# A STUDY OF SMART INTEGRATED RENEWABLE ENERGY SYSTEMS (SIRES)

By

ZEEL MAHESHWARI

Bachelor of Engineering
Visvesvaraya Technological University
Hubli, India
2011

Master of Science
Oklahoma State University
Stillwater, Oklahoma
2013

Submitted to the Faculty of the
Graduate College of
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
September, 2017

A STUDY OF SMART INTEGRATED RENEWABLE ENERGY SYSTEMS (SIRES)

Dissertation Approved:

Dr. R Ramakumar

Dissertation Advisor

Dr. Martin Hagan

Dr. Qi Cheng

Dr. Russ Rhinehart

ACKNOWLEDGMENTS

After an exhaustive period of 3 years, 8 months and 15 days, it boils down to this document: "Dissertation". Jotting down this note of gratitude is the finishing touch on my dissertation. It has been a span of intense learning experience for me, not only in the academic realm but also on a personal level. I would like to reflect on the people who have supported and assisted me throughout this phase.

I'm highly indebted to my advisor, Dr. R Ramakumar, for his invaluable guidance, patience and persistent help. Without his unconditional support and wholehearted care, this dissertation would not have been possible.

My deepest gratitude to my committee members, Dr. Martin Hagan, Dr. Russ Rhinehart and Dr. Qi Cheng for being a significant part of my advisory committee. Their brilliant comments and valuable suggestions have been extremely beneficial in the course of my research.

I also acknowledge OSU Energy Engineering laboratory and the PSO/Albrecht Naeter Professorship in the School of Electrical And Computer Engineering for providing financial support in the form of research assistantship.

I dedicate this dissertation and my degree to my family. My father, Mr. Ketan Maheshwari: he is my role model and a pillar of strength throughout my life. My mother, Mrs. Rita Maheshwari: she is my moral and emotional support. My sister and my backbone, Shreya: Her caring and joyful persona has added essence to my life. Thank you, for all sacrifices and constant encouragement.

I thank Nancy Crenshaw, who is a mother-like figure to me in Stillwater. I will always cherish her words of motivation and world affair talks with her.

A very special gratitude to my best friends: Archana and MS Vinay, for their enduring support and sympathetic ear despite being thousands of miles away. My closest buddy, Basheer: he believed in me more than I did and assisted me in every possible manner. My ATRC companions, Arjun and Prateek: late night studies, dine-outs, discussing each others difficulties and uproarious laughters- it was all worth it. It pacified my journey as a doctorate student. I would also like to thank Kiran and Lakshmy for being there whenever I needed them.

Finally, I'm grateful to my other family members, colleagues and friends who have supported me along the way.

---

Acknowledgements reflect the views of the author and are not endorsed by committee members or Oklahoma State University.

Name: Zeel Maheshwari

Date of Degree: September, 2017

Title of Study: A STUDY OF SMART INTEGRATED RENEWABLE ENERGY SYSTEMS (SIRES)

Major Field: Electrical and Computer Engineering

Energy availability is a severe problem in majority of the remote rural areas of the world. Development of energy-resources-poor rural areas has been discussed by many in the past. Rural electrification was the first major effort undertaken globally. Harnessing locally available renewable energy resources as an environmentally friendly option is gaining momentum. Smart Integrated Renewable Energy Systems (SIRES) offer a resilient and economic path to “energize” the area and reach this goal. The hallmark of the proposed SIRES is the smart utilization of several renewable resources in an integrated fashion and matching of resources and needs *a priori* with the ultimate goal of “energization”, not just “electrification”. Historical background leading to this approach is succinctly presented along with a comprehensive schematic diagram. Modeling of various components and their collective use in optimizing SIRES with the aid of genetic algorithm are presented using a typical hypothetical example. SIRES is also compared with various approaches for rural development based on Annualized Cost of System (ACS) and installation costs. Economic, social and environmental aspects of viability of SIRES for sustainable development are reviewed. This study also discusses intelligent control of SIRES using neural networks and fuzzy logic. Simulation results show that the operation of SIRES can be kept within defined constraints for critical storage devices. Technical effectiveness of SIRES is assessed based on a novel index, Need Fulfillment Probability (NFP). NFP is estimated for four different weather conditions where insolation and wind resources are varied and compared to microgrid for the considered weather conditions. Hierarchical markov modeling approach is applied to determine the availability of SIRES characterized by system component failure and repair rates. SIRES promote socio-economic development and improve the living environment by fulfilling the fundamental energy requirements with the help of low cost renewable technologies and intelligent energy management systems. Implementation of SIRES will lead to overall sustainable development of rural communities.

TABLE OF CONTENTS

LIST OF TABLES

## LIST OF FIGURES

Figure Page

NOMENCLATURE

| | |
|---|---|
| $P_{bio}(t)$ | Energy generated by biogas generator (kWh) |
| $V_{bio}(t)$ | Volume of biogas ($m_3$) |
| $P_{hydro}(t)$ | Energy generated by picohydro powerplant (kWh) |
| $\rho_w$ | Density of water (1000kg/$m_3$) |
| g | Acceleration due to gravity (9.8m/$s^2$) |
| $H_d$ | Effective height of the reservoir |
| $P^i_{PV}(t,\beta)$ | Energy generated by PV module (kWh) |
| $N_s$ and $N_p$ | Number of modules in series and parallel |
| $V^i_{oc}(t)$ | Open circuit voltage |
| $V_{OC,STC}$ | Open-circuit voltage under Standard Test Conditions (STC) |
| $K_V$ | Open circuit temperature coefficient (V/°C) |
| $I^i_{SC}(t,\beta)$ | PV module short-circuit current (A) |
| $I_{SC,STC}$ | Short circuit current under STC (A) |
| $G^i(t,\beta)$ | Global irradiance (W/$m^2$) |
| $K_1$ | Short circuit temperature coefficient (A/°C) |
| NCOT | Nominal Cell Operating Temperature (°C) provided by the manufacture |
| $FF^i(t)$ | Fill Factor |
| $P^i_{WG}(t)$ | Energy generated by wind at time t (kWh) |
| $P_r$ | Rated electrical power (kW) |
| $v_c$ and $v_r$ | Cut-in and rated wind speed in m/s. |
| $v_f$ | Cut-off wind speed m/s |
| $v^i(t,h)$ | Wind speed at desired wind turbine installation height h |

| | |
|---|---|
| $Q_t$ | Water flow rate of the picohydro powerplant($m_3/s$) |
| $Q_{WG}(t)$ | Water pumped by wind mechanical water pumps ($m^3$) |
| $Q_{PV}(t)$ | Water pumped by PV powered water pumps ($m^3$) |
| $Q_{Bio}(t)$ | Water pumped by biogas power water pump ($m^3$) |
| $Q_{SH}(t)$ | Water stored in the reservoir ($m^3$) |
| $\eta_{pd}$ | Efficiency of the pump at design point |
| $\rho_a$ | Density of air (kg/$m^3$) |
| $D_T$ | Diameter of the wind rotor (m) |
| $V_d$ | Design wind velocity(m/$s^2$) |
| $C_{pd}$ | Design power co-efficient of the wind rotor |
| $N_{pd}$ | Speed of the pump at design point (m/$s^2$) |
| G | Gear ratio |
| $\lambda_d$ | Design tip speed ratio of the wind rotor |
| $\eta_p$ | Efficiency of PV water pump |
| $\eta_{pump}$ | Efficiency of biogas water pump |
| $\eta_{engine}$ | Efficiency of engine |
| $P_B^i(t)$ | Battery input/output energy (kWh) |
| $P_{load}^i(t)$ | Energy needed to fulfill the load (kWh) |
| $C_{min}$ | Minimum permissible battery capacity |
| DOD | Maximum permissible depth of discharge |
| $C_n$ | Nominal Capacity |
| $C^i(t)$ | Available battery capacity (Ah) at hour t |
| $V_{DC,bus}$ | DC bus voltage (V) |
| $n_B^s$ | Number of batteries in series |
| $\Delta t$ | Simulation time step and is equal to 1 |
| $D_V$ | Biogas Digester volume |
| $\eta_b$ | Battery Efficiency |

| | |
|---|---|
| $\eta_{inverter}$ | Efficiency of inverter |
| $\eta_{bio}$ | Efficiency of biogas generstor |
| $W_{load}(t)$ | Amount of water required to fulfill needs ($m^3$) |
| $T_A^i(t)$ | Ambient temperature (°C) |
| $T_C^i(t)$ | Cell temperature (°C) |
| $E_{load-annual-capita}$ | Annual electricity consumption per person |
| $E_{load}$ | Annual energy consumed by load |
| $F_{max-E-Excess}$ | Maximum excess energy that can be used |
| $F_{max-E-Load}$ | Factor that |
| $E_{excess}$ | Annual excess energy generated |
| $JC_{RET}^r$ | Job creation factor for renewable technology 'r' |
| $P_{RET}^r$ | Peak value of the corresponding renewable technology |
| $C_P(t)$, $C_D(t)$ | Biogas produced and cooking demand at hour t |
| $DW_S(t)$, $DW_W(t)$, $DW_B(t)$ | water pumped by solar energy, wind energy and biogas respectively |
| $DW_D(t)$, $E_D(t)$, $IW_D(t)$ | Domestic water, Electricity and Irrigation water demand respectively |
| $E_S(t)$, $E_W(t)$, $E_B(t)$, $E_H(t)$ | Electricity produced by solar, wind, biogas and pico-hydro respectively |
| $IW_S(t)$, $IW_W(t)$, $IW_B(t)$ | water pumped by solar energy, wind energy and biogas respectively |
| P | Population of the community |
| $n_i$ | $i^{th}$ need per person per hour 't' |
| $N_1^t$ | Total need $n_1$ required for hour 't' |
| m | Number of different system components in SIRES |
| $r_m$ | Output obtained from one component |
| $x_m$ | Optimal number of $m^{th}$ system component |

| | |
|---|---|
| $R_1$ | Total net output for $x_1$ number of components |
| $RN_1^t$ | Resource-Need ratio for $N_1$ at hour 't' |
| $S_1^t$ | Success factor for $N_1$ at hour 't' |
| $P_{N_1}$ | Probability that need $N_1$ is fulfilled |
| f(t) | Continuous failure data density function |
| Q(t) | Failure distribution function |
| R(t) | Success distribution function |
| $\lambda$ | Failure rate of a component |
| $\mu$ | Repair rate a component |
| $\rho_{ij}$ | Rate of departure from state $S_i$ to state $S_j$ |
| $\lambda_p$, $\lambda_w$, $\lambda_b$, $\lambda_h$ | Failure rate of solar pv, wind system, biogas and hydropower system respectively |
| $\mu_p$, $\mu_w$, $\mu_b$, $\mu_h$ | Repair rate of solar pv, wind system, biogas and hydropower system respectively |
| $\lambda_{WS}$, $\lambda_{Ele}$, $\lambda_{Bio}$, $\lambda_{ES}$ | Failure rate of water system, electricity system, biogas and energy storage system respectively |
| $\mu_{WS}$, $\mu_{Ele}$, $\mu_{Bio}$, $\mu_{ES}$ | Repair rate of water system, electricity system, biogas and energy storage system respectively |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

When electricity was first introduced in the late 19th century, the major resource used to produce electricity was non-renewable. Humans kept using these limited resources inefficiently without realizing that these resources will deplete sometime in the future. However in the light of new technologies such as fracking, it would take several hundreds of years before the fossils fuels are exhausted. In addition, fossil fuels are also used for various purposes such as plastics, transportation, pharmaceuticals manufacturing and so on, that it would be unwise to depend on it for electrical energy. With the ever growing population of the world with increasing expectations and the associated environmental concerns, it is not prudent to rely solely on fossil fuels in the long-term. Rapid depletion of fossil fuels and the ever-increasing need for energy is opening up new opportunities for alternative energy sources to supply quality energy in a sustainable manner.

A historic agreement took place between 195 countries in the 2015 United Nations Climate Change Conference held at Paris, France. The agreement is aimed at reducing global warming which is already melting ice caps and raising oceans levels threatening the lives of animals and plants. These countries agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and also make efforts to limit the temperature increase to 1.5°C. For this, the key is to reduce the dependence on fossil fuels and cutting greenhouse emissions. Global environmental concerns such as climate change and high levels of $CO_2$ coupled with steady progress

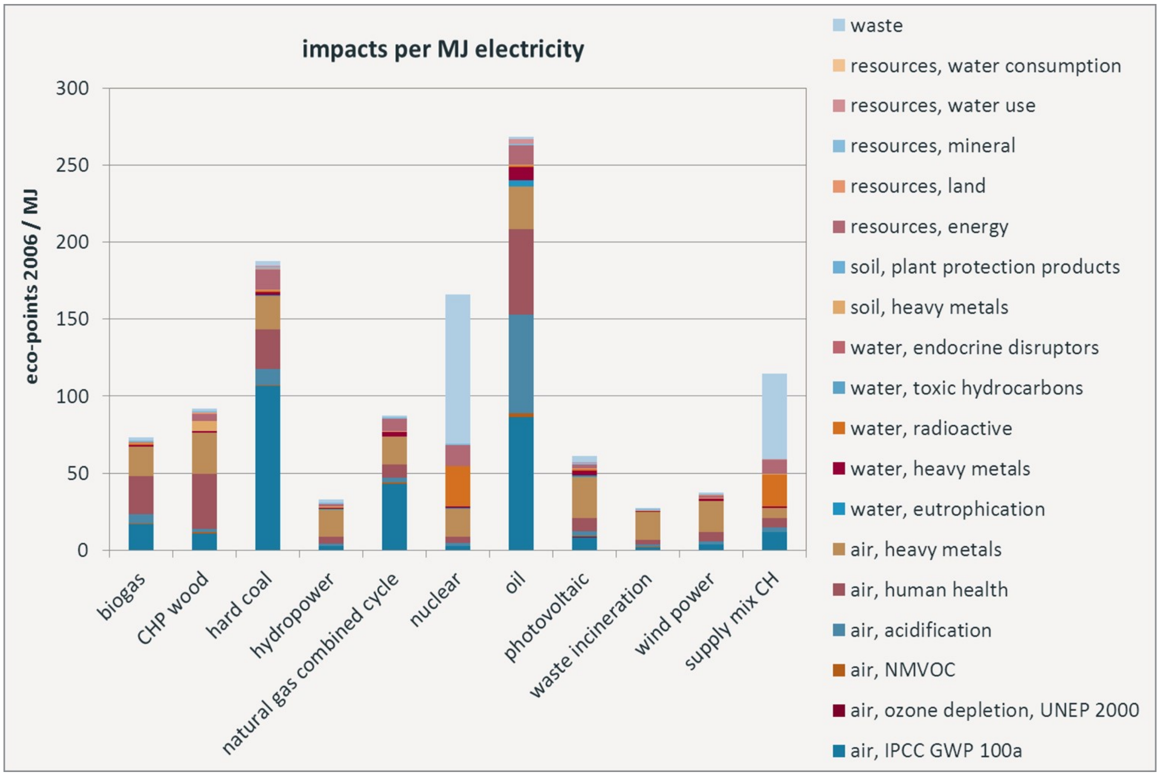



Figure 1.1: Environmental assessment of energy systems based on life cycle assessment

in renewable energy technologies has increased interest in the use of renewable energy. Significant cost reductions in the past few decades have made a number of renewable energy resources competitive with fossil fuels in various applications [1]. Figure 1.1 shows the impact of various energy sources on the environment. Energy efficiency and the environmental performance differ substantially between various technologies. Primary energy needs are more efficiently met by renewable energy technologies such as hydropower, wind power, biogas, and photovoltaics [2].

In September 2000, the largest gathering of world leaders in history, called the millennium summit, adopted the UN Millennium Declaration. It required the nations of the world to commit to a new global partnership to reduce extreme poverty and set a series of time-bound targets. These well defined goals have now become known as the Millennium Development Goals. Millennium Development Goals (MDGs) are the world's first time-bound and quantified targets for addressing extreme poverty in its many dimensions while promoting gender equality, education, and environmental sustainability. They are also basic human rights-the rights of each person in the planet to health, education, shelter, and security [3].

As a follow up, another set of goals called Sustainable Development Goals (SDGs) were built on the successes of the MDGs with a vision of fulfilling these goals while safeguarding the environment by 2030. On $25^{th}$ September 2015, SDGs were formed as an ambitious set of goals from the discussions at UN Sustainable Development Summit 2015. The SDGs were recorded in a document entitled "Transforming our world : Toward the Agenda 2030 for Sustainable Development". Goal number 7 of this agenda signifies the need to ensure access to affordable, reliable and sustainable energy for all. Additional set of targets in SDGs included climate change, economic inequality, innovation, sustainable consumption, peace and justice, among other priorities. The goals are interconnected  often the key to success of one will involve tackling issues more commonly associated with another [4]. These apply particularly to rural areas of sub-Saharan Africa, Latin America, the Middle east, North Africa and parts of Asia. Energy in various forms is required for growth and development in rural areas. Renewable resources are an indispensable alternative for fossil fuels to provide sustainable energy for development. Various steps have to be taken to improve the basic living environment and meet the energy and other necessities of these rural areas in a sustainable manner [5],[6].

## 1.2 Energy Crisis and Population Challenge

According to International Energy Agency (IEA), 2.5 billion people rely on fuelwood, charcoal, agriculture waste and animal dung to meet their needs for cooking. In many countries, these resources account for over 90% of household consumption. However, use of these resources in an unsustainable manner is leading to serious adverse consequences for health and environment. About 1.3 million people (mostly

Table 1.1: Percentage of Energy Deprived Rural Areas

| Basic Needs | Population without access (in world) | Percentage living in rural areas |
|---|---|---|
| Safe Water | 750 million | 90% |
| Proper stove for cooking | 2.5 billion | 85% |
| Electricity | 1.3 billion | 85% |

women and children) die prematurely per year solely because of the indoor pollution caused by burning biomass [7]. Moreover about 2.6 hour and about 4.8 km walk is required per day per family to collect about 10 kg of firewood [8]. Therefore valuable time and energy are wasted for fuel collection.

According to World Health Organization (WHO), about 750 million people lack access to safe water. Of these, almost 25% (175 million) rely on untreated surface water and over 90% live in rural areas [9]. Fetching water for domestic consumption utilizes a great deal of human energy. On an average, 1.5 hour and 1.7 km per day per household is required to fulfill a mere domestic water consumption of 17 liters per day which is significantly below the average consumption [8]. According to the IEAs World Energy Outlook, approximately 1.2 billion people in the world have no access to electricity and 85% of them live in rural areas [10]. Table 1.1 gives a summary of percentage of people living in rural areas who are deprived of the basic energy needs [7],[9],[10].

A major challenge is providing electricity and other basic needs to more than one billion people living in isolated rural areas around the world, where fuel delivery and grid extension are not cost effective options. Energy, and in particular electricity, is required for growth and development in rural areas. Steps must be taken to improve the basic living environment and meet the energy and other necessities of these rural areas [11].

Table 1.2: Electricity Access in 2013: Regional Aggregates

| Region | Population without electricity millions | Electrification rate% | Urban electrification rate% | Rural electrification rate% |
|---|---|---|---|---|
| Developing countries | 1,200 | 78% | 92% | 67% |
| Africa | 635 | 43% | 68% | 26% |
| North Africa | 1 | 99% | 100% | 99% |
| Sub-Saharan Africa | 634 | 32% | 59% | 17% |
| Developing Asia | 526 | 86% | 96% | 78% |
| China | 1 | 100% | 100% | 100% |
| India | 237 | 81% | 96% | 74% |
| Latin America | 22 | 95% | 98% | 85% |
| Middle East | 17 | 92% | 98% | 79% |
| Transition economies | 1 | 100% | 100% | 100% |
| WORLD | 1,201 | 83% | 95% | 70% |

### 1.3 Urban Development vs Rural Development

The fact that developing countries are developing is that development takes place primarily in urban areas, whereas rural areas are highly under-developed. About 1 billion people are living in the remote scattered areas of developing countries in the world. These people are caught in an agonizing race between demography and development. The increasing yearn for better standard of living along with extremely slow growth of opportunities in rural areas has forced a rapid and massive rural-to-urban migration, resulting in an explosive growth and plentiful slum areas around larger cities [5].

A large number of private utility companies, who provide electricity to most of the consumers, are unwilling to electrify isolated rural areas because it is too expensive to string electric lines to these inaccessible parts with low load factors. Moreover some utility companies also claim that, the people living in these areas are too poor to be able to afford electricity. Development in the urban areas takes place on social, political and economic grounds whereas development in rural areas is neglected and overlooked [12]. Table 1.2 shows the urban electrification rate versus rural electrification rate [13].

## 1.4 Renewable Energy Sources for Rural Areas

More than two-thirds of the populations of developing countries live in rural areas. There is a lack of fossil fuels in developing countries for rural electrification and funds for the development of these are limited. Hence, importing the needed resources will make the situation financially very untenable. In recent years there has been a significant increase of interest in utilizing renewable energy resources by developing countries. But, this wide gap between interest and implementation of use of renewables is yet to be bridged. This gap is due to the absence of large and effective infrastructure to generate energy by using renewable sources in rural areas [11]. One way to bridge this gap is by effectively and efficiently utilizing the resources that are readily available in these areas. It is a known fact that rural population heavily depends on agriculture and hence uses traditional biomass resources extensively. Renewable energy sources such as solar, wind and water are abundantly available in rural areas. Also it is a known fact that majority of rural population depends on agriculture and hence uses traditional biomass resources extensively. Another added advantage of rural areas is open spaces that can be utilized to set up renewable energy systems. Hence integrating all these resources in an effective manner could fulfill the needs of rural areas.

## 1.5 Objectives of Study

A novel approach entitled "Smart Integrated Renewable Energy System (SIRES)" is introduced for sustainable development of remote rural areas. The predominant objectives of this study include:

- Introducing the concept of "Energization"

- Development of a genetic algorithm for optimal sizing to minimize cost and maximize reliability for SIRES (multi resource-multi need system)

- Collection of data for parameters, such as weather (insolation, wind speed, rainfall, humidity, temperature), domestic water consumption and electricity use

- Comparison of cost (ACS, Net Present Cost (NPC) and installation cost) with existing methods, such as grid extension, microgrid (with and without diesel generator)

- Evaluation of Human Development Index (HDI), Job Creation Factor (JCF) and Greenhouse Gas (GHG) emissions of SIRES when compared to current approaches

- Neural network forecasting and Fuzzy Logic based intelligent control of SIRES

- Assessment of technical effectiveness of SIRES using a new reliability index called Need Fulfillment Probability (NFP)

- Estimation of Mean Time To Failure (MTTF), Mean Time To Repair (MTTR) and Availability of SIRES and its subsystems

## 1.6 Organization of Thesis

Approaches for rural developments are discussed in Chapter 2. In Chapter 3, components of SIRES and a schematic diagram with its components are presented. In Chapter 4, detailed explanation for three stages of optimization: initial analysis, modeling and optimization, is presented. Chapter 5 reviews the results of optimal sizing of system components and cost comparison with various approaches. In addition, economic, social and environmental impacts of SIRES are discussed. Intelligent control of SIRES combined with neural network forecasting of one-hour demands is described in chapter 6. In chapter 7, a novel probability index called 'Need Fulfillment Probability (NFP)' is introduced to assess the uncertainty of renewable resources. Hierarchical markov modeling technique to evaluate reliability based on component failures is explained in chapter 8. In Chapter 9, concluding remarks and future scope are succinctly presented.

# CHAPTER 2

## APPROACHES TO RURAL DEVELOPMENT

Energy, and more particularly electricity, is the essence for development in rural areas. Installation of modern energy systems improves access to potable water through pumping and distribution system and lowers malnutrition of children by employing food preservation technologies. Enabling cold storage of medication and access to modern healthcare technologies can decrease the incidences of diseases. This in turn leads to reduced rates of child and maternal mortalities. It aids education and welfare of rural regions by providing adequate lighting and communication. It relieves women of fuel and water collecting tasks and significantly contributes to improving gender equity. Moreover using environmental friendly technologies will directly contribute to global environmental sustainability. Although energy alone cannot mitigate poverty, it is undoubtedly necessary for progress in rural areas. Significant development is unattainable without a growing number of people gaining sustainable energy access. With modern renewable energy systems, it is feasible to achieve ubiquitous access to electricity and basic energy in the near future [1].

To exploit renewables resources for the development of rural areas, several methods have been suggested and implemented as follows:

1. National Grid Extension
2. Electricity Home Systems
3. Microgrids
4. Integrated Renewable Energy Systems (IRES)

5. IEEE Smart Village

6. Smart Integrated Renewable Energy Systems (SIRES)

## 2.1 National Grid Extension or Rural Electrification

Extension of grid, commonly known as rural electrification, was the earliest solution adopted to electrify rural areas. Moreover extending the national grid is an infeasible and ineffective option in many countries because of the high cost of grid extension. Additionally, due to low potential electricity demand in these areas, grid extension is often not a cost competitive option. Difficult terrain in many rural regions also increases expansion costs significantly. Mountainous or forest areas, for instance, will be difficult to access for machinery and require more time and resources to install transmission lines. A study of the World Bank on rural electrification programs placed the average cost of grid extension per km at between $8,000 and $10,000, rising to around $22,000 in difficult terrains [14]. Table 2.1 gives an estimate of the grid extension cost in certain selected countries in $ per kilometer [15].

Table 2.1: Costs of grid extension in selected countries

| Country | Labor and Other costs | Materials | Total |
|---|---|---|---|
| Bangladesh | $350 | $6,350 | $6,890 |
| Laos | $1,420 | $7,320 | $8,650 |
| El Salvador | $2,090 | $6,160 | $8,250 |
| Kenya | $6,590 | $5,960 | $12,550 |
| Senegal | $5,150 | $10,810 | $15,960 |
| Mali | $2,590 | $15,170 | $19,070 |

A critical mass is necessary for a grid extension project to be viable. Rural areas are vast and have a relatively small energy demand per connection. Hence the amount of demand (that determines the cost per kWh of grid extension) is very small, which makes it economically non-viable to extend the grid. Another major drawback of this solution is lack of generation capacity due to unavailability of fossil fuels and other conventional resources. Consumers may only have access to the electricity during limited hours each day and blackouts or brownouts are common. If the generation capacity does not increase, then it will only aggravate the situation and reduce quality of service. Table 2.2 shows comparison of typical features of urban and rural electrification [16].

Table 2.2: Typical features of urban and rural electrification

| Feature | Industrial/urban supply areas | Rural supply areas |
|---|---|---|
| Area load density (kW/Km2) | 500 to 100,000 | 2 to 50 |
| Consumer Density (conn/Km2) | >500 | 1 to 75 |
| Number of consumers per km line length (both MV and LV included) | >75 | 1 to 75 |
| Consumption density (kWh/km2) | >2,000,000 | 5,000 to 200,000 |

## 2.2 Electricity Home Systems (EHS)

These small power systems are designed to power individual homes or small buildings and provide an easily accessible, relatively inexpensive, and simple to maintain solution. Since houses in rural area are dispersed, it is an ideal setting for these solutions. Pico PV systems (PPS), Solar Home Systems (SHS) or Wind Home Systems (WHS) offer a solution for providing electricity to isolated places. In these stand-alone systems, power generation is installed close to the load so that there are no transmission and distribution costs. Also to keep prices affordable, cost of components are minimized and capacities are maintained low mainly serving small DC appliances for lighting and communication.

Stand-alone PV systems can be categorized as: Pico PV Systems (PPS), Solar Home Systems and Solar Residential systems (SRS) [1].

### 2.2.1 Pico PV Systems (PPS)

A Pico PV system is a small system with power output of 1 to 10W. It is mainly used for lighting, thus replacing inefficient and unhealthy sources such as kerosene lamps and candles. In addition they can be used for mobile phone charging or radio. A schematic diagram of Pico PV system (PPS) is shown in figure 2.1.

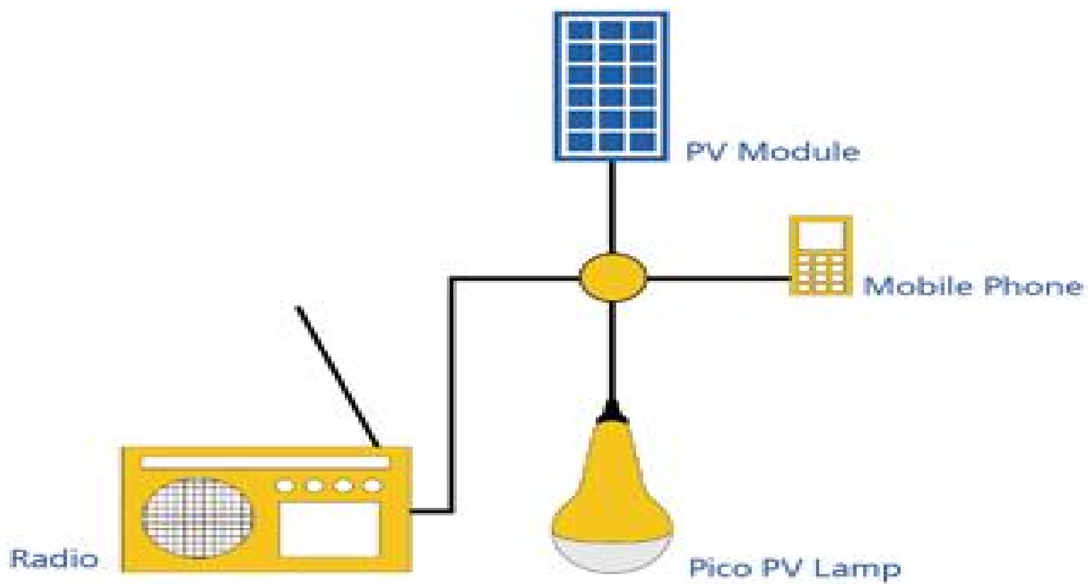



Figure 2.1: Pico PV system

### 2.2.2 Solar Home Systems (SHS)

Solar Home Systems (SHS) have a power output in the range of 250W peak. They are normally composed of several independent components: modules, charge controller, battery and the loads. Energy management is performed by charge controller, which is the central component of the system. SHS can be used to serve DC loads such as DC energy saving lamps, radios, DC TV and special DC fridges directly usable by the system. Figure 2.2 shows a possible schematic for DC Solar home system.

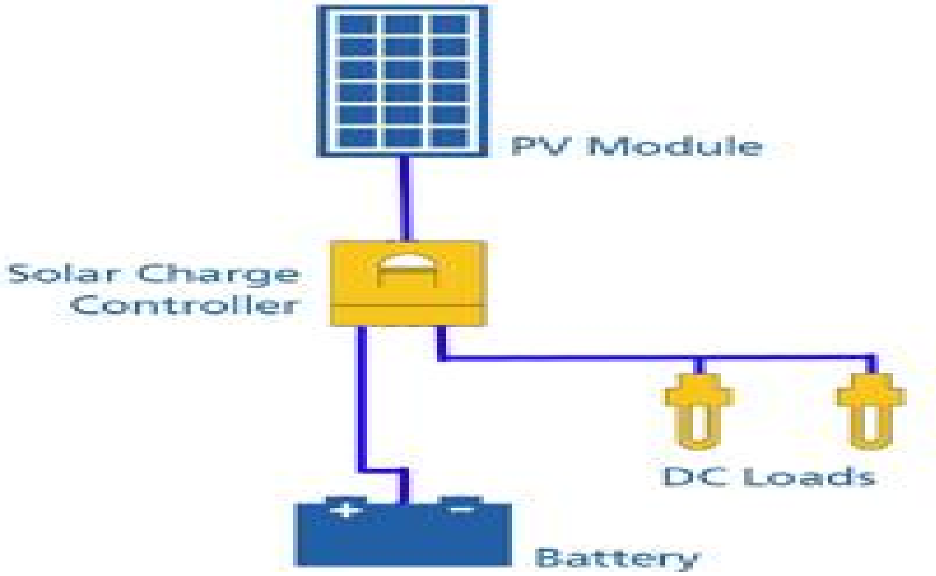



Figure 2.2: DC Solar Home System

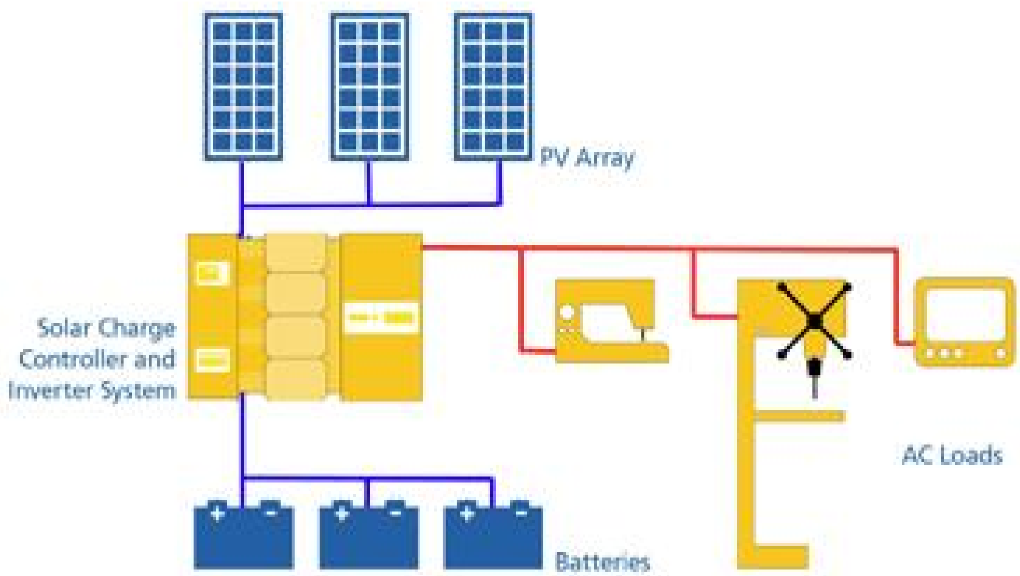



Figure 2.3: An AC Solar Residential System

### 2.2.3 Solar Residential Systems (SRS)

Larger stand-alone PV systems called Solar Residential Systems (SRS) can provide electricity to large individual places such as hotels, hospitals, schools, factories etc. They offer a wide range of applicable loads and are easy to operate and maintain. They also include an inverter allowing the use of AC loads. A typical power output range is from 500 W to 4000 W. Figure 2.3 illustrates an AC solar residential system.

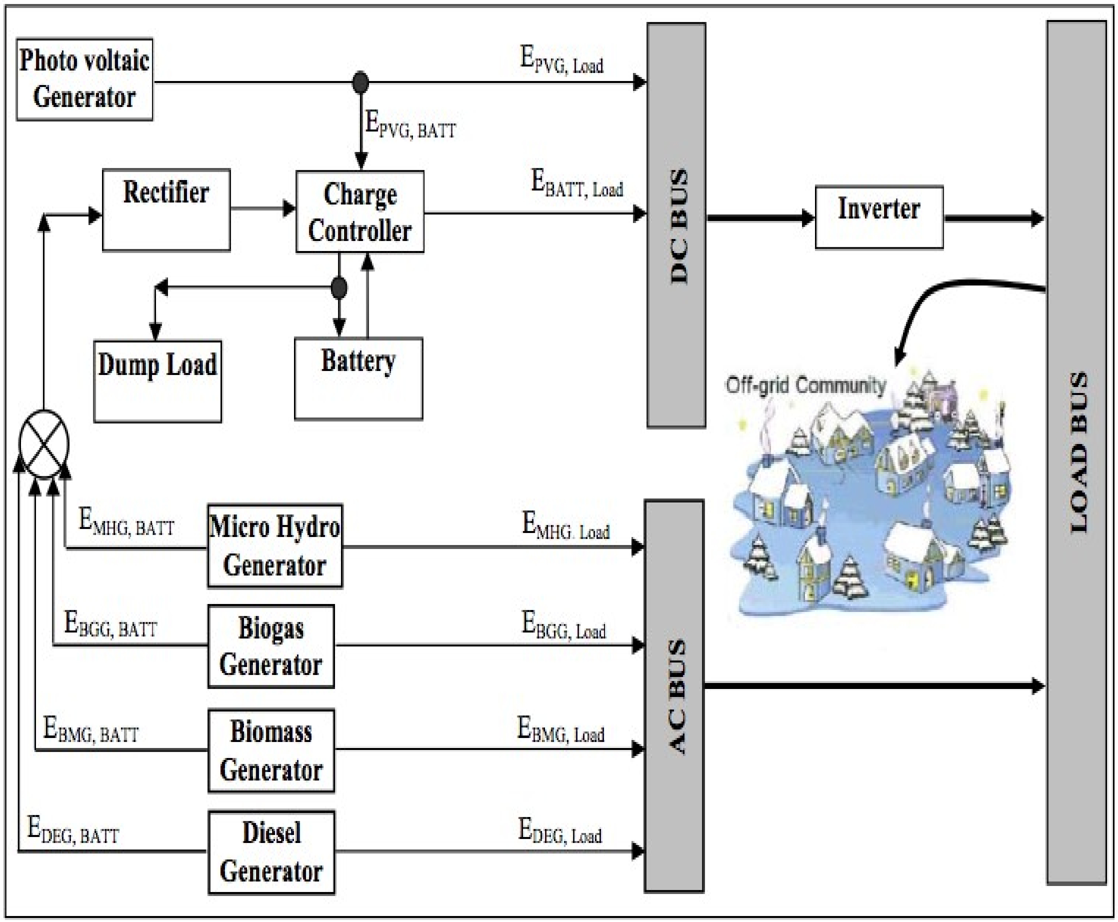



Figure 2.4: Configuration of microgrid

### 2.3 Microgrids

According to the US department of energy, microgrids are a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that act as a single controllable entity with respect to grid [and can] connect and disconnect from the grid to enable it to operate in both grid-connected or islanded mode. For the development of rural areas, several microgrids have been installed with ratings ranging from as little as 1 kW to as large as a few hundred kilowatts. Microgrids can either be AC or DC. These microgrids fulfill a range of needs from lighting, communication to commercial purposes.

Microgrids employ various generation resources such as diesel, solar photovoltaics

(PV), micro-hydro, biomass gasifiers, wind turbines as well as hybrid combination of these technologies such as wind-diesel, PV-diesel and so on. Diesel-based microgrids are most commonly used throughout the world as they have relatively low upfront capital cost of the generator and its wide spread availability. Micro-hydro based microgrids are typically run-of-the-river type schemes where water from a river or stream is diverted through a pipe into turbine to generate electricity. Biomass gasifiers system produces biogas anaerobically. Biogas is later fed into an engine to generate power. But both micro-hydro and biomass gasifiers are limited to areas with adequate water and biomass supply. Solar and wind systems produce power whenever resources are available and hence need a battery storage system to smooth out supply and store it for the times when it is needed the most. Seven such cases installed in India, Malaysia and Haiti have been studied in depth in reference [17]. An example of microgrid is shown in figure 2.4 [18].

