constantly increasing in modern lives due to advancement in technologies. Hence, for the system to work efficiently for its entire lifetime, load forecasting of coming 25 years is very crucial.

- Critical stability and power quality problems can be caused by the dynamic interaction between the load requirement and the HRES components [17]. Hence, to ensure uninterrupted power follow between the components of the system, a proper power flow management is required for HRES.

To improve the performance and the efficiency of HRES several researches have been conducted. To conduct feasibility study, for forecasting the load demand more accurately, to model the system components accurately, to size the components of the HRES optimally and for power management between the components of the HRES, various methods have been studied and established. Some of the numerous methods that has been studied and investigated during the present work related to the various parts of the design of HRES are discussed in the following chapters.

3.2 Meteorological and Climatological data for designing HRES

The feasibility study of the aimed location is carried out as the first step of designing the HRES. This study is customised for the targeted location which includes the analysis of the meteorological conditions, accessibility of the renewable resources and assessment of present and past load demand and prediction of future load demand. This study is very important to determine the potentials of setting up a HRES for any location.

The accessibility and efficiency of the PV/wind energy of a location are determined by meteorological conditions. The climatic conditions are the main factors that decide the availability and significance of solar and wind energy of a site. For different locations, the climatic conditions, such as solar radiation, average wind speed, air temperature, etc. are always altering. For better exploitation of the solar and wind energy resources, analysis of the attributes of solar radiation and wind conditions at a prospective site should be made at the stage of establishment [23]. Feasibility of establishing a solar–wind HRES mainly depends on solar radiation and wind energy potential of the targeted location. Hence, designing a hybrid renewable energy system one requires appropriate weather data.

The maps for the potentials for global wind and solar energy are shown in Figs 3.5 and 3.6 [19].

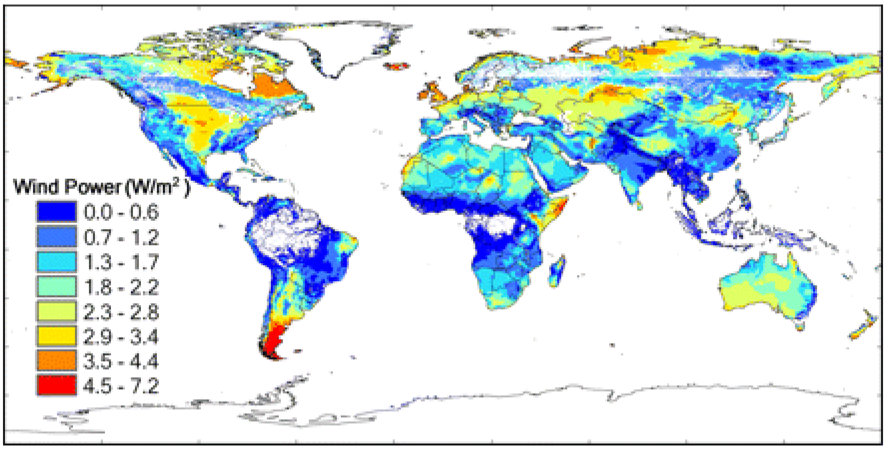


Fig 3.5 Map for global distribution of wind power potential (W/m2) (annual average onshore) for 2006

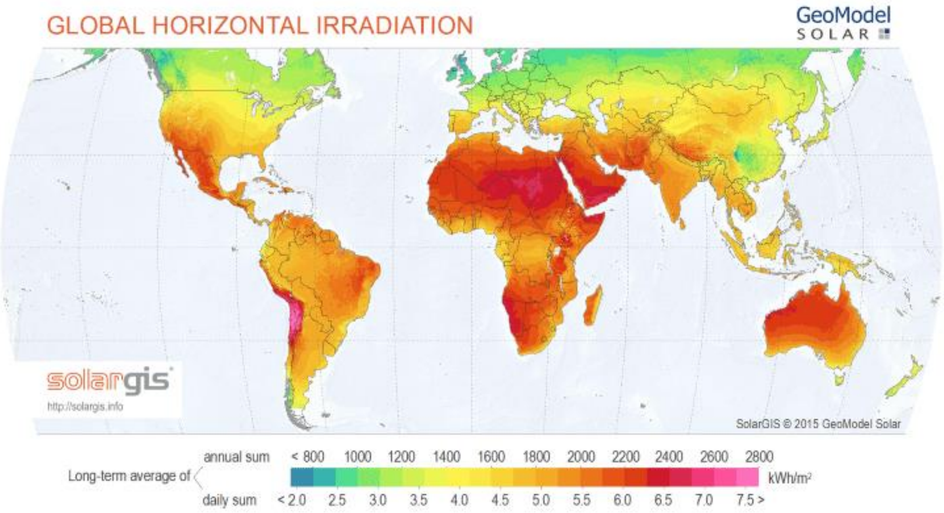


Fig 3.6. The map for global solar energy potential [20]

The assessment of appropriate RES technology for the targeted location should be conducted with precise data and information related to long-term availability of all possible RES (e.g., through meteorological, wind, solar radiation, and other RES measurements). It is also very important that the operation of the RES is assessed with respect to an appropriate time frame considering the present electrical energy demand and future development of the HRES in order to meet change (i.e., increase) of energy demand [26].

3.2.1 Time-series meteorological data

For the targeted location, the analysis of suitable RES should be carried with accurate data and statistic in relation to the long-term obtainability of all renewable resources considered. That should consider climatological conditions, wind speed, solar irradiation, and all other possible qualities of the renewable resources.

To guarantee reliable power supply and increased efficiency of such systems, researchers utilised time-series climatological statistics for feasibility study and design of the HRES. Various climatological data like hourly solar radiation, average wind speed, and atmospheric temperature are considered to analyse the performance of these systems. The required comprehensive whether information can be attained from different resources. Using these global weather conditions for the targeted location the performance of an HRES can be estimated.

To determine the most viable HRES configuration, site based climatic data is generally required [21]. Research has been undertaken on analysing and figuring out the potentials of using solar and wind energy in different locations and countries [22 - 26]

3.2.2 Statistical climatological data

The hourly climatological data might not be available for many locations for long periods. In such situations the climatic data can be attained in two methods [27]. The first process is to populate the required data from the average monthly values of the available climatic data of the location. Using some statistical properties of the wind speed and solar radiation this can be achieved [28]. The alternative method would be by extrapolating the weather data from a nearby site and making some required alternation [29]. When the complete weather data is not available for any location, it is beneficial to work with artificially generated data which reduces computational effort. To generate the data for solar radiation and wind speed and temperature information of a site various investigations has been reported in literature. An hourly basis and daily solar radiation generators have been developed by Gordon and Reddy [30][31]. A mechanism of populating the hourly data for solar radiation and ambient temperature has been presented by Knight et al. [32]. The procedure to obtain the humidity and wind speed data was also suggested by them. In the algorithm they use the existing monthly-average solar radiation information for the selected site to populate the hourly solar radiation depending upon the cumulative frequency distributions of the daily clearness index.

Typical meteorological year’ (TMY) is a very well-known synthetic data sequence commonly used for simulating the solar data. For any site, the hourly TMY data generally consists of one years of hourly data. The best characteristic of a month is nominated from long-term meteorological information.

However, the same information also can be obtained from numerous years of climatic data resulting the same statistic i.e., clearness index and average solar radiation.

A methodology was developed by Hall et al. to obtain the TMY data [33]. That is an investigational method of choosing a distinct month from different years using a technique called the Filkenstein–Schafer statistical method. Various studies have been reported to generate TMY for different locations [34-35]. Various weighting factors of climatological parameters are considered in these studies. Yang and Lu developed a local TMY for solar and wind energy assessment. Their study also shows the importance of the determination of correct climatic parameters and also their weighting factors for deploying the TMY.s for various RES.

To assess the performance of different HRES, various feasibility and performance studies have been reported in literature constructed on statistical climatological data [37-39].

The targeted community is located at Portland Victoria Australia (38° 20′ 0″ S, 141° 36′ 0″ E). Feasibility study has been conducted to check the prospects of developing a hybrid renewable energy system comprising of solar generators and wind generators as primary sources. Irradiance and wind speed data for Portland have been obtained from the website of Australian Bureau of Meteorology for this study. Figs 3.7 and 3.8 represents the seasonal variations of average sunshine hours, Figs 3.9 and 3.10 shows the daily global solar exposure of Portland of the months of July and January and Fig 3.11 represents the Mean 9am and 3pm wind speed of Portland(km/h) for one year. From these figures, one can observe a significant seasonal variation of the climatological conditions.

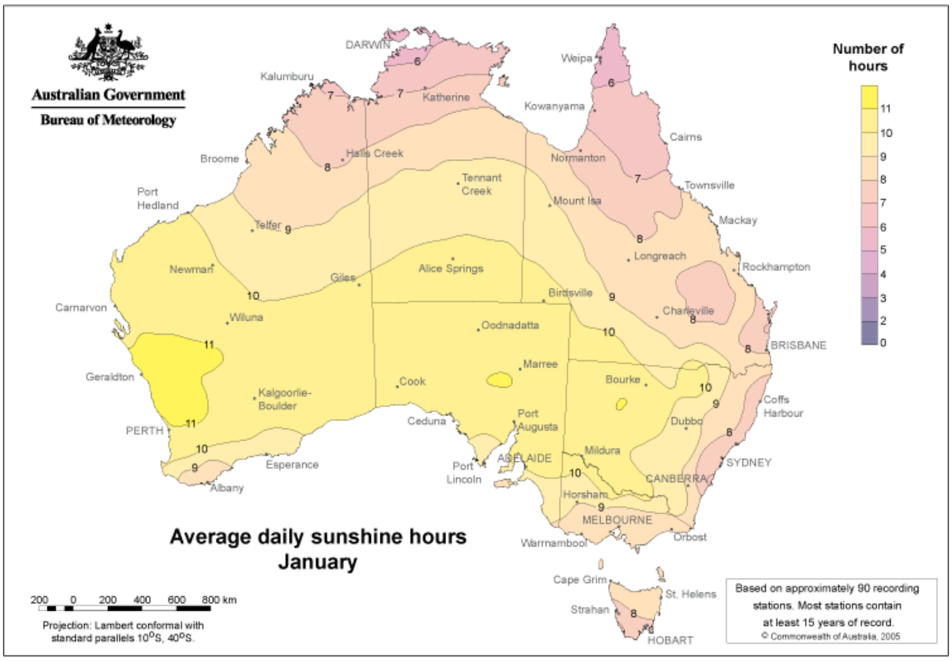


Fig 3.7 Average daily sunshine hours for January

Source: Australia Govt. Bureau of Meteorology

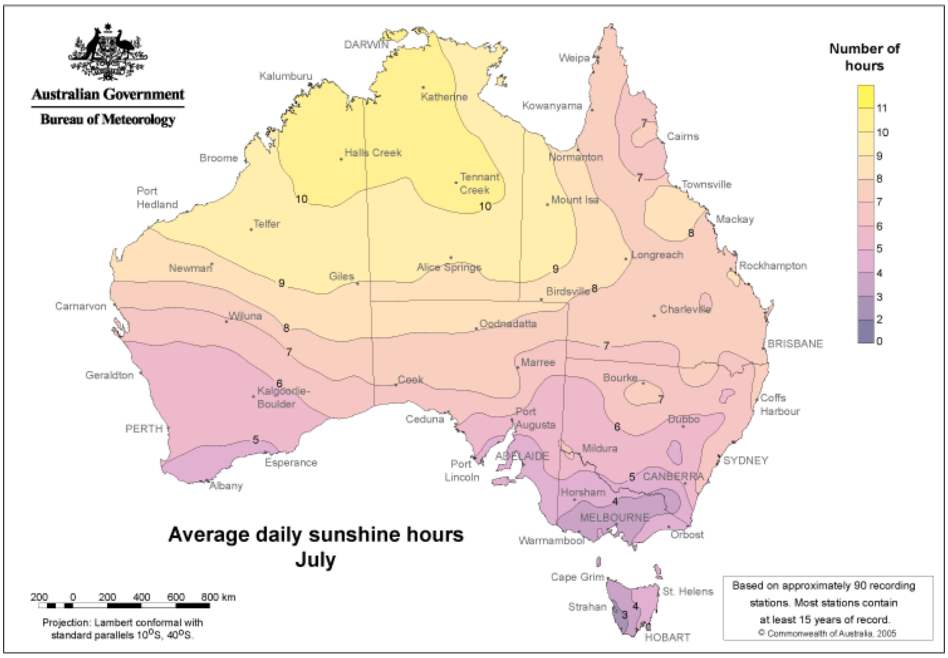


Fig 3.8 Average daily sunshine hours for July

Source: Australia Govt. Bureau of Meteorology

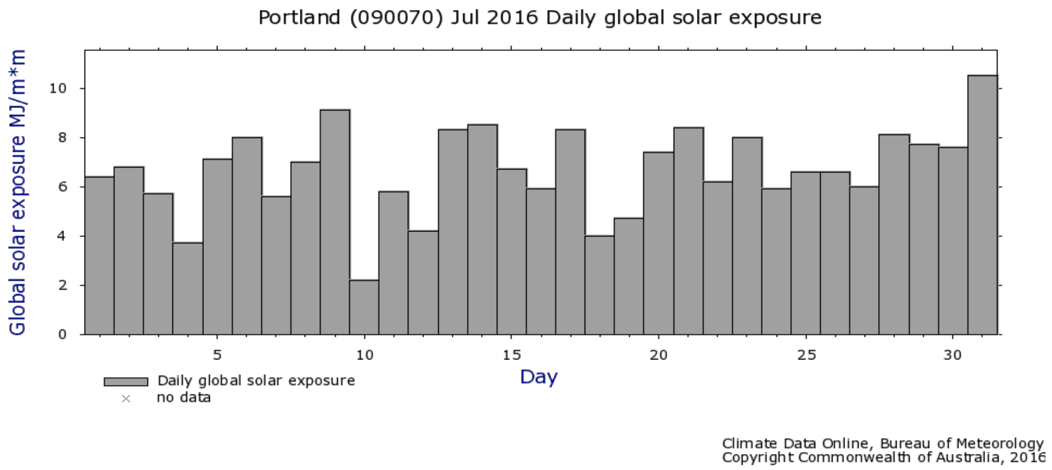


Fig 3.9 Portland Daily global solar exposure July

Source: Australia Govt. Bureau of Meteorology

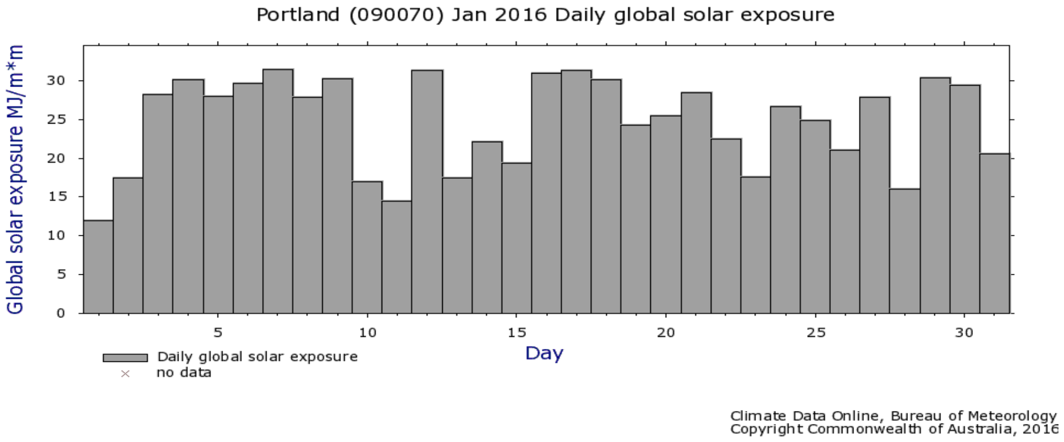


Fig 3.10 Portland Daily global solar exposure July

Source: Australia Govt. Bureau of Meteorology

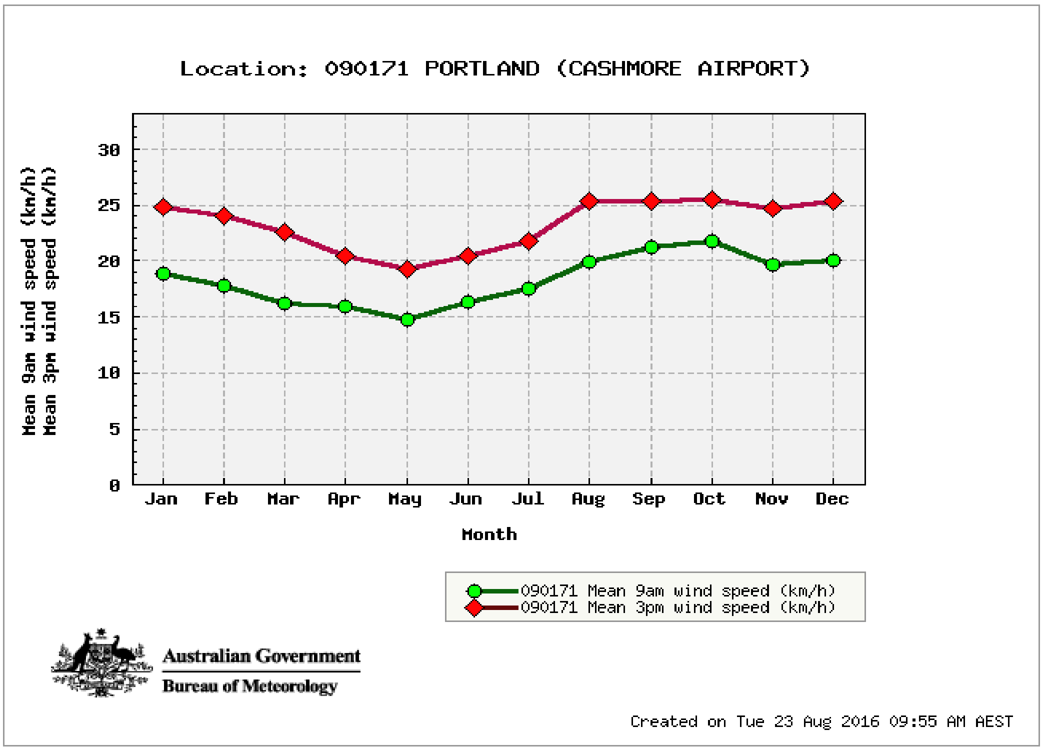


Fig 3.11 Mean 9am and 3pm wind speed of Portland(km/h)

Source: Australia Govt. Bureau of Meteorology

From the data obtained from Australia. Bureau of Meteorology (BOM) were also considered the average solar radiation for Portland, Victoria, is approximately 4.43 kWh/m^2/day. As per BOM, the annual average wind speed of Portland, Victoria is approximately 5.6m/s. So as per the data Portland has good prospect for solar and wind generation.

3.3 Simulation modelling of HRES components

Standalone solar/wind HRES normally comprising of PV arrays, wind generators, storage battery, inverters, controllers and other required devices and wirings. The PV panels and the wind turbines are the main generators of the types of standalone HRES. When the power generated by these generators are more than the load demand the excess generation is utilised to charge the storage battery bank till its maximum state of charge (SOC) is reached. When the generated power is less than the load demands the battery, bank is discharged to supply the load demand till it reaches its minimum SOC.

The performance of the standalone PV/Wind HRES is primarily dependent on the performance of its components. Hence to forecast the system's performance accurately it is crucial to model the individual components correctly. Once that is done, their combined performance can be evaluated to satisfy the desired reliability of power supply. The consequent configuration will be able to supply the load requirement cost effectively if the forecasted power generation is accurate enough.

3.3.1 Modelling of photovoltaic system

To select the right components of HRES and predict their power generation accurately it is very important to analyse their performances under various operating conditions. PV modules performance depends on their material, temperature and solar radiance on their surface. Numerous studies have been conducted on the influence of environmental factors on PV panels performance [40-47]. A approach for determining the optimal size of a battery bank and PV array for a freestanding hybrid wind/PV power system is developed in [43]. The researchers used 30-year-old data on wind speed and irradiance for every hour of the day. The average power generated by a wind turbine and a PV module for each hour of a normal day in a month was calculated using these data.

Researchers reported their discoveries on the effect of temperature on the silicon photocells. Results of the monocrystalline solar cells and photodiodes were utilised with a substantial light sensitive area for assessment purpose [40]. The dependency of the system performance on the temperature coefficient were studied by Nishioka et al [41] for assessing the yearly production of a PV system under real operating situation. It has been detected that the yearly generation of energy of the PV system has been improved by about 1% by an enhancement of 0.1%/C of the temperature coefficient.

Some basic simulation models, i.e. power efficiency models, have been examined many researchers [42-47], to forecast the time series or average performance of the PV system under numerous environmental circumstances for various engineering applications.

A new procedure to obtain the current–voltage (I–V) characteristics of PV units were investigated by Kerr and Cuevas [48]. That procedure calculates the open-circuit voltage (V_{oc}) simultaneously as a function of a slowly varying light intensity. The theoretic investigation and understanding of such quasi-steady-state V_{oc} measurements were clarified in their research.

A methodology to compute the maximum power output of any particular PV panel depending upon the solar radiation on the PV panels ambient temperature was presented by Borowy and Salameh [43] Zhou et al.[44] represented a model to forecast the PV panels performance for different applications which is based on the I-V curve of the PV panel. Due to compound dependency of PV generator performance on PV module temperatures and solar radiation intensities. The author suggested that this basic model is beneficial for engineers to compute the performance of the PV generators under various working circumstances, when inadequate data is supplied by the PV generator manufacturers.

Jones and Underwood presented a model to calculate the output power of the PV panels which is built on an adaptation of the conventional PV fill factor process [47] [49]. Authors considered the solar radiation and temperature features in the conventional theory to establish the overall PV power efficiency mode. The PV array generated AC power was projected as a function of the number of PV modules N_m in the array, the power output of a single PV module and the efficiency of the inverter η_{inv} which can be presented as equation (3.1) [47][49]

$$P_{Array} = FF \cdot \left(I_{SCO} \cdot \frac{G}{Go}\right) \cdot \left(V_{OCO} \cdot \frac{In\,(K_1\,G)}{In\,(K_1\,G_0)} \cdot \frac{T_0}{T_{module}}\right) \cdot N_m \cdot \eta_{inv} \qquad (3.1)$$

K_1 = Constant k1 = around $10^6 m^{2}$ /W

I_{sco} = The short circuit current (A)

V_{oco} = The open circuit voltage (V)

G = The solar irradiation on an inclined plane in (W/m^2)

G_0 = Solar irradiance reference (1000W/m^2)

N = Number of modules constituting the PV field

FF = Form factor

The established model was validated using the data that was measured from a 39.5 kW PV system. The power output of the PV generators was calculated under two different weather conditions, for clear sky situations and overcast sky situations. The yearly data were collected for this purpose

3.3.2 Modelling the wind energy system

To derivation of the mathematical model of a wind energy generator one needs to include the dynamics of wind turbine and modelling of the generator. As per the existing literature on the assessment of the wind energy systems not much studies have been conducted in this area. Studies has been reported on regional wind energy assessment [51], financial aspects of wind energy [52] and local wind energy guidelines [53].

The output power performance characteristics is different for different wind generators. The wind generators performance differs depending upon the wind turbine models. Hence, it is important to select an appropriate wind turbine model for simulating the wind turbine performance which is an important step to plan and implement the wind generator projects. To obtain the long-term performance of the wind system, the hourly wind speed data can be used. The power generation of a wind turbine normally starts and the cut-in speed and rises linearly with wind speed rise from cut-in speed to rated speed.

Due to safety reasons the wind turbine shuts down when the cut-out wind speed is reached. Based on the estimations discussed above a basic model of a wind turbine is offered in the literature to simulate the power generation of a wind turbine [54]. In their work some researchers presented similar form model in relation to the Weibull shape parameter k [55][56]. Borowy and Salameh [57] presented a mathematical model of a horizontal axis wind turbine with three blades. The generated mechanical power output from the wind turbine can be presented as [58]

$$P_t = -\frac{\left(C_{P\ \lambda}\, \rho\, A\, V^3\right)}{2} \qquad (3.2)$$

The developed torque by the wind generator is expressed in equation (3.3)

$$T_t = \frac{P_t}{wm} \qquad (3.3)$$

Where the output power is P_t, the torque generated by wind turbine is represented by T_t, the power co-efficient is denoted by C_p, the tip speed ratio is λ, ρ represents the air density in kg/m^3, the frontal area of wind turbine is A and the wind speed is V.

$$\lambda = \frac{wR}{v} \qquad (3.4)$$

The turbine rotor speed is denoted by w in rad/s, radius of the turbine blade in m is presented by R, and v is the wind speed in m/s.

Zamani and Riahy [59] presented as new method to calculate the output power of wind generators that considers wind speed variations. In their study, they evaluated the rate of wind speed dissimilarities by the energy pattern factor (EPF) of real wind. They also assessed the performance of rotor speed and pitch angle controllers using wind turbine controllability (Ca). The power curve is adjusted bearing in mind the additional power captured by the controllers.

3.3.3 Modelling of battery storage system

Renewable energy has some advantages and disadvantages. Incorporation of renewable energies has some technical and financial complications. The power generated from these sources cannot be straightforwardly stored or transported like the power generated by the conventional sources.

Additionally, power generated by these sources can be very irregular and inconstant. Due to this constrain storage systems or batteries are essential to recompense the irregular power distributions of solar and wind generator.

Studies has been reported in literature on development of the behavioural model of battery. In their research Kim and Hong [46] studied the discharge performance of a flooded lead–acid battery cell. Their research was influenced by the works of Gu et al. [60], Ekdunge and Simonsson [61]. In their work, Ekdunge and Simonsson investigated the integration of mechanism of diffusion–precipitation in the kinetics reaction of the negative electrode.

Bernardi and Carpenter [62] established a mathematical model for led-acid batteries where they added the oxygen recombination reaction. Nguyen et al [63] presented an equivalent model of the flooded type. The examined the dynamic characteristics of the cell while discharging with respect to cold cranking amperage and reserve capacity. As per them, the battery bank models are complicated to express as there are several parameters involved. Many of these parameters can be determined by determining the internal components or by investing extensively. Yang et al. [64] suggested that the lead–acid battery characteristic can be presented by two indexes. They are the state of charge (SOC) of the battery and the floating charge voltage which also called as the terminal voltage. In their work , Morgan et al. [65] investigated the performance of the battery units of an independent hybrid energy system at diverse temperatures taking into account the state of voltage (SOV) as an alternative of SOC. Researchers also presented the models on floating charge voltage simulations [66] where they described the interconnections between the floating charge voltage, the current rate and the battery SOC.

Numerous researches have revealed that the battery charge is a composite function of the battery's operational situations. Hence, the determination of the correction factors is very crucial [67].
The system models used in the study have been explained in detail in following sections (optimum sizing).

3.4. Optimization techniques for the components of HRES

To use the HRES in most proficient and conservative manner ideal estimating of the components is vital. This is critical to guarantee that the most extreme usage of the components with least investment. This is additionally essential to ensure that the HRES can work ideally as far as investments and power unwavering quality obliges. An ideal plan of the components of HRES is the best design compromising between power reliability and framework cost. Thus, while choosing an ideal setup of the parts for a HRES one should assess considering the power dependability and framework life-cycle cost. The implicit rules or approaches commonly used to ideally estimate the parts of HRES [67]. Different Optimum estimating measures/procedure of sunlight-based breeze HRES are introduced in Fig 3.12.

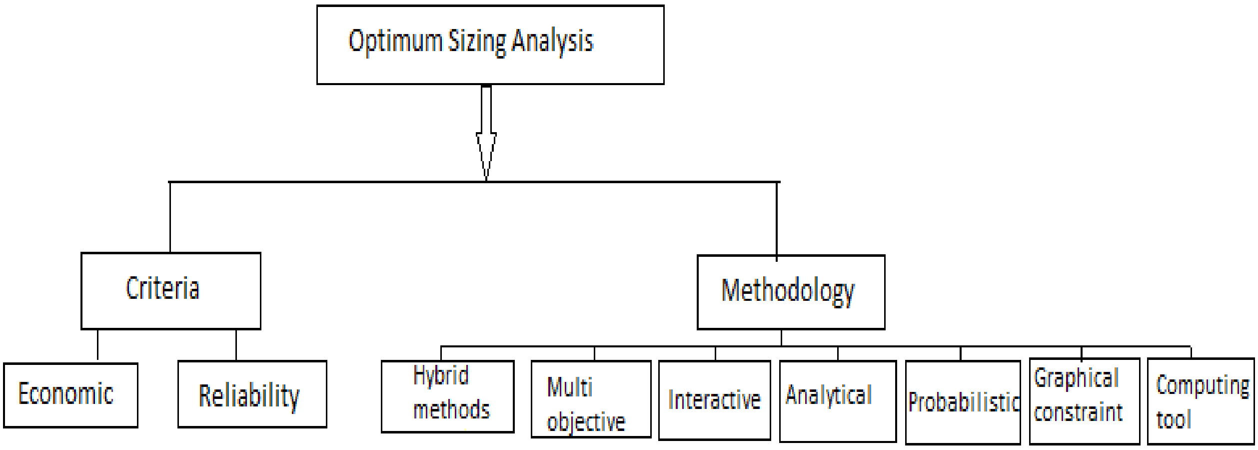


Fig. 3.12 Optimum sizing criteria/ methodology of solar wind HRES

3.4.1 Criteria for hybrid solar–wind system optimization

3.4.1.1 Power reliability analysis

The power generated from the HRES is exceptionally impacted by solar radiation and wind speed. Power reliability analysis is an essential step for ideal framework plan because of the sporadic nature of these elements. Various strategies have been accounted for in writing to calculate the dependability of the HRES. Loss of power supply probability (LPSP) is the most widely recognized one in the midst of them.

LPSP measures the probability of power shortages due to inadequate power generation from hybrid systems (PV, wind, energy storage) to meet load demand [68] [69] [70]. LPSP can be expressed as Equation (3.5)

$$\text{LPSP} = \frac{\sum_{t=1}^{T} DE(t)}{\sum_{t=1}^{T} P_{load}(t)\Delta t} \qquad (3.5)$$

where DE(t) is the deficit energy at hour t and $P_{load}(t)$ is the load demand.

Two methods of applying LPSP to design stand-alone HRES including solar/wind generators have been reported in the literature. The first method is based on time series simulation. This is computationally complex and requires data availability over a specific period of time. Another method is based on probabilistic methods that consider the changing nature of generation and load demand and avoid the need for time series data [69].

Several other performance reliability criteria have also been reported in the literature. For example Load Loss Probability (LOLP), System Performance Level (SPL), and Load Time Loss (LOLH). The probability that system demand will exceed the system's power capacity over each period is measured by LOLP. This is expressed as an estimated number of days over a long period of time [16]. The probability of not being able to handle the load is defined by the SPL. The study also examined a LOLR (Loss of Load Risk) -based method for determining the optimal combination of solar and wind energy in a hybrid system [71]. LCE can be expressed as Equation [70] (3.6).

$$\text{LCE} = \frac{TAC}{E_{tot}} \qquad (3.6)$$

The total annual cost is expressed in TAC and the total annual energy production is E_{tot}. You can calculate the TAC taking into account the current cost. The present value of costs may include the initial value, the present value of maintenance costs and the present value of replacement costs, and the HRES capital recovery factor (CRF). CRF is [73]

$$\text{CRF} = \frac{d(1+d)^t}{(1+d)^t-1} \qquad (3.7)$$

Where the discount rate is represented by d and the useful life of RES is represented by t. Research is also being conducted on other economic approaches, such as System levelized cost [74] and life cycle cost [75]. Scientists have also considered other economic approaches, such as system levelized costs [74] and life cycle costs [75].

3.4.1.2 System Cost Analysis

The Levelized Cost of Energy (LCE), Net Present Cost (NPC), and Life Cycle Cost are just a few of the various economic criteria available in the literature. The sum of the present value of cash flows over time is expressed in NPC. System component setup costs, all component replacement costs, and maintenance costs are included in the NPC [72, 28]. If there is a salvage cost, it is also included in the NPC and its value remains in the system components at the end of system life [33]. A well-known optimization software called HOMER (Hybrid Optimization Model of Electric Renewable Energy) uses the entire NPC to optimize the size of renewable energy sources. The ratio of the system's annual cost to the annual power supplied by the system is expressed by LCE and is defined as [64] [70]. It has been extensively studied by scientists to evaluate hybrid PV / wind system configurations [89]. The following formula represents LCE

$$\text{LCE} = \frac{TAC}{E_{tot}} \tag{3.8}$$

Here, the total annual cost is represented by TAC, and the total energy produced annually is Etot. To calculate the TAC, the present value of the cost and the HRES capital recovery (CRF) are taken into account. The present value of an expense is the value of an upcoming expense or series of upcoming payments on a particular date and is reduced to represent the time value of HRES money. System initial cost, current maintenance cost, and current replacement cost. CRF can be represented as [73]

$$\text{CRF} = \frac{d(1+d)^t}{(1+d)^t-1} \tag{3.9}$$

where d presents discount rate, and t presents the lifetime of the HRES.

Some of the best sizing methods for the HRES components that make up the solar wind system are described below.

3.5 Methodology for hybrid solar–wind system optimization

3.5.1 Probabilistic methods

The easy way to determine the sizes is the probabilistic method. However, the solution obtained using this method may not be optimal. This technique typically takes into account one or two system performance indicators to optimize the size of the HRES component under consideration. The effects of solar radiation and wind speed fluctuations take into account the optimal dimensions of HRES system components in a stochastic approach.

Bucciarelli [76] presented a method for sizing HRES components by considering storage energy fluctuations as a random walk. Several studies have estimated the daily increase or decrease probability density of storage levels from the probability distributions of the two events [77]. This method was further examined and expanded by Bucciarelli [78], taking into account the results of the correlation between daily radiation levels.

The method proposed by Bucciarelli [79] has been further modified by Gordon. In their study, the stored energy transition was estimated by a three-event probability method that overcomes the limitations of the traditional two-event method by fitting the actual distribution of energy generated by HRES.

3.5.2 Analytical methods

HRES is presented as a mathematical model that is a function of feasibility in analytical methods [70]. System performance is therefore measurable over a range of possible system configurations and/or system component sizes. A number of performance indicators are analysed to determine the optimal configuration of HRES. This method allows one to analyse the performance of many HRES configurations. However, this technique requires a long time series of weather conditions (sun and wind) data for the calculation, typically one year. Performance evaluation of HRES can be performed using a mathematical model. Numerous computational tools are available to assess the performance of HRES, helping designers consider incorporating renewable resources.

Connolly Et El analyzed various computational tools for simulating HRES and compared their performance [80]. In their review, they reported a widely recognized analytical tool for assessing the performance of HRES called HOMER, developed by the National Institute of Renewable Energy (NREL) in the United States. Researchers have often used HOMER for optimal sizing of HRES components [81,82-84].

3.5.3 Iterative methods

The iterative method uses a recursive procedure to evaluate HRES performance and ends when the optimal configuration is reached according to design constraints [70]. Yang et al. [29] proposes an HRES optimization model consisting of wind and PV generators using iterative optimization methods LPSP and LCE models to analyse power reliability and system cost. The analysis examines three size specifications: PV array size, wind power generator power rating, and battery bank size. The optimum size setting for a component can be obtained by iteratively searching for all possible system combinations to obtain the minimum LCE for the desired LPSP value.

Ashok [85] designed the optimal HRES for rural communities under a variety of renewable energy configurations. Their study minimized the overall life cycle cost and confirmed the reliability of the system. In this study, a numerical algorithm based on the quasi-Newton method was used to calculate the optimal system configuration.

Interactive artificial intelligence (AI) technology is widely used to optimize the size of HRES components to maximize commercial gain. [86] AI techniques used for these purposes include genetic algorithms (GA), fuzzy logic, and artificial neural networks (ANN). AI technology allows machines and objects to act like human thoughts [87].

Genetic algorithms are probabilistic global searches and optimization techniques based on the natural evolution of species. GA can find global optimal solutions in a multimodal and multi-optimized way [70]. GA is very useful for non-linear systems that are difficult to find Globally optimal. GA is not constrained by local optimization due to the probabilistic development of the solution. GA can find a combination of global optimal systems with simple calculations compared to other traditional optimization methods such as dynamic programming and gradient methods.

Koutroulis et al. [88] proposed the optimal design method for HRES using the genetic algorithm (GA). In their study, the optimal number and type of units were selected from a list of commercially available system devices. This minimizes the cost of the entire system for 20 years, with the constraint that the load supply is completely covered. Yang et al. We designed a pilot HRES consisting of a photovoltaic project using GA. The purpose of this project was to use RES on a remote island in China to power telecommunications relay stations. [74]

ANN (Artificial Neural Network) is a well-known computational model based on biological neural networks. ANN consists of a set of interconnected artificial neurons that allow the model to process information using connectionist computational methods [90]. Kalogirou [88] proposed an optimized model for PV systems using ANN and GA using a computer program called TRNSYS, taking into account the climatic conditions of Cyprus. This study uses a typical Meteorological Year (TMY) file. He trained ANN using a limited number of TRNSYS simulations. The next step is to use GA to estimate the optimal system configuration, maximize the system life cycle, and significantly reduce design time.

Particle swarm optimization (PSO) is another interactive optimization technique described in literature. [88]. Inspired by the social behaviour of flock of birds and flock of fish, PSO is a population-based stochastic optimization method. In this technique, a flock of birds or a flock of fish is the collective movement of multiple self-propelled objects [88]. In their work, Dehgan et al. [91] used PSO to dimension a hydrogen-based wind / PV system for reliability indicators. Changes to the PSO algorithm were made by Wangetal. It was proposed. [92] To develop a multicultural design for integrated power generation systems. In their study, sensitivity studies were conducted to investigate the effects of various system parameters on design performance.

3.5.4 Graphic construction technique

A graphical design method for PV generators and wind turbines was designed based on satisfying the average load demand based on the average production of PV generators and wind turbine generators.

With this method, the optimization process considers only two decision variables. This method typically considers a combination of PV wind or PV batteries [93,94].

Optimal dimensions for stand-alone HRES sources and batteries have been designed using long-term climate data such as hourly solar radiation and wind speed documented in this way over a very long period of time [95]. Some researchers use monthly averages of meteorological data [96].

It is possible to attain the optimum sizes of the PV and wind generators of a HRES, for a given load condition and a specific LPSP, in case the total system cost is linearly connected to number of PV modules and batteries [97]. At the point of tangency of the curve which represents the mathematical relation between the number of solar panels and the total number of batteries will be the point representing the minimum system cost.

Optimal sizing of HRES sources from PV and wind turbines can be obtained if the total cost of the system is linearly related to the number of PV modules and batteries for a given load requirement and LPSP [97]. The point of tangency of the curve represents the ratio of the number of PV modules to the number of batteries are the minimum cost of the system.

Seasonal surveys are being conducted on changes in generator demand and resource availability between winter and summer. Based on this, dimension curves are created between the various available sizes of wind turbines and PV modules. With access to large amounts of data, one can get more sophisticated curves. Some researchers use long-term solar irradiance and wind speed data recorded every hour of the day for 30 years [43]. In this task, typical Massachusetts household load consumption data was entered as the load demand for the HRES design. In this task, the optimal configuration or number of batteries and PV modules was calculated for a particular load demand and selected LPSP based on the minimum cost of the system.

In a study on a particular LPSP [43], researchers plotted the number of PV modules as a non-linear function of the number of batteries. The following cost function has been used to get a PV / battery configuration that minimizes system costs.

$$C = \alpha \cdot N_{PV} + \beta \cdot N_{batt} + C_0 \qquad (3.10)$$

Where

C – represents capital cost of the HRES,

α – Represents cost of a PV module,

β – Represents cost of a battery,

C_O - Represents the total constant costs including the cost of design.

An optimum system combination is achieved when

$$\frac{\delta N_{PV}}{\delta N_{batt}} = -\ \frac{\beta}{\alpha} \qquad (3.11)$$

The solution was demonstrated using the graph shown in Fig.3.13. In this graph the point S correspond to the system configuration which is optimum. The line inclination is equal to (- $\frac{\beta}{\alpha}$) [43].

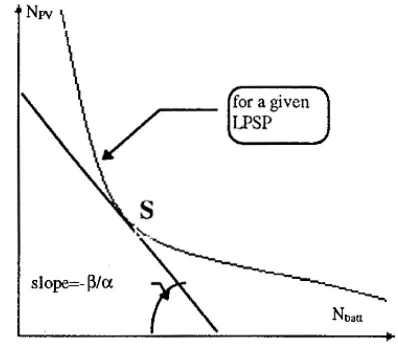


Fig. 3.13 Plot of Number of PV modules versus Number of Batteries for a given LPSP. [43]

3.5.5 Multi-objective design

Before implementing a design in a technical field, designers consider several objectives at once. In some cases, while doing so, conflicts can arise [98]. To optimally design HRES components, a designer should consider at least two objectives. These are minimization of system cost and emission of pollutants [90]. However, the two design objectives are ultimately in conflict because reducing design cost increases pollutant emissions and vice versa. Therefore, the design task becomes a complex one with multiple objectives. The use of mathematical models, with many variables to consider, greatly complicates the design process. Traditional optimization methods require more computation time. It may not be possible to describe all features related to design issues

Methodologies for designing these systems are reported in Refs [38, 72, 99]. In most cases, these studies focus on finding configuration and control mechanisms that minimize the system's total cost of ownership over its lifetime. However, environmental aspects must also be considered when developing this type of system.

Most design methods calculate optimal pollutant emissions and design systems at minimal cost. Some design methods use HOMER when pollutant emissions due to economic development are taken into account and can be considered part of the cost objective function. The cost and emissions mapping used in this manner has a significant impact on design results. The multi-objective design approach used in HOMER is recognized as a weighting method [74]. Another popular multi-objective design task called

Multi-Objective Evolutionary Algorithm (MOEA) has been studied by many researchers. pellets, etc. MOEA was used to optimize the system cost and his CO2 emissions of a standalone HRES intended to cover the load demands (heat and electricity) of his three hotels and cities in the Tunisian Sahara [74].

MOEA was developed by Bernal-Agustin et al. [28] They presented a multi-objective optimization method considering NPC and CO2 emissions for solar/wind/diesel HRES with battery storage using MOEA. Dufo-López and Bernal-Agustín [28] proposed a three-pronged approach to simultaneously minimize total costs, pollutant (CO2) emissions and unmet load demands during the life cycle of a plant. We have presented a methodology that considers optimization. They used MOEA and GA together to find the best combination of system components and HRES control strategies.

3.5.6 Hybrid methods

Methods that combine two or more optimization methods to optimize the dimensions of the HRES components are called hybrid methods. This approach seems to be the best way to solve multi-objective design problems. The literature describes his two general approaches to multi-objective problems. First, merge the individual objective functions into a single composite function. The second technique determines the entire Pareto optimal solution set [100].

Arnette and Zobel discussed multi-objective linear programming (MOLP) models for optimizing components of renewable energy sources and presented fossil fuel power plants on a regional basis [101]. Techniques for optimally sizing wind turbines, PV modules and batteries to construct an optimal HRES on many criteria such as cost, reliability and emissions have been reported in the literature [92]. By Dufo-Lopez et al. he proposed three multi-purpose design methods. Proposed. For isolated hybrid systems by simultaneously minimizing total installed lifetime costs, pollutant emissions, and uncovered loads [102].

3.5.7 Computing tools

For evaluation of the performance of HRES, various simulation programs and software are used by the researchers. We take advantage of computer simulation/software in determining the optimal size of the HRES components by comparing the system performance and production costs of energy for different system combinations. Between the numerous available software tools for optimization HOMER, HYBRID2, iHOGA and HYBRIDS, RETSCREEN are well known. HOMER (The Hybrid Optimization Model for Electric Renewables) is the utmost admired tool for optimizing components of HRES developed by the National Renewable Energy Laboratory. This is the most commonly used software tool for optimizing HRES in both grid-connected and standalone systems [103]. The software can run multiple analyses simultaneously to help answer a variety of design questions. HOMER is used for designing the most cost-effective system, optimizing the dimensions of the HRES components, and for economic analysis. It can also be used for system sensitivity analysis under changing conditions such as load fluctuations and battery prices. HOMER calculates the lowest-cost system combination that meets your specific load needs. This is mainly done through three main steps: simulation, optimization and sensitivity analysis.

3.5.7.A SIMULATION

HOMER simulates system operation by calculating the energy balance every 8,760 hours of the year. HOMER can compare both the electrical and thermal load for each hour to the energy the system can produce at that hour. HOMER also allows one to decide every hour whether to charge or discharge the system's battery. HOMER calculates the total life cycle cost of the system to meet the load demand for one year. This includes capital, operating, maintenance and replacement costs.

3.5.7.B OPTIMIZATION

After HOMER simulates all possible system configurations, it presents a list of viable solutions and ranks them according to lifetime cost. Therefore, one can easily identify the lowest cost system. Depending on requirements, one can choose the most practical solution from the displayed results.

3.5.7.C SENSITIVITY ANALYSIS

HOMER helps one to explore the effects of changing input variables on their design. By assigning multiple values to each input variable, HOMER can perform sensitivity analysis on almost any input variable. Repeat the optimization process for different values of the input and examine the effect on the optimization process. One can specify multiple sensitivity variables. HOMER can analyze the results obtained using its powerful graphing capabilities. To achieve optimal goals, HOMER uses hourly simulations. It evaluates renewable energy systems using hourly load and climate data inputs. The optimal RES is generated based on the current net cost of a given range and set of sensitivity variables.

Researchers have used HOMER in numerous studies [14, 104-106]. HOMER is easy to use and its functionality is very basic. However, depending on the number of sensitivity variables, simulating with HOMER can take a long time. HOMER's fundamental shortcomings are its inability to automatically select suitable system components and its inability to access algorithms and calculations to the user.

The Renewable Energy Laboratory (RERL) at the University of Massachusetts has developed another well-known piece of software called HYBRID2, software that simulates hybrid systems. IT departments can accurately simulate systems and define times from 10 minutes to an hour. The Renewable Energy Laboratory proposes to use HOMER to design an optimal system and use HOMER to further improve it [107].

Another commonly used software for optimizing hybrid renewable energy systems is iHOGA (Advanced Hybrid Optimization with Genetic Algorithms). It was developed in a C++ environment by researchers at the University of Zaragoza (Spain). This software can simulate and optimize hybrid stand-alone renewable energy systems [108]. One can model hybrid systems consisting of generators and AC/DC loads. You can also use PV generators, wind turbines, hydrogen, hydro turbines, inverters or inverter chargers, auxiliary generators, etc. H. Diesel or gasoline, lead-acid or lithium batteries include hydrogen components such as battery chargers, charge controllers, electrolyzers, hydrogen tanks and fuel cells. The software can simulate both grid-connected and stand-alone systems of any size.

Because the software uses detailed models of system components, it can predict system behaviour very accurately. iHOGA uses Genetic Algorithm (GA) to obtain the optimal system configuration. The computation time of this software is very short. Solaris Homes has developed HYBRIDS software that can assess the technical outlook of RES for a given configuration and identify potential ratios and economic feasibility based on NPC. The software is based on a Microsoft Excel spreadsheet with his estimated average daily exposure and climate data for each month of the year. HYBRIDS cannot simulate multiple system configurations such as HOMER and iHOGA. This software cannot provide an optimal system configuration. Advanced knowledge and understanding of RES components is required to operate this software.

Another software tool used to analyse the energy efficiency and affordability of RES is RETScreen, a Microsoft Excel-based software. RTScreen can analyse the energy efficiency of the system, including energy production, life cycle costs and greenhouse gas emissions [109].

Several other software tools for designing and analysing components of HRES have been reported in the literature, some of which is GAMS called The General Algebraic Modelling System [110]. LINDO [111-112], Sim Pho Sys (simulation of photovoltaic systems) [113], GRHYSO (Grid-connected Renewable Hybrid Systems Optimization) [114-115], H2RES [116] ETC.

3.6. Summary

Some widely studied methods of feasibility study and optimisation of HRES is discussed in this chapter.

Feasibility study for an optimized hybrid renewable energy system is crucial in ensuring that the project is technically, economically, and environmentally feasible and can be successfully implemented and tested with optimization techniques to achieve improved efficiency, reduced costs, increased reliability, and better resource management.

The optimization of hybrid renewable energy systems can provide several benefits, including:

Improved Efficiency: Optimization techniques can help improve the efficiency of the renewable energy system by maximizing the energy generation and storage capacity to meet the energy demand, reducing energy waste and increasing overall system efficiency.

Reduced Costs: Optimization techniques can help reduce the costs associated with the renewable energy system by minimizing energy waste, reducing operating costs, and improving the return on investment.

Increased Reliability: Optimization techniques can improve the reliability of the renewable energy system by ensuring that energy is generated and stored efficiently, minimizing downtime and power outages.

Flexibility: Optimization techniques can make the renewable energy system more flexible by allowing it to adapt to changes in energy demand, weather conditions, and other variables.

Better Resource Management: Optimization techniques can help manage the renewable energy resources more effectively by determining the best combination of energy sources and storage systems to meet energy demand.

Environmental Sustainability: Optimization techniques can help make the renewable energy system more environmentally sustainable by reducing its environmental impact, improving its overall efficiency, and promoting the use of renewable energy sources.

Overall, the optimization of hybrid renewable energy systems can lead to a more efficient, reliable, and cost-effective energy system that is better suited to meet the energy demands of the future while promoting environmental sustainability.

DIFFERENT OPTIMIZATION TECHNIQUES
INVESTIGATED IN THIS STUDY

CHAPTER

4

Chapter 4. Different Optimization techniques investigated in this study

4.0 Introduction

Several optimization techniques/tools were studied in this project to understand different aspects. That is HOMER iHOGA and DPSP. They are described in the next sections. However, for the purposes of this study, the technique/methodology used to optimize the size of the HRES components is a MATLAB program based on the DPSP algorithm. This technique was chosen to gain hands-on experience in designing optimal systems using available algorithms. This work was presented at an international conference. As the target site for this project is Portland, Victoria, this research was all conducted to help Portland gain more knowledge about the site's climatic conditions and wind and solar prospects.

4.1 Optimum standalone hybrid renewable energy system design using HOMER for a small community of Portland, Victoria

4.1.1 Introduction

This project aims to design an optimum hybrid standalone renewable energy system for a small community located at Portland Victoria using HOMER.

To design a standalone HRES for a rural area several factors needs to be considered. Firstly, one need to select the most suitable renewable source for that location depending upon the availability of resources. One should also consider the capacity and no of the generation sources, total system cost, the greenhouse gas emission that can be avoided, the excess energy generation, the un-met load, the cost of the storage devices, the variation in the load demand etc.

The work mainly focuses on designing and planning of the optimal standalone HRES for a small community that consists of ten households which is located in the targeted location, Portland. To design the system, sensitivity analysis has been conducted for numerous values of hourly wind speed, solar irradiation, annual average load demand for the community and annual capacity shortage for the community. From the results obtained from the sensitivity analysis, the optimum system was selected.

4.1.2 Proposed system

The study aims to design system which is expected to meet the load requirement of a small community located in Portland, Australia (38° 20′ 0″ S, 141° 36′ 0″ E). The standalone HRES is comprising of wind generators, PV generators, battery storage and converters. Fig. 4.1 represents the proposed system configuration. The wind and solar generators produce electricity according to the available solar and wind resources and supplies the load demand. The battery bank acts as storage which supplies the load demand where there is not enough production from the renewable sources. They also store the excess generation from the renewable sources when the power generation is more than the load demand. The estimated lifetime of the project is 25 years and for calculation purpose, it has been considered that the annual interest rate is fixed at 4%

4.1.3 Electrical Load

The load profile of the targeted community is illustrated in Fig. 4.2 .The average energy consumption of the community is 111.46 kWh/ day with a peak demand 23.93kW.

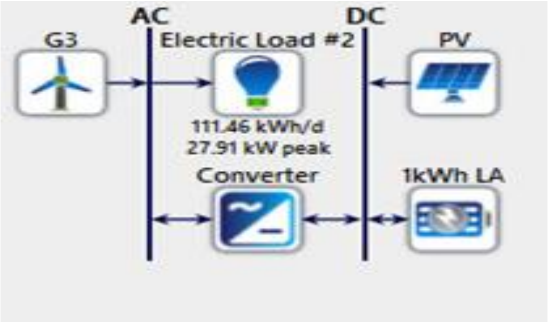


Fig 4.1 Proposed system configuration in HOMER

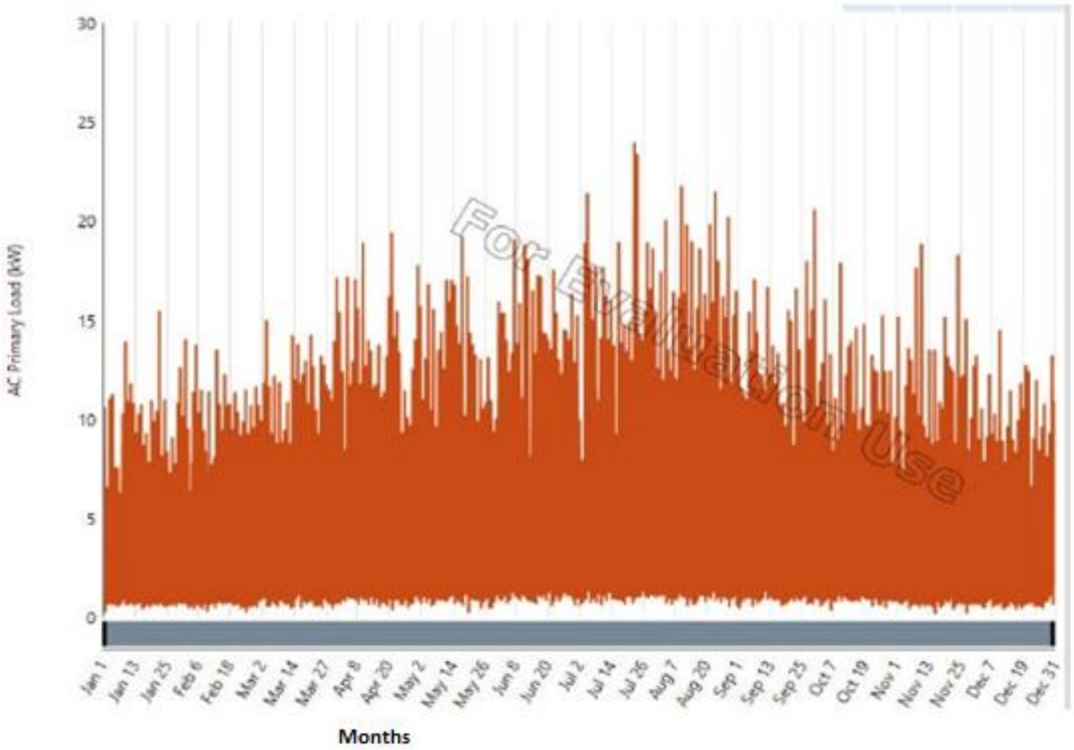


Fig. 4.2 Primary load profile

4.1.4 Solar resources

HOMER accesses the climatic data , i.e. solar radiation , wind profile for the targeted location that is Portland , Victoria (38°20′0″S 141°36′0″E)) from the NASA Surface Meteorology and Solar Energy website [104]. As per NASA website the average annual solar radiation for Portland is 4.43 kWh/m2/day. Fig 4.3 represents the average solar radiation data of Portland over a period of one year.