## 2.4 Integrated Renewable Energy Systems (IRES)

Four decades ago, a concept called Integrated Renewable Energy System (IRES) was introduced [11]. IRES can be described as a system that harnesses two or more forms of locally available renewable energy resources to supply a variety of energy and other needs of a remote area in a most efficient, cost effective and practical way, with the ultimate goal of amalgamating the benefits at the user end. Needs include medium grade thermal for cooking, potable and domestic water, water for irrigation, low grade heating, electricity for lighting, communication, cold storage and educational purposes. This approach requires deliberate and calculated strategies for matching needs and available resources to maximize the benefits and efficiency.

IRES is a stand-alone system that makes remote rural areas self-sufficient for basic needs such as cooking, domestic and potable water supply and electricity in a cost effective and efficient manner. The prime distinction of IRES is its focus to

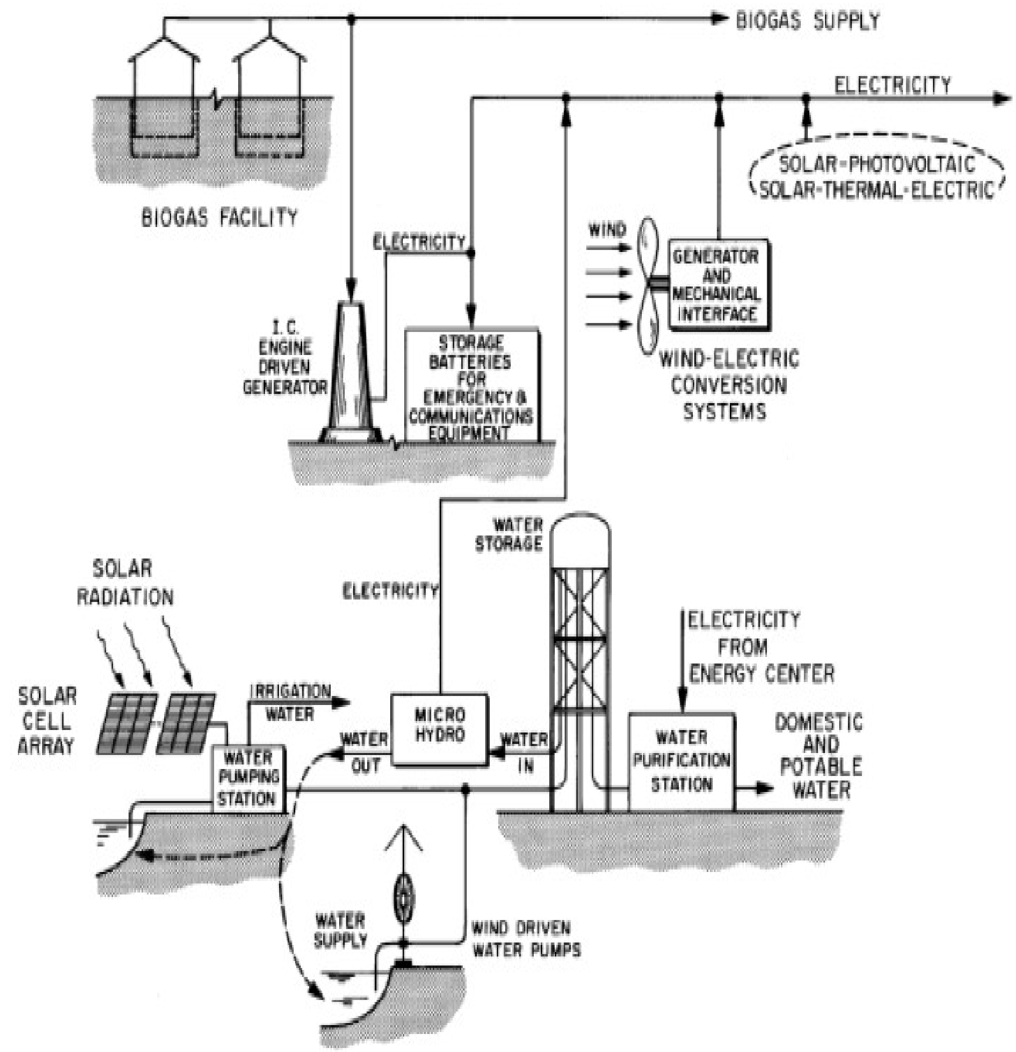



Figure 2.5: A possible schematic diagram of IRES

energize remote rural areas rather than electrify as promoted by hybrid systems and microgrids, in order to achieve sustainable development and improve the basic living environment of rural masses. . Multiple inputs to IRES are of different forms and so are the multiple outputs. The ultimate goal of IRES is to integrate the benefits at user end. A possible schematic diagram of IRES is shown in figure 2.5 [19].

## 2.5 IEEE Smart Village

In 2009, Community Solutions Initiative (CSI) was launched to address the situation of rural population who have no access to electricity. A model was developed and demonstrated in Haiti after an earthquake had hit the region. Since then this model was introduced in various African countries which were highly deprived of electricity. CSIs technical model consists of a standardized charging station called SunBlazer. It is a mobile platform with up to 80 portable battery packs (PBKs) and home lighting kits per station. Each kit provides power for lighting up to 2 rooms and operates auxiliary 12V DC loads. Every station can charge 80 battery packs every 3-4 days to provide electricity to about 500 people. With the help of SunBlazer, about 1162 homes (around 7000 people) obtained access to electricity. After successful design, testing and installation of SunBlazer, a new model called SunBlazer II was introduced in 2014. Major improvements obtained were delivery in kit form instead of a complete plug-and-play assembly on a trailer. Other improvements in the new design were lighter weight, simpler and versatile solar panel mounting, better station battery security and lower cost [20]. Figure 2.6 depicts a typical SunBlazer II.

CSI was rebranded as IEEE Smart Village in November 2014. Its mission is to empower off-grid communities through education and creation of sustainable, affordable, locally owned entrepreneurial energy businesses. It is being funded by qualified non-government organization (NGO) partners who receive sufficient seed funding to start-up and demonstrate implementation of micro utilities. IEEE Smart village has been serving numerous countries such as Benin, Cameroon, India, Kenya, Malawi, Namibia and so on [21].

Figure 2.6: SunBlazer design deployed in Haiti

## 2.6 Smart Integrated Renewable Energy Systems (SIRES)

Smart Integrated Renewable Energy System (SIRES) is an improved and a smarter version of IRES [22]. In SIRES, each system component is optimally sized to minimize cost and maximize reliability using techniques such as genetic algorithm. Smart sensors will be strategically placed at locations where amount of resources have to be monitored. Sensors will also be placed at locations where the status of system components should be monitored. Intelligent controllers will be used to turn on/off renewable technologies. Data obtained from the sensors can be transmitted through a basic telemetry/cellular network for use in further research and improvement. Intelligent control techniques are implemented. The basic working of SIRES and its components is discussed in the next chapter.

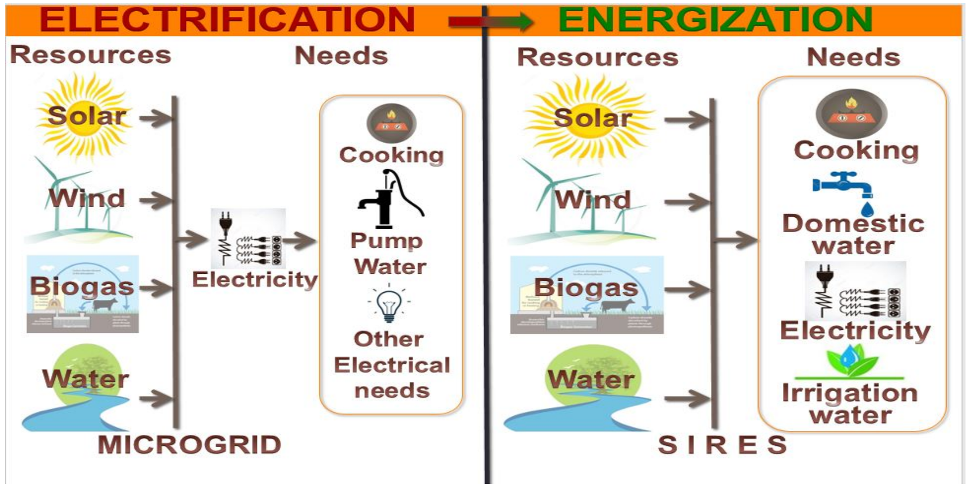



Figure 2.7: Electrification vs Energization

## 2.7 Electrification vs Energization

The concept of energization refers to the best use of energy in available resources to satisfy various needs. In energization, any one resource can be used to satisfy more than one need. The goal is to use all the resources to meet all the needs in the most efficient manner by matching the resources with the needs as appropriate in an integrated manner. Electrification converts all forms of energy resources to electrical form which is then used to satisfy various needs with no consideration to the overall efficiency of utilization. These terms are often mistaken to be analogous to each other, but in reality Electrification can be considered as a subset of Energization. Figure 2.7 depicts the vital differences between electrification and energization.

Microgrids, a version of electrification, converts all the available resources into "electricity". For instance, biogas is converted into electricity and then used for cooking. Another example is wind energy is used to produce electricity. The generated electricity is subsequently used to pump water. This process reduces the end-use efficiency. On the other hand, in SIRES, an example of energization, resources are directly utilized to fulfill basic needs as much as possible. In addition, these resources can be used generate electricity as and when required. For instance, biogas is directly used for cooking rather than converting into electricity and then using it for cooking. Similarly, water is pumped to overhead reservoir using solar and wind mechanical water pumps.

## 2.8 Comparison of various approaches

Comparison of various approaches to rural development is shown in Table 2.3.

Table 2.3: Comparison of various approaches of rural development

| Approach to rural development | Purpose | Resources used | Needs Fulfilled | Storage devices | Sensors and controllers |
|---|---|---|---|---|---|
| Rural electrification | Extending grid to remote areas with no electricity | Conventional resources | Providing electricity to remote rural areas | — | — |
| Electricity Home Systems (EHS) | Providing electricity to mostly DC appliances and sometimes AC appliances | PV, wind | Providing electricity for DC appliances such as lighting, cell phone charging and few AC appliances | Batteries | Charge controller used sometimes |
| Microgrids | Providing basic electrical access to areas which have little or no access to electricity. | Diesel, Biomass, PV, Wind and Small Hydro | Providing electricity for lighting, cell phone charging and few appliances | Batteries, Flywheels, Energy capacitors | Used occasionally |
| IEEE Smart Village | Providing basic electrical access and educational services to the rural areas. | Portable PV and Battery kit | Lighting, cell phone charging and basic electrical access | Batteries | Battery Charge controllers |
| IRES | Providing basic needs and electricity with help of energization rather than electrification | Biogas, Water, Solar and Wind | Basic needs such as biogas for cooking, water for domestic and irrigation purpose and electricity | Pumped hydro, Biogas digesters and Batteries | — |
| SIRES | Providing basic needs and electricity with help of energization rather than electrification. Also using smart energy management techniques and intelligent control | Biogas, Water, Solar and Wind | Basic needs such as biogas for cooking, water for domestic and irrigation purpose and electricity. Other needs such as low grade and medium grade heating also fulfilled. | Pumped hydro, Biogas digesters | Smart sensors used to check resource availability. Intelligent controllers to turn on and off the renewable technologies. |

# CHAPTER 3

# SMART INTEGRATED RENEWABLE ENERGY SYSTEMS (SIRES)

This thesis proposes the integrated use of several resources to meet various energy needs. Several previous attempts have employed multiple resources in a hybrid manner with electricity as the means to satisfy the needs. The uniqueness of the proposed approach is to consider the issue on a system level with different resources meeting different needs in an interchangeable manner as the situation warrants to maximize the overall energy use efficiency to improve economic, social and environmental aspects of the rural area.

The basic tenet of SIRES is to match various forms of energy resources to the needs of an isolated rural area in an efficient and economical manner. SIRES utilizes several renewable energy sources, conversion technologies, and end-use technologies to provide a variety of energy and other needs. It primarily comprises of biogas digesters and stoves, wind-electric conversion systems, wind mechanical conversion systems, PV modules, PV-powered water pumps, pico hydro power plants, elevated water storage tanks, biogas powered generator, biogas powered water pump, batteries, fuel cells, converters and inverters. Fundamental needs of rural areas include potable and domestic water, water for irrigation, medium grade thermal energy for cooking, low-grade for heating, and electricity for lighting, communication, cold storage and educational purposes [22]. System may be connected to a central grid or can be stand-alone. The ultimate goal of SIRES is to integrate the benefits at the user end. One possible schematic of SIRES employing multiple resources and needs at a particular site is shown in Figure 3.1.

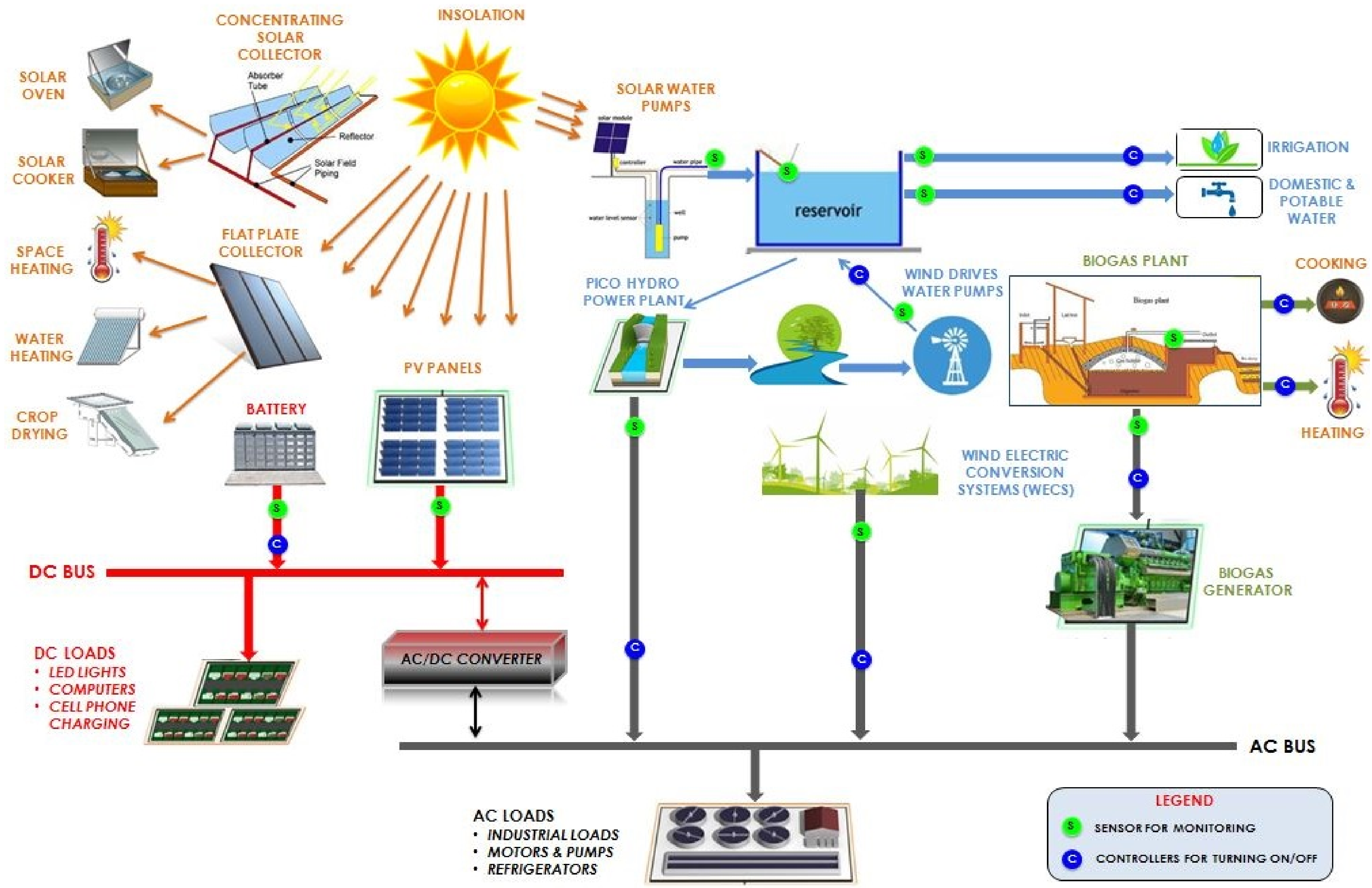



Figure 3.1: Schematic diagram of SIRES

### 3.1 What is smart about this approach?

Several aspects of SIRES make it smart. Firstly, SIRES maximizes the impact by energization as compared to electrification which is not efficient and cost-effective for demands such as cooking, water pumping etc. Although electricity can be used for cooking, it is more efficient and cost-effective to use biogas instead. Similarly, it is smart to use wind and solar based pumps to pump and store water in an overhead reservoir for distribution and for energy storage.

Secondly, needs are prioritized based on necessities of daily life. For example, cooking would be on a higher priority when compared to electricity, and water for domestic purpose would be on a higher priority when compared to irrigation water. Resources are matched to needs *a-priori*. Third aspect of SIRES that makes it smart is genetic algorithm, which optimizes the operation of system components to minimize annualized cost of system and maximize reliability. Lastly, operation and resiliency are enhanced by using smart sensors and intelligent controllers.

### 3.2 Operation of SIRES

The most often used and easily available renewable resources as inputs to SIRES are:

1. Biomass
2. Hydro
3. Solar (Insolation)
4. Wind

These resources are inputs to SIRES. Biomass constitutes agriculture residues, livestock manure, dead trees remains, human wastes and other organic wastes. Collected biomass is digested anaerobically to produce biogas. Biogas is primarily used for cooking, which is the highest priority need for SIRES. Leftover biogas is used to generate electricity and pump water to overhead reservoir. Water from rivers, ponds and streams is pumped by using wind mechanical water pumps and PV powered water pumps into an overhead reservoir. It is used to fulfill domestic and irrigation water needs of rural areas. Water remaining in the reservoir is utilized to generate electricity by employing a pico-hydro unit. Wind electric conversion systems and solar photovoltaic arrays utilizing insolation (incident solar radiation) are employed to generate electricity. Solar flat plate collectors can fulfill low-grade thermal demands of rural areas. Electricity generated is supplied to rural areas through two buses: AC bus and DC bus. AC bus supplies loads such as motors, pumps, industrial appliances and devices, refrigerator and so on. DC bus supplies loads such as communication and educational devices, thermoelectric cooler, cell phones chargers, computers and laptops, domestic and street LED lighting etc. Smart sensors are strategically placed at locations where availability of resources have to be monitored. Sensors will also be placed at locations where the status of system components should be monitored. Intelligent controllers will be used to turn on/off equipment. Data obtained from the sensors can be transmitted through a basic telemetry/cellular network for use in further research and improvement.

# CHAPTER 4

# STAGES OF OPTIMIZATION

Optimization of SIRES can be divided into three stages. Initial analysis of resources is performed in stage 1. Stage 2 comprises of modeling system components, system reliability and Annualized Cost of System (ACS). Genetic Algorithm based optimization takes place in stage 3. Figure 4.1 illustrates the stages of optimization with the objectives associated with each stage [23].

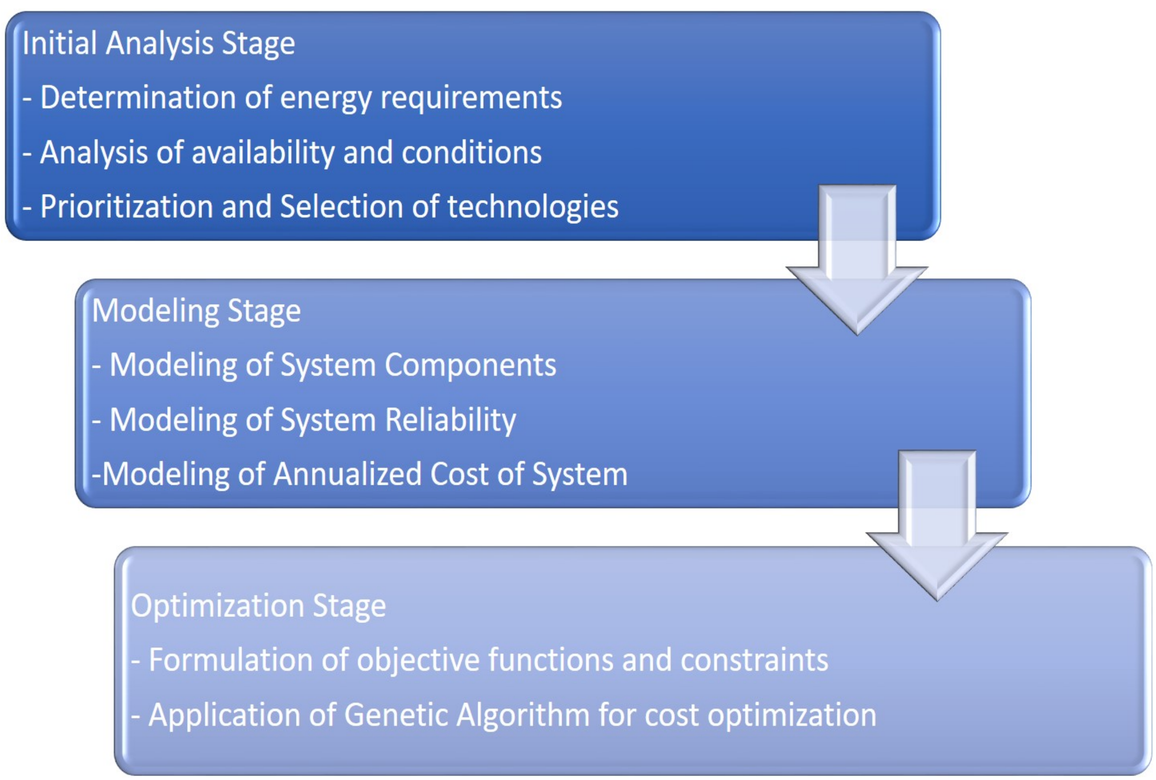



Figure 4.1: Stages of Optimization

## 4.1 Stage 1: Initial Analysis

In order to fulfill basic needs of a rural area, it is mandatory to determine the most appropriate and affordable technologies, equipments and facilities. For this purpose, the first stage will be to determine the energy requirements. Resources and energy requirements are site specific.

### 4.1.1 Determination of Energy Requirements

Projecting energy requirement that reflect reality is rather difficult, especially for prospective consumers who have little or no experience with assessing energy requirements. A viable approach to assess demand is to survey households in adjoining, already electrified areas or in a region with similar economic activities, demographic characteristics etc. For this study, majority of the energy requirement details have been gleaned from suitable references.

A typical hypothetical rural area with population of 700 in 120 households and 450 cattle is considered for the study. It is assumed to be located at 36.1156°N, 97.0584°W. Most of the people have agriculture as their basic occupation. 200 acres (80 hectares) is considered available for agriculture. Based on this consideration and appropriate references, energy requirement is determined. Four basic needs are considered.

1. Cooking
2. Domestic Water
3. Electricity
4. Irrigation Water

Biogas constitutes of methane (50-70%), carbon-dioxide (30-50%) and small traces of hydrogen sulphide and other gases. In this respect, the mixure of gases, with the exception of carbon dioxide, is same as conventional cooking gas. Hence biogas is used for cooking in SIRES because it is the most effective, economic and efficient option. Every person requires about 0.34-0.42 $m^3$ of biogas every day for cooking purpose [24]. Therefore for 700 people, about 238-294 $m^3$ for biogas is needed every day for the rural area under consideration. Pattern of biogas consumption for cooking is decided empirically.

Average level of water consumption per capita for domestic use in rural area is estimated to be 71.3 liters per day [25]. Water used for drinking water, showering, laundry, personal hygiene, house and yard cleaning and washing vessels is included in the domestic water consumption. To assess the pattern of consumption of domestic water, water utility engineer at City of Stillwater was contacted. Hourly water consumption for one year was collected. Data provided by water utilities included data for the whole town (about 50,000 water meter points). An XML document is generated every day. The XML file is converted to Excel sheet using the software ITRON given by the water utilities. This excel sheet contains all the location IDs of the town. Each water meter corresponds to one location ID. Hence the first step was to sample 120 residential location IDs using the software ARCmap. It is Geographic Information System (GIS) -based software that supports a certain number of meter points to be selected. 7 random residential areas in Stillwater were selected to sample 120 houses. Hence to select the data corresponding to location IDs of interest, SAS software was used. Output of this software is an excel sheet that contains total hourly water consumption utilized by the chosen households for one year. Urban water usage is more compared to rural areas. Hence the water consumption is scaled by 2/3 to match the average consumption per capita in rural area.

As mentioned earlier, making electricity load projections for people who have little or no experience is difficult task. Therefore based on empirical knowledge and available literature, a list of appliance and their average usage every day is estimated. Table 4.1 shows basic electrical appliances required in the rural area with their usage

Table 4.1: Estimated Electricity Demand per Household

| Appliance | Rating (W) | Quantity | Hours of daily usage | Total Energy consumption (Wh)/day |
|---|---|---|---|---|
| Bulbs | 15 | 4 | 5 | 300 |
| TV | 70-150 | 1 | 5 | 350-750 |
| Radio | 15 | 1 | 2 | 30 |
| Refrigerator | 100 | 1 | 24 | 1200* |
| Cellphone | 5-10 | 2 | 2 | 20-40 |
| Fan | 100 | 2 | 3 | 600 |
| Miscellaneous | | | | 100-300 |
| **Total** | | | | **2500-2940** |

* Average consumption of refrigerator whenever compressor is on

hours and quantity for every house hold [26]-[27]. Due to high cost of electricity generation, it is very important to choose the most efficient appliances. The basis for all assumptions is the projected use of such appliances.

Therefore for 120 households, daily electrical consumption varies from 300 kWh-360 kWh. Electricity for community purpose is assumed to vary from 45 kWh-55 kWh per day. Hence the total electricity consumption for the rural area will vary from 345-415 kWh/day.

Majority of rural areas have agriculture as their main occupation. Hence providing water for irrigation becomes an integral part of SIRES. Crops have growing cycles of 100-150 days. With good water management system, water required per crop is 4000 $m^3$/hectare but under less favorable conditions water required is 13,000 $m^3$/hectare. Therefore the typical requirement will be 30-130 $m^3$/ha range (3-13mm/day) [28]. Estimated daily water requirement for various types of crop is given is table 4.2 [29].

As mentioned earlier, 80 hectares need to be irrigated. Based on the references and considering efficient irrigation, it is estimated that 30-60 $m^3$ per hectare per day. Therefore about 100-200 $m^3$ per hour is required for the entire irrigated land. Average

Table 4.2: Estimated Electricity Demand per Household

| Crops | Daily Water Requirement ($m^3$/ha) |
|---|---|
| Rice | 100 |
| Rural Village Farms | 60 |
| Cereals | 45 |
| Sugar cane | 65 |
| Cotton | 55 |

annual precipitation in assumed area is 37.29 inches (941 mm) [30]. Effective rainfall for crops is believed to be 70% (660 mm). Therefore the water required will be 75-175 $m^3$/ hour.

### 4.1.2 Analysis of Availability and Conditions

The rural area considered is assumed to have ample water resources from rivers and streams along with adequate sunshine and medium to high wind speeds around the year. Most people have agriculture as their major occupation and hence a significant amount of agriculture and animal waste is generated that can be used to produce biogas. Based on these, resources that could be inputs to SIRES are biomass, water, solar and wind.

Biomass largely constitutes of dead trees, tree branches, yard clippings, leftover crops, wood chips, bark and sawdust from lumber mills, garbage, livestock manure and municipal wastes. Residues from forests, wood processing, and food crops are dominant in biomass energy. A striking feature of biomass is that it is widely and freely available, simple to use and low cost. Biomass is used largely and inefficiently at present in rural areas for cooking and heating purposes. One method to use biomass efficiently is to convert it into biogas. It is produced when collected biomass undergoes anaerobic fermentation in bio-digesters. Heating value of biogas is about 4600-6000 kcal/$m^3$. As mentioned earlier, number of cattle in rural area is 450 and irrigated land in 80 acres. Table 4.3 shows animal, human and agriculture waste produced [24], [31].

Table 4.3: Animal, Human and Agriculture Waste

| Source | Total waste/kg/day | Collectible Waste |
|---|---|---|
| Calf (0-6) | 6 | 5 |
| Dairy Cow (6-15) | 14 | 10 |
| Dairy Cow (15-24) | 21 | 17 |
| Dairy Cow (24+) | 47 | 40 |
| Man | 0.75 | 0.75 |
| Kitchen Waste | 0.25 | 0.25 |
| Sheep | 0.75 | 0.25 |
| Pigs | 1.3 | 0.75 |
| Crop | Crop Yield (t/ha/year) | Residue Produced (t/ha/year) |
| Rice | 2.5 | 5 |
| Wheat | 1.5 | 2.6 |
| Maize | 1.7 | 4.3 |
| Sorghum | 1.0 | 2.5 |
| Barley | 2.0 | 3.5 |
| Millet | 0.6 | 1.2 |

Approximately 9 tons of wet animal and human dung is produced every day. This is equivalent to about 300 $m^3$ of biogas. About 1 ton of dry matter of crop residue is considered which generates about 50 $m^3$ of biogas. Hence 350 $m^3$ of biogas is produced every day [31]. The slurry that remains after biogas production is rich in nutrients for plants and can be used as fertilizers for crops. Biogas production is assumed to be constant every hour.

Hourly solar irradiation and wind data are obtained from the Climate and Data Services, Oklahoma Climatological Survey. Ample water is available from the river and lakes.

### 4.1.3 Selection of Technologies

Basic needs, current approaches and technologies to be used in SIRES to fulfill needs are documented in Table 4.4.

Table 4.4: Comparison of current approaches and technologies to be used in SIRES

| Needs | Current Approach | Technologies to be used in SIRES |
|---|---|---|
| Cooking | Woodstoves, Biomass, Charcoal | Biogas obtained from biogas digesters and household digesters, Solar Cooker, Improved cooking stoves |
| Water (drinking, domestic and community purpose) | Hand pumps, Wells, Electricity powered pumps | Wind turbines powered water pumps, PV powered water pumps |
| Lighting (domestic and community including street lighting) | Oil and kerosene lamps, Unreliable and short duration electricity | PV cells, Electricity from SIRES with several sources like pico-hydro power, WECS, PV, biogas fueled generator |
| Small- scale industries, shops, educational institutions, cold storage, hospitals | Grid based or no electricity, Human and animal power for motive power, Traditional methods | Electricity from SIRES |
| Communications (radio, television sets, cell phone chargers) | Grid based, Battery banks and charging stations in a few places | Solar home systems, Electricity from SIRES |
| Low grade heating (space and water heating, crop drying) | Wood Charcoal, Animal dung and crop residues | Flat plate solar collectors, Solar crop dryers, Biogas |
| Medium grade heating (industrial process heating, crop processing) | Wood, Biomass | Concentrated solar collectors, Electricity from SIRES |
| Water (irrigational purpose) | Electricity powered water pumps | Wind turbines powered water pumps, PV powered water pumps, Water available in reservoir, Biogas driven water pumps |
| Energy Storage | Battery | Biomass and biogas energy storage, Potential energy in form of water, Battery storage |

### 4.1.4 Priority, Choice and Allocation

As discussed earlier, the advantage of SIRES is prioritization of needs and resources to fulfill basic requirements of rural area. Hence in the first stage, resources are matched to needs in a smart and efficient manner. The order of priority of needs based on everyday use is decided empirically: cooking, potable and household water, electricity, irrigation water. Order of priority of resources can be also decided empirically based on the need. For cooking, highest priority is given to biogas followed by solar cookers and finally electricity. For water pumping, highest priority is given to solar and wind resources followed by biogas powered water pumps. For electricity, priority is given to solar and wind resource followed by pico hydropower, biogas and electricity stored in battery.

## 4.2 Stage 2: Modeling

Stage 2 is the planning stage. The objective of this stage is to model system components, system reliability and annualized cost of system. System components such as biogas digester, biogas generator, PV panels, wind turbines, pico hydropower plant, PV powered water pumps, wind powered water pumps, biogas powered water pumps, reservoir and batteries are modeled. Once this is achieved, system components are optimally sized to minimize annualized cost and maximize reliability using genetic algorithm.

### 4.2.1 Modeling System Components

All the models presented in this section are based on hourly values of the quantities of interest and hence can be classified as hourly models. Equations (4.1)-(4.15) define the modeling of system components such as biogas generator, pico hydropower generator, PV panels, Wind turbines, wind driven mechanical pumps, PV powered water pumps, biogas powered water pumps, battery bank and biogas digester. On a given $i^{th}$ day and at time 't', the following models apply for various components.

**PV array modeling**

A PV array that consists of $N_p$ strings in parallel and $N_s$ modules per string in series is considered. The current-voltage and power-voltage characteristics of a PV array in each power generation block is shown in Figure 4.2 [34].

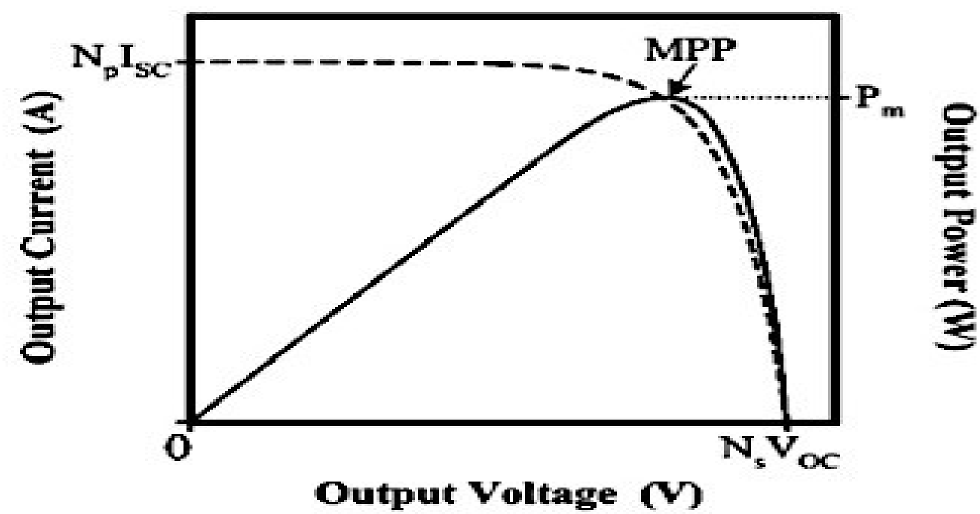



Figure 4.2: PV module current-voltage and power-voltage characteristics

The maximum output power of the PV array ($P^i_{PV}$(t,$\beta$)) in kWh placed at a tilt angle $\beta$ on a day i (1 $\leq$ i $\leq$ 365) and at hour t (1 $\leq$ t $\leq$ 24) is calculated using the specifications of the PV module under Standard Test Conditions (STC) as well as the ambient temperature and irradiation. At STC, the cell temperature is 25 °C and solar irradiance is 1 kW/$m^2$. $P^i_{PV}$ (t, $\beta$) (kWh) is given by the following equations

[32]-[33]:

$$P_{PV}^{i}(t,\beta) = N_s * N_p * V_{oc}^{i}(t) * I_{sc}^{i}(t,\beta) * FF^{i}(t) \quad (4.1)$$

$$I_{sc}^{i}(t,\beta) = \{I_{SC,STC} + K_1[T_C^{i}(t) - 25\,°\mathrm{C}]\} * \frac{G^{i}(t,\beta)}{1000} \quad (4.2)$$

$$V_{OC}^{i}(t) = V_{OC,STC} - K_V * T_C^{i}(t) \quad (4.3)$$

$$T_C^{i}(t) = T_A^{i}(t) + \frac{NCOT - 20\,°\mathrm{C}}{800} G^{i}(t,\beta) \quad (4.4)$$

Where $V_{oc}^{i}(t)$ is open-circuit voltage, $V_{OC,STC}$ is open-circuit voltage under Standard Test Conditions (STC),$K_V$ is open-circuit temperature coefficient (V/°C), $I_{SC}^{i}(t,\beta)$ is PV module short-circuit current (A), $I_{SC,STC}$ is short-circuit current under STC (A), $G^{i}(t,\beta)$ is global irradiance (W/$m^2$), $K_1$ is short-circuit temperature coefficient (A/°C), $T_A^{i}(t)$ is Ambient temperature (°C), $T_C^{i}(t)$ is cell temperature (°C), NCOT is Nominal Cell Operating Temperature (°C) provided by the manufacture and provided by the manufacture and is defined as the cell temperature when the PV panel operates under 800 W/$m^2$ of solar irradiation and 20 °C of ambient temperature. Normally NOCT is between 42 °C and 46 °C. $FF^{i}(t)$ is the fill factor and can be defined as the ratio of the maximum power from the solar cell to the product of $V_{oc}$ and $I_{sc}$. Graphically, the FF is a measure of the "squareness" of the solar cell output characteristic and is also the area of the largest rectangle which will fit in the current-voltage curve.

### Wind turbine modeling

The plot of wind generator (WG) output power versus wind speed is shown in Figure 4.3 [34].

Power output from wind system is expressed as a function of wind speed. A simple

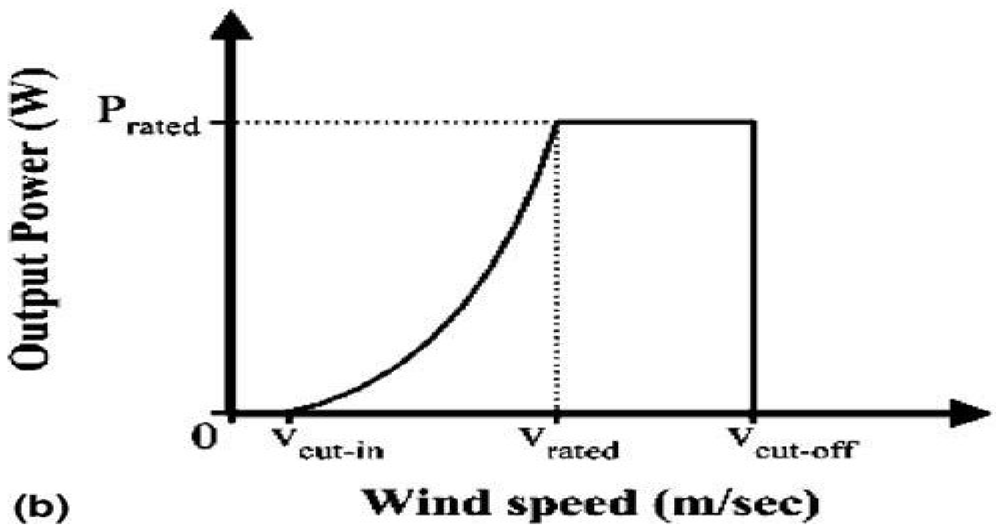


Figure 4.3: WG power versus wind speed characteristics

model for the wind system output can be expressed as follows [32]-[33]:

$$P_{WG}^{i}(t) = \begin{cases} P_r \frac{v^i(t,h) - v_c}{v_r - v_c} & v_c \leq v^i(t,h) \leq v_r \\ P_r & v_r \leq v^i(t,h) \leq v_f \\ 0 & \text{otherwise} \end{cases} \tag{4.5}$$

where $P_r$ is rated electrical power (kW), $v_c$, $v_r$ and $v_f$ cut-in, rated and cut-off wind speed in m/s respectively. $v^i(t,h)$ is wind speed at desired wind turbine installation height h.

The wind speed, $v^i$(t,h), at the desired WG installation height (h) is usually different from the height corresponding to the wind speed input data. The following exponential law is used to calculate $v^i$(t,h),

$$v^i(t,h) = v_{ref}^{i}(t).(\frac{h}{href})^a \tag{4.6}$$

where $v_{ref}^{i}(t)$ is the reference (input) wind measured at height $h_{ref}$ and a is the power law exponent, ranging from 1/7 to 1/4.

### Biogas Digester

When biomass undergoes anaerobic fermentation, biogas is produced. Anaerobic fermentation of organic substances is the process, which takes place in the absence of air. Oxygen deficiency in this fermentation process leads to production of a mixture of methane and carbon dioxide (biogas). Anaerobic fermentation takes place in a biogas digester. Sizing of biogas digester is given by following equation [31],

$$D_V = [manure(m^3/year) + co - substrate(m^3/year)] * \frac{retentiontime(days)}{365} \quad (4.7)$$

### Biogas Generator

A biogas generator consists of biogas digesters, a biogas collection tank, a biogas-driven engine generator as well as piping and controls for successful operation. The biogas generator is illustrated in figure 4.4. The controller is designed to track the maximum output power and keep the output voltage constant [35].

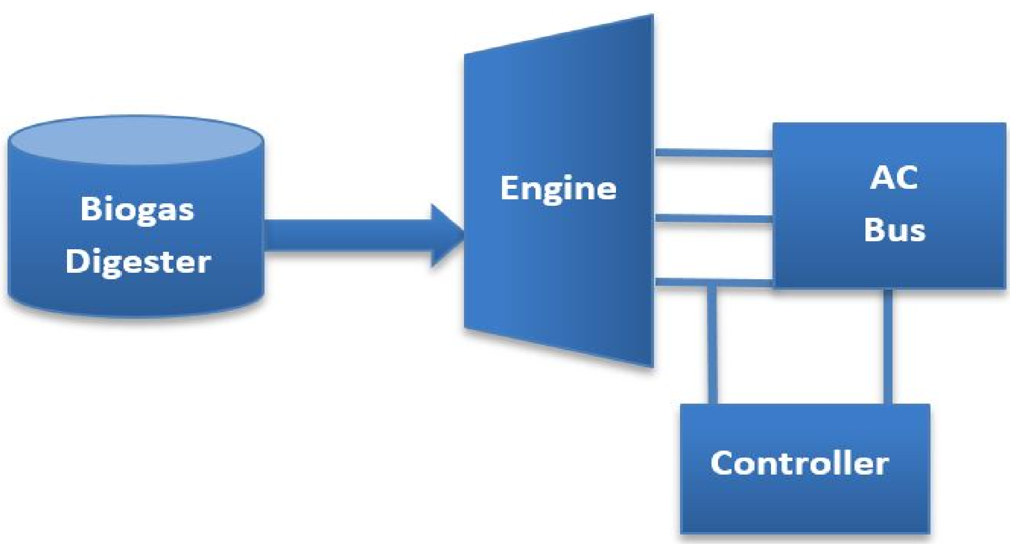



Figure 4.4: Biogas generator schematic model

Energy in kWh produced by a biogas generator can be represented as follows:

$$P_{bio}(t) = n_{bio} * V_{bio}(t) * Energy\ Equivalent\ of\ biogas\ (5.6kWh/m^3) \quad (4.8)$$

Where $P_{bio}(t)$ is energy generated by biogas generator (kWh), $V_{bio}(t)$ is volume of biogas ($m^3$) and $n_{bio}$ is efficiency of biogas generator

Energy equivalent of biogas is typically assumed as 5.6 kWh/$m^3$. It can be interpreted that the energy delivered also depends on the composition of the biomass used to generate biogas as well as the ratio of water to the biomass used. Normal value of water to biomass ratio is 4:5 by volume [36].

**Pico hydro power plant**

The term hydropower usually refers to generation of rotary mechanical power from falling water. This mechanical power most often is used to generate electricity. Continuous and large amounts of electrical energy can be obtained from hydropower as compared to PV or wind systems. Pico hydro power plant refers to units with generation capacity of less than 10 kW.

When a water discharge $Q_t$ ($m^3$/s) passes through the plant, the delivered power of a picohydro power plant is calculated as shown in equation below [37]:

$$P_{hydro}(t) = \rho_w * g * Q_t(t) * H_d \quad (4.9)$$

$P_{hydro}(t)$ is energy generated by picohydro powerplant (kWh), $\rho_w$ is the density of water (1000kg/$m_3$), g is Acceleration due to gravity (9.8m/$s^2$) and $H_d$ is effective height of the reservoir (m).

### Wind-driven mechanical water pumps

A wind-driven mechanical water pump comprises of a medium solidity wind rotor coupled mechanically to a roto-dynamic pump through the mechanical power transmission mechanism. The speed of the wind rotor can be stepped-up several times to meet the requirement of the roto-dynamic pump using suitable gear arrangement [38].

The power developed by the rotor at the design point ($P_T$) can be given as

$$P_T = \frac{1}{2}\rho_a \left[\frac{\pi D_T^2}{4}\right] V_d^3 C_{pd} \tag{4.10}$$

Where $\rho_a$ is density of air, $D_T$ is the diameter of the wind rotor, $V_d$ is the design wind velocity and $C_{pd}$ is design power co-efficient of the wind rotor.

And the power consumed by the pump at this point ($P_p$) is given by

$$P_p = \rho_w \frac{g H_d Q_d}{\eta_{pd}} \tag{4.11}$$

Where $\rho_w$ is the density of water, g is acceleration due to gravity, $H_d$ is design pumping head, $Q_d$ is discharge at design point and $\eta_{pd}$ is efficiency of the pump at design point.

At design point, both turbine and pump efficiencies are at its peak. Therefore

$$P_{TD} = P_{PD} \tag{4.12}$$

Where $P_{TD}$ is power generated by the wind rotor at design point and $P_{PD}$ is power demand of the pump at design point.

From the above equations, the discharge of the system at the design point can be estimated as

$$Q_d = \frac{1}{2}\eta_{pd} C_{pd} \frac{\rho_a}{\rho_w} \left[\frac{\pi D_T^2}{4}\right] \frac{V_d^3}{g H_d} \tag{4.13}$$

For an ideal roto-dynamic pump,

$$Q \propto N_p D_p^3 \tag{4.14}$$

Where $N_p$ is the speed of the pump and $D_p$ is the diameter of the pump.

In terms of discharge at the design point, discharge of the pump at any velocity V ($Q^i_{wind}(t)$) can be given as,

$$Q^i_{wind}(t) = Q_d \left(\frac{N_{pV}}{N_{pd}}\right) \tag{4.15}$$

Here $N_{pV}$ and $N_{pd}$ is speed of the pump at wind velocity V and design point respectively.

The rotational speed of the pump at any velocity can be represented as

$$N_{pV} = G\lambda_d V \left(\frac{1}{\pi D_T}\right) \tag{4.16}$$

G is the gear ratio and $\lambda_d$ is the design tip speed ratio of the wind rotor.

At any wind velocity $V^i$ (t), water discharge can be given as

$$Q^i_{WG}(t) = \frac{1}{8}\eta_{pd} C_{pd} v^i(t) D_T \frac{\rho_a}{\rho_w} \left[\frac{G\lambda_d}{N_{pd}}\right] \frac{V_d^3}{g H_d} \tag{4.17}$$

**PV powered water pumps**

PV powered water pumps consists of PV array, pump controller and submerged pump. A schematic diagram of the direct coupled PV water pumping system is shown in Figure 4.5

Water flow rate of the pump depends on the power produced and can be given as

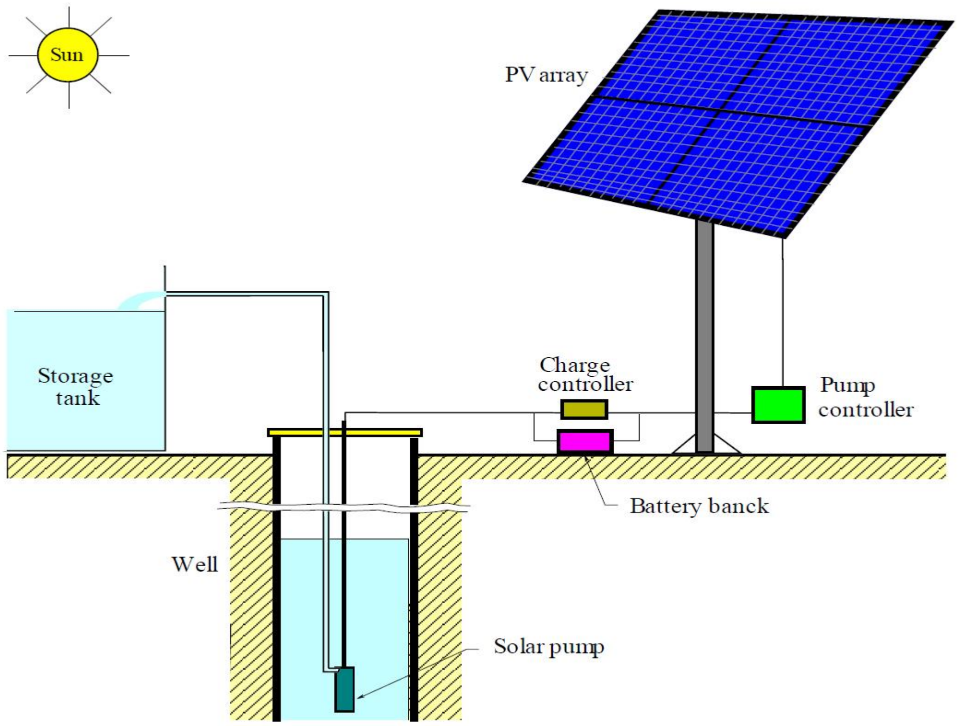



Figure 4.5: Schematic diagram of the direct coupled PV water pumping system

[39],

$$Q^i_{PV}(t) = \frac{(N_s * N_p) * \eta_p * P^i_{PV}(t, \beta)}{\rho_w * g * H_d} \tag{4.18}$$

Where $N_S$*$N_P$ is the total number of cells, $H_d$ is the height of the reservoir and $\eta_p$ is the pump efficiency.

### Biogas powered water pumps

A biogas powered water pump mainly consists of an engine, a submerged pump and biogas inlet. The volume of water pumped by biogas ($Q^i_{bio}(t)$) can be expressed as [28],

$$Q^i_{bio}(t) = \frac{\eta_{pump} * \eta_{engine} * V^i_{bio}(t) * 5.6 * 367}{H_d} \tag{4.19}$$

Where $\eta_{pump}$ and $\eta_{engine}$ is the pump and engine efficiency respectively.

$V^i_{bio}$ (t) is the volume of biogas in $m^3$.The number 5.6 denotes kWh energy value of 1 $m^3$ of biogas.

### Battery Bank

The battery bank, with a nominal capacity ($C_n$) is permitted to discharge up to a limit defined by the maximum permissible depth of discharge (DOD) (%). DOD is usually specified by the user at the beginning of the optimal sizing process. The minimum permissible battery capacity ($C_{min}$) during discharging is giving as follows [34],

$$C_{min} = DOD * C_n \tag{4.20}$$

Depending on energy produced and load demand requirements, the battery state of charge is found during the simulation as follows:

$$\begin{aligned} P_B^i(t) &= P_{WG}^i(t) + P_{PV}^i(t, \beta) + P_{hydro}^i(t) && (4.21) \\ &\quad + P_{bio}^i(t) - P_{load}^i(t) \\ C^i(t) &= C^i(t-1) + \eta_b \frac{P_B^i(t)}{V_{DC,bus}} \Delta t && (4.22) \\ C^i(24) &= C^{i+1}(0) && (4.23) \end{aligned}$$

Where $C^i$ (t) and $C^i$ (t-1) is the available battery capacity (Ah) at hour t and t-1 respectively, of day i. $\eta_b$ =80% is the battery efficiency during charging and $\eta_b$ =100% is the battery efficiency during discharging. $V_{DC,bus}$ is the DC bus voltage (V). $P_B^i$ (t) is the battery input/output power (W) [$P_B^i$ (t) $< 0$ during discharging and $P_B^i$ (t) $> 0$ during charging] and $\Delta$ is the simulation time step and is equal to 1.

The number of batteries connected in series, $n_B^s$, depends on the nominal DC bus voltage and the nominal voltage of each individual battery, $V_B$ and is calculated as follows,

$$n_B^s = \frac{V_{DC,bus}}{V_B} \tag{4.24}$$

The battery bank nominal capacity is related with the total number of batteries, the number of series connected batteries and nominal capacity of each battery and is given as follows,

$$C_n = \frac{N_{Bat}}{n_B^s} C_B \tag{4.25}$$

### 4.2.2 Modeling system reliability and annualized cost

Reliability is the probability of a device performing its purpose adequately for the period of time intended under operating conditions encountered. Several reliability indices have been introduced in the past decades. Some of the most commonly used indices in the reliability evaluation of generating systems are Loss of Load Expectation (LOLE), Loss of Energy Expectation (LOFE), Expected Energy not Supplied (EENS), Loss of Power Supply Probability (LPSP) and Equivalent Loss Factor (ELF) [40].

#### Power reliability model based on LPSP concept

Solar radiation and wind speed characteristics are intermittent and have high influence on the resulting energy production. Hence power reliability analysis has been considered as an important step in any system design process. A reliable electrical power system is a system that has sufficient power to feed the electrical load demand during a given period. In other words, it has a small loss of power supply probability (LPSP). For a considered period, LPSP is the ratio of all the loss of power supply over the total load required during that period. It is defined as the probability that an insufficient power supply results when the hybrid system is unable to satisfy the load demand. A LPSP of 0 means the load will always be satisfied and a LPSP of 1 means that the load will never be satisfied. Since LPSP is a ratio, it is a non-dimensionless statistical parameter. During a bad resource year, the system will suffer from a higher probability of losing power and LPSP will be close to 1 [32].

There are two approaches to the application of LPSP in designing a SIRES. One is based on chronological simulation and the other is based on the probabilistic techniques. First approach is computationally burdensome and requires the availability of data spanning a period of several years although it is realistic. Second approach incorporates the fluctuating nature of resources and the load thus eliminating the need for a time series data. First approach is used in this study considering the energy accumulation effect to the battery and presents the system working conditions more precisely [41] - [42].

The objective function, LPSP, from time 1 to T can be described as,

$$LPSP = \frac{\sum_{t=1}^{T} Time(P_{available}(t) < P_{load}(t))}{T} \tag{4.26}$$

where T is the number of hours in this study with hourly weather input data. In other words, LPSP can be defined as

$$LPSP = \frac{\sum_{t=1}^{T} LPS}{\sum_{t=1}^{T} P_{load}(t)\Delta t} \tag{4.27}$$

Loss of power supply (LPS) at hour t can be expressed as

$$\begin{aligned} LPS = P_{load}(t)\Delta t - ((P_{WG}(t) + P_{PV}(t) + P_{hydro}(t) \\ + P_{bio}(t))\Delta t + C(t-1) - C_{min})\eta_{inverter} \end{aligned} \tag{4.28}$$

where $\Delta$ t is the time step used for calculations. In this study, it is considered as 1 hour. During the time step, power generated by wind turbine, PV module, pico hydropower plant and biogas generator is assumed to be constant.

The power failure time is defined as the time that the load is not satisfied by insufficient power generated and the storage is depleted. The power required by the load can be given as [33],

$$P_{load}(t) = \frac{P_{ACload}(t)}{\eta_{inverter}(t)} + P_{DCload}(t) \tag{4.29}$$

**Water reliability model based on LWSP concept**

Based on the concept LPSP, another probability called Loss of Water Supply Probability (LWSP) is introduced. Since SIRES has multiple outputs, it is mandatory to build reliability model for each output, one of them being water supply for potable, domestic and irrigation purposes. Water is pumped and stored in an overhead reservoir and used whenever need arises. Wind mechanical conversion systems, PV powered water pumps and biogas powered water pumps are used to pump water to the overhead reservoir. For a considered period, LWSP is the ratio of all the loss of water supply over the total water required during that period. When LWSP is 0, it means the water required has been satisfied. Otherwise when LWSP is 1, the water required has never been satisfied.

The objective function, LWSP, from time 1 to T can be described as,

$$LWSP = \frac{\sum_{t=1}^{T} Time(Q_{available}(t) < Q_{load}(t))}{T} \tag{4.30}$$

where T is the number of hours in this study with hourly weather input data. In other words, LWSP can be defined as

$$LWSP = \frac{\sum_{t=1}^{T} LWS}{\sum_{t=1}^{T} W_{load}(t)\Delta t} \tag{4.31}$$

where $W_{load}(t)$ is amount of water required to fulfill needs ($m^3$).

Loss of water supply (LWS) for an hour t can be expressed as

$$LWS = W_{load}(t)\Delta t - ((Q_{WG}(t) + Q_{PV}(t) + Q_{bio}(t) + Q_{SH}(t))\Delta t)\eta_{pump} \tag{4.32}$$

$Q_{SH}(t)$ is water stored in reservoir ($m^3$). where Δt is the step of time used for calculations. In this study we consider it as Δt=1 hour. During that time the water pumped by wind mechanical conversion systems, PV powered water pumps and biogas powered water pumps is assumed to be constant.

### Annualized Cost of System (ACS)

To identify the optimum combination of system components for SIRES, a tradeoff is made between the two objectives considered: the system reliability and system cost. Cost analysis in this study based on the concept of Annualized Cost of System (ACS). ACS comprises of annualized capital cost ($C_{cc}$), annualized replacement cost ($C_{rc}$) and annualized maintenance cost ($C_{mc}$). Main components of SIRES considered for the economic model are biogas digester ($B_D$), biogas powered generator ($B_G$), biogas powered water pump ($B_P$), hydro-turbine ($H_T$), wind turbine ($W_T$), wind powered water pump ($W_P$), PV panel ($P_E$), PV powered water pump ($P_P$) and battery bank ($C_B$).

Annualized capital cost ($C_{cc}$) of each component takes into account the installation cost and is given as [43],

$$C_{cc} = C_{ij}.CRF(r, n_{ij}) \tag{4.33}$$

Where $C_{ij}$ is the capital cost of equipment that uses $i^{th}$ resource to fulfill the $j^{th}$ task ($), $n_{ij}$ is the lifetime in years for $i^{th}$ - $j^{th}$ combination, r is the annual rate of interest and CRF is the Capital Recovery Factor. CRF can be defined as a ratio to calculate the present value of an annuity (a series of equal annual cash flows) and can be expressed as

$$CRF = \left(\frac{r(1+r)^{n_{ij}}}{(1+r)^{n_{ij}} - 1}\right) \tag{4.34}$$

Annual rate of interest is related to nominal interest rate $r'$ and the annual inflation rate $f$ by the equation given below

$$r = \frac{r' - f}{1 + f} \tag{4.35}$$

Annualized replacement cost of a system component is the annualized value of all the replacement costs occurring throughout the lifetime of the project and is given as

$$C_{rc} = C_{rep}.SFF(r, n_{rep}) \tag{4.36}$$

Where $C_{rep}$ is the replacement cost of equipment (\$), $n_{rep}$ is the component lifetime in years and SFF is the sinking fund factor. SFF is a ratio to calculate the future value of an annuity and is given as

$$SFF = \left(\frac{r}{(1+r)^{n_{rep}} - 1}\right) \tag{4.37}$$

System maintenance cost, which includes inflation rate $f$ is given as,

$$C_{mc}(n) = C_{mc}(1).(1+f)^n \tag{4.38}$$

Where $C_{mc}$ (n) is the maintenance cost of the $n^{th}$ year.

Then ACS for water supply is given as

$$ACS_w = C_{cc}(B_p + W_p + P_p) + C_{mc}(B_p + W_p + P_p) + C_{rep}(B_p) \tag{4.39}$$

And ACS for electricity supply is given as

$$\begin{aligned} ACS_e = C_{cc}(B_G + W_T + P_E + H_T + C_B) + C_{mc}(B_G \\ +W_T + P_E + H_T + C_B) + C_{rep}(B_G + +C_B) \end{aligned} \tag{4.40}$$

## 4.3 Stage 3: Optimization Stage

### 4.3.1 Literature Review

Koutroulis et al. have proposed a methodology for optimal sizing of stand-alone PV/Wind systems using Genetic Algorithms (GA) [34]. The suggested approach has been applied to design a power generation system for a residential household. A Hybrid Energy System (HES) was developed by Ashok to provide electrification of the rural villages in Western Ghats (Kerala), India [44].The combination of micro-hydro and wind systems was optimized by minimizing life-cycle cost. An optimal sizing method for stand-alone solar-wind system using genetic algorithm was proposed by Yang et al [43]. Minimum Annualized Cost of System (ACS) and required Loss of Power supply probability (LPSP) were the two objective functions considered. Kanase-Patil et al. formulated and optimized IRES for different available options for a cluster of villages to supply electricity. Reliability worth, Cost of Energy (COE), effect of sensitive prices of biomass fuel have also been studied [45].

A decentralized, off-grid electrification using renewable energy technologies for rural Tanzania and Mozambique is recommended by Ahlborg [46]. This thesis also included an exhaustive list of barriers to rural electrification in sub-Saharan Africa, as perceived by power sector actors. A multi-objective optimization model is suggested by Agarwal et al. to optimally size grid independent solar-diesel-battery based hybrid system. The proposed model was applied to unelectrified remote village of India to minimize total life cycle cost of the system and minimize $CO_2$ emissions from the system [47]. Ramoji et al. presented a Genetic Algorithm and Teaching Learning Based Optimization (GA and TLBO) to economically size PV-Wind hybrid energy system [48].Ko et al. designed a multi-objective optimized hybrid energy system consisting of three types of renewable energy and six types of fossil fuels. The aim of the paper was to minimize Life Cycle Cost (LCC) while simultaneously maximizing the penetration of renewable energy and minimize annual Greenhouse Gas (GHG) emissions [49]. A study was carried out by Barman et al. in four districts of Assam, India to assess the technical functionality of Solar Home Lighting Systems (SHLS) [50].

Previously, optimization techniques such as genetic algorithm have been used to optimally size the components for only single output (electricity) systems. In this thesis, GA has been used for a multi-output (biogas for cooking, water for domestic and irrigation use, electricity) systems. A notable complexity dealing with multi-resource multi-need system is that one resource will be used to fulfill various needs simultaneously. This requires additional energy management techniques, which have been embedded in SIRES. The flowchart of the optimization process is illustrated in Figure 4.6.

### 4.3.2 Introduction to Genetic Algorithm (GA)

Holland and his colleagues developed the concept of genetic algorithm in 1960-70s and is inspired by the evolutionist theory explaining the origin of species [51]. In GA terminology, a solution vector $x \in X$ is called an individual or a chromosome. Chromosomes are made of discrete units called genes and each gene controls one or more features of the chromosome. A chromosome corresponds to a unique solution x in the solution space. This requires a mapping mechanism between the solution space and chromosomes. This mapping is called an encoding. In fact, GA works on the encoding of a problem, not on the problem itself. GA operates with a collection of chromosomes called a population. It uses two operators called crossover and mutation to generate new solutions from existing ones. Among them, crossover operator is the most important. In crossover, generally two chromosomes called parents are combined together to form new chromosomes, called offspring. The mutation operator introduces random changes into the chromosome characteristic.

A generic GA has the following procedure:

Step 1: For i=1, n solutions are randomly generated to form the first population, P1. Next the fitness of solutions in P1 is evaluated.

Step 2: Crossover operation- an offspring population Qi is generated as follows. Two solutions x and y are chosen from Pi based on the fitness values. Using a crossover operator, an offspring is generated and added to Qi.

Step 3: Mutation- Each solution $x \in$ Qi is mutated with a predefined mutation rate.

Step 4: Fitness Assignment- Each solution $x \in$ Qi is evaluated and assigned a fitness value based its objective function value and infeasibility.

Step 5: Selection- N solutions from Qi are selected based on their fitness and assigned them Pi+1.

Step 6: Once stopping criteria is satisfied, the search is terminated and returned to the current population. Else i is set as i=i+1 and step 2 is evaluated.

GA is well suited to solve multi-objective optimization problems, as they are population-based. A single-objective GA can be easily transformed into a multi-objective to find a set of multiple non-dominated solutions in a single run. GA has the ability to simultaneously search different regions of a solution space. This makes it possible to find a diverse set of solutions for complex problems with discontinuous, non-convex and multi-modal solution spaces. Another advantage of multi-objective GA is that most of GAs do not require prioritization, scale, or weigh objectives [52].

Schaffer proposed the first multi-objective GA called Vector Evaluated Genetic Algorithm (VEGA) [53]. Other important multi-objective evolutionary algorithms such as Multi-objective Genetic Algorithm (MOGA) [54], Niched Pareto Genetic Algorithm [55], Random Weighted Genetic Algorithm (RWGA) [56], Non-dominated Sorting Genetic Algorithm (NSGA) [57], Strength Pareto Evolutionary Algorithm (SPEA) [58], Fast Non-dominated Sorting Genetic Algorithm (NSGA-II) [59], Multi-objective Evolutionary Algorithm (MEA) [60] were developed.

### 4.3.3 Application of GA to SIRES design

Genetic Algorithm (GA) is an advanced search and optimization technique. It is robust in finding global optimal solutions especially for multi-objective optimization problems, as it is a population-based approach. A single-objective GA can be easily transformed into a multi-objective to find a set of multiple non-dominated solutions in a single run. GA has the ability to simultaneously search different regions of a solution space. This makes it possible to find a diverse set of solutions for complex problems with discontinuous, non-convex and multi-modal solution spaces. Another advantage of multi-objective GA is that most of GAs do not require prioritization, scale, or weigh objectives [43],[52].

In the proposed method, optimum number of biogas digester ($B_D$), biogas powered generator ($B_G$), biogas powered water pump ($B_P$), hydro-turbine ($H_T$), wind turbine ($W_T$), wind powered water pump ($W_P$), PV panel ($P_E$), PV powered water pump ($P_P$) and battery bank ($C_B$) is generated using Genetic Algorithm such that the 25-year lifetime annualized cost is minimized. The optimum number of system components along with the height of wind turbine comprise the set of decision variables. One year of hourly data for solar radiation, ambient air temperature, wind speed, water availability, biogas availability, load power consumption, domestic and irrigation water demand and cooking demand is used in the model.

Initial assumptions for the system configuration are subject to the following constraints:

$$Min(B_G, B_P, H_T, W_T, P_E, P_P, C_B) \geq 0 \tag{4.41}$$

Subject to:

$$LPSP_{min} \leq LPSP \leq LPSP_{max} \tag{4.42}$$

$$LWSP_{min} \leq LWSP \leq LWSP_{max} \tag{4.43}$$

$$C_{min}(t) \leq C^i(t) \leq C_{max}(t) \tag{4.44}$$

$$h_{low} \leq h \leq h_{high} \tag{4.45}$$

A genetic algorithm for optimal sizing of SIRES is formulated to minimize ACS subject to reliability. An initial population of a set of chromosomes which forms the first generation, is randomly generated and the constraints are evaluated for each chromosome. If any chromosome of the initial population violates the constraints, then it is replaced by a new chromosome that fulfills these constraints. The chromosome for genetic algorithm has 9 genes and is of the form $[P_E \mid W_T \mid B_G \mid H_T \mid h \mid C_B \mid P_P \mid W_P \mid B_P\ ]$.

Energy produced by renewable technologies of SIRES is calculated. The system configuration is then optimized by employing a genetic algorithm, which dynamically searches for the optimal configuration to minimize ACS. For every system configuration, the systems LPSP and LWSP is calculated and verified if it meets the set target. The lower cost configurations is subject to the crossover and mutation operations of the GA. This step produces the next generation population. The process continues till a criterion that determines convergence is satisfied. Optimal configuration for the desired LPSP and LWSP is identified both technically and economically from the set of configurations by achieving the lowest ACS. The flowchart of the optimization process is illustrated in Figure 4.6.

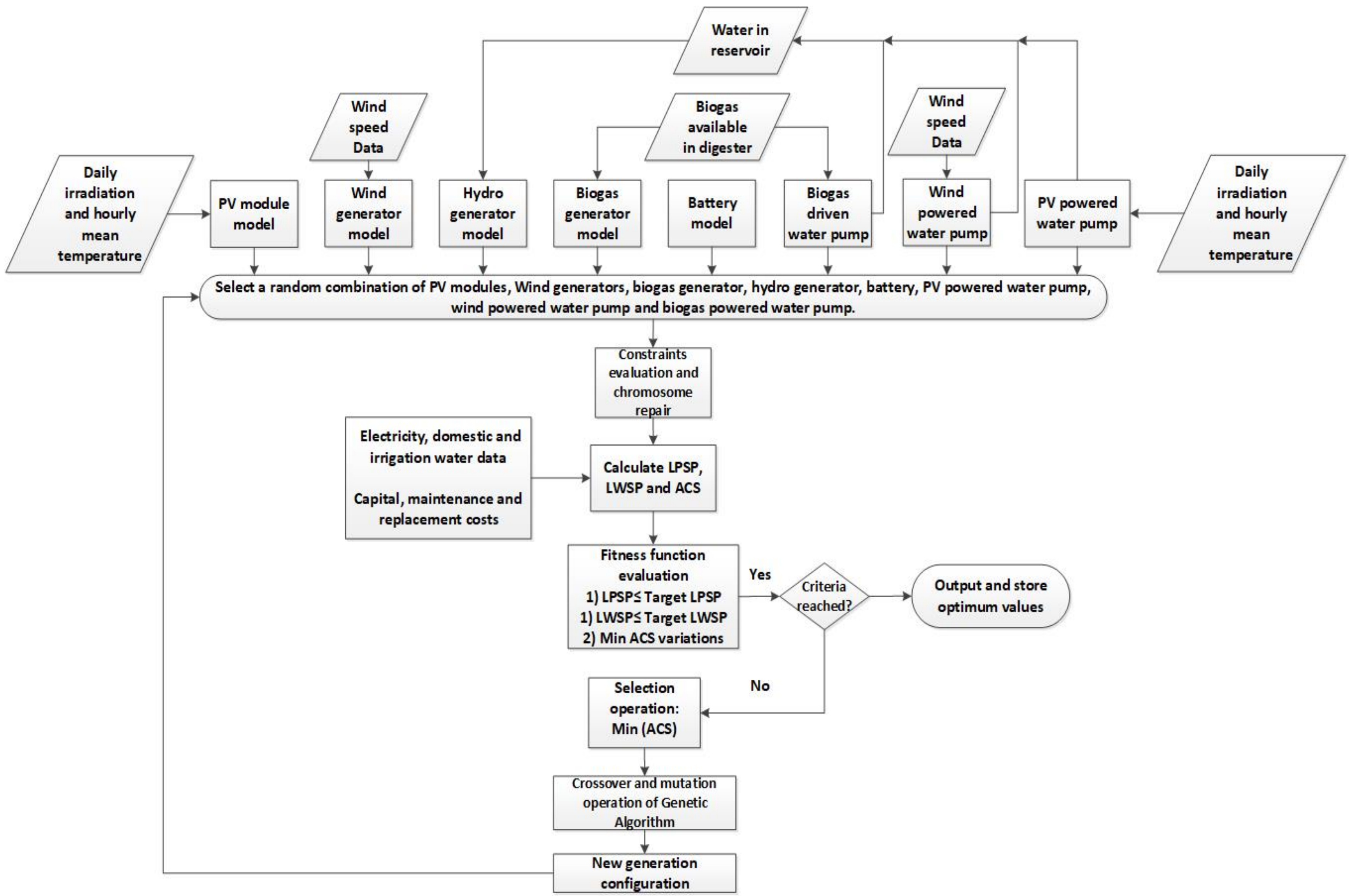



Figure 4.6: Flowchart of the optimal sizing model of SIRES using GA

# CHAPTER 5

# ECONOMIC, SOCIAL AND ENVIORNMENTAL IMPACTS OF SIRES

In this chapter, economic, social and environmental aspects of SIRES are studied and compared with microgrid with diesel generator (MDG) and microgrid without diesel generator (MDWG). All the parameters used for estimation may vary for different locations and time taken into consideration. Economic impacts are discussed based on optimal sizing obtained using Genetic Algorithm.

## 5.1 Economic Impacts of SIRES

Optimum combination of system components in SIRES varies as weather conditions and available resources vary during the time in question: for example, hourly, monthly, seasonally or yearly. Therefore, if the system is to be designed to supply needs throughout the year, then SIRES should be designed accordingly. Hence to obtain an acceptable design of SIRES, one year of hourly data for temperature, wind speed, solar irradiation, water in reservoir and biogas produced are given as input resource data. One year of hourly data for cooking, domestic water, electricity and irrigation water is given as demand data. In this research, the period from September $1^{st}$ 2014 to Aug $31^{st}$ 2015 is chosen as an example to represent climatic conditions for the SIRES design and optimization process. Table 5.1 summarizes the needs required per day. Figure 5.1 to Figure 5.8 show plots of input resource and needs data.

Table 5.2 provides the related capital costs, maintenance costs and replacement costs, which are also inputs to optimal sizing procedure for SIRES [61]-[64]. Capital cost of the system components includes installation cost. Replacement cost is

Table 5.1: Summary of Daily Needs

| Sl no. | Purpose/Need | Quantity per day |
|---|---|---|
| 1 | Biogas for cooking | 238-294 $m^3$ |
| 2 | Domestic water | 50 $m^3$ |
| 3 | Electricity load | 345-415 kWh |
| 4 | Irrigation water | 2000-4800 $m^3$ |

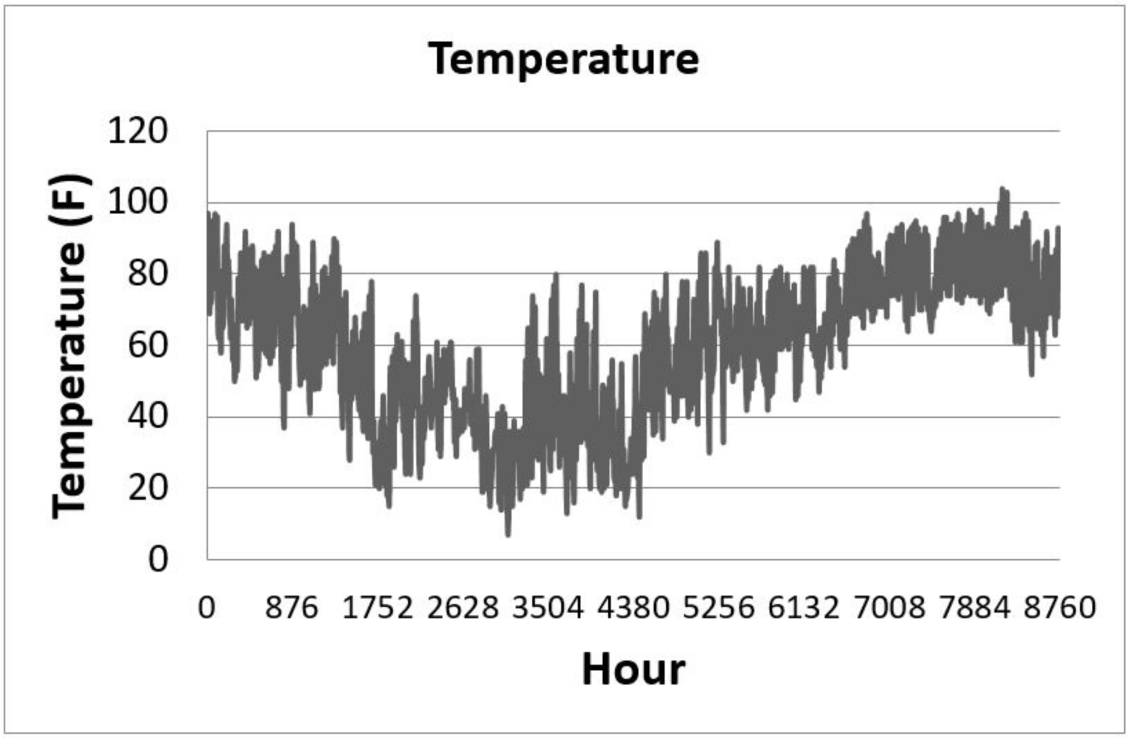



Figure 5.1: Temperature variations for one year

considered for biogas generator, battery and biogas powered water pump. Lifetime of the system is considered to be 25 years. Technical characteristics of all system components used in SIRES are summarized in Table 5.3 [43], [65]-[68].