Generic flat plate PV panels were considered for calculation purposes for this project. This project considers the capital cost of the PV panels as $3000/kW and the replacement cost considered in this project is $3000/kW. The timeline considered for the PV panels is 25 years and operation and maintenance cost is considered as $10/kW per year.

Fig 4.3 Yearly Solar radiation data of Portland, Victoria

4.1.5 Wind resource

As per Nasa website, the annual average wind speed of Portland is 6.71m/s which indicates that Portland has a good prospect for wind energy generation. Fig 4.4 represents the annual wind data of Portland as per NASA website. The wind speed considered on the website is measured 50 meters above the earth's surface.

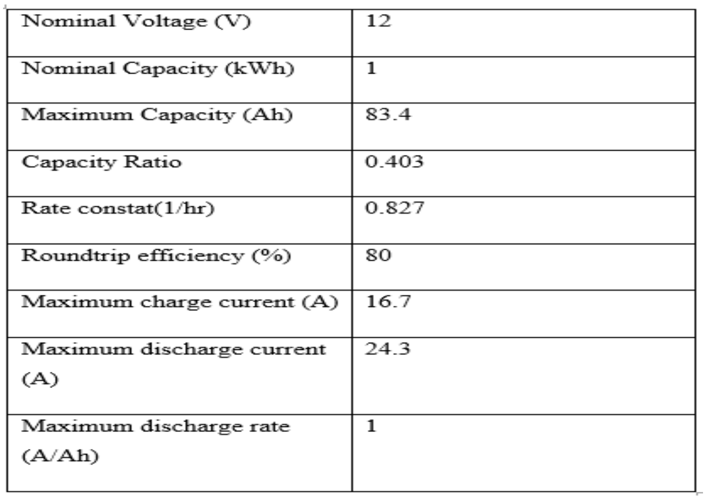
Fig 4.4 annual wind data of Portland as per NASA

This project considers generic 3kW wind turbine for calculation purpose. The turbine has a hub height of 17 meters, the cost of the wind generator is considered as $18,000 per unit, replacement cost considered is $18000 and maintenance and operation cost considered is $180 per year. The project considers the wind turbine lifetime as 20 years.

4.1.6 Storage (Battery)

This project considers generic 12V 1kWh Lead Acid battery, the per unit cost for which will be $300, replacement cost considered is $300 and operation and maintenance cost considered is $30. The lifetime of battery is considered as10 years and throughput is 800 kWh. This project considers the minimum state of charge of the battery bank as 40%. Table 4.1 represents the detail properties of the battery bank.

Table 4.1 Kinetic Mattery Model characteristic



Nominal Voltage (V)	12
Nominal Capacity (kWh)	1
Maximum Capacity (Ah)	83.4
Capacity Ratio	0.403
Rate constat(1/hr)	0.827
Roundtrip efficiency (%)	80
Maximum charge current (A)	16.7
Maximum discharge current (A)	24.3
Maximum discharge rate (A/Ah)	1

4.1.7 Results and discussion

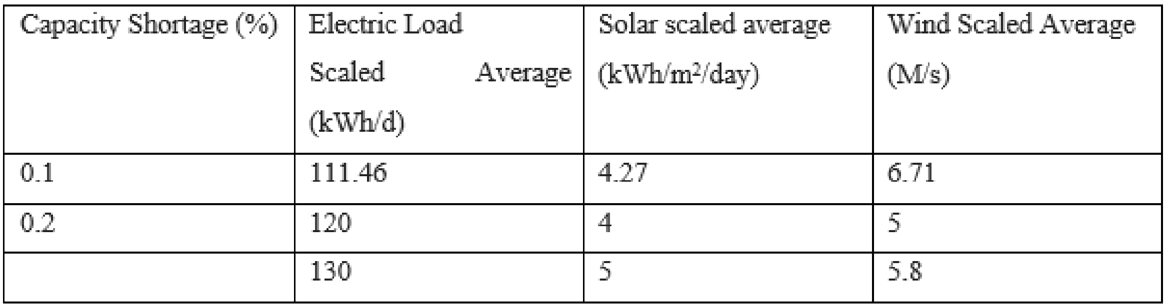
4.1.7.A Optimisation and Sensitivity analysis

Multiple sensitivity variables have been incorporated in the present work to optimally size the components of the HRES for the targeted community. Table 4.2 represents the multiple sensitivity variables that have been considered in this work. HOMER finds the optimum system configuration using this sensitivity variables by running the test for each of the values of this variables and displays the optimum configurations.

For the given values of the variables in the current work, HOMER simulates 54,614 solutions. Due to the capacity shortage constraint, 30,664 of the solutions are feasible. Also 6,980 solutions were omitted due to numerous reasons like lacking or adding unnecessary converter to the solution or for having no power sources.

Upon observing the results obtained it can be observed that the systems that contain both PV and wind generators along with battery back-up are the ones which have lesser NPC. Hence the system that has been selected in this work is the one that contains both PV wind and battery storage.
From the results obtained, the most and least expensive systems are presented in the Table 4.3

Table 4.2 Sensitivity variables and their values



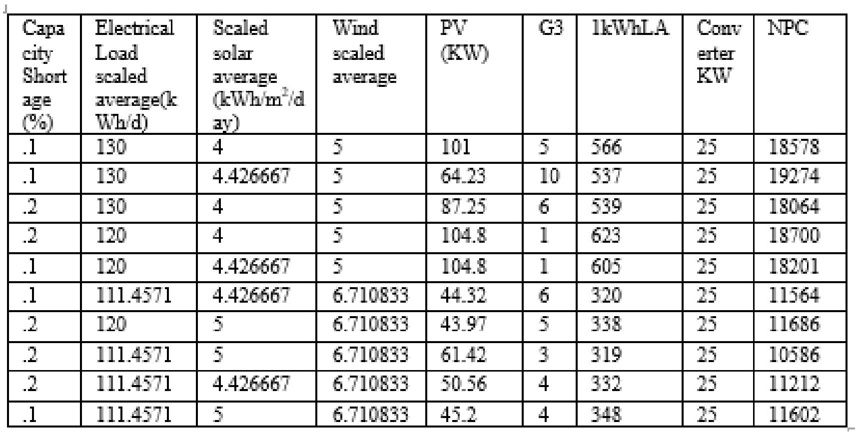
Capacity Shortage (%)	Electric Load Scaled Average (kWh/d)	Solar scaled average (kWh/m^2/day)	Wind Scaled Average (M/s)
0.1	111.46	4.27	6.71
0.2	120	4	5
	130	5	5.8

The results indicate that the optimum system cost is minimum when the average wind speed and solar radiations are at maximum, the average electrical load is at its maximum and capital shortage is considered at 1%. The system selected system consists of PV generator of capacity of 101.107041 kW, 5 wind turbines and a battery storage of 566 kWh LA.

The system with least NPC comprising of 45.19896315 kW PV generators, 4 no's of wind turbine of selected type, and a battery storage of 384 kWhLA. NPC of the system is $462282.9. This is achieved when the wind speed and solar radiation is maximum.

The results indicate that the optimum system cost increases with increased storage battery size. Table 4.3 shows some of the results obtained using HOMER Optimser™ . The top rows of the table show the most expensive systems and the bottom five show the least expensive ones.

Table 4.3. The Optimum system configurations as per HOMER Optimiser™ Top five rows show most expensive systems and the bottom five rows show least expensive systems.



Capacity Shortage (%)	Electrical Load scaled average(kWh/d)	Scaled solar average (kWh/m^2/day)	Wind scaled average	PV (KW)	G3	1kWhLA	Converter KW	NPC
.1	130	4	5	101	5	566	25	18578
.1	130	4.426667	5	64.23	10	537	25	19274
.2	130	4	5	87.25	6	539	25	18064
.2	120	4	5	104.8	1	623	25	18700
.1	120	4.426667	5	104.8	1	605	25	18201
.1	111.4571	4.426667	6.710833	44.32	6	320	25	11564
.2	120	5	6.710833	43.97	5	338	25	11686
.2	111.4571	5	6.710833	61.42	3	319	25	10586
.2	111.4571	4.426667	6.710833	50.56	4	332	25	11212
.1	111.4571	5	6.710833	45.2	4	348	25	11602

The results clearly indicate that the sensitivity variables have significant impact on the optimum configuration of the system, specially the annual average solar radiation and the average wind speed. When these two variables have higher values, the system requires lesser storage and lesser generating units. This therefore reduces the NPC and cost of energy (COE) is also reduced.

4.1.7.B Selection of Optimum System

Some factors are to be considered before selecting the optimum system configuration for the target community. The expected lifetime of the system is 25 years. Hence while selecting the system, one must consider the increasing demand of electricity in modern lives. Taking that into consideration the value of average electrical load has been taken as 130kWh/day.

As discussed earlier, the climatic data HOMER uses are obtained for NASA Surface Meteorology and Solar Energy website. This project also considers the climatic data obtained from Australia Bureau of Meteorology (BOM) [104]. As per BOM, the average solar radiation of the target location Portland, Victoria, is 4.43 kWh/m^2/day approximately. Hence ideally the selected system should consider the average solar radiation of 4 kWh/m^2/day or 4.43 kWh/m^2/day.

As per data obtained from BOM, the annual wind speed of Portland, Victoria is 5.6m/s approximately. This value is less than the value obtained from NASA website as per which the value is 6.71m/s. One important factor to remember that the power generated by the wind turbine changes significantly with a slight variation in the wind speed. Hence the wind speed selection is very crucial factor for selecting the optimum system configuration. Hence it would be a very optimistic act to select the wind speed as 6.71 m/s. This selection might lead to inability to supply the load demand reliability. Hence the average wind speed considered in this project is 5.8m/s.

To ensure minimum interruption to supply the annual shortage will be considered to 1%.

The optimum system selected considering all those factors are presented in the Table 4.4

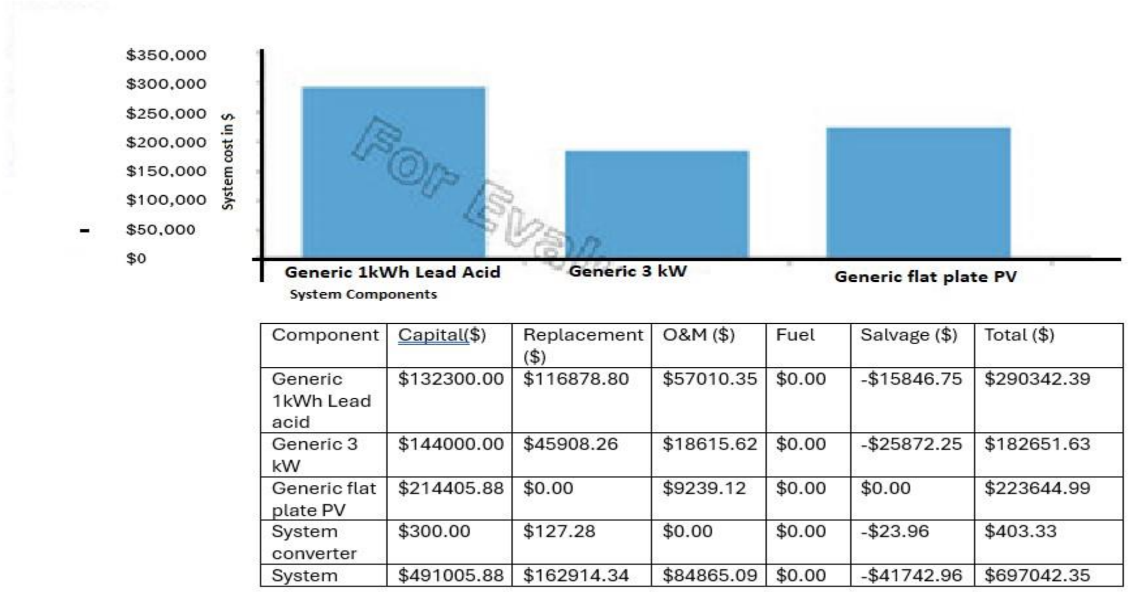
Table 4.4. Selected system configuration

Capacity Shortage (%)	Electrical load scaled Average.	Solar Scaled Average (kWh/m^2/day)	Wind Scaled Average (m/s)	PV(kW)	G3	1kWhLA	Converter (kW)	CoE ($)	NPC ($)	Operating Cost ($)

0.1	130	4	5.8	71.5	8	441	25	1.14	697,042	15,938

The NPC of the system that has been selected is $697,042. The COE for this selection is $1.14, which is significantly higher than the normal charges of grid electricity which is approximately 26.4740 cents per unit for residential customers [105].

The various characteristics of the selected system is represented in Figs 4.5 to 4.10. The cost summary of the system is represented in Fig. 4.5. The cash flow of the system by components in 25 years is shown in Fig 4.6. The monthly average production of electricity by the system components is shown in Fig 4.7whereas Fig 4.8 represents the battery SOC and the battery bank characteristics. The primary AC load of the community and the load served by the designed system are represented in Fig 4.10. Fig 4.11 represents possible excess energy generated by the system and the capacity shortage under the considered climatic condition. These results clearly indicate that system selected can perform optimally under the considered climatic conditions in terms of reliable load supply and cost.



Component	Capital($)	Replacement ($)	O&M ($)	Fuel	Salvage ($)	Total ($)
Generic 1kWh Lead acid	$132300.00	$116878.80	$57010.35	$0.00	-$15846.75	$290342.39
Generic 3 kW	$144000.00	$45908.26	$18615.62	$0.00	-$25872.25	$182651.63
Generic flat plate PV	$214405.88	$0.00	$9239.12	$0.00	$0.00	$223644.99
System converter	$300.00	$127.28	$0.00	$0.00	-$23.96	$403.33
System	$491005.88	$162914.34	$84865.09	$0.00	-$41742.96	$697042.35

Fig 4.5 Cost summary of the selected system

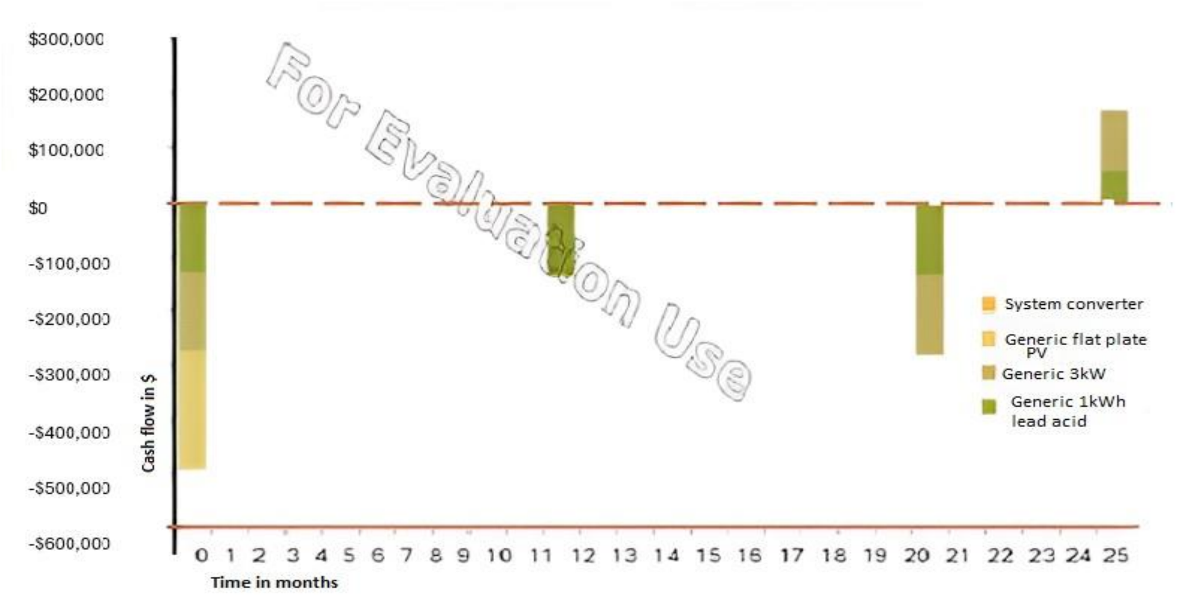


Fig 4.6 Cash flow of the system in 25 years

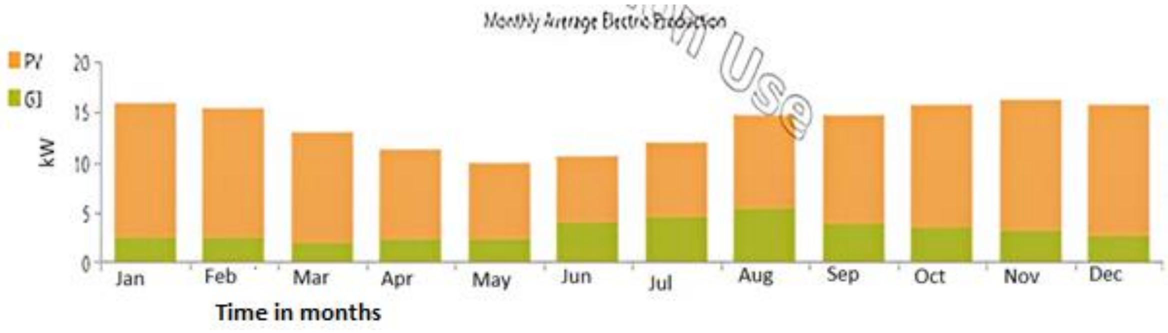
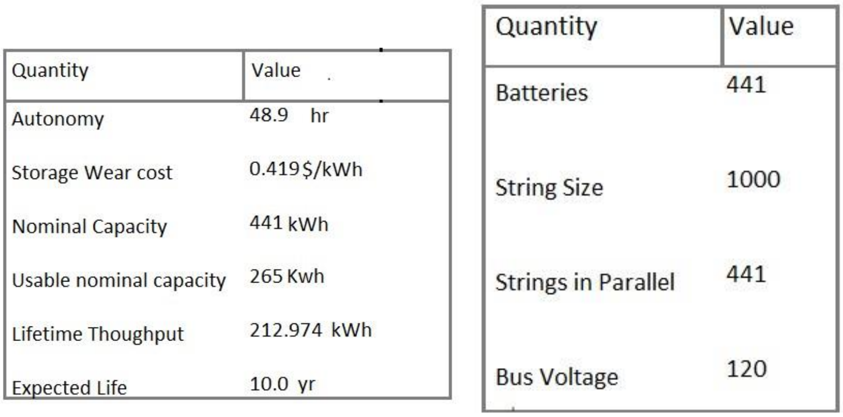


Fig 4.7 Monthly average electric production by component

Fig 4.8 SOC of the battery



Quantity	Value
Autonomy	48.9 hr
Storage Wear cost	0.419$/kWh
Nominal Capacity	441 kWh
Usable nominal capacity	265 Kwh
Lifetime Thoughput	212.974 kWh
Expected Life	10.0 yr

Quantity	Value
Batteries	441
String Size	1000
Strings in Parallel	441
Bus Voltage	120

Fig 4.9 Battery bank characteristics

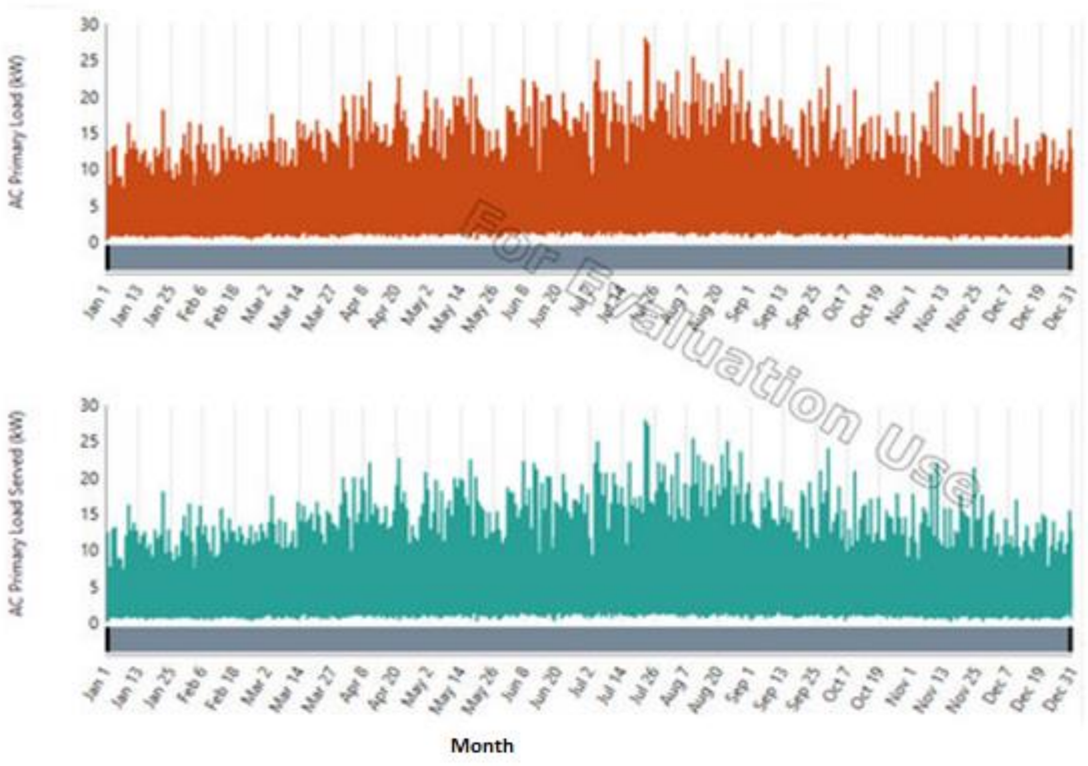


Fig 4.10 AC primary load (top) and AC primary load served (below)

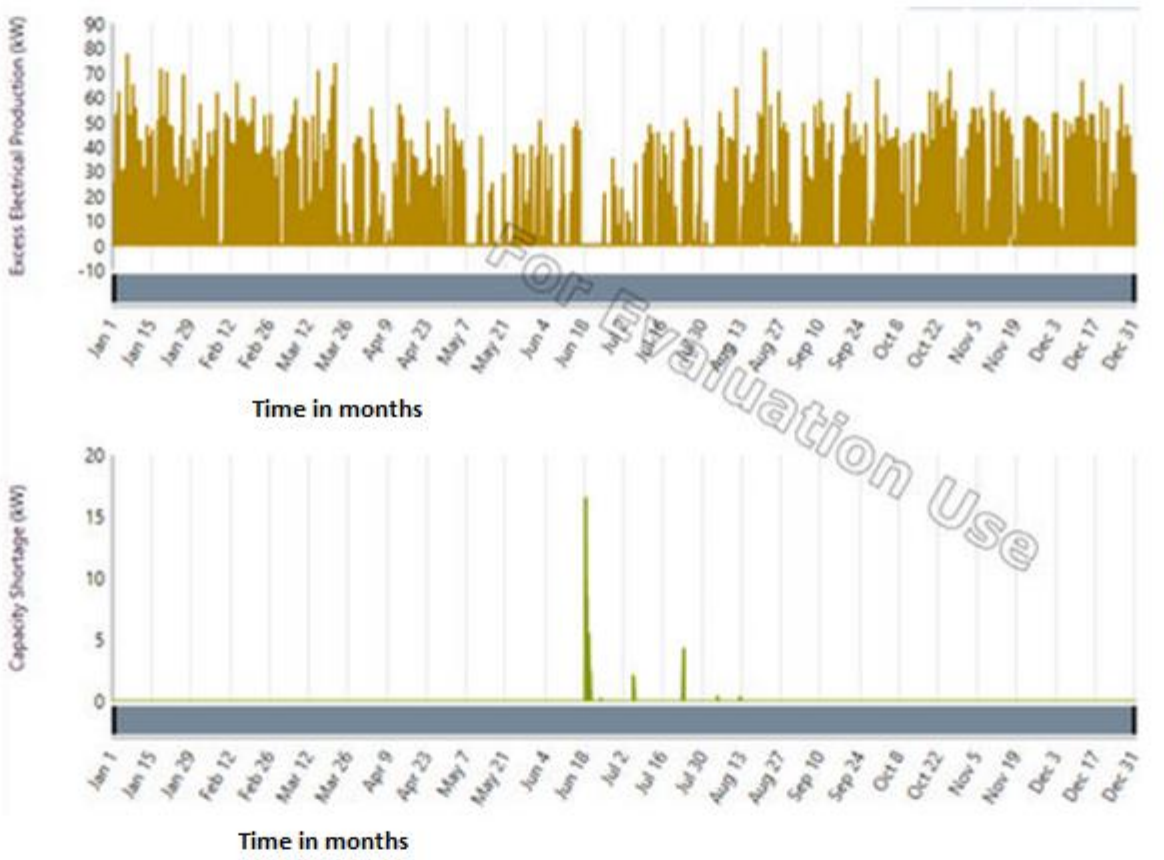


Fig 4.11. Excess electrical production (top) and Capacity shortage (below)

4.1.8 Summary

A detailed methodology to optimally size the components of a standalone HRES for a small community located in Portland Australia using HOMER was investigated in this work. The results obtained clearly indicates that the systems that are consists of PV, wind sources along with battery storage and inverters are economically most suited solution for the targeted community. This work also discusses and analyses the optimum results obtained for different sensitivity variables. The selection criteria for the optimum system and the various aspects and characteristics of the selected system is discussed in detail. The results show that the selected system can meet the load demand successfully keeping the capacity shortage within the specified limit. Though the COE in the selected system is higher that the grid electricity cost, but these kind of HRES will play very crucial role in coming days as they have huge to potential to protect the environment while catering the increasing power need of the developing need of the rural communities.

4.2 Design an Optimum Standalone Hybrid Renewable Energy System for a Small Town at Portland, Victoria using iHOGA

4.2.1 Introduction

This research work investigates a detailed methodology to optimally size the components of a standalone hybrid renewable energy system which is designed to cater the power requirement of a small town located in Portland, Victoria, Australia using iHOGA. Different solutions obtained are analysed and the optimum solution is selected from the obtained solutions. The various characteristics of the selected system are discussed in detail.

iHOGA (Improved Hybrid Optimization Genetic Algorithm) is an optimization tool for the components of HRES developed by the Electric engineering department of the University of Zaragoza, Spain. This tool can evaluate the optimum system configuration of a HRES for a specified load requirement and specified climatic condition. This tool also gives the designer the flexibility to investigate the economic and technical feasibility of the designed system. The study mainly concentrates on designing an optimum system with minimum NPS of RES which will be able to supply the load demand of the small town with minimum interruption.

4.2.2 Proposed System

The basic components of a HRES would be renewable energy sources (AC/DC), i.e. PV generators, wind turbines, they may also include a non-renewable source, i.e. diesel generator, power conditioning units, storage devices, i.e. battery, AC/DC load. These kinds of systems can be grid connected or standalone.

The HRES considered here is a standalone system comprising of PV and wind generators and battery storage. This system is designed to supply the load demand of a small town located in Portland Australia (38° 20′ 0″ S, 141° 36′ 0″ E) which has an AC load demand. The wind turbines and the PV panels produce electricity according to the local wind speed and solar radiation and supplies the load demand. The battery bank is used to store the excess energy generations when the energy production is more than load demand and supply the load demand when there is insufficient generation from the renewable sources. The system configuration is shown in Fig 4.12. The estimate lifetime of the project is expected to be 25 years. The nominated interest rates considered in this work is 4% and annual inflation rates is considered 2% for operations and maintenance.

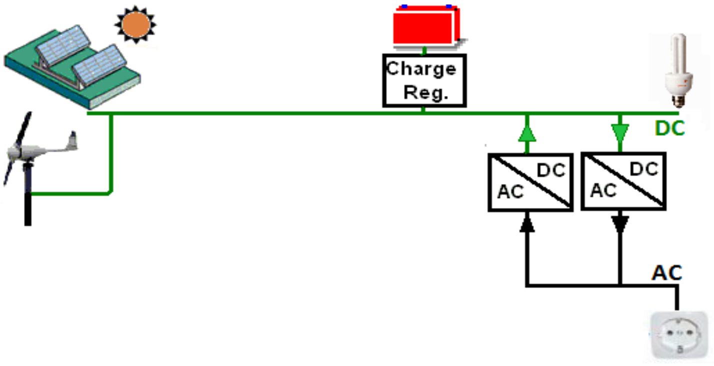


Fig 4.12. Proposed system configuration in iHOGA

4.2.2.1 Electrical Load

The load profiles for the small town located in Portland Victoria is presented in the Figs 4.13 – 4.17 The average load demand of the targeted town is 38.45 kWh/day.

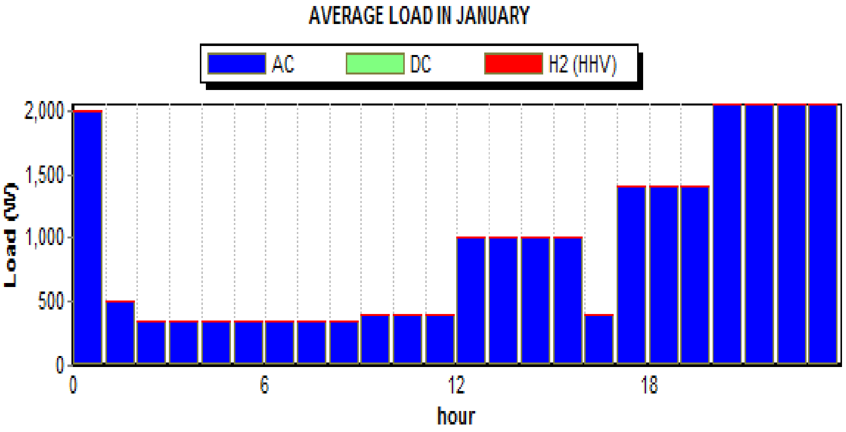


Fig 4.13 Load profiles of the town at the months of January

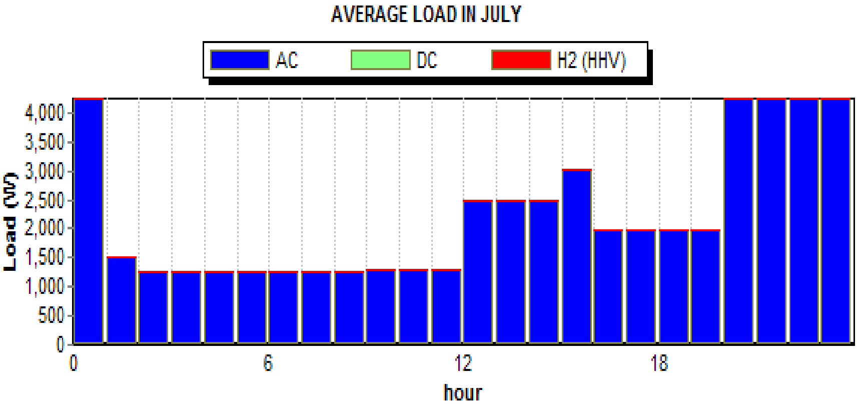


Fig 4.14 Load profiles of the town at the months of July

4.2.2.2 Solar Generators

iHOGA uses the climatic data provided in NASA website [104] for Portland Victoria (38°20′0″S 141°36′0″E). As per NASA the average solar radiation of the target location is 4.16 kWh/m2/day. The annual solar radiation profile used by iHOGA in this work is presented in Fig 4.15.

iHOGA uses an wide-ranged database of system components. This project considers PV panels of aSi12-Schott: ASI100 type. The nominal voltage of each unit is 12 V and power is 100 W. The cost of acquisition for each PV unit is \$165. The operation of maintenance cost of each unit is considered as \$1.65 per year.

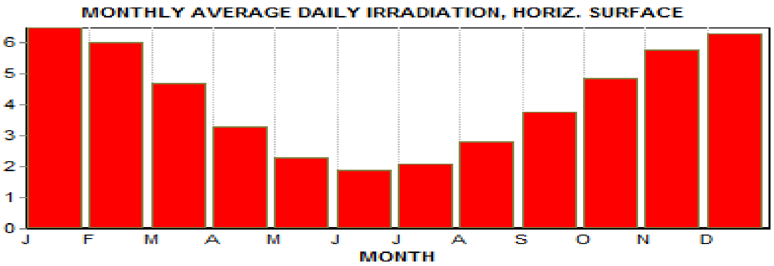


Fig 4.15. Solar radiation profile of Portland, Victoria

4.2.2.3 Wind generator

iHOGA uses the wind profile provided by the NASA website. AS per the data accessed from NASA website annual average wind speed of Portland would be 6.76m/s which indicates that Portland has a great prospect for wind generation. The wind speed considered here is measured 50 above the earth surface. iHOGA uses a wide ranged data base for numerous types of wind generators for calculation purposes. The wind profile used in this work is presented in Fig 4.16.

Fig 4.16 Wind profile of Portland Victoria

4.2.2.4 Battery bank

The sizing of battery is dependent on numerous factors, i.e. depth of discharge, temperature correction, battery life and rated capacity of the battery bank. This project considers OPZS-Hawker: TVS-5 of 390 Ah battery for calculation purposes. The acquisition cost of the battery bank is $247.35 per unit and operation and maintenance cost is $2.575 per unit per year. Battery life considered here is 18 years. The minimum state of charge considered for the battery bank is 20% as specified by the manufacturers. Fig 4.17 presents the details properties of the battery bank.

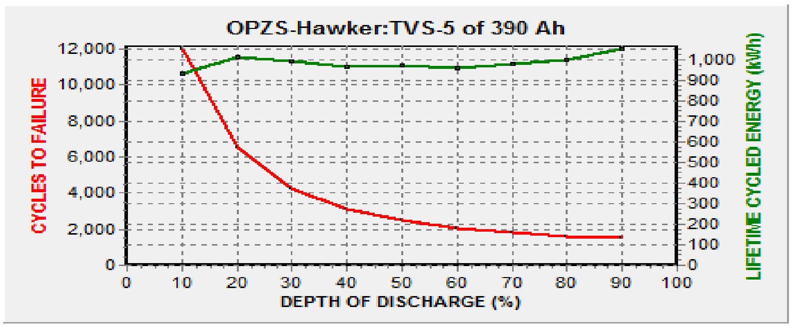


Fig 4.17 OPZS-Hawker: TVS-5 battery characteristics

4.2.2.5 System Inverters

The inverter used in this project for simulation purpose is a generic 6000 CH type. Th inverter's rated power is 6000VA, lifespan considered is 10 years, the average power considered is 26.7 % of the rated power and the efficiency of the inverter 90.4%.

4.2.3 Objective Function

The Objective Function selected in this study is with the aim to minimize the Net Present Cost (NPC) which is a collective cost that includes capital cost of the components, replacement and maintenance costs of the components i.e. PV panels, wind generators, battery bank and converters. iHOGA runs the optimisation process for all the values of some predefined factors called sensitivity variables and displays the results for all possible solutions. iHOGA considers the best solution for each sensitivity cases with various types of wind turbines, PV panels and battery bank to meet the load demand while minimising the NPC. Hence the study considered the solution with minimum NPC for specific set of Sensitivity variables. Details of the procedure is described in section 4.2.5

4.2.4 iHOGA

The tool iHOGA (improved Hybrid Optimization by Genetic Algorithms) is developed in C++ by the Researchers of the University of Zaragoza (Spain) for optimization and simulation of standalone HRES those are comprising of renewable energy sources. This software is capable of modelling systems with AC/DC electrical load, might include Hydrogen and the consumption of water from tank or reservoir previously pumped. This software can be used to optimally size the components of a HRES including PV generators, wind generators, hydroelectric turbines, auxiliary generators,i.e. diesel , gasoline , storage battery ,i.e. lead acid or lithium , inverter, inverter chargers, battery chargers, battery charge controllers and hydrogen components i.e. electrolysers, hydrogen tank and fuel cells. This software can simulate or optimise both grid connected or standalone system of any size. It has options for both mono and multi objective optimization. The simulation time steps considered is 1 minute in this tool, this also can conduct sensitivity analysis probability analysis etc. This software uses a very detailed model of each component which results in very precise estimation of the system operation. iHOGA incorporates the advance optimisation technique powered by Genetic Algorithm which leads to very low computational time for the optimisation process.

4.2.5 Results and discussions

4.2.5.A Optimisation and Sensitivity analysis

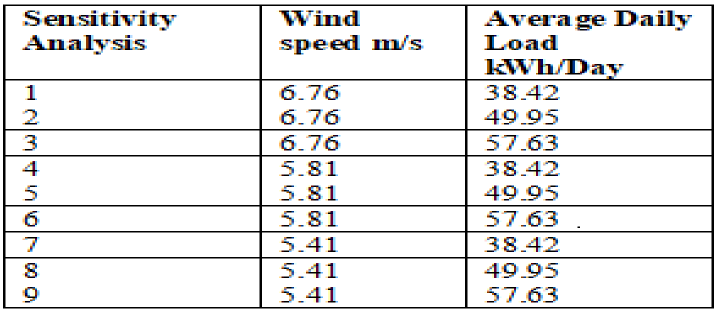
To design the optimum HRES for the targeted town located in Portland, Victoria using iHOGA two sensitivity variables were considered. They are the wind speed and average daily load demand.

iHoga downloads the wind speed data from NASA website, which states that the average wind speed is 6.7 m/s. Another set of climatic data obtained from BOM states the average wind speed of Portland is approximately 5.6 m/s. As already mentioned, a slight variation of wind speed can impact the power generation of a wind turbine significantly, selecting the wind speed as 6.76 m/s might be a very optimistic consideration which might lead to inability to supply the load demand during the off peak seasons. Hence the sensitivity analysis was conducted on three vales of wind speeds, 6.7m/s, 5.81m/s and 5.41m/s.

As the system lifespan is 25 years, three different values of average daily load demand have been considered as another sensitivity variable.

The software runs the optimisation process for all the values of the sensitivity variables displays the results for all possible solutions. The values of the sensitivity variables are presented in the Table 4.5. iHOGA considers the best solution for each sensitivity cases with various types of wind turbines, PV panels and battery bank to meet the load demand while minimising the NPC.

Table 4.5. Sensitivity analysis cases and the values of the corresponding sensitivity variables



Sensitivity Analysis	Wind speed m/s	Average Daily Load kWh/Day
1 2	6.76 6.76	38.42 49.95
3	6.76	57.63
4 5	5.81 5.81	38.42 49.95
6	5.81	57.63 .
7	5.41	38.42
8 9	5.41 5.41	49.95 57.63

Fig 4.18 displays the results obtained by simulating different sensitivity analysis.

It can be evidently observed from the results that the optimum system cost is significantly impacted by the sensitivity variables. With an increased daily average load consumptions, the system cost increases. Another fact that is prominent from the results that is the for same average daily load consumptions the system cost is minimum when the wind speed is 5.8m/s. The results show that the minimum system cost is achieved when wind speed is 5.81m/s and average daily load demand is 38.42kWh/day.

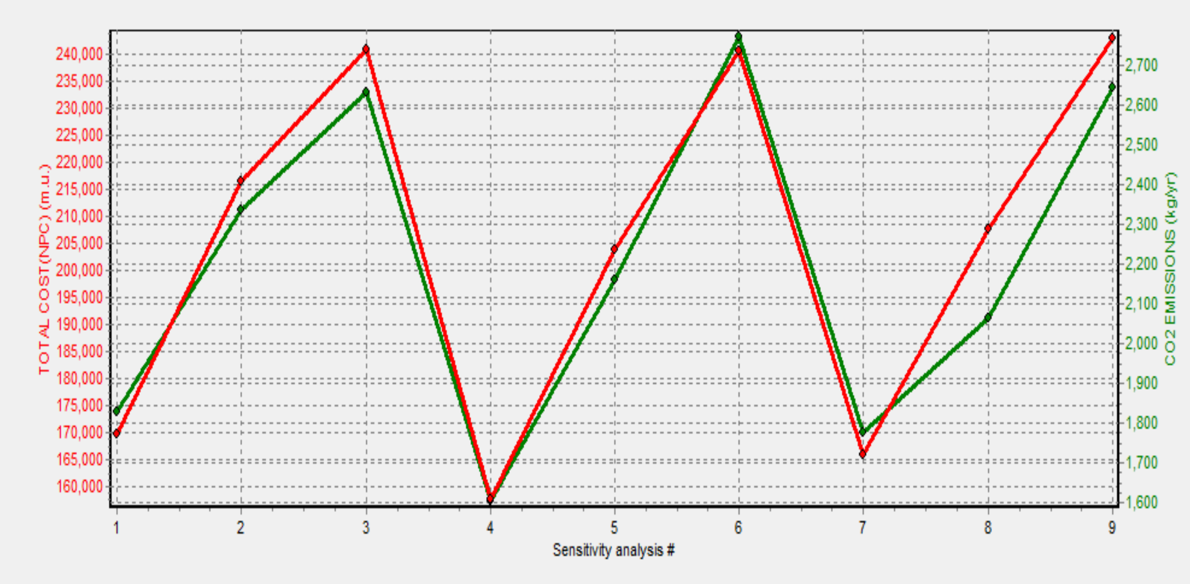


Fig 4.18. The sensitivity analysis results

For each sensitivity cases the system configuration selected can be summarised as follows:

Sensitivity case 1

Components:

PV pan aSI12-Schott :ASI100(100Wp): 4 s ×59 p. Ptotal =23.6kWp, 60^0 slope
Batt. OPZS -Hawker :TVS-5 (Cn=390 A.h) : 24 s × 18 p. E total =336.9 kWh (5.8 d.aut)
1 Wind T. DC Southwest :Whisper100 (925 Wat 14m/s).P.total 0.925 kW
Inverter Generic :6000 CH, rated power 6000 VA
PV Battery charge controller Generic of 521 A

Sensitivity case 2

Components:

PV pan aSI12-Schott :ASI100(100Wp): 4 s ×40 p. Ptotal =16kWp, 60^0 slope
Batt. OPZS -Hawker :TVS-5 (Cn=390 A.h) : 24 s × 17 p. E total =318.2 kWh (5.5 d.aut)
1 Wind T. DC Bornay:3000 (3471 Watt 14m/s).P.total 3.471kW
Inverter Generic :6000 CH, rated power 6000 VA
PV Battery charge controller Generic of 354 A

Sensitivity case 3

Components:

PV pan aSI12-Schott :ASI100(100Wp): 4 s ×58 p. Ptotal =23.2kWp, 60^0 slope
Batt. OPZS -Hawker :TVS-5 (Cn=390 A.h) : 24 s × 17 p. E total =318.2 kWh (5.5 d.aut)
1 Wind T. DC Bornay:1500 (1660Watt 14m/s).P.total 1.661kW
Inverter Generic :6000 CH, rated power 6000 VA
PV Battery charge controller Generic of 512 A

Sensitivity case 4

Components:

PV pan aSI12-Schott :ASI100(100Wp): 4 s ×81 p. Ptotal =32.4 kWp, 60^0 slope
Batt. OPZS -Hawker :TVS-5 (Cn=390 A.h) : 24 s × 26 p. E total =486.7 kWh (5.6 d.aut)
1 Wind T. DC Bornay:3000 (3471 Watt 14m/s).P.total 3.471kW
Inverter Generic :6000 CH, rated power 6000 VA
PV Battery charge controller Generic of 715 A

Sensitivity case 7

Components:

PV pan aSI12-Schott :ASI100(100Wp): 4 s ×58 p. Ptotal =23.2kWp, 60^0 slope
Batt. OPZS -Hawker :TVS-5 (Cn=390 A.h) : 24 s × 17 p. E total = 318.2 kWh (5.5 d.aut)
1 Wind T. DC Bornay: 1500(1660 Watt 14m/s).P.total 1.66 kW
Inverter Generic :6000 CH, rated power 6000 VA
PV Battery charge controller Generic of 512 A

Sensitivity case 9

Components:

PV pan aSI12-Schott :ASI100(100Wp): 4 s ×81 p. Ptotal =32.4kWp, 60^0 slope
Batt. OPZS -Hawker :TVS-5 (Cn=390 A.h) : 24 s × 26 p. E total = 486.7 kWh (5.6 d.aut)
1 Wind T. DC Bornay: 3000(3471 Watt 14m/s).P.total 3.471 kW
Inverter Generic :6000 CH, rated power 6000 VA
PV Battery charge controller Generic of 715 A

4.2.5.B Selection of the Optimum System Configuration

The results obtained from sensitivity case 9 is selected keeping in mind the increasing load requirement in modern life and the wind speed data gained from two different sources. This system was selected to ensure that selected HRES can supply the load requirement of the small town under variable load conditions and wind speed conditions for coming 25 years with minimum interruptions and with minimum cost of energy.

For the selected sensitivity case, the selected system configuration and cost summary of the selected system are presented below:

- The initial investment required is 236908 AUD where Loan 80%, annual quota: 26983.3 AUD.
- For 25 years lifespan NPC of the system is as follows (comparing to AC grid, 21037kWh/yr,NPC=112059 AUD)
    - ✓ PV panel cost (NPS): 65122 AUD
    - ✓ The cost of the Battery bank (NPC): 217719 AUD
    - ✓ Cos of Wind turbine (NPC): 19197 AUD
    - ✓ The cost of the Auxiliary components (NPC) 16471 AUD
    - ✓ The cost of the Inverter (NPC): 11353 AUD

The summary of cost for the system selected can be presented in the pie chart shown in Fig 4.19

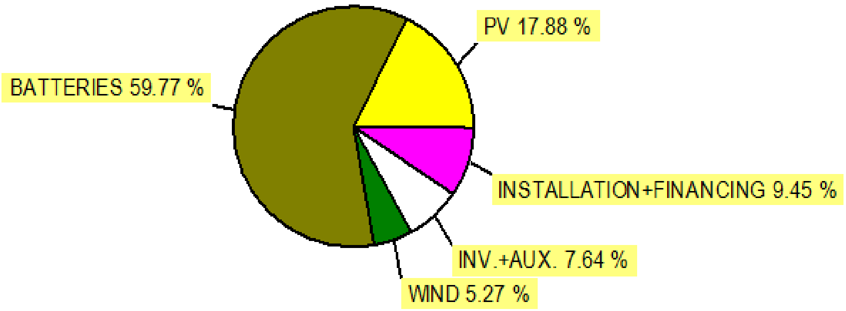


Fig 4.19 The cost summary of the selected system

For one year the energy balance of the system is detailed below:

- ✓ Overall load energy requirement :21036 kWh/yr
- ✓ Total excess energy generation 17682 kWh/yr
- ✓ Total energy delivered by the PV generators :33241 kWh/yr
- ✓ Total energy delivered by the wind turbines:10120 kWh/yr
- ✓ Total energy charged by the battery bank: 10585 kWh/yr
- ✓ Total energy discharged by the battery bank: 10585kWh/yr
- ✓ The lifetime of battery bank 18 years.
- ✓

For one-year period the energy balance of the selected system can be represented as Fig 4.20

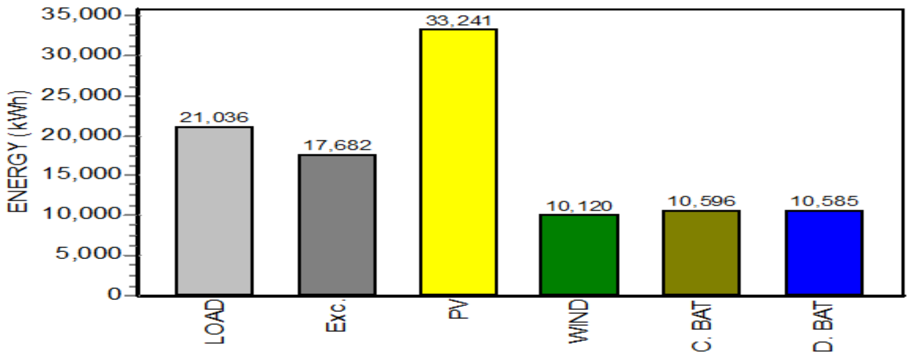


Fig.4.20. Energy balance of the selected system for one year

The results obtained clearly indicates that the system optimised using iHOGA for the small town located in Portland, Victoria, can perform optimally under the specified meteorological conditions in terms of load demand supply and cost of energy. Generating 100% renewable energy this system can reduce the greenhouse gas emission significantly.

4.3 Optimum Sizing of standalone PV/Wind Power Generating System with Storage

4.3.1 Introduction

As the renewable sources are irregular, to allow their real penetration optimum sizing is required for designing HRES. Otherwise the system might not be able to cater the load demand reliably or might cause huge establishment cost due to oversizing. An optimisation technique to size the components of a hybrid renewable energy system comprising of PV generators, wind turbines and battery storage is presented in this work. This study uses the interactive optimization technique and utilises Deficiency of Power Supply Probability (DPSP) for power reliability for power reliability to optimise the components of the hybrid renewable energy system. By minimising the system cost this methodology ensures reliable and economic performance of the designed system to cater the load demand of the targeted community which is located at Portland Australia. The details of the design are discussed in the following sections.

Storage cost is a major economic constrain for considering the standalone application of renewable energy systems. Combining different types of renewable sources like solar or wind can reduce the storage requirement and hence can reduce the overall system cost. This algorithm was developed for a specified load characteristic and specific battery storage capacity to calculate the numbers of PV modules and numbers of wind turbines that would be able to achieve the required Deficiency of Power Supply Probability (DPSP). While developing the algorithm, the seasonal variation of wind speed, load demand, average sun hour has been considered. Hence two peak season's data have been considered to ensure the system can operate reliably under various weather conditions.

4.3.2 Proposed System

The standalone HRES considered here is comprising of three parts: PV panels, wind turbines and battery storage. The wind and PV generators produce electricity in accordance with local solar and wind resources to cater the load demand of the targeted community. The battery bank forms the storage, which can store any excess generation from the renewable sources when the generation exceeds the load requirement and can supply the load demand when the load demand is higher than the production. Due to the unpredictable and fluctuant nature of renewable sources energy storage system becomes an essential part of the standalone renewable energy systems.

4.3.3 The mathematical model of the PV generator

The hourly output power generated by the PV panels with an area $A_{pv}(m^2)$ is given by equation 4.1 [106]

$$P_{PV}=\eta_{pv} A_{pv} G_t \qquad (4.1)$$

Where the solar radiation on tilted plane module is presented as Gt (W/m^2) and η_{pv} represents the PV generator efficiency. η_{pv} is given by equation 4.2

$$\eta_{pv}= \eta_r \eta_{pc} [1-\beta(T_c - T_{cref})] \qquad (4.2)$$

Where η_r represents the efficiency of the reference module, η_{pc} represents the power conditioning efficiency of the module, which is equal to 1 when a perfect maximum power point tracker (MPPT) is used. The generator efficiency temperature coefficient is presented by β which is presumed to be a constant. For silicon cells the range for β is 0.004-0.006 (℃).T_{cref} represents the reference cell temperature in (℃) and Tc represents the cell temperature (℃) which can be presented by the following equation

$$T_c=T_a+[(NOCT-20)/800]G_t \qquad (4.3)$$

Where the ambient temperature is presented by T_a in (^{o}C). NOCT stands for the nominal cell operating temperature in (^{o}C). The parameters η_{pc} , β, NOCT and A_{pv}, dependent upon the type of module used in the study. Hence these data can be acquired from the manufacturers of the PV module

4.3.4 The mathematical model of the wind turbine

The power output from the wind generators are dependent on the wind speed distribution of the targeted location and the output characteristics of the selected wind turbine. Hence selection of a proper wind turbine model is very crucial to predict the power output from the turbine accurately.

A very simplified model for wind turbine power simulation can be described by equation (4.4)

$$P_w(V) = \begin{cases} P_R\left[\left(V2 - V_C^2\right)/V_R^2 - V_C^2\right], & V_C \leq V \leq V_R \\ P_R, & V_R \leq V \leq V_F \\ 0, & Otherwise \end{cases} \tag{4.4}$$

In the equation above P_R represents the rated electrical power, the cut-n wind speed is V_C, the rated wind speed is presented by V_R and the cut off wind speed is presented by V_F. This study takes into consideration the adjustment of wind profile height utilising the power low which is considered as a helpful tool to model the vertical wind speed profile. This is presented by equation (4.5)

$$\frac{V(H)}{V\left(H_{ref}\right)} = \left(\frac{H}{H_{ref}}\right)^{\propto} \tag{4.5}$$

V(H) represents the wind speed at a hub height H m/s, V(H_{ref}) represents the wind speed at the reference height H_{ref} m/s. The power low exponent is represented by α which is very important factor, hence it is very important determine the value of α. When no specific site data is not available the value of α is taken as 1/7 [107].

4.3.5 Mathematical model of the battery bank

The battery storage needs to be optimally sized to meet the load demand for the period when the renewable energy sources are not available due to unfavourable climatic conditions, this is commonly denoted by the days of autonomy. Generally, the days of autonomy is considered for 2/3 days.

The sizing of battery bank is dependent on few factors. They would be maximum depth of discharge, rated capacity of the battery, temperature correction and battery lifespan. The expression of the total capacity of the battery bank required to meet the load demand is expressed in the following equation [106].

$$C_B = \frac{E_L S_D}{V_B (DOD)_{\max} T_{cf} \eta_B} \tag{4.6}$$

E_L representing the load demand in Wh, battery autonomy days or storage days is presented by S_D , the voltage of the battery bank is V_B , The maximum depth of discharge for the battery bank is presented by DOD_{max} . The temperature correction factor is represented by T_{cf} ,and battery efficiency is presented by η_B . the state of charge of the battery bank can be calculated using the following equations depending on the productions from the PV and wind generators and the load power requirements:

When the battery is charging:

$$SOC(t) = SOC(t-1)\cdot(1-\sigma) + [E_{Gen}(t) - E_L(t)/\eta_{inv}]\cdot\eta_B \quad (4.7)$$

When the battery is discharging:

$$SOC(t) = SOC(t-1)\cdot(1-\sigma) + [E_L(t)/\eta_{inv} - E_{Gen}(t)] \quad (4.8)$$

The states of charge of battery bank (Wh) at the time instance t and t-1 is presented by SOC(t) and SOC(t-1) respectively. The hourly self-discharge rate of the battery is presented by σ. The total energy produced by the PV panels and the wind generators after the energy loss by the controllers is presented by $E_{Gen}(t)$.The total load requirement at the time t is presented by $E_L(t)$. The efficiency of the battery bank is presented by η_B and η_{inv} represents the efficiency of the inverter. The charged quantity of the battery bank at any time t is dependent on two constraints presented below:

$$SOC_{min} \le SOC(t) \le SOC_{max} \quad (4.9)$$

SOC_{max} , that represents the maximum charge quality of the battery bank, takes the value of C_B, which represents the nominal capacity of battery bank and the minimum charge quantity of the battery bank which is presented by SOC_{min} , determined by the maximum depth of discharge (*DOD*): $SOC_{min} = (1-DOD).C_B$.

As specified by the manufacturers, the battery lifetime increases if the value of DOD is ranged between 30-50%. The present work considers the value of DOD as 50%.

4.3.6 Optimal Sizing Criteria

Numerous methodologies have been reported in literature to optimally evaluate the sizes of the components of the HRES comprising of wind solar generators and battery bank, such as energy to load ratio, battery to load ratio, non-availability of energy etc. In order to select the optimum combination of the components for a HRES evaluations can be performed based on reliability of power supply and economic criterion. The study considers Deficiency of Power Supply Probability (DPSP) technique to optimally size the components of a HRES.