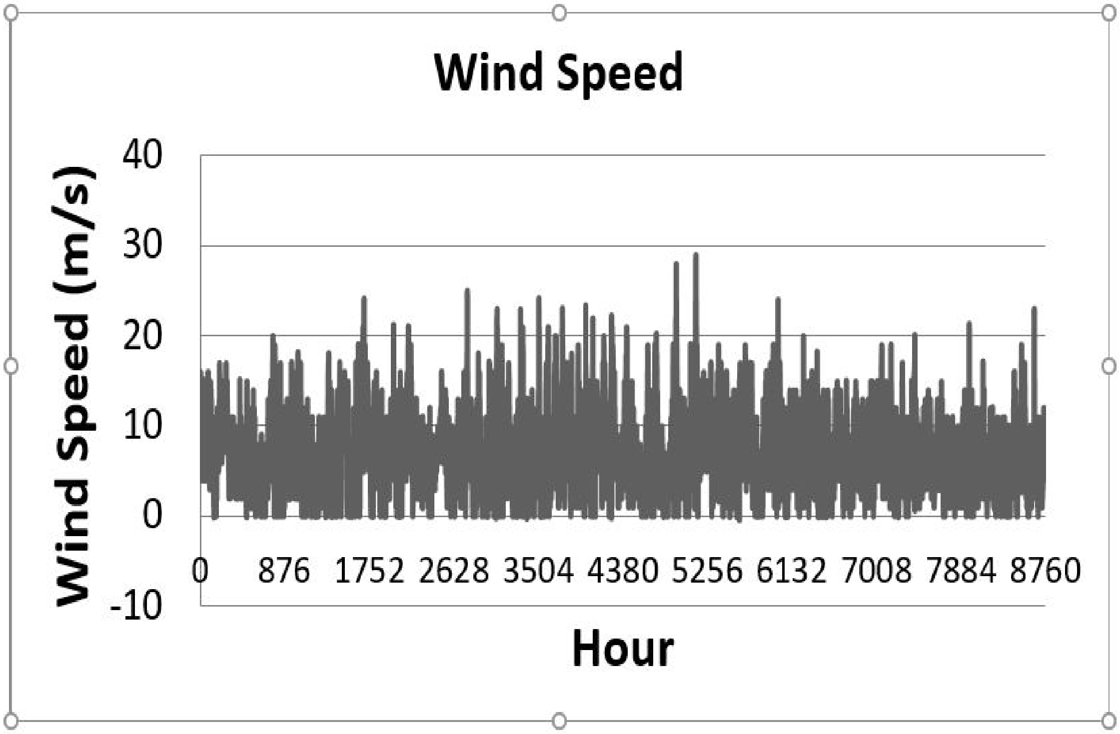



Figure 5.2: Wind Speed variations for one year

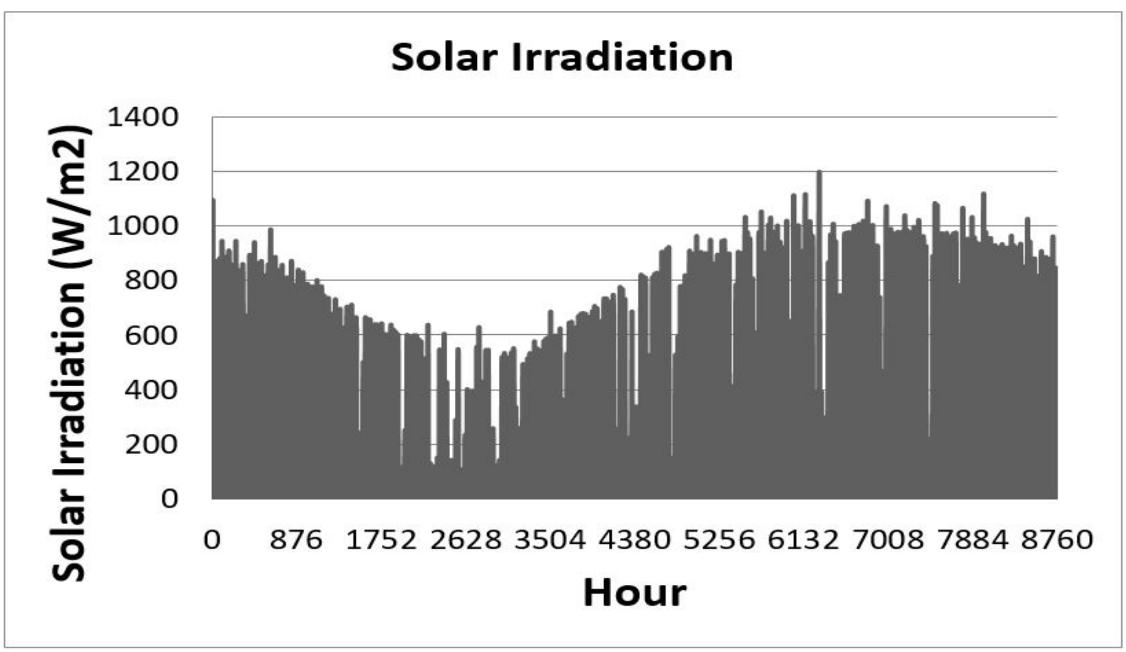



Figure 5.3: Solar irradiation variations for one year

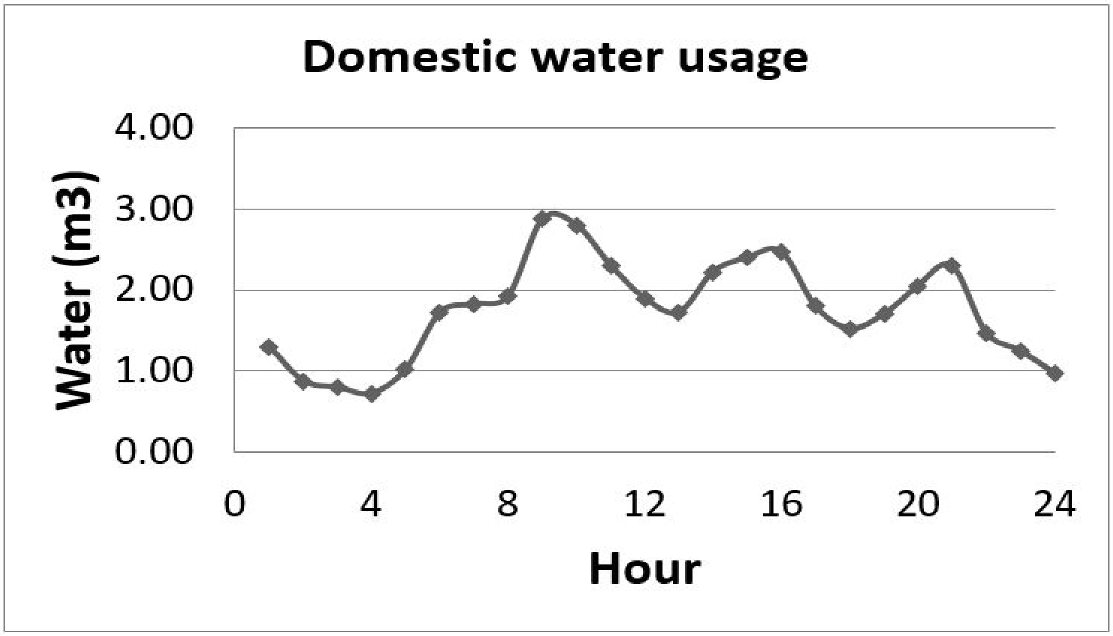



Figure 5.4: Domestic water usage pattern for 24 hours

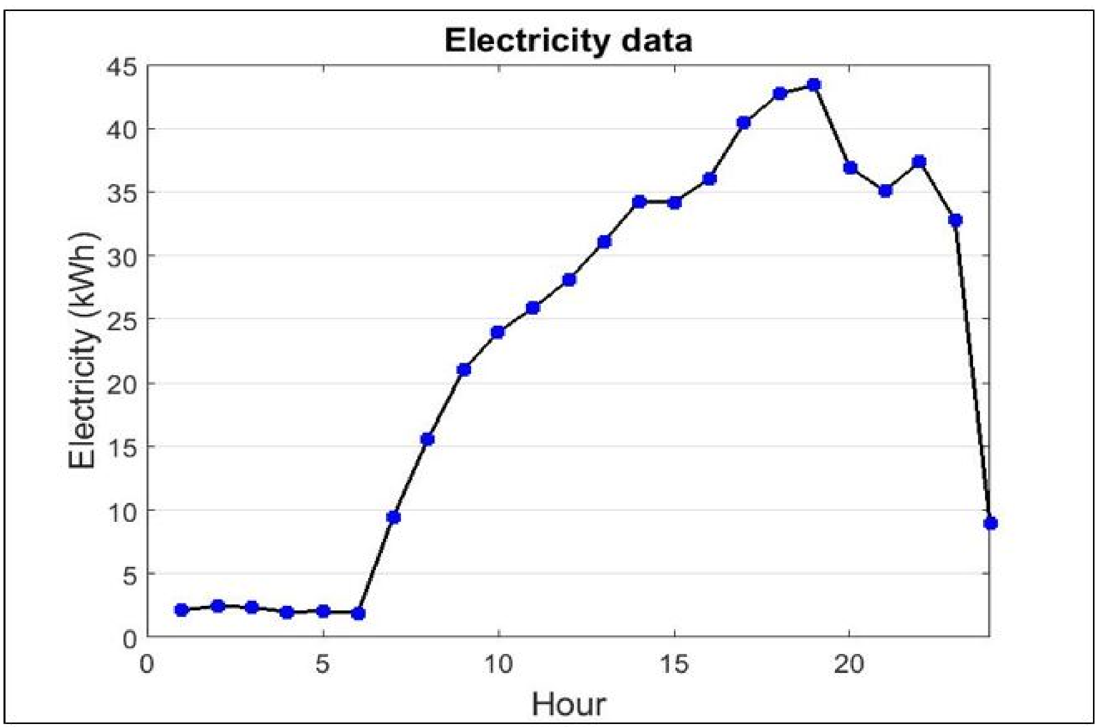



Figure 5.5: Electricity usage pattern for 24 hours


Figure 5.6: Cooking demand pattern for 24 hours

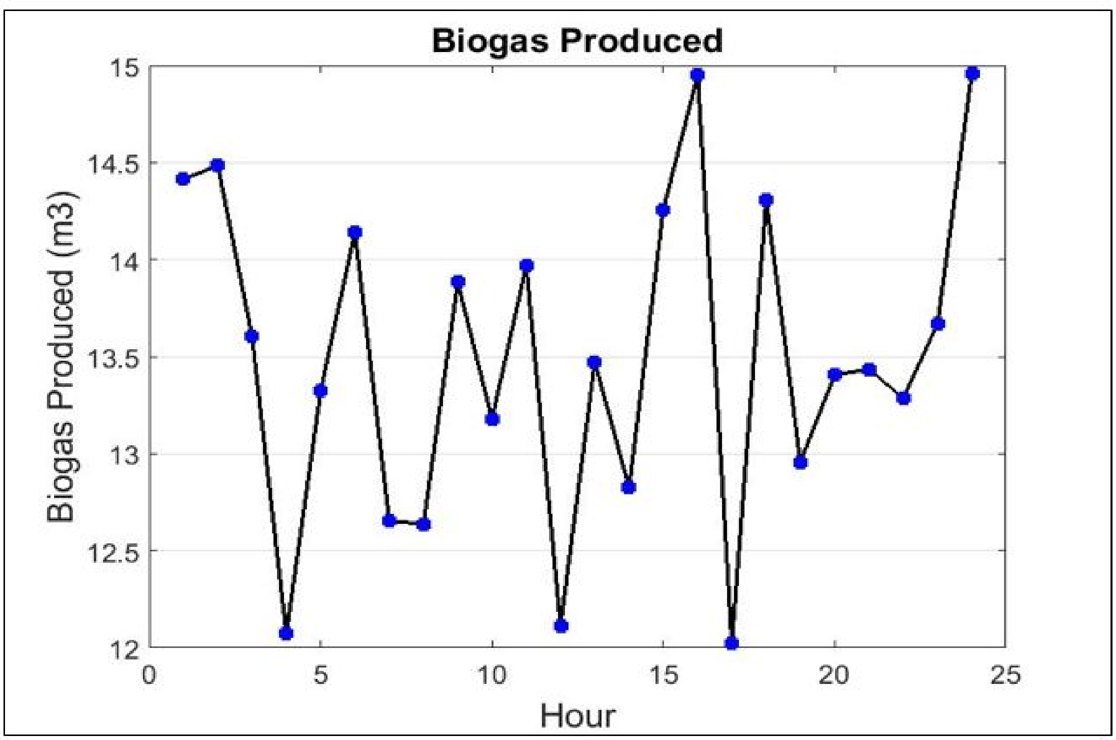



Figure 5.7: Biogas produced over 24 hours

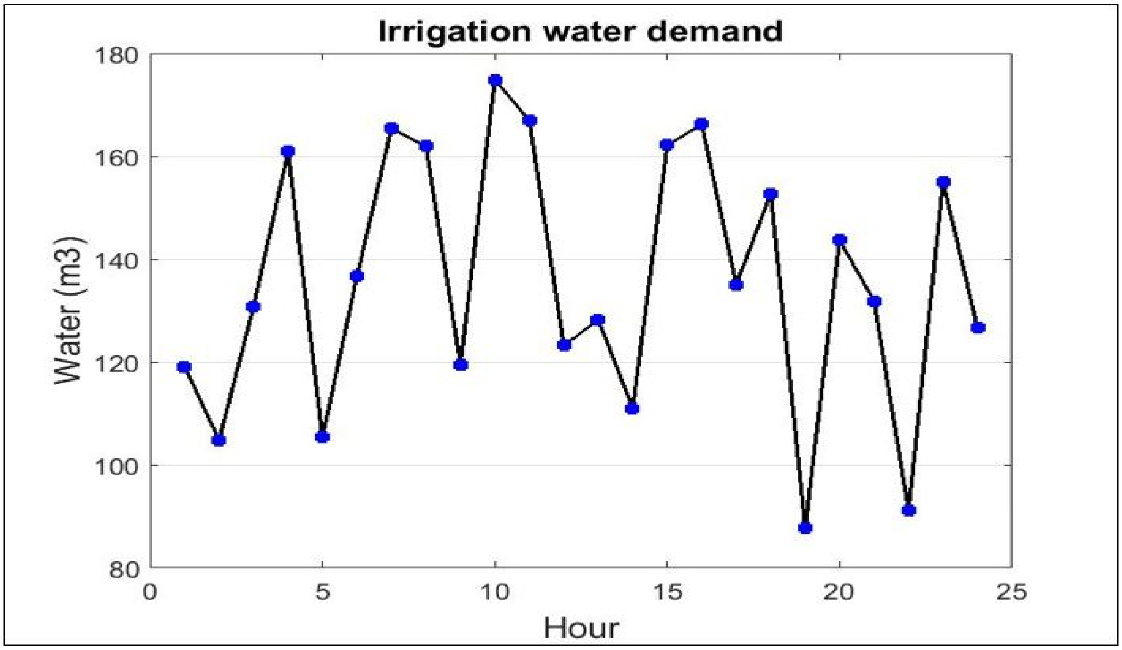



Figure 5.8: Irrigation water usage pattern for 24 hours

### 5.1.1 Results for different electricity configurations of SIRES

Optimal sizing of SIRES is performed in MATLAB using the global optimization toolbox. It contains heuristic algorithms such as the genetic algorithm, particle swarm optimization and so on. A MATLAB code is written with the help of genetic algorithm functions. Three random days are selected from every month within the period September $1^{st}$ 2014 to August $31^{st}$ 2015 since giving one-year data slows down the optimization process. An initial population of 50 chromosomes, comprising the 1st generation is randomly generated subject to the upper and lower bound constraints of genes. The code runs for 200 generations (iterations). Target LPSP and LWSP values are set at 1%.

Wind and solar energy are given the highest priority to fulfill electricity and pumping water needs. The reason to use wind and solar energy is because majority of biogas is used for cooking and water needs to be stored in reservoir to fulfill water demands and for emergency reasons. Three different cases are studied depending on basic needs, normal needs and extended needs for household electricity consumption

Table 5.2: Capital cost, Maintenance cost and Replacement cost for System Components

| Component | Capital Cost (per unit) | Maintenance Cost (/year) | Replacement cost | Lifetime (years) |
|---|---|---|---|---|
| Solar PV | $ 3000/kW | $ 65 | $ 0 | 25 |
| Wind Turbine | $ 1800/kW | $ 95 | $ 0 | 25 |
| Biogas Digester | $ 65/$m^3$ | $ 100 | $ 0 | 25 |
| Biogas Generator | $ 1200/kW | $ 100 | $ 1000 | 8 |
| Reservoir | $ 2000/acre-ft | $ 50 | $ 0 | 25 |
| Pico Hydropower | $ 2300/kW | $ 15 | $ 0 | 25 |
| Battery | $ 1500/kAh | $ 50 | $ 1500 | 8 |
| Wind powered water pump | $ 1000/pump | $ 100 | $ 0 | 25 |
| Solar powered water pump | $ 6000/kW | $ 50 | $ 0 | 25 |
| Biogas powered water pump | $ 2500/kW | $ 100 | $ 2500 | 25 |
| Diesel Generator | $ 500/kW | $ 135 | $ 500 | 8 |
| Other components | $ 10,000 | $ 80 | $ 0 | 25 |

whereas community electricity consumption varies from 45-55 kWh per day. Rest of needs such as domestic and irrigation water are kept the same for all three cases.

Table 5.3: Technical Specifications of System Components

| Specifications | Values |
|---|---|
| **Solar PV module specifications** | |
| Open-Circuit Voltage (Voc) | 44.6V |
| Optimum Operating Voltage(Vmp) | 36.0V |
| Short-Circuit Current (Isc) | 3.03A |
| Optimum Operating Current(Imp) | 2.78A |
| Maximum Power at STC (Pmax) | 100Wp |
| Module Efficiency | 13.8% |
| Nominal Operating Cell Temperature (NOCT) | $48 \pm 3\,^{\circ}C$ |
| Temperature Coefficient of Voc | 0.36%/°C |
| Temperature Coefficient of Isc | +0.06%/°C |
| Module Dimensions | 1090 x 665 x 35mm |
| **Wind turbine specifications** | |
| Cut-in Wind Speed | 2.5 m/s |
| Rated Speed | 11m/s |
| Furling Speed | 13m/s |
| Rated power | 1kW |
| Rotor Diameter | 2.5m |
| **Pico-Hydro power specifications** | |
| Height of reservoir | 20m |
| Flow rate | 10 l/s |
| Efficiency | 70% |
| **Biogas Digester specifications** | |
| Size ($m^3$) | 140 |
| **Biogas Generator specifications** | |
| Efficiency of generator | 70% |
| **Wind powered water pump** | |
| Rotor diameter | 5m |
| Tower height | 20m |
| Pump diameter | 200mm |
| **Solar powered water pump** | |
| Maximum suction lift | 3m |
| Minimum PV array power | 1.1 kW |
| Maximum Current | 22.3 A |
| Pump rate | 30 gpm |
| **Biogas powered water pump** | |
| Power rating | 3.8 kW |
| Efficiency | 50% |
| **Overhead Reservoir** | |
| Size (acre-foot) | 5 acre-feet |
| **Battery Specifications** | |
| Rated Capacity, Voltage | 1000Ah, 24V |
| Charging Efficiency | 90% |

Table 5.4: Different case comparison for household consumption

| Appliance | Basic Needs | Normal Needs | Extended Needs |
|---|---|---|---|
| Bulbs | 15W x 4 x 5h | 15W x 4 x 5h | 15W x 4 x 5h |
| TV | 70W x 5h | 150Wx 5h | 150W x 5h |
| Radio | 15W x 2h | 15W x 2h | 15W x 2h |
| Refrigerator | — | 50W* x 24 | 50W* x 24 |
| Cellphone | 5W x 2 x 2h | 5-10W x 2 x 2h | 5-10W x 3 x 2h |
| Fan | 100W x 2 x 3h | 100W x 2 x 3h | 100W x 3 x 3h |
| Miscellaneous | 100-300Wh | 100-300Wh | 300-600Wh |
| Total | 1400-1600 Wh | 3000-3220 Wh | 3510-3840 Wh |

Table 5.4 shows comparison of different cases for household electricity consumption. For the Annualized Cost of System (ACS) calculations, lifetime of the system is considered to be 25 years. Nominal interest rate (r) is assumed to be 3.75% with an inflation rate of 1.5%. Net present cost (NPC) for a period of 25 years can be calculated as [69],

$$Net\ Present\ Cost\ (NPC) = \frac{ACS}{CRF(r,n)} \tag{5.1}$$

CRF is the Capital Recovery Factor for a rate of interest 'r'and 'n'years. CRF for the case considered is 0.0524. With the NPC, costs are positive and revenues are negative. This is the opposite of the Net Present Value (NPV). As a result, the NPC differs from NPV only in sign [70].

Internal Rate of Return (IRR) is another measure of using the discounted cash flow for arriving at the worth of the project and it is obtained at NPV=0. Higher IRR signifies greater capacity of the project to generate benefits over a period of time [71]. In this work, the Microsoft Excel function IRR was used to obtain IRR for the cases considered.

### Case I: Basic Needs

Basic needs for electricity consumption include basic appliances for lighting and communication such as light bulbs, TV, radio, cell phones, fans and miscellaneous appli-

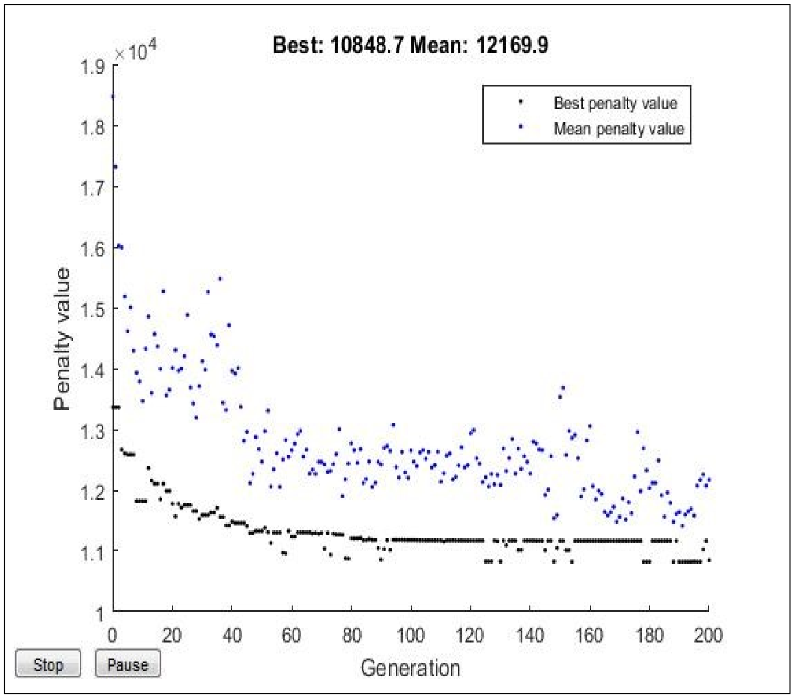



Figure 5.9: Variations of ACS during GA optimization process for case I

ances. The result obtained is arranged in the order of [$PV panels$ | $Wind\ turbines$ | $Biogas\ generators$ | $Micro\ hydroturbine$ | $Battery$ | $PV\ powered\ water\ pump$ | $Wind\ powered\ water\ pump$ | $Biogas\ powered\ water\ pump$] and remains same for all cases. Best annual ACS was found to be $10,848.7 and the corresponding initial installation cost is $106,100. Net present cost for this case is found to be $207,022.9. Figure 5.9 shows the variations of ACS during the GA optimization process. Figure 5.10 presents optimal sizing of system components for case I.

```
xbest =

   50.0000    5.0000    1.0000    3.0000   21.3124    5.0000    3.0000   10.0000    1.0000


Cost function returned by ga = 10848.7
```

Figure 5.10: Optimal Sizing of System Components for case I

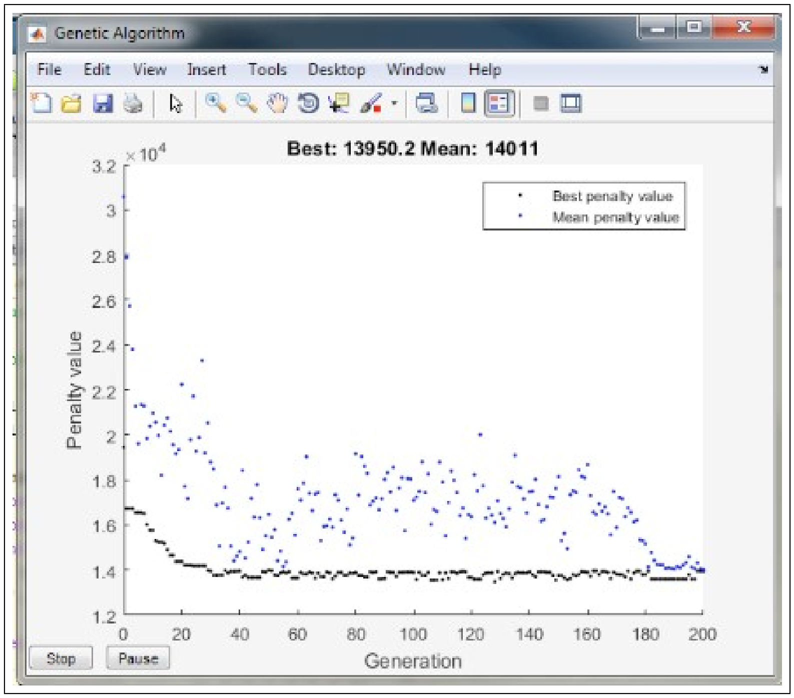



Figure 5.11: Variations of ACS during GA optimization process for case II

### Case II: Normal Needs

Normal needs for electricity consumption include appliances for lighting and communication such as light bulbs, TV, radio, cell phones, fans, refrigerator and miscellaneous appliances. Best ACS was found to be $13,950.2 and the corresponding initial installation cost is $122,900. Net present cost for this case is $266,225.19. Figure 5.11 shows the variations of ACS during the GA optimization process. Figure 5.12 provides optimal sizing of system components for case II.

```
Optimization terminated: maximum number of generations exceeded.

xbest =

   75.0000    9.0000    1.0000    5.0000   20.0004    5.0000    4.0000   10.0000    1.0000


Cost function returned by ga = 13950.2
```

Figure 5.12: Optimal Sizing of System Components for case II

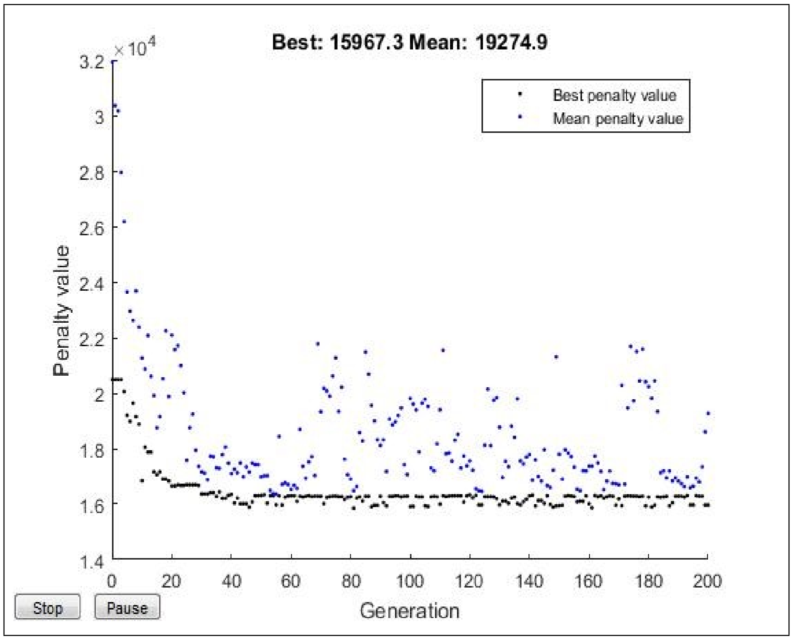



Figure 5.13: Variations of ACS during GA optimization process for case III

### Case III:Extended Needs

Extended needs for electricity consumption include appliances for lighting and communication such as light bulbs, TV, radio, cell phones, fans, refrigerator and additional miscellaneous appliances in comparison to basic and normal needs. Best ACS was found to be $15,967.3 and the corresponding initial installation cost is $150,450. Net present cost for this case is $304,719.46. Figure 5.13 shows the variations of ACS during the GA optimization process. Figure 5.14 presents optimal sizing of system components for case III.

Table 5.5 shows cost and system component ratings comparison between various

```
xbest =

  129.0000   15.0000   1.0000   5.0000   20.4445   5.0000   3.0000   10.0000   1.0000


Cost function returned by ga = 15967.3
```

Figure 5.14: Optimal Sizing of System Components for case III

electricity consumption cases.

### 5.1.2 Cost Comparison of SIRES with various approaches for Rural Development

Cost of SIRES is compared with alternative approaches for rural development such as grid extension, microgrid with and without diesel generator.

#### Rural Electrification or Grid Extension

Grid extension or Rural Electrification has several drawbacks as discussed earlier. However several countries still follow this traditional method to electrify rural areas. Typical costs for grid extension were discussed earlier. Assume $6000/km is average cost for extending the national grid (from Table 2.1 ) and the rural area is 50 km (30 miles) away from the main grid. Then the cost of extending grid to rural area is

Table 5.5: Cost and system component ratings comparison between various cases

| Component | Case I: Basic Needs | Case II: Normal Needs | Case III: Extended Needs |
|---|---|---|---|
| PV panels | 5 kW | 7.5 kW | 13 kW |
| Wind Turbine | 5 kW | 9 kW | 15 kW |
| Biogas Generator | 6 kW | 6 kW | 6 kW |
| Pico Hydro turbine | 3 kW | 5kW | 5 kW |
| Height of wind turbine | 21 m | 20 m | 20 m |
| Battery | 5 strings | 5 strings | 5 strings |
| PV powered water pumps | 3 units | 4 units | 3 units |
| Wind powered water pumps | 10 units | 10 units | 10 units |
| Biogas powered water pumps | 1 unit | 1 unit | 1 unit |
| Annualized Cost of System (ACS) | $ 10,848.7 | $13,950.2 | $15,967.3 |
| Initial Installation Cost | $106,100 | $122,900 | $150,450 |
| Net Present Cost (NPC) | $ 207,022.9 | $266,225.19 | $304,719.46 |

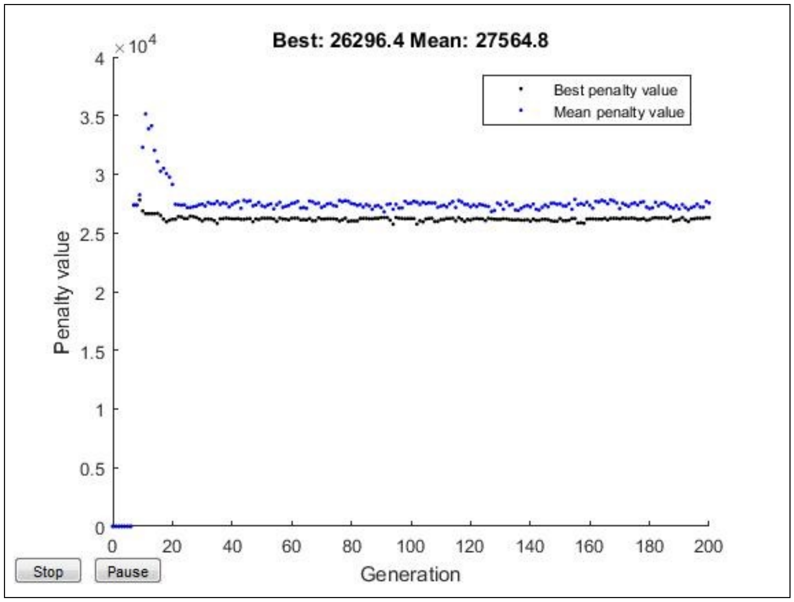


Figure 5.15: Variations of ACS microgrid with diesel generator

\$300,000.

### Microgrid with diesel generator

Microgrids have been gaining importance recently to develop rural areas. As discussed earlier, renewable energy technologies such as solar, wind and biogas are coupled with diesel generators to provide electricity to rural areas. In this case, solar energy, wind, hydropower and biogas coupled with diesel generator are used. Major drawbacks of microgrids including diesel generator are availability of diesel in remote rural areas and environmental effect caused by burning diesel.

Electricity equivalent of 0.05 $m^3$ of biogas used for cooking is 0.17 kWh [72].

Table 5.6: Electricity equivalent of needs fulfilled by SIRES

| **Needs** | **SIRES** | **Microgrid** |
|---|---|---|
| Cooking | 250 $m^3$ of Biogas | 850 kWh |
| Pumping Water | 3600 $m^3$ of Water | 400 kWh |
| Electricity | 300 kWh | 300 kWh |

```
xbest =

  396.0000   15.0000    5.0000    5.0000   20.5297    5.0000   30.0000


Cost function returned by ga = 26296.4
```

Figure 5.16: Optimal Sizing of System Components for microgrid with diesel generator

Energy required to pump water ($E_{pump}$) to overhead reservoir is obtained from [28] as,

$$E_{pump} = \frac{Q * H_d}{\eta_{pump} * 367} \tag{5.2}$$

Where Q is the amount of water to be pumped every day and $H_d$ is effective height of reservoir.In this case, Q is equal to 3600 $m^3$ and $H_d$ is equal to 20 m. Pump efficiency $\eta_{pump}$ is assumed to be 50%. Energy needs fulfilled by SIRES per day are converted to electricity and are given in Table 5.6.

Figure 5.15 shows ACS variations during GA optimization process for microgrid

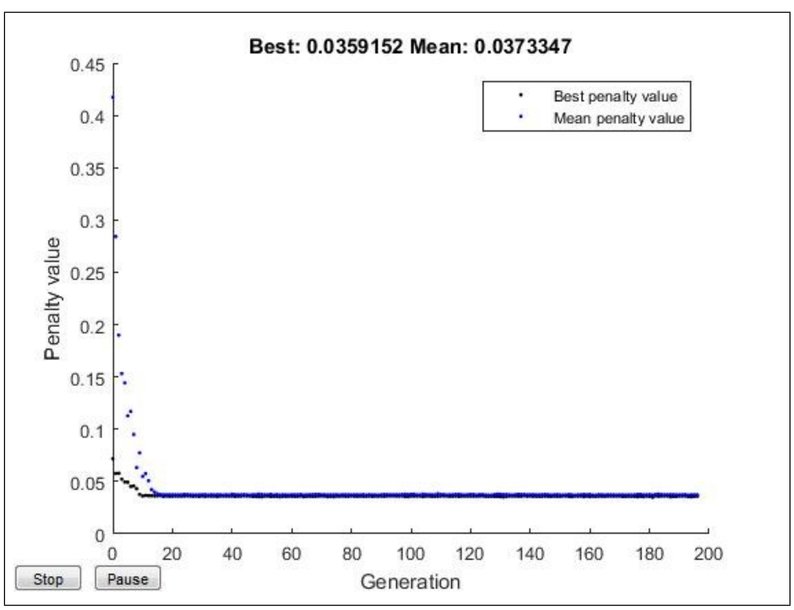



Figure 5.17: Variations of ACS microgrid without diesel generator

```
xbest =

   500.0000   10.0000    5.0000    6.0000   22.3968    5.0000


Cost function returned by ga = 22197.9
```

Figure 5.18: Optimal Sizing of System Components for microgrid without diesel generator

with diesel generator. Optimal sizing of system components of microgrid with diesel generator is arranged in the order of $[PVpanels \mid Wind\,turbines \mid Biogas\ generators \mid Micro\ hydroturbine \mid HeightofWindTurbine \mid Battery \mid DieselGenerator]$ and is shown in Figure 5.16. Best ACS was found to be \$26,296.4 and the corresponding initial installation cost is \$217,000. Net present cost for this case is \$501,839.69.

**Microgrid without diesel generator**

In this case, microgrid uses renewable energy resources such as solar, wind, hydropower and biogas to fulfill the electricity demand. In other words, same resources that are input to SIRES are also given as input resources to microgrid. The main difference is microgrid electrifies the rural area whereas SIRES energizes it. If electricity is used to fulfill all needs, then the annualized cost of system is \$22,197.9 and initial installation cost is \$225,300. Net present cost for this case is \$423,624.04. Figure 5.17 shows ACS variations during the GA optimization process. Optimal sizing of system components of microgrid without diesel generator is arranged in the order of $[PVpanels \mid Wind\ turbines \mid Biogas\ generators \mid Micro\ hydroturbine \mid HeightofWindTurbine \mid Battery]$ and is shown in Figure 5.18.

Table 5.7: Cost Comparison of various Approaches to Rural Development

| Approach to rural development | Grid Extension | Microgrid with diesel generator (MDG) | Microgrid without diesel generator (MWDG) | SIRES |
|---|---|---|---|---|
| Annualized Cost of System (ACS) | – | $26,296.4 | $22,197.9 | $13,950.2 |
| Initial Installation Cost | $300,000 | $217,000 | $225,300 | $122,900 |
| Net Present Cost (NPC) | – | $501,839.7 | $ 423,624.04 | $266,225.2 |
| Internal Rate of Return (IRR) | – | 11% | 9% | 10% |

**SIRES**

The ACS, initial installation cost and net present value of SIRES for normal needs (Case II) is $13,950.2, $122,900 and $266,255.19 respectively as discussed earlier. It is clearly evident that SIRES is a more cost effective system to fulfill the same needs as compared to grid extension, microgrid with diesel generator and microgrid without diesel generator.

Table 5.7 summarizes the cost comparison of various approaches used to fulfill same needs. It is clearly evident that SIRES is a more cost effective system to fulfill the same amount of needs as compared to grid extension, microgrid with diesel generator and microgrid without diesel generator. Another note-worthy point is the installation cost for MDG is less when compared to MWDG. However, net present cost for MDG is higher when compared with MWDG due to the usage of diesel fuel for a period of 25 years. IRR for MWDG is the least and highest for MDG. However, MDG will have adverse effects on the environment as compared to the proposed SIRES.

## 5.2 Social Impacts of SIRES

This section emphasizes the social impacts of SIRES when compared to microgrid. As discussed earlier, readily available renewable resources are utilized to fulfill basic needs. However, the meaning of term ‘basic ’can vary depending on the context for improving the economy of developing countries. Target communities for SIRES installation are remote rural areas that are deprived of elementary needs such as cooking, domestic water and electricity. Implementation of SIRES leads to technical progress and improve the standard of living. Other social benefits include improved health, better education, work opportunities and self-reliance [73]. Researchers have found links between development and rural electrification through the Human Development Index (HDI)[74]. Excess energy that remains after satisfying fundamental needs can be utilized by new extra business or services (extra electrical load with their own battery storage). In addition, construction, manufacturing, installation, operation and maintenance of system components of SIRES creates job opportunities that can be quantified by Job Creation Factor (JCF). Figure 5.19 depicts the influence of energy on socio-economic condition of developing countries[75].

### 5.2.1 Human Development Index (HDI)

Human Development Index (HDI) is defined as an indicator of the country's development that takes into account life expectancy at birth, expected years of schooling and gross national per capita income [76]. HDI is an index that was proposed by the United Nation Development Program (UNDP) in the early 90s to compare countries' development around the globe. The three components of HDI (life expectancy, educational level and income)are equally weighted; 1/3rd for each component.Amongst these components, life expectancy and educational level belong to social viewpoint whereas income considers the economic issues. Figure 5.20 illustrates the vital components of HDI.