4.3.6.A Reliability criterion based on DPSP

DPSP is a measurement of power supply reliability which represents the probability of inefficiency in power supply resulted when the renewable sources, i.e. solar and wind generators and storage system are unable to supply the load demand. The methodology is explained below:

- When the power generated by the renewable sources(PV/ Wind generators) is greater or equal to the load demand the generated power will be utilised to supply the load demand first , any excess energy will be utilised to charge the battery bank till the battery bank reaches its maximum state of charge (SOC). The SOC is presented by the equation (4.7). When the state of charges reaches its maximum SOC_{MAX} , The control system disconnects the battery from charging.

- When the power generated by the renewable sources is less that the load requirement, the control system will start discharging the battery bank to meet the load demand till the battery bank reached its minimum value of SOC (SOC_{MIN}). Under this scenario the SOC can be calculated using equation (4.8)

- The scenario when the battery bank reached its minimum SOC and the power generated by the renewable sources still insufficient to supply the load demand is called a Deficiency of Power Supply (DPS). At this stage the control disconnects battery from the load to ensure any further discharge of the battery. Deficiency of Power Supply at hour t is expressed by the following equation:

$$DPS(t) = E_L(t) - [E_{Gen}(t) + SOC(t-1) - SOC_{\min}]\eta_{inv} \tag{4.10}$$

- For a specific period, Deficiency of Power Supply Probability (DPSP) can be presented as the ratio of all DPS vales for that time period to the sum of the total load demand for that period. Hence the value of DPSP 1 means that the load demand is never satisfied and the DPSP value 0 indicated that the load will be always satisfied. For a given time period, DPSP can be represented as [108]:

$$\mathrm{DPSP} = \sum_{t=1}^{T} DPS(t) / \sum_{t=1}^{T} E_L(t) \tag{4.11}$$

Based on the methodology described above a MATLAB program was developed to determine the sizes of the components for a specified DPSP values specified by the user. The flowchart for the program is illustrated in Fig.4.22. The variables $N_{w,min}$, $N_{w,max}$,$N_{pv,min}$, $N_{pv,max}$ and used in the flowchart represents the lower and higher limits of the variation interval of wind and PV generators rated power. The maximum number of storage days are represented by $NS_{D.}$ This study considers NS_D =2. The variation steps of the PV and wind sources rated power is presented by ΔNpv and ΔN_W .

Hourly mean values of ambient temperature and, wind speed, hourly solar irradiation on a tilted plane, value of DPSP specified by the user, load profile for a desired period and the system devices specifications are the inputs to the MATLAB program. The program developed based on the flowchart presented in Fig 4.23 helped to determine a set of system configuration to meet the specified DPSP value. After this stp performed, the optimum number of the PV modules and wind turbines we determined based on the economic approach.

4.3.6.B Economic approach for optimum sizing

The number of PV panels obtained using the MATLAB program was plotted against the number of wind turbines for a given value DPSP. An example of the plot is presented in the Fig (4.21)

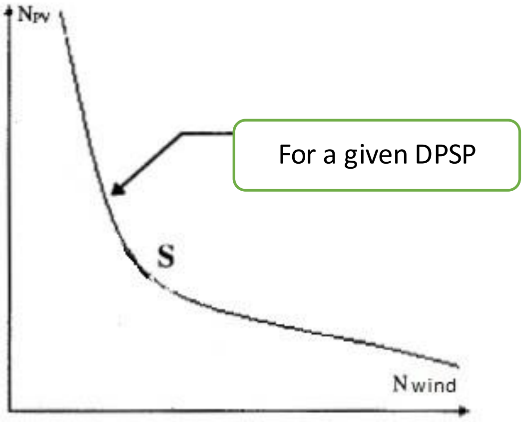


Fig. 4.21 Plot of PV module vs number of wind turbines [43]

To obtain the PV panel and wind turbine combination that results in minimum cost a cost function has been considered which is presented in equation (4.12)

$$C=\alpha.N_{PV}+\beta.N_{wind}+C_0 \qquad (4.12)$$

C represents the total capital cost of the system,

N_{PV} represents the total capacity of PV generators in KW

N_{wind} represents the total capacity of wind generator in KW

α represents the unit cost of a installed PV module in \$/KW

β represents the unit cost of a wind turbine in \$/KW

C_0 represents the total constant costs including installation and battery bank and the cost of design

The condition to attain the optimum solution from equation (4.13).

$$\frac{\partial Npv}{\partial Nwind} = -\frac{\beta}{\alpha} \qquad (4.13)$$

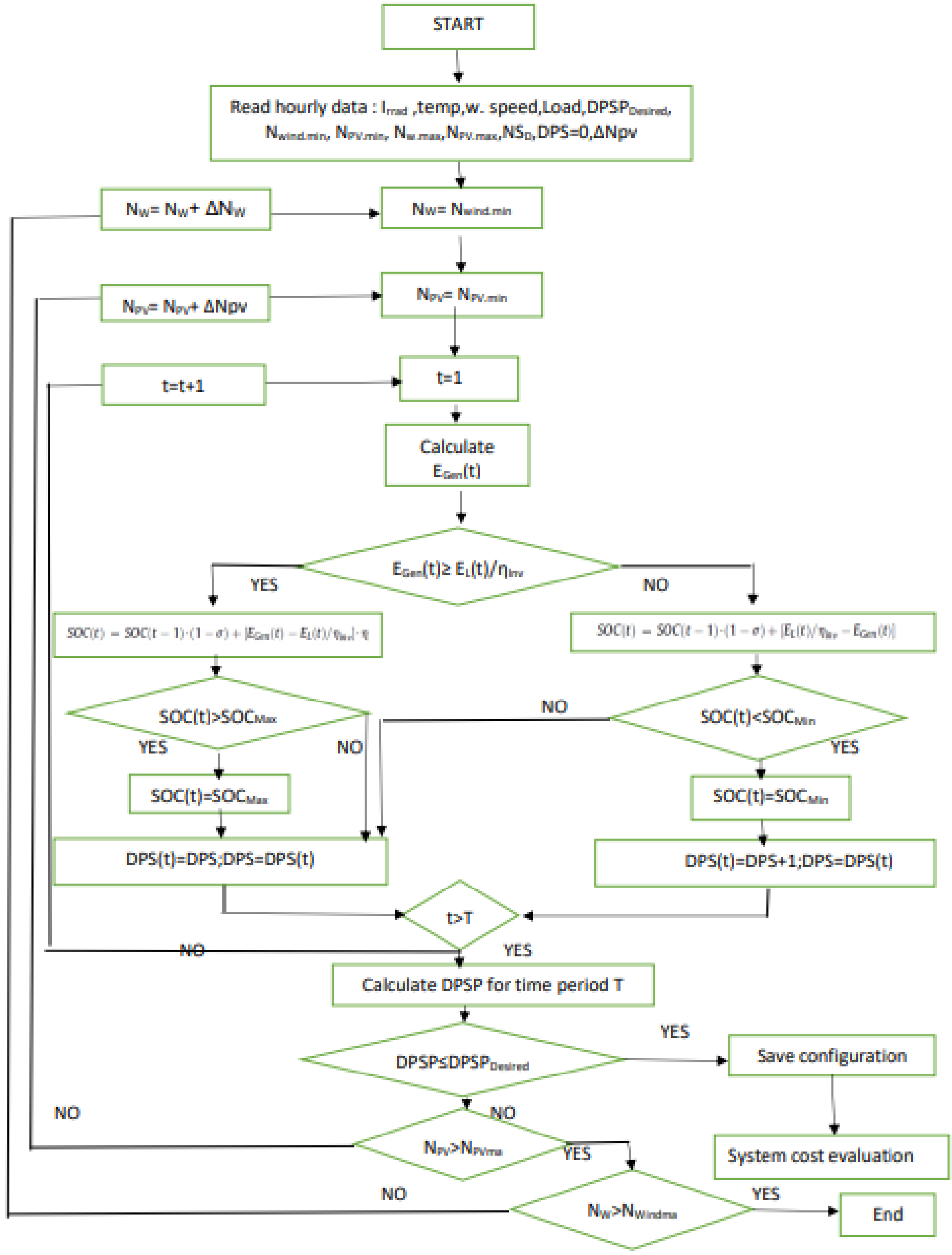


Fig 4.22. Flowchart for optimal sizing of RES using DPSP criteria[108]

4.3.7 Results and discussions

The methodology discussed above is utilised to optimally size the components of a standalone hybrid renewable system comprising of PV wind generators and battery back-up to supply the load demand of small community of twenty residential households located in Portland, Victoria Australia (38° 20′ 0″ S, 141° 36′ 0″ E). The specifications of the PV panels, wind turbines and battery bank used in this project are listed in Tables 4.6- 4.8

In this project the data for solar irradiance and wind speed for Portland were gained from Australian Bureau of Meteorology (BOM) website. The seasonal variation in the average sun hour is presented in Figs 4.23 – 4.24. The daily global solar exposure of Portland for the months of July and January are presented in the Figs 4.25 – 4.26. The Mean 9 am and 3 pm wind speeds of Portland in km/h is presented in Fig 4.27. These figures clearly show that there is a significant seasonal variation in the meteorological conditions in Portland.

The load characteristics of a household the targeted community for the months of January and July are presented in Fig 4.28 which clearly shows that there is a significant variation in load demand too. A MATLAB program has been designed by these facts into consideration to optimally size the sources and the storage of the standalone HRES for the targeted community considering the value of DPSP .03 and two days of autonomy of battery bank.

Table 4.6: Specification of PV panels:

Type	Voc (V)	Isc(A)	Max system Voltage	Opt. Operating current(A)	Pmax(W)
CS6K 295MS	39.5	9.75	1000 V(IEC)	9.14A	295W

Table 4.7: Specifications of wind turbine:

Type	Rated power	Cut-in speed	Rated speed	Survival wind speed	Rotor height
AWS-V	5kw	2.5m/s	10m/s	55m/s	5.3m

Table 4.8: Specification of a Single battery:

Type	Nominal capacity (Ah)	Voltage	Round-trip efficiency	DOD(%)
Varta Solar	100	12	.85	50

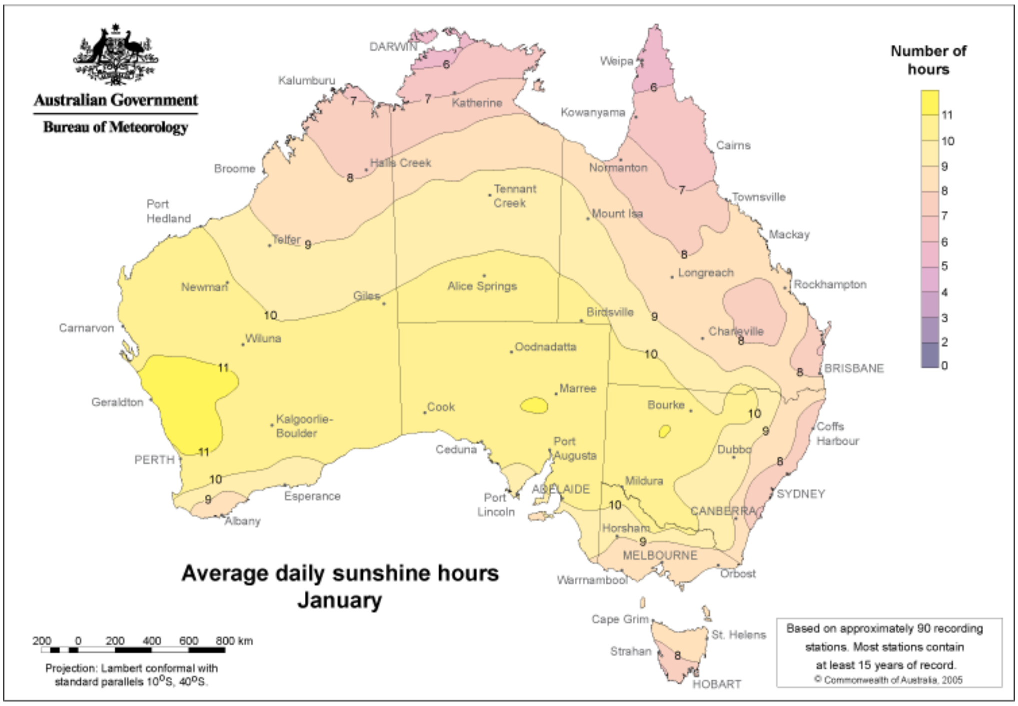


Fig 4.23 Average daily sunshine hours for January

Source: Australia Govt. Bureau of Meteorology

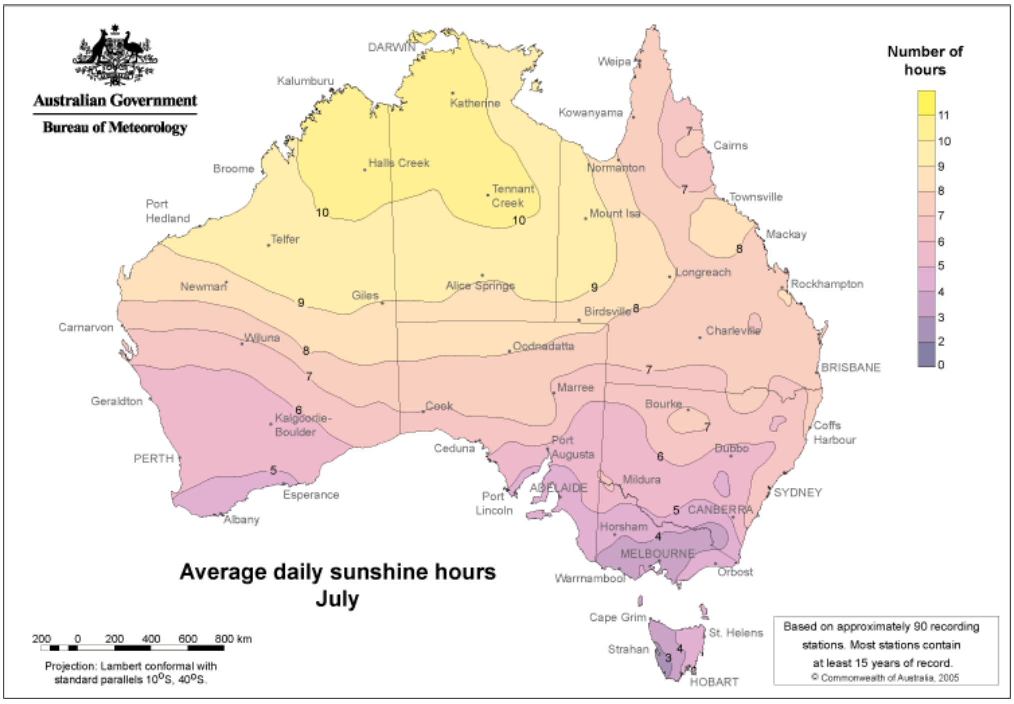
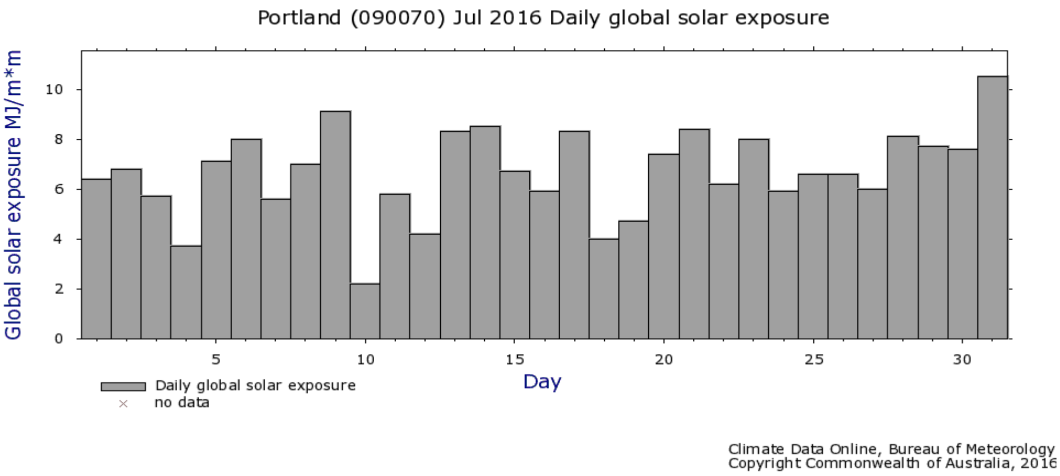


Fig 4.24 Average daily sunshine hours for July

Source: Australia Govt. Bureau of Meteorology



Climate Data Online, Bureau of Meteorology
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Fig. 4.25 Portland Daily global solar exposure July

Source: Australia Govt. Bureau of Meteorology

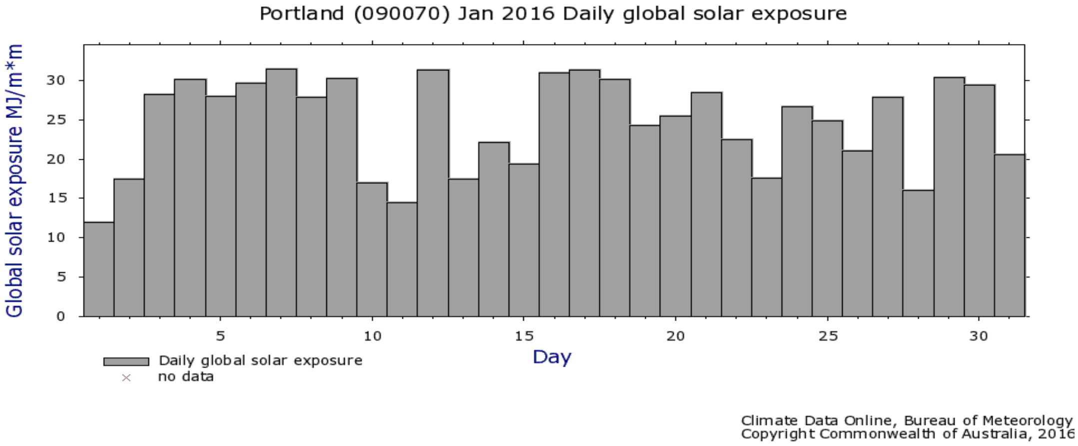


Fig. 4.26 Portland Daily global solar exposure Jan

Source: Australia Govt. Bureau of Meteorology

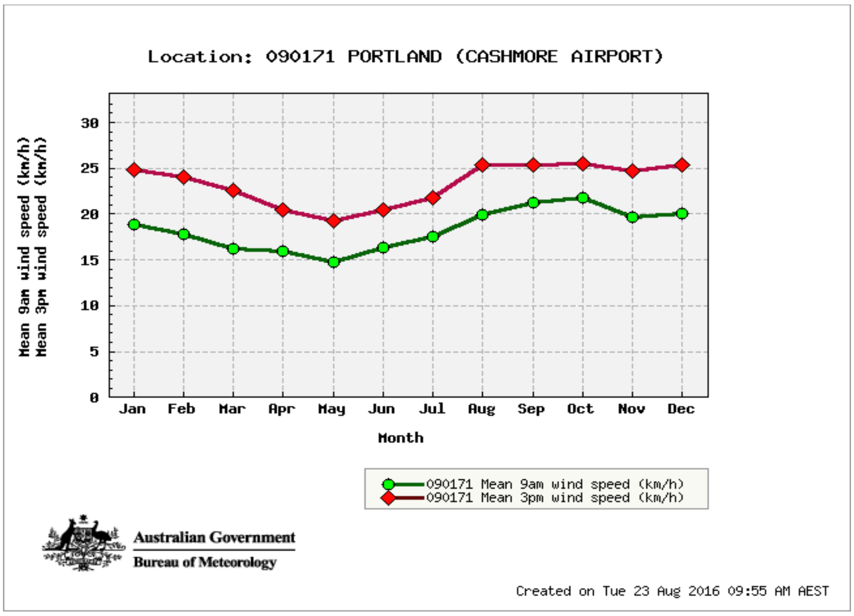


Fig.4.27 The Mean 9 am and 3 pm wind speeds of Portland in km/h

Source: Australia Govt. Bureau of Meteorology

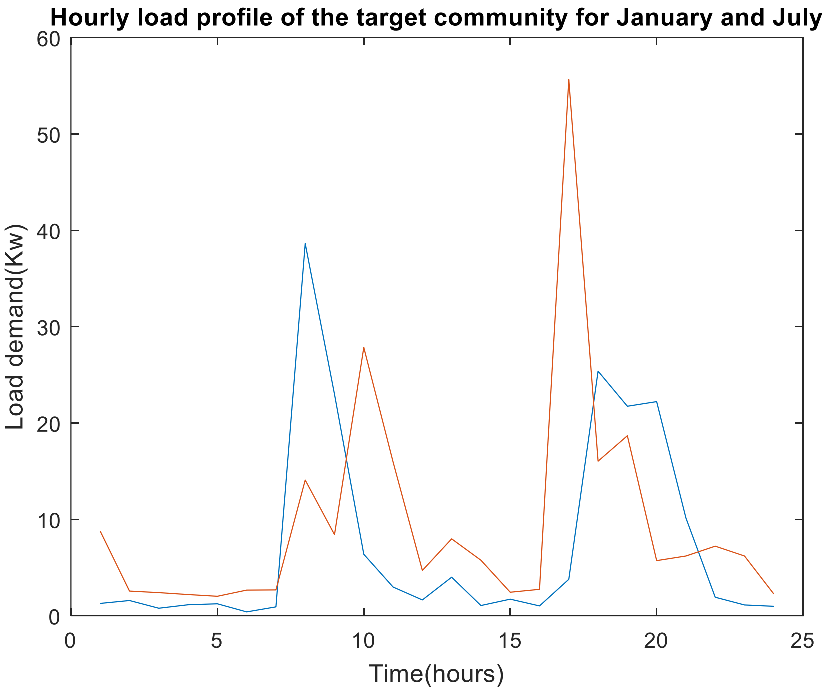


Fig 4.28 Hourly load profile of the target community for January (Red) and July (Blue)

Utilising the MATLAB program developed based on the methodology described in former sections a series of possible combinations of PV module and wind turbines were calculated for two days of battery autonomy. In the next step an optimum combination was selected to minimise the system cost for a given unit price of wind turbines and PV modules. For a given DPSP value, the numbers of PV module versus the numbers of wind turbines obtained were plotted, which is represented in Fig. 4.29. To select the optimum system configuration the point was selected on the graph which satisfies the minimum cost condition presented in equation (4.13). As per that criterion the optimum no of wind turbines would be 2 and no of selected PV modules will be 56.

The performance of the designed system was analysed for various seasons for the optimum combinations of wind turbine and PV module. Figs 4.30 and 4.31 illustrates one example of the system performance. The load demand of the targeted community for two days of the month February is represented in Fig 4.30. the power generated by the designed system for those two days is also presented in the same figure. The state of charge of battery is presented in Fig 4.31 for those two days.

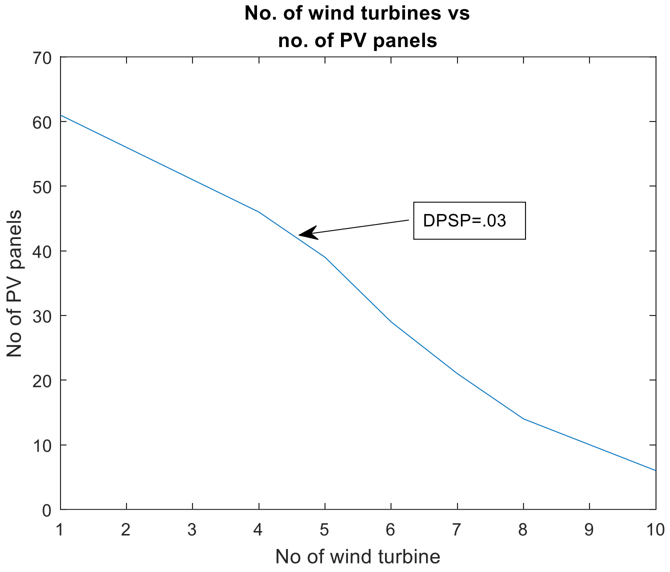


Fig. 4.29 System configurations for a specified DPSP for 2 days of autonomy of the battery bank

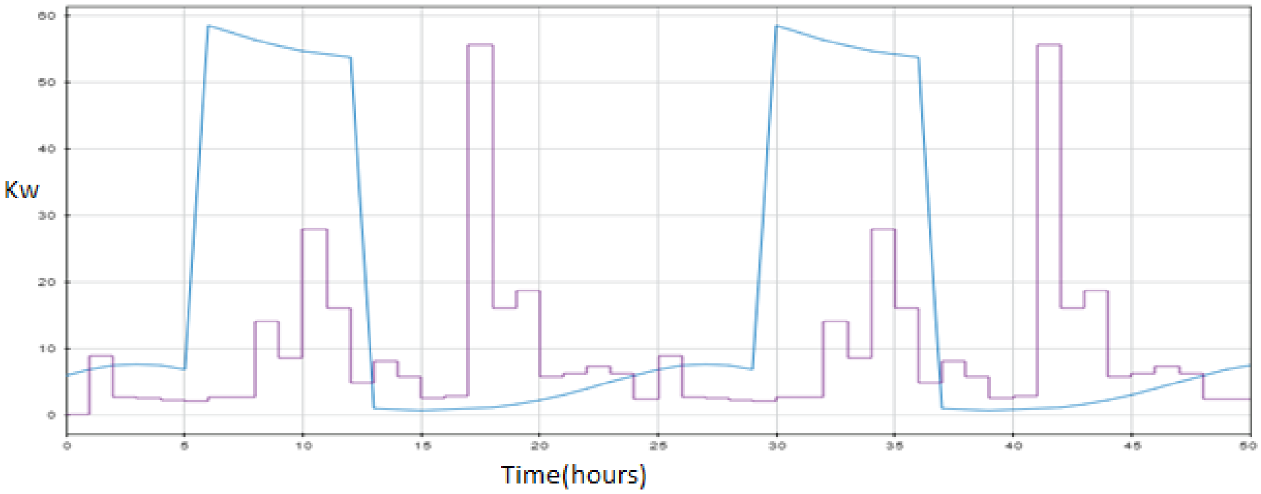


Fig. 4.30 Load demand for two days of February(purple) and Total generated power (blue) of the system after optimum sizing

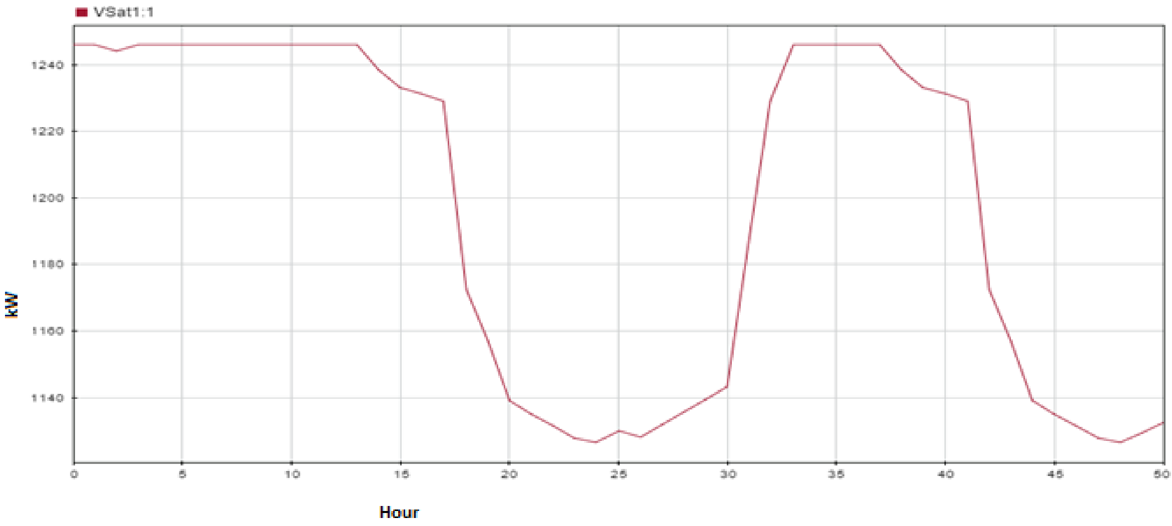


Fig 4.31 Battery state of charge

4.3.8 Summary

From the results demonstrated this can be clearly observed that the system designed using the discussed algorithm can successfully cater the load demand of the targeted community reliably while ensuring the minimum system cost. This methodology considers real user data and seasonal variations of the targeted location. It can be concluded from this study that the optimum numbers of the PV modules and wind turbines are dependent on the location, load profile, and the desired reliability of the power supply of the hybrid system.

4.4 Optimum system selection for the targeted community

Any of the methodologies discussed in this chapter can be used to optimally size the components of the HRES under consideration for the targeted community based on Portland Victoria. Each methodology has its own advantages. The advantage of algorithm-based methodology over the tool- based methodology is any exceptions can be handled in better way when a program is written based on an algorithm. The limitation of using the tools is that the programs used in developing the tools like HOMER or iHOGA are not accessible. A user written MATLAB program based in the last section can allow the users to incorporate any custom information in the programming if required.

However, the results obtained using the optimisation method using HOMER has been used in rest of the research work as HOMER can provide a detail insight of the financial aspects of the system selected. As discussed already, HOMER can provide a detail results on financial model in term of system cost, cost of energy etc. Hence, the following sections will be using the data that has been obtained in the optimisation process using HOMER.

4.4.1 The system characteristics

4.4.1.A The load profile:

When designing an optimum HRES for a targeted location of community, the load profile is a very crucial part. It is important because all the components and design will focus on meeting the load demand and design a system which will be able to cater the load for around the year. Hence availability of load profile plays important role in the accuracy or optimal performance of the designed system.

However, the constrain of this study is the availability of load data. Due to strict privacy rules, load data is not easily available this study has considered the data prototype available for a community located at Portland, Victoria, Australia, which has been used in section 4.1.3.

However, one need to remember that this data may vary as every household and each community has unique requirements. Hence the actual community load profile can be significantly varying from the data used in this study. But the advantage of using any of these methodologies is the optimization can be done for any load profile by making change to the load profile only in case someone using tools like HOMER or iHOGA. In case of MATLAB programming suggested in last section also one can modify the load profile in the basic program to achieve the optimum configuration without making any significant change to the basic program structure. Hence even though the data used in this study is not accurate, but one can use this work as a guidebook and replace the data to design the optimum HRES for a targeted location.

Due to this data constrain, additional study was conducted beyond the scope of this main work, to learn the procedure of load forecasting. Author has worked on short term load forecasting methods using Fuzzy Logic to forecast the load profile. This work has been presented in Appendix (**A.2 Short term load forecasting using Fuzzy Logic, Page 208)** However due to time constraint work could not be conducted on long term load forecasting.
However, even though unavailability of actual data is a major constrain of this work, but this makes this work a flexible one to be used for any time of system with any kind of load profile.

Keeping this constrain in mind, the load profile used in this study for the targeted community is the load profile used in section 4.1.3 which can be represented can be represented in Fig. 4.32. The energy consumed by the community is 111.46 kWh/day with a 23.93 kW peak demand.

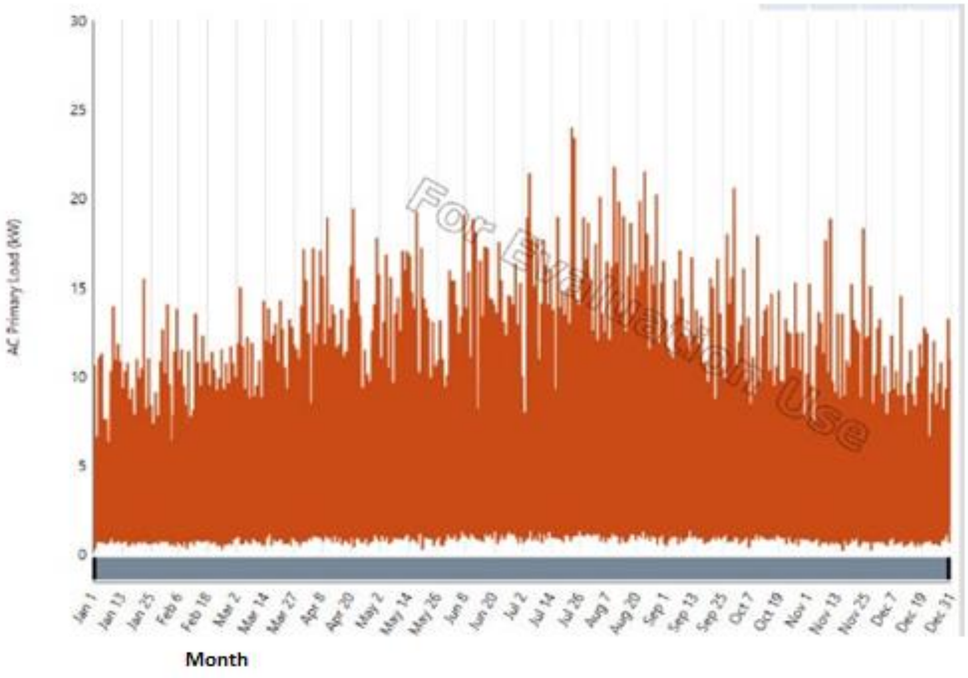


Fig. 4.32 Load profile of the targeted community

4.4.1.B Selection of system components

The wind turbines, PV panels and battery bank specifications and their mathematical model provided in section 6.1 have been used in this study.

4.4.1.C Sizing the generators and the battery bank

As discussed already, the sizes of the components obtained in section 4.1 has been used here. The optimum system configuration can be presented as in table 4.9:

Table 4.9: Selected system configuration

Capacity Shortage (%)	Electrical load scaled Average.	Solar Scaled Average (kWh/m^2/day)	Wind Scaled Average (m/s)	PV(kW)	G3	1kWhLA	Converter (kW)	CoE ($)	NPC ($)	Operating Cost ($)

0.1	130	4	5.8	71.5	8	441	25	1.14	697,042	15,938

The load profile presented in Fig 4.31 clearly indicates there is a significant seasonal variation in the load profile. The load demand of the community increases significantly in winter. The average sun hour and daily solar exposure also reduces significantly during the wintertime (January). As mentioned earlier, this study considers the system configuration obtained using HOMER, HOMER takes into account all these seasonal variations while calculating the battery bank size.

However, when someone using the MATLAB programming to calculate the optimum system configuration, they need to consider these factors. As the winter load demand is higher than the summer load demand, one should size the battery bank as per this requirement to ensure reliability of power supply during peak demand seasons. To understand this battery sizing technique, let us consider the average daily load demand of the community on a peak winter day is 171.57 kWh (Again, one need to remember that it is just for calculation purpose and actual data may vary from the considered data).In case one considering 2 days of autonomy, battery voltage is 12V, minimum depth of discharge is 50%, temperature correction factor considered as 1.3 considering the coldest temperature of the area as around 4.4 C [109], efficiency of battery is .85 .Hence the capacity of the battery bank is calculated as 74 Amp hours [109].

4.4.1.D System performance

The selected system performance has been discussed in detail in section 4.1 It has been shown that the selected system could successfully meet the load demand of the targeted community with 1% annual shortage. The AC primary load and the AC primary load served are presented in Fig 4.33.

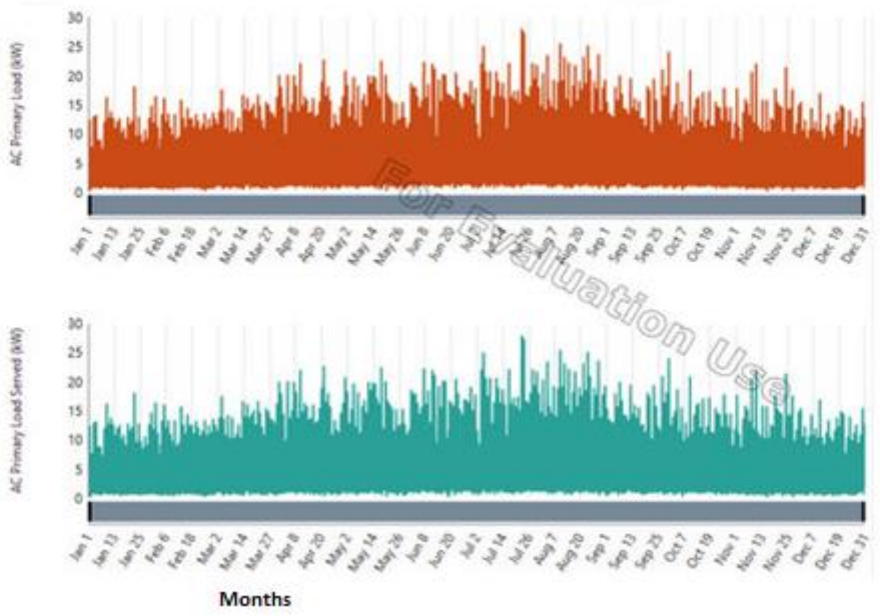


Fig 4.33 AC primary load (top) and AC primary load served (below)

The excess energy production and capacity shortage is presented in Fig 4.34

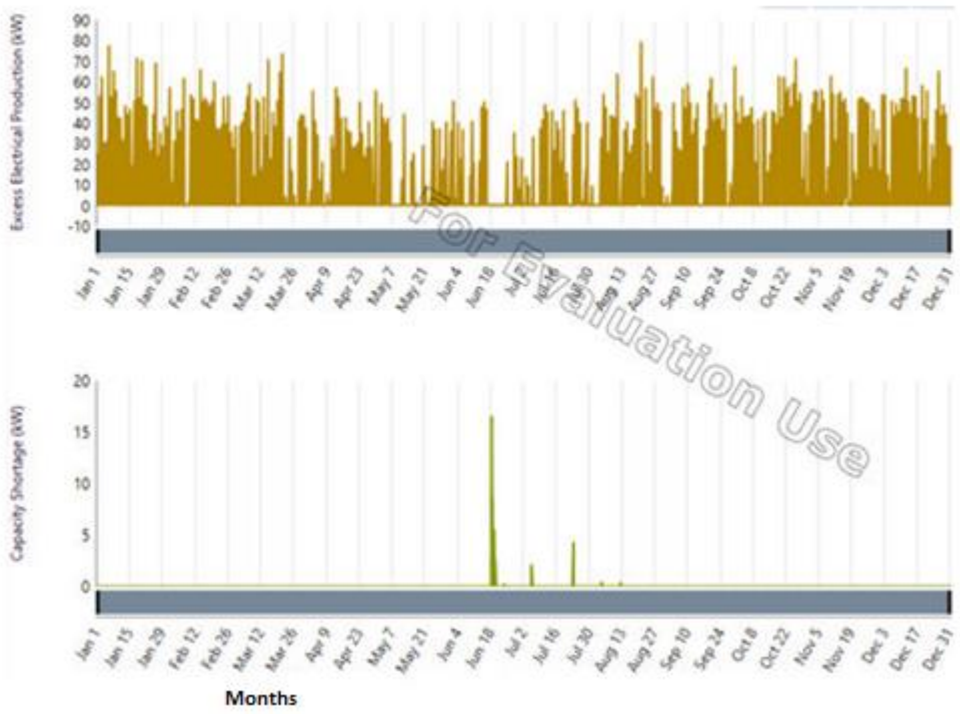


Fig 4.34 Excess electrical production (top) and Capacity shortage (below)

One can use any of the methodologies used in this section to optimally size the components of the HRES. However, the optimum system selected using HOMER has been used for the rest of the study. This is because as HOMER can provide a detail insight of the financial aspects of the selected system. Hence, this can reduce the afterwards calculation for investigating financial aspects. However, one can use any other methodology or tool for the purpose of optimum system selection and carry the calculation of the financial details of the system using any tool or calculating manually.

Once the optimised system configuration is selected, the next step would be to design a proper control mechanism for the HRES to ensure proper power management between the components of the designed system.

The next section will discuss the development of the control mechanism for the HRES under consideration.

4.5 Summary

This chapter discusses various optimization methods used for hybrid renewable energy systems, including:

A. DPSP Algorithm (Deficiency of Power Supply Probability): This is a dynamic programming-based algorithm used to optimize the power generation and storage strategy of hybrid renewable energy systems. The goal is to minimize the overall cost of the system while ensuring a reliable power supply.

B. iHOGA (Improved Hybrid Optimization by Genetic Algorithms): This is an optimization algorithm that utilises Genetic Algorithm to optimize the power generation and storage strategy of hybrid renewable energy systems. The goal is to minimize the overall cost and environmental impact of the system.

C. HOMER (Hybrid Optimization Model for Electric Renewable): This is a computer model used to optimize the design and operation of hybrid renewable energy systems. It uses a simulation-based approach to optimize the size of the system, the mix of renewable energy sources, and the energy storage capacity to meet the energy demand at minimum cost.

All these optimization methods aim to improve the performance and efficiency of hybrid renewable energy systems by optimizing the power generation and storage strategy. They can help reduce the overall cost, increase the reliability of the system, and promote the use of renewable energy sources, leading to a more sustainable energy future.

DESIGNING THE CONTROL SYSTEMS FOR THE HRES

CHAPTER

5

Chapter 5. Designing the Control systems for the HRES

5.0 Introduction

Due to exhaustion of natural resources like coal and fossil fuel renewable are being broadly acknowledged as a, alternative. However, to design HRES, one must consider that the dynamic interaction in-between load requirement and the HRES can result in critical stability and power quality issues, which is uncommon in conventional power systems [2][128]. It is important to establish a proper management of energy flow to ensure uninterrupted power supply for the load requirement. Control strategies play crucial role in maintaining system efficiency and power generation of a power plant. Hence a proper selection of control technique is important for designing a power plant. To ensure a continuous and reliable power supply by the HRES a proper power management strategy is henceforth essential. This in the other hand, also increases the operational lifetime of the HRES and quality of the energy flow. Numerous studies have been reported in literature [117].

The traditional method for power control is based on controlling the power as per the load requirement. This has been used by many HRES. This is gained by using power electronics-based DC to Dc converter to harvest maximum solar and wind energy from the available resources. Apart from the conventional approaches some advance control techniques are available in literature. These techniques can successfully compensate the power variation that is caused by the variation of power generated by the renewable sources which can affect the supplied power quality.

In their work, Jonathan et al. [118] suggested a control technology for HRES tan monitor and decide the appropriate control decisions based on the definite battery state of charge (SOC). This method demonstrates noteworthy advantages over other available methods. On the other had Ottoson et al. [119] presented a method that uses a data logger and can give a complete analysis of the energy production and performance of HRES that includes PV, wind and diesel plants. In their research Nogaret et al. explained a control mechanism based on the expert system for HRES. This method, by using advance control mechanism for HRES ensures optimal operation and supervision of HRES.

Chedid et al. [121] used a computer aided design tool that considers all environmental factors for optimum design and control of HRES comprising solar and wind generators. Research has been conducted using Linear programming techniques that can reduce the production cost while meeting the load requirement. In their work, Pitrone and Pitrone [122] presented an expert system in which they incorporated fuzzy logic, Neural Network and PLC (programmable logic controllers) for supervising and controlling the HRES online.

The control mechanism for the proposed HRES was developed in multiple stages. This section will discuss numerous control technologies investigated and developed during this study.

5.1 The system structure of the proposed HRES

To develop the control mechanism of the proposed HRES it is important to understand the basic structure of the system. This chapter will discuss the system structure and power management strategies of the proposed system in details.

The schematic diagram of the proposed system was presented in Fig 5.1.

The targeted community is comprising of ten households individually installed with solar panels and a small battery back-up. Apart from that, there would a central battery bank is incorporated as storage device along with a wind turbine and a standby diesel generator and a dump load. Hence the HRES considered here has three different types sources, they are photovoltaic (PV) arrays and a wind turbine and a diesel generator. The main power generating sources for the system are the PV panels and wind turbine. As the main power generating sources and the storage used in the this HRES are environment friendly, the power generated by this system can be considered as complete ‘Greenpower.

The power management strategy of the proposed HRES can be described as follows:

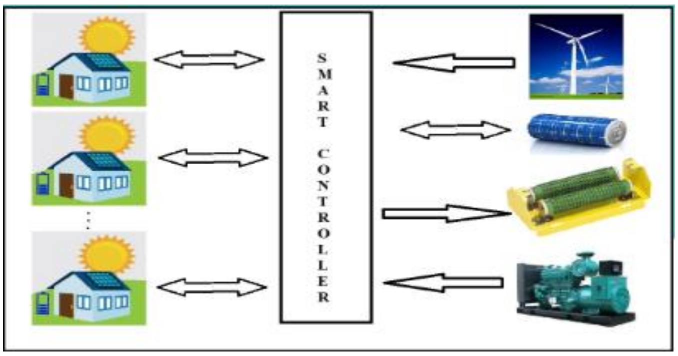


Fig. 5.1. The schematic diagram of the proposed HRES

- The PV and wind generators will produce electricity in accordance with the local solar and wind resources.

- Each household will be using the power generated by the in-house solar panels first.

- When the power generated by the in-house solar panels are more than the load demand, the excess power will be stored into the in-house battery till it reaches its maximum depth of charge

(DOC). Once that stage reached, the excess energy will be stored into the central battery bank until it reaches its maximum DOC.

- When both in-house and central battery bank reaches their maximum DOC any excess generation from solar panels or wind turbine will be sent to dump load.

- If at any stage, the power generated by the in-house solar panels is less than the load demand or during the night time when there is no generation from the solar panels, the in-house battery bank will be responsible for supplying the load demand of the household. The battery bank will continue to do so till it reaches its minimum DOC.

- Once the battery bank reaches its minimum DOC it will stop discharging and will get disconnected from the load. At this stage the excess load demand will be fulfilled by the central battery bank.

- The central battery bank will supply the load demands till it reaches its own minimum DOC. In worst weather conditions, when the power generated by the renewable energy sources are significantly low, the central battery bank might reach its minimum DOC while supplying the load demand for a longer time. In that situation, it will get disconnected from the load demand. At this stage, the diesel generator will get switched on and will continue to supply the load demand.

- The power generated by the wind turbine will be utilised for charging the central battery bank.

- A smart central controller would be responsible for the overall power management of the system.

The key aspect of the power management strategy for the HRES is the **load sharing option between the neighbours**. This makes the system structure complex. Each household can store the excess generation from the PV panels to the central battery bank which can be used by the any other members of the community. Hence this way the control system should enable the load sharing between the neighbours. This allows each household to utilise any excess generation from the inhouse PV panels at the best possible way, this also reduces the waste of energy also reduces the storage requirement. Hence the power management strategy should take this into account and should ensure that the desired performance in achieved. It also would ensure that the designed system should be able to supply the load demand with minimum interruption.

The key factors that influences the power management strategies of a HRES are the level of power generated by the renewable sources, i.e. wind turbines and PV panels and also the state of charge (SOC) of the battery bank. As the system considered in the study is a standalone system with renewable sources the design of the control mechanism becomes even more crucial and complicated.

The generation of wind power is higher during winter times than the summer times as average wind speed is higher in summer than winter and the production from the PV panels if higher during summer seasons than the winter day for Portland as the average sun hour decreases in winter than summer. Hence the combination of wind and solar power is ideal for most of the standalone applications as they can compensate each other for seasonal variation in their productions. In this combination one's weakness becomes other's strength. However, it is important to design the capacity of the PV /wind generators and the storage system optimally to satisfy the load requirement under various conditions to ensure the power supply reliability and also to avoid any excess set up cost due to oversizing.

To provide a combined dynamic performance for the combination of different types of micro sources, the energy storage systems plays a crucial role. The decisive measures of the ratio of energy storage to source and the size of the storage device is primarily based on the microgrid characteristics, specially, on the dynamic response of the sources and the quality of power required by the loads [144]. Another factor that impacts the size of the storage device is the power quality. When the power quality requirement of the microgrid is higher, it would require bigger storage. When a microgrid has the ability to accept low power quality its storage requirement reduces. Hence the energy storage devices not only provide a back-up power supply, they also improve the power quality and improves system reliability. The system also has a diesel generator which acts as a back-up power source when the renewable sources along with the battery storage are unable to meet the load demand.

5.2 Development of control strategy for the HRES

This study has investigated various control techniques and has developed control strategies to manage the power flow between the sources, load, storage devices and standby generator and also to extract maximum power from the wind turbines using Artificial Intelligence (AI) techniques like Fuzzy Logic Control and Cuckoo Search Algorithm.

A Comprehensive Fuzzy Logic Controller (FLC) has been designed to manage the power flow between the various components of the HRES which can perform efficiently under various load and supply conditions. This FLC is capable of detecting any abrupt change in the load demand and power generation conditions which might be caused by any transient circumstances and take appropriate control actions avoiding any overcharging or discharging of the storage devices. The performance of the controller has been analysed under various load demand conditions which includes sudden change in power generation and load demand conditions that can lead to any transient situations, i.e. Passing cloud. This design was done in various steps which will be discussed in following sections.

Apart from designing the control strategy for the power flow management of the HRES, this study also designed a control mechanism to extract maximum power from the wind turbine. An optimised FLC was developed using Cuckoo Search Algorithm (CSA) which can enhance the performance of the wind turbine by capturing the maximum energy. This study will be discussed in later sections.

5.3 Development of control strategy for the power flow management

The development of the power flow management was done in few steps. The design was mainly done in MATLAB/ SIMULINK environment. The steps are discussed in the following sections.

5.3.1 Design of the control mechanism considering the concentrates sources

In the first stage of the design a SIMULINK model was created using the optimised numbers of wind turbines and PV panels along with the battery bank, dump load and diesel generator. Here the ten household of the community was considered as a single load and all the PV panels and the wind turbines have been considered as a centralised power generating unit. The total capacity of the battery bank is considered a central storage. The schematic diagram of the proposed HRES under this consideration can be presented as Fig.5.2

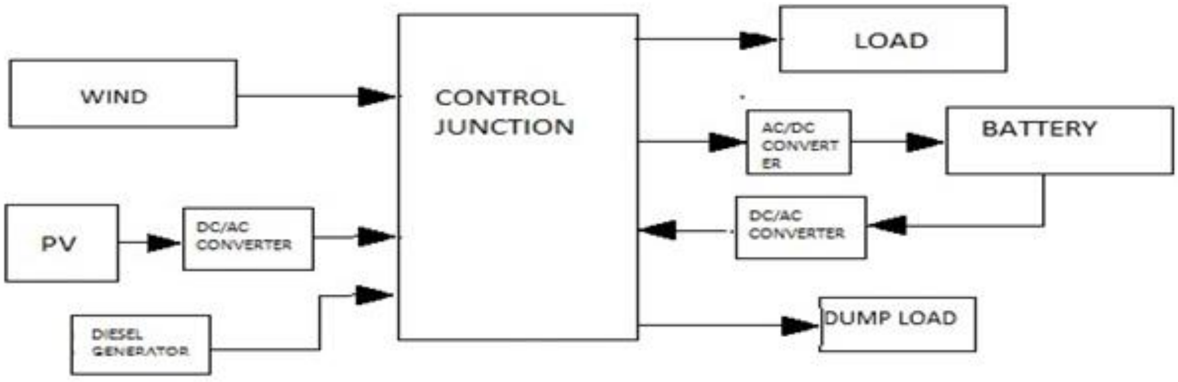


Fig 5.2 Schematic diagram of HRES as considered in stage 1

Based on the mathematical expressions provided in previous sections for the PV panels, wind turbine, battery SOC, a SIMULINK model was created to develop and investigate the power flow strategy of the HRES described in stage 1 of the development of the control strategy. The simplified SIMULINK model is presented in Fig 5.3.

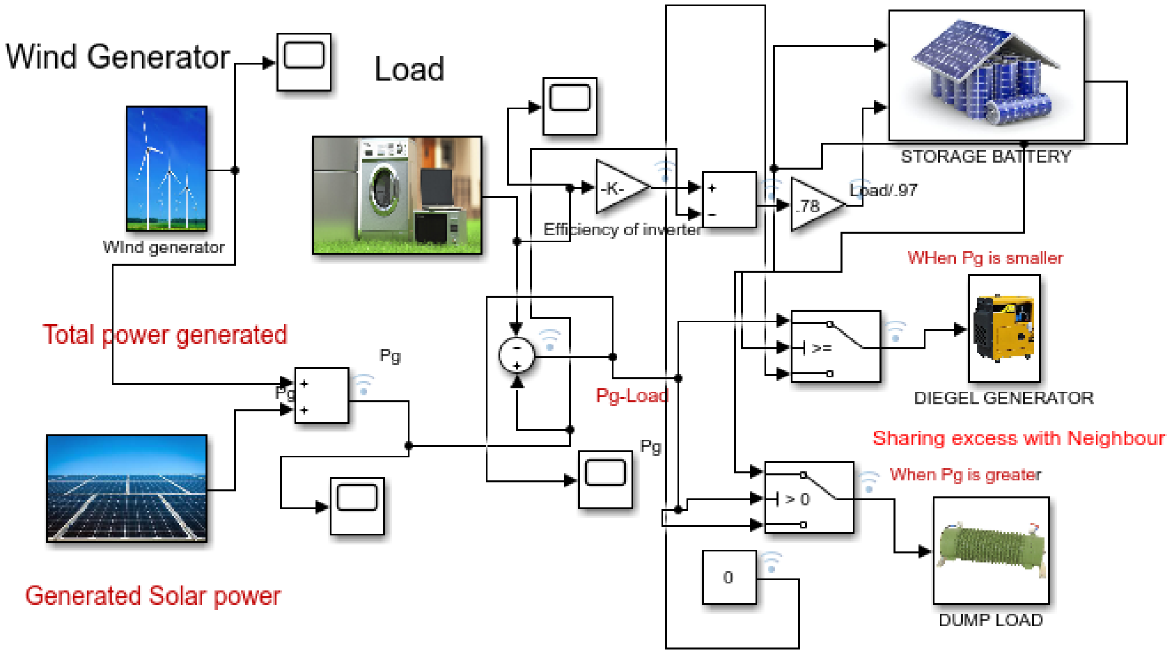


Fig 5.3 The SIMULINK model of the system considered under stage 1

At this stage, the power management strategy can be explained as follows:

- The total power generated is combination of power generated by the PV panels and wind turbines, will be utilised the supply the total load demand of the community
- When the load demand is less than the generated power, the excess power will be stored in the central battery bank till central battery bank reaches its maximum SOC.
- Once the central battery bank reaches its maximum SOC any excess generation will be sent to the dump load.
- When the total power generated is less that the load demands the central battery bank will be discharged and cater the load demand of the community till it reaches its minimum SOC.
- Once the central battery bank reaches its minimum SOC the battery will be disconnected from the load and diesel generator will be turned on to supply the load demand.

The energy management strategy in presented in 5.4.

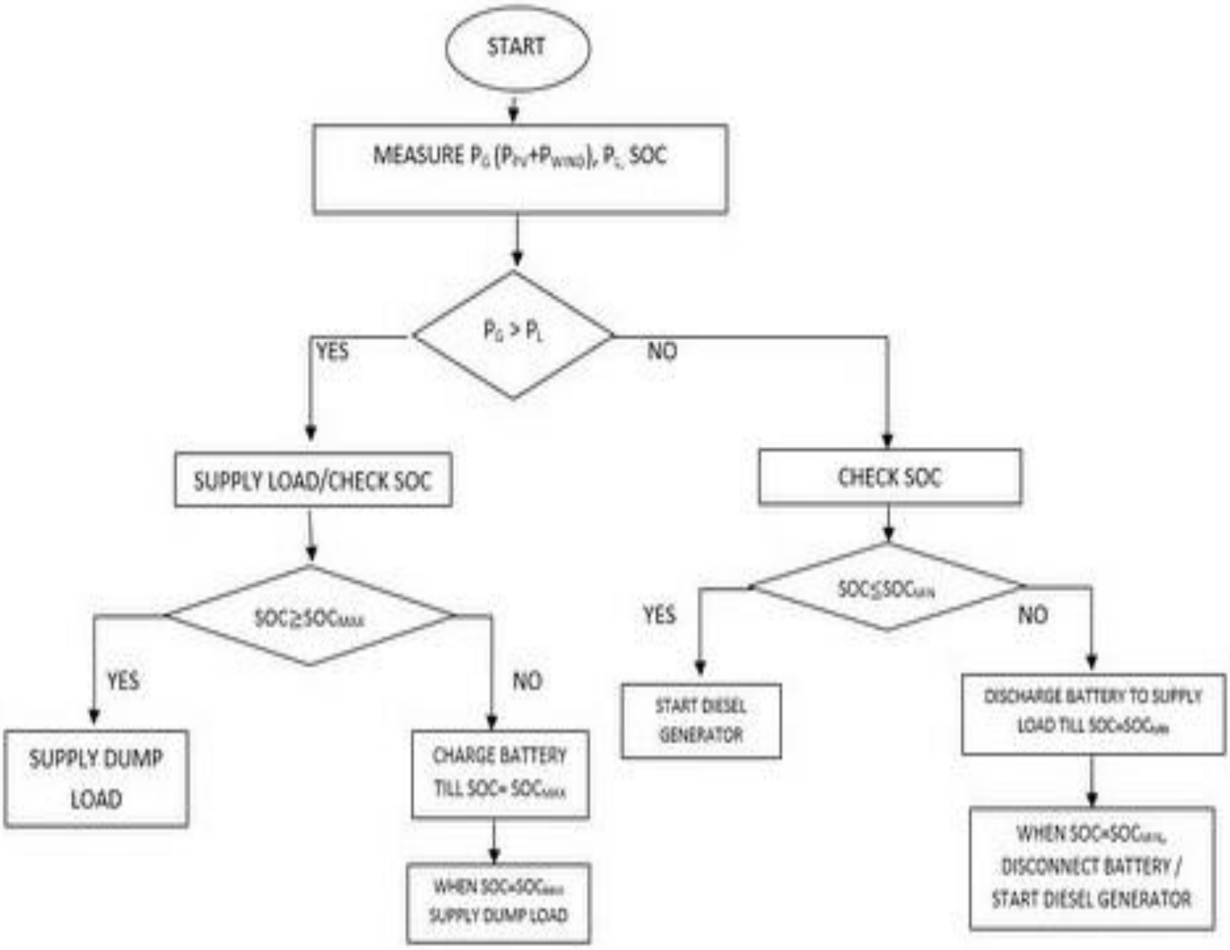


Fig. 5.4 Energy management strategy for developing the control mechanism for the HRES

The overall system performance was achieved by designing the Simulink controller. The performance of the system under various conditions is presented in Figs. 5.5 – 5.6.

It can be observed from both the figures that the control system manages the load flow successfully under different load and generation condition. When the load requirement is greater than the total power generated, the battery bank discharges and supplies the load, hence the SOC of the battery bank decreases. When the generated power is more than the load demand the excess power is utilised to charge the battery hence the SOC of the battery increases. Once the SOC reaches its maximum the excess power is sent to the dump load. Hence the designed control system can reliably manage the power flow among the system components ensuring reliable power supply to the load.

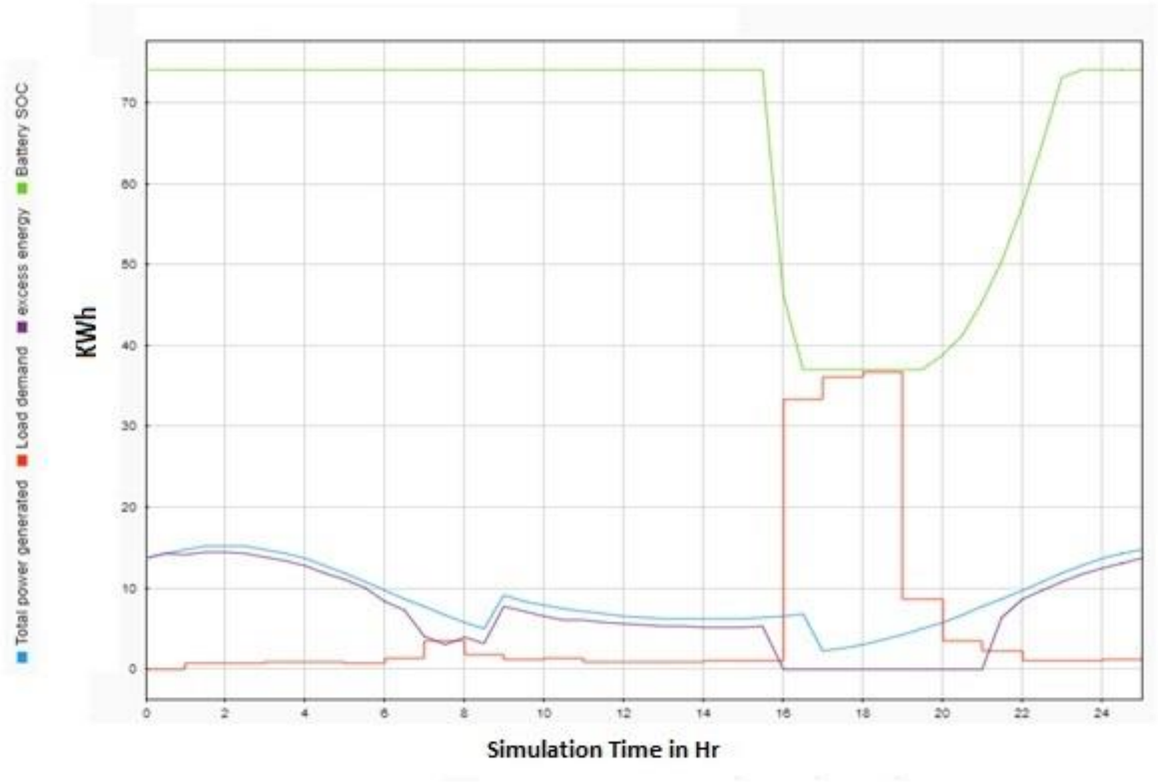


Fig 5.5 System performance when load demand is significantly high

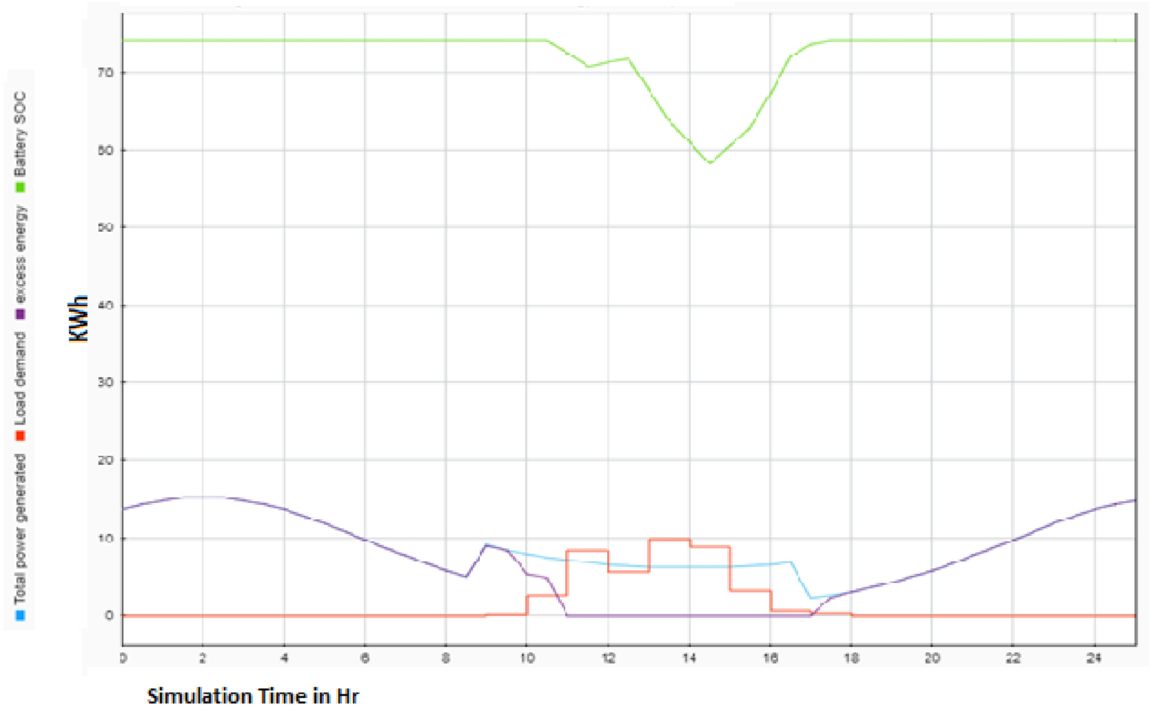


Fig 5.6 System performance when load demand is moderate

5.3.2 Development of a Fuzzy Logic Controller to manage the power flow considering the concentrates sources

After the initial stage of the development of the control system, in the next step of the study an intelligent controller was developed using Fuzzy Logic for the system that has been described in Fig. 5.7.

Before designing the Fuzzy Logic Controller (FLC) for the proposed system, study been conducted to understand and learn the process of designing a FLC for a simple system , and also the process of optimising that using Genetic Algorithm. The aim of that study was to design a heuristic Fuzzy Logic Controller which would be capable of maintaining the liquid level of the tank to a specified set point and optimise the performance of the designed FLC using Genetic Algorithm. This work was conducted to gain knowledge of design process and optimisation techniques of the FLC to get better performance and gain more knowledge on optimisation using Genetic Algorithm. This work has been presented in Appendix (Appendix A.1 Page 199 **A.1 Modelling of an optimum Fuzzy Logic Controller using Genetic Algorithm)**

Once the designing process of FLC is learned as described above, A Fuzzy Logic Controller has been designed for power management for the HRES. The designed FLC can minimise the cost of operation and the environmental impact of the HRES. This FLC improves the economic and technical performance of the power supply significantly. The FLC can ensure reliable power management between the generators, storage and load of the HRES. The designed FLC demonstrates high performance in simulation results. This work has been published as a paper in Engineers Australia Technical journal [134]. Hence this section will consider and discuss the process of the design of the control mechanism based on the load and power generation data considered in the paper. In later stages of the design necessary changes have been made in the FLC design as per the load data available for the targeted community which was easily done without making any significant changes to the algorithm.

The power management strategy that has been developed in this study for the proposed HRES presented in Fig 5.1 using Fuzzy Logic Control is presented in Fig 5.9. The Energy Management Strategy (EMS) can determine the spilt power between the PV panels, wind turbines and storage and also meets the load demand. As presented in Fig 5.9, in the designed methodology the wind/PV generators and the storage battery bank are connected to one central junction, that central junction is an AC bus. The energy Flow between these components of the HRES are managed and controlled by the designed FLC as presented in Fig 5.9. The overall process goal is similar as presented in previous sections, presented in Figs 5.2, 5.3 and 5.4. However here the FLC is taking over the over of the overall control action and deciding when to use inhouse solar output or charge or discharge batter etc.

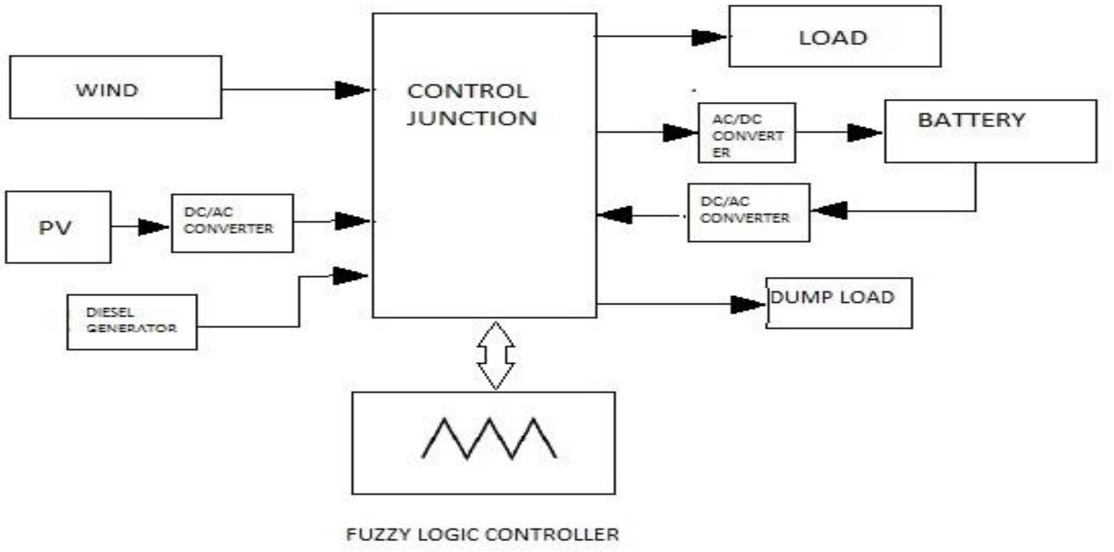


Fig 5.7. The schematic diagram of the proposed HRES in stage 2

Using Fuzzy Logic Control, a comprehensive controller has been designed in this stage to proficiently manage the power flow between the renewable sources, load, battery and the diesel generator. This is capable of working efficiently under various power flow conditions. The controller is capable of detecting any sudden change in the load demand or power generation due to any transient circumstances and can take proper action accordingly to avoid any over-charging or over discharging of the battery bank. The behaviour of the controller was analysed under various load demand and generation conditions to ensure its reliable performance.

The behaviour of the controller was analysed under two different scenarios:

Scenario 1: Total generated power of all the sources is greater than load demand: -

It is possible to reach a condition when both solar and wind generators have reached their maximum generating point and load demand is minimum. As presented in a study [145] the excess generation usually less than half of the maximum possible value. The excess energy production increases with increased solar energy penetration.

In this scenario the controller tracks the load demand and feeds the demand utilising the generated power. Any excess generation then would be utilised to charge the battery bank for future use. One key point to remember, that to increase the battery life it is important to ensure any deep discharge or overcharging of the battery bank. For this study the SOC of the battery bank has been regulated between 50% - 90%. This numbers can be altered as per the design requirement without changing the algorithmic framework.

Scenario 2: Total generated power of all the sources is lesser than load demand: -

In a scenario when the load demand is greater than generated power the controller should first the SOC of the battery bank. If the SOC is greater than the minimum SOC of the battery bank, the controller would start discharging the battery bank to supply load demand till it reaches its minimum SOC which is considered 50% in this study. Once the battery bank reaches minimum SOC, it will be disconnected from the load to avoid any deep discharging of the battery bank. At this stage the FLC turns on the diesel generator. This away the controller improves the efficiency of the battery bank by avoiding the deep discharge. The cost of charging the battery increases with the battery efficiency.

The battery charging/discharging control algorithm as well as energy management strategy used in the design of the FLC is same as illustrated in Fig. 5.4.

As mentioned earlier, determination of the split power between the renewable sources and storage is the main aim of the Energy Management Strategy (EMS). The load demand is not easily predictable and varies frequently. The power generation from the RES is highly dependent on climatic conditions due to which the structure of HRES becomes more complex.

Numerous control strategies have been reported in the literature for implementing energy management algorithm. FLC found to be a very efficient among them due to lower power dissipation, optimised cost, reliability and stability [17].

5.3.2.1 Design methodology of the FLC

Fuzzy Logic Controller is a controller based on Fuzzy set theory. As pert Fuzzy set theory the decision is made by three main operations. They are fuzzification process, An inference engine for the rule base and defuzzification process [146]. Fuzzy logic is a mathematical system that can analyse the analogue input values in terms of logical variables which can take a continuous value between 0 and 1. The fuzzy rule base uses the expert knowledge of an experienced operator to design the knowledge base of the controller. The configuration of fuzzy logic is presented in Fig. 5.8 [147-149].

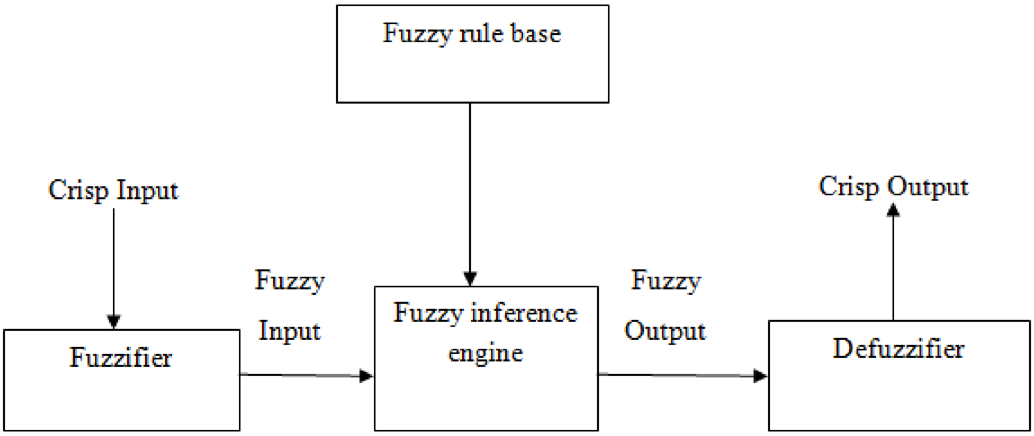


Fig 5.8 Configuration of fuzzy logic

In this stage of the study a FLC was designed to replace the conventional controller to make decisions regarding power flow management between the components of the HRES. Conventional controllers are commonly used in this kind of scenarios, but incorporation of FLC allows the experienced user to feed their knowledge about the system into the controller to design the knowledge base. This allows the controller the take decision based on multiple inputs and generate multiple outputs even though no clear mathematical relation between the inputs and outputs are not available. As this field of study is even evolving, once the basic FLC design is done, it would be possible to incorporate more variables and achieve more precise control actions between the variables. Henceforth this study emphasises on designing a FLC to acquire analogue control actions of a conventional controller.

The Energy Management System based on Fuzzy Logic checks the load status , total power generation from the wind and solar energy sources, SOC of the battery bank and takes appropriate control actions to charge or discharge the battery bank or activates the diesel generator or send the excess energy to the dump load.

The selection and design of the Membership Functions (MFs) is a crucial part of FLC design. This selection is case sensitive. The range of the MFs changes with the set of generators, load characteristics and battery storage capacity. This ranges can be altered as per system requirement easily without making any significant change in the basic algorithm. In this study these ranges have been selected as per the load profile and power characteristics of the HRES for one-year period.

The designed FLC has two input and three output variables. The input variables are ‘Battery SOC’ and ‘Excess Energy’. Where the ‘Excess Energy’ represents the difference between the total generated power by the renewable sources and load demand. Excess Energy' has two membership functions. When the power generation from the renewable sources is greater than the load demand 'Excess Energy' is 'positive' or else it would be 'Negative'.

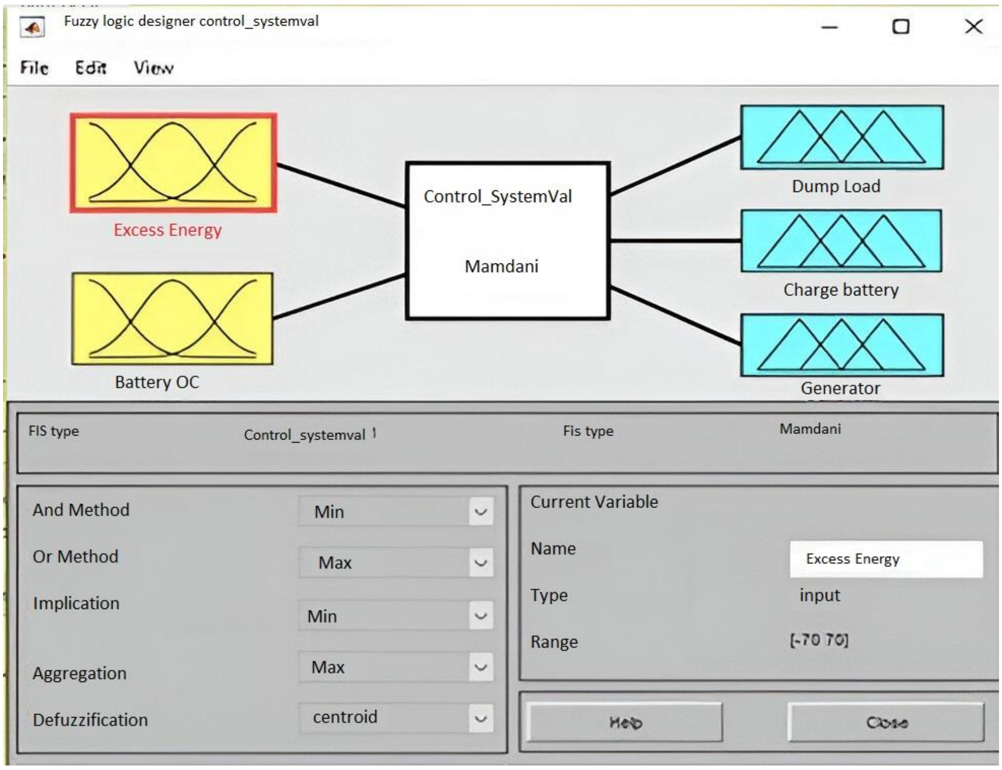
Before designing the FLC the study of the available data was conducted. Hence as per the investigation the range of the excess energy generation has been considered as -70 to 70 where the unit of excess energy is kWh. Hence the range of the MFs are considered between -70 to 70.

The state of charge of the battery bank is presented by the MF 'Battery SOC'. The input 'Battery SOC' has three MFs, 'low', 'medium' and 'High'. As per the available data the range of SOC considered in this study is 50-90 % for the purpose of analysis. This range also can be changed as per the available data without making any significant changes to the basic system structure. For the purpose of this study as per the considered data the total capacity of the battery bank was 1000Ah. Based on that the range of the MFs of Battery SOC is considered as 200-1000 for this study keeping in mind the actual working conditions. However, the rule base was designed to ensure that the SOC varies within its specified range of 50% - 90%.

The designed FLC has three output variables, 'Charge Battery', 'Generator' and 'Dump Load'. Variable output Charge Battery' is a signal that decides if the battery will charge or discharge. This output variable has two MFs, 'positive' and 'Negative'. When it is 'Positive' the battery will charge, and the battery will discharge if it is 'Negative'. The output 'Generator' is a signal which decides when to start the diesel generator. This output has two MFs , 'positive 'and 'negative'. The generator should be on when the signal is 'positive 'and the generator remains off when this signal is 'negative'.

The third output signal is "Dump load' which associated with the excess energy being sent to the dump load when the battery SOC reaches its maximum value. It has Two MFs, 'positive' and 'negative'. When this signal is 'positive', the excess energy will be sent to the dump load. IN case it is 'negative' the excess energy will be used to charge the battery bank.

The designed FLC with two inputs and three outputs is presented Fig 5.9 The controller was fed with a programmed set of rules which leads to a control surface shown in the Fig 5.10



FIS type Control_systemval
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And Method Min
Or Method Max
Implication Min
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Defuzzification centroid

Current Variable
Name Excess Energy
Type input
Range [-70 70]

Fig 5.9. Fuzzy Logic Controller with Two inputs and three outputs

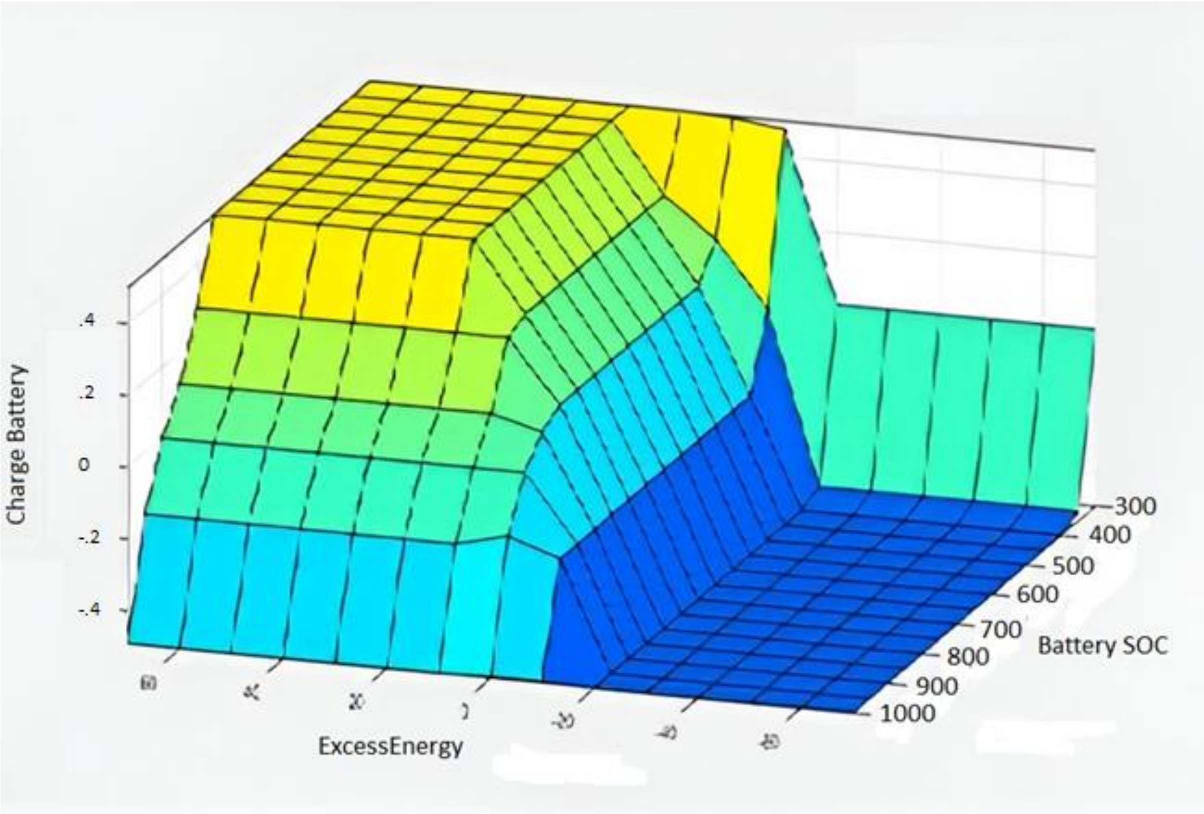


Fig 5.10. The Surface viewer for the rules

As mentioned earlier, at this stage it is desired to design the FLC so that it can demonstrate the performance which can be comparable to the conventional controller. Hence the Fuzzy knowledge base is designed on very straightforward rules.

For example:

If ‘Excess_Energy’ is ‘negative’ and Battery_SOC is ‘high’ then ‘Share’ is ‘positive’ and ‘Charge_Battery’ is ‘negative’.

If ‘Excess_Energy’ is ‘’ and Battery_SOC is ‘low’ then ‘Share’ is ‘negetive’ and ‘Charge_Battery’ is ‘positive’.

These rules lead to the surface that is presented in Fig 5.10. The MFs of the FLC are presented in Figs 5.11 – 5.15.

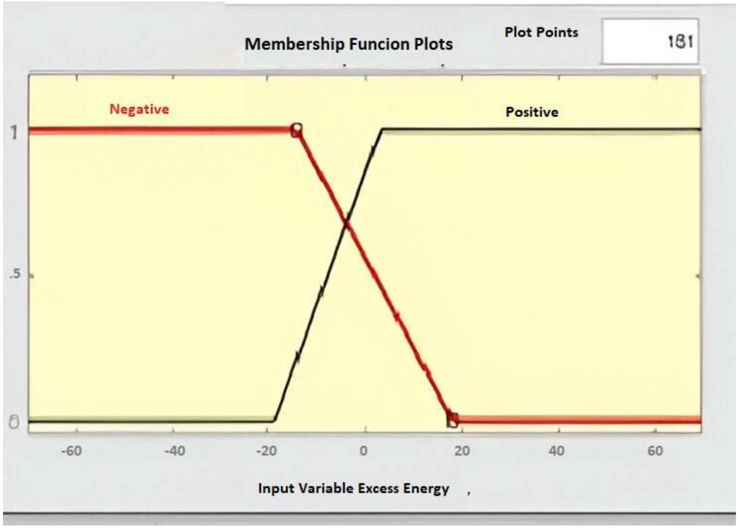


Fig 5.11. Membership function for input 1: (Excess Energy)

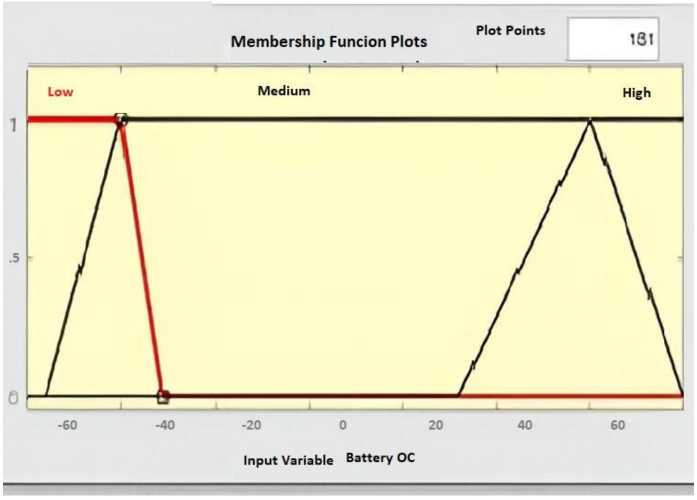


Fig 5.12 Membership function for input 2: (Battery SOC)

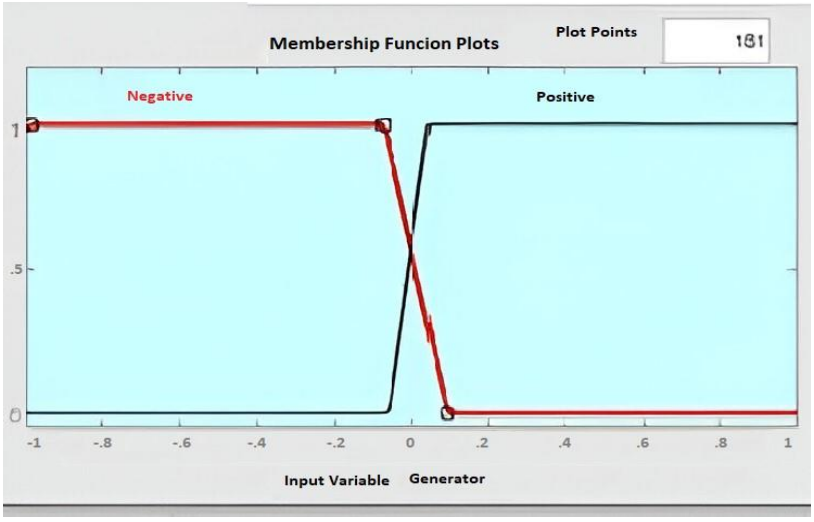


Fig 5.13 Membership function of output ‘Generator’

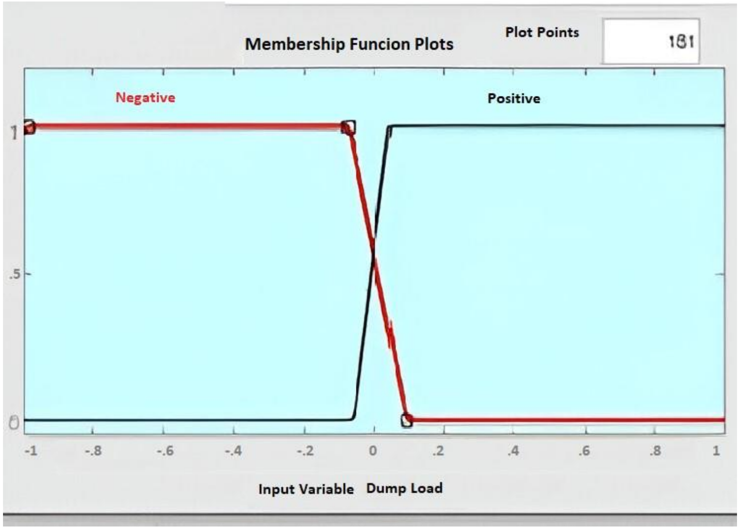


Fig 5.14 Membership function of output ‘Dump load’

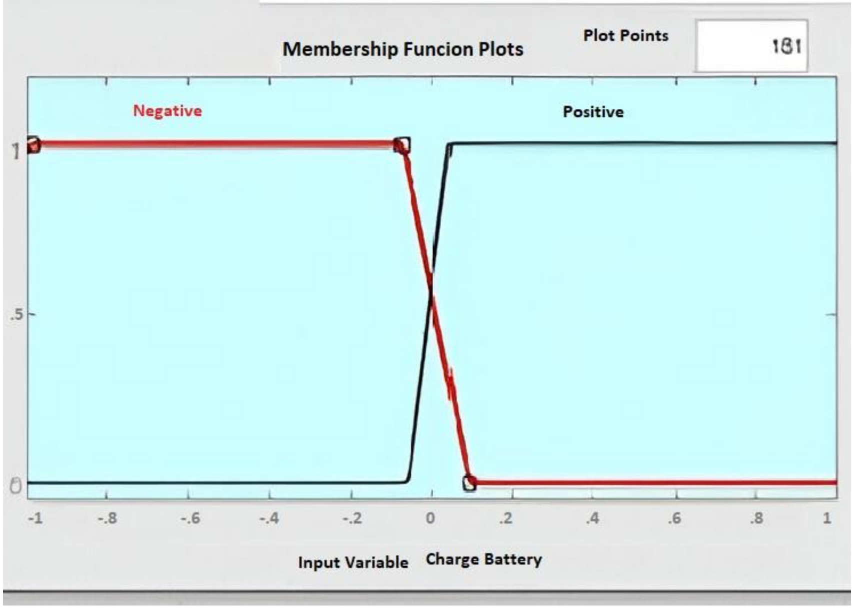


Fig 5.15 Membership function of output ‘Charge Battery’

5.3.2.2 Simulations and results

A model was created in MATLAB /SIMULINK environment to simulate the control methodology for energy management. The FLC was designed using Fuzzy Logic Toolbox of SIMULINK. The schematic diagram is presented in Fig 5.16. The wind turbine PV panels and battery bank were modelled using the same methodology described in stage 1. The weather data collected from BOM [Australia's Official Weather Forecasts & Weather Radar - Bureau Of Meteorology]. To analyse the performance and system efficiency the system was simulated under two different load demand and power generation conditions. This is to ensure that the designed FLC can perform reliably in comparison with the conventional controllers. These two scenarios are discussed below :

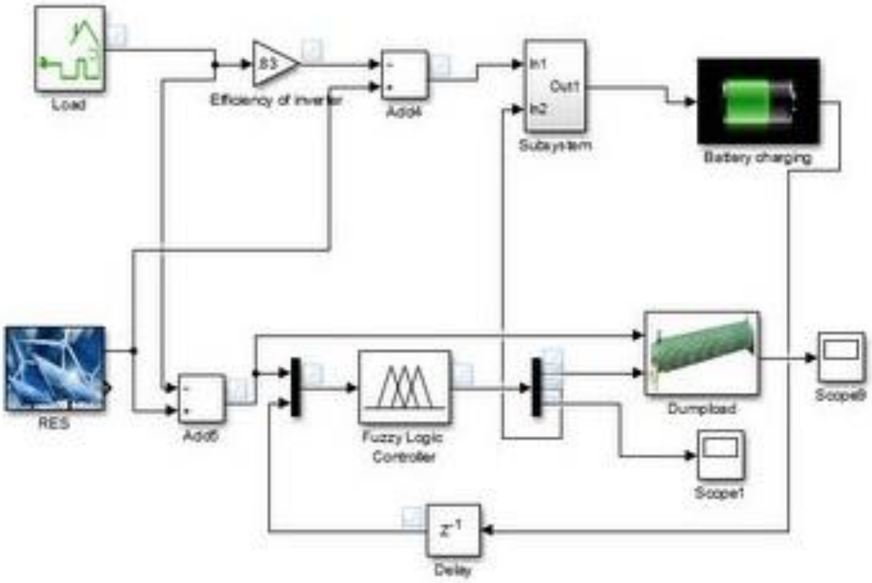


Fig 5.16. Simulink model for Fuzzy Logic-based energy management system

- **When the initial SOC of battery is 70%**

Fig 5.17 represents the system performance under this condition. When the load demand is less than the generated power and the battery SOC is less than maximum SOC, so at this stage the excess power is utilized to charge the battery bank. So, at this stage the SOC of the battery increases. Under the situation when the load demand is greater than the generated power the battery bank discharges to supply the load demand as a result of which the SOC of the battery bank decreases. As there is no excess energy, no power is being sent to the dump load. Henceforth It can be said that the designed FLC can perform as desired under the presented power generation and load demand condition.

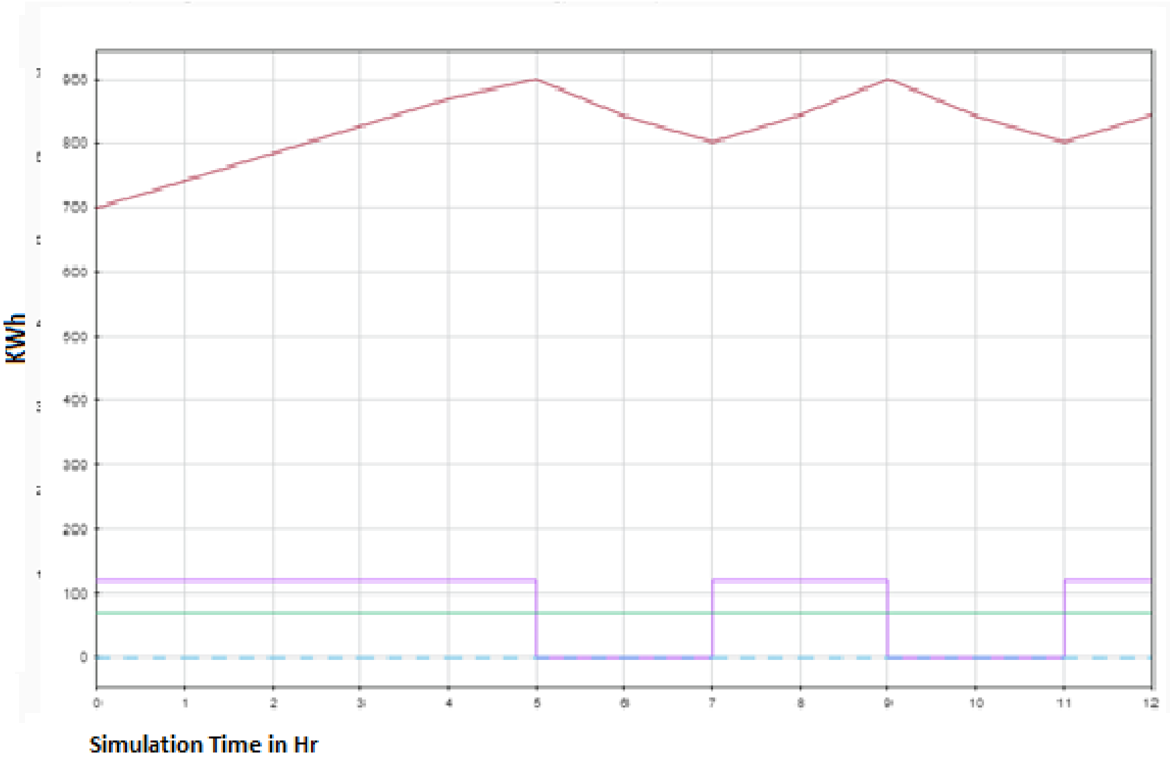


Fig 5.17. Generated power (Purple), Load demand (Green), Battery SOC (Burgundy), Dump load (Blue dotted) with initial battery SOC 70%

- **Initial SOC of the battery is 90%**

Fig 5.18 represents the system performance under this condition. In the initial stage the load requirement is lesser than the power generated by the renewable sources and the SOC of battery bank is at its maximum value. Hence, as in this situation the excess energy cannot be stored in the batter, it is being sent to the dump load. So, this way the controller avoided any overcharging of the battery bank. When the load demand is greater than the generated power the battery bank discharges to supply the load demand. As a result, the battery SOC decreases.

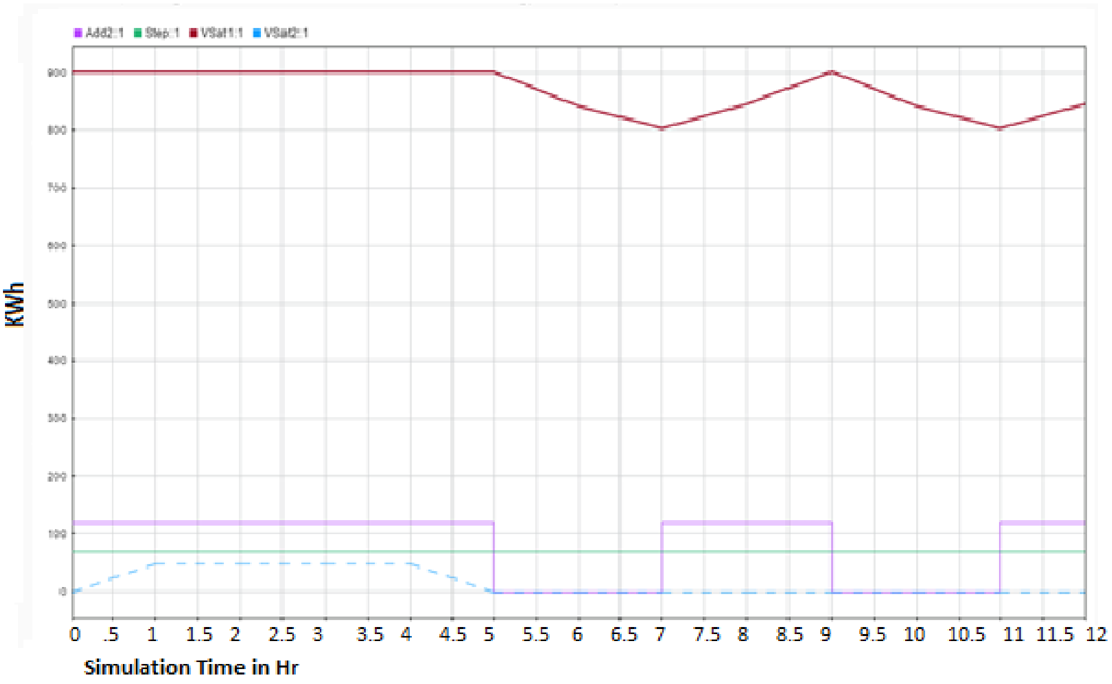


Fig 5.18 Generated power (Purple), Load demand (Green), Battery SOC(Burgundy), Dump load (Blue dotted) with initial battery SOC 90%

Hence a FLC was successfully developed for efficient power management between the generators battery bank, load and dump load and dump generator. The proposed FLC can take decision to charge and discharge the battery bank or send the excess energy to the dump or to start the diesel generator as per system requirement.

The incorporation of Fuzzy Logic to the power management of the HRES is interesting, this allows the user to achieve the desired control action using multiple inputs and can generate multiple outputs based on some rules based on some linguistic variable. It increases the battery life by avoiding any overcharging and deep discharging. Hence it can be concluded the designed FLC has made the power management of the HRES more efficient.

5.3.3 Design of the control mechanism considering the distributed sources

Once the study successfully completed the design of the control mechanism and the FLC considering the concentrates sources, in the next step the study concentrates on designing the control mechanism for the HRES considering distributed source. This study has been published in an international conference (ICPECA)

The system structure under this condition becomes more complicated, hence the development of control mechanism becomes more complex. Before developing the control mechanism for the power management, it is important to understand the system architecture of the proposed HRES. The system architecture has been presented in Fig.5.19 and the power management strategy has been presented in Fig 5.20.

5.3.3.1 Deigning the system architecture

As per the proposed architecture each ten household of the small community will be installed with solar panels and small battery back-up. Based on the data considered optimum sizes of the PV panels and wind generators were selected, the methodology and results were discussed in Charter 7. As per the results obtained the no of solar panels were 60. While designing the HRES for the targeted community the solar panels were equally distributed among the ten households. Hence each household will be installed with six solar panels.

The total capacity of the battery bank required for two days of autonomy was calculated to be 70Ah based on the data available [109]. As per the design architecture this battery bank needs to be distributed among ten households as in-house battery storage and also as central battery bank. To determine the size of the battery as in-house storage, average daily load profile of one of the households was considered for a summer day, as per which the daily usage was determined as 10 kWh. Using this value, the storage battery size was calculated considering two days autonomy [109] which would be 4 Ah. Hence each household is installed with 4Ah storage battery. So the remaining 30 Ah will be installed as the central battery bank.

The reason why a peak summer day was selected to size the battery is during the summer days the solar panels produce electricity than winter days as the average sun hours are more during summer than winter. Hence the most of the load demands will be meet by the power generated by the panels and any excess can be stored in the in house battery or the central battery. The central battery bank will be mainly charged by the wind turbines, wind turbines produce more electricity during the winter seasons than summer. Hence a bigger battery bank storage would be able to utilise the power generated by the wind turbines more than a smaller battery bank. Hence as the inhouse batteries are sized for summer load demand, during the winter period if there is excess load demand which can not be fed by the solar panels or inhouse battery bank that demand can be met by the central battery bank as they can be charged utilising the power generated by the wind turbines. If the inhouse batteries are sized based on winter load, their sizes will be bigger but during the winter period when there is not enough generation due to lack of excess energy from the solar panels they will not be properly charged and as a result they wont be able to meet the load demand during winter times. Due to installing major part of the battery bank the central battery bank size will also reduce, hence the production of the wind turbine will mostly be wasted as the smaller capacity central battery bank will need smaller energy to reach its minimum state of charge. So, it is clear from this discussion that if the inhouse battery bank is sized as per the winter load demand neither the load demand can be fulfilled properly during peak demand times, not the power harvested from the wind turbines can be efficiently utilised. This will actually result in waste of energy. Hence the inhouse battery was sized as per the summer load demand.

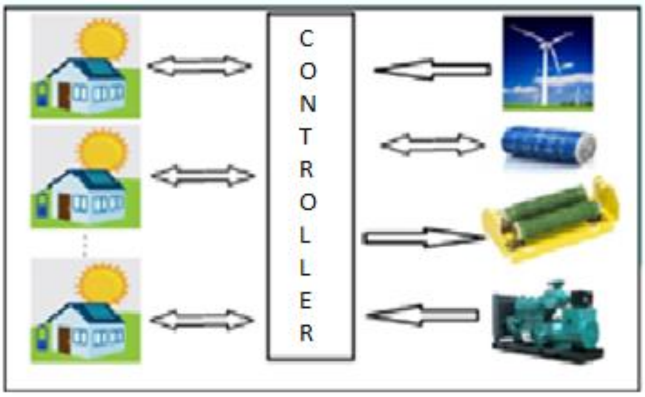


Fig 5.19 The system architecture of the proposed HRES

5.3.3.2 Implementing the control mechanism for the distributed sources

Till now while developing the control mechanism the total load demand of the community was considered being a single load demand. All the generating units were considered as a concentrated generating unit and the total capacity of the battery bank was considered as a concentrated storage system. This simplified version was considered to develop the algorithm and make the basic structure of the control mechanism and check the performance. Once the desired results been obtained with the simplified version of the HRES, the study now concentrates to implement the studied control mechanism and algorithm on the actual system structure and analyse the various aspects and observe the performances of the system.

The power management strategy of the proposed HRES can be summarised as follows:

- The community considered in this study has ten households, each will be installed with PV panels and a small battery back-up. Apart from that there is a central battery bank and wind turbine to charge the central battery bank.
- The solar panels will be responsible for catering the load demand of each household.
- When there is excess generation from the inhouse battery bank the excess will be stored in inhouse battery till it reaches its maximum SOC, at that stage the excess energy will be sent to

the central battery bank till its maximum SOC is reached. At that stage the excess energy will be sent to the dump load.

- When there is insufficient generation from the solar panels the load demand of any household will be served by the central battery bank till the central battery bank reaches its maximum SOC.
- If the insufficient generation continues and the central battery bank reaches its minimum state of charge, the central battery gets disconnected from the load and diesel generator turns on.

The flowchart for the energy management algorithm for in-house PV panels and in-house battery bank and the flowchart for the power management strategy for central battery bank are presented in Figs 5.20 – 5.21.

The overall control mechanism was developed in MATLAB/ SIMULINK environment based on the mathematical model of the system components discussed in chapter 5.3.3 and following the flowchart provided in Figs 5.20 – 5.21 The energy management model created in SIMULINK is presented in Figs 5.22 – 5.23.

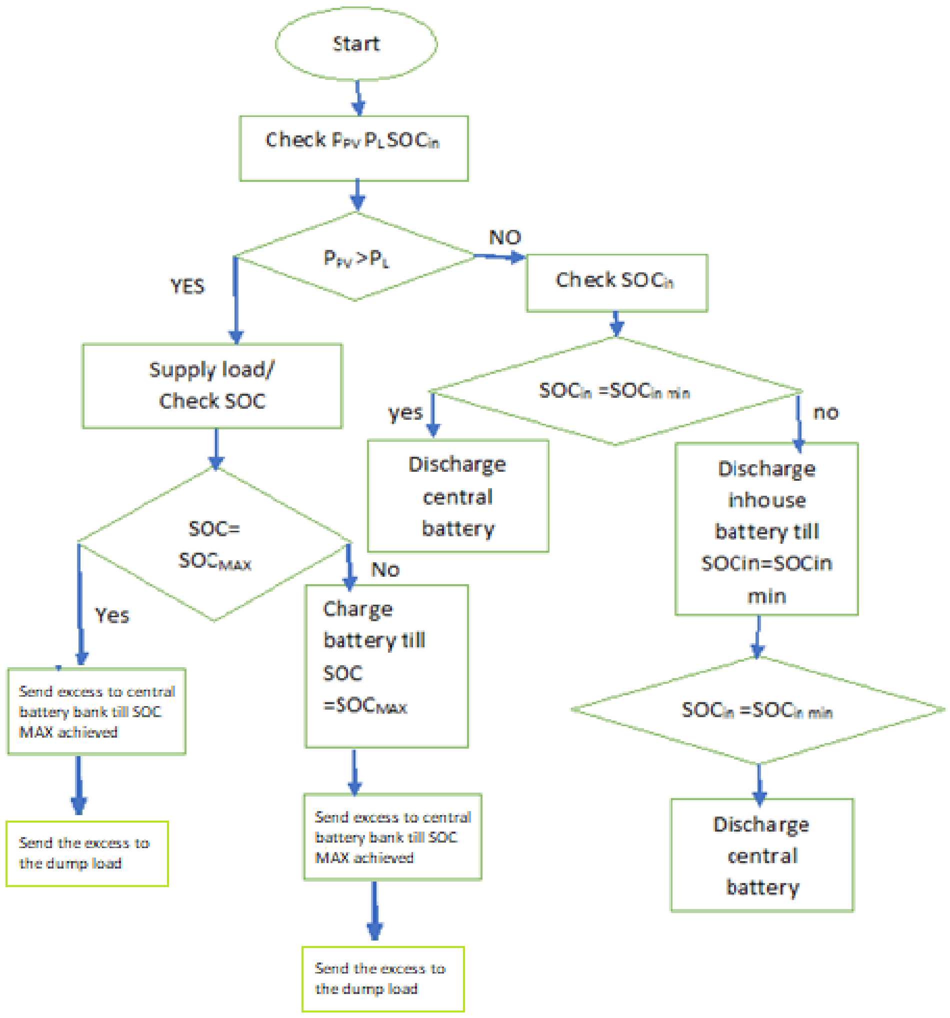


Fig 5.20. The energy management algorithm for in-house PV panels and in-house battery bank

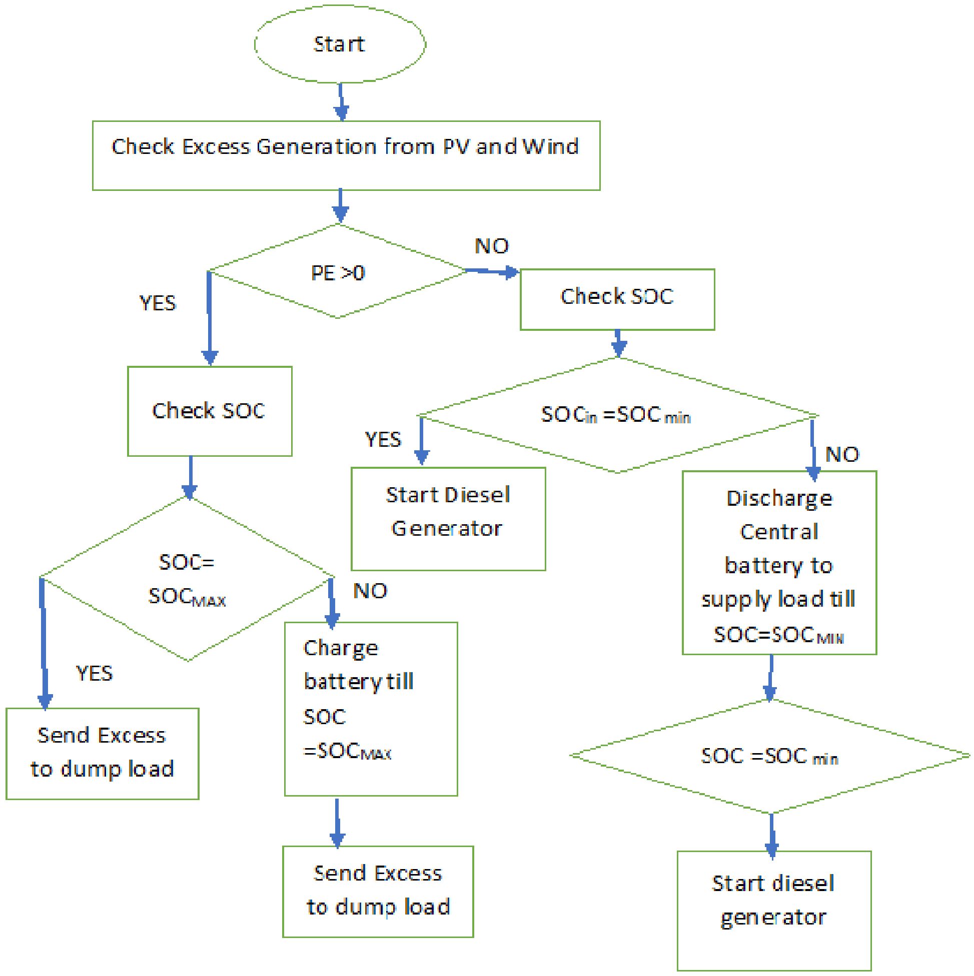


Fig 5.21 the power management strategy for central battery bank

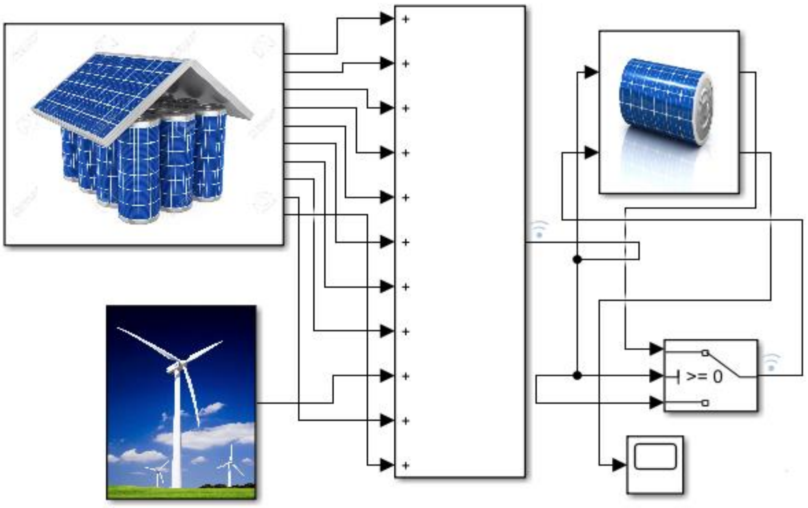


Fig. 5.22 The energy management model created in SIMULINK

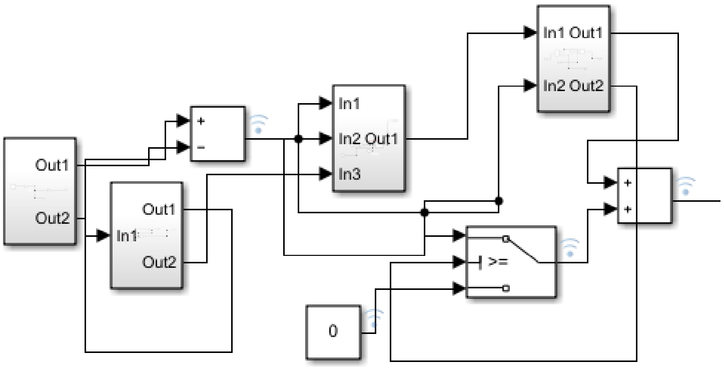


Fig. 5.23 The SIMULINK model of the subsystem for each household

5.3.3.3 Simulations and results

The performance of the designed system has been investigated under two different load demand and power generation conditions to examine the efficiency of the power management system.