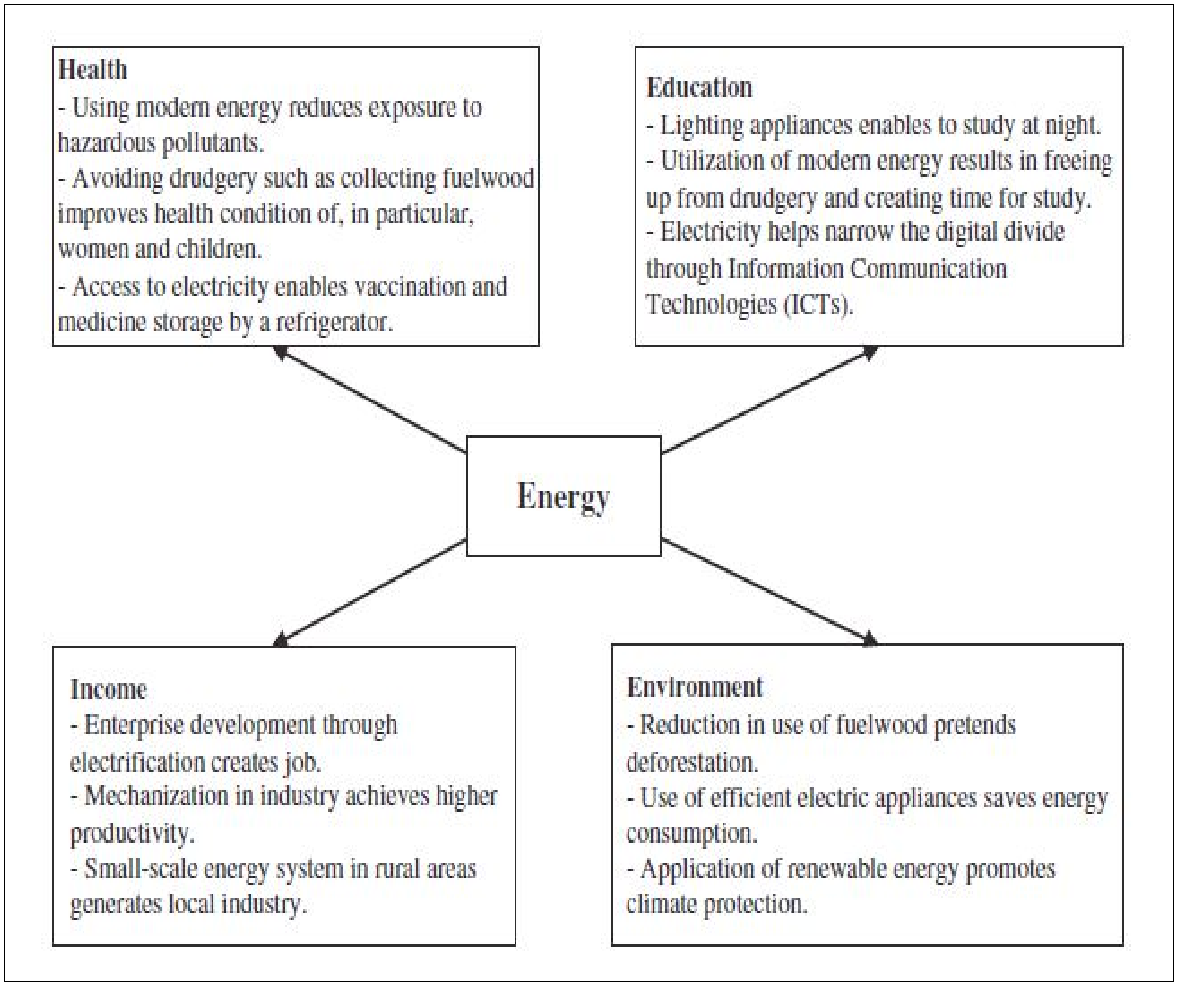



Figure 5.19: Links between energy and other components of developing countries

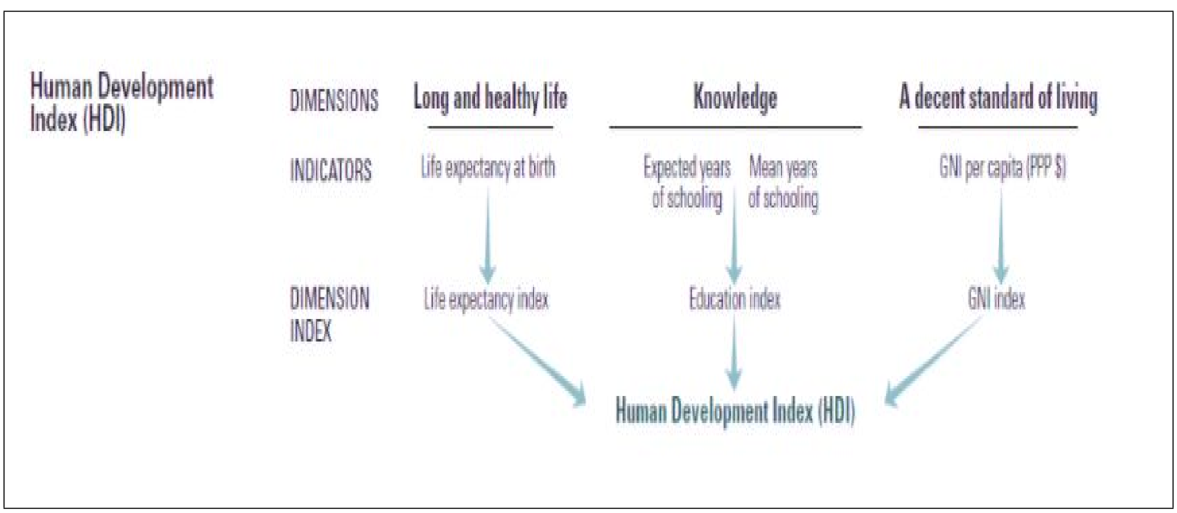



Figure 5.20: Components of Human Development Index(HDI)

Countries with a HDI higher than 0.8 are considered highly developed, countries with HDI values between 0.5 and 0.8 are in the medium development category and those with HDI lower than 0.5 are classified under low development category [74].

Access to electricity can improve all the components of HDI and consequently increase the HDI. SIRES not only provides electricity but also provides biogas for cooking and water for domestic and irrigation purposes. Resources such as insolation, wind, biogas and falling water can generate electricity. The electricity generated fulfills the hourly electrical load and the remainder is stored in battery. When the battery is full, the extra electrical energy can be given to dump load. On the contrary, it can be used by new business ventures or services to generate monetary profits. This excess electricity can be stored in batteries that are owned by these new businesses or services.

Excess electricity can be used to improve educational services as it enables the use of computers and internet. Life expectancy can be improved by health facilities and medicines that require cold storage. Gross national income per capita also increases with new businesses.

Based on the data for 60 countries from the 1999 United Nations Human Development Report (UNHDR), an equation was introduced by Pasternak that shows the logarithmic dependency of electricity use per capita for the calculation of HDI [77].

$$HDI = 0.091ln(E_{load-annual-per-capita}) + 0.0724 \tag{5.3}$$

where $E_{load-annual-per-capita}$ (kWh/yr/person) is the annual electricity consumption.

Later Rojas-Zerpa revised the logarithmic equation based on data for 128 countries [78]

$$HDI = 0.0978ln(E_{load-annual-per-capita}) - 0.0319 \tag{5.4}$$

Consider a fraction of annual excess energy to be used by new businesses, services or small workshops which can improve the standard of living and thereby increasing the HDI. The equation introduced by Rojas-Zerpa was modified by R. Dufo-Lopez to include the fraction of annual excess as given below [78],

$$HDI = 0.0978ln[(E_{load} + min(F_{max-E-Excess}.E_{excess}, F_{max-E-load}.E_{load}))/N_{population}] - 0.0319 \tag{5.5}$$

where $E_{load}$ is the annual energy consumed by load, $E_{excess}$ (kWh) is the annual excess energy in the system, $F_{max-E-excess}$ is the factor to obtain the maximum excess energy that can be used by the new AC extra loads and $F_{max-E-load}$ is the factor to multiply the annual AC load so that the maximum excess energy used by the new AC extra loads cannot be higher than the product. $N_{population}$ is the population living in the community. For instance, if the new businesses/services cannot use more than 10% of the excess energy and the excess energy load cannot be greater than 60% of the expected load, then $F_{max-E-excess} = 0.1$ and $F_{max-E-load} = 0.6$

In this work, $E_{load}$ is the sum of all the energy needs that are fulfilled by SIRES and not just electricity as in the case of previous work. In addition, the excess energy in terms of biogas and water in overhead reservoir can be converted into electricity to serve the new businesses since electricity is a critical form of energy to improve and consequently increase HDI. Table 5.8 provides the information of the excess energy that is produced in various forms for SIRES.

Table 5.8: Excess Electricity, Excess Biogas and Excess Water Pumped per year

| **Parameter** | **Electricity (kWh)** | **Biogas($m^3$)** | **Water($m^3$)** |
|---|---|---|---|
| Produced | 1.19891 x $10^5$ | 1.2702 x $10^5$ | 1.18337 x $10^6$ |
| Need | 1.04610 x $10^5$ | 1.2114 x $10^5$ | 1.1095 x $10^6$ |
| Excess | 1.5281 x $10^4$ | 5.8 x $10^3$ | 7.3877 x $10^4$ |
| Excess (kWh) | 1.5281 x $10^4$ | 2.2736 x $10^4$ | 2.815 x $10^3$ |

Total Excess Energy (kWh)= 1.5281 x $10^4$ + 2.2736 x $10^4$ + 2.815 x $10^3$

Total Excess Energy (kwh)= 40,832.53 kWh/year

Total Energy load (kWh)= 4.7954 x $10^5$

In this work, $F_{max-E-excess}$ is assumed as 0.3 and $F_{max-E-load}$ is assumed as 0.5. As mentioned in section 4.1.1, the population is assumed to be 700. HDI for SIRES was estimated to be 0.6091.

The same procedure is repeated for microgrid with and without diesel generator to compare with the HDI of SIRES for the same energy load.

Electricity generated by microgrid with diesel generator (kWh)= 4.9474 x $10^5$ (kWh/year)

Excess electricity for MDG (kWh)= 1.52 x $10^4$ (kWh/year)

HDI for MDG= 0.60761

Electricity generated by microgrid without diesel generator (kWh)= 4.8951 x $10^5$ (kWh/year)

Excess electricity for MWDG (kWh)= 9.97 x $10^3$ (kWh/year)

HDI for MWDG= 0.6072

Therefore HDI for SIRES is greater than that of microgrid with and without diesel generator. HDI= 0.6091 for SIRES signifies that implementation of SIRES will result in medium level of development in the remote rural area.

### 5.2.2 Job Creation Factor (JCF)

In this sub-section, employment creation associated with the deployment of SIRES to fulfill basic needs is discussed. International Renewable Energy Agency (IRENA) has estimated an increase in global renewable energy employment by 1% in 2016 to reach 9.8 million. In particular, 1.5 million people are employed by large hydropower. Solar

PV was the largest renewable employer with 3.1 million jobs worldwide (12% increase compare to 2015). New wind installations in the USA, Germany, India and Brazil contributed to 7% increase in global wind employment that reached 1.2 million jobs. Liquid biofuels (1.7 million jobs), solid biomass (0.7 million) and biogas (0.3 million) were also major employers, with jobs concentrated in feedstock supply. China, Brazil, USA, India, Japan and Germany are the countries with the highest number of jobs in renewable energy sector [79].

Various researchers have conducted studies to analyze different types of jobs that influence the employment factors of renewable energy technology [80]. Universally accepted terms to categorize jobs are direct, indirect and induced jobs [81].

1. Direct Jobs: The jobs in this category are related to core activities such as manufacturing/construction/fabrication, site development, installation, and operation and maintenance (O & M). Direct jobs are relatively easier to estimate and are directly proportional to the increase in the growth of renewable technologies.

2. Indirect Jobs: The jobs in this category are related to the supply and support of the renewable energy industry at a secondary level. For instance, jobs for the processing of raw materials (steel and copper), marketing and selling and work performed by regulatory bodies, consultancy firms and research organizations fall into this category. While some indirect jobs (raw material processing jobs) maybe directly proportional to the installed capacity, others may have lesser obvious linkages (in support organizations).

3. Induced Jobs: Jobs that arise from the economic activities of direct and indirect employees, shareholders and government (via associated tax revenues) fall into the category of induced jobs. The earnings spent can stimulate the economy other industries too that may have no direct connection with renewable energy industry. For instance, an employee of the renewable energy industry can pur-

chase car or home which can in turn increase the revenues of the automobile industry or real estate business. However, induced jobs are often difficult to estimate and hence there is limited literature review in this category.

There is a dedicated terminology to define various employment terms. One job-year (or person-year or full-time equivalent) is full time employment for a duration of one year [82]. Some researchers have also used number of employees per GWh/year to estimate the job creation factor while other researchers preferred job-years per MW (peak for PV and maximum power output for wind) to calculate jobs in manufacturing and installation. On the other hand, jobs in operation and maintenance (O & M) (jobs that require continuous activities for the lifetime of system)are estimated in jobs/MW. To interpret the different terms, an example is provided below:

Consider a 50 MW power plant that requires 100 workers to manufacture its components for 1 year. Another set of workers of 50 workers to install it that requires 6 months. Then,

Number of job-year/ MW or person-years/MW = (100 jobs x 1 year+ 50 jobs x 0.5 year)/50= 2.5 job-year/MW or person-years/MW

If the lifetime of the project is assumed to be 25 years, then average employment for this phase in jobs/MW= 2.5 job-year/MW/25 years= 0.1 jobs/MW.

If the same project requires 10 people for its operation and maintenance (O & M) for its lifetime, then 10 persons/50 MW = 0.125 jobs/MW for O & M.

Therefore over its lifetime, full-time employment is 0.1 + 0.125 = 0.225 jobs/MW.

This work considers only direct jobs for the estimation of Job Creation Factor (JCF). Two job function groupings namely construction, installation and manufacturing (CIM), and operation and maintenance (O& M) were studied in this thesis. Items in the first group are typically documented in "job-years per MW installed" while items in the second group are documented in jobs per MW peak. In this work, all the calculations are made in terms of jobs/MW peak to maintain uniformity. Jobs-

Table 5.9: Job creation for renewable energy technologies used in SIRES

| Renewable Energy Technology | CIM | | O & M |
|---|---|---|---|
| | jobs-year/MW peak | jobs/ MW peak | jobs/MWpeak |
| PV electricity(7.5 kWp) | 30 | 1.2 | 0.37 |
| Wind electricity (9 kWp) | 6.6 | 0.264 | 0.4 |
| Biogas electricity (6kWp) | 8.5 | 0.340 | 1.21 |
| Hydropower (5kWp) | 5.71 | 0.228 | 1.14 |
| PV water pump (3.3 kWp) | 30 | 1.2 | 0.37 |
| Wind water pump (11 kWp) | 6.6 | 0.264 | 0.4 |
| Biogas water pump (17 kWp) | 8.5 | 0.340 | 1.21 |
| Biogas cooking (50 kWp) | 8.5 | 0.340 | 1.21 |

year/ MW peak for CIM and jobs/MW peak for O & M for renewable technologies considered were obtained from reference [82]. Table 5.9 summarizes the Job Creation Factor (JCF) for CIM and O & M for renewable technologies used in SIRES.

It is important to note the units such as $m^3$ for water and biogas are converted into their electrical equivalent for simplification in calculations. Jobs/MW for CIM is highest for PV whereas jobs/MW for O & M is least for PV. Manufacturing and deployment of PV panels require more employees compared to other renewable technologies. On the contrary, maintenance is least for PV which is evident from the table. In case of biogas, large number of employees are required for the collection and processing of the biomass. Job Creation Factor (JCF) for SIRES can be given by the following equation,

$$JCF = \sum_{r=1}^{R} JC_{RET}^{r} * P_{RET}^{r} \tag{5.6}$$

where $JC_{RET}^{r}$ is the job creation factor for renewable technology 'r', $P_{RET}^{r}$ is the peak value for the corresponding renewable technology. In case of SIRES, R=8 as job creation related to battery is not considered since it is negligible. From the table, values are substituted into the equation and following results are obtained.

JCF for SIRES (CIM)= 0.048016 jobs/MW

Table 5.10: Job creation for renewable energy technologies used in MDG

| Renewable Energy Technology | CIM jobs/ MW peak | O & M jobs/MWpeak |
|---|---|---|
| PV electricity(39.6 kWp) | 1.2 | 0.37 |
| Wind electricity (15 kWp) | 0.264 | 0.4 |
| Biogas electricity (30 kWp) | 0.340 | 1.21 |
| Hydropower (5 kWp) | 0.228 | 1.14 |
| Diesel (30 kWp) =1.8144 x $10^4$ kWh/year | 0.14/Gwh/yr | 0.5 |

JCF for SIRES (O & M) = 0.10545 jobs/MW

JCF for SIRES (Combined CIM and O & M)= 0.15346 jobs/MW

JCF for microgrid with and without diesel generator is estimated in the same manner as SIRES. Tables 5.10 and 5.11 outline the values for job creation for CIM and O & M for renewable technologies used for microgrid with diesel generator and without diesel generator respectively.

JCF for MDG (CIM)= 0.0874 jobs/MW

JCF for MDG (O & M) = 0.077652 jobs/MW

JCF for MDG (Combined CIM and O & M)= 0.16505 jobs/MW

JCF for MWDG (CIM)= 0.0657 jobs/MW

JCF for MWDG (O & M) = 0.06564 jobs/MW

JCF for MWDG (Combined CIM and O & M)= 0.1398 jobs/MW

From the results obtained, it is evident that JCF for MDG was the highest when

Table 5.11: Job creation for renewable energy technologies used in MWDG

| Renewable Energy Technology | CIM jobs/ MW peak | O & M jobs/MWpeak |
|---|---|---|
| PV electricity(50 kWp) | 1.2 | 0.37 |
| Wind electricity (10 kWp) | 0.264 | 0.4 |
| Biogas electricity (30 kWp) | 0.340 | 1.21 |
| Hydropower (6 kWp) | 0.228 | 1.14 |

Table 5.12: Comparison of JCF for SIRES, MDG and MWDG

| Approach to rural development | JCF for CIM jobs/ MWp | JCF for O & M jobs/MWp | Total JCF jobs/MWp |
|---|---|---|---|
| SIRES | 0.0480166 | 0.10545 | 0.15346 |
| MDG | 0.0874 | 0.077652 | 0.16505 |
| MWDG | 0.0657 | 0.06564 | 0.1398 |

compared to that of SIRES and MDWG. JCF for CIM was greater for MDG and MWDG when compared to SIRES. This is because both MDG and MWDG utilize high levels of PV. Besides, JCF for O & M was greater for SIRES when compared to MDG and MWDG due to the large usage of biogas in SIRES. Table 5.12 summarizes the comparison of JCF for SIRES, MDG and MWDG.

## 5.3 Environmental Benefits of SIRES

There is substantial awareness of the adverse affects of Greenhouse Gas (GHG) emissions. Their implications to climate change and rising sea levels have created a spur in the renewable technology industry around the globe. Hence, estimation of lifecycle GHG emissions are necessary to evaluate the possible solutions for rural development. It is widely recognized that GHG emissions resulting from the use of a particular energy technology need to be quantified over all stages of the technology and its fuel lifecycle [83]. Each energy generation technology produces GHGs in varying quantities through construction, manufacturing, operation and deployment[84]. While electricity generation using fossil fuels emit GHGs in large amounts, renewable energy generation such as solar, wind, biogas and hydropower do not emit any GHGs during operation. In this work, life-cycle approach for estimating GHG emissions is taken into consideration since it accounts for emissions from all phases (construction, transportation and deployment). Lifecycle emissions for SIRES were compared with that of microgrid with and without diesel generator.

Table 5.13: Summary of Lifecycle Emissions

| Technology | Mean | Low | High |
|---|---|---|---|
| | tonnes $CO_2$e/GWh | | |
| Lignite | 1054 | 790 | 1372 |
| Coal | 888 | 756 | 1310 |
| Oil | 733 | 547 | 935 |
| Natural Gas | 499 | 362 | 891 |
| Solar PV | 85 | 13 | 731 |
| Biomass | 45 | 10 | 101 |
| Nuclear | 29 | 2 | 130 |
| Hydroelectric | 26 | 2 | 237 |
| Wind | 26 | 6 | 124 |

World Nuclear Association (WNA) composed a report for comparison of lifecycle Greenhouse Gas (GHG) emissions of various electricity generation sources including renewable energy technologies [84]. The report was based on literature that included lifecycle GHG emissions associated with electricity generation. Lifecycle GHG emissions for different electricity generation methods are provided in Table 5.13. Solar PV technology has made rapid advancement over the past decade which led to exponential decrease in the lifecycle emissions. Nuclear energy has lower GHG emissions when compared to Solar PV and Biomass. However, disposal and transport of nuclear waste is extremely hazardous and can leak radiations if not stored properly.

The lifecycle emissions associated with all the system components of SIRES are calculated using the following equation,

$$\begin{aligned} Annual\ CO_2\ Emissions(TonnesCO_{2e}) = Generation\ Capacity(GW)\ * \\ Number\ of\ Hours\ of\ Operation(h) \\ *\ Emission\ Factor(TonnesCO_{2e}/GWh) \end{aligned} \quad (5.7)$$

In SIRES, energy is in the form of electricity, pumped water and biogas. The lifecycle emissions are calculated in terms of Tonnes $CO_{2e}$ where 'e' stands for the electrical equivalent. Hence, the values of water and biogas are converted into their

Table 5.14: Annual lifecycle GHG emissions for SIRES

| Technology | Energy generated per year (kWh) | Emissions (Tonne $CO_{2e}$) |
|---|---|---|
| **Electricity** | | |
| Solar PV | 1.2112 x $10^4$ | 1.029 |
| Wind | 1.8804 x $10^4$ | 0.4489 |
| Biogas | 5.1396 x $10^4$ | 2.312 |
| Hydro | 3.7579 x $10^4$ | 0.977 |
| **Water-pumping** | | |
| Solar PV | 2456.89 | 0.208 |
| Wind | 8405.29 | 0.218 |
| Biogas | 34.3 x $10^3$ | 1.543 |
| **Cooking** | | |
| Biogas | 91250 $m^3$ | 9.125 |
| **Total** | | **15.9** |

Table 5.15: Annual lifecycle GHG emissions for microgrid with diesel generator

| Technology | Energy generated per year (kWh) | Emissions (Tonne $CO_{2e}$) |
|---|---|---|
| Solar PV | 6.3952 x $10^4$ | 5.435 |
| Wind | 3.134 x $10^4$ | 0.814 |
| Biogas | 2.5807 x $10^5$ | 11.61 |
| Hydro | 3.757 x $10^4$ | 0.976 |
| Diesel | 1.8144 x $10^4$ | 14.007 |
| **Total** | | **32.844** |

Table 5.16: Annual lifecycle GHG emissions for microgrid without diesel generator

| Technology | Energy generated per year (kWh) | Emissions (Tonne $CO_{2e}$) |
|---|---|---|
| Solar PV | 8.0747 x $10^4$ | 6.863 |
| Wind | 2.089 x $10^4$ | 0.543 |
| Biogas | 2.5786 x $10^5$ | 11.603 |
| Hydro | 4.5073 x $10^4$ | 1.17 |
| **Total** | | **20.179** |

electrical equivalent. It is assumed that the GHG emissions remains same for all system components for a particular renewable technology. For example, GHG emissions for wind turbines and wind mechanical water pumps remain same. 0.286 g$CO_{2e}$ is emitted per kWh for battery and 1000 g$CO_{2e}$ is emitted per 1 $m^3$ of biogas produced [85], [86]. Since GHGs mostly constitute of $CO_2$ gas, GHG emissions are equivalent to $CO_{2e}$ emissions. Table 5.14 provides the annual lifecycle GHG emissions for SIRES.

Lifecycle GHG emissions for microgrid with and without diesel generator is es-

Table 5.17: Economic, Social and Environmental Impacts of SIRES, MDG and MWDG

| Parameter | SIRES | MDG | MWDG |
|---|---|---|---|
| Installation Cost | $ 122,900 | $ 217,000 | $ 225,300 |
| NPC | $ 266,225.2 | $ 501,839.7 | $ 423,624.04 |
| HDI | 0.6091 | 0.60761 | 0.6072 |
| JCF | 0.15346 | 0.16505 | 0.1398 |
| Lifecycle GHG | 15.9 Tonne $CO_{2e}$ | 32.844 Tonne $CO_{2e}$ | 20.179 Tonne $CO_{2e}$ |

timated in the same manner as SIRES. Table 5.15-5.16 summarizes the values for annual lifecycle GHG emissions for renewable technologies used for microgrid with diesel generator and without diesel generator respectively.

From the results obtained, it is clear that annual lifecycle GHG emissions for SIRES is the least when compared to microgrid with and without diesel generator. In cab be noted that the emissions from SIRES are 50% less when compared to microgrid with diesel generator.

Table 5.17 summarizes the economic, social and environmental impacts of SIRES when compared to microgrid with and without diesel generator. Although HDI for all the three cases are essentially the same, SIRES has the advantage of minimal environmental burden and is more economical. Despite JCF was higher in MDG, SIRES has an overall better impact. Considering all the aspects for sustainable development in rural area, SIRES is a more suitable option when compared to current approaches for rural development.

# CHAPTER 6

# INTELLIGENT CONTROL OF SIRES

Approaches such as microgrids, Hybrid Renewable Energy Systems (HRES) and solar home systems harness renewable energy for the development of rural areas. Uncertainty is the preeminent characteristic of renewable energy. To tackle uncertainty, forecasting and energy management techniques are of prime importance. Zhang et al. presented an energy management strategy with the help of fuzzy logic to reduce electricity bill and $CO_2$ emissions using photovoltaics (PV) and energy storage systems [87]. The authors designed a supervision system for a commercial building. Chaouachi et al. proposed a multi-objective intelligent energy microgrid to minimize the operational cost and the environmental impact by taking into account the future availability of renewable energies and load demand [88]. Neural Network was developed to forecast 24-hr ahead photovoltaic generation, 1-hr ahead wind power generation and load demand. A fuzzy based expert system was formulated for scheduling battery to decrease the battery maintenance cost and extend the operation lifetime cost.

A Fuzzy Logic Energy Management System (FLEMS) for polygeneration microgrids was suggested by Kyriakarakos et al. [89]. These microgrids fulfilled the electricity, transport and water needs and thus its outputs were power, hydrogen fuel for transportation and potable water through desalination. Arcos-Aviles et al. formulated the design of a low complexity fuzzy logic-based energy management system for a residential grid-connected microgrid that consisted of PV panels, wind turbines and battery [90]. An experimental validation in a real microgrid was carried out at the Public University of Navarre Spain to confirm simulation results. Chen et al. presented the modeling, analysis, and design of fuzzy control to optimize energy management system for a DC microgrid [91].

In this study, a novel approach entitled Smart Integrated Renewable Energy Systems (SIRES) is introduced to employ renewable energy resources to fulfill basic requirements such as cooking, electricity and water for domestic and irrigation purpose in a cost effective manner. Smart sensors will be strategically placed at locations where the quantity of resources have to be monitored. Sensors will also be placed at locations where the status of system components should be monitored. Intelligent controllers will be used to turn on/off system components. A framework for intelligent control of SIRES is presented in [92]. In order to actuate the controllers, a combination of neural network and fuzzy logic control is used. In this thesis, improvements are made to the control algorithm to make it more suitable for real-time applications. Further, the results obtained for the control part of SIRES are discussed.

Intelligent control constitutes of two main parts: Neural Network Forecasting and Fuzzy Logic Controller. Figure 6.1 summarizes the control approach for SIRES. Historical demand data as well as weather data such as temperature, wind speed, humidity and rainfall are the prerequisites to forecast demands such as cooking, electricity, domestic and potable water and water for irrigation purposes. On the other hand, data from the sensors such as available water, biogas, and charge in the battery etc are gathered and inputted to mathematical models of system components. In addition, weather data is used to estimate the energy outputs for solar and wind renewable technology devices. Estimated outputs of the system components and the forecasted demand for the next hour are provided as input to the fuzzy logic controller. The output of fuzzy logic is fed back to the system components for the calculation of the next hour generation.

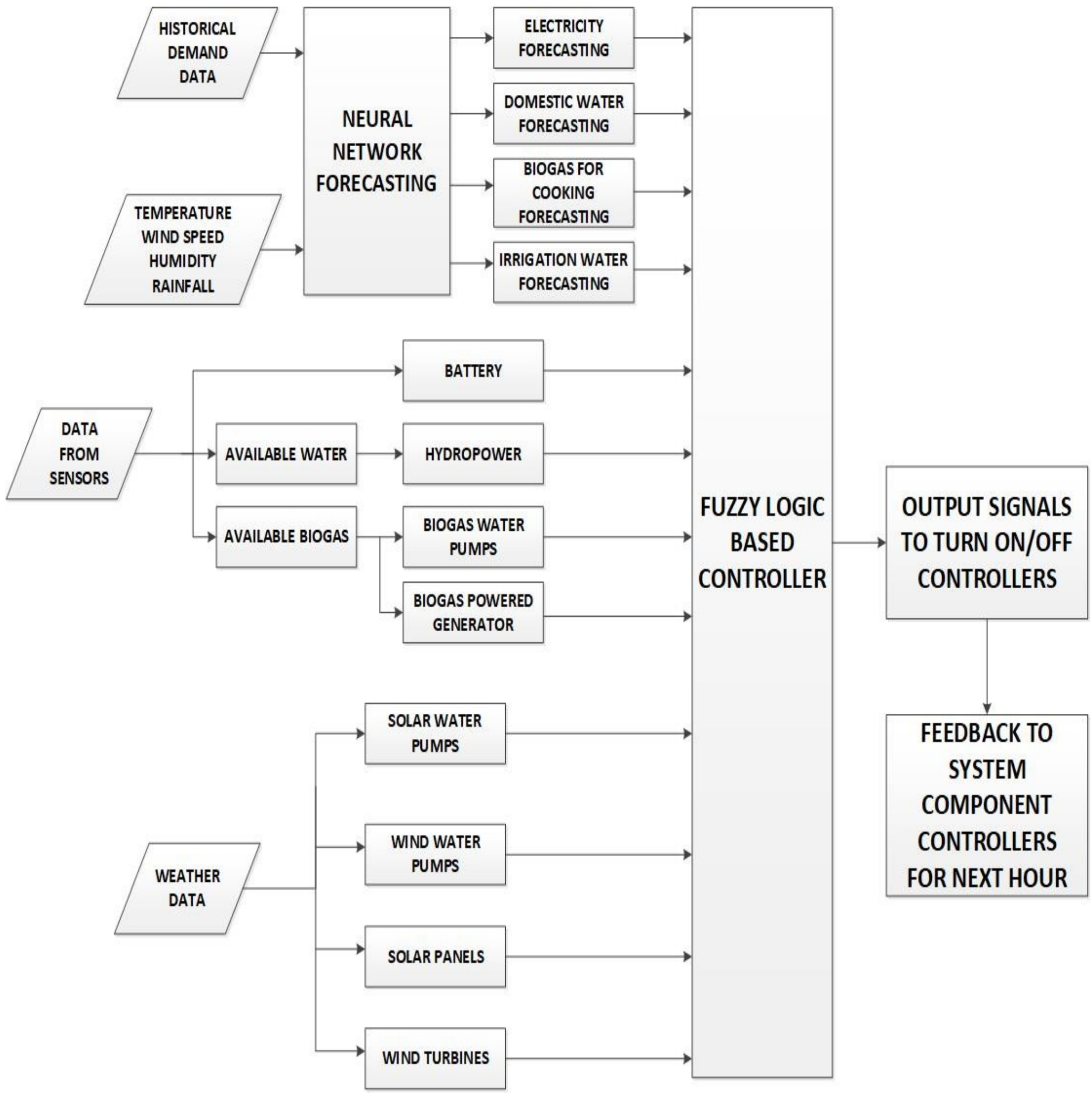



Figure 6.1: Schematic diagram of intelligent control for SIRES

## 6.1 Neural Network Forecasting

Forecasting the demands is a significant aspect in control for SIRES. Generally, load forecasting models can be classified into two categories: time-of-day models and dynamic models. Time-of-day model is a non-dynamic approach and expresses the load at once as discrete time series consisting of predicted values for each hour of the forecasting period. The second classification involves the dynamic model that recognizes the fact that the load is not only a function of the time of the day but also the loads most recent behavior [93].

Similar day approach, regression models, neural networks, expert systems, fuzzy logic, statistical learning algorithms and so on are widely used in forecasting. Amongst these methods, neural networks have been universally accepted to be one of the most effective methods for short term forecasting [94]. Neural Networks (NN) offer the ability to model the non-linearities that are known to be part of the demand pattern. Another advantage of NN is to automate the process of constructing forecasting model. Given the set of examples of demand and related variables, NNs can construct a model automatically [95].

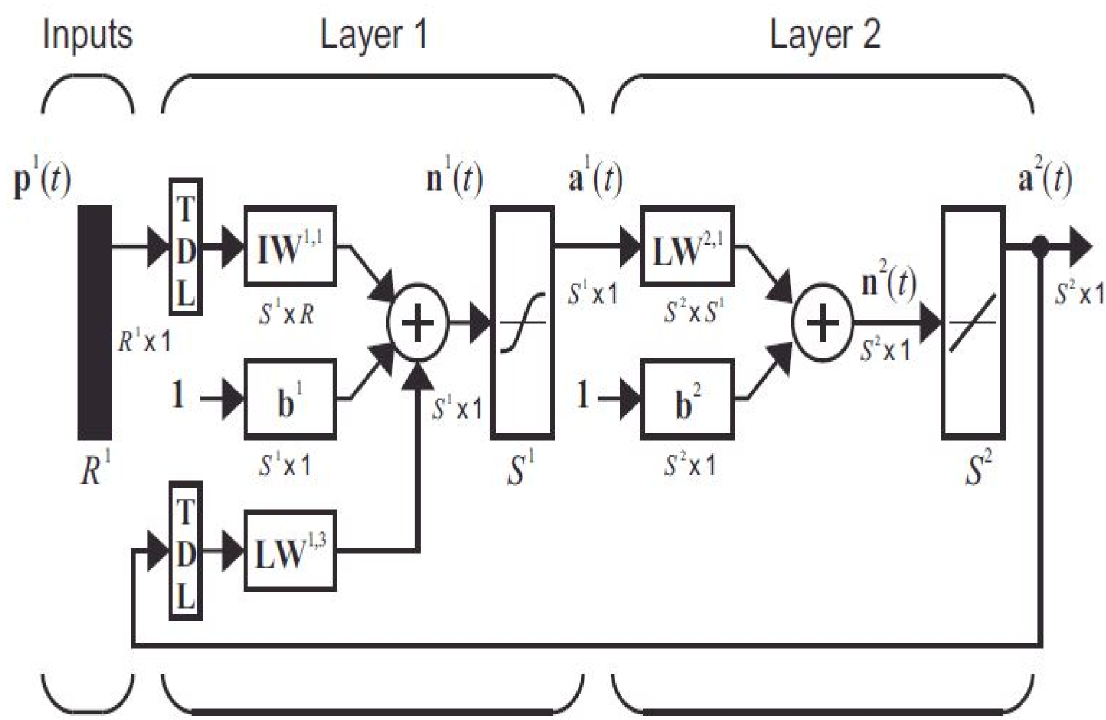



Figure 6.2: NARX Neural Network

### 6.1.1 Selecting the Architecture

Forecasting or prediction requires the use of dynamic neural networks since it is classified as time series analysis or dynamic modeling. For the purpose of dynamic modeling, Non-linear AutoRegressive model with eXogenous input (NARX) is suitable. This network has an advantage of being trained using static backpropagation algorithm because the tapped-delay-line at the input of the network can be replaced with an extended vector of delayed input values [96]. NARX neural network architecture is shown in Figure 6.2.

### 6.1.2 Data Collection

For appropriate control of SIRES, it is required to predict needs such as amounts of biogas for cooking, domestic water, electricity and irrigation water, which are output variables of NN. These needs depend on weather conditions such as temperature, wind speed, humidity and rainfall. Hence weather data is the input variable to NN. One year of hourly data (8760 data points) for input and output variables are used to train NN. Data collection was discussed in detail in section 4.1

### 6.1.3 Training Neural Network

Neural network toolbox in MATLAB is used to develop the NARX network. Levenberg-Marquadt (LM) algorithm is used to train the NARX network. Number of neurons in the hidden layer was set as 40 and the delay is set as 4. Data collected is divided into training (70%), validation (15%) and test sets (15%). The network was trained for 1000 iterations until an acceptable Mean Square Error (MSE) is obtained.

## 6.2 Fuzzy Logic based Controller

SIRES control is a challenging problem since the mathematical model is difficult to build. It consists of numerous renewable technology devices that are actuated depending on the demands. In this paper, fuzzy logic (FL) based control is applied to turn on/off renewable technologies devices. FL has not only excellent expression ability of general knowledge but also powerful reasoning ability of expert system. If exact mathematical mode is difficult to build, FL can provide suitable tool for controlling the system [97]. Further, FL can encompass such subjective decision-making process due to its ability to define human reasoning that can handle uncertainties regarding to the SIRES exogenous environment and the uncertainty of the forecasted parameters. Such an approach can be easily extended to SIRES irrespective of the generation rating and the architecture of its components [88]. Fuzzy Logic Designer toolbox in MATLAB is used.

### 6.2.1 Fuzzification

Four demands, cooking, domestic water, electricity and irrigation water are required to be fulfilled by SIRES. The objective of SIRES is to meet these demands in a cost effective and efficient manner. For this, highest priority is given to solar energy and wind energy followed by water and biogas since both resources are used to fulfill other needs as well. In addition, solar energy and wind energy are freely available and should be used whenever possible.

To fulfill cooking demand, biogas is the only resource that can be used. Biogas is produced every hour at the rate of 12-15 $m^3$/hour and hourly cooking demand varies from 0-35 $m^3$ depending on the hour of the day. If biogas produced is not sufficient to fulfill the demand at that hour, then stored biogas is used to fulfill the demand. The associated difference parameters can be given as,

$$\Delta C_1(t) = C_P(t) - C_D(t) \tag{6.1}$$

where $C_P$ (t) and $C_D$ (t) is biogas produced and biogas demand for cooking at hour t respectively.

For domestic water demand, water pumped by solar energy and wind energy is given the highest priority, followed by water stored in reservoir and biogas powered water pump. Domestic water demand varies from 0-8 $m^3$ per hour. To fulfill this demand, it is necessary to turn on/off the water pumps depending on the need. The associated difference parameters can be given as,

$$\Delta DW_1(t) = DW_S(t) - DW_D(t) \tag{6.2}$$

$$\Delta DW_2(t) = DW_S(t) + DW_W(t) - DW_D(t) \tag{6.3}$$

$$\Delta DW_3(t) = DW_S(t) + DW_W(t) + DW_B(t) - DW_D(t) \tag{6.4}$$

where $DW_S$ (t), $DW_W$ (t) and $DW_B$ (t) are water pumped by solar energy, wind energy and biogas respectively at hour t. $DW_D$ (t) is the domestic water demand at hour t.