- ***When the load demand of a household is fulfilled by the PV generation and in-house battery bank***

System performance under this condition can be observed from Figs. 5.24 – 5.26. Under this condition the load requirement of a typical household is less than the power generated by the inhouse solar panels. As a result, there is excess generation. But as the inhouse battery already reached its maximum SOC this excess generation can not be stored in inhouse battery bank. Hence this this excess generation is sent to the central battery bank. However, under the present scenario the SOC of the central battery bank already reached its maximum. So, to avoid any overcharging the controller sends the excess energy to the dump load. Fig 5.24 represents the load demand of a single household and power generated by the inhouse solar panels. Fig 5.25 shows the SOC of the inhouse batter bank. So as initially the power generated is less than the load demands the load demand is catered by the inhouse battery bank. As a result, the SOC of the inhouse battery bank decreases till the power generated by the inhouse panels increases. At this stage when solar panels start generating power, the load demand is lesser than the generated power. Hence there is excess generation. Tis excess energy is utilised to charge the inhouse battery bank till it reaches its maximum SOC. At this stage the excess generation is sent to the dump load. As the central battery bank is already at its maximum SOC the power generated by the wind turbine is also sent to the dump load. Fig 5.26 shows the SOC of the central battery bank and the energy sent to the dump load.

Hence from the performance presented under this condition clearly states that the designed controller can successfully manage the power flow as desired under this load demand and power generation condition. It discharges the inhouse battery as required and utilises the excess generation to charge the inhouse battery till it reaches its maximum SOC. It stops charging the inhouse battery once it reaches maximum SOC and avoids overcharging. It also avoids overcharging of central battery bank by sending the excess energy to dump load as the central battery bank has already reached its maximum SOC. This way by avoiding overcharging of both inhouse and central battery bank it increases the battery bank and thus increases the battery performance.

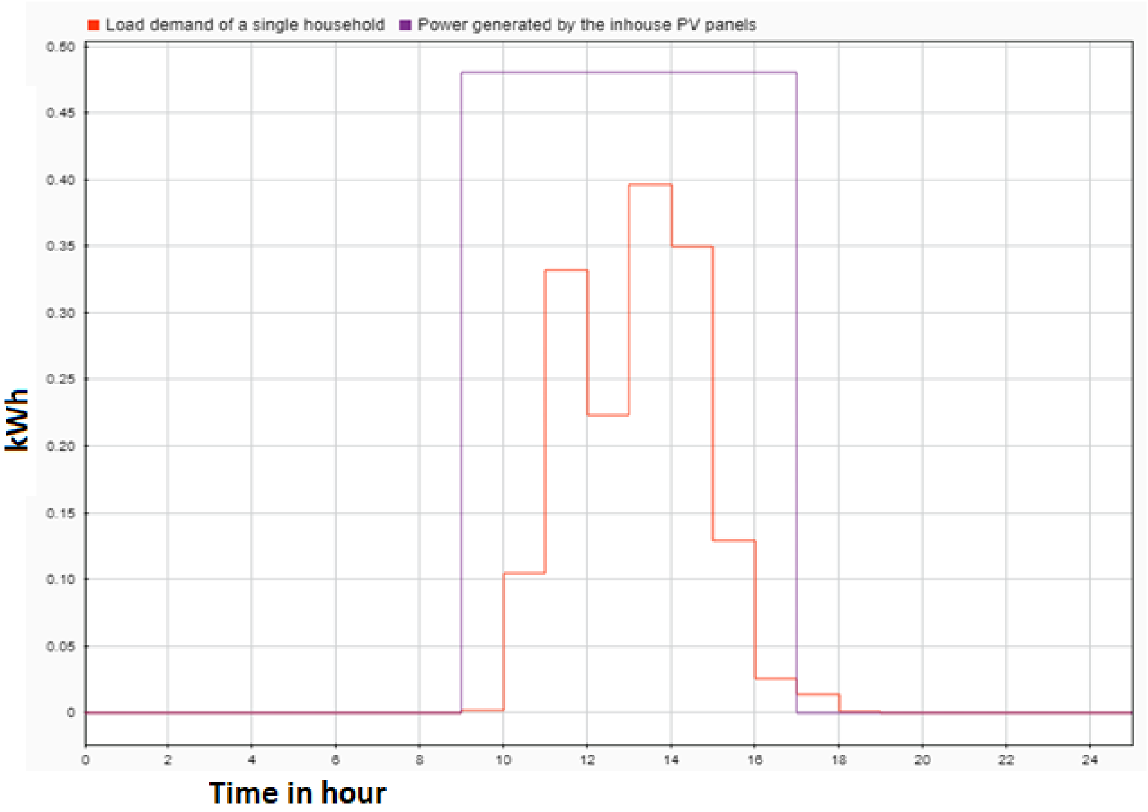


Fig 5.24 Load demand of a single household and power generated by the inhouse solar panels

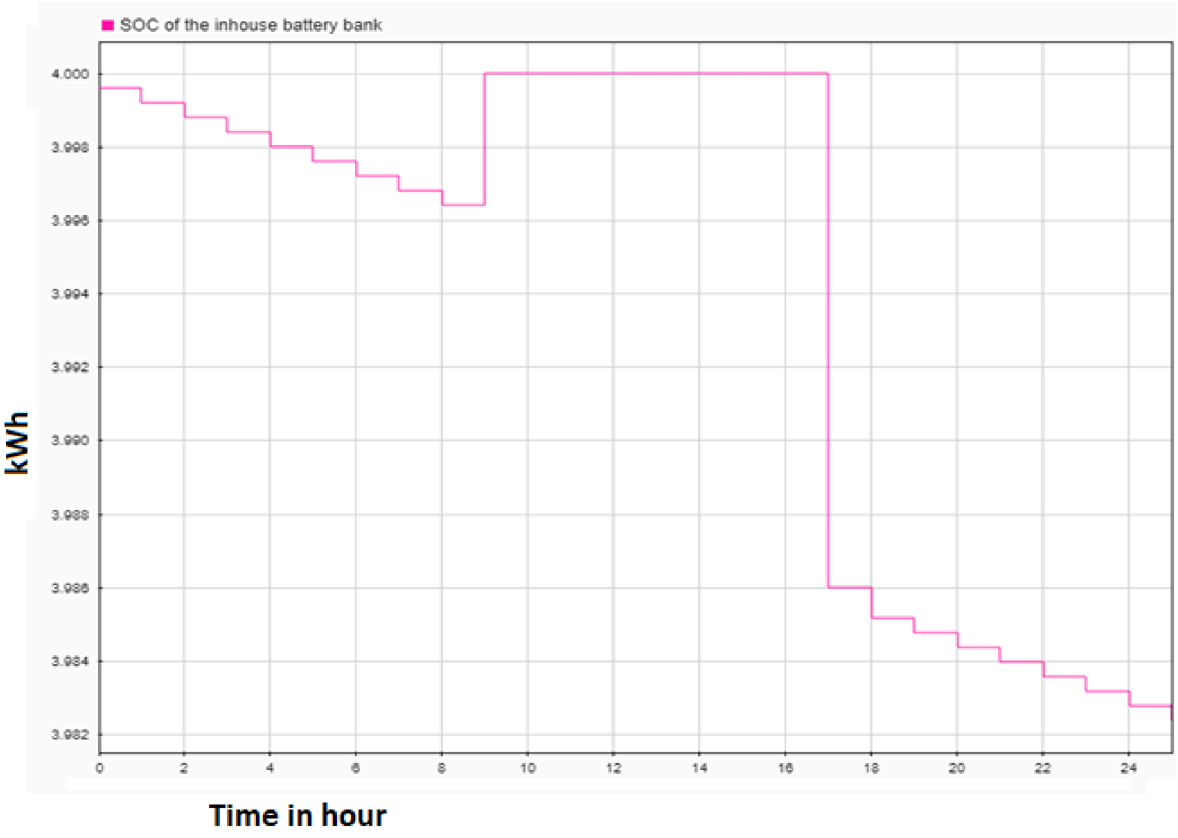


Fig. 5.25 SOC of the inhouse battery bank

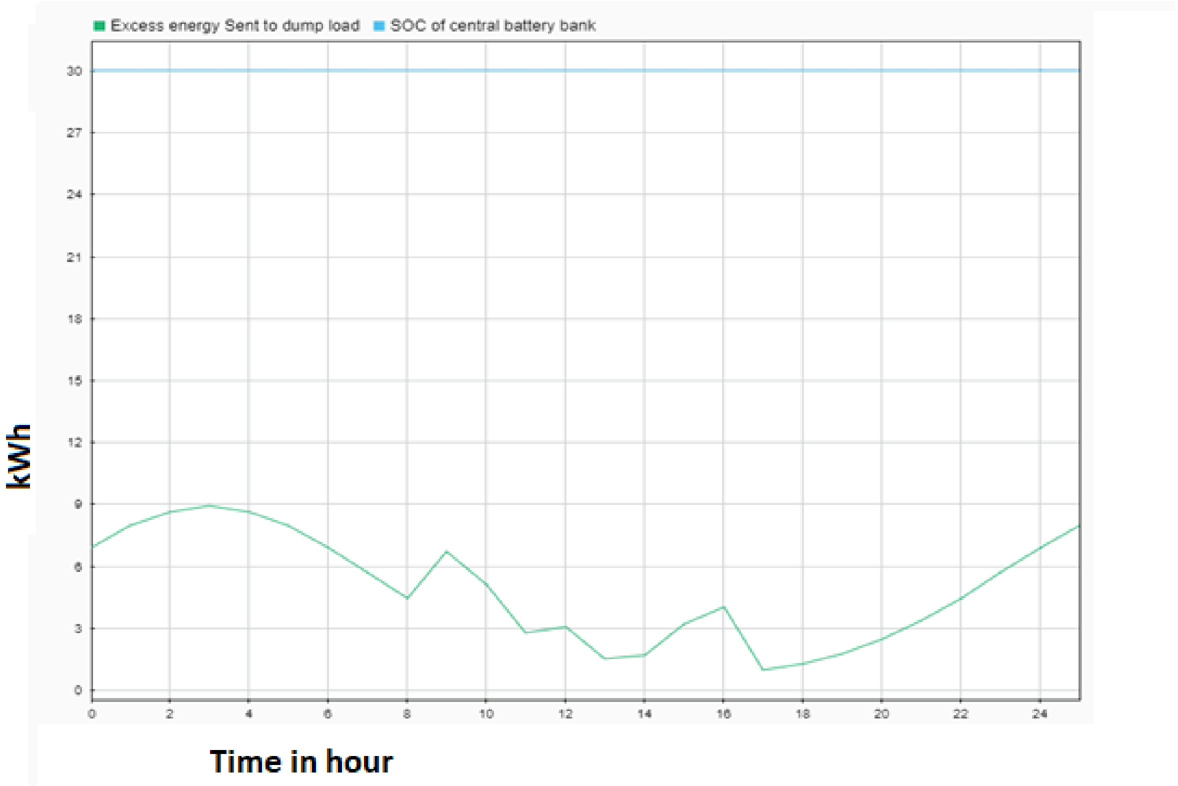


Fig 5.26 SOC of the central battery bank and the energy sent to the dump load

- ***When the load requirement is not satisfied by the in-house PV generation and the in-house battery bank***

System performance under this condition can be observed from Figs.5.27- 5.29. Under this condition the load requirement of a typical household is greater than the power generated by the inhouse solar panels. The load demand, the power generated by the inhouse PV panels and the inhouse battery SOC is presented in Fig 5.27. Hence under this condition, the load demand can not be met by the power generated by the inhouse PV panels. So, the inhouse battery bank starts discharging to meet the load demand. As the power generated by the PV panels continue to be lower than the load demand the SOC of the inhouse battery bank reached its Minimum SOC at one stage. At this stage the inhouse battery bank gets disconnected and stops supplying the load demand to void any deep discharge. At this stage the central battery bank starts supplying the load demand , hence the SOC of the inhouse battery bank decreases. However, at one stage the load demand drops at this stage the central battery bank stops discharging. At this stage the SOC of the central battery bank increases as it stars getting charged by the power generated by the wind turbine till it reaches its maximum SOC. Once the central battery bank reaches its maximum SOC it stops charging to avoid any overcharging. Any excess generation from the wind turbine is sent to the dump load under this condition. Fig 5.27 represents the load demand of a single household, power generated by the inhouse solar panels and SOC of the inhouse battery bank. Fig 5.28 represents the SOC of the central battery bank and the excess energy sent to dump load. Fig 5.29. shows the SOC of the inhouse battery bank and SOC of the central battery bank.

From these results it can be clearly observed that the proposed control system demonstrates high performance under the specified load demand and power generation conditions. It discharges the inhouse battery bank to supply load demand when the generation from the PV panels is not enough also disconnects the inhouse battery bank when it reaches the minimum SOC to avoid any deep discharge of inhouse battery bank. It successfully discharges the central battery bank to supply the load demand under this condition till load demand is higher than generated power. It also utilises the power generated by the wind turbines to charge the central battery bank till it reaches its maximum and stops charging it at this stage to avoid any overcharging. The controller also manages to send the excess energy to dump load at this stage. Hence this control mechanism successfully avoids any deep discharge of the inhouse and central battery bank, which increases the performance and life span of the batteries.

Hence it can be concluded that the designed controller can successfully demonstrate the desired control action under various load demand and load generation avoiding any deep discharge of the batteries, keeps the load demand meet continuously and can successfully achieve the power flow under various supply demand condition.

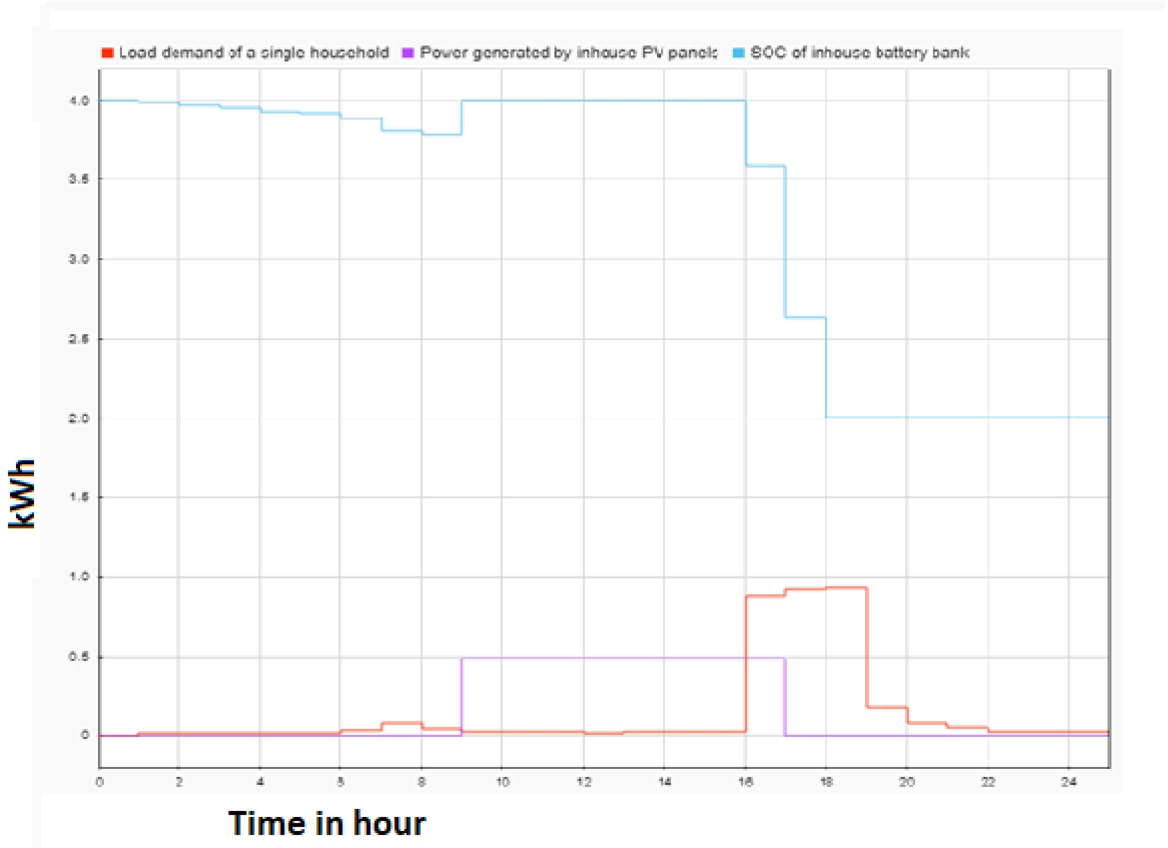


Fig 5.27 Load demand of a single household, power generated by the inhouse solar panels and SOC of the inhouse battery bank

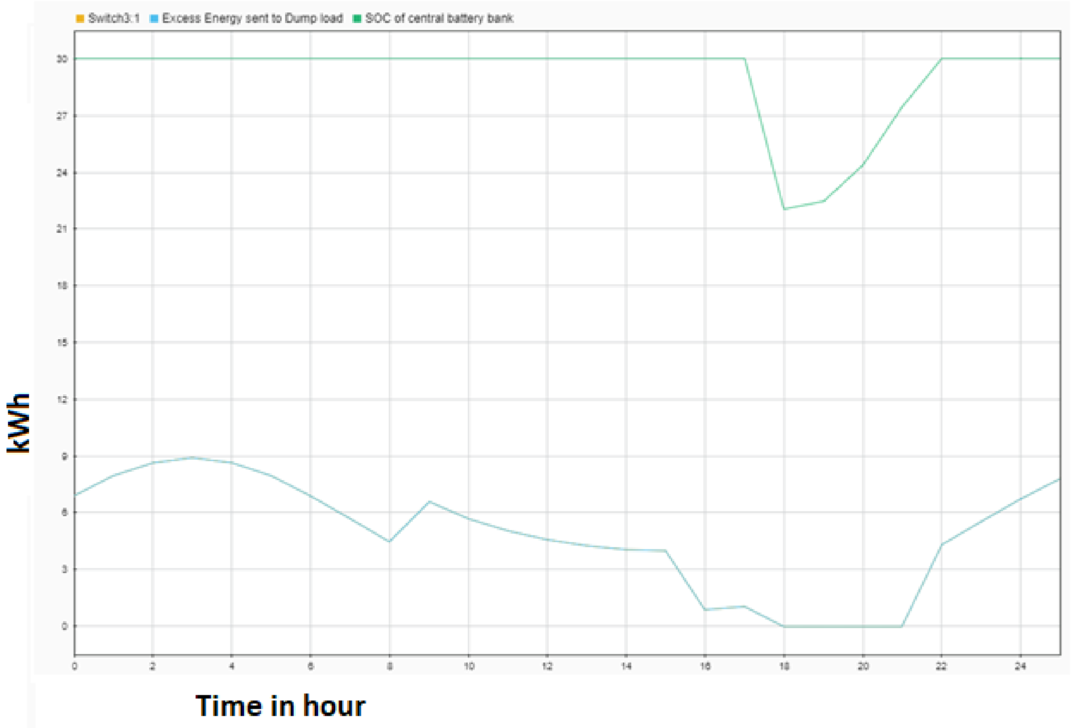


Fig 5.28 SOC of the central battery bank and the excess energy sent to dump load

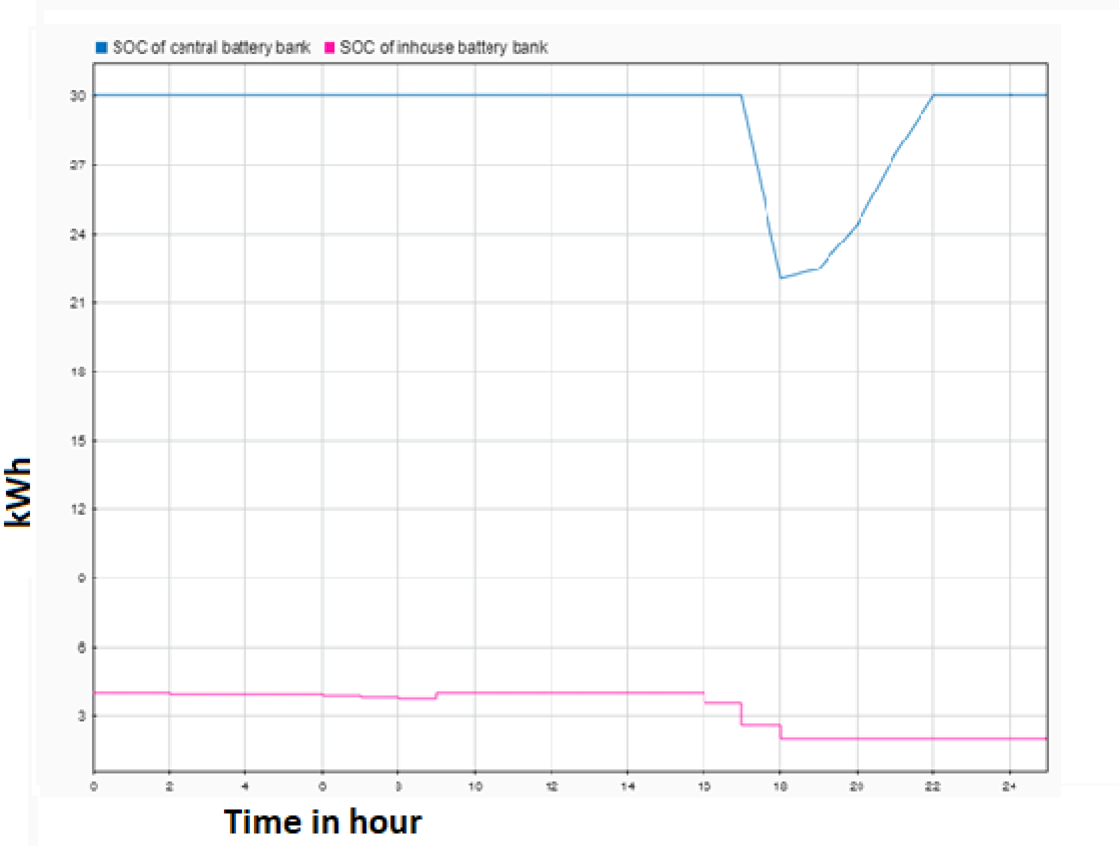


Fig. 5.29. The SOC of the inhouse battery bank and SOC of the central battery bank.

5.3.4 Design of the control mechanism using Fuzzy Logic considering the distributed sources

After the successful development of the controller considering the distributed sources the last step of development of the control mechanism is developing a Fuzzy Logic Controller that can successfully perform the power flow management using the distributed sources.

As it has been discussed already in previous sections of control mechanism development, the reason to design the FLC is to replace the conventional controller to make decision regarding the power management between the components of the HRES as the FLC allows the expertise of a user to feed into the controller while designing the rule base. That allows the controller to work with multiple input and output variables even though no clear mathematical expression between the input and output variables can be established. Hence the incorporation of Fuzzy Logic control allows the system to be more flexible and simpler as complex mathematical structures can be avoided. The field of renewable energy research is ever evolving, with growing demand of electrical power and depletion of natural sources like coal and gas have led the researchers to find more opportunities of incorporating the renewable sources in modern life. Community power is one of the emerging fields where these hybrid renewable systems can be implemented successfully which will result in reduced carbon footprint for the community and also increase job opportunities for community members. This also gives the power to the community members to generate their own electricity and help them to fight the global warming.

Hence the successful implementation of the FLC can be encouraging for the future researchers to implement more and more variables that can affect the power management of a HRES with complex structure by avoiding complicated mathematical structure and improve the overall efficiency of the system. This will encourage the more and more communities to participate in these kinds of standalone HRES projects which is beneficial for the communities as well as the environment.

Hence while designing the FLC one need to ensure that it can effectively achieve the desired control actions and can replace a conventional controller described in stage 3 of the design of the control mechanism.

5.3.4.1 Design of the power management strategy

The power management strategy described in 5.3.3 of the design of the control mechanism is followed in this section. Hence the flowcharts for the power management strategy will follow the same as presented in Fig 5.20 (the energy management algorithm for in-house PV panels and in-house battery bank) and Fig 5.21 (the power management strategy for central battery bank). The Energy Management System based on Fuzzy Logic checks the load status, total power generation from the wind and solar energy sources, SOC of the inhouse battery bank and central battery back and take the proper action to ensure the following:

- The power generated by the inhouse PV panels will be utilised the load demand of the household.
- Any excess generation from inhouse battery bank should be stored in inhouse battery bank till its maximum SOC reached. Once inhouse battery reaches its maximum SOC the excess should be sent to central battery bank. Once the central battery bank reaches the maximum SOC the excess is sent to the dump load.
- When there is insufficient generation by inhouse solar panels the inhouse battery discharges and supplies the load demand till it reaches its minimum SOC.
- At this stage if the power generation is still low the inhouse battery gest disconnected and the central battery bank starts supplying the load till it reaches its minimum SOC. At this stage the central battery bank gets disconnected from the load and the diesel generator takes over.

5.3.4.2 Design of the FLC

The FLC that has been designed at this final stage, has two input and three output variables. The input variables are ‘Battery SOC’ and ‘Excess Energy’.

At any instance the summations of the excess generations from all the inhouse solar panels after the inhouse battery reached its maximum SOC and the power generated by the wind turbines are combined as the variable which is represented as the input ‘Excess Energy’. This Excess Energy’ has two membership functions. When the summation of total excess generation from all the household PV panels and the wind turbine is positive, the variable ‘Excess Energy’ is ‘positive’. This condition indicates that there is excess generation from the PV panels after successfully charging the inhouse battery banks till they reached their maximum SOC and also there might be enough wind generation.

When the power generated by inhouse PV panels is less that the load demand and inhouse battery has reached the maximum SOC this variable ‘Excess Energy’ is ‘negative’. This is to ensure that the central battery bank starts supplying the load demand of the household when the inhouse battery has reached its minimum SOC.

Before designing the FLC the study of the available data was conducted. Hence as per the investigation the range of the excess energy generation has been considered as -20 to 200 where the unit of excess energy is kWh. Hence the range of the MFs are considered between -20 to 20.

The state of charge of the battery bank is presented by the MF ‘Battery SOC’. The input ‘Battery SOC’ has three MFs, ‘low’, ‘medium’ and ‘High’. As per the available data the range of SOC considered in this study is 50-100 % for the purpose of analysis. This range also can be changed as per the available data without making any significant changes to the basic system structure. For the purpose of this study as per the considered data the total capacity of the central battery bank was 30Ah. Based on that the range of the MFs of Battery SOC is considered as 6 – 30 Ah for this study keeping in mind the actual working conditions. However, the rule base was designed to ensure that the SOC varies within its specified range of 50% - 100%.

The designed FLC has three outputs, ‘Charge Battery’, ‘Generator’ and ‘Dump Load’. The output ‘Charge Battery’ is a signal that decides if the battery will charge or discharge. This output variable has two MFs, ‘positive’ and ‘Negative’. When it is ‘Positive’ the battery will charge, and the battery will discharge if it is ‘Negative’. The output ‘Generator’ is a signal which decides when to start the diesel generator. This output has two MFs , ‘positive ‘and ‘negative’. The generator should be on when the signal is ‘positive’ and the generator remains off when this signal is ‘negative’.

The third output signal is “Dump load’ which associated with the excess energy being sent to the dump load when the battery SOC reaches its maximum value. It has Two MFs, ‘positive’ and ‘negative’. When this signal is ‘positive’, the excess energy will be sent to the dump load. IN case it is ‘negative’ the excess energy will be used to charge the battery bank.

As the basic control strategy remains the same the structure of the FLC is similar to what was described in stage 2 of the development of the control strategy for power management. The controller was designed in MATLAB /SIMULINK environment using the Fuzzy Logic toolbox. The simplified Simulink model for Fuzzy Logic-based energy management model for the distributed system is presented in Fig 5.30.

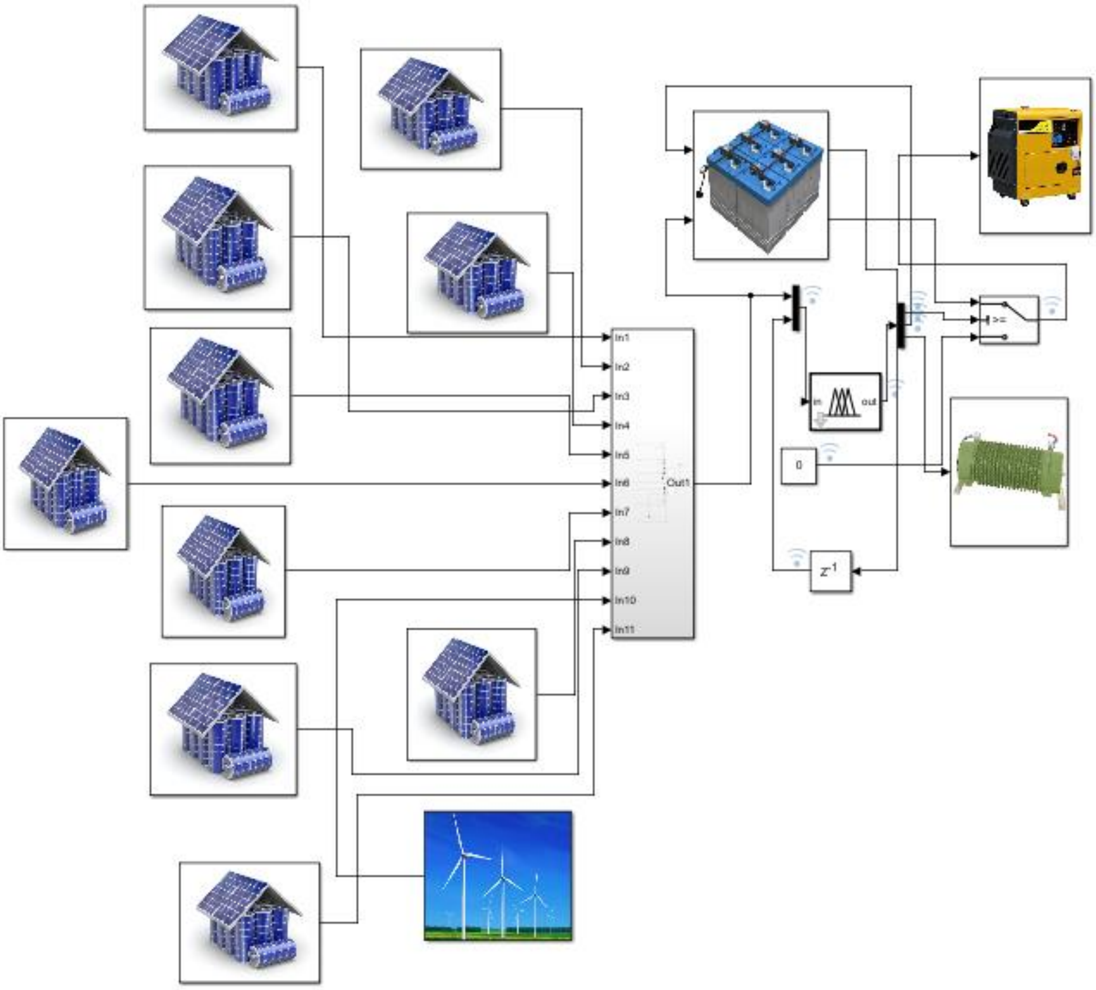


Fig 5.30 Simplified model of the Fuzzy Logic-based energy management model for the distributed system

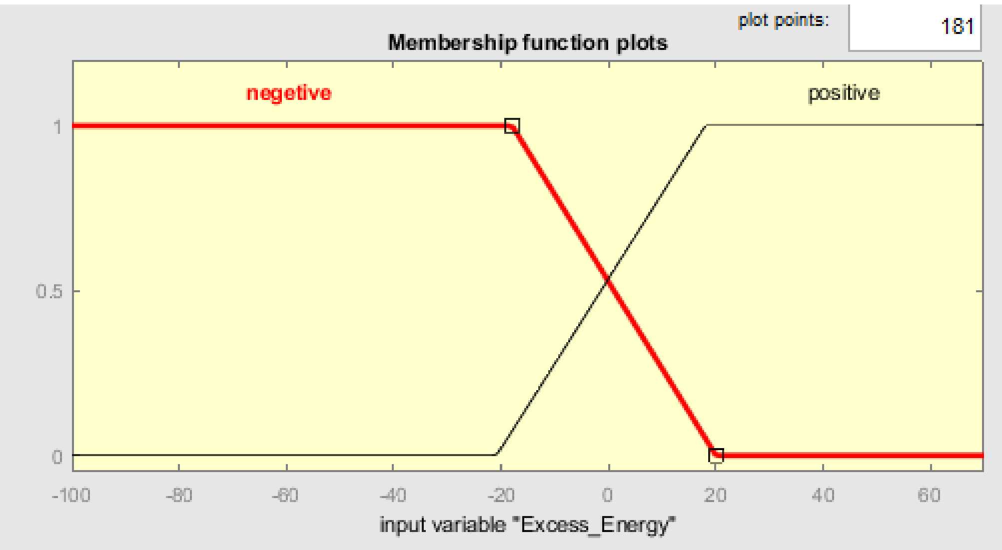


Fig 5.31 Membership function for the input variable ‘Excess energy’

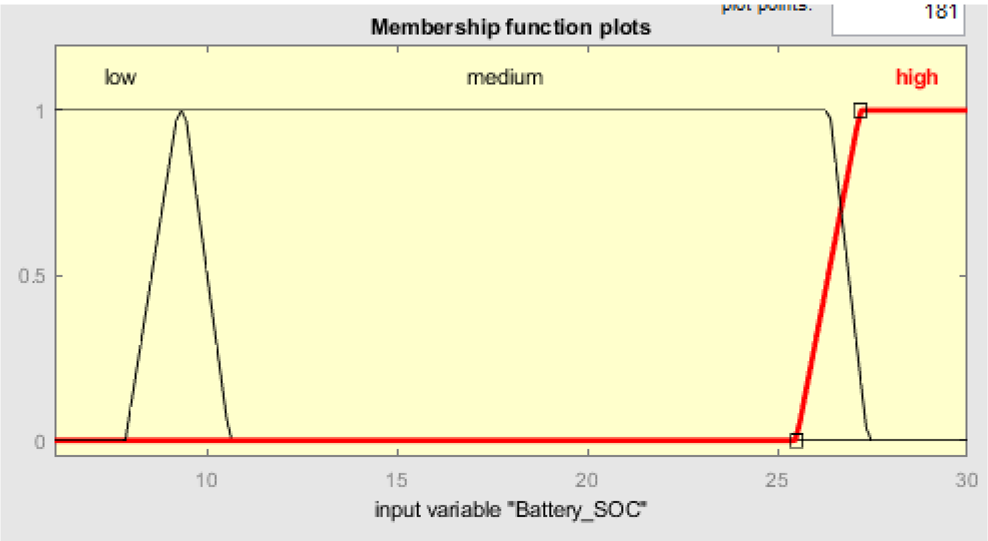


Fig 5.32 Membership function for the input variable ‘Battery_SOC’

The member functions of the output variables remain the same as presented in Figs 5.31.- 5.32 due to similar structure of the FLC. The Fuzzy knowledge base is designed on very straightforward rules as described in stage 5.3.2.

For example:

If ‘Excess_Energy’ is ‘negative’ and Battery_SOC is ‘high’ then ‘Share’ is ‘positive’ and ‘Charge_Battery’ is ‘negative’.

If ‘Excess_Energy’ is ‘’ and Battery_SOC is ‘low’ then ‘Share’ is ‘negative’ and ‘Charge_Battery’ is ‘positive’.

These rules are as same as the FLC designed at stage 5.3.2 as the similar control action is required.

5.3.4.3. Performance assessment of the controller optimised by Fuzzy Logic techniques

The performance of the FLC is investigated under two different scenarios.

Scenario 1: Total generated power of all the sources is greater than load demand: -

It is possible to reach a condition when all inhouse solar panels and the wind generators have reached their maximum generating point and load demand of all the households are minimum. So in that case the excess generation from each household after charging the inhouse battery will be sent to the first control junction as ‘positive’ excess energy.

In this scenario the controller tracks the summation of excess generations and the power generated by the wind turbine. This power is utilised to charge the central battery bank till it reaches its maximum SOC. This is to ensure any overcharging of the central battery bank. After this point any excess generation should be sent to the dump load.

Scenario 2: Total generated power of all the sources is lesser than load demand: -

When the power generated by any in house battery bank is less than the load demand of the household, the inhouse battery supplies the demand. At the point when the inhouse battery reaches in minimum SOC it gets disconnected. The load demand should be catered by the central battery bank till it reaches its minimum SOC. Once it reaches that point this should be disconnected from the load to avoid any deep discharge. The diesel generator should turn on at this stage.

To analyze the performance of the control mechanism, the performance of the system was analyzed using three different types of load data. However, one need to remember that the limitation of this work is the availability of load data. Hence the study is based on the data available for one household. However, upon availability of real data it would be possible to design the control mechanism using the methodology and algorithm discussed in this study as the structure of algorithm does not change based on data.

For these case studies, three different load signals were created. For this case studies it has been considered that all the household has same load profile for simplify the analysis. When the load is considered high, under this condition all the household will have similar high load, hence the system performance can be analyzed as the overall load demand of the community high. When the load demand of a household is considered as low, the overall load demand of community is low, hence under this load profile one can observe the system performance for low load demand of the overall community. Using different load profile for each household would lead to lengthy discussions.

Under each load data the performance of the control system with FLC that has been compared with the performance of the controller designed for the distributed system in stage 5.3.3. The observations are presented below.

5.3.4.4 Case study 1

The load profile under this condition is presented in the Fig 5.33 , the SOC of the inhouse battery bank and the load profile is presented in Fig 5.34, Fig 5.35 represents The SOC charge of inhouse battery bank, SOC of central battery bank and Load demand (With FLC). Fig 5.36 shows the response of the control system designed in stage three without FLC. The variables presented in this figure are load demand, SOC of inhouse battery bank and SOC of the central battery bank. Fig 5.37 represents the SOC of central battery bank for the same load demand considered in case study 1 without Fuzzy Logic Control.

From the Figs 5.33 – 5.37 it is clear that the designed FLC can perform as per the desired power management strategy. When the load demand of a household is higher than the generated power, the inhouse battery bank supplies the load demand till it reaches its minimum SOC. At this stage the central battery bank starts supplying the load demand hence it starts discharging. As a result, the SOC of the battery bank decreases. When the load demand decreases the SOC of the central battery bank starts increasing. Once the SOC reaches its maximum SOC the controller stops it from charging. This way the controller could successfully start the central battery bank when it was required to supply the load and provided a reliable continuous load supply. It also successfully avoids any overcharging of the battery bank. The controller sent the excess generation to the dump load when the central battery bank is not charging. Fig 5.38 presents the plots of Excess energy sent to dump load and the SOC of the central battery bank. Hence it can be stated that under the specified load condition the controller could achieve the desired control action as an analogue controller. Fig 5.39 shows the control signal generated for starting the diesel generator is zero as the SOC of central battery bank did not reach the minimum SOC.

One very significant observation is presented in Fig. 5.37 For the same load and similar system configuration the characteristic of SOC of central battery bank is shown in Fig 5.37 for both the control system with FLC and without FLC. It can be clearly observed that under similar load condition and system specifications the reduction in SOC of the central battery bank is significantly higher for the control system without FLC, than the reduction in SOC of the central battery bank for the control system with FLC. It also can be observed that the variation in the SOC of the central battery bank is smoother in case of Fuzzy Logic control than without Fuzzy Logic control. Hence the Fuzzy Logic based control mechanism can manage the change in battery SOC in better way than the control mechanism without Fuzzy Logic. With the smother variation of SOC the FLC actually ensures increased battery performance and this increased battery performance increased battery life.

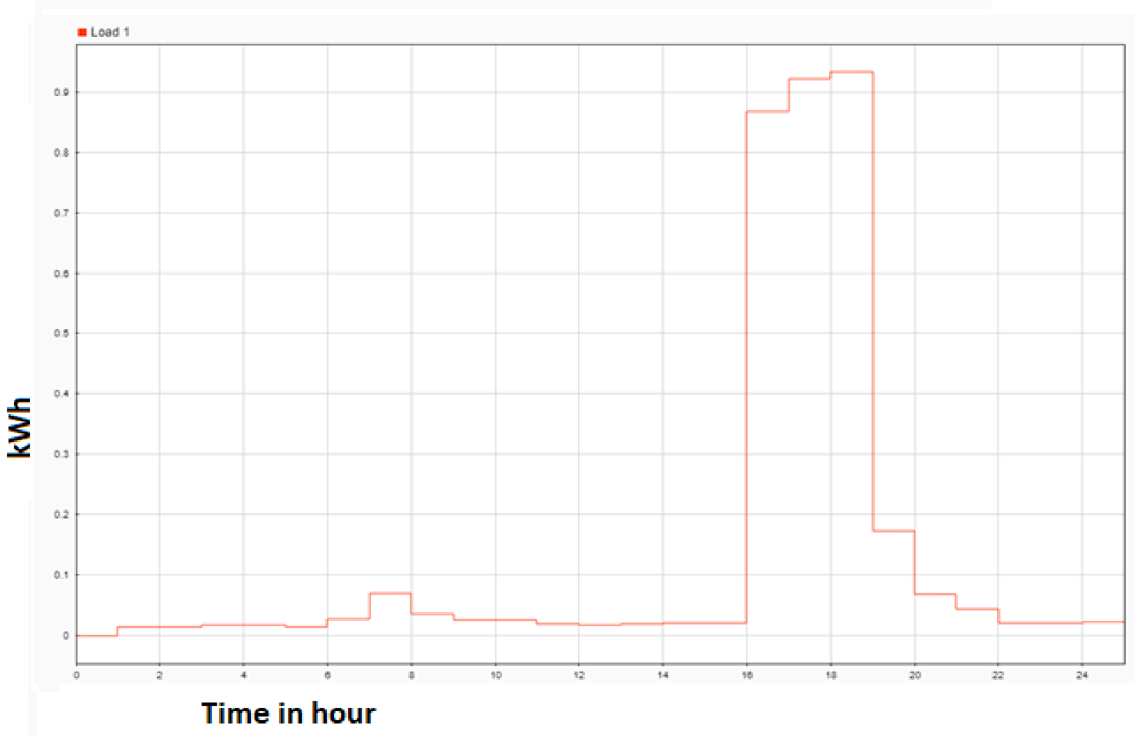


Fig 5.33 Load profile considered in case study 1

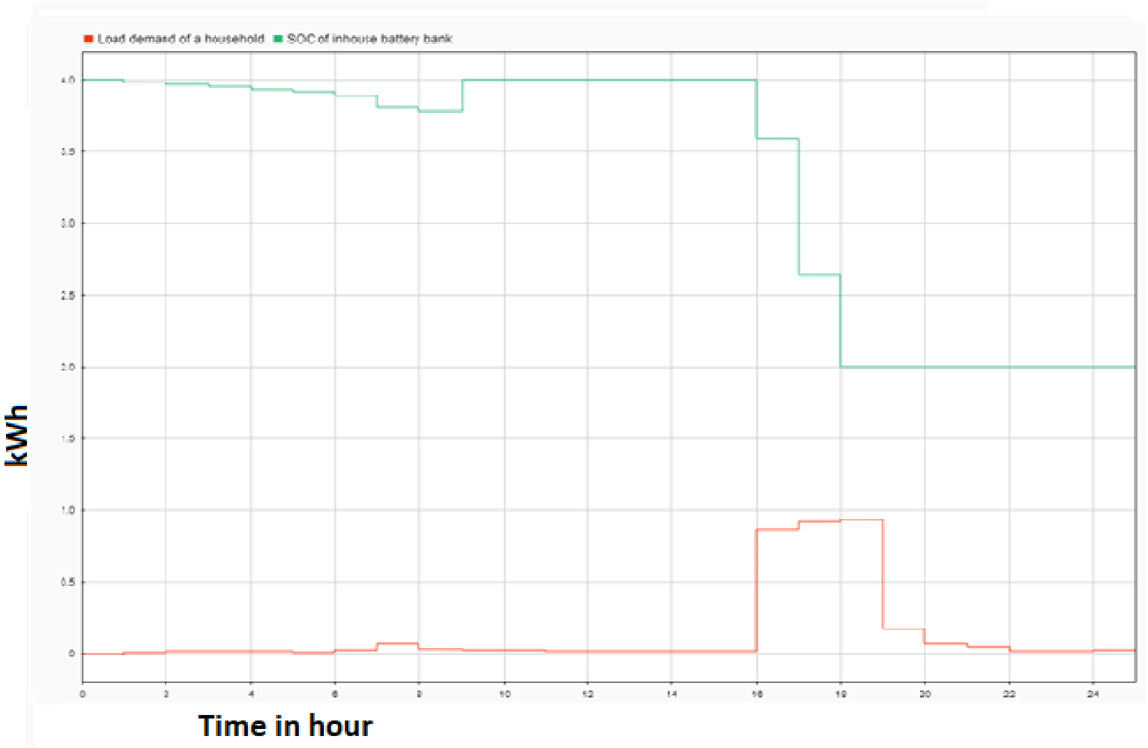


Fig. 5.34 The SOC of the inhouse battery bank and the load profile

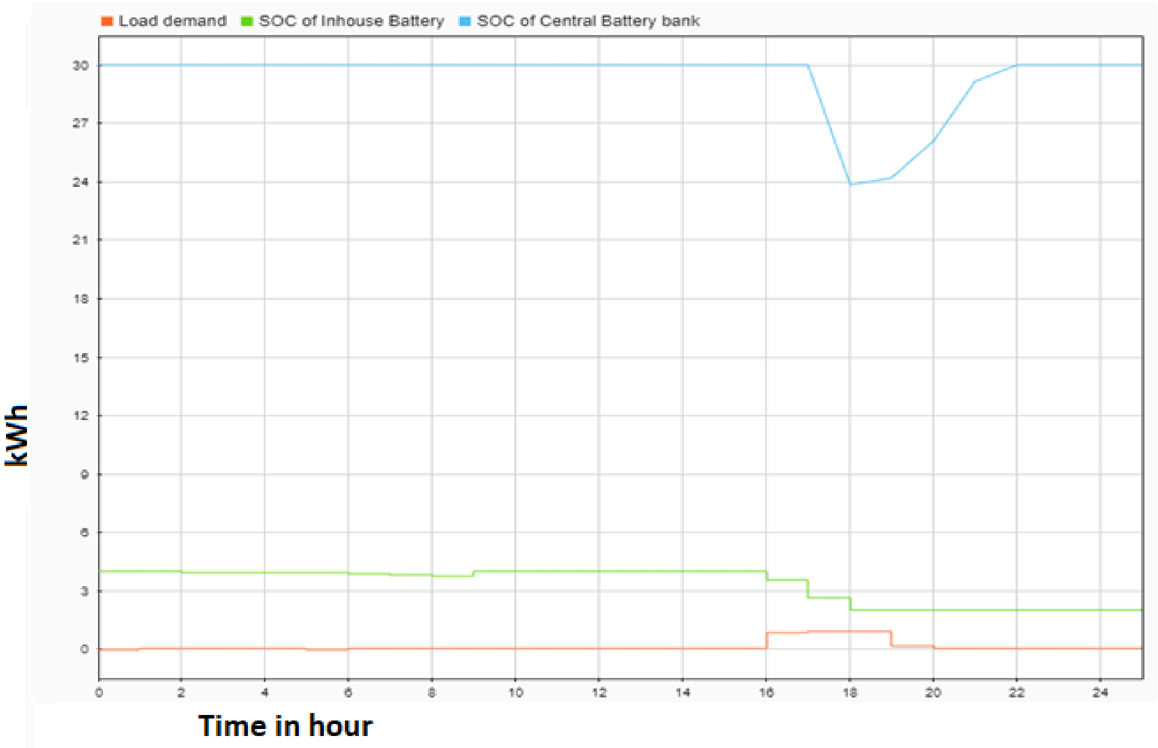


Fig 5.35 The SOC charge of inhouse battery bank, SOC of central battery bank and Load demand (With FLC)

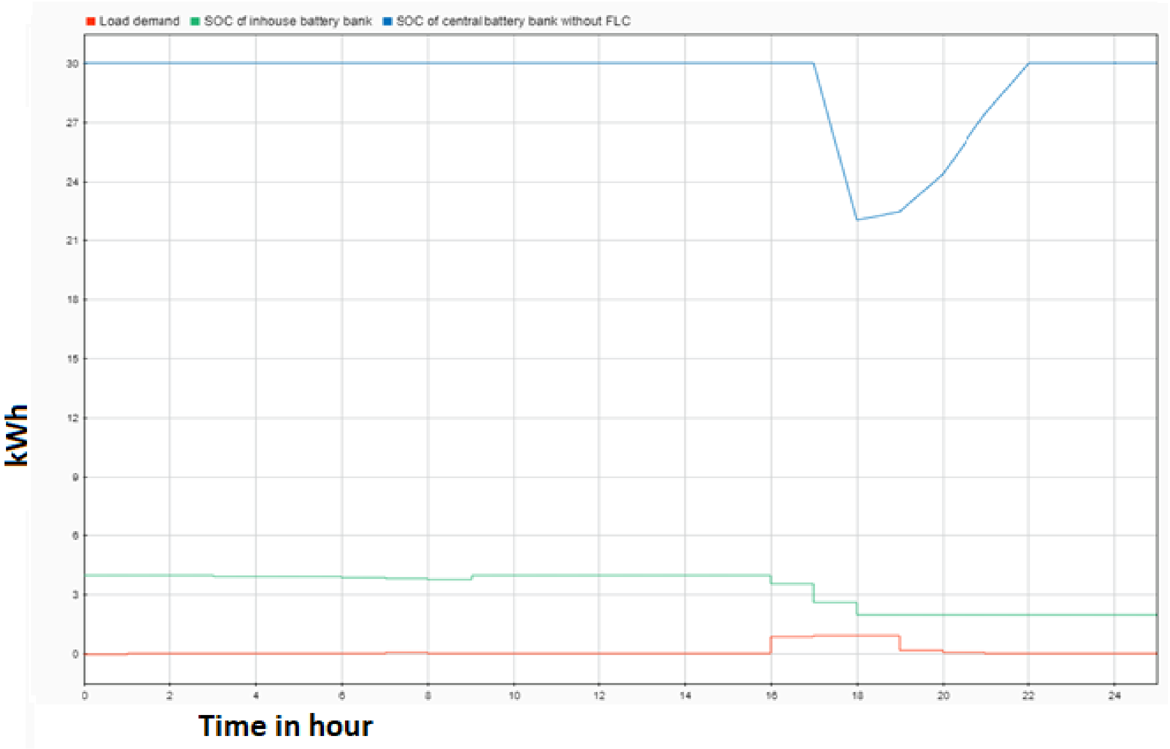


Fig 5.36 Load demand, SOC of inhouse battery bank and SOC of the central battery bank for the same load demand considered for the control system without FLC.

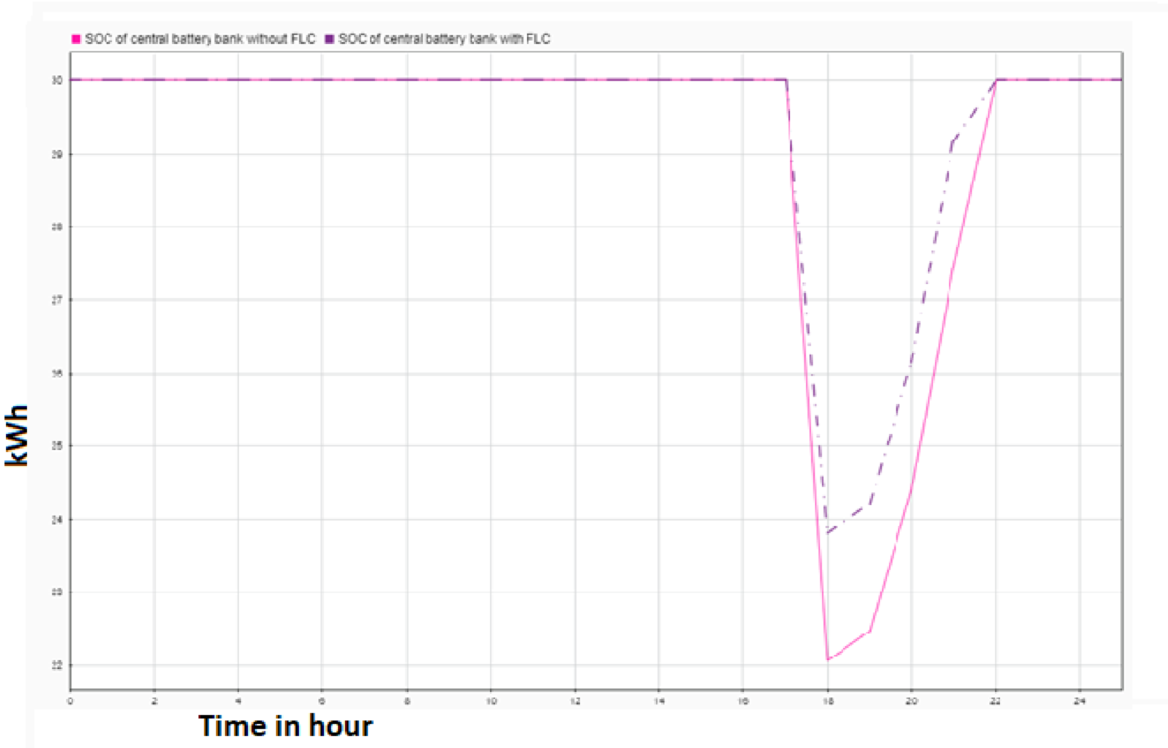


Fig 5.37 SOC of central battery bank for the same load demand considered in case study 1 with and without Fuzzy Logic Control.

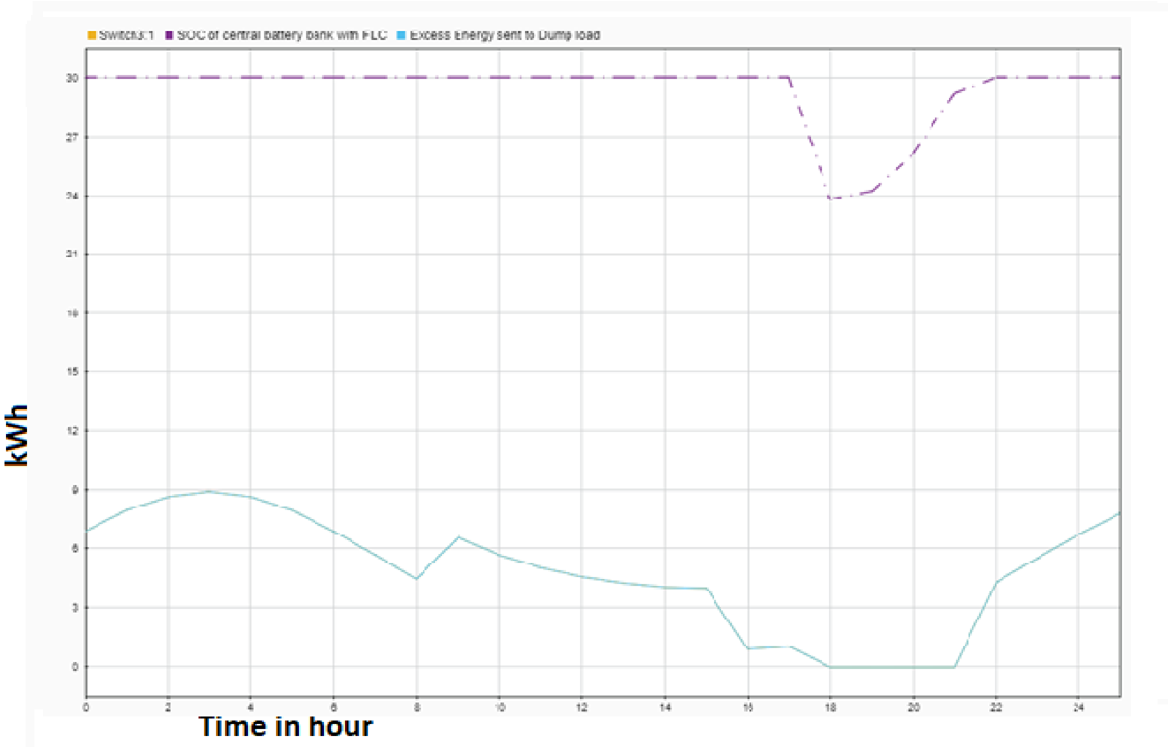


Fig 5.38 Excess energy sent to dump load and the SOC of the central battery bank with Fuzzy Logic Control

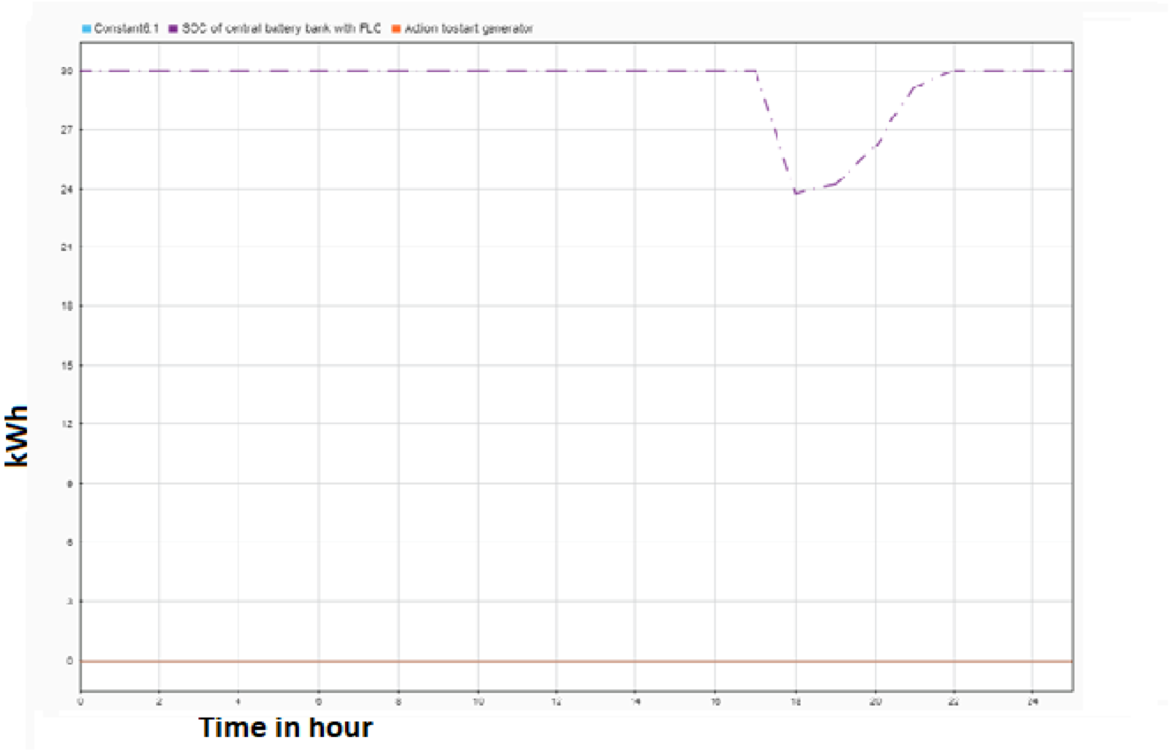


Fig 5.39 SOC of inhouse battery bank and control signal to start diesel generator.

5.3.4.5 Case study 2

The load profile under this condition is presented in the Fig 5.40. The SOC of the inhouse battery bank and the load profile is presented in Fig 5.41. Fig.5.42 represents The SOC charge of inhouse battery bank, SOC of central battery bank and Load demand with FLC. Fig 5.43 represents the load demand, SOC of inhouse battery bank and SOC of the central battery bank without FLC. Fig 5.45 represents the SOC of central battery bank for the same load demand considered in case study 2 with and without Fuzzy Logic Control. Fig 5.46 shows the SOC of the central battery bank and action signal generated to start the generator.

From the Figs 5.40 – 5.45 it can be clearly observed that the designed FLC can successfully perform the power management as desired under the presented load profile. When the load demand of a household is higher than the power generated by the inhouse PV generations the inhouse battery bank supplies the load demand till it reaches its minimum SOC. AT this stage the central battery starts supplying the load demand till it reaches its minimum SOC. At this stage the central battery bank gets disconnected and the action signal to start the generator gets positive and starts the generator. Hence under this load demand condition the control system designed with Fuzzy Logic can take appropriate actions. It starts supplying the load demand by inhouse battery bank till its minimum SOC reached. It disconnects it upon reaching the minimum SOC to avoid any deep discharge of the battery banks which increases the battery performance and battery life. This control system successfully starts the diesel generator and ensures the reliable load supply with minimum interruption. Hence under this condition the system reliably supplies the load demand ensuring batter battery performance.

The performance of the control mechanism without Fuzzy Logic and with Fuzzy logic under this condition can be observed in Fig 5.45. Both the control systems discharge the central battery bank to supply the load demand but the change in SOC without FLC is sharper than the one with FLC. It means the Fuzzy Logic based control mechanism can manage the change in battery SOC better than the control mechanism without Fuzzy Logic. By smoothening the change of SOC the FLC increases the battery life and battery performance. Hence it can be stated that under this load demand and power generation the FLC based control system performs better than non-Fuzzy one as it can improve the battery life.

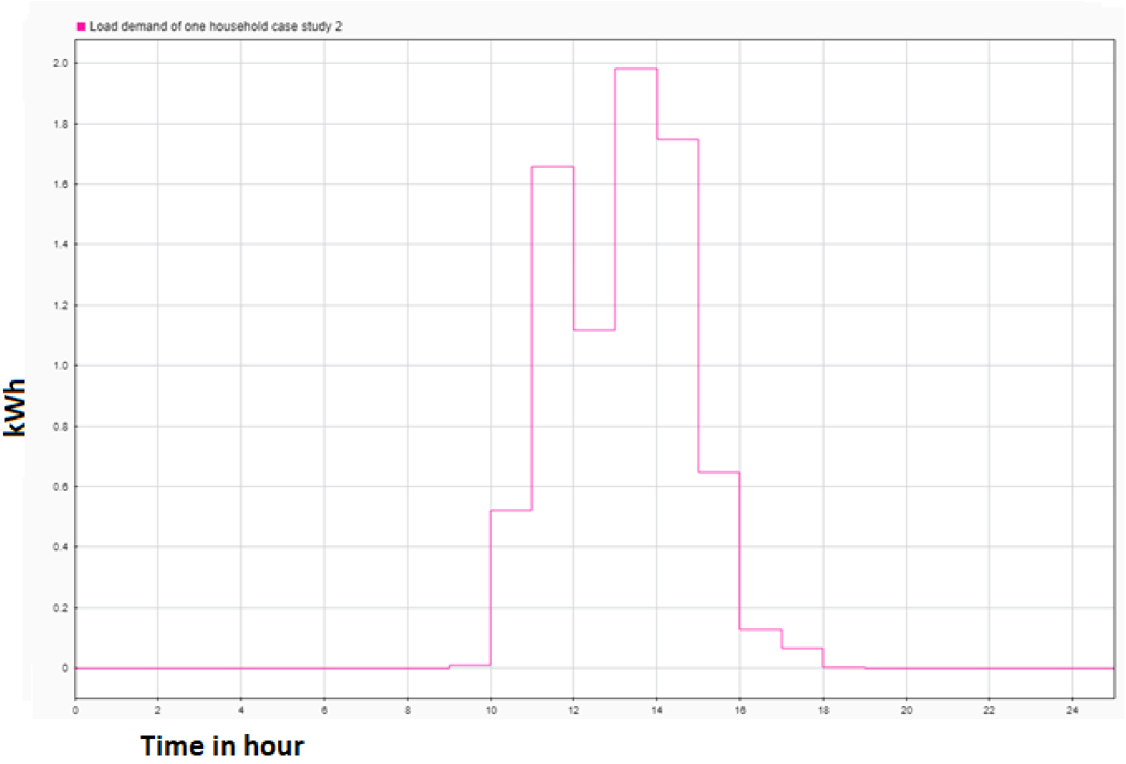


Fig. 5.40 Load profile of a single household considered in case study 2

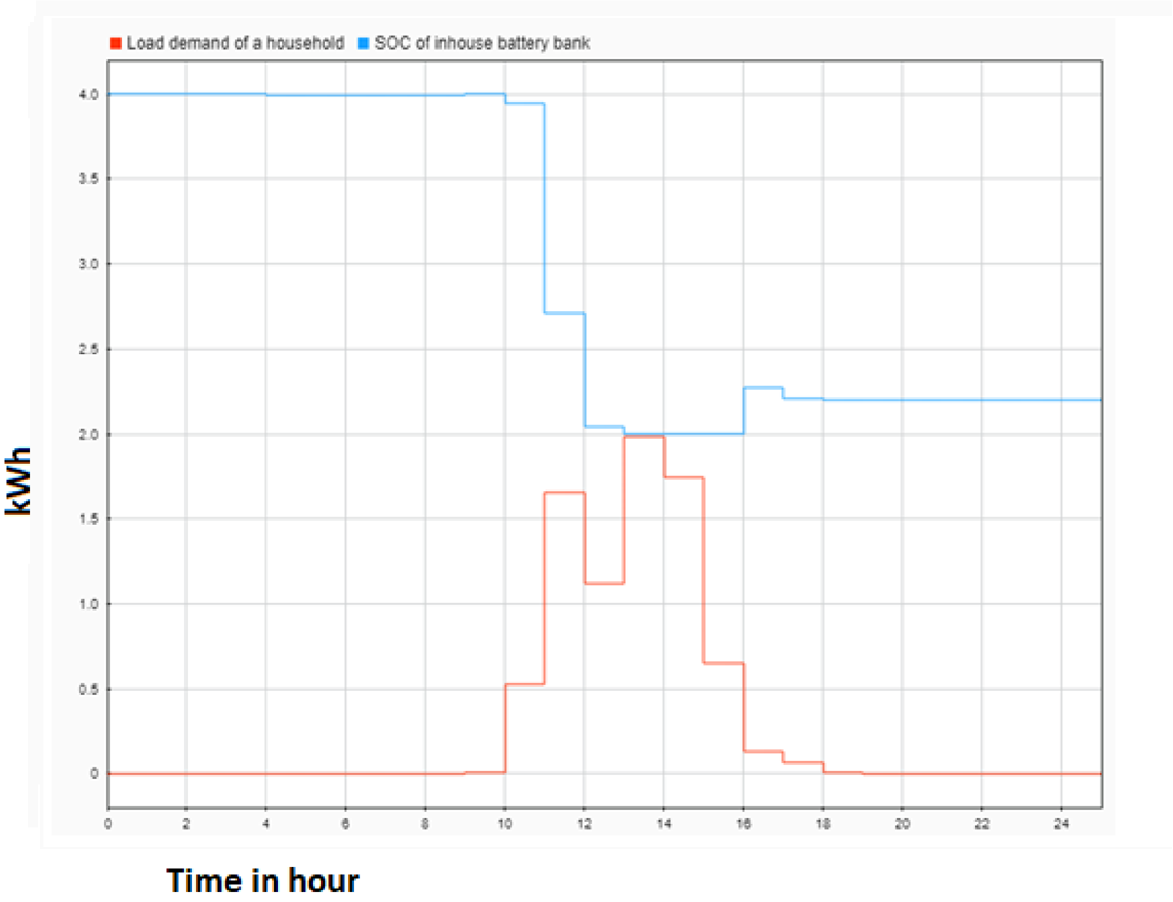


Fig. 5.41 The SOC of the inhouse battery bank and the load profile

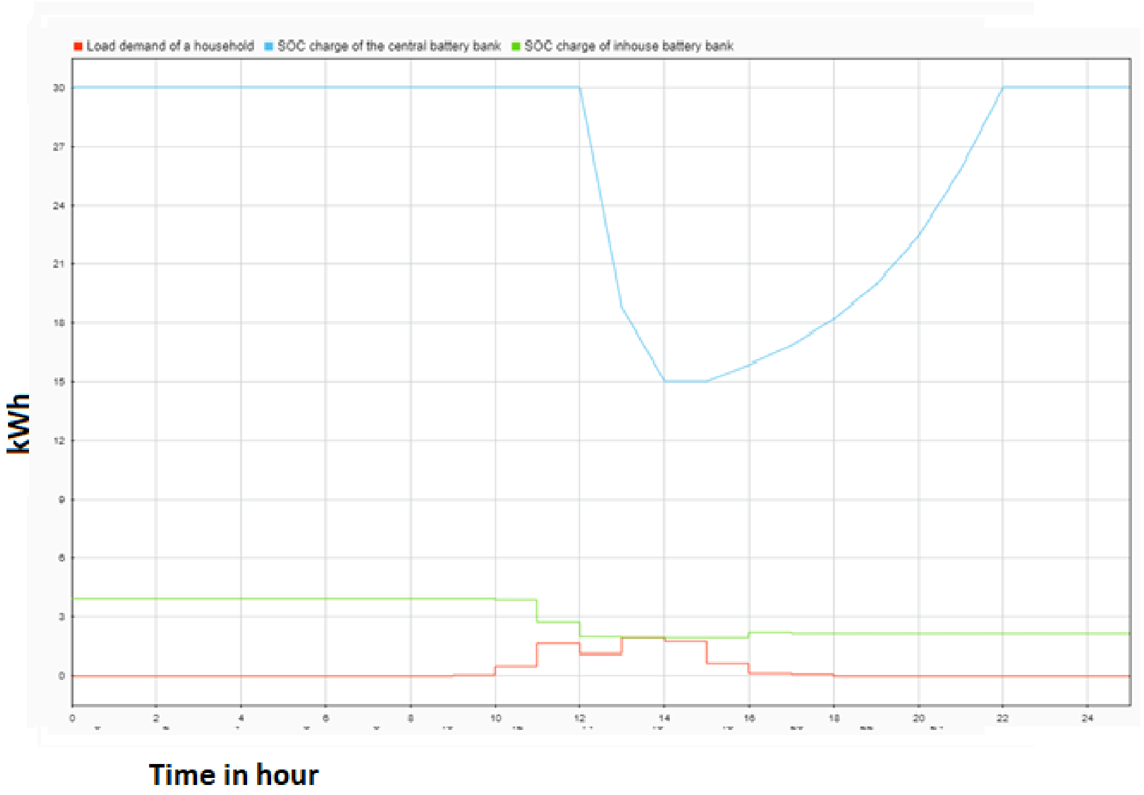


Fig 5.42 The SOC charge of inhouse battery bank, SOC of central battery bank and Load demand (With FLC)

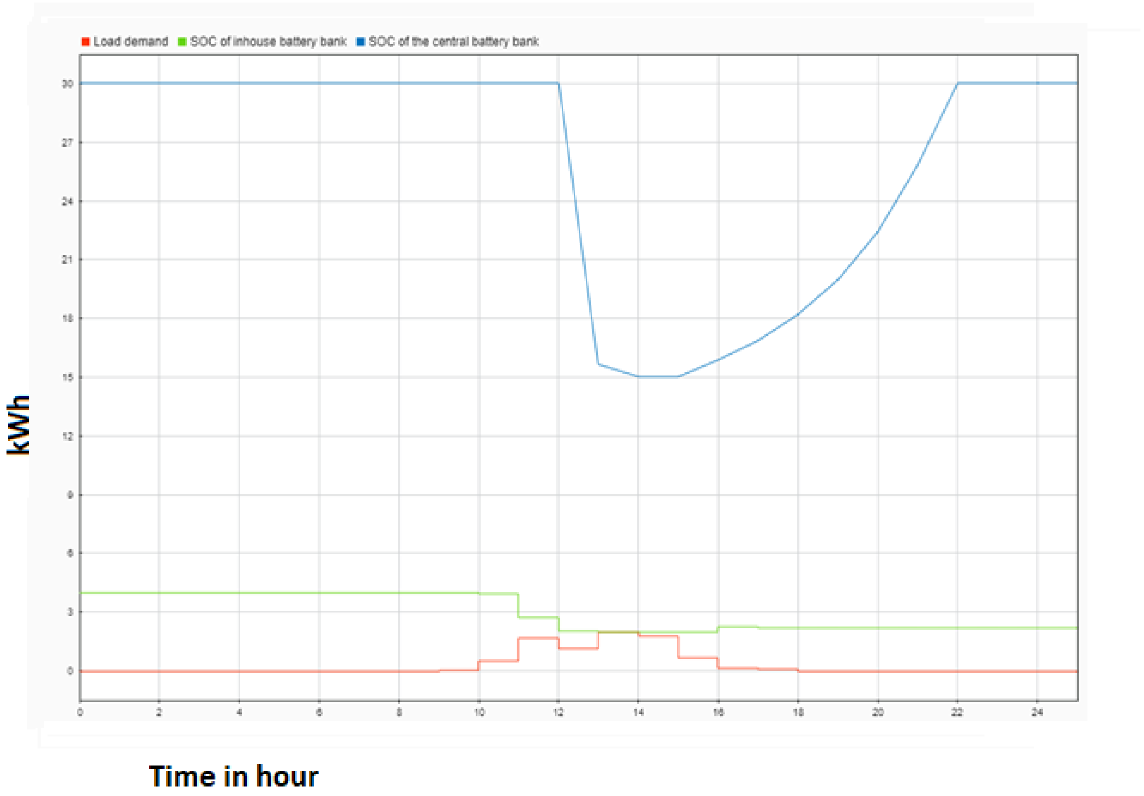


Fig 5.43 load demand, SOC of inhouse battery bank and SOC of the central battery bank (without FLC)

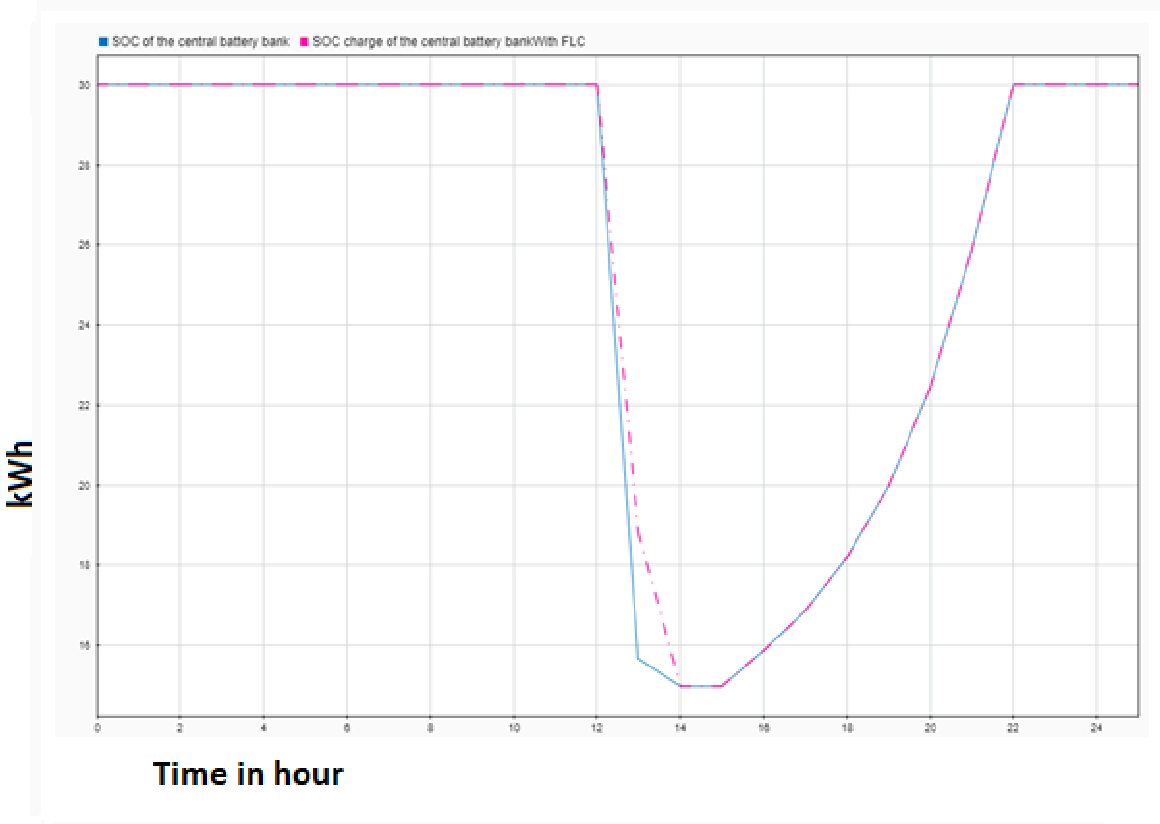


Fig 5.44 The variation in SOC of central battery bank for the same load demand considered in case study 2 with and without Fuzzy Logic Control

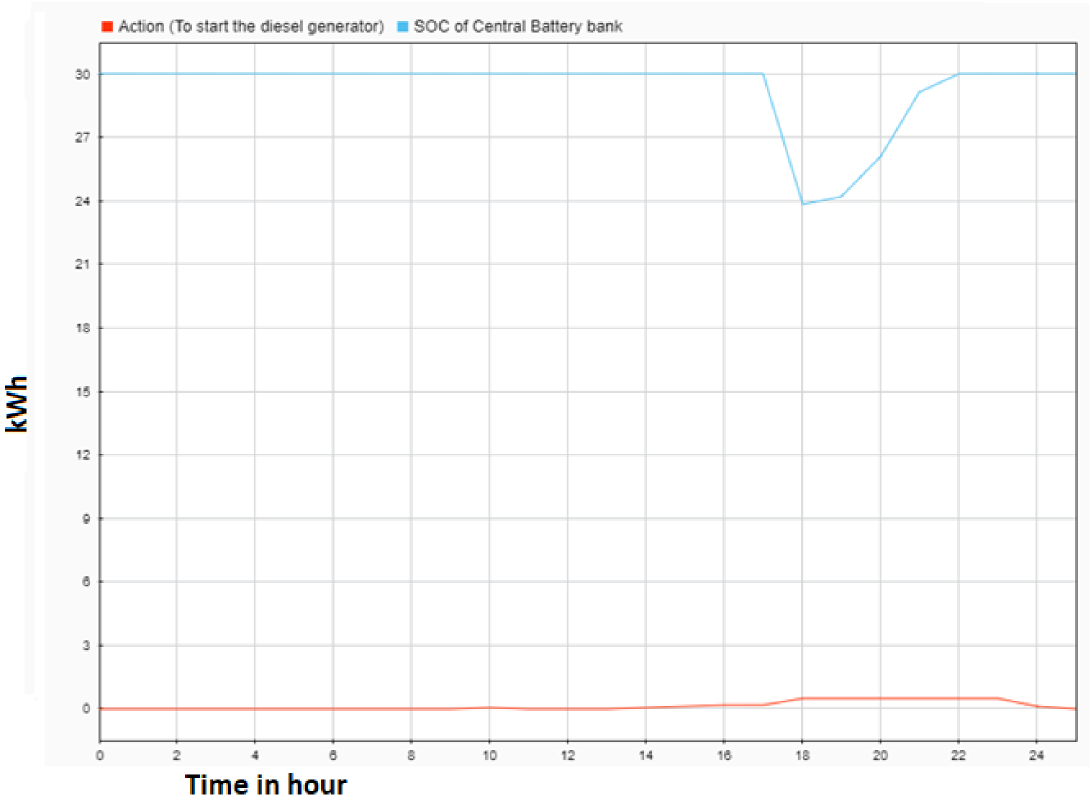


Fig 5.45 The SOC of the central battery bank and the signal to start the generator.

5.3.4.6 Case study 3

The load profile under this condition is presented in the Fig 5.46. The SOC of the inhouse battery bank and the load profile is presented in Fig 5.47. Fig.5.48 represents The SOC charge of inhouse battery bank, SOC of central battery bank (with FLC). Fig 5.49 shows the response of the control system designed without FLC. The variables presented in this figure are SOC of inhouse battery bank and SOC of the central battery bank. When the load demand of a household is grater the generated power the inhouse battery bank supplied the demand to ensure uninterrupted load supply. The load demand then decreases, but there is excess generation from inhouse solar panels, hence the SOC of inhouse battery bank increases. As the inhouse battery SOC never reaches its minimum SOC during this load demand the central battery bank SOC remains in its maximum.

Hence it can be stated that the desired control action is achieved with the control system designed with FLC under this load demand and power generation conditions.

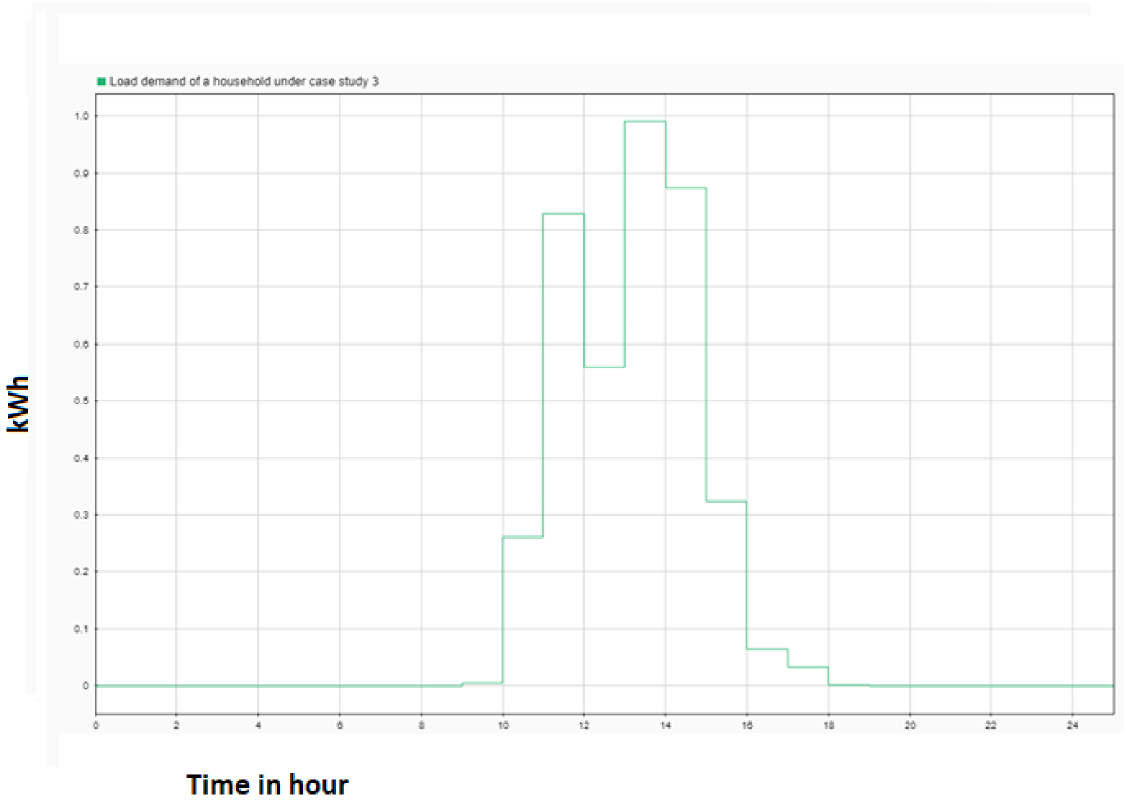


Fig 5.46. The load profile considered in case study 3

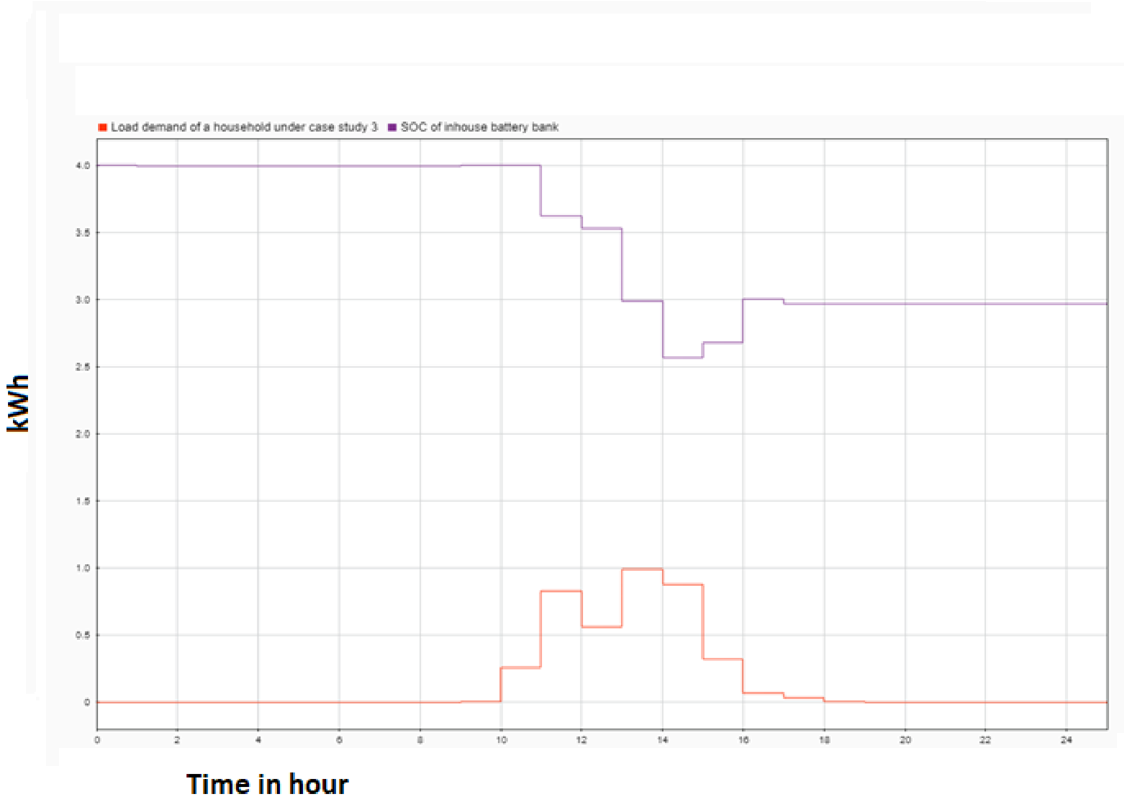


Fig. 5.47. The SOC of the inhouse battery bank and the load profile

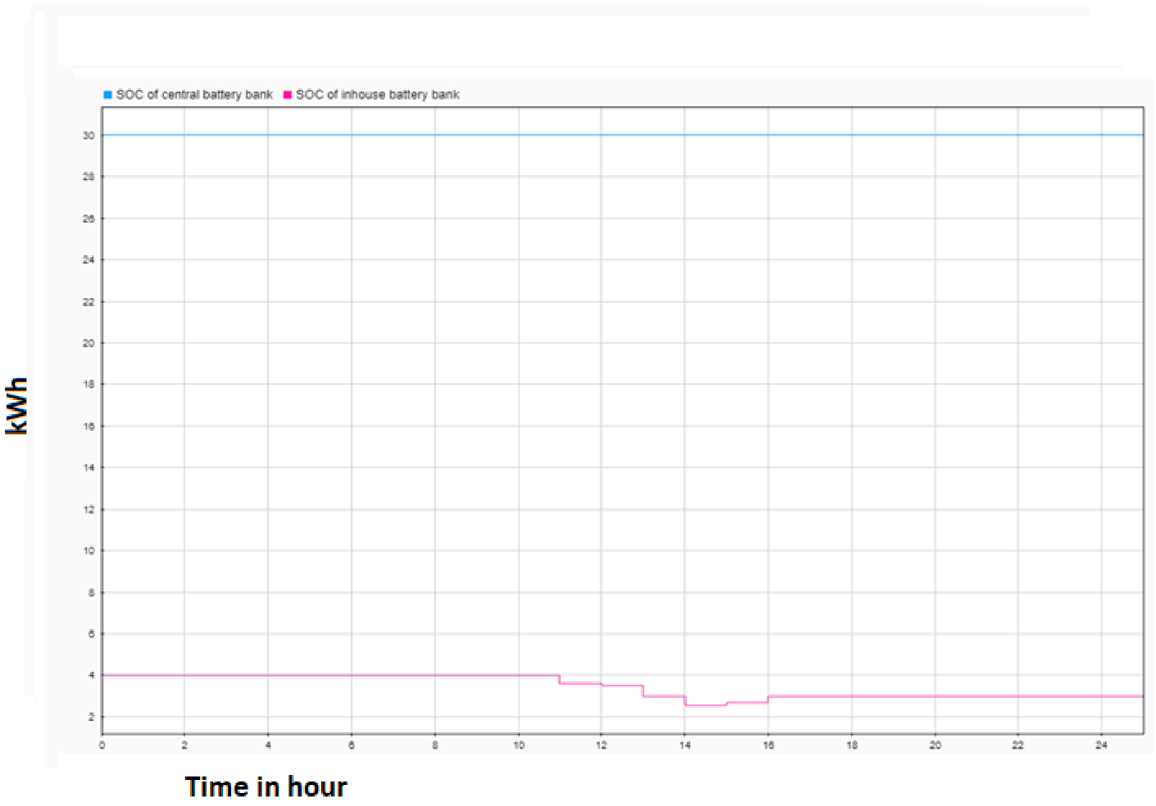


Fig 5.48 SOC charge of inhouse battery bank and SOC of central battery bank with FLC

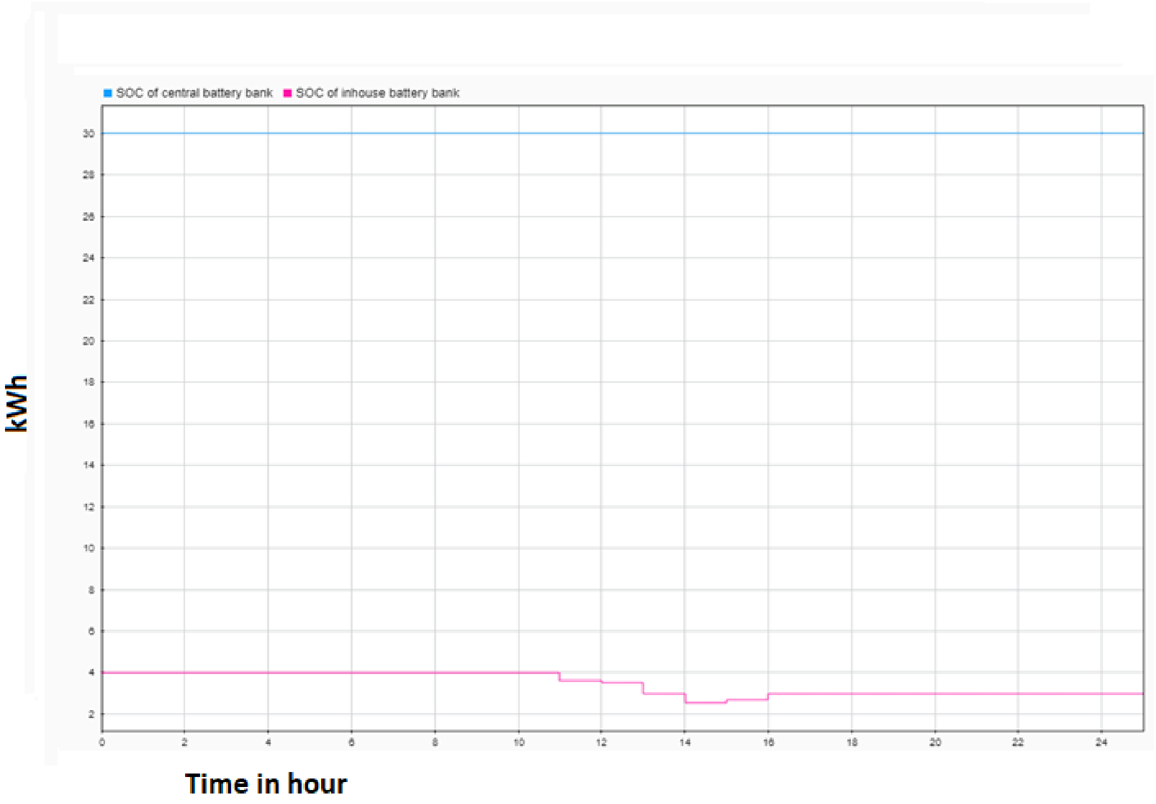


Fig 5.49 SOC charge of inhouse battery bank and SOC of central battery bank without FLC

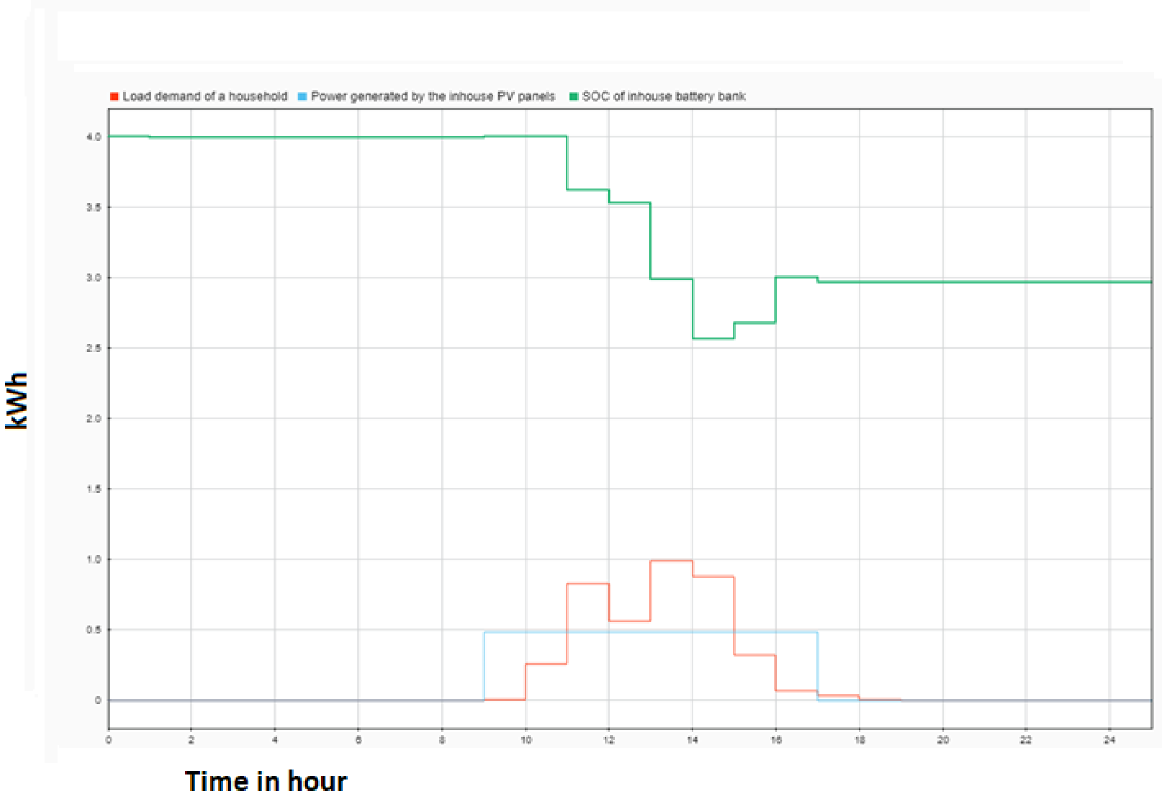


Fig 5.50 Load demand of each household, SOC of inhouse battery and power generated by inhouse solar panels

5.3.4.7 Summary

From the case studies discussed above it can be clearly concluded that this study successfully developed a control mechanism using Fuzzy Logic techniques for load management of a HRES designed for a small community with load sharing options. This developed control mechanism can successfully achieve the desired control action under various load and power generation conditions. The Fuzzy Logic based control mechanism demonstrated high performance during the case studies and has shows better performance than the control system without Fuzzy Logic. The system could successfully supply the load with minimum interruption. The control system successfully discharges the inhouse battery bank when the load demand is higher than the inhouse PV generation till it reaches its minimum SOC. At this stage it successfully discharges the central battery bank to supply the load demand till it reaches its minimum SOC. At this stage the control mechanism starts the diesel generator.

When there is excess generation from the inhouse battery bank the control, system stores the excess energy to the central battery bank which can be used by the other community members when needed. This way the designed control mechanism can successfully allow the load sharing between the community members. Additionally, the Fuzzy Logic based control mechanism can manage the change in battery SOC better than the control mechanism without Fuzzy Logic. This results in better battery performance and increases battery life. Hence the replacement cost of the battery reduces. Hence it can be stated that implementing Fuzzy Logic Control can actually help to utilize the investment in better way.

After successfully developing the control mechanism for the power management of the HRES the study developed a methodology for designing an optimised Fuzzy Logic Controller (FLC) system using Cuckoo Search Algorithm (CSA) for enhancing the performance of wind turbine by maximizing the captured energy. This work has been published in an international journal (AMSE JOURNALS-AMSE IIETA) [151].

5.4 Optimum fuzzy logic control system design using cuckoo search algorithm for pitch control of a wind turbine

5.4.1 Introduction

Due to the huge impact of the conventional sources on the environment and contribution to greenhouse gas production, the research focus has transferred to the renewable and alternative energy sources from the conventional energy sources. The energy production plans of the countries are getting modified to encourage the renewable technologies via numerous policies like tax reduction.

Among all renewable sources the fast-growing renewable energy technology is wind energy as the world has a massive resource for wind energy. As per studies 10 percent of the wind energy available can supply the energy need of the world. Wind energy has huge potential to become a major player in world's energy future with improved technologies and reduced costs and low environmental impact. However, as wind is an intermittent resource, the control mechanism and efficiency of the generators are of outmost importance. The most common methodology to adjust the aerodynamic torque of wind turbine is pitch control when the wind speed is above the rated speed. This study presents the methodology of designing an optimised Fuzzy Logic Controller (FLC) system using Cuckoo Search Algorithm (CSA) to enhance the performance of a wind turbine and also maximises the energy captured from the wind turbine.

In this study an Optimum Fuzzy Logic Controller (FLC) was designed using Cuckoo Search Algorithm for the pitch control of a 1.5 MW horizontal axis wind turbine. Many studies are reported in literature exploring numerous optimisation techniques which are inspired from the natural processes. Genetic Algorithm (GA) is one of the most well known techniques among them which is inspired by natural genetic variation and based on natural selection process. Another emerging technique is Particle Swarm Optimization (PSO) which was developed the researchers Eberhart and Kennedy in 1995. This technique is inspired by the bird flocking behaviour or fish schooling behaviour. Researches are been conducted on optimisation algorithms which are based on nature. New methodologies are being developed increasingly to solve different nonlinear problems.

Cuckoo Search Algorithm (CSA) is a relatively new revolutionary algorithm for optimization. This algorithm is inspired by the lifestyle of cuckoo. This algorithm is developed by researchers Xin – she Yang and Suash Deb in the year 2009 [150]. The basis of this novel algorithm is the procedure of egg lying and breeding of the cuckoo birds specifically [150].

In this study, CSA has been used for optimizing the pre- processor parameters of the Fuzzy Logic based control system for controlling the pitch of a wind turbine. The system performance and the outcomes were analyzed and reported in this study.

5.4.2 Wind Turbine Model

The wind turbine model construction is based on a mechanical turbine which consists of a low speed rotor and blades, the gearbox which is the multiplicative and a generator with consists of a high-speed rotor. The system can be presented in Fig. 5.51 [152]

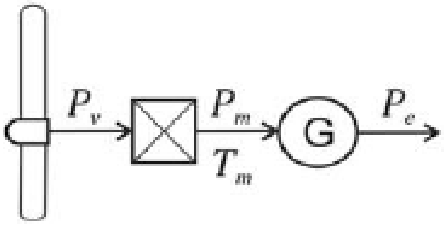


Fig. 5.51 Wind turbine model diagram. Mechanical wind turbine (*left*), gearbox (*middle*), squirrel cage induction generator (*right*) [152].

The wind power is proportional to the cube of the wind speed. This can be represented by equation [153]

$$P_v = 0.5\ \rho\ A\ v_w^3 \qquad (5.1)$$

In this equation ρ represents the air density, the area swept by blades is presented by A, υ_w represents the wind speed. Only a part of the wind power can be extracted by the wind turbines, this is restricted by Betz limit. The maximum value that can be achieved is 59%. This fraction can be expressed by C_p, which is called the power coefficient of the turbine. This can be represented as function of the blade pitch angle to the tip speed ratio.

The gearbox is a mechanical device that is used to multiply the rotational speed of the mechanical turbine and achieve the rotational speed required for the electric generator. P_m is the mechanical power which is delivered as the output of an idea gearbox. P_m is equal to the power extracted from the wind multiplied by the power coefficient C_p [152]. Under standard wind conditions [*101.3 kPa y 273 K]* and wind density value ρ = 0.647 kg/m^2, P_m can be represented by the equation (5.2):

$$P_m = C_p\ (\beta,\lambda)\ P_v \qquad (5.2)$$

The gearbox is a mechanical device that is used to multiply the rotational speed of the mechanical turbine and achieve the rotational speed required for the electric generator. P_m is the mechanical power which is delivered as the output of an idea gearbox. P_m is equal to the power extracted from the wind multiplied by the power coefficient C_p [152]. Under standard wind conditions [*101.3 kPa y 273 K]* and wind density value $\rho = 0.647$ kg/m^2 , P_m can be represented by the equation (5.3):

$$P_m = C_p (\beta,\lambda) P_v \qquad (5.3)$$

Hence, the mechanical power extracted by the wind turbine can be represented as [152]

$$P_m = 0.647\, C_p (\beta,\lambda)\, \tfrac{1}{2}\, A v_w^3 \qquad (5.4)$$

The power coefficient of the wind turbine is represented by C_p , the blade pitch angle is presented by β and the tip speed ratio is presented by λ. The ratio between the blade speed and the wind speed υ_w is represented by tip speed ratio which is presented in equation (5.5)

$$\lambda = \frac{\Omega R}{\upsilon_w} \qquad (5.5)$$

TSR (Tip Speed Ratio) is defined by the ratio between the speed of the tip of the turbine blade and the speed of the wind. TSR greatly impacts the efficiency and performance of the turbine.

When the turbine blades are not fast enough they are not efficiently harvesting most of the wind energy .Too fast tip speed results in higher noise levels and increases the requirement of stronger blades due to the effect of larger centrifugal forces. Hence determination of an optimum TSR is important to harvest maximum energy from the wind turbine which makes TSR an important factor in wind turbine design [193].

The turbine rotor speed is presented by Ω and the radius of the wind turbine blade is presented by R. For a selected average site, the performance curves that are frequently used to design a wind turbine are the $C_p - \lambda$ curves. The information related to the wind speed and angle of attack at which the maximum power coefficient C_{pmax} is obtained is presented in these curves. The following expression presents the relation between C_p and λ [152]

$$C_p = c_1 \left(\frac{C2}{\lambda i} - c_3\beta - c_4 \right) e^{-c5/\lambda i} \qquad (5.6)$$

$$\frac{1}{\lambda i} = \frac{1}{\lambda + C6\beta} - \frac{C7}{\beta^3 + 1} \qquad (5.7)$$

The constants c_1 , c_2 ,….. c_7 are related to the wind turbine's aerodynamic design , they are specific for each wind turbines. The angle of attack of the wind at the blade is presented by . *β (deg*)

Fig 5.52 the C_p - λ curves for different vales of β for a 1.5 MW wind turbine [152]. From these curves it can be observed that the mechanical power that is converted the turbine blades can be represented as a function of rotational speed. The power converted is maximised at that specific rotational speed for numerous wind speed.

This project selected the squirrel cage induction motor generator. These types of generators are very commonly used for generating in wind turbines.

The wind turbine model was designed and analysed in MATLAB and SIMULINK environment. The mechanical turbine model was created using the equations 5.2- 5.5. The parameters that were used in the design for the 1.5 MW wind turbine and aerodynamic parameters of the wind turbine is presented in the Table 5.1 and 5.2

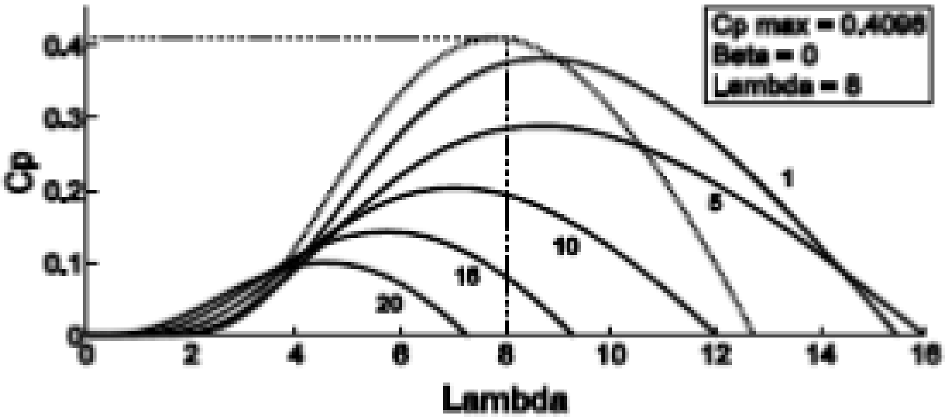
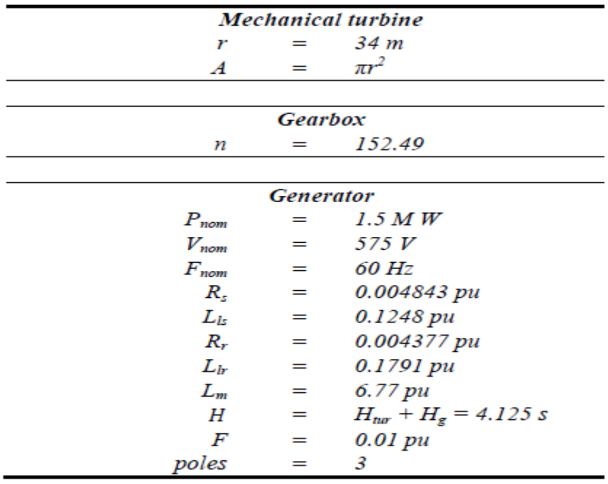


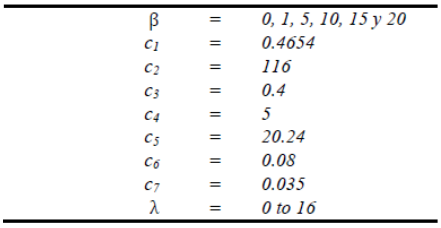
Fig.5.52 C_p - λ curves for different values of β [2]

Table 5.1 Wind turbine model parameters



Mechanical turbine		
r	=	34 m
A	=	πr^2
Gearbox		
n	=	152.49
Generator		
P_{nom}	=	1.5 M W
V_{nom}	=	575 V
F_{nom}	=	60 Hz
R_s	=	0.004843 pu
L_{ls}	=	0.1248 pu
R_r	=	0.004377 pu
L_{lr}	=	0.1791 pu
L_m	=	6.77 pu
H	=	$H_{tur} + H_g = 4.125$ s
F	=	0.01 pu
poles	=	3

Table 5.2 Wind turbine aerodynamic parameters [2]



β	=	0, 1, 5, 10, 15 y 20
c_1	=	0.4654
c_2	=	116
c_3	=	0.4
c_4	=	5
c_5	=	20.24
c_6	=	0.08
c_7	=	0.035
λ	=	0 to 16

5.4.3 Fuzzy logic controller (FLC)

Fuzzy Logic Control (FLC) techniques are widely used in recent days I many industrial process /applications. The application of FLCs are more beneficial in complex processes where definite mathematical relationships between the variables are not available. Especially the processes which can be controlled by an expert human operator who might not have necessary knowledge of the underlying process dynamics [154 – 157]. FLC is a rule-based control system which is based on Fuzzy set theory. They elements of Fuzzy theory and logic there are three key operators based on which the decision is made. These three key operators are: The fuzzification process, Fuzzy inference engine for rule base and the defuzzification process [158]. FLC is a mathematical system that is capable of analysing the analogue input values converting them into logical variables which can take a continuous value between 0 and 1 where the classical logic can operate on discrete value, either 1 or 0.The expert knowledge of a user is utilized to design the knowledge base of the fuzzy logic controller. The configuration of the proposed Fuzzy Logic Control is presented in the Fig. 5.53 [151].