For electricity demand, electricity produced by solar energy and wind energy is given the highest priority, followed by water stored in reservoir and biogas powered generator. Hourly electricity energy demand varies from 0-30 kWh. To fulfill this demand, it is necessary to turn on/off the generators depending on the need. The associated difference parameters can be given as,

$$\Delta E_1(t) = E_S(t) - E_D(t) \tag{6.5}$$

$$\Delta E_2(t) = E_S(t) + E_W(t) - E_D(t) \tag{6.6}$$

$$\Delta E_3(t) = E_S(t) + E_W(t) + E_H(t) - E_D(t) \tag{6.7}$$

$$\Delta E_4(t) = E_S(t) + E_W(t) + E_H(t) + E_B(t) - E_D(t) \tag{6.8}$$

where $E_S$ (t), $E_W$ (t), $E_H$ (t) and $E_B$ (t) are electricity produced by solar energy, wind energy, pico hydro and biogas respectively at hour t. $E_D$ (t) is the electricity energy demand at hour t.

For irrigation water demand, water pumped by solar energy and wind energy is given the highest priority, followed by water stored in reservoir and biogas powered

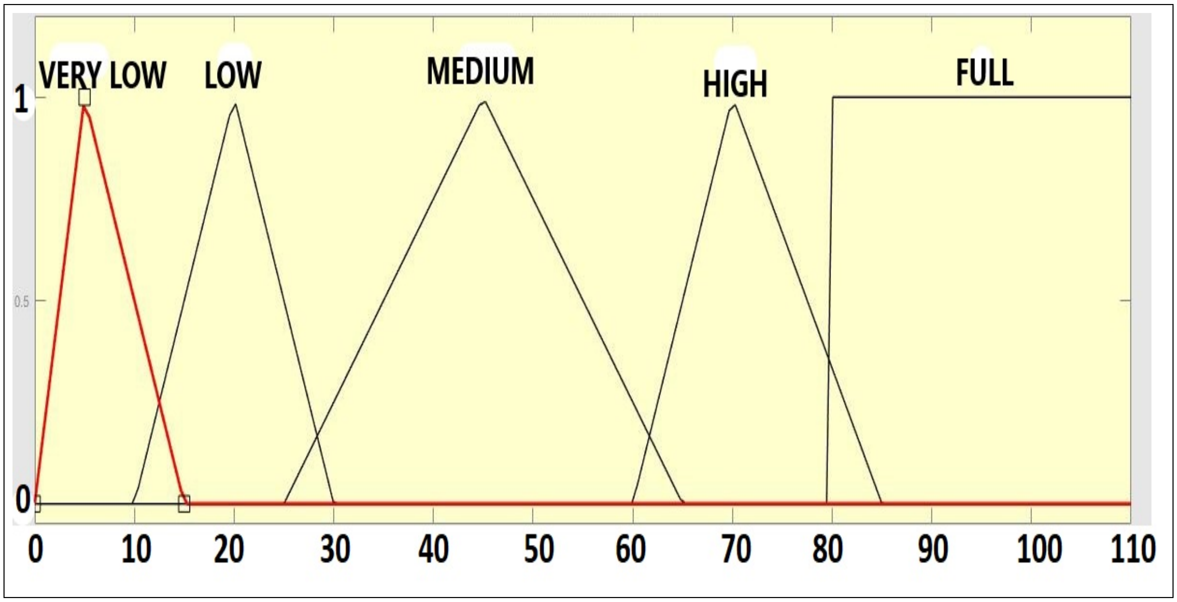



Figure 6.3: Membership Function for Available water in the reservoir

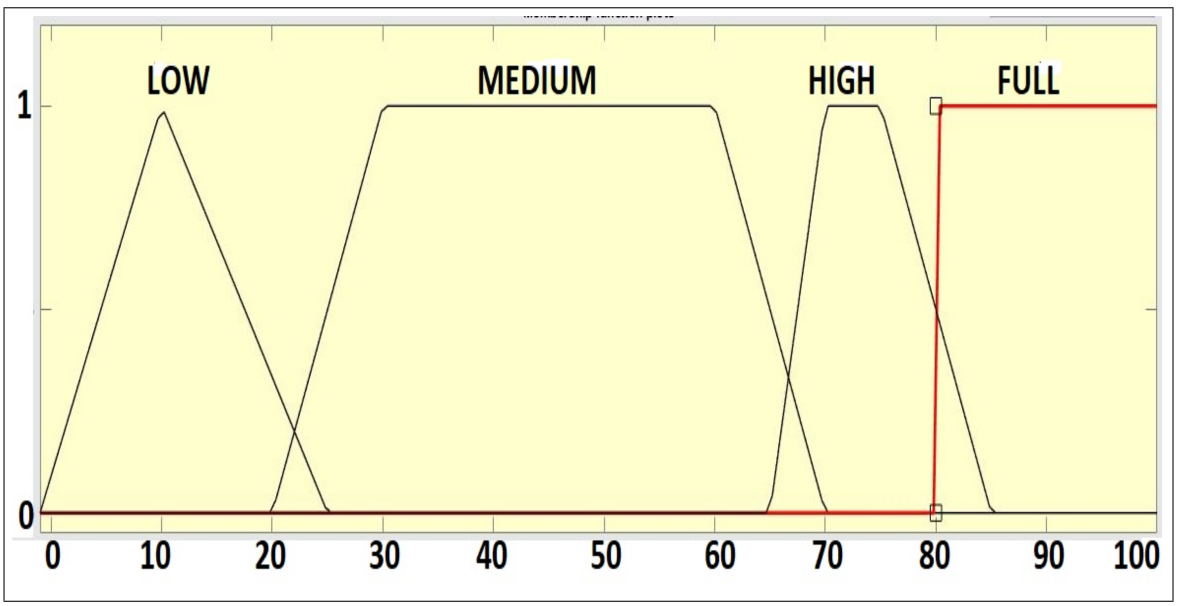



Figure 6.4: Membership Function for Available Charge in Battery/Stored Biogas in Digester

water pump. Irrigation water demand varies from 100-130 $m^3$ per hour. To fulfill this demand, it is necessary to turn on/off the water pumps depending on the need.

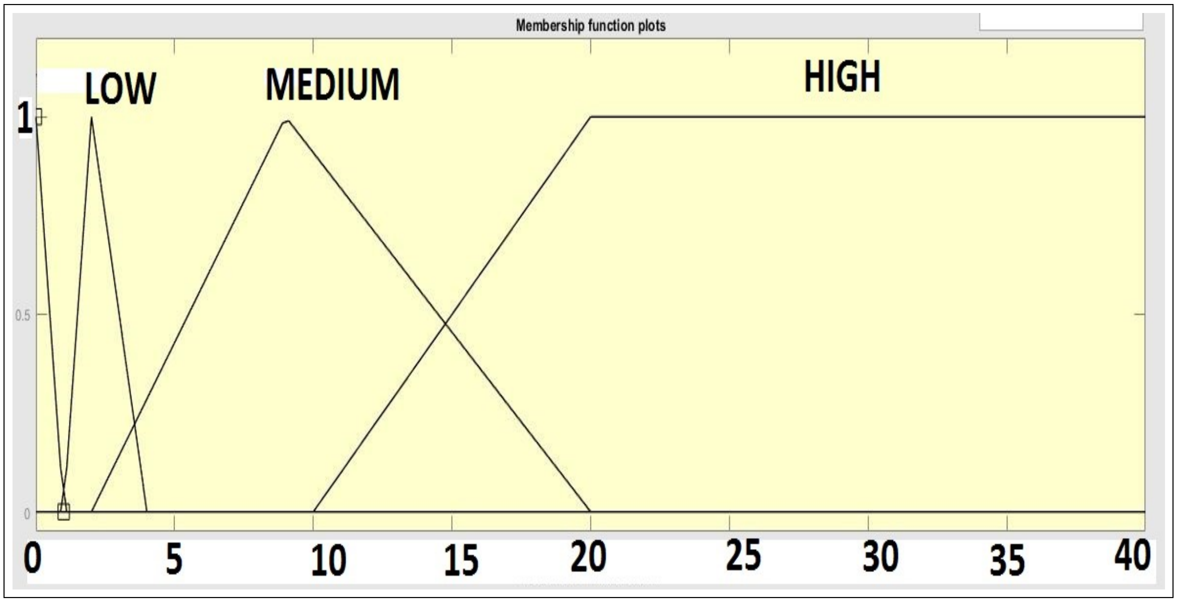



Figure 6.5: Membership Function for Biogas Demand

The associated difference parameters can be given as,

$$\Delta IW_1(t) = IW_S(t) - IW_D(t) \tag{6.9}$$

$$\Delta IW_2(t) = IW_S(t) + IW_W(t) - IW_D(t) \tag{6.10}$$

$$\Delta IW_3(t) = IW_S(t) + IW_W(t) + IW_B(t) - IW_D(t) \tag{6.11}$$

where $IW_S$ (t), $IW_W$ (t) and $IW_B$ (t) are water pumped by solar energy, wind energy and biogas respectively at hour t. $IW_D$ (t) is the irrigation water demand at hour t.

Membership function plots for available water in the reservoir, charge available in battery/stored biogas in the digester, and biogas demand are as shown in Figure 6.3, 6.4 and 6.5 respectively. If biogas demand is between 0 to 1 $m^3$, then membership assigned is Very Low.

Membership function plots for $\Delta C_1$(t), $\Delta C_2$(t), $\Delta DW_1$(t), $\Delta DW_2$(t), $\Delta DW_3$(t), $\Delta E_1$(t), $\Delta E_2$(t), $\Delta E_3$(t), $\Delta E_4$(t), $\Delta IW_1$(t), $\Delta IW_2$(t) and $\Delta IW_3$(t) are the same and is shown in Figure 6.6.

Membership function plots for controllers of all system devices is shown in Figure

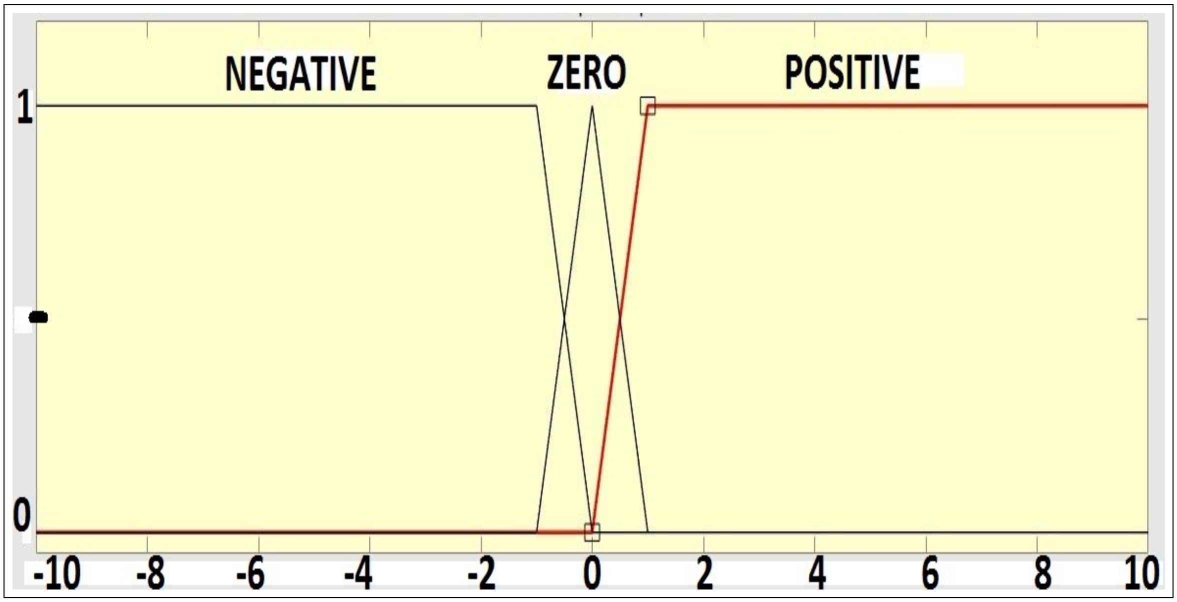



Figure 6.6: Membership Function Plot

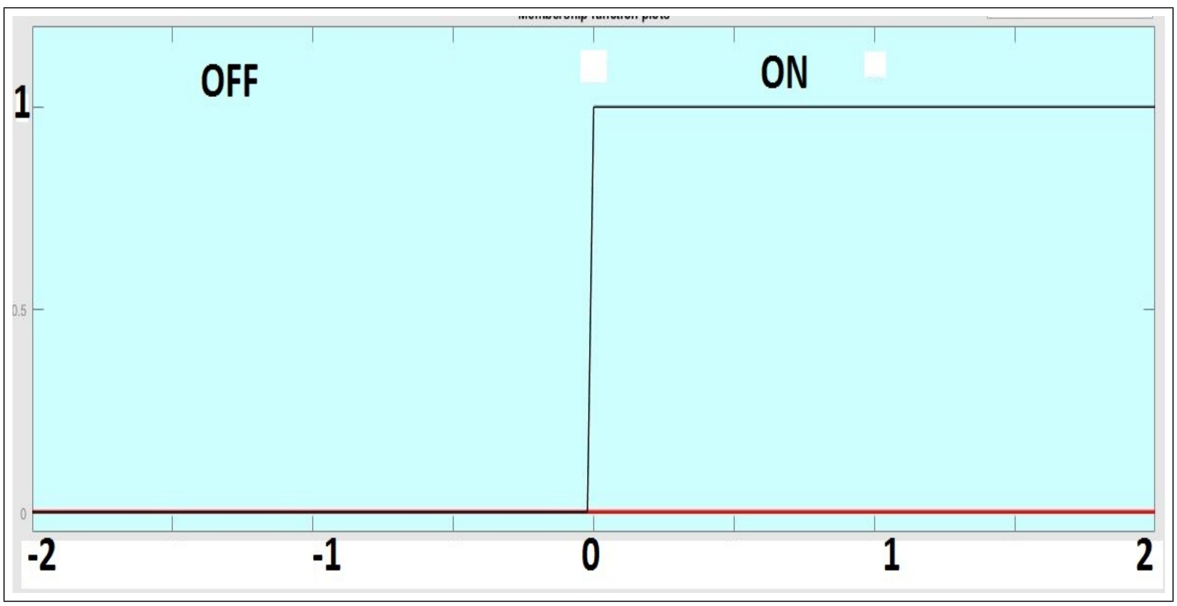



Figure 6.7: Membership Function Plot for Controllers

6.7.

### 6.2.2 Inference Engine

Once the degrees of membership functions of each fuzzy set have been determined for a particular input, they are forwarded to the inference engine that defines which rules should be evaluated. Four demands need to be satisfied by SIRES. To fulfill each demand, several rules are developed. Examples of fuzzy rules in each case are given here. It is important to note that all rules have not been mentioned.

Cooking demand

If ($\Delta C_1$ is not Negative) and (Stored-Biogas is not high) and (BiogasDemand is high) then (Biogas-for-Cooking is ON) (Biogas-Produced in ON)

If ($\Delta C_1$ is Negative) and (Stored-Biogas is high) and (BiogasDemand is low) then (Biogas-for-Cooking is ON) (Biogas-Produced in ON)

If ($\Delta C_1$ is not Negative) and (Stored-Biogas is high) and (BiogasDemand is medium) then (Biogas-for-Cooking is ON) (Biogas-Produced in OFF)

If ($\Delta C_1$ is not Negative) and (Stored-Biogas is not high) and (BiogasDemand is very-low) then (Biogas-for-Cooking is OFF) (Biogas-Produced in OFF)

Domestic Water demand

If ($\Delta DW_1$ is not Negative) and Available-water-reservoir is not full then Solar is ON, Wind is OFF, Biogas is OFF

If ($\Delta DW_1$ is Negative) and ($\Delta DW_2$ is Negative) and (Available-water-reservoir is high) then Solar is ON, Wind is ON, Biogas is OFF

If ($\Delta DW_1$ is Negative) and ($\Delta DW_2$ is Negative) and (Available-water-reservoir is low) and ($\Delta DW_3$ is not Negative) then Solar is ON, Wind is ON, Biogas is ON

If (Available-water-reservoir is Full) then Solar is OFF, Wind is OFF, Biogas is OFF

Electricity demand

If ($\Delta E_1$ is not Negative) and (Available-charge-battery is not High) then Solar is ON, Wind is OFF, Battery is Charging, Hydropower is OFF, Biogas is OFF

If ($\Delta E_1$ is Negative) and ($\Delta E_2$ is not Negative) and (Available-charge-battery is not High) then Solar is ON, Wind is ON, Battery is Charging, Hydropower is OFF, Biogas is OFF

If ($\Delta E_1$ is Negative) and ($\Delta E_2$ is Negative) and (Available-charge-battery is not High) and ($\Delta E_3$ is not Negative) then Solar is ON, Wind is ON, Battery is Charging, Hydropower is ON, Biogas is OFF

If ($\Delta E_1$ is Negative) and ($\Delta E_2$ is Negative) and (Available-charge-battery is low) and ($\Delta E_3$ is Negative) and ($\Delta E_4$ is Negative) then Solar is ON, Wind is ON, Battery is Discharging, Hydropower is ON, Biogas is ON

Irrigation Water demand

If ($\Delta IW_1$ is Negative) and ($\Delta IW_2$ is not Negative) and (Available-water-reservoir is not Full) then Solar is ON, Wind is ON, Biogas is OFF

If (Available-water-reservoir is Low) then Solar is ON, Wind is ON, Biogas is ON

### 6.2.3 Defuzzification

The last step in fuzzy logic control is defuzzification. If the output is positive, the corresponding renewable technology device is turned on. On the contrary, if the output is negative, the corresponding renewable technology device is turned off.

## 6.3 Simulation results and Discussions

System components of SIRES are optimally sized individually to minimize Annualized Cost of System (ACS) and meet target reliability simultaneously using genetic algorithm. The optimum number of system components such as biogas generators, PV panels, wind turbines, pico hydro power plant, PV powered water pumps, wind-powered water pumps, biogas powered water pumps, and batteries are estimated. The result obtained is arranged in the order of [$PVpanels$ | $Wind\ turbines$ | $Biogas\ generators$ | $Micro\ hydroturbine$ | $Battery$ | $PV\ powered\ water\ pump$ | $Wind\ powered\ water\ pump$ | $Biogas\ powered\ water\ pump$] and is equal to [75 | 9 | 1 | 5 | 5 | 4 | 8 | 1]. Once the optimum number of components are found, the system

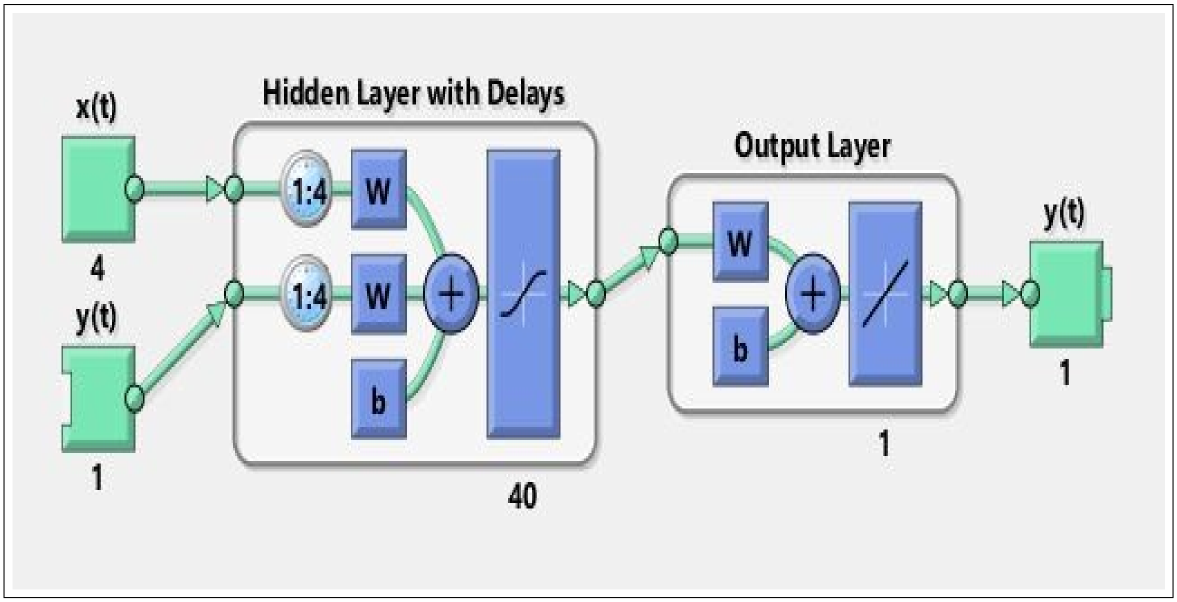


Figure 6.8: NARX network in Matlab Neural Network toolbox

components of SIRES including water level in reservoir and charge is battery are modeled in MATLAB Simulink environment. Simulink model for the NARX neural network and Fuzzy logic controller are developed and integrated together as discussed previously. Technical specifications of system components are mentioned in section 5.2. Model of NARX neural network in Matlab NN toolbox is illustrated in figure 6.8.

### 6.3.1 Forecasting Results

As mentioned earlier, NARX Neural Network (NN) is used to forecast the demands such as cooking, electricity, domestic and irrigation water. One-year of historical demand data is one set of input to NN and historical weather data is the other set of input. Weather data is vital to forecast the demands especially for electricity, domestic and irrigation water. Electricity demand depends on temperature, humidity, wind speed, and rainfall. Domestic water consumption increases with increase in temperature and humidity whereas irrigation water demand is reduced with the increase in precipitation levels (rainfall, snow). Figures 6.9-6.12 show the predicted

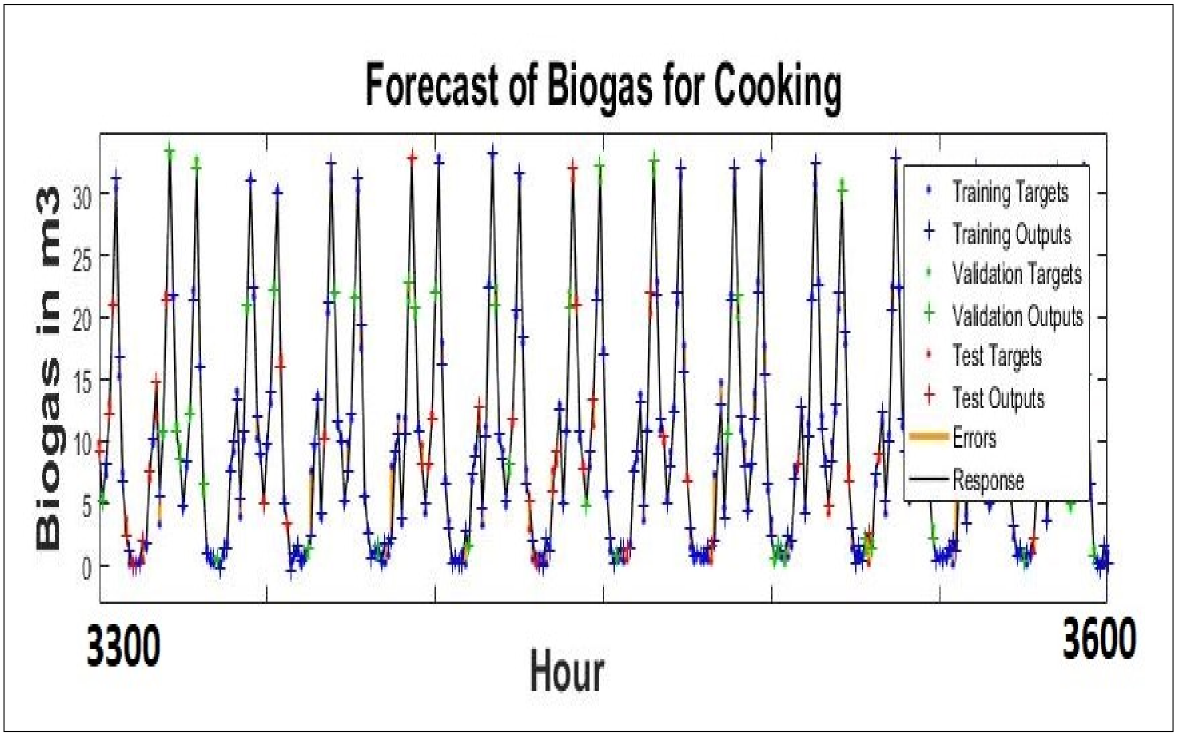



Figure 6.9: Forecasted output vs targeted data for cooking needs

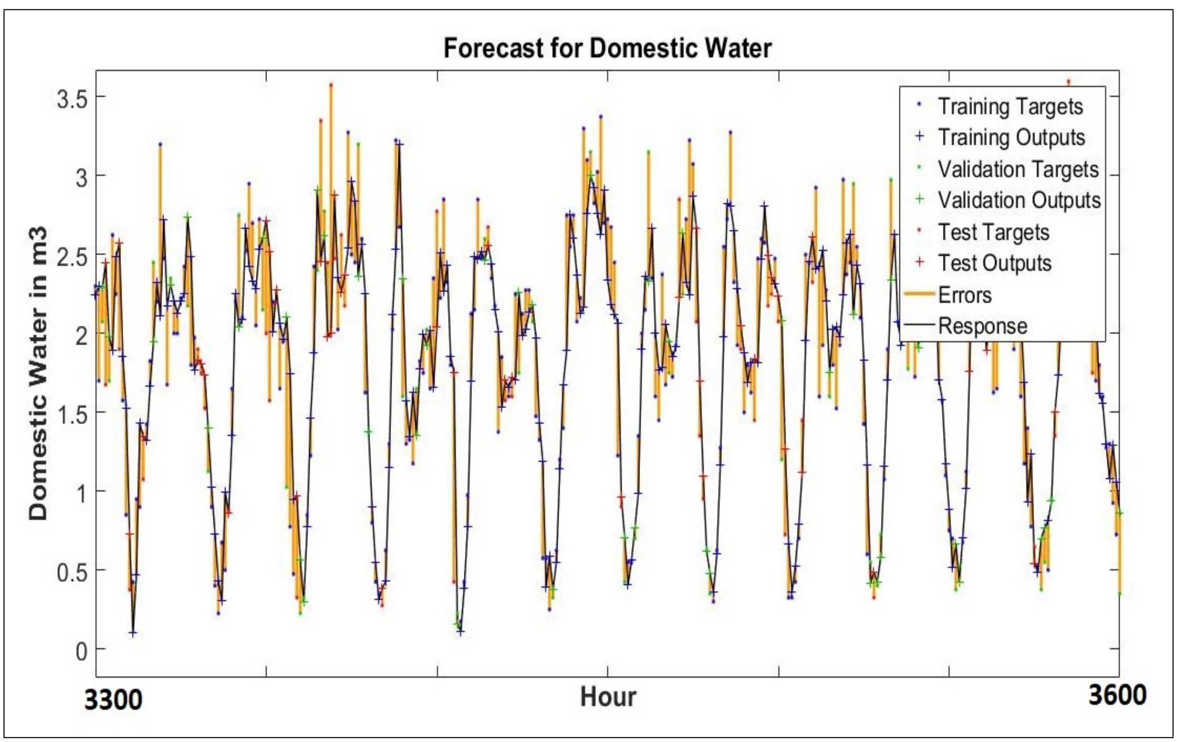



Figure 6.10: Forecasted output vs targeted data for domestic water

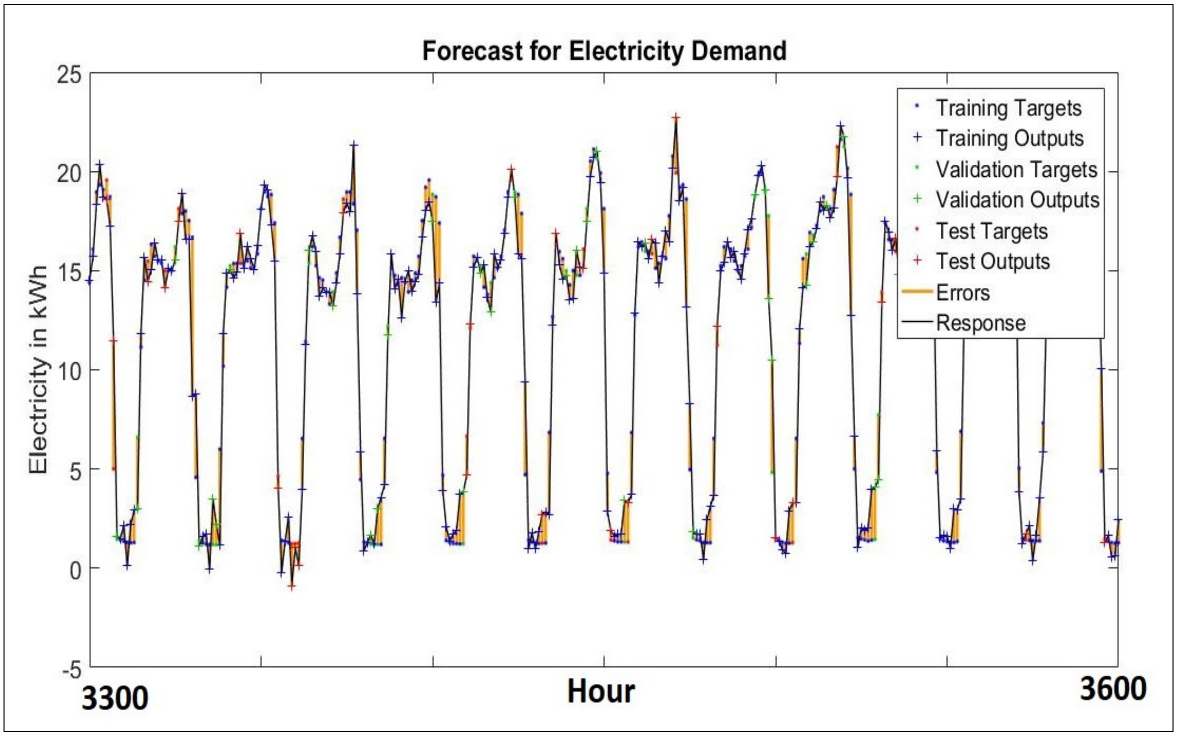



Figure 6.11: Forecasted output vs targeted data for electricity

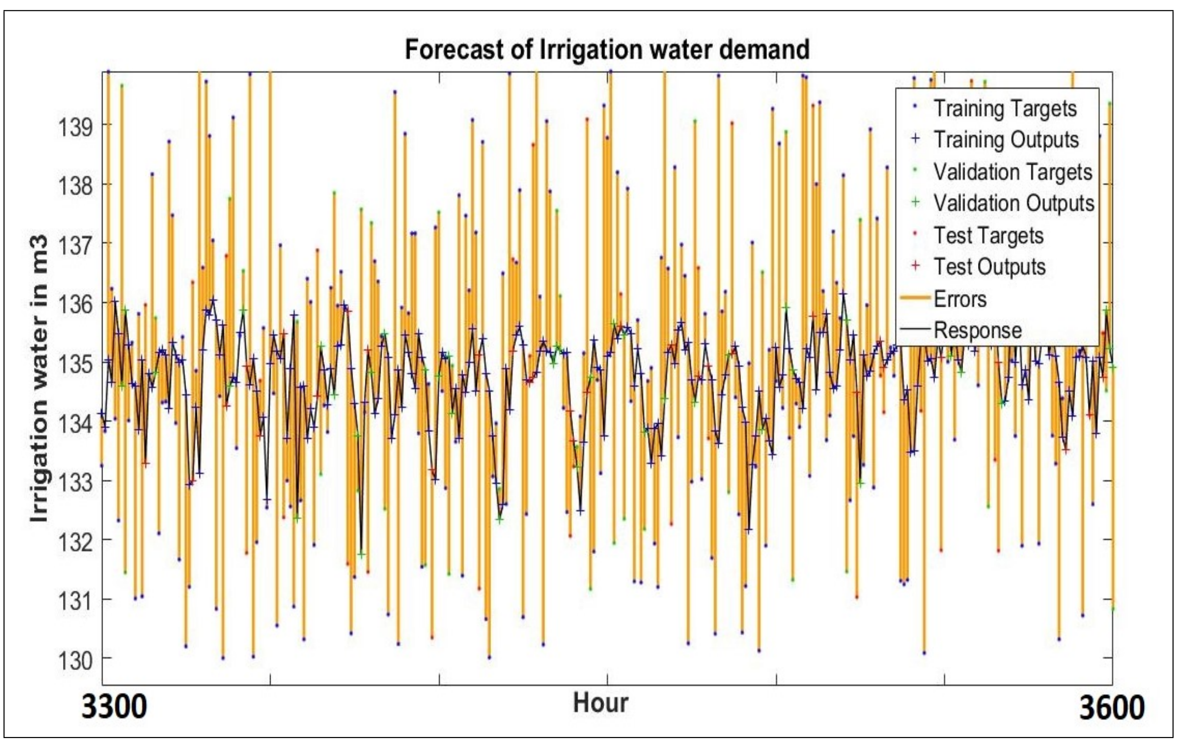



Figure 6.12: Forecasted output vs targeted data for irrigation water

Table 6.1: Mean Square Error (MSE) for different needs

| Basic Needs | Mean Square Error (MSE) |
|---|---|
| Cooking | 4.15% |
| Domestic Water | 3.57% |
| Electricity | 7.612% |
| Irrigation Water | 6.797% |

demand versus target data for cooking, domestic water, electricity and irrigation water demand respectively. The graphs have been zoomed in from $3300^{th} - 3600^{th}$ hour (as an example) to clearly represent the target and forecasted values. Table 6.1 lists the Mean Square Error (MSE) for the four needs considered.

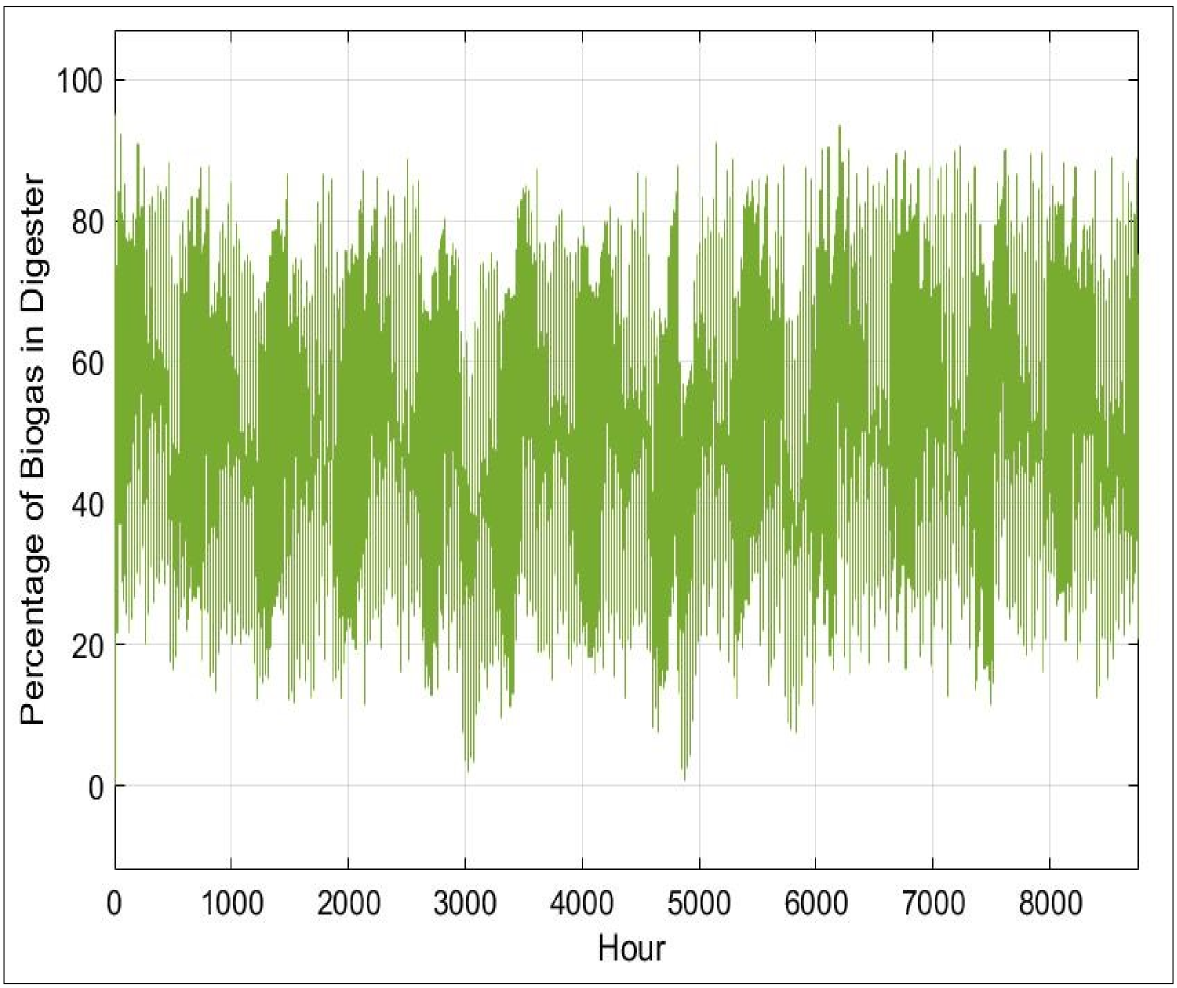



Figure 6.13: Variation of biogas in percentage

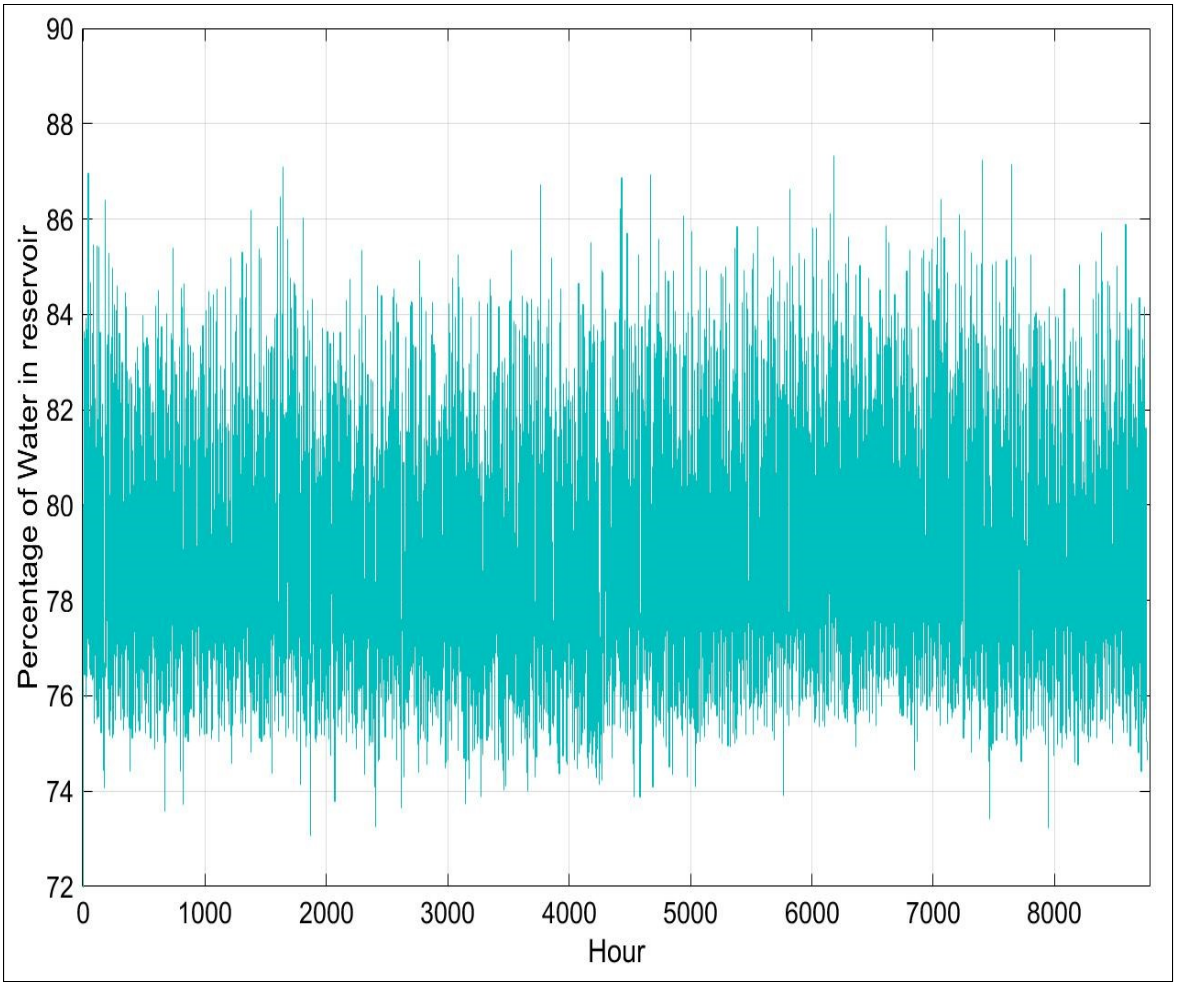



Figure 6.14: Variation of water in reservoir in percentage

### 6.3.2 Intelligent Control

A Mamdani based Fuzzy Logic Controller was designed to actuate renewable energy technologies using Matlab Fuzzy Logic Designer Toolbox. Neural Network and Fuzzy Logic models were integrated into Matlab SIMULINK environment. Output of fuzzy logic controller will turn on/off the system components. While pico hydropower and biogas generator can be instantly turned off when not required, energy produced by PV panels and wind turbines can be diverted to dump loads when energy storage such as reservoir and batteries are full.