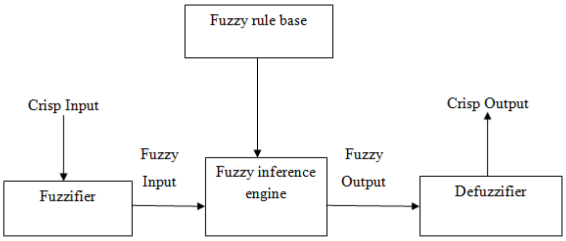


Fig 5.53 Configuration of fuzzy logic

5.4.4 Cuckoo search algorithm (CSA)

The Cuckoo Search Algorithm (CSA) is a very efficient and powerful optimization technique that is inspired by the fascinating breeding behaviour like brood parasitism which can be observed in certain species of the cuckoo birds [150]. These species of cuckoo bird have a very aggressive type reproduction strategy. These birds lay their eggs in the nest of the host birds, they have astonishing ability to select these host nests. They use some very incredible techniques such as selecting a nest which has been spawned recently and then they remove the existing eggs which actually increases the probability of hatching of their own eggs [159]. The host birds assume those cuckoo eggs as their own eggs and takes care of those eggs till they hatch. Under the unfortunate circumstances if the host birds identify the eggs as not their own, they would through out those unfamiliar eggs out of their nest or they would abundant the nest and would look forwards building a new egg in a different location.

This peculiar breeding behaviour analogy is the motivation behind this optimization algorithm CSA. *Cuckoo search* is one of the current metaheuristic algorithm which is inspired by nature, invented by Xin-She Yang and Suash Deb [150]. CS is designed based on the brood parasitism characteristic of certain type of cuckoo species. This powerful algorithm is enriched by the Lévy flights [150][159-160][192] instead of simple isotropic random walks. Latest researches indicate that CS is significantly more efficient than other optimisation techniques like PSO and genetic algorithms [192]. This is the main inspiration to explore this study.

The details of the methodology can be obtained from the literatures presented in [150] and [160]. The key steps that of Cuckoo Search (CS) can be presented by the following chat [161]:

Step 1, →

Specify current place of residence of cuckoos randomly

Step 2, →

Assign a number of eggs to each cuckoo.

Step 3, →

Specify the laying radius of each cuckoo.

Step 4, →

Cuckoos are laying on the host nests in their lay radius.

Step 5, →

Eggs that are identified by the host birds are destroyed

Step 6, →

Cuckoo eggs that have not been identified are grown.

Step 7, →

Evaluate the place of residence of new cuckoos.

Step 8, →

Specify the maximum number of cuckoos that are in a place to live and eliminate those that are in unsuitable places.

Step 9, →

cluster the cuckoos using k-means clustering method and specify the best group of cuckoos as the objective place of residence.

Step 10, →

New cuckoo's population are moving to the objective location.

Step 11, →

stop if the stop condition has been established, otherwise, go to step 2.

The present work uses CSA to optimize the pre-processor parts of the FLC to harvest maximum power from a 1.5 MW wind turbine under changing wind speed conditions.

5.4.5 Fuzzy logic controller design

This research uses a self-tuneable Fuzzy controller to control the pitch angle of a variable speed wind turbine. The aim of this work is to harvest maximum power from the wind by controlling the pitch angle by replacing the linear controller by the Fuzzy controller. The inputs of the suggested FLC are wind speed *v(t)* and an error signal *e(t)* [162]. Fig 5.54 represents the closed loop diagram for the suggested system.

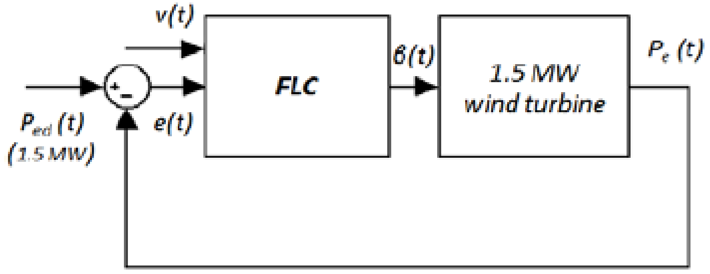


Fig 5.54 Feedback control closed loop for the proposed FLC [162]

As presented in Fig 5.54, the Fuzzy controller has two inputs, the wind speed v and the error signal e which represents the difference between reference power and the power generated. The FLC generates an output signal β.

Fig 5.55 [161] represents the detailed structure of the FLC that has been investigated in this research.

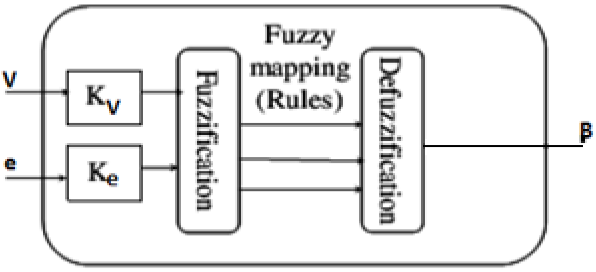


Fig 5.55 The structure of the FLC [161]

The performance curves can be used to analyse the pitching to feather methodology to harvest electric power from the wind turbines. For this purpose, the most powerful performance curves are the P_e -V curves. The power generated by the wind turbines versus the wind velocity at a specified value of angle β is represented by the P_e -V curves [162]. Fig 5.56 represents some of those curves .The P_e -v curves presented in this figure is drawn for the vales of β =0, 2, 12, 18 and 23.Once can clearly observe from these curves that the blade pitch angle β should be changed to obtain a constant 1.5 MW power production from the wind turbine under the variable wind speed conditions.

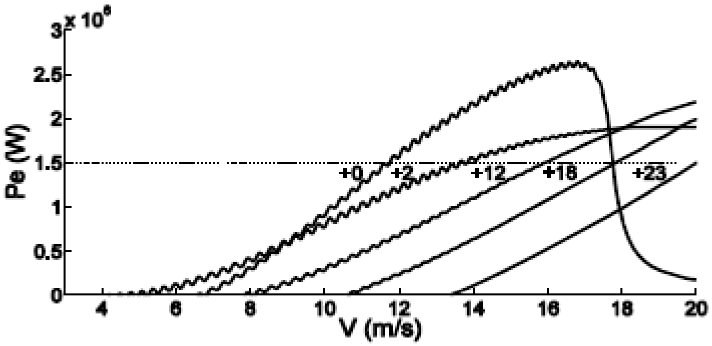


Fig. 5.56 $P_e - v$ curves for $\beta = 0, 2, 12, 18$ and 23. Optimum β angle for current wind speed can be obtained at the intersection with the 1.5 MW dotted line [162].

The membership functions and the rule base of the FLC is designed observing the performance curves. Figs 5.57 – 5.59 represents the input and output membership functions. Table 5.3 represents the system rules.

The coefficients Ke and Kv effects system performance to great extent. They are presented in Table 5.4. Hence, it is very important to select appropriate value for these variables to achieve desired system performance. To strengthen the performance of the Fuzzy controller, this research selects the optimum values of these pre-processors parts of the Fuzzy controller using CSA within a specified range. The objective function was selected with the aim to maximise the generated power for a given period. The parameters that have been used to develop the Cuckoo Search have been presented in table 5.5. Table 5.6 represents the ranges or the bound of the search domain of the optimisation variables
The optimization process has been simulated using MATLAB programming.

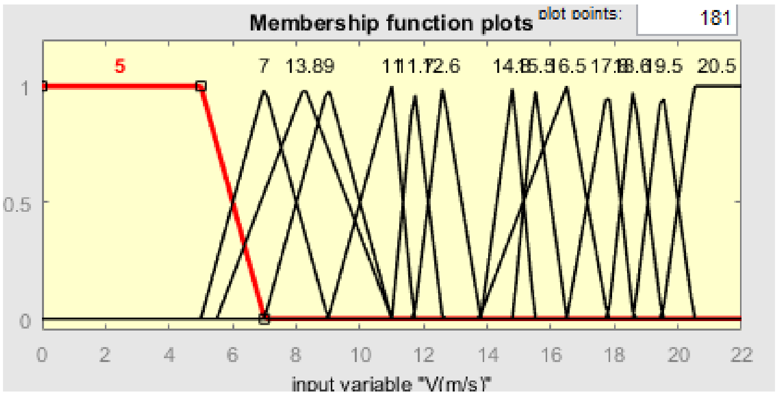


Fig. 5.57 Membership functions of the input variable V(m/s) (Wind speed) [162]

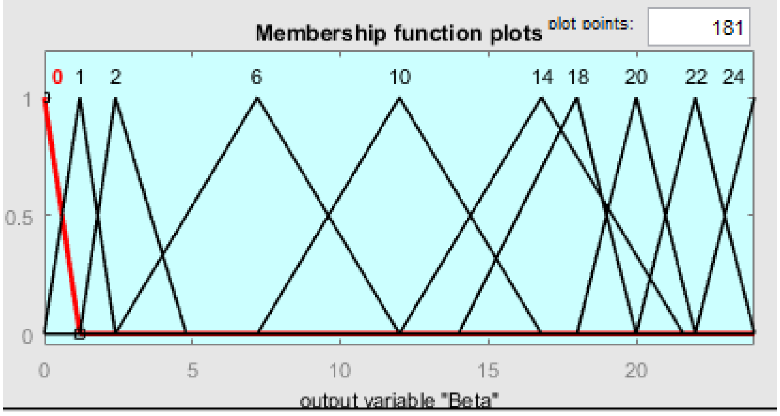


Fig. 5.58 Membership functions of the output variable Beta (pitch angle) [162]

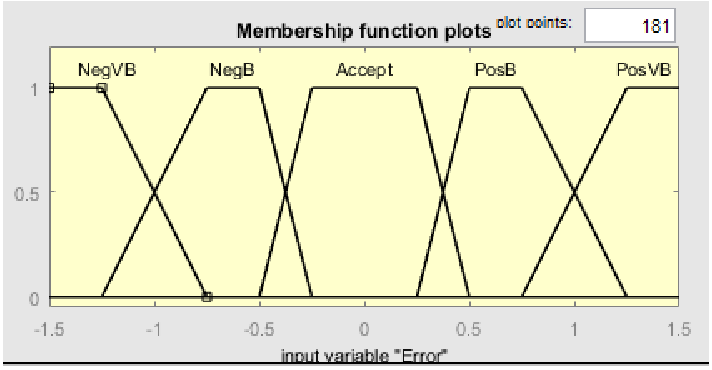
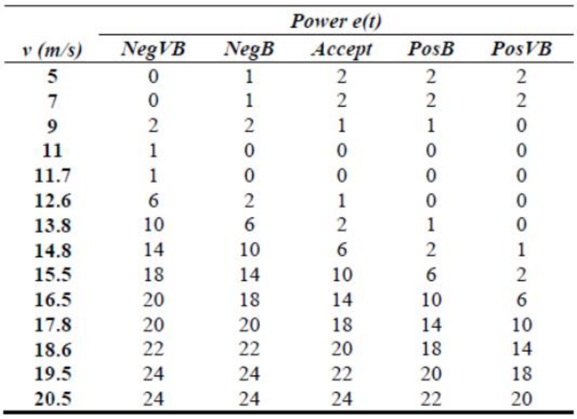


Fig 5.59 Membership functions of the input variable Error (Power error) [162]

Table 5.3 FLC rules



	Power e(t)				
v (m/s)	*NegVB*	*NegB*	*Accept*	*PosB*	*PosVB*
5	0	1	2	2	2
7	0	1	2	2	2
9	2	2	1	1	0
11	1	0	0	0	0
11.7	1	0	0	0	0
12.6	6	2	1	0	0
13.8	10	6	2	1	0
14.8	14	10	6	2	1
15.5	18	14	10	6	2
16.5	20	18	14	10	6
17.8	20	20	18	14	10
18.6	22	22	20	18	14
19.5	24	24	22	20	18
20.5	24	24	24	22	20

Table 5.4 Optimized values of the pre-processing parameters

K_v	Ke
1.685074075795595	1.208470477655286

Table 5.5 Cuckoo Search parameters

Number of iterations	1000
Number of nests	25
Discovery rate of alien egg/solutions	0.25

Table 5.6 The limits of the optimization variables

	K_v	K_e

Upper limit	.05	.05
Lower limit	2	2

5.4.6 Results and Discussions

A detail system model has been developed using MATLAB programming to verify the performance of the control mechanism developed in this research work. Wind signal was generated for simulation purpose in MATLAB environment by randomly varying the wind speed. The generated signal is presented in Fig 5.60. The wind speed is varying within the range of 8m/s to 17m/s where the rated speed of the turbine is 13 m/s. This generated wind signal has been used to assess the performance of the suggested wind turbine system that uses the optimized FLC and compares the performance of the system with a conventional PID controller. The power output of the wind turbine will vary with the variable wind speeds.

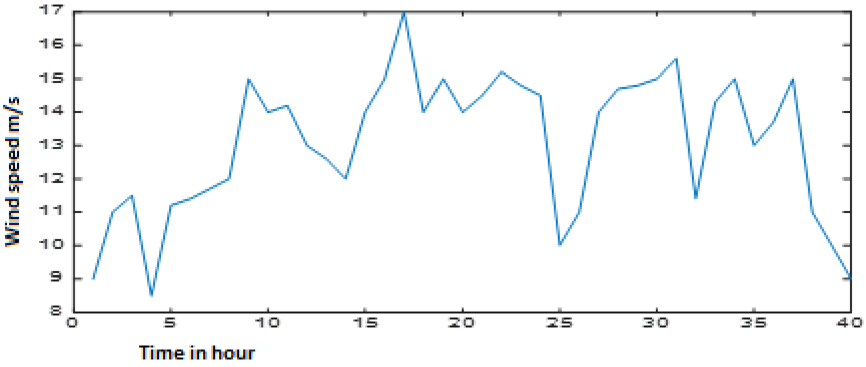


Fig. 5.60 Wind speed variation (m/s)

Fig 5.61 represents the comparison between the power outputs of the wind generation system with FLC which does not have the pre-processor parts and the power output of the wind generator system with PI(Proportional Integral) controller. Whereas Fig 5.62 represents the comparison between the power generated by the wind generator system with FLC that has the optimized pre- processor parts with the power generated by the wind generator system with PI controller.

Studying the curves represented in Figs 5.61 and 5.62 it can be clearly observed that for a specified wind speed, the FLC provided better results in comparison with conventional PI controller, especially when the wind speed is low. Further this can be observed from the curves that the wind generator system with FLC with optimized pre-processor parameters perform even better compared to the FLC that does not have the optimized pre- processor parts at the lower wind speed as that system can harvest more power from the wind.

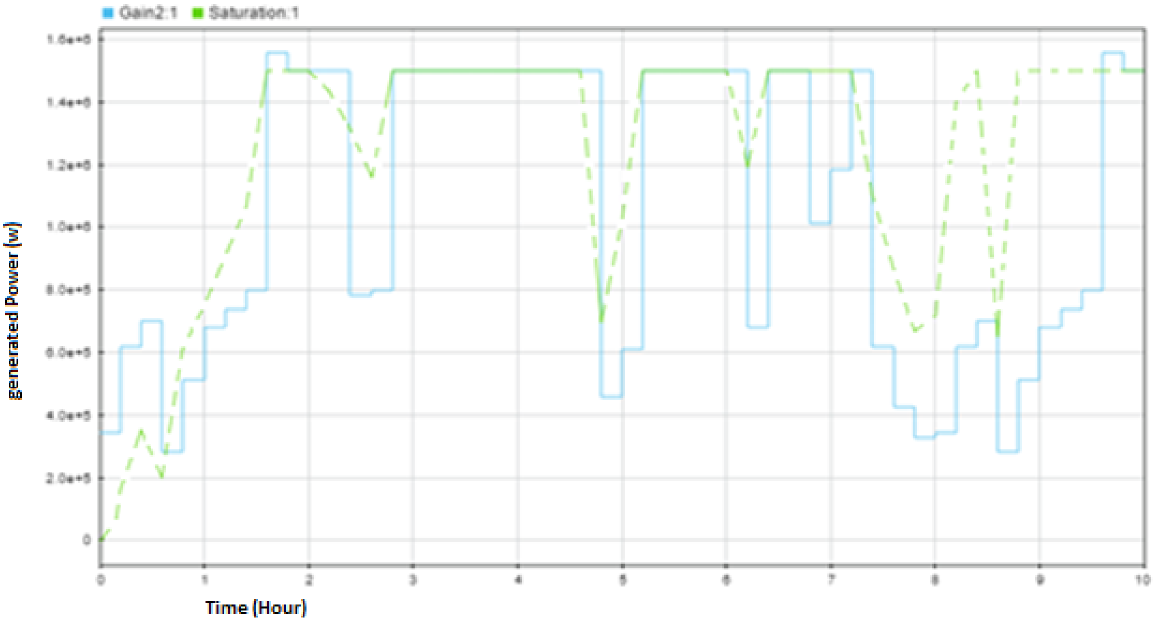


Fig. 5.61 The blue (solid) line represents the generated power of the wind power system with PI controller and green (dotted) line represents the generated power of the wind power system with FLC -without pre-processors.

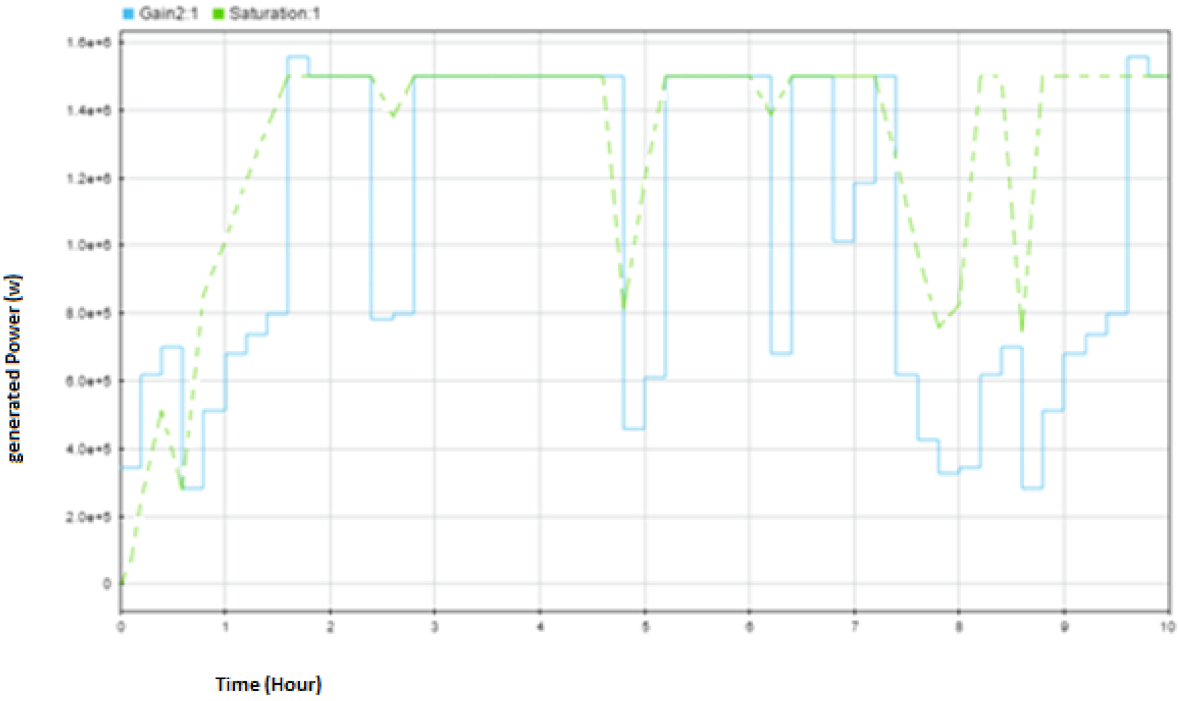


Fig. 5.62 The blue (solid) line represents the generated power of the wind power system with PI controller and green (dotted) line represents the generated power of the wind power system with FLC with optimized pre-processing parameters.

5.4.7 Summary

For efficient and reliable power generation, design of a proper control mechanism of the wind generation system is very crucial. This current work represents a very efficient and effective tuning mechanism for the control system of the wind power generation system using Cuckoo Search Algorithm. The study shows how by optimally tuning the pre- processor parts of the Fuzzy Logic control system the maximum power can be harvested from a 1.5 MW wind turbine controlling the pitch angle. From the results obtained it is evident that incorporation Fuzzy Logic Control can significantly improve the performance of the power generating system compared to conventional PI controllers, especially when the wind speed is in low range. One can also observe from the results that an optimized FLC can improve the system performance even more by extracting maximum power from the wind compared to the un- optimized FLC or the standard PI controller under lower wind speed condition due to the inherent characteristics of the optimized controller to deal with non-linear models. This optimized controller also performs better and satisfactorily as per the requirement under high wind speed conditions compared to the un- optimised FLC or standard PI controller. Results obtained from the simulations clearly shows the robustness of the FLC which has been optimally tuned using the Cuckoo Search Algorithm. The soft and nonlinear control action obtained using this controller improves the performance of the wind generation system at low and rated speed hence increases the reliability of the system.

HARDWARE IMPLEMENTATION OF THE CONTROL MECHANISM

CHAPTER

6

Chapter 6: Hardware implementation of the control mechanism

6.1 Introduction

The aim of the project is to design a standalone hybrid renewable energy system comprising of solar and wind generators, battery storage, dump load and a standby diesel generator to supply the load demand of a small community located in Portland Victoria. The community under consideration comprising of ten households. As per the proposed system, each household has inhouse PV generators and an inhouse battery storage. Apart from the inhouse battery bank and PV generators there would be a central battery bank and wind generators. The diesel generator is there to supply the load demand when there is not enough generation from the PV/ Wind generators and both inhouse and central battery bank reaches their minimum state of charge. In case of excess generation from the PV panels the excess energy is stored in inhouse battery till it reaches its maximum state of charge. Once it reaches its maximum state of charge the excess generation will be stored in central battery bank till the central battery bank reaches its maximum state of charge. Once the central battery bank reaches its maximum state of charge any excess generation will be sent to dump load.

The overall system structure is very complex. Hence design of a proper control system is very crucial for load management of the overall system. During this study a central controller was designed to achieve to achieve desired control action using Fuzzy Logic in MATLAB / SIMULINK environment. The heart of the overall control system is the central controller. The controller decides when to charge or discharge the central battery bank, start the generator or send the excess to dump load. The controller was designed in various steps. The design steps and methodology were discussed in detail in Chapter

7. The performance analysis of the designed system clearly indicates that the designed controller could achieve the overall control action and satisfy the load demand with minimum interruption. Further studies were conducted to design a testbed using hardware and implement a central controller to achieve the similar control actions. As discuss in previous sections, the overall system structure can be presented as in Fig 6.1.

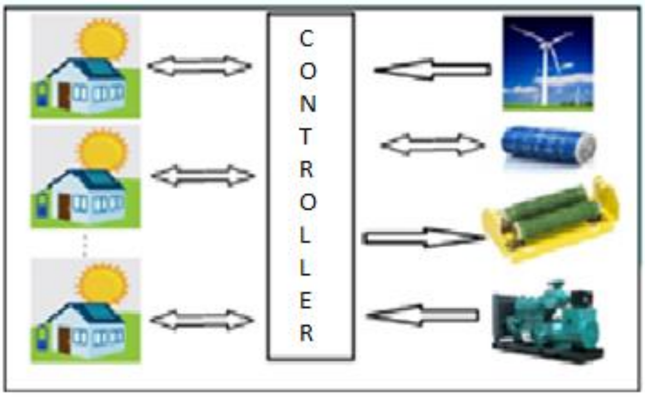


Fig 6.1 The system architecture of the proposed HRES

This section of the study concentrates on designed a central controller using hardware. However, one need to remember that the main aim of this section of the study is to design the controller to achieve the desired control action under different supply and demand conditions. This is a system prototype. The controller needs to generate control actions as per the state of generated power and load demand. This system is designed in the laboratory environment; hence while designing the hardware, signal generators were used to simulate different power generation conditions from PV panels/ wind generators and load demand. The overall system has been simulated using module called Janztec emView -7/RPI3BP which is Janztec designed system based on Raspberry Pi 3BP with their own 7" touch screen. The entire system is assembled and enclosed in a powder coated steel enclosure.

This Raspberry Pi 3B+ based emView product with 7" display with CoDeSys SL gives the user the opportunity to develop a full-fledged application to simulate a complete micro grid system with multiple sources of energy and also a storage battery to accumulate the charge which allows the flexibility to charge or draw off depending on the nature of demand and day/night and load cycles.
Some of the special characteristics of the module are:

a. This module includes CoDeSys 3.5 Run time license
b. ESX-IOX CANopen slave with the ability to process upto 26 I/Os

c. 3 x Potentiometers, 2x switches
d. IEC power connection with switch
e. USB port for easy access to the data logging memory stick without opening the system
f. A rugged powder coated painted steel enclosure

The overall system structure and hardware used is discussed in following sections.

6.2 The hardware module

This hardware module was created by incorporating the required hardware to provide the test and simulation environment to simulate various energy sources and load demand for the standalone hybrid renewable energy system.

The overall module overview can be presented in Fig 6.2

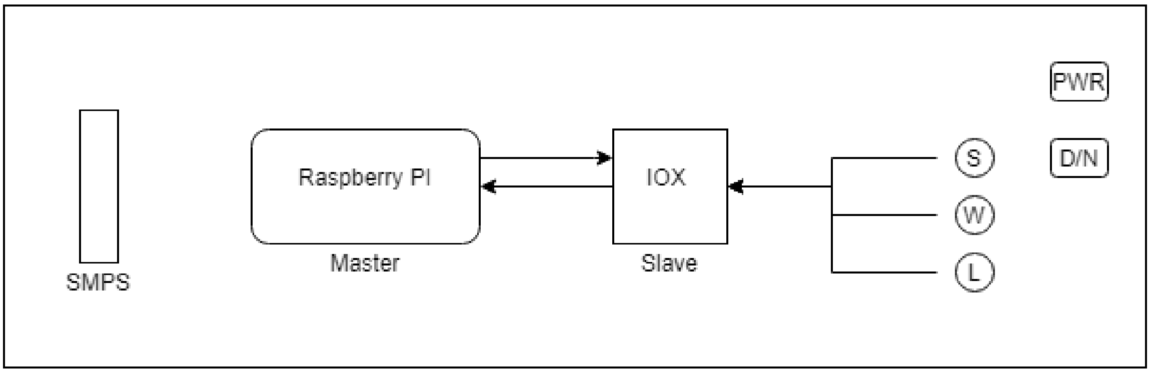


Fig.6.2 Overview of the hardware module

Where,

S represents Power generated by the PV panels in W
W - represents Power generated by the wind turbine in W
L - represents Load in W
D/N - Day /Night mode Switch
PWR - Power switch (9 – 32 V)

The module consists of three potentiometers to simulate conditions (by rotating potentiometer in anti-clockwise directions) such as:

- No load demand to max load demand
- No Solar power generation to maximum solar power generation
- No wind power plant generation to maximum wind power plant generation

The Raspberry PI display is presented in Fig 6.3

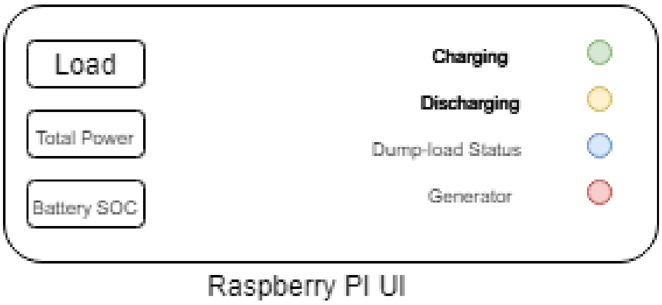


Fig 6.3 Raspberry PI display

The Raspberry PI screen is used to display the status of Battery Charging/Discharging, Dump-load status, and Generator status. It also includes the Trace of Load, Total power, and batter SOC for user to see online data as the simulation continues. The data generated by simulation and trace can be dumped to an Excel file through suitable coding to a destination drive (such as USB or SD card) by adding them at the Linux kernel through shell scripting.

Once coded the emView 7” ARPI provides a standalone method of generating simulated data for Micro grid applications using various energy sources, load, day/night cycles and battery charge discharge cycles under the control of the program.

The main components used in this Hardware module are discussed :

- **EmVIEW-7RPI**

EmVIEW-7RPI is a product by Janz Tec AG . With emPC-A/RPI3+ Janz Tec AG provides a device which uses an original Raspberry Pi 3 model B+ module inside. This module is mounted on a selfdeveloped mainboard providing a 24VDC power supply, an additional CAN interface, a real-time clock, digital inputs and outputs and an additional RS232/RS485 interface. The module is presented in Fig. 6.4.

Fig. 6.4 EmVIEW-7RPI

The modules display features can be presented as follows:

i. 7.0” WVGA display size
ii. LED backlight technology
iii. Aspect ratio 15:9 (Landscape)
iv. Resolution 800 x 480
v. Luminance 350 cd/m² (typ.)
vi. Front frame in brushed aluminium or black
vii. Touch Screen
viii. Projected capacitive touchscreen (PCAP) (with multitouch capabilities)
ix. Glass surface
x. Power supply
    1. Input 9 … 32 V_{DC}
    2. Power consumption: 7 Watt
xi. Physical condition:
    1. Ambient operating temperature 0 °C ... 35/45°C^2
    2. Non-operating temperature -20 °C … 75 °C
    3. Humidity 5 % ~ 95 %, non-condensing
xii. Dimension:
    1. 203x121 x 55 mm (w x h x d)
    2. Weight approx. 0.6 kg

3. DIN rail mounting

- **The controller:**

The central Processor of the system is powered by Raspberry Pi 3, Model B+ which comes with

xiii. Quad-Core CPU based on ARM Cortex-A53 with 4 x 1.4 GHz 1
xiv. Fan-less cooling concept
xv. Real-time clock, battery buffered

This controller takes the control action as desired. The programming of the controller has been done with CoDeSys 3.5 to achieve the desired control actions under various load demand, power generation and battery state of charge conditions.

- **Memory**

i. System memory 1 GB DDR2 RAM
ii. External accessible µSD card slot

- **Interfaces**

Following hardware have been used for interfacing.

xvi. 1 x 10/100/1000 MBit/s Ethernet
xvii. 1 x HDMI graphic interface
xviii. 4 x USB (v2.0)
xix. 1x BCM43143 WLAN on board
xx. 1 x 9-pin D-SUB connector for serial debug console
xxi. 1 x I/O connector, providing:
xxii. 1 x CAN
xxiii. 1 x RS232 or switchable to RS485
xxiv. 4 x digital inputs (isolated from logic)
xxv. 4 x digital output (0.5 A max.)

- **ESX-IOX CANopen slave module:**

Cost-optimized CANopen-slave-I/O module has been used for the extension of the inputs/outputs of a master control unit via CAN. The communication of the master control unit takes place via CANopen or a layer 2 protocol. This low-cost version is perfect for smaller applications with up to 28 I/O's. It is a remote I/O module for both analog and digital I/O and works as a slave module that can communicate using the CANopen protocol. This module is presented in Fig 6.5

Fig 6.5 ESX-IOX CANopen slave module

Product Specifications can be stated as follows:

- Designed to work as a slave module
- Maximum 20 Digital Inputs
- Maximum 2 Frequency Inputs
- Maximum 12 Analog Inputs
- Maximum 4 x 3A PWM Outputs
- Maximum 8 x 4A Digital Outputs
- 10V Stabilized output voltage
- 1 x CAN 2.0B
- IP67 and IP69K

The module incorporates all the components discussed above to achieve the system prototype of a standalone hybrid renewable energy system. The block diagram of the complete system can be presented as in Fig 6.6

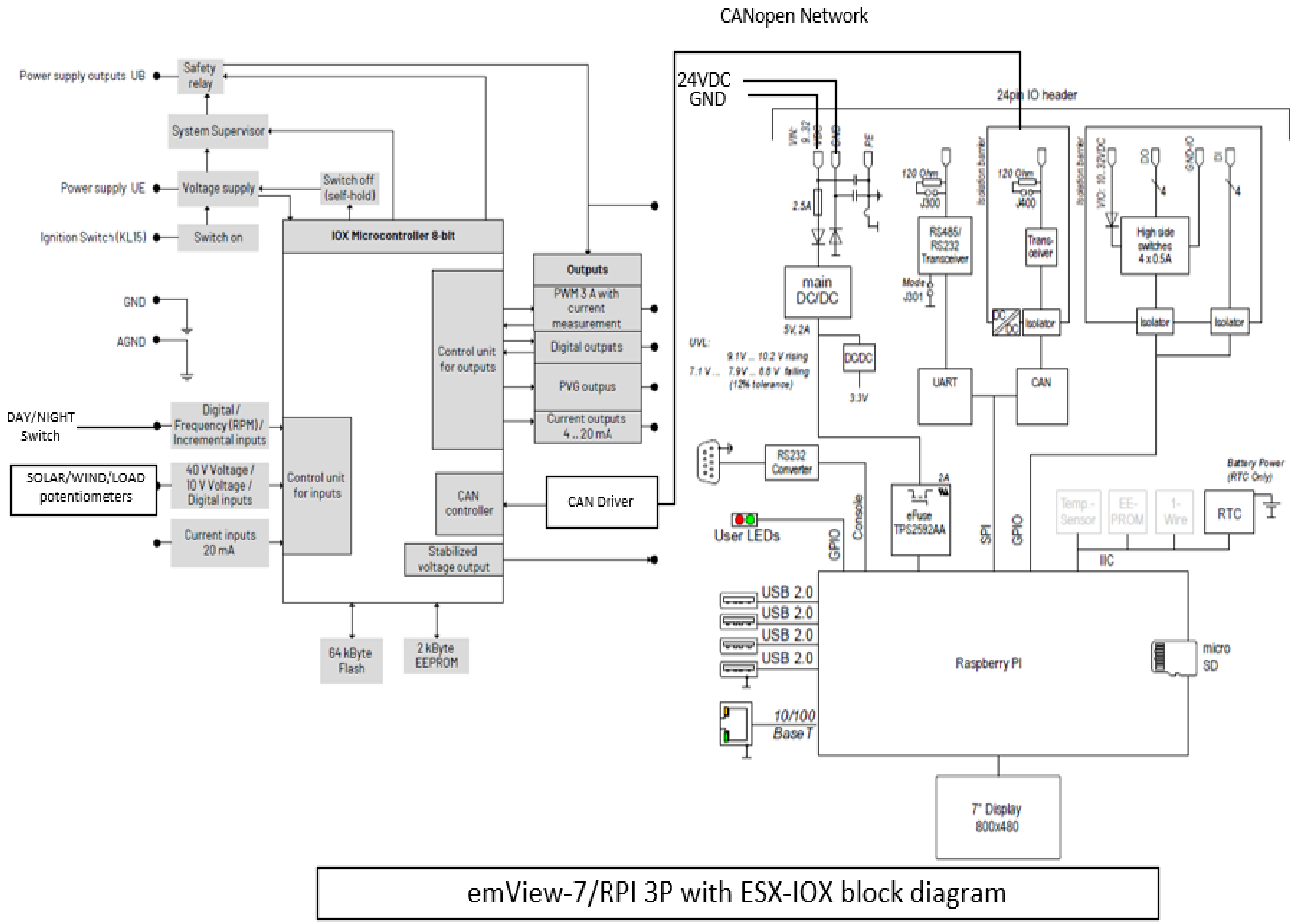


Fig 6.6 EmView – 7 /RPI 3 P with ESX- IOX block diagram

6.3 The operational characteristics of the hardware module and simulation

6.3.1 Opertational Charateristic of the module

EmView-7RPI is a Panel PC with a 7” touch screen with licensed CoDeSys 3.5 (IEC 61131 PLC programming interface) programming run time license. The functionality required to provide a simulated test environment of a micro grid can be achieved by programming the controller using CoDeSys. SOme of the charateristics of the module can be presented as below:

- Day/Night Switch: This allows the user to simulate day and night conditions. For example this switch can help the user to simulate practical conditions such as when the switch is ON, the solar data is to be taken into account and when it is in OFF, no solar data condition is considered.

- IOX On/Off: This switch controls the IO module (STW IOX) which gives the analog signal generated by Solar, wind and Load. One need to remember that this switch must remain ON during operation of this device for the presence of Solar, Wind generation and Load: Rotating these knobs will generate analog signals of respective labels.

- By rotating the knobs in counterclockwise direction maximum output upto 16 MW can be achieved, this output is scalable through CoDeSys interface. The solar knob will generate signal Irrespective of Solar Switch being on or off. But the output is excluded from calculations.

The various conditions in a micro grid can be simulated by using following methodology:

a. Solar Generation : Available solar energy is simulated using analog voltage from a potentiometer connected through the ESX-IOX unit.
b. Wind energy (simulated through analog voltage using potentiometer connected to ESX-IOX)
c. Loads (consumer enery loads -simulated through analog voltage input) using potentiometers connected to ESX-IOX.
d. Day/night switch: This is to indicate different consumption and generation patterns during daytime and night time and a simple switch can be used to trigger default conditions during day or night time.

The unit has some additional interfaces:

1. Switch to enable ESX-IOX CANopen slave: This should be in ‘ON’ condition when doing any data log as all our analog and digital inputs are processed by this module.

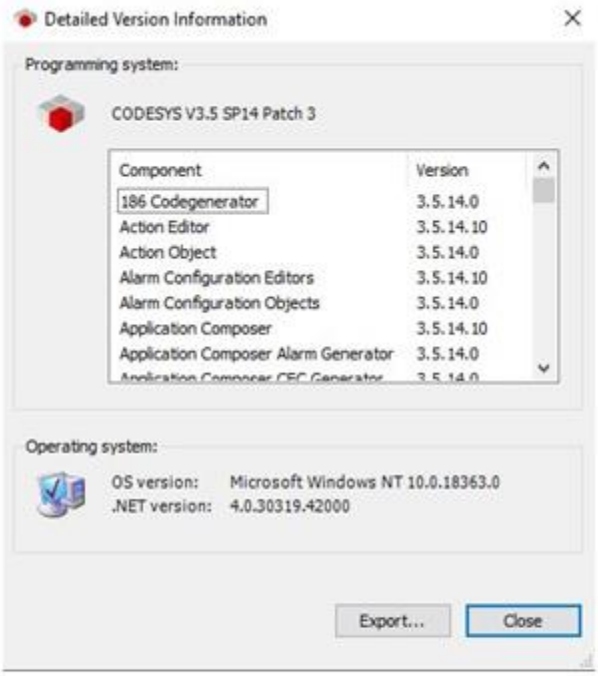
2. Power supply input at 240VAC using an IEC 3 x pin plug, This also has an intregrated switch which can be used to power off the system.

3. Panel mount USB port that allows the user to connect a USB memory stick for data logging.

The potentiometer reads 0-5V and convert it into CAN messages for Master to read and interpret into variables that is used to compare and calculate different scenarios. The data from these potentiometers is computed in PI module (by implementing Continuous Flow Chart in Codesys) to determine the following:

- Status of Battery (Charging and discharging)
- Status of Dump load (on or off)
- Status of generator (Generator on or off)
- Power Supplied by battery (when discharging)
- Power Supplied by Generator

The emView-7RPI3P system has been programmed using a version of CoDeSys 3.5 which has been downloaded from CoDeSys website. The version that has been used is CODESYS V3.5 SP14 Patch 3. This is based on the licensed runtime in the emView-7RPI system. The details of the version is prsented in Fig 6.7



Programming system:

CODESYS V3.5 SP14 Patch 3

Component	Version
186 Codegenerator	3.5.14.0
Action Editor	3.5.14.10
Action Object	3.5.14.0
Alarm Configuration Editors	3.5.14.10
Alarm Configuration Objects	3.5.14.0
Application Composer	3.5.14.10
Application Composer Alarm Generator	3.5.14.0
Application Composer CFC Generator	3.5.14.0

Operating system:

OS version: Microsoft Windows NT 10.0.18363.0
.NET version: 4.0.30319.42000

Fig. 6.7 The deatailed Version of the CODESYS used

The Raspberry PI has been programmed using CODESYS 3.5 to achieve the desired control actions under the various conditions of a microgrid. By running the program one can simulate various conditions of solar/wind energy generation, battery charge/discharging , various load coonditions under day/night conditions .This program also allows the user to organise and achieve a time based data log which can then be saved in a USB memory stick. The path for the storage device where the data files will be logged can be changed.

The Fig 6.8 presents the program which has been developed to simulate the various conditions of the microgrid and create a data log.

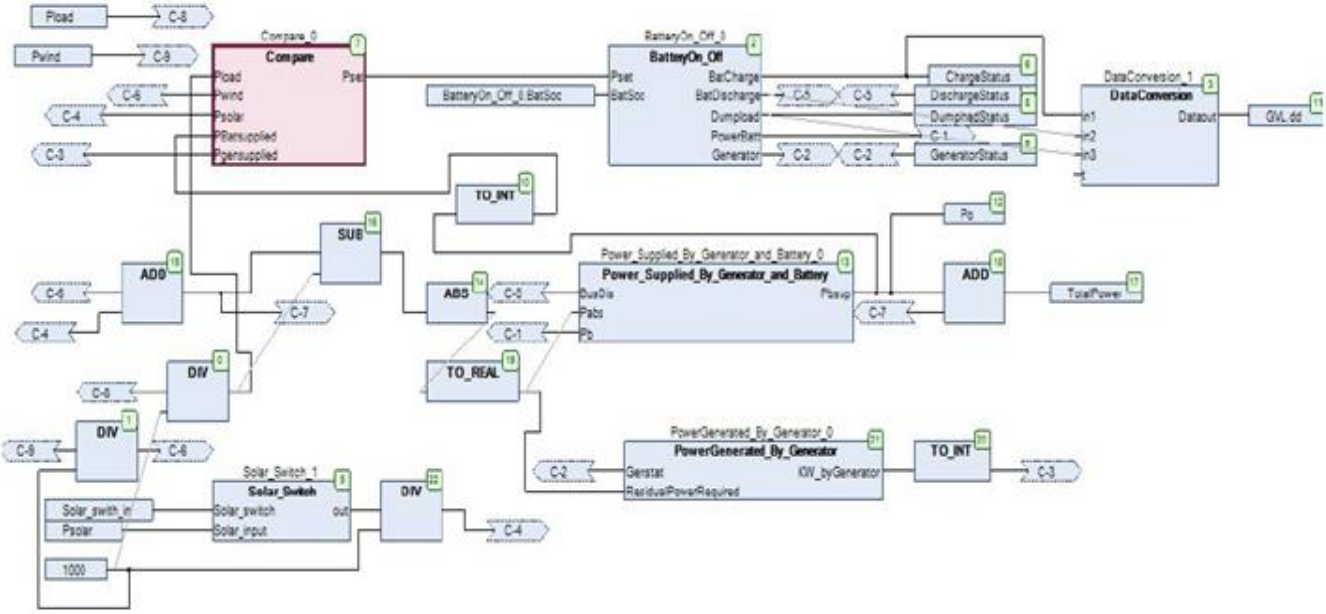


Fig 6.8 CODESYS program to simulate microgrid

6.3.2 Simulation Process

The emView-7RPI3P system module is presented in Fig 6.9

Fig 6.9 The emView-7RPI3P system module

- Day/Night Switch: Allows you to simulate day and night conditions. When it is in ON position the solar data is considered and when it is in OFF position the solar data is not considered

- IOX On/Off: This switch controls the IO module (STW IOX) which gives the analog signal generated by Solar, wind and Load. IOX Note: Switch must remain on during operation of this device

- Solar, Wind and Load: Rotating these knobs will generate analog signals of respective labels. Rotation is in counterclockwise direction (Max output 16 MW, this output is scalable through codesys interface)

- Solar knob will generate signal Irrespective of Solar Switch being on or off. But the output is excluded from calculations.

When booting the device for the first time, the first step would be to turn the power on after connecting the appropriate connector to the power outlet. The overall Codesys program is show in Fig 6.8 The scaling of signals can be done using Compare function (double click the blocks to open) .The declaration of new variable can be done as:

Ploadnew:=Pload*0.20 and then using Ploadnew in IF loop instead of Pload. All other variables such as Psolar, Pwind, can be scaled following the similar process.

The Data conversion block creates the string of data for analysis and sends it to a data logging program. Codesys can only store strings which must be in one row. This can be done by using CONCAT in codesys. One need to remember CONCAT only combines two strings, therefore, to combine more strings one needs to use CONCAT multiple times. It is also important to ensure to include space before declaring strings example: ‘ batteryStatus’ . If space is not added the two strings will come right after each other. It will make it look like loadstatusbatterystatus. When space is inclused, the string will look like loadstatus batterystatus. Additional Blocks are for analysis and can be used to calculate the power generation by Generator and Battery.

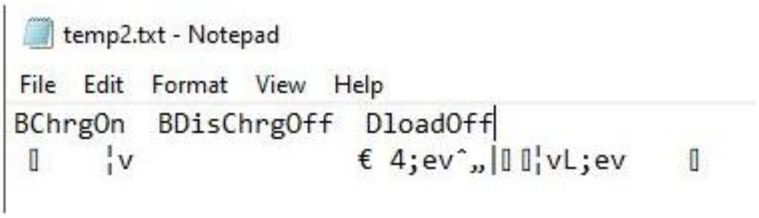
The Fig 6.10 represents the display of the system simulation under a specific load – generation condition.

Fig.6.10 The emView-7RPI3P system moduleunder operating condition

The Working module under a specific condition is presented in Fig 6.10. The lights indicate the status of different operations. Using this model various load demand conditions can be generated and monitored.

The switch is for logging purposes. The battery SOC is displayed as a number which is in percentage.

Using this module different load generation scenario can be simulated and analysed. The Function FILEMANAGER is used for data logging. When viewed in PI the output would be clear. This function can be used to explore more options in terms of data logging. At this stage the data is overwritten again and again. To append the data the same function can be used. This required more analysis and the codesys resources can be used for the implementation of this feature. Below shows the output from data logging:



```
BChrgOn  BDisChrgOff  DloadOff
 ▯    ¦v              € 4;evˆ„|▯ ▯¦vL;ev    ▯
```

Fig 6.11 Data logging output

Following are the steps to Configure or to make changes to PI and Connect with Codesys:

- ➢ Switch off the module and remove the power plug from the outlet.

- ➢ Open four screws from front panel

- ➢ Check if all the wires are properly connected.

- ➢ In case any wire is not connected, close the panel and contact CAN Automotion at (03) 9568 4432. Note: Do not connect the wire or power the device on. It may damage the PI and IO module

- ➢ If all wires are connected, connect one end of ethernet cable to pi and the other end to your laptop.

- ➢ Close the panel as best as you can, make sure it stays on top of the metallic box.

- ➢ Install codesys from Codesys Website after creating an account. Install the version 3.5.14.30 or lower. Note: Raspberry PI will not connect and work with the new version. To ensure hardware- software compatibility it is recommended that you must use the specified version or older version.

- ➢ Once connected open the program and make changes, accordingly, build and log in to upload it to Raspberry PI.

6.4. Simulation results

The system was simulated to analyse its performance under various supply demand conditions. It can be clearly observed from the system performance that the system is successfully delivering the desired results.

Condition 1

When the total generation from solar and wind generators is more than the load demand:

When the total generation from the renewable sources including solar and wind are more than the load demand of the community, under this condition the battery state of charge is less than the maximum state of charge and there is excess generation. Hence this excess generation is being used to charge the battery. Hence it can be observed that the under this condition the battery is charging. Fig 6.12 shows the system performance under the conditions

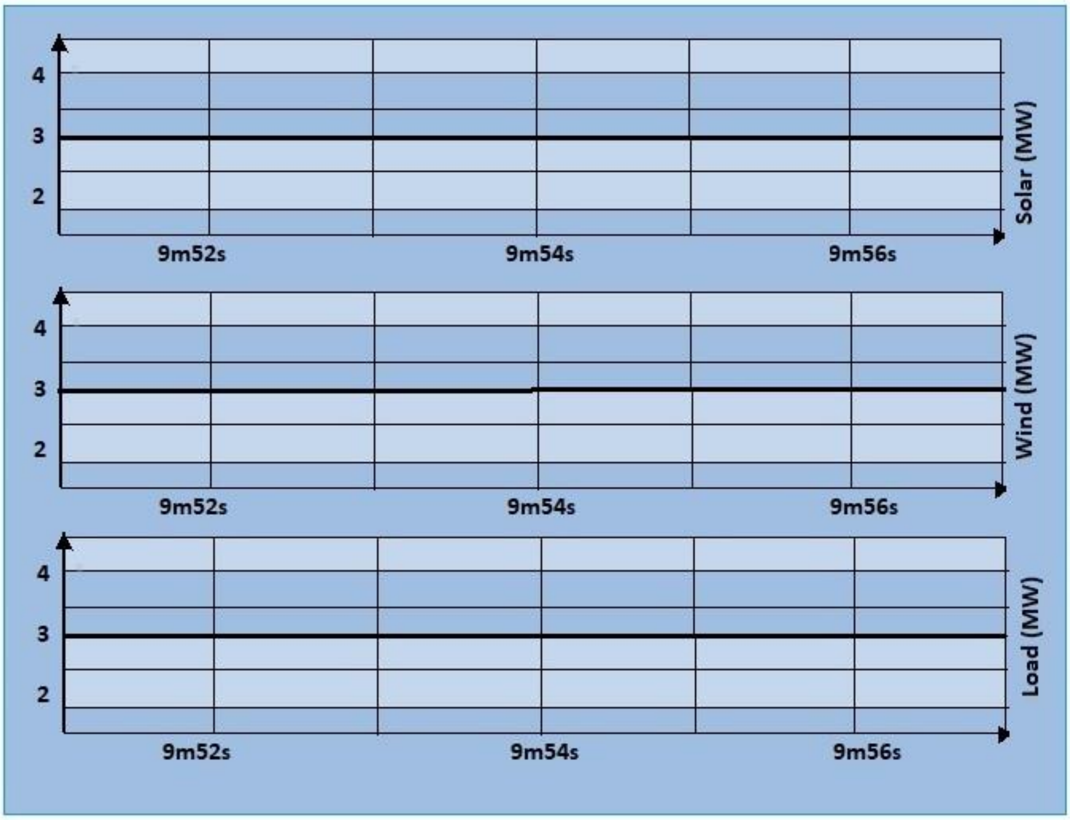


Fig. 6.12 System performance when load is less than generation

Condition 2

When the total generation from solar and wind generators are less than load demand

When the total generation from the renewable sources including solar and wind are less than the load demand of the community, at this stage the battery starts discharging to supply the additional load demand. Hence it can be clearly seen on the unit that the battery is discharging. Fig 6.13 represents the system performance under these conditions.

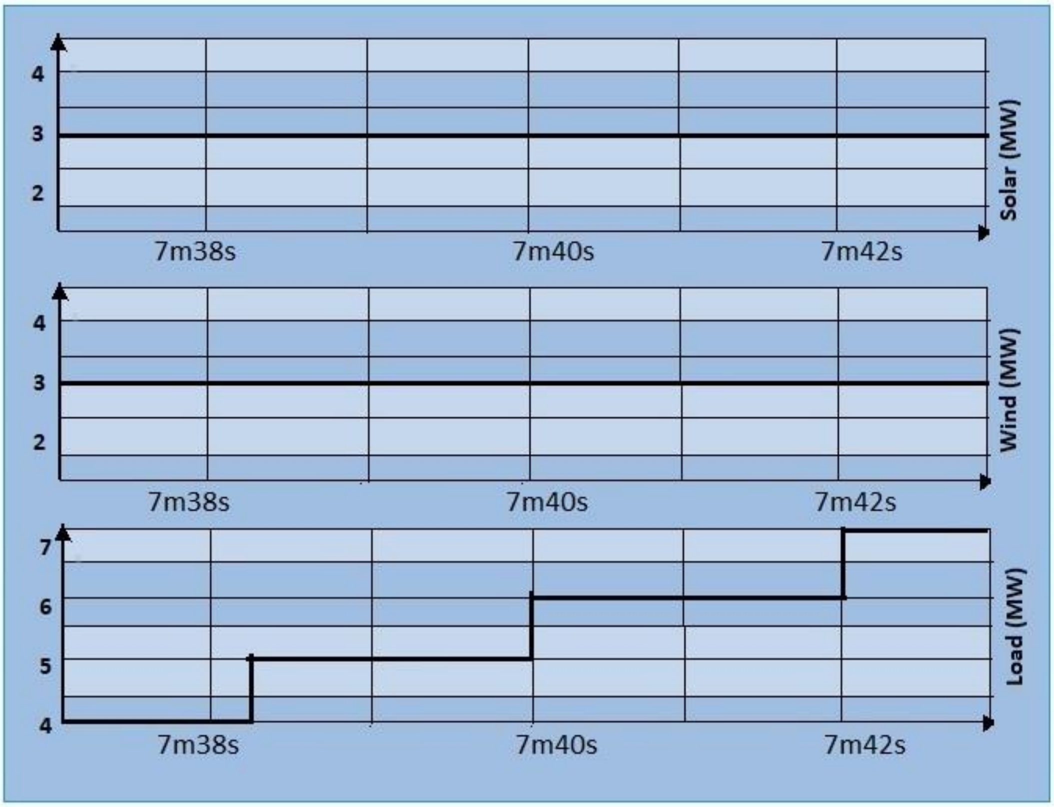


Fig 6.13 system performance when load is higher than supply

Condition 3

When the total generation from solar and wind generators are less than the load demand also the battery state of charge has reached the minimum state of charge.

Under some situations situation can arise when the total generation from the renewable sources including solar and wind are less than the load demand of the community and the battery bank has reached its minimum SOC. At this stage, the battery cannot supply the load demand anymore. Hence the battery stops discharging and the generators gets started and starts catering the load demand. System performance under this condition is shown in Fig 6.14

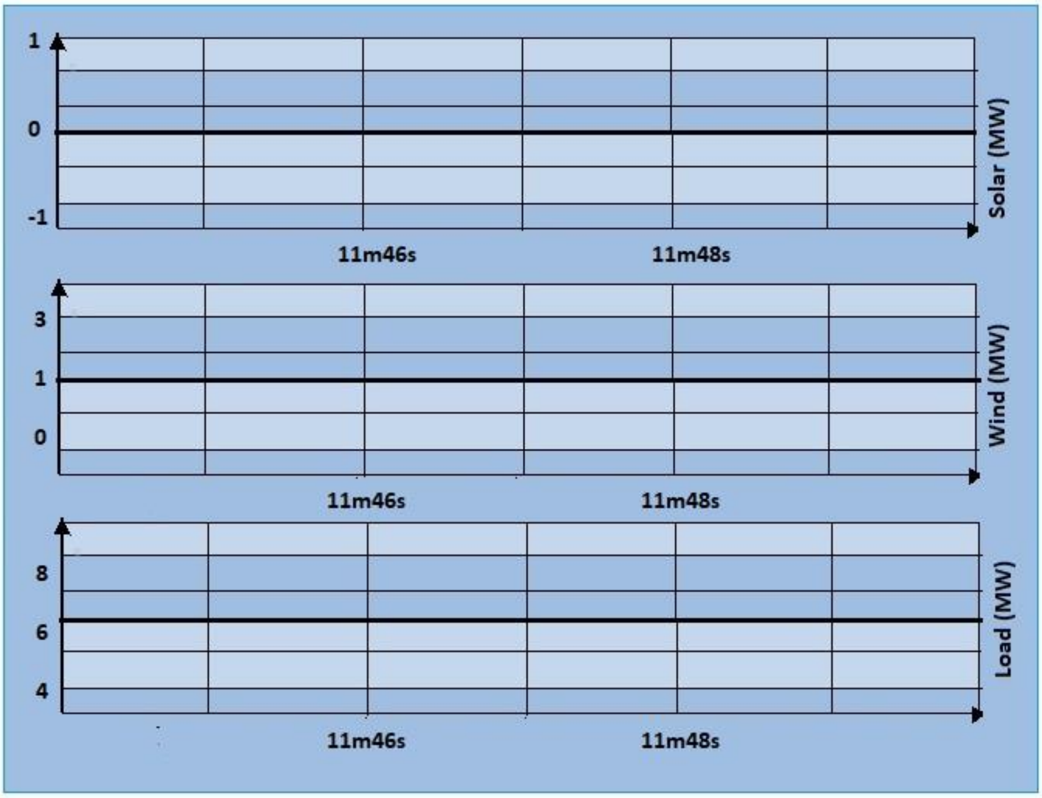


Fig 6.14 System performance when load demand is more than generation and battery reaches minimum state of charge

6.5 Summary

A simple hardware model of the complex system designed in this project was implemented using Raspberry Pi and CoDeSys. This Raspberry Pi 3B+ based emView product with 7" display with CoDeSys SL provided the user the opportunity to develop a full-fledged application to simulate a complete micro grid system with multiple sources of energy and also a storage battery to accumulate the charge which allows the flexibility to charge or draw off depending on the nature of demand and day/night and load cycles. This system was just designed as a prototype of the main system. The system was simulated under various load supply demand to check the performance. This enables one to monitor the supply demand conditions under one display which is very user friendly.

CONCLUSION AND SCOPE OF FURTHER RESEARCH

CHAPTER

7

Chapter 7. Conclusion and scope of Further Research

7.0 Introduction

Community power has huge potential in future to replace conventional sources as it reduces fossil fuel usage and reduces environment pollution and empowers the community. This kind framework can be particularly gainful for distant regions where network expansion will be extravagant and where there is the accessibility of space for introducing this sort of frameworks. They would be extremely simple to keep up with, as it would be completely computerized and can be monitored and controlled online. As, the proposed framework will be ideally planned in term of the size of fuel sources, it would make some one-time capital/foundation cost. After the recompense period, the establishment cost of energy of this framework diminishes altogether. Around then the local area individuals will pay less sum for their energy utilization. However, before designing this kind of systems, it is important to analyse the financial aspects of setting up this kind of projects.

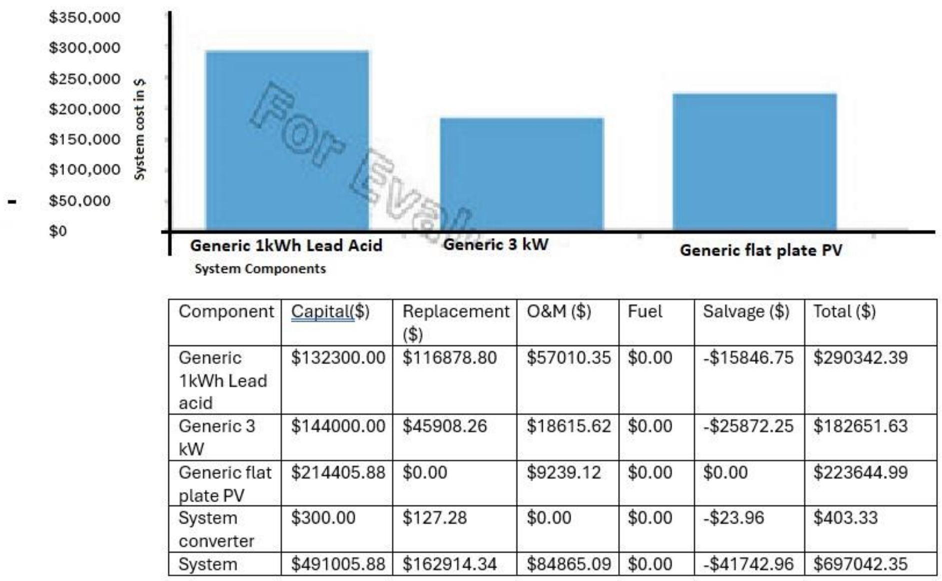
7.1 Financial aspects of the selected system

The system selected for this study which has been optimized using HOMER for the community under consideration for the specified load profile for the targeted location. The lifetime of the system is considered 25 years. As discussed previously, the system configuration can be presented in Table 7 .1

Table 7.1 Selected system configuration

Capacity Shortage (%)	Electrical load scaled Average.	Solar Scaled Average (kWh/m^2/day)	Wind Scaled Average (m/s)	PV(kW)	G3	1kWhLA	Converter (kW)	CoE ($)	NPC ($)	Operating Cost ($)
0.1	130	4	5.8	71.5	8	441	25	1.14	697,042	15,938

Fig 7.1 represents the cost summary of the selected system. The Net Present Cost of the optimum system selected is $697,042. The Cost of Energy (COE) is $1.14 HOMER broke that total cost down and Fig 7.1 showing individual costs of the components and their contribution to the total cost. which is however higher than the normal grid electricity charge which is around 26.4740 cents per unit for residential customers. However, there are huge benefits of this community power projects. One needs to remember the positive impact of the green energy on the environment, and the limitation of fossil fuel resources and their significant impact on the environment. Also, this HRES allows the community to go off grid completely, allows the community involvement on its own power generation. This kind of project increases the awareness about community members and increases the job prospects for technicians and community members. So, it is hugely beneficial for the community even though it is costing more for per unit of energy.



Component	Capital($)	Replacement ($)	O&M ($)	Fuel	Salvage ($)	Total ($)
Generic 1kWh Lead acid	$132300.00	$116878.80	$57010.35	$0.00	-$15846.75	$290342.39
Generic 3 kW	$144000.00	$45908.26	$18615.62	$0.00	-$25872.25	$182651.63
Generic flat plate PV	$214405.88	$0.00	$9239.12	$0.00	$0.00	$223644.99
System converter	$300.00	$127.28	$0.00	$0.00	-$23.96	$403.33
System	$491005.88	$162914.34	$84865.09	$0.00	-$41742.96	$697042.35

Fig 7.1 Cost summary of the selected system

The cash flow of the system in 25 years is presented in Fig 7.2. Monthly average electric production by component is presented in Fig 7.3.

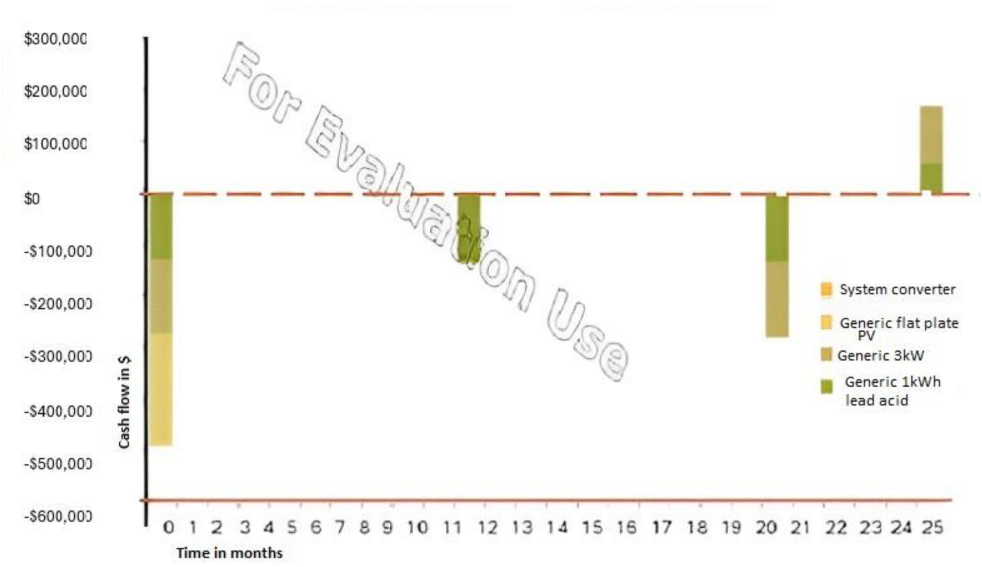


Fig 7.2 Cash flow of the system in 25 years

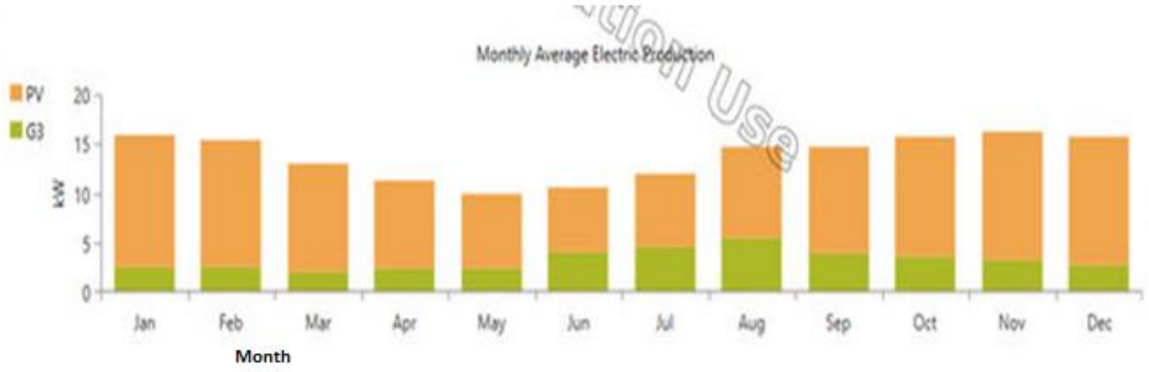


Fig 7.3 Monthly average electric production by component

Even though the cost of electricity obtained from the projected system is more than the cost of grid electricity but keeping in mind the obligation of environmental protection and keeping in mind the present living standard of rural communities these kind of standalone hybrid renewable systems will play a crucial role specifically for the remote sites and islands.

7.2 Scope of further work

Standalone community power is relatively new concept in Australia. This kind of systems can be beneficial for remote communities where extension of grid power can be significantly high. This project works with a small community prototype located in Portland, Victoria. This project streamlines the numerous steps that needs to be undertaken to achieve the design. It investigates numerous techniques presented in literature in current situation, for example, it investigated most recent optimisations tools and techniques presented in section 5. It used AI techniques to design the controller to achieve a smooth and reliable control action. This work can be used as a handbook to develop this kind of situation based on currently available techniques. Although, this work has some limitations. Due to unavailability of data this project uses a data prototype in section 6.1.3. To design the system to be more accurate and precise it's important to obtain accurate usage data of the targeted community.

However, there are scope for further work based on the basic framework presented in this study. They can be summarised as below:

i. Renewable energy related technologies are evolving rapidly. New techniques methodologies tools are being investigated and added to the list. For example, new techniques most likely to get added by researchers for optimizing the sizes of the components of the renewable energy systems. New techniques can be incorporated for controlling the power management in future with development of technology and so on. In future while designing this kind of systems there might be scopes for investigating most recent studies and techniques and incorporating them into the design.

ii. There is huge scope of designing the overall control mechanism. This study designs the system such a way that the excess generation from each household gets stored into central battery bank. Further work can include designing another controller in between each household and the central battery bank which might be able to share the excess energy between the households directly at the first place in case there is excess demand in one household and there is excess generation in one. After catering neighbour if there is any excess that can be stored in central battery bank. This is going to be a complex network and beyond the scope of this project. Hence a further development work can be done on this area to take this work to next level.

iii. This work uses Fuzzy logic techniques to design the central controller. There might be other new evolving technologies in coming days which can achieve the similar kind of results in more efficient way. Basically, this work can be taken as a framework and further development can be done incorporating new available technologies in all areas investigated here.

iv. There is a huge scope of developing this using hardware in different manner. This project uses Raspberry pi as a controller for the system prototype. Different other available hardware can be incorporated to achieve similar results. This work used a simple prototype of the system considering a centralised system in terms of load and sources, further work can be done using distributed sources which will be a complex system and itself can be a big project.

v. This project includes solar wind energies however there are possibilities of inclusion of other renewable sources while designing these kinds of systems. For example, biomass or micro hydro. However, inclusion of any renewable source depends on the energy requirement and availability of resources, hence based on the targeted location one can consider including these sources.

vi. Further study can include the study of using different types of wind turbine based on the targeted location. For example, vertical axis wind turbines are more advantageous over floating wind turbines in gusty win situations. Hence further study might be extended to find best suitable wind turbine for the targeted location based on feasibility study budget etc.

vii. Current project includes a dump load where the excess generation can be sent. However, there might be many efficient ways to use this excess generation. Further study can include the study of renewable curtailment to reduce the loss of power generation during peak hours.

7.3 Summary

This project represents a methodology for designing the control mechanism for a community owned standalone hybrid renewable energy system that can cater the load demand of the community without taking any power from the grid. Every important aspect of the design methodology which needs to be undertaken for designing a standalone hybrid renewable energy system have been discussed this this project. This includes feasibility study, optimum sizing of the system components and design of the control mechanism. This study also involves designing s prototype of the system using hardware. A Standalone HRES been designed to cater the need of a small community based in Portland Victoria. The size of the system components were selected by optimising keeping in mind the cost of the components and power reliability criteria. Control mechanism been developed using AI techniques to make sure that the system can efficiently cater the power need of the community by taking proper control action by charging / discharging the in house and central battery bank, switching on the diesel generator when needed and send the excess power to the dump load when all batteries reach maximum SOC. A smooth operation been obtained by using FLC. Control mechanism been developed using CSA to harvest maximum power from the wind turbine. A hardware model been developed that presents a system prototype and achieve the desired control action in hardware environment. A financial study also been done to understand the financial aspects of the design.

By doing this this project works like a baseline guidebook to design an similar kind of system by bringing all basic technologies required to design similar systems under one roof .

Community power is a new concept in Australia, specially not work has not been reported in literature on designing the standalone community power system. Due to depletion of natural resources and their significant environmental impact, these kinds of systems have huge future potential to e alternative energy sources for communities. The best part of this project is it brings most of the steppingstones of designing this kind of systems under one umbrella. This can be used as a guidebook for designing any community owned standalone hybrid renewable energy system as the design methodology is quite generic. Only varying the load demand, weather data and few more location and resources specific information this project can be used for any location and load demand for designing similar kind of systems.

The proposed venture can fundamentally influence the climate and networks. As referenced before, not much review has been accounted for in the writing on community power sharing networks. The planned framework would have the option to supply the load demand of a local area with least interference without being dependant on grid power. This sort of frameworks would be progressively famous in coming days which will diminish the non-renewable energy source use, lessening contamination and creation of greenhouse gasses advancing a cleaner climate. Then again, expanding prominence of these frameworks will make more job positions in power industry for the community members and contributing a lift in the neighbourhood economy.

Hence it can be said that this kind of system would be increasingly popular in future as it can be a powerful replacement of conventional fossil fuel-based energy sources. Not only that it will empower the local communities providing the options for being responsible for their own power generation.

APPENDIX

A.1 Modelling of an optimum fuzzy logic
controller using genetic algorithm.
A.2 Short term load forecasting using Fuzzy Logic

Appendix

During this research work, additional study has been conducted to the related fields. Once of the research explores other Artificial Intelligence techniques to optimize the Fuzzy Logic controllers. This research represents an optimization technique of a fuzzy logic controller using Genetic Algorithm (GA) to control the liquid level of a tank. This study uses the Fuzzy Logic model developed by Takagi-Sugeno (T-S). The parameters of T-S type FLC have been optimized within a defined range using GA.
The other research work presents a fuzzy logic model for short-term (hourly) load forecasting. These two-research works are presented in following sections.

A.1 Modelling of an optimum Fuzzy Logic Controller using Genetic Algorithm

A.1.1 Abstract

Due it’s linguistic based structure and robust performance for nonlinear systems Fuzzy Logic Control has become a popular control technique. By articulating the heuristic knowledge and by using a "trial and error" approach for fine-tuning it is possible to design a Fuzzy Logic Controller (FLC) for many real-life problems. However sometimes becomes a tedious task to tune the parameters to achieve desired performance as the FLC includes a large number of parameters that need to be tuned. Numerous advanced optimization techniques have been presented in the literature to overcome this problem. This research work presents a optimization technique of a FLC using Genetic Algorithm (GA) to control the liquid level of a tank. A Fuzzy Logic model presented by Takagi – Sugeno (T-S) has been used in this study. The parameters of a T-S type FLC have been optimized using GA within a specified range.

A.1.2 Introduction

For many recent control applications, Fuzzy Logic is emerging as active research area. For the control applications where any specific mathematical model is not available clarifying the relationship between the input and output variables, Fuzzy Logic can be a very powerful reasoning method [163]. On the other hand, in recent days the T – S Fuzzy modelling technique is emerging as a powerful engineering tool helping researchers to model and study the control actions of many complex nonlinear systems [164]. T-S type Fuzzy models are the dynamic Fuzzy models or Fuzzy systems that can help researchers to create a linear representation of a non-liner system and can be described by Fuzzy if – then rules [165]. AS the T-S model employs the linear model of a nonlinear system, it allows the application of the conventional linear system theories to the system which makes the system analysis and synthesis easy. The study of the T-S Fuzzy model from data is based on the concept of consecutive structure and parameter identification [164].

When the numbers of system input and output variables of a FLC increases, the tuning process becomes more tedious and complicated. Researchers have studied numerous evolutionary algorithms for tuning the FLC by tuning the membership functions [166]. Genetic Algorithm [GA] is a very powerful and efficient technique that can be used to optimally tune the parameters of the FLC [167]. GA is a systematic optimization technique inspired by the principle of biological evolution. GA manipulates the coding that represents a parameter set to achieve a near optimal solution [168].

A.1.3 Takagi- Sugeno type fuzzy logic controller

As mentioned before, T- S Fuzzy model which is described by the Fuzzy IF-THEN rules can provide a local linear illustration of a nonlinear system by disintegrating the input space into numerous fractional Fuzzy spaces and by presenting each output space with a linear equation [164].T-S type FLC model has the ability to approximate a wide range of nonlinear systems.

T-S model is comprising of a set of IF-THEN rules. The rule premises can be expressed by Fuzzy sets and rule consequents can be expressed as linear functions of input variables. Hence, the model can be formulated as follows [169]:

R_i : **If** x_i is A_{i1} **and** . . . x_n is A_{in} **then**
$g_i = p_{i1} x_1 + \ldots\ldots p_{in} x_n + p_{i(n+1)}$, $i=1,\ldots.M$, (A.1.1)

where $x = [x_1, \ldots\ldots\ldots\ldots x_n]^T$ is the vector of input variables, g_i the output variable, R_i i-th fuzzy rule,

$A_{i1},\ldots A_{in}$ are Fuzzy sets which are defined in the premise space by the membership functions $\mu_{Aij}(x_j)$ and p_{i1} . . . , $p_{i(n+1)}$ and subsequent parameters. The output variable y of the model can be presented as a weighted mean of the individual Fuzzy rule contributions.

$$y = \frac{\sum_{i=1}^{M} \beta_i g_i}{\sum_{i=1}^{M} \beta_i}, \qquad \text{(A.1.2)}$$

where β*i* represents the degree of fulfilment of the *i*-th rule:

$$\beta_i = \prod_{j=1}^{n} A_{ij}(x_j),\ i = 1, \ldots, M, \qquad \text{(A.1.3)}$$

where *Aij*(*xj*) represents the membership of input variable *xj* in the fuzzy set *Aij* .

Commonly, the selections process of fuzzy rules and premise inputs and subsequent parameters is based on trial and error method or based on the usage of some clustering methods. In the discussed work, the subsequent parameters of a T-S type FLC, p_{i1} . . . , $p_{i(n+1)}$ are optimized using GA to control the liquid level of a tank [170].

A.1.4 Genetic Algorithm

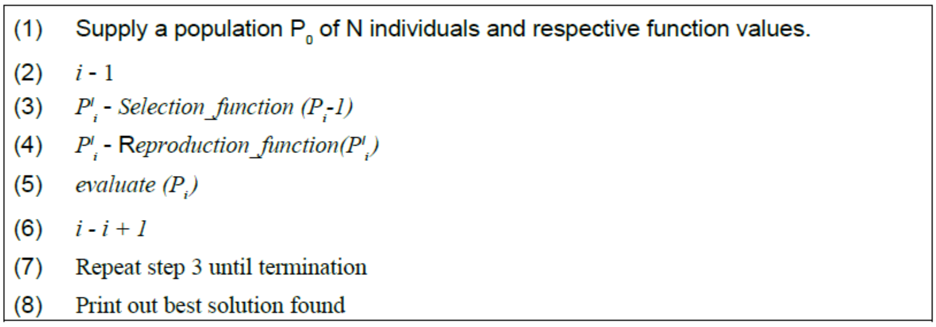
Genetic Algorithm (GA) is a search algorithm that is inspired by the mechanism of natural selection and natural genetics [171]. GA incorporates the principle of survival of the fittest among the string structures following an organized yet randomised information exchange to construct the search algorithm.

GA explores the solution space of a function by using the simulated evolution, for example, the strategy of the survival of the fittest. Generally, the individuals of any population which are the fittest will tend to reproduce and would survive to the next generation. This ensures the improvement of the successive generations [172].

Genetic Algorithm was developed by Holland [172] to create a simulation model of the natural evolution process which operates on the chromosomes [167]. Genetic Algorithm can provide reasonably acceptable solutions in many practical optimization problems. The strength of Genetic Algorithm is its robustness. In engineering processes, the artificial systems are expected to be more robust as this helps to reduce or eliminate costly redesign process. When higher adoption level achieved, the designed system performs longer and better.

GA consists of three basic operators: 1. Reproduction 2. Crossing over, 3. Mutation

GA can be represented as in Fig A.1.1 as a summery



```
(1)   Supply a population $P_0$ of N individuals and respective function values.
(2)   $i - 1$
(3)   $P'_i$ - Selection_function ($P_i$-1)
(4)   $P'_i$ - Reproduction_function($P'_i$)
(5)   evaluate ($P_i$)
(6)   $i - i + 1$
(7)   Repeat step 3 until termination
(8)   Print out best solution found
```

Fig A.1.1 GA optimization algorithm

A.1.5 Modelling of liquid level system

The present work considers the liquid level system presented in in Fig A.1.2 [173]. The considered system has one inflow and one outflow. The aim of this research is to design a heuristic Fuzzy Logic Controller which would be capable of maintaining the liquid level of the tank to a specified set point. Current work assumes that the level of liquid would be controlled by controlling the input inlet valve only.

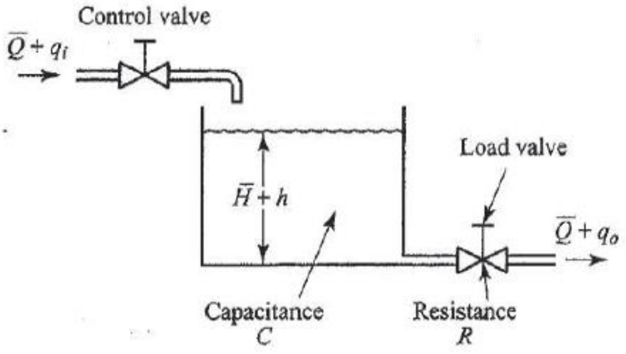


Fig A.1.2 liquid level system [173]

The system variables considered can be defined as follows [170][174]:

- *Qin*: Represents the rate of flow of liquid into the tank at time t, *m*3/sec.
- *Qout* : Represents the rate of flow of liquid out of the tank at time t, *m*3/sec.
- q_i: Represents the small deviation of inflow rate from its steady-state value, *m*3/sec.
- q_o: Represents the small deviation of outflow rate from its steady-state value, *m*3/sec.
- H : Represents the steady state height, m.
- h: Represents the small deviation of head from its steady-state value, m.
- R: Represents the resistance for the liquid flow out, sec/*m*2.
- A: Represents the cross-sectional area, *m*2.

In the current work, the angular position of the valve is assumed to be equal to the rate of flow in liquid, which means that before any change occurs, the ratio between the steady state flow rate and the flow in the liquid is equal to one. This study considers the flow rate as turbulent, not laminar flow rate. Henceforth the resistance for the liquid flow R is considered as *Rt*.

$$Q=k\times \sqrt{H} \tag{A.1.4}$$

Where K is a constant. For turbulent flow, the resistance *Rt* can be obtained as:

$$R_t = \frac{dH}{dQ} \tag{A.1.5}$$

From equation (A.1.4) one can derive:

$$dQ = \frac{k}{2\sqrt{H}}dH \tag{A.1.6}$$

$$\frac{\mathrm{dH}}{\mathrm{dQ}} = \frac{2\sqrt{\mathrm{H}}}{\mathrm{k}} = \frac{2\sqrt{\mathrm{H}}\sqrt{\mathrm{H}}}{\mathrm{Q}} = \frac{2\mathrm{H}}{\mathrm{Q}} \qquad \text{(A.1.7)}$$

As $R_t = \frac{2H}{Q}$

The turbulent flow Rt is dependent on the rate of flow and the head. The relationship between Q and H can be expressed as follows using the turbulent flow resistance:

$$\mathrm{Q} = \frac{2\mathrm{H}}{\mathrm{Rt}} \qquad \text{(A.1.8)}$$

During a small time interval *dt,* the difference between the inflow and the outflow, would be the amount of additional amount stored in the tank. This can be expressed as:

$$\mathrm{Adt} = (q_i - q_o)\ \mathrm{dt} \qquad \text{(A.1.9)}$$

As per the definition of resistance, the relationship between q_o and h can be represented as:

$$q_o = \frac{h}{R} \qquad \text{(A.1.10)}$$

for a constant value of R, the differential equation for this system can be presented as

$$\mathrm{RC}\frac{\mathrm{dh}}{\mathrm{dt}} + \mathrm{h} = \mathrm{R}q_i \qquad \text{(A.1.11)}$$

RC represents systems time constant. Laplace transforms of both sides of equation (A.1.11) assuming zero initial condition leads to:

$$(\mathrm{RCs} + 1)\ \mathrm{H(s)} = \mathrm{R}Q_i\mathrm{(s)} \qquad \text{(A.1.12)}$$

Where $H(s) = L[h(t)]$ and $Qi(s) = L[qi(t)]$

The transfer function can be represented as follows considering *Qi* as input and H as output,

$$\frac{H(s)}{Qi(s)} = \frac{R}{RCs+1} \qquad \text{(A.1.13)}$$

Considering H=1m, k=1 and $C = 0{:}5m2$

$$R = \frac{2H}{Q} \qquad (A.1.14)$$

$$Q = K\sqrt{H} = 1 \ and \ R = \frac{2H}{k\sqrt{H}} = 2$$

Henceforth the transfer function can be expressed as:

$$\frac{H(s)}{Q(s)} = \frac{2}{s+1} \qquad (A.1.15)$$

A.1.6 Fuzzy Logic Controller design

The suggested T-S type FLC has been implemented using MATLAB/ SIMULINK environment. The block diagram of the control system considered is presented in Fig A.1.3. The designed FLC has two input variables. One is e(t) which is the error signal representing the difference between the reference value and the process value. The other input variable is differential of *e(t)* presented as $\frac{de(t)}{dt}$. The output of the FLC is a control signal to control the actuator [175]. For input variables of the FLC, the built in triangular shaped membership functions have used. Figs A.1.4-A.1.5 represents the membership function for the input variables.

The output variable has three constant parameters. Fig A.1.6 represents the surface of the FLC before optimization.

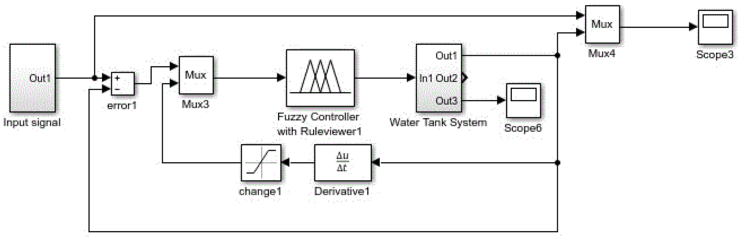


Fig. A.1.3 The SIMULINK block diagram of the liquid level control system

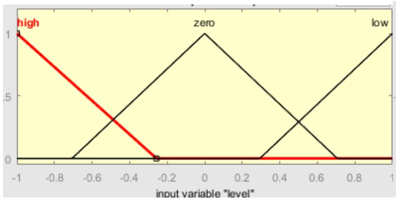


Fig A.1.4 Membership functions of the input variable ‘error’

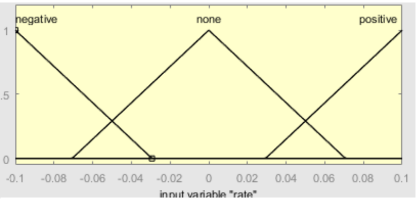


Fig A.1.5 Membership function of the input variable ‘rate’

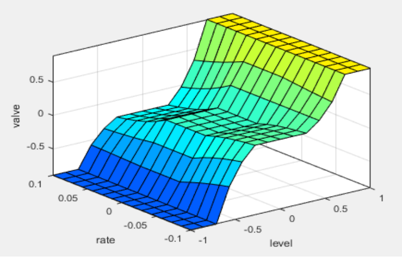


Fig. A.1.6 The control surface of the un-optimized FLC

The output of the FLC is applied to the actuator which controls the liquid level of the tank. Which in terms adjusts the flow of the liquid to achieve the desired level.

The FLC knowledge base has five rules. Using equations A.1.1- A.1.3 one can calculate the output of the T-S type FLC. The parameters of the T-S type FLC were optimized by using GA for a specified range. MATLAB programming has been used in the optimization process. Each rule of the FLC rule base uses 3 variables, hence for 5 rules there are total 15 variables. The MATLAB program optimizes all those 15 variables which are called the population using GA. To get the optimum results, this program continues until 200 generations. The fitness function or the evaluation function used in this study can be represented by Equation A.1.14 [175].

$$\text{Fitness} = \text{sse}\ (y - \hat{y}) + 100 \times \text{Overshoot} \qquad (\text{A.1.16})$$

In this equation ‘sse’ represents the sum squared error performance function, reference input is presented by y and the output of the Simulink model is presented by $\hat{y}$. The optimized values obtained for the parameters of the T-S type FLC are then incorporated in the controller to achieve the optimized controller for the system under investigation.

A.1.7 Simulation and results

The liquid level of the system with the un-optimized FLC against the reference input is represented in Fig A.1.7. Fig A.1.8 represents the output of the system using a conventional PID controller. The system output using optimized FLC against the reference input is presented in Fig A.1.9. Investigating the results from Figs A.1.7 -A.1.9 one can easily compare the performance of the three controllers. It is evident that the optimized FLC performs more accurately and acceptably compared to the other two controllers. Fig A.1.10 represents the control surface of the optimized FLC.

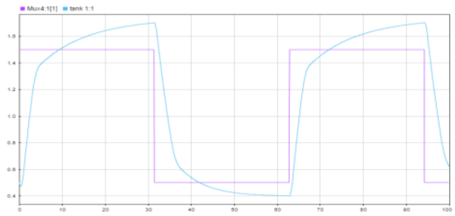


Fig A.1.7 Liquid level of the tank with un-optimized FLC ,Purple line represents the set input and the blue line shows the actual liquid level

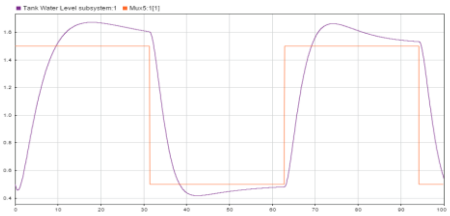


Fig A.1..8 Liquid level of the tank with PID controller. Orange line represents the set input and the purple line shows the actual liquid level

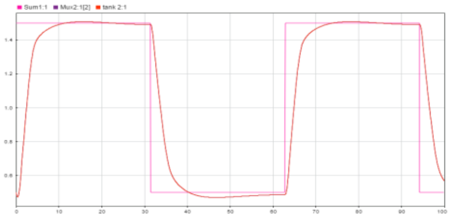


Fig A.1.9 Liquid level of the tank with optimized FLC

Pink line represents the set input and the red line shows the actual liquid level

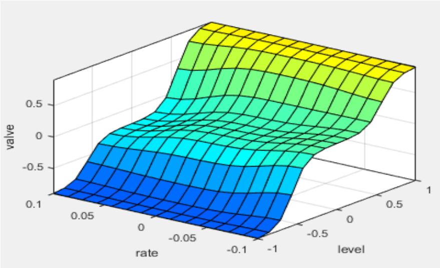


Fig. A.1.10 Control surface of the optimized FLC

A.1.8 Summary

An efficient and effective tuning methodology using Genetic Algorithm is presented in this study which is used to optimally used to tune a Takagi-Sugeno type Fuzzy Logic Controller to control the liquid level of a tank. The results clearly demonstrate that the optimized controller can show superior performance compared to unoptimized FLC or conventional PID controller. GA is capable of tuning the parameters of a Fuzzy Controller promptly with topmost level of accurateness.

A.2 Short term load forecasting using Fuzzy Logic

A.2.1 Abstract

Load forecasting is very important part of economic power generation. Load forecasting is also important factor for unit commitment scheduling or in other words for economic allocation between plants, scheduling a maintenance and also for ensuring the security of the system under peak load sharing conditions by interchanging power among the interconnected units. The current research presents a methodology of short term (hourly) load forecasting using Fuzzy Logic model. Historical load data has been used in this methodology. The historic data of load requirement of a specific time of the day has been used to design the Fuzzy rule base. The performance observed clearly shows that the Fuzzy Logic model can predict the short term load demand in an efficient manner minimising the error.

A.2.2 Introduction

Load forecasting is a very crucial part of power system operations. This is a vital part of the energy management system for the purpose of operation and planning. Load forecasting is a methodology used to predict the electric load demand. For the planning and operation of the electrical energy management systems, it is s fundamental and essential process [176]. There are two different categories of load forecasting. Long term and short term.

For the purpose of scheduling the regular maintenance of the generating units of planning future capacity requirements of the power system long term load forecasting is necessary. Long this also required for engaging into any arrangements with neighbouring utilities which might be having either excess or shortage of energy, for energy interchange etc.

However, short term load forecasting is needed for daily operation purpose of the plant, to cover shorter periods like a day or a week. This is important to select sufficient generating capacity to cater the forecasted demand and for sustaining the required spinning reserve. Spinning reserve represents the excess generating capacity of the committed generating units of actual loading. The conventional models for are mainly based on time series model or regression models [177]. The time series model generally uses the previous load data and predict the future load demand. However, these methods are very intricate, and it required a large amount of data to create a comprehensive system for load forecasting. The other popular modelling technique used for short term load forecasting is the regression model [178]. This methodology divides the database into smaller segments.

For each small section a regression model might be created, for example, for a specific season or day of the week. The advantage of this methodology is that the estimated parameters can be easily interpreted. However, this method has a major disadvantage that they need a significant amount of database that possibly includes obsolete historical data.

Fuzzy logic can provide an efficient alternative to conventional methods of short term load forecasting. Fuzzy logic is a great choice when there is no such mathematical expression is available between the historical data. Fuzzy logic can be integrated into expert systems or can be incorporated with Artificial Neural Network (ANN) to utilise both the expertise of the user and numerical data. However, one major drawback in the implementation and use of short term load forecasting model is the lack of user's confidence on the model [179]. The method of designing a model for short term load forecasting that captures non linear relationship between the input variables, for example, 'previous day's load', 'peak load', 'day', 'time'' etc and predicted load as output is very complex. It is more complicated to represent them in term of mathematical relationship. This does not provide any intuitive understanding to the user either. The use of Fuzzy logic can help the user to express this input output relationship as a logic table. Such as a representation of IF – THEN statements. For example, 'IF the Day is Weekend and Time is 1 THEN Load is Mf1'. This presentation gives more confidence to the user regarding usability of the model. Using expert knowledge these statements can be developed using a historical observation set. The present work converts historical load information such as 'Day' and 'Time' into 'Fuzzy' information. To produce a 'Fuzzy' forecast. Defuzzification is then performed to produce a point estimate of the system load. More accurate results have been achieved using this model compared to other complicated statistical models [177] [180].

This current work presents a method of hourly load forecasting using Fuzzy Logic. One year data from the large-scale power system has been used for load forecasting. In the proposed method, Fuzzy rules have been used to incorporate historical load data with time and date. In this study the term ‘Day’ is used to represent Weekend or Weekdays. The work aims to determine the probable load curve of a specific day utilising a year worth of data from large scale industry.

A.2.3 Fuzzy Logic methodology for short term load forecasting

A.2.3.A Fuzzification

Fuzzification is a process of converting the crisp numerical values into the degree of membership related to the corresponding Fuzzy sets. The crisp value is accepted by the Membership Function (MF) as its argument and then it returns the degree to which that value belongs to the fuzzy set which the MF represents. The current study arranges of fuzzy subsets for different input and output variables in a complete universe of disclosure as a membership function to express the fuzziness of the data. The benefit of Fuzzy Logic model is that it allows to express the values of input and outputs in natural language. As an example, a variable ‘Load’ can obtain a ‘Fuzzy’ value, such as ‘VVL’ that denotes ‘very very low’ or ‘VL’ for ‘Very low’. Fuzzy Logic Model can map the input variables to the output values by the use of simple IF – THEN logic statements.

A.2.3.B Fuzzy Rule-Base

The heart of Fuzzy model is the Fuzzy Rule Base. While designing the Fuzzy Rule Base the heuristic knowledge of an expert is stored in term of IF – THEN rules. To send the information to the Fuzzy Inference System (FIS), this rule base is used. FIS process this information through inference mechanism and numerically evaluates the information which is embedded in the Fuzzy Rule base to gain the output. Fuzzy Inference uses Fuzzy Logic and generates the mapping from a given input to an output. Then a basis is provided by the mapping from which one can make decisions or patterns can be discerned. An example of Fuzzy rule is : IF ‘Day’ is ‘Holiday’ and the ‘Time’ is ‘1am’ THEN the ‘Load’ is ‘Mf4’ which represents the configuration of Fuzzy Logic. The configuration of fuzzy logic in represented in Fig A.2.11.

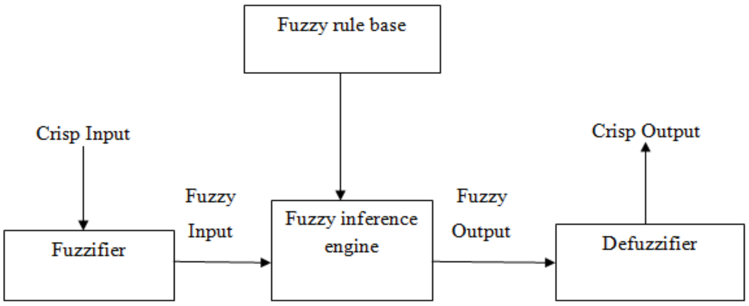


Fig A.2.11. Configuration of Fuzzy logic

A.2.4 Proposed methodology

By studying the data set one can observe that the load demand of a specific time, for example from 10 am -11 am of a day is dependent on certain factors. The load demand is dependent on the time the load is being forecasted, the maximum forecasted load of the day, whether the day the load forecasting being done is a weekend or weekday and also on historical load. From the data set it can be observed that in case of the holidays or weekend, the load demand of the day is more dependent on previous days load demand than the forecasted maximum load of the day. On the contrary, in case of weekdays, the load demand depends more on forecasted maximum load of the day than previous day's load demand. Fuzzy logic has been used in this study to incorporates all these factors that might affect the hourly load forecasting. To do these two Fuzzy Logic models have been developed and then by multiplying the outputs of those two Fuzzy Logic models. The schematic diagram of the model suggested using Fuzzy Logic is presented in Fig A.2.12.

As previously suggested, two Fuzzy Logic models that have been designed, the first model uses 'Time' and 'Day' as inputs. Where 'Day' means if it is a weekday or weekend or holiday. It is observed that load demand of a weekday or weekend follow dissimilar patterns. The membership functions of inputs 'Time' and 'day' are presented in the figs A.2.15 and A.2.14

It can be observed that the variable 'Day' has two membership functions. One is 'holid' that represents the holidays or weekends and the second membership function is 'weekday'. The variable 'Time' has 12 membership functions (mf1, mf2,….mf12). Figs. A.2.13- A.2.19 represents the membership functions of the designed Fuzzy Logic model.

Observing the test data 24 rules have been formulated. This has been done using the methodology suggested in [181] and [182] which have successfully generated forecasts. This Fuzzy model one can generate forecasted load that is dependant only on the day and time. However, these two inputs are insufficient as that would generate similar load profile for all weekdays of the year and also similar patterns for all weekends which is impractical. Load demand also depends on other factors.

Studying the test data, it can be observed that the hourly load depends on previous days load demand of the same time for which is load needs to be forecasted. Hourly load demand is also dependent on the maximum forecasted load of the day. From the maximum minimum temperature and previous day's peak load demand the peak or maximum load demand of the day can be forecasted [178]. Hence another Fuzzy Logic model has been developed to incorporate other two variables. The output generated from this Fuzzy Logic model is a factor that is dependent on previous days load and the forecasted maximum load of the day. The inputs to this Fuzzy Model are prevdload' that stands for the previous day load demand on the same time 'maxload' which represents the maximum forecasted load of the day and 'day' which represents if it is a weekend/Holiday or weekday. The output of the Fuzzy Logic Model is 'Factor'. All the membership functions discussed are presented below. As it is already discussed that as per the observations the weekend's load profile depends more on previous days load demand rather than that of weekdays and the weekday's load curve depends more on the peak forecasted load of the day. Hence, another input factor 'day' has been incorporated. In this current study, 89 rules have been formed based on the observation of the historical load profile get achieve more accurate predictions.

To forecast the hourly load profile for a day a set of test data is required. The first Fuzzy Model generates the value of the load and the second model generates a factor for each hour which is multiplied with the output generated by the first model. Multiplying the outputs from two Fuzzy models one can generate the forecasted load profile for 24 hrs. Further tuning to the Fuzzy Logic system can be done comparing the generated load profile with the test data set to achieve finer prediction. This can be achieved by modifying the shapes of the membership functions or rules or modifying both.

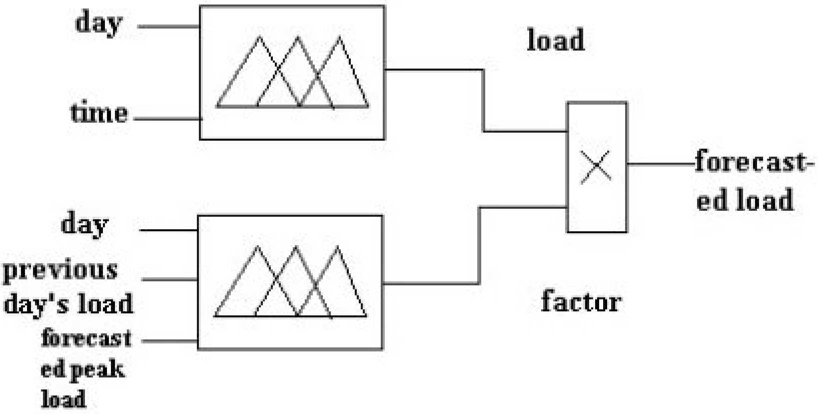


Fig. A.2.12 schematic diagram of the fuzzy logic model

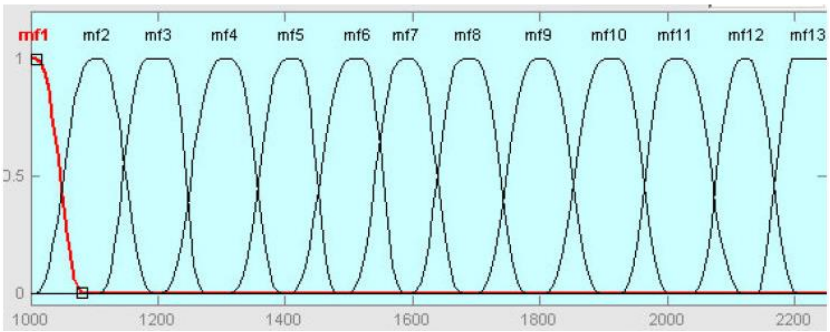


Fig A.2.13 Membership function of output of fuzzy logic model 1- ‘load’ (forecasted)

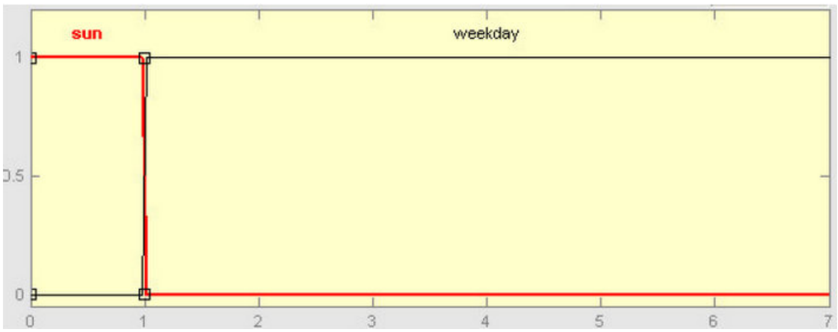


Fig A.2.14 Membership function of input of fuzzy logic model 1- ‘day’

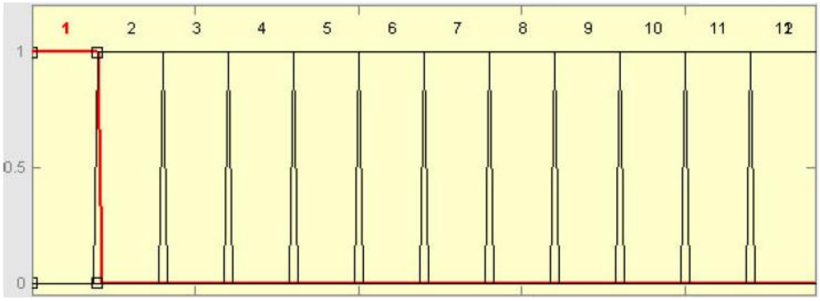


Fig A.2.15 Membership function of input of fuzzy logic model1 - 'time'

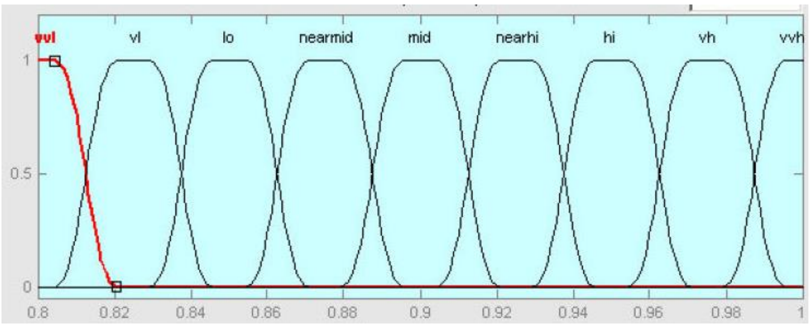


Fig A.2.16 Membership function of output of fuzzy logic model2 - 'factor'

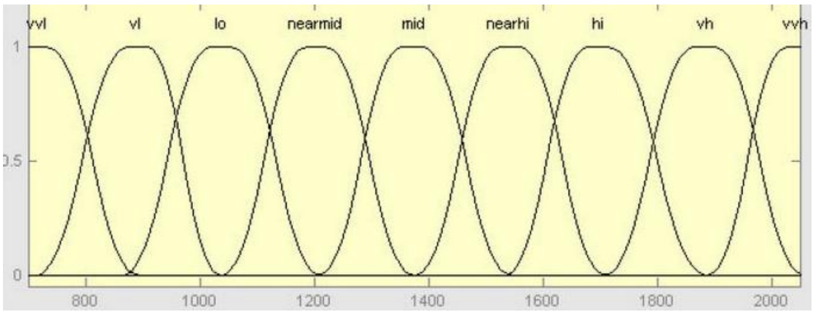


Fig A.2.17 Membership function of input of fuzzy logic model2 'prevdload'

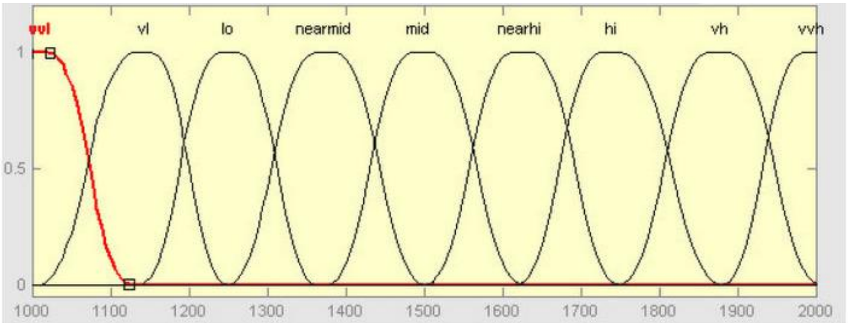


Fig A.2.18 Membership function of input of fuzzy logic model 2- ‘maxload’

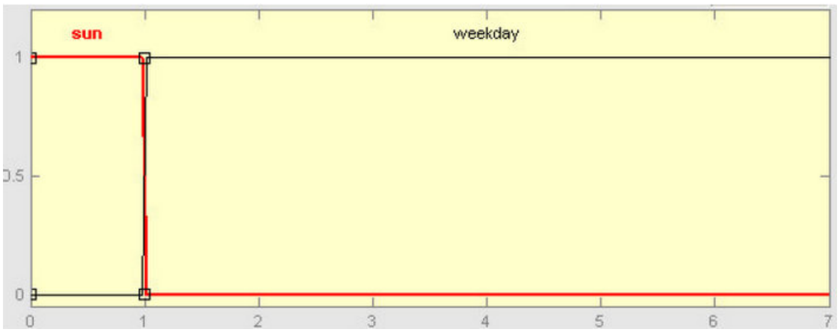


Fig A.2.19 Membership function of input of fuzzy logic model2- ‘day’

A.2.5 Simulation and results

MATLAB/SIMULINK environment has been used for simulation purpose. This study uses Fuzzy Logic Toolbox to create the Fuzzy Logic models discussed above. Figs A.2.20 -A.2.22 presents the actual load demand vs forecasted load demand for different days. These results clearly demonstrate that the designed Fuzzy Logic model can forecast the short term load demand satisfactorily. To study the performance of the Fuzzy Logic model, the mean absolute percentage error (MAPE) has been used in this study. MAPE can be defines as:

$$MAPE=\left(\frac{1}{N}\right)\sum_{i=1}^{N}\frac{|\text{forecasted load}-\text{actual load}|\times 100}{\text{actual load}} \qquad (A.2.16)$$

The load has been forecasted for each day for 24 hours. The results clearly demonstrates that the designed Fuzzy Logic model can forecast the daily load satisfactorily with permissible error.

N represents the total number of observations in the test data set. Table A.2.1 represents the MAPE and maximum percentage error for seven days.

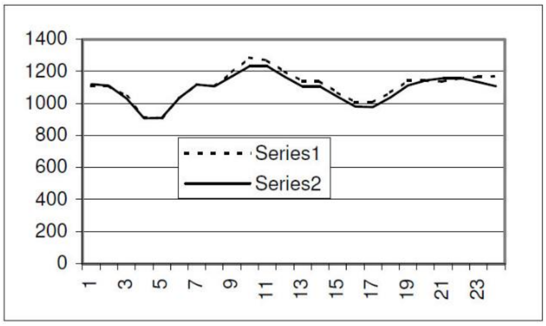


Fig A.2.20 Load curve of Sunday/Weekend – series1 represents actual load, series2 represents forecasted load

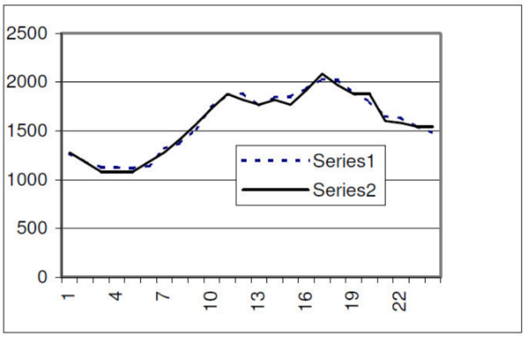


Fig A.2.21 Load curve of Monday –series1 represents actual load, series2 represents forecasted load

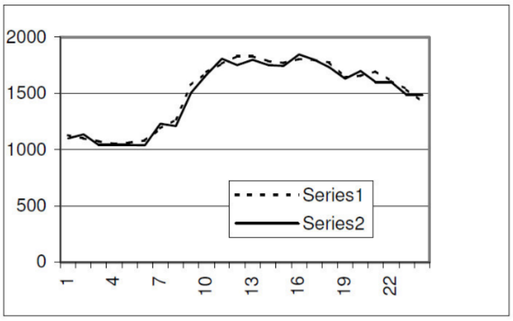
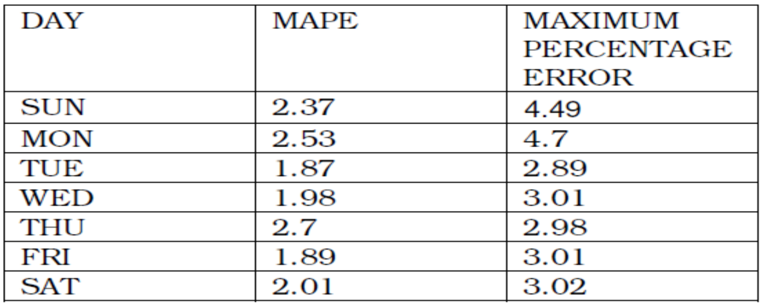


Fig A.2.22 Load curve of Tuesday – series 1 represents actual load, series 2 represents forecasted load

Table A.2.1 MAPE for seven days



DAY	MAPE	MAXIMUM PERCENTAGE ERROR
SUN	2.37	4.49
MON	2.53	4.7
TUE	1.87	2.89
WED	1.98	3.01
THU	2.7	2.98
FRI	1.89	3.01
SAT	2.01	3.02

A.2.6 Summary

The current study represents a short-term load forecasting model using Fuzzy Logic. The designed Fuzzy Logic model is capable if satisfactorily forecasting the short-term load demand for different day and time. However, one need to understand the limitation of the model. This model would not be able to predict any abrupt change in load demand. If due to some unpredictable reason the load demand changes for few hours, this model would not be able to follow that change and predict the load accordingly. Hence under that situation the model won't be able to forecast load demand within permissible error range. Apart from this constrain these model works satisfactorily.

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