Figure 6.13 shows the variations of biogas in biogas digester in terms of percentage for a period of one year. As expected, the percentage of biogas varies in between 0 to 100%. From the graph, it can be observed that the percentage of biogas reduces to very low levels for the hour 3000 to 3500 corresponding to December in the data considered. This is due to low insolation during winter, which leads to higher usage of biogas for electricity and water pumping purposes during this period. The same inference can be drawn for the hour 4500 to 5000 corresponding to the month of February. Biogas is at higher levels during summer because insolation is high and biogas is utilized in lesser quantity.

Figure 6.14 illustrates the varying water level in the reservoir in terms of percentage. The initial level of water in the reservoir is considered as 80%. As observed in the graph, the water level in the reservoir varies between 70% to 90% since the

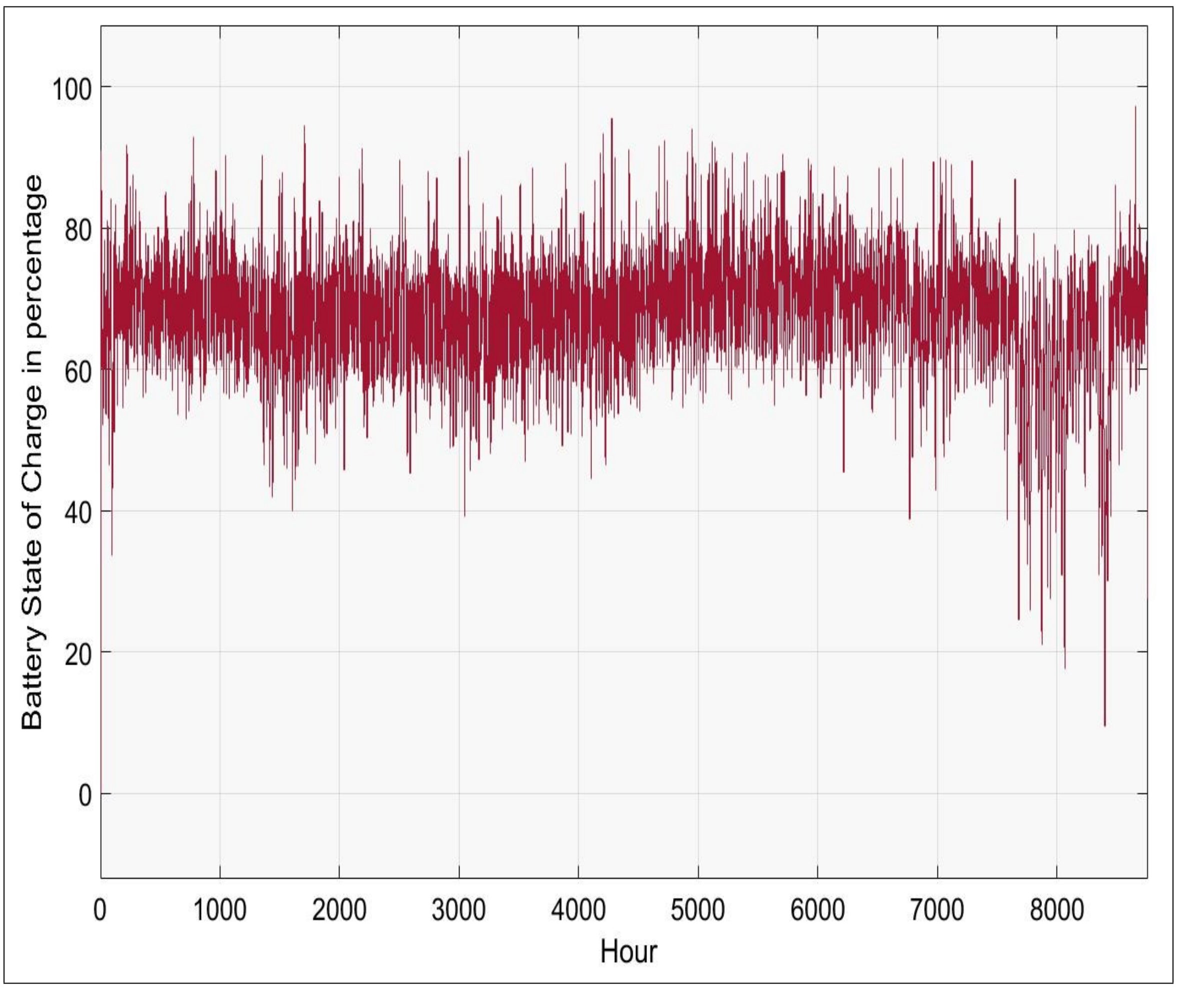



Figure 6.15: Variation of level of charge in battery

reservoir is considered full when the reservoir is greater than 90%. From the graph, it can be inferred that water in reservoir does not vary depending on the climatic conditions. This is because the magnitude of water stored in the reservoir is very large when compared to the daily combined consumption of domestic and irrigation water.

Figure 6.15 illustrates the level of charge in battery in terms of percentage and its initial level is assumed as 80%. As observed in the graph, the level of charge in the battery varies between 10% to 100%. From the graph, it can be inferred that charge in the battery is low in summer. During summer, the electricity load is at peak consumption when compared to other seasons. Hence, usage of battery is greater in summer when compared to the other seasons.

# CHAPTER 7

## NEED FULFILLMENT PROBABILITY(NFP)

Incident solar radiation (insolation) and wind speed characteristics are intermittent and have high influence on the resulting energy production. Use of renewable energy increases the difficulty of achieving a reliable system that will operate under uncertain situations. Hence reliability analysis has been considered an important step in any system design process, especially for stand-alone solar-wind systems [98]. The term "System reliability" is of utmost importance in such scenarios. System reliability is the probability that the system will perform its intended function for a specified interval of time under stated conditions [99].

Several methods to assess the reliability of systems such as hybrid renewable energy systems and microgrids have been considered in the literature. Negi and Mathew presented a review on stand-alone hybrid renewable energy system which highlighted research on unit sizing and optimization including reliability analysis. Several parameters such as Loss of power supply probability (LPSP) , Loss of Load Probability (LOLP), System Performance Level (SPL), and Loss of Load Hours (LOLH) to evaluate reliability were mentioned [100]. Another set of reliability indices such as Loss of Load Expected (LOLE), Loss of Energy Expected (LOEE) or Expected Energy not Supplied (EENS), and Equivalent Loss Factor (ELF) were recognized by Jahanbani and Riahy [40].

Li et al. developed a novel technique based on fault tree analysis (FTA) to evaluate the reliability of islanded microgrids in an emergency mode [101]. Conti et al. proposed an innovative formulation to evaluate distribution system reliability for islanded operation of microgrid. Probabilistic models were used for adequacy calculation of conventional and renewable distributed generators supplying microgrids [102]. A systematic scenario based approach for quantified evaluation of reliability was introduced by Lovelady et al. The authors considered multiple renewable Distributed Generators (DGs) and energy sources to demonstrate evaluation of reliability indices [103]. Wang et al. designed a two-step Monte-Carlo simulation (MCS) to calculate reliability and assess economic feasibility of microgrids in distribution system [104].

SIRES utilizes renewable resources and it is challenging to predict whether variable needs will be fulfilled by the intermittent resources available at any instant of time. Therefore, to assess the technical effectiveness of SIRES, a novel reliability index called Need Fulfillment Probability (NFP) is proposed. It is computed for four different weather conditions: high wind sunny, low wind sunny, high wind cloudy and low wind cloudy day. In this section, formulation of NFP and estimation of NFP for different weather conditions is discussed. NFP of SIRES was compared to that of microgrid.

## 7.1 Formulation of Need Fulfillment Probability (NFP)

Availability of renewable energy resources such as solar and wind are characterized by uncertainty. Hence it is necessary to form a reliability index, which can imbibe uncertainty and assist in understanding the amount of need fulfilled at any given day. Need Fulfillment Probability (NFP) of SIRES can be described as the probability that the available resources completely satisfy all user-defined primary needs. In other words, it is the average of the individual probabilities of need fulfillment of SIRES [105]. To formulate an equation for NFP, it is assumed that all the system components of SIRES are installed in a rural community. The optimal number of each system component are found using optimization techniques such as minimization of Annualized Cost of System (ACS) as discussed in section 5.1. The result obtained is arranged in the order of [$PV panels$ | $Wind\ turbines$ | $Biogas\ generators$ | $Pico\ hydroturbine$ | $PV\ powered\ water\ pump$ | $Wind\ powered\ water\ pump$ | $Biogas\ powered\ water\ pump$] and is equal to [75 | 9 | 1 | 5 | 4 | 10 | 1]. Storage devices such as battery, reservoir and biogas digester are considered to be low and hence cannot be used to fulfill the needs.

Consider 'P' to be the population of a rural community. Assume $n_1$,$n_2$,... $n_i$ to be the various needs per person at hour 't'. Total need at hour 't'for the considered rural area is then given by,

$$Total\ for\ need\ n_1(N_1^t) = P * n_1^t \tag{7.1}$$

Consider $r_1$,$r_2$ ... $r_m$ to be output obtained from one system component at hour t. Considering 'm' components, the optimal number of each component can be generalized as $x_1, x_2 \ldots x_m$. In this case, 7 different system components are considered as mentioned above. [$x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ | $x_6$ | $x_7$ | $x_8$] and it corresponds to [75 | 9 | 1 | 5 | 4 | 10 | 1] respectively.

$$Net\ output\ using\ available\ resource(R_1) = x_1 * r_1^t \tag{7.2}$$

All resources and needs have the same unit ($m^3$ for biogas/water or kWh for electricity). The classical definition of probability is the ratio of the number of favorable cases to the total number of cases and is given by,

$$P(success) = \frac{Number\ of\ success}{Total\ number\ of\ possible\ outcomes} \tag{7.3}$$

If probability of need fulfillment is being calculated for one day,

Total number of possible outcomes= 24 (one day)

Assume $RN^t$ to be the resource-need ratio at hour 't'. It is the ratio of summation of all the available resources to the demand required at time 't'and can be represented as,

$$RN_1^t = \frac{R_1^t + R_2^t + \cdots + R_m^t}{N_1^t} \tag{7.4}$$

When a particular system component is not used to fulfill need, then $R_m^t$ is zero for the considered need.

Assume $S^t$ to be the success factor. If available resources fulfill the demand, then it is a successful event and success factor ($S^t$) is equal to one. If available resources do not fulfill the demand, then it is a failure and success factor ($S^t$) is equal to $RN^t$.

$$RN_1^t = \frac{\sum_{m=1}^{8} R_m^t}{N_1^t} \begin{cases} \geq 1, then\ success\ and\ S_1^t = 1 \\ < 1, then\ partial\ success\ or\ failure \\ and\ S_1^t = \frac{\sum_{m=1}^{8} R_m^t}{N_1^t} \end{cases} \tag{7.5}$$

$P_{N_1}$ is the probability that need $N_1$ will be fulfilled and its value lies between 0 and 1

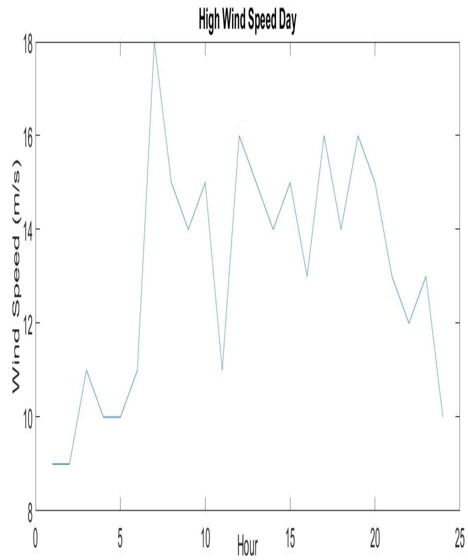
$$P_{N_1} = \frac{\sum_{t=1}^{24} S_1^t}{24} \tag{7.6}$$

Under the assumption that there are four needs: cooking, domestic water, electricity and irrigation water, Need Fulfillment Probability (NFP) of SIRES can be given as,

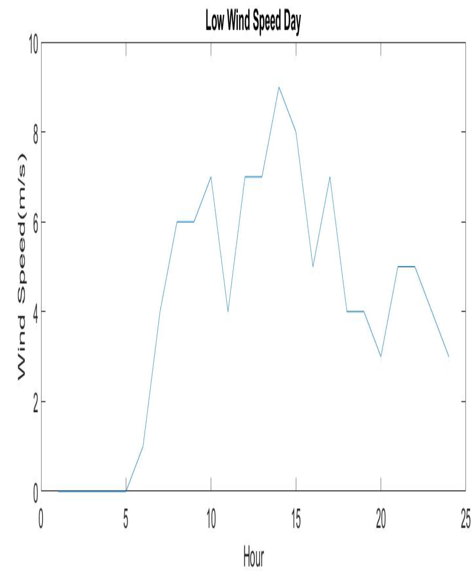
$$NFP = \frac{\sum_{i=1}^{4} P_{N_i}}{4} \tag{7.7}$$

### 7.2 NFP Estimation for different weather conditions

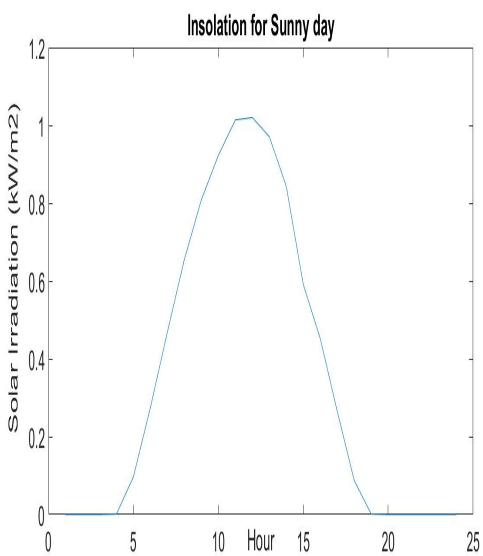
A typical rural area with population of 700 in 120 households and 450 cattle is considered. Most of the people have agriculture as their basic occupation. 200 acres



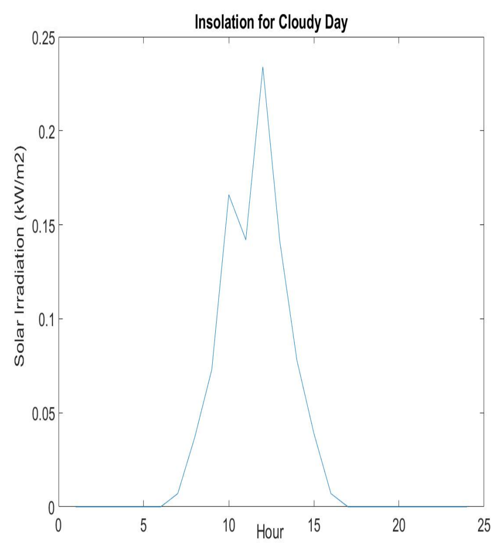

(a) High Wind Configuration




(b) Low Wind Configuration




(c) Sunny day configuration

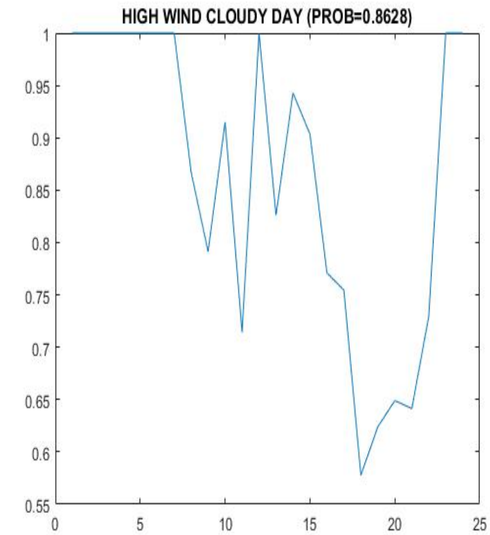



(d) Cloudy day configuration

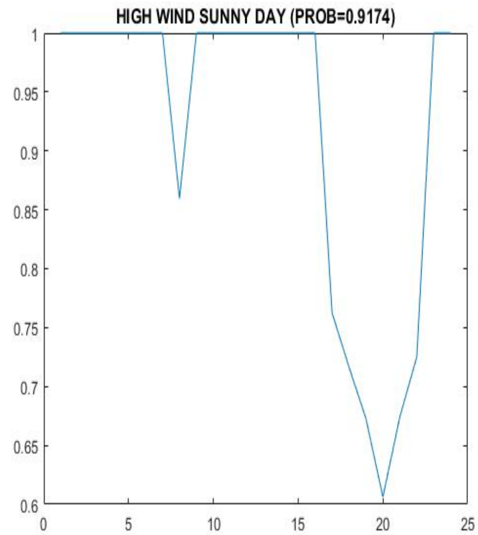
Figure 7.1: Different weather conditions considered

(80 hectares) is considered for agriculture. Estimated biogas production per day is approximately 350 $m^3$. Hourly solar irradiation and wind data are obtained from the Climate and Data Services, Oklahoma Climatological Survey. Ample water is assumed to be available from rivers and lakes.

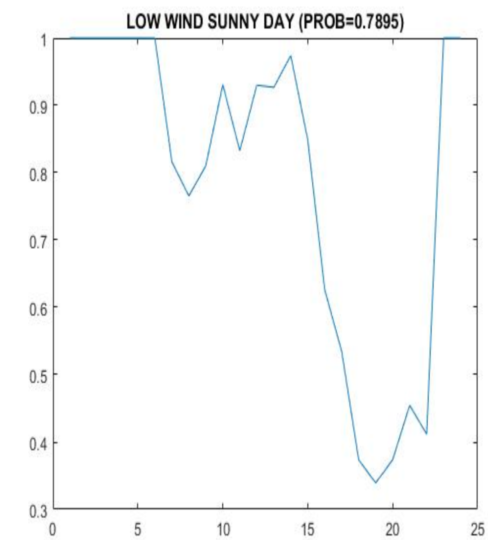
Every person requires about 0.34-0.42 $m^3$ of biogas every day for cooking purpose



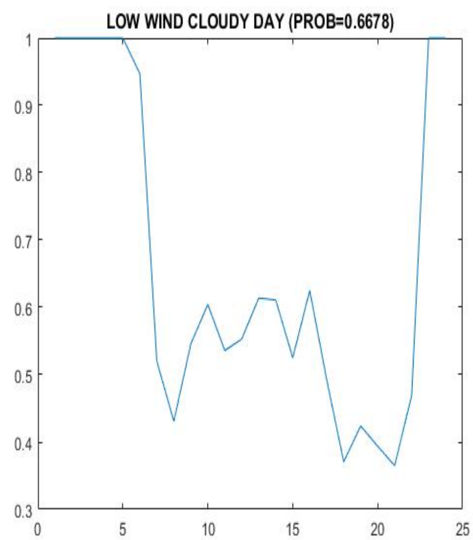

(a) High Wind Cloudy day




(b) High Wind Sunny day




(c) Low Wind Sunny day




(d) Low Wind Cloudy day

Figure 7.2: Need Fulfillment Probability (NFP) for different cases for electricity need

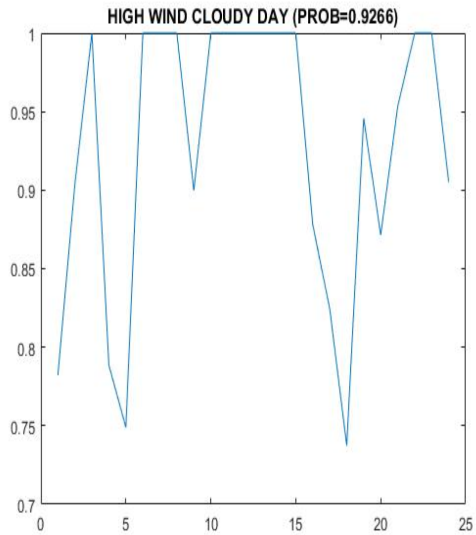
[24]. Therefore for 700 people, about 238-294 $m^3$ for biogas is needed every day for the rural area. Pattern of biogas consumption for cooking is decided empirically. Average level of water consumption per capita for domestic use in rural area is estimated to be 71.3 liters per day [25]. To assess the pattern of consumption of domestic water, water utility engineer at City of Stillwater was contacted. Urban water usage is more

compared to rural areas. Hence the water consumption is scaled by 2/3 to match the average consumption per capita in rural area as mentioned earlier. Making energy requirement projections that reflect reality is a difficult task to accomplish, especially for prospective consumers who have little or no experience with basic needs and other energy requirements.For this study, majority of the energy requirement details have been considered from suitable references [27]-[26]. Daily electricity demand varies from 300 kWh-360 kWh for 120 households. Electricity for community purpose is assumed to vary from 45 kWh-55 kWh/day. Hence the total electricity consumption for the rural area will vary from 345-415 kWh/day. Daily requirement for irrigation water is between 30-130 $m^3$/ha (3-13mm/day) [28].

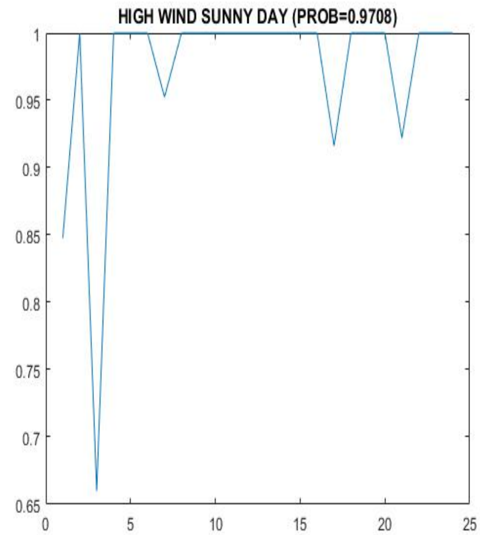
As mentioned earlier, NFP is calculated for a period of 24-hours. Nonetheless, it can be extended for any given period depending on the requirement. NFP is calculated for electricity and water needs (domestic and irrigation) separately. NFP for cooking is assumed to be 1 since the production of biogas changes only marginally depending on weather conditions such as insolation and wind speed. Four cases are considered in this work: sunny low wind day, cloudy windy day, cloudy low wind day and sunny windy day. Electricity and water needs are assumed to remain for the cases so that the comparisons are simplified.

Plots of Need Fulfillment Probability (NFP) for varied weather conditions for electricity need are shown in Figure 7.2. As expected, the highest probability that electricity need is fulfilled was obtained on a High Wind Sunny day since insolation and wind speed values are higher for this day. On the other hand, the least NFP was obtained for a Low Wind Cloudy day. A noteworthy point that is common for all the conditions was that there was depression in probability for $19^{th}$ to $22^{th}$ hour. This is because the electrical load is at the peak during this period. Hence, the probability of fulfilling the need reduces drastically.

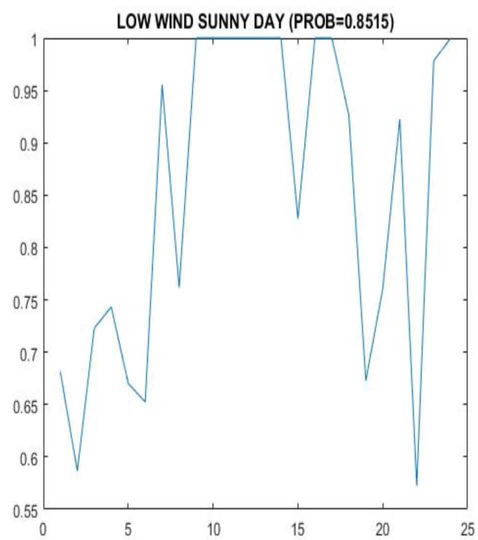
Plots of Need Fulfillment Probability (NFP) for the cases considered for water



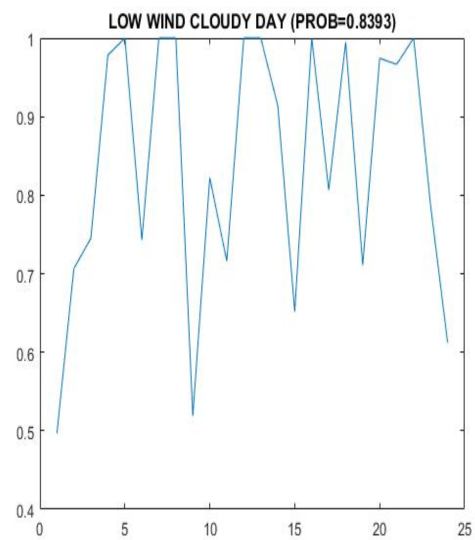

(a) High Wind Cloudy day




(b) High Wind Sunny day



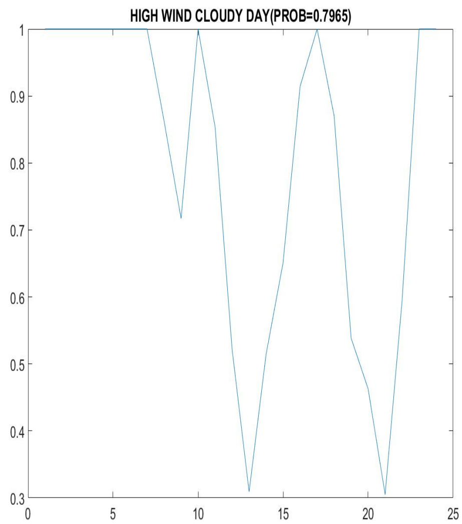

(c) Low Wind Sunny day



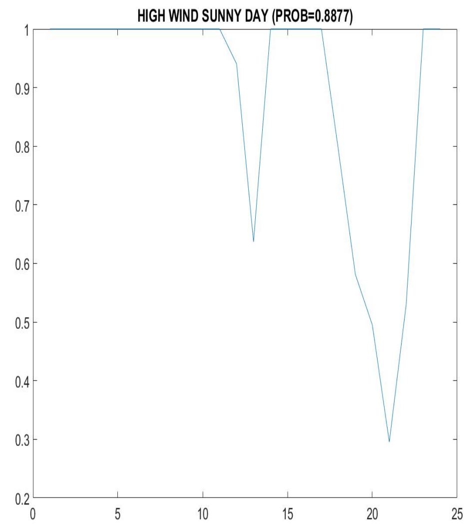

(d) Low Wind Cloudy day

Figure 7.3: Need Fulfillment Probability (NFP) for the considered cases for water needs

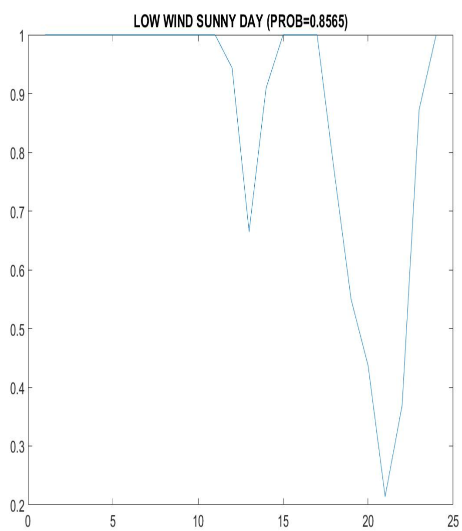
needs are shown in Figure 7.3. As expected, the highest probability that water needs are fulfilled was obtained on a High Wind Sunny day. On the other hand, the least NFP was obtained for a Low Wind Cloudy day. Unlike the electricity need, there is no typical pattern that is common for all the cases. One of the fundamental reasons is the large amount of water that is stored in reservoir. On the contrary, the magnitude



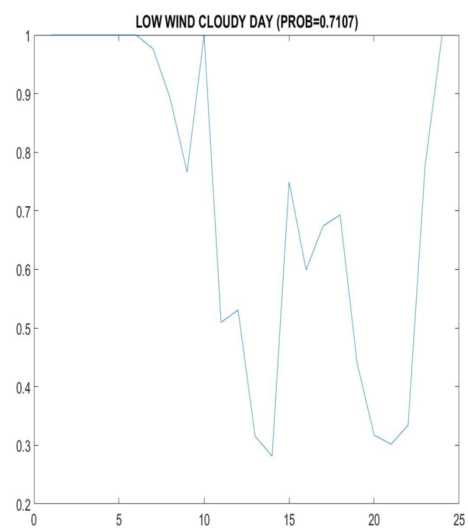

(a) High Wind Cloudy day




(b) High Wind Sunny day




(c) Low Wind Sunny day




(d) Low Wind Cloudy day

Figure 7.4: Need Fulfillment Probability (NFP) for the considered cases for Microgrid

of battery charge is small when compared to the reservoir.

## 7.3 Comparison of NFP of SIRES and Microgrid

NFP for microgrid is calculated for the exact same weather conditions, resources, and needs as that of SIRES. Needs such as water pumping ($m^3$) and cooking (biogas in

Table 7.1: Need Fulfillment Probability (NFP) for four considered cases for SIRES and Microgrids

| NFP | High Wind Cloudy | Low Wind Cloudy | High Wind Sunny | Low Wind Sunny |
|---|---|---|---|---|
| Electricity (SIRES) | 0.8628 | 0.6678 | 0.9174 | 0.7895 |
| Domestic and Irrigation water (SIRES) | 0.9266 | 0.8393 | 0.9708 | 0.8515 |
| SIRES (Total) | 0.9284 | 0.8357 | 0.9627 | 0.8803 |
| Microgrid | 0.7965 | 0.7107 | 0.8877 | 0.8565 |

$m^3$) are converted into electrical units (kWh). Optimal number of system components for microgrid are also found using Genetic Algorithm. Result obtained is arranged in the order of $[PVpanels \mid Wind\ turbines \mid Biogas\ generators \mid Micro\ hydroturbine]$ and is equal to [500 | 10 | 5 | 6] as discussed in section 5.1. Highest NFP was obtained for high wind sunny day followed by low wind sunny day. This is due to the large amount of PV panels that are integrated in microgrid. Lowest NFP was obtained for Low Wind Cloudy day. Plots of NFP for microgrid are shown in Figure 7.4

For each condition, probability that all needs are completely or partially satisfied is calculated and is shown in table 7.1. It is evident that NFP of SIRES was better when compared to microgrids for the same weather condition.

# CHAPTER 8

# RELIABILITY ASSESSMENT OF SIRES USING MARKOV MODEL

Every repairable component, device or system manufactured has associated failure and repair rates. Hence reliability considerations can be beneficial in almost all stages of engineering endeavors. Attention to reliability can reduce the risk of failure, lower the costs and improve the performance of the system. Regardless of the type and complexity of the system, three steps are crucial to assess the reliability of the system [99].

1. Construct a reliability model

2. Model analysis and appropriate reliability indices

3. Results obtained must be evaluated and analyzed

A markov mathematical model for PV based microgrid to assess reliability was presented by Esau et al. Mean Time To Failure (MTTF) and Mean Time to Repair (MTTR) were calulated for the proposed system [106]. Shi et al. reviewed three reliability analysis approaches to evaluate reliability for microgrid. The approaches used were Reliability Block Diagrams (RBD), Fault Tree Analysis (FTA) and Markov Reliability Modeling (MRM). While each of the approaches has its advantages and disadvantages, MTTF obtained for all 3 cases was approximately the same [107]. Jiang et al. proposed a markov model of power system reliability evaluation that incorporated protection system failures [108]. In [109], the authors investigated the effect of energy storage on the availability of microgrids using markov chain model. The markov model was used to represent the charging and discharging processes of energy storage for different architectures of renewable energy sources based microgrid. Srinivasan et al. developed a framework for reliability of Integrated Renewable Energy System (IRES) using hierarchical markov models [110]. However, the proposed markov model was based on assumption that all subsystems are in series which may not reflect the real world situation. In addition, proposed markov model was elementary (binary) and designed for only electricity system.

In this thesis, a detailed hierarchical markov model is proposed to perform reliability analysis for SIRES. All the possible combinations of subsystems of SIRES are considered to simulate real-time applications. Markov approach was developed assuming SIRES to be a series- parallel system to calculate MTTF and MTTR and hence, evaluate the availability of SIRES.

## 8.1 Review of component failures

In this work, the main focus is on failure of physical components in SIRES which are treated as a "system" and the effects of such failures on the performance of SIRES to meet the needs. Markov based reliability modeling used in this thesis can be applied for a lifetime estimation and can therefore be used to enhance the reliability of SIRES at design stage. There can be various factors that lead to failure of the system component. Some of the physical component failures are mentioned in the section below. It is important to note that failure of the system due to unavailability of resources is not considered in this chapter.

### 8.1.1 Solar PV System

It is often claimed that PV modules are the most reliable element in PV systems. This high reliability is reflected in the manufacturer's warranty for PV modules (either mono or poly crystalline). However, PV panels are prone to faults such as module and cell faults [111].

Module failures consists of open circuits, short circuits, fractured glass and delamination of PV panels. Open circuit takes place in bus wiring and between junction boxes that tie PV panels. It can occur as a result of manufacturing,transportation and installation defects and insulation degradation with weather. Severe weather such as wind, hail, snow, sand, salt, dust and humidity may cause short circuit faults. PV panels are covered with glass which may shatter due to vandalism, thermal stress, handling, wind or hail. Delamination results from the loss of adhesion between the encapsulant and other front surface material of the modules [112].

Cell faults include solar cell degradation, short and open circuited cells, interconnect open circuits and hot spot failure. Solar cells degrade with time that results in reduction of the power produced by the PV panels. Degradation of PV panels or in particular, solar cells may be caused by the virtue of impurities on the surface, increase in the cells'series resistance, decrease in the cell shunt resistance, degradation of the cells'anti-reflection coating, mismatch of cells or degradation induced due to temperature and light. Short circuited cells occur across the cells'inner connections, which is a common failure mode since top and rear contacts are much closer together with each other and more chance of being shorted together by impurities. Open circuited cells mainly occur due to corrosion and result in an increased resistance of the cell. Cell cracking can be caused by thermal stress and hail. Cyclic thermal stress and wind loading lead to interconnect open circuit failures. Hot-spot failures happen when the operating current of the cell is too large. By-pass diode failure operation is mainly due to overheating [112].

In addition to PV panels, Solar PV system also constitutes of an inverter that is connected between AC bus and DC bus of SIRES. Inverter failure may affect the PV array, the power conversion efficiency, and the amount of power that may be converted to AC power. Two main fault types are open-circuit and short-circuit faults in inverter components. They can occur in the switch, MOSTETs, IGBTs and other components [112].

### 8.1.2 Wind System

Wind turbine consists of several mechanical and electrical components such as generator, gearbox, bearings, rotors, blades, yaw systems, mechanical brakes, hydraulic systems, sensors and control systems. The top four drivers for the failure of wind system are gearbox, generator, hydraulics and electrical system (controls and sensors) [113]. Repairing a impaired gearbox is a tedious and time consuming process. Hence, repair rate or the downtime is the highest for gearbox for wind turbine system. Failure of gearbox bearing and gears may be caused due to micropitting, spalling, fretting corrosion, scuffing and lack of lubrication.

Generator of wind turbine can fail if there is loss in magnetic wedge, contamination in generator, electric arc damage or fluting. Doubly fed induction generators (DFIGs) are commonly used in wind turbines. Failure in the induction generator may induce unbalanced stator voltages and currents, decreased average torque, excessive heating, and low efficiency.

As already mentioned, wind turbines mainly consists of mechanical components that require periodic lubrication. Failure of lubrication can lead to temperature rise, increase in moisture, attract foreign materials and affect the viscosity. Temperature variations cause overloading, over greasing, improper cooling and wrong viscosity. Moisture content may lead to improper seals, leaking cooling system, hot operation and improper vents. Foreign materials cause improper filtration and poor lube storage methods. Lubrication of mechanical components maintains the viscosity which may otherwise result in oxidation, moisture and lack of additives [113]. Power electronics and electric control failures occur due to semiconductor device faults which include short and open circuits, gate drive circuit faults, and wiring damages. Rotors and blades fail due to corrosion, mechanical damages, and manufacturing defects.

### 8.1.3 Hydro power system

A hydropower station consists of various sub-units such as [114]

- Generator
- Turbine (inlet gate, penstock, spiral case, butterfly valve, runner and turbine bearing)
- Excitation (thyristor, cooling system, equipped transformer)
- Governor System (servo motors, wicket gates, speed governor)

From the case studies in literature, hydropower turbine is most likely to fail. Failure of turbine may occur due to damage of guide vane link rod, shear pin, and head cover, infrequent lubrication of bearings and lack of maintenance of inlet gate [115]. The causes of failures of a generator can be categorized in the following order: breakdown of electrical insulation system; mechanical defects and thermal problems; and, lastly, failures due to generator bearings. Breakdown in electrical insulation is commonly caused by aging and contamination of winding by dust and humidity. Electrical failure mechanisms are caused by internal partial discharges at the corona protection of the voltage grading and by voltages that were too high. Due to vibrations its possible that bars can loosen in their position or in the overhang (slot wedges) [116].

### 8.1.4 Biogas System

Biogas system consists of biogas digester, generator and controls. Failure in biogas system may be divided into five categories namely [117]

- Site Planning and Design: Includes site plan development and integration into existing facility

- Engineering: includes all engineering related activities (civil, structural, electrical and mechanical)

- Construction and Equipment: includes construction quality and equipment selection for the digester

- Biogas Utilization: includes equipment selection and system integration of the biogas system

- System Control and Operation: monitoring and control

According to literature review, more than 60% of the failures arise in design and construction phase [118]. Failure in site planning and design may exist due to excess heat loss and high solids content of manure that require additional dilution. Failure examples in the engineering category are gas leakage from the concrete hard top of digester which causes loss of energy and difficulty in heating the manure due to frozen manure clogged pipes. Failure in Combined Heat and Power (CHP) units, mechanical issues with genset, valves, muffler and biogas lines lie in the category for failure of construction and equipment. Failure in biogas utilization can be a result of boiler corrosion and incorrect size of biogas pipe that connects the flare. Finally, examples of failure in control and operation are variable biogas pressure and methane concentration, periodic operation of mixers and difficulty in maintaining digester temperatures.

The expected value of the continuous random variable called time to failure is known as the Mean Time To Failure (MTTF). A knowledge of the MTTF is enough to assess the quantity and usefulness of a certain component or a system [99]. Mean Time To Repair (MTTR) is the expected or mean value of the random variable called time to repair. The Mean Time Between Failures (MTBF) is the expected or mean value of the random variable called “time between failures”.

## 8.2 Hierarchical Markov model for reliability analysis

### 8.2.1 Primary Model

Reliability analysis of SIRES is performed using the hierarchical markov model technique. The primary model of SIRES is shown in figure 8.1. It consists of four subsystems: Water System (WS), Electricity System (Ele), Biogas System (Bio) and Energy Storage (ES). SIRES is considered to be operational when at least 3 subsystems are 'UP'. SIRES is considered inactive or inoperable when 2 or more subsystems are 'DOWN'. In this work, the following assumptions are made:

- Failure and repair rates remain constant over the lifetime
- A failure is considered only when a component has physical failures as described in section 8.1.
- All failures are mutually independent
- Repair of the system restores it to as good as new
- Failure and repair rates are considered for the combined system components of the same kind and not for individual system components
- Failure and repair rates remain same for the system components that utilize same resource. For example, failure and repair rate wind turbines and wind mechanical water pumps are same

### 8.2.2 Secondary Model

As mentioned, SIRES consists of four subsystems. Further, each subsystem consists of individual system components that are explained in the following sections.

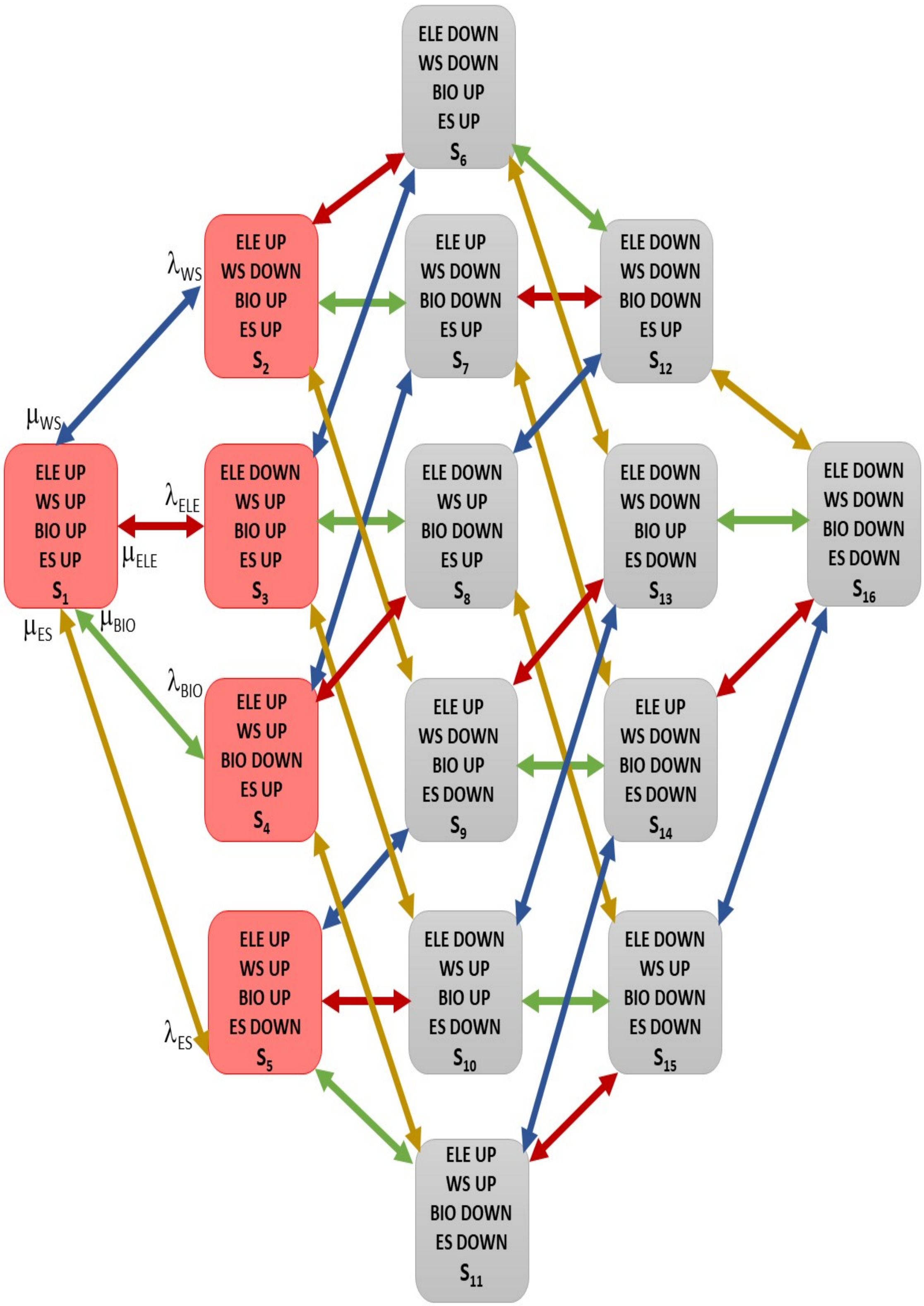



Figure 8.1: Markov Model for SIRES

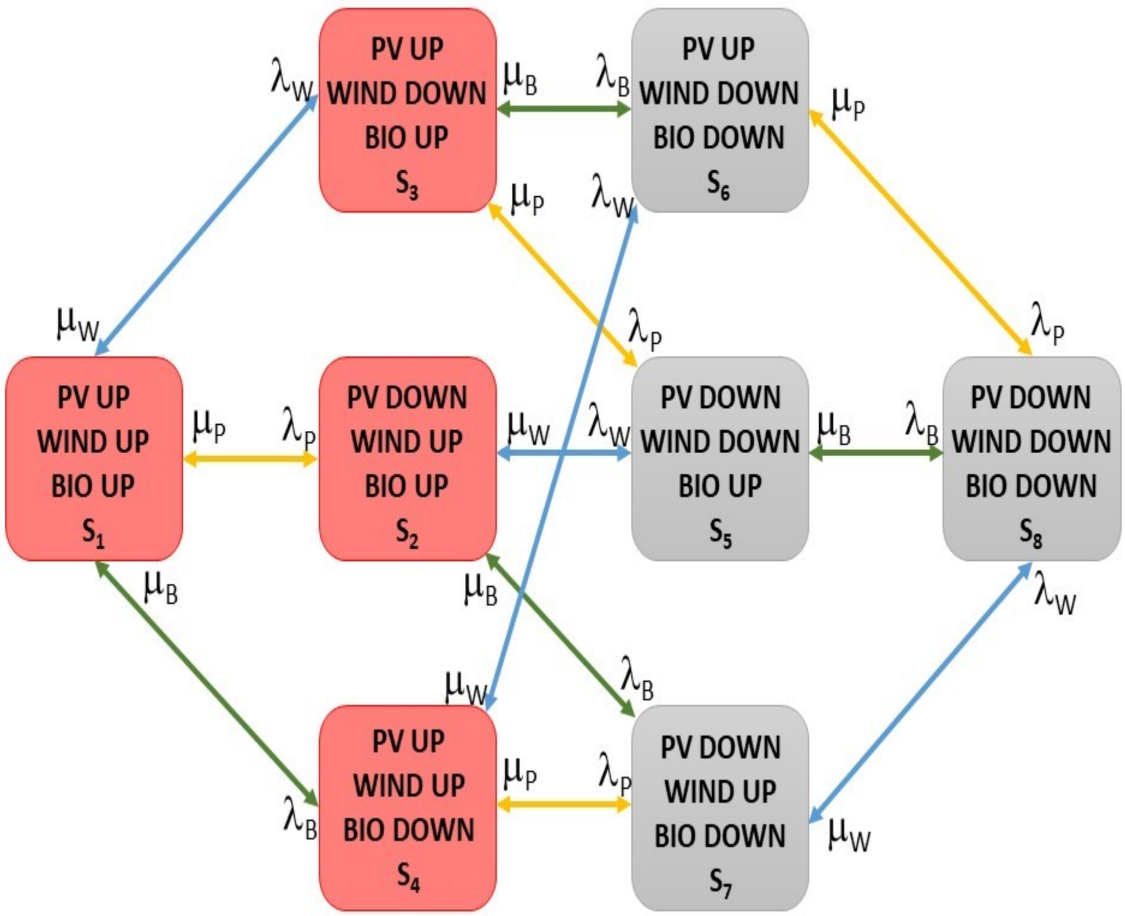



Figure 8.2: Markov Model for Water system

**Water System (WS)**

Water system (WS) includes PV water pump system, Wind water pump system and Biogas water pump system. Water system is considered to be in operation only when at least 2 water pump systems are 'UP'. Water system is considered inactive or inoperable when 2 or more water systems are 'DOWN'. Markov model of water system is illustrated in figure 8.2.

**Electricity System (Ele)**

Electricity system (Ele) includes PV electricity system, Wind electricity system, Biogas electricity system and Hydropower electricity system. Electricity system is consid-

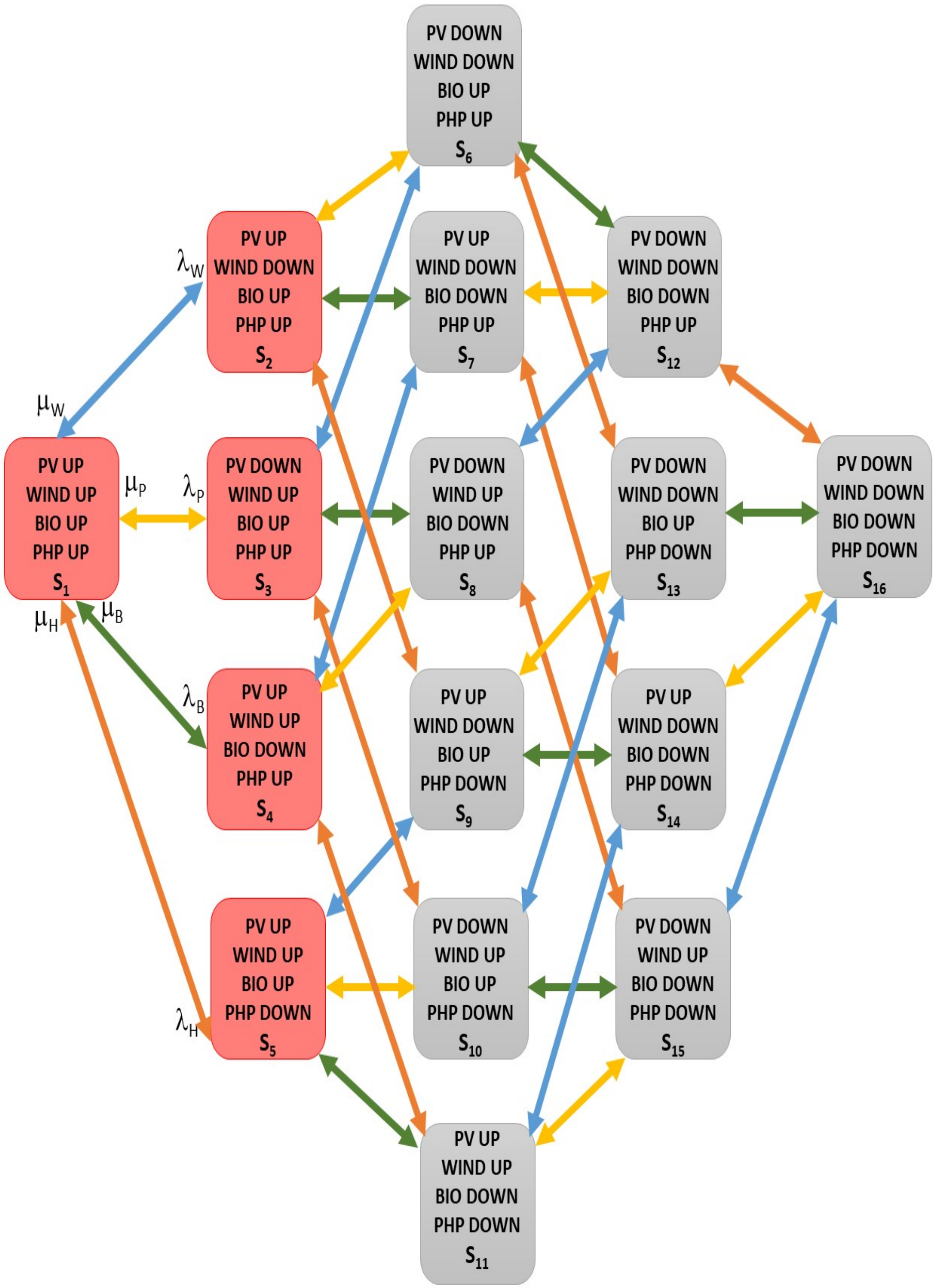



Figure 8.3: Markov Model for Electricity system

ered to be in operation only when at least 3 electricity subsystems are 'UP'. Electricity system is considered inactive or inoperable when 2 or more electricity subsystems are 'DOWN'. Markov model of electricity system is illustrated in figure 8.3.

### Energy Storage (ES)

Energy storage system (ES) includes water reservoir, battery and biogas storage. Energy storage system is considered to be in operation only when at least two energy storage subsystems are 'UP'. Energy storage system is considered inactive or inoperable when 2 or more energy storage subsystems are 'DOWN'.

### Biogas System (Bio)

Biogas system consists of biogas digester. When the biogas digester is down, biogas system is down. Hence the cooking need will not be fulfilled.

Failure rates and repair rates differs for different locations and countries. A detailed survey is required to evaluate the Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) for SIRES.

# CHAPTER 9

# SUMMARY AND CONCLUDING REMARKS

For the socio-economic development and growth of rural areas, basic needs such as domestic and potable water, cooking and electricity must be provided in a sustainable manner. Renewable energy resources such as biogas, hydro, insolation and wind are locally available in rural areas and can be harnessed in an efficient manner to fulfill these basic requirements in remote rural areas. In this study, Smart Integrated Renewable Energy Systems (SIRES) is introduced for sustainable development in rural areas. It is an effective and a viable strategy that can be employed to harness renewable energy resources to "energize" (not just electrify) remote rural areas of developing countries. Applying intelligent techniques to implement SIRES for a selected area makes it more advantageous when compared to hybrid energy systems. SIRES is flexible in implementation and is easily adaptable. Its configuration can be modified depending on available resources and needs of the particular rural area under consideration.

## 9.1 Summary

In this study, a methodology for optimization of SIRES to minimize ACS and maximize reliability is described. A hypothetical rural area with a population of 700 was considered as an example and basic energy requirements for this area were estimated. Availability of resources and weather conditions were analyzed. Needs were prioritized depending on the daily necessities and suitable renewable technologies were selected. System components, Annualized Cost of System (ACS) and System Reliability were modeled. A flowchart for implementation of genetic algorithm was developed. After the implementation of GA, optimal number of system components and minimum ACS for target reliability was obtained. Optimal sizing and annualized cost of system (ACS) for three different cases of SIRES have been analyzed depending on the varied electricity needs. A similar procedure was followed to obtain ACS for microgrid with and without diesel generator. In addition, installation cost and Net Present Cost (NPC) were calculated. It was found that installation of SIRES costs at about 40% less when compared with other current approaches including grid extension.

Employment of SIRES also reduce greenhouse gas (GHG) emissions, improves the Human Development Index (HDI) and Job Creation Factor (JCF). HDI was greater for SIRES when compared to microgrid with and without diesel generator. Although JCF was marginally higher for microgrid with diesel generator(MDG) when compared to SIRES, there is 50% reduction in emission of GHG when compared to MDG.

For successful operation of SIRES, smart sensors and intelligent controllers are employed to effectively utilize available resources. Fuzzy Logic Controller (FLC) in tandem with neural network forecasting of the demands constitute the intelligent control part of SIRES. Mean Square Error(MSE) of the forecasted demands lies between 3-8%. Forecasted demands, renewable technology models, and data from controllers are given as inputs to the Fuzzy Logic Controller that actuates the systems components for the next hour. Intelligent control of SIRES results in operation of appropriate subsystems such as storage that is well within the defined constraints.

Renewable resources such as insolation and wind energy are stochastic in nature. Therefore, it is essential to assess the technical effectiveness of SIRES for a rural community. In this study, Need Fulfillment Probability (NFP) is proposed as a novel index to measure uncertainty of resources and is calculated for one day (24 hours). However, it can be extended to any given period. Four days with different weather conditions were considered. As expected, the maximum NFP of SIRES was obtained on a high wind sunny day and minimum NFP was achieved on a low wind cloudy day. NFP for microgrid was calculated and compared to that of SIRES. It was found that NFP of SIRES was greater than microgrid for the same weather conditions. Estimation of NFP provides an interpretation of percentage of needs that will be fulfilled for a given time period.

In chapter 7, NFP is proposed as a reliability index to evaluate the uncertainty of resources. Apart from uncertainty of resources, it is critical to assess reliability based on the physical failure of system components. An overview of the potential faults of renewable technology devices was presented. The aim of the study was to propose a framework to estimate Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) of SIRES using Hierarchical Markov Model. Detailed explanation of Markovian based reliability modeling was provided. State-space diagram for markov process for SIRES and its subsystems such as water system and electricity system were illustrated.

Introduction of SIRES in rural communities brings about improvements in living environment and community welfare by supplying the basic needs such as biogas for cooking, water for domestic, potable and irrigation purposes and electrical energy for lighting, communication, cold storage, educational and small- scale industrial needs. Along with social and economic improvements in the rural community, implementation of SIRES can provide employment opportunities for the local people.

## 9.2 Concluding Remarks

The most important step in the development of SIRES is to establish an experimental prototype system with all the necessary measurement and monitoring systems. Data acquired from the operation of this system can be used to verify and improve the models and procedures presented in this thesis. This will also lead to better designs with built-in resiliency and reliability.

In future, Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR) of SIRES can be estimated for a particular site depending on the failure and repair rates. The influence of unavailability of system components (while they are being repaired) on fulfillment of needs can be analyzed. A detailed reliability assessment can be carried out for the combination of unavailability of resources and device failures. In aforementioned case, meticulous energy management techniques needs to be implemented to satisfy demands in a effective manner. Besides, sensitivity analysis of SIRES on varied levels of uncertainty can be conducted. Further, with development of real-time simulation of SIRES, one can scrutinize the failures and reliability concerns that are crucial for practical implementation of SIRES.

A variety of optimization techniques such as Particle Swarm Optimization (PSO), Teaching Learning Based Optimization (TLBO) can be implemented to optimally size system components of SIRES. The results obtained can be compared to that of Genetic Algorithm (GA) to validate the better optimization technique. A comprehensive Graphical User Interface (GUI) can be developed to optimally size SIRES for user defined values to meet demands depending on the site taken into consideration. Finally, a multi-objective optimization algorithm may be developed that incorporates objectives such as HDI, JCF and GHG emissions in addition to ACS and reliability.

## References


[1] Rolland, S. Rural Electrification with Renewable Energy. *ARE publication* **2010**.

[2] Environmental assessment of energy systems based on life cycle assessment *Treeze* Available online: http://treeze.ch/projects/case-studies/energy/

[3] United Nations Development Programme (UNDP), Energizing the Millenium Development Goals. New York, **2005** Available online:http://www.unmillenniumproject.org/goals/

[4] United Nations Development Programme (UNDP), Sustainable Development Goals, Rio De Janerio, **2012** Available online: http://www.undp.org/content/undp/en/home/sustainable-development-goals.html

[5] Ramakumar, R ;Hughes,W. Renewable Energy Sources and Rural Development in Developing Countries. *IEEE Trans. on Education* **1981**, *E-24*, no. 3.

[6] Decisions by Topic: Rural Development. United Nations. *Sustainable development knowledge platform* Available online: https://sustainabledevelopment.un.org/topics/ruraldevelopment/decisions

[7] Energy for cooking in development countries *International Energy Agency (IEA)* Available online: https://www.iea.org/publications/freepublications/publication/cooking.pdf

[8] Reddy, A. K. N;Subramanian, D. K. In The design of rural energy centers.

In *Rural Technology*; Indian Academy of Sciences; Macmillann India Press: Bangalore, India, **1979**; 109-131.

[9] Progress on Drinking Water and Sanitation. *World Health Organization and UNICEF Joint Monitoring Programme (JMP)* **May 2014**. Available online: http://www.unicef.org/publications/files/JMP_{}report_{}2014_{}webEng.pdf

[10] Energy for all: Financing access for the poor Available online: http://www.worldenergyoutlook.org/media/weowebsite/energydevelopment/weo2011_{}energy_{}for_{}all.pdf

[11] Ramakumar,R. Renewable Energy Sources and Developing Countries. *IEEE Trans. on Power Apparatus and Systems*, *Vol. PAS-102*, No. 2, **February 1983**.

[12] Maheshwari,Z. An approach to modeling and optimization of Integrated Renewable Energy Systems (IRES). Masters thesis, **December 2013**, Oklahoma State University.

[13] Electricity Access in 2013: Regional Aggregates. Available online: http://www.worldenergyoutlook.org/resources/energydevelopment/energyaccessdatabase/

[14] Best practices of the Alliance for Rural Electrification: what renewable energy can achieve in developing countries. *Alliance for Rural Electrification* Available online: http://www.ruralelec.org/fileadmin/DATA/Documents/06_Publications/Position_papers/ARE_Publication_-_Case_studies_for_renewables_in_Developing_countries.pdf

[15] Rolland,S; Glania, G. Hybrid Mini-Grids for Rural Electrification: Lessons Learned. **March 2011** *Alliance for Rural Electrification.*

[16] Zomers,A. N. Rural Electrification. Ph.D. dissertation, **2001** University of Twente.

[17] Schnitzer,D; Lounsbury,D; Carvallo,J. P; Deshmukh, R; J. A; Kammen, D.M. Microgrids for rural electrification: A critical review of best practices based on seven case studies. **February 2014** *United Nations Foundation (UNF).*

[18] Gupta, A; Saini, R.P; Sharma, M.P. Computerized modelling of hybrid energy systemPart I: Problem formulation and model development. *In Electrical and Computer Engineering* **2008**. ICECE 2008. International Conference on, 7-12.

[19] Ramakumar, R. Energizing rural areas of developing countries using IRES. *Energy Conversion Engineering Conference* **1996**, IECEC 96., Proceedings of the 31st Intersociety, *3*.

[20] Larsen,R.S.;Welbourn,D.;Wessner,D.;et al. Learning beyond the Light Bulb, among Least Developed Countries based on a sustainable PV solar utility model. *Global Humanitarian Technology Conference (GHTC)*, **2014**, 106-114.

[21] IEEE Smart Village, Frequently asked questions. Available online:`http://ieee-smart-village.org/resources/faq/`

[22] Maheshwari, Z.; Ramakumar, R. Smart Integrated Renewable Energy System (SIRES) for Rural Communities. *Proc. IEEE PES General Meeting 2016*, **17-21 July 2016**,Boston, USA.

[23] Maheshwari, Z.; Ramakumar, R. Smart Integrated Renewable Energy Systems (SIRES): A Novel Approach for Sustainable Development. *Energies* **2017**, *10*, no.8, 1145.

[24] Brown,N L.; Tata,P.B.S. Biomethanation. In *Bioenergy*; International Development Research Centre: **1990**, 111-117.

[25] Fan,L.; Li,G.; Wang,F.; Geissen,V.; Ritsema,CJ. Factors Affecting Domestic Water Consumption in Rural Households upon Access to Improved Water Supply: Insights from the Wei River Basin, China.. *PLoS ONE* **2013**, *8(8): e71977.*

[26] Bassam, E.; Maegaard,P. In *Integrated Renewable Energy for Rural Communities*,Elseveir publication,**2004**, 10-11.

[27] Longe, O.M.; Ouahada, K.; Ferreira, H.C.; Chinnappen, S.Renewable Energy Sources microgrid design for rural area in South Africa. In *Innovative Smart Grid Technologies Conference (ISGT)*, **2014** IEEE PES, 1-5.

[28] Fraenkel,P.L. Water Lifting Devices, *Food and Agriculture Organization of the United Nations* **1986**,Rome, 31-32.

[29] Argaw,N.; Foster, R.; Ellis, A. Renewable Energy for Water Pumping Applications in Rural Villages. National Renewable Energy Laboratory **July 2003**, 5-6.

[30] U.S climate data.Available online:`http://usclimatedata.com/climate/stillwater/oklahoma/united-states/usok0507`

[31] Caslin,B. Potential of Farm Scale AD in Ireland. *Agriculture and Food Development Authority* **2009**.

[32] Lotfi,S.; Trazouei,F.L.; Ghiamy,M. Optimal Design of a hybrid Solar-Wind-Diesel Power System for Rural Electrification using Imperialist Competitive Algorithm. *International Journal of Renewable Energy Research* **2013**, *3*, No.2.

[33] Rouhani, A.; Kord, H.; Mehrabi, M. A comprehensive method for optimum sizing of hybrid energy systems using intelligence evolutionary algorithms. *Indian Journal of Science and Technology*, *6*,no.6,4702-4712.

[34] Koutroulis,E.;Kolokotsa,D.;Potirakis,A;Kalaitzakis,K. Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms. *Solar Energy* **2006**, *80*,1072-1088.

[35] Zhang,Y.;Kang,L.;Cao,B.;Huang,C.;Wu,G. Simulation of biogas generation. *Transmission & Distribution Conference & Exposition: Asia and Pacific* **2009**, 1-5.

[36] Ashenayi,K. Optimization And Design Of Stand-Alone Integrated Renewable Energy Systems. PhD Thesis, **December 1986**, Oklahoma State University.

[37] Gupta, A., Saini, R.P. and Sharma, M.P. Modelling of hybrid energy systemPart I: Problem formulation and model development. *Renewable Energy* **2011**, *36*, no. 2, 459-465.

[38] Mathew,S.; Pandey,K.P.Modelling the integrated output of wind-driven roto-dynamic pumps. *Renewable energy*, **June 2003**,*28*,Issue 7,1143-1155.

[39] Helmy,E.G; Safya,M.E. Using Photovoltaic Array for Solar Water Pumping in Toshka Region, Egypt. *15th International Water Technology Conference*, IWTC, Alexandria, Egypt.

[40] Jahanbani, F.; Riahy, G.H. Optimum design of a hybrid renewable energy system. *In Renewable Energy-Trends and Applications* **2011**. InTech.

[41] Abouzahr,I.; Ramakumar, R. Loss of power supply probability of stand alone wind electric conversion systems: A closed form solution approach. *IEEE transactions on Energy Conversion* **September 1990**, *5*, no.3, 445-452.

[42] Abouzahr,I.; Ramakumar, R. Loss of power supply probability of stand alone photovoltaic systems: A closed form solution approach. *IEEE transactions on Energy Conversion* **March 1991**, *6*, no.1, 1-11.

[43] Yang,H.;Zhou,W.;Lu,L.;Fang,Z.Optimal sizing method for stand-alone hybrid solarwind system with LPSP technology by using genetic algorithm. *Solar Energy* **April 2008**,*82*,Issue 4,354-367.

[44] Ashok, S. Optimised model for community-based hybrid energy system. *Renewable energy* **2007**,*32*,no. 7,1155-1164.

[45] Kanase-Patil,A.B.; Saini,R.P.;Sharma,M.P.Integrated renewable energy systems for off grid rural electrification of remote area. *Renewable Energy* **2010**, *35*,no. 6,1342-1349.

[46] Ahlborg, H. Electricity for better lives in rural Tanzania and Mozambique. *PhD Dissertation, Chalmers University of Technology* **2012**, Gothenburg, Sweden.

[47] Agarwal,N.;Kumar,A.Optimization of grid independent hybrid PVdieselbattery system for power generation in remote villages of Uttar Pradesh, India. *Energy for Sustainable Development* **2013**,*17*,no. 3, 210-219.

[48] Ramoji,S.K.;Kumar,B.J.Optimal economical sizing of a PV-wind hybrid energy system using genetic algorithm and teaching learning based optimization. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering* **2014**, *3*, no. 2, 7352-7367.

[49] Ko,M.J.;Yong,S.K.;Min,H.C.;Hung,C.J.Multi-objective optimization design for a hybrid energy system using the genetic algorithm.*Energies* **2015**, *8*, no. 4, 2924-2949.

[50] Barman,M.;Mahapatra,S.;Palit, D.; Chaudhury, M.K. Performance and impact evaluation of solar home lighting systems on the rural livelihood in Assam, India. *Energy for Sustainable Development* **2017**, *38*,10-20.

[51] Holland, J.H., Adaptation in Natural and Artificial Systems. University of Michigan Press, Ann Arbor, **1975**.

[52] Konak,A.; Coit, D. W.; Smith, A. E. Multi-Objective Optimization Using Genetic Algorithms: A Tutorial. *Reliability Engineering & System Safety* **2006**, *91*, no.9, 992-1007.

[53] Schaffer, J.D. Multiple Objective optimization with vector evaluated genetic algorithms in International Conference on Genetic Algorithm and their applications. **1985**.

[54] Fonseca, C.M.; Fleming, P.J. Multiobjective genetic algorithms. *in IEE Colloquium on Genetic Algorithms for Control Systems Engineering* (Digest No. 1993/130), **28 May 1993**, London, UK.

[55] Horn, J.; Nafpliotis, N.; Goldberg, D.E. A niched Pareto genetic algorithm for multiobjective optimization. *In Proceedings of the First IEEE Conference on Evolutionary Computation.* **27-29 June 1994**. Orlando, FL.

[56] Murata, T.; Ishibuchi, H. Multi-objective genetic algorithms (MOGA).*In Proceedings of IEEE International Conference on Evolutionary Computation*, **29 Nov-1 Dec 1995**. Perth, WA, Australia.

[57] Srinivas, N.; Deb, K. Multi-objective Optimization Using Non dominated Sorting in Genetic Algorithms. *Journal of Evolutionary Computation* **1994**, 221-248.

[58] Zitzler, E.; Thiele, L. Multi-objective evolutionary algorithms: a comparative case study and the strength Pareto approach. *IEEE Transactions on Evolutionary Computation* **1999**, 257-271.

[59] Deb, K.; Pratap, A.; Agarwal, S.; Meyarivan, T. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation* **2002**, 182-197 .

[60] Sarker, R.; Liang, K.-H.; Newton, C. A new multi-objective evolutionary algorithm. *European Journal of Operational Research* **2002**, 12-23.

[61] Taylor,M.; Daniel, K.; Ilas, A.; Young, E.; Renewable Power Generation costs in 2014. *International Renewable Energy Agency (IRENA)*, **January 2015.**

[62] Purohit,P. Financial evaluation of renewable energy technologies for irrigation water pumping in India. *Energy Policy* **2007**, *35*, 31343144.

[63] Paulsen,J.; Reynolds, T. Alternative Energy Pumps to Irrigate Smallholder Farmers Land: What is the State of the Art? *Evans School Policy Analysis and Research,* **December 13 2010**.

[64] Kossmann,W.; Ponitz, U.; Habermehl,S.; et al. Biogas Digest: Biogas-Costs and Benefits. *Information and Advisory Service on Appropriate Technology.* Volume III, 10-11.

[65] altE Polycrystalline Photovoltaic Module Available online:`https://www.altestore.com/static/datafiles/Others/ALT100-24P_alte-solar-modules-spec-sheet.pdf`

[66] Bergey Excel 1kW wind turbine. Available online: `http://bergey.com/products/wind-turbines/bergey-excel-1`

[67] Solar powered water surface pumps. Available online:`https://www.altestore.com/store/solar-water-pumps/surface-solar-pumps/suncentric-centrifugal-pump/dankoff-suncentric-7521-dc-surface-pump-p392/`

[68] Wind mechanical water pumps. Available online:http://www.ironmanwindmill.com/pumping-capacity.htm

[69] Lambert,T.; Gilman, P.; Lilienthal,P.; Micropower System Modeling with HOMER. *National Renewable Energy Laboratory* **2006**, 415-416.

[70] HOMER Energy Support. *Total net present cost in HOMER* Available online:http://usersupport.homerenergy.com/customer/en/portal/articles/2187252-total-net-present-cost-in-homer

[71] Basu, A.K.; Chowdhury, S.; Chowdhury, S. P. Value-Based Operational Strategy of CHP-Based Microgrid: A Comparative Analysis. In *IEEE Universities Power Engineering Conference (UPEC)* **2010**, 1-5.

[72] Dutt, G. S.; Ravindranath, N. H. Bioenergy: Direct Applications in Cooking. In *Renewable Energy: Sources of Fuels and Electricity*; Owino, F., Desai, A.; Wiley Eastern Limited, 1993, 676-677.

[73] Akella, A.K.; Saini, R.P.; Sharma, M.P. Social, economical and environmental impacts of renewable energy systems. *Renewable Energy*, **2009**, *34*, no.2, 390-396.

[74] Gmez, M.F.; Silveira, S. Rural electrification of the Brazilian AmazonAchievements and lessons. *Energy policy*, **2010**, *38*, no.10, 6251-6260.

[75] Kanagawa, M.; Nakata, T. Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries. *Energy Policy*, **2008**, *36*, no.6, 2016-2029.

[76] United Nations Development Program. Human Development Report **2016**. Available online: http://hdr.undp.org/en/2016-report

[77] Pasternak, A.D. Global energy futures and human development: a framework for analysis. *US Department of Energy*, **2000**, Oak Ridge.

[78] Dufo-Lpez, R.; Cristbal-Monreal, I.R.; Yusta, J.M. Optimisation of PV-wind-diesel-battery stand-alone systems to minimise cost and maximise human development index and job creation. *Renewable Energy* **2016**, *94*, 280-293.

[79] International Renewable Energy Agency.Renewable energy and jobs annual review **2017**. Available online: `http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=3852`

[80] Simas, M.; Pacca, S. Assessing employment in renewable energy technologies: A case study for wind power in Brazil. *Renewable and Sustainable Energy Reviews*, **2014**, *31*, 83-90.

[81] Cameron, L.; Van Der Zwaan, B. Employment factors for wind and solar energy technologies: a literature review. *Renewable and Sustainable Energy Reviews*, **2015**, *45*, 160-172.

[82] Wei, M.; Patadia, S.; Kammen, D.M. Putting renewables and energy efficiency to work: How many jobs can the clean energy industry generate in the US?. *Energy policy*, **2010**, *38*, no.2, 919-931.

[83] Weisser, D. A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy* **2007**, *32*, no. 9, 1543-1559.

[84] World Nuclear Association. Comparison of lifecycle Greenhouse Gas Emissions of Various Electricity Generation Sources.

[85] Denholm, P.; Kulcinski, G. Net energy balance and greenhouse gas emissions from renewable energy storage systems, Energy Center of Wisconsin **June 2013**

[86] Szab, G.; Fazekas, I.; Szab, S.; Szab, G.; Buday, T.; Paldi, M.; Kisari, K.; Kernyi, A. The carbon footprint of a biogas power plant. *Environmental Engineering and Management Journal* **2014**, *13*, no.11, 2867-2874.

[87] Zhang, H.; Davigny, A.; Colas, F;, Poste, Y.; Robyns, B. Fuzzy logic based energy management strategy for commercial buildings integrating photovoltaic and storage systems. *Energy and Buildings* **2012**, *54*, 196-206.

[88] Chaouachi, A.; Kamel, R.M.; Andoulsi, R.; Nagasaka, K. Multiobjective intelligent energy management for a microgrid. *IEEE Transactions on Industrial Electronics* **2013**, *60*, no.4, 1688-1699.

[89] Kyriakarakos, G.; Dounis, A.I.; Arvanitis, K.G.; Papadakis, G. A fuzzy logic energy management system for polygeneration microgrids. *Renewable Energy* **2012**, *41*, 315-327.

[90] Arcos-Aviles, D.; Pascual, J.; Marroyo, L.; Sanchis, P.; Guinjoan, F. Fuzzy logic-based energy management system design for residential grid-connected microgrids. *IEEE Transactions on Smart Grid* **2016**. (In press)

[91] Chen, Y.K.; Wu, Y.C.; Song, C.C.; Chen, Y.S. Design and implementation of energy management system with fuzzy control for DC microgrid systems. *IEEE Transactions on Power Electronics* **2013**, *28*, no.4, 1563-1570.

[92] Maheshwari, Z.; Ramakumar, R. A Framework for Intelligent Control of SIRES for Rural Communities. *In Power and Energy Society General Meeting (PESGM)*, **2017**, Chicago, 1-5. IEEE. (Paper number: 17PESGM0738)

[93] Amakali, S. Development of models for short-term load forecasting using artificial neural networks, Doctoral dissertation, Cape Peninsula University of Technology, **2008**.

[94] Hippert, H.S.; Pedreira, C.E.; Souza, R.C. Neural networks for short-term load forecasting: A review and evaluation. *IEEE Transactions on power systems* **2001**, *16*, no.1,44-55.

[95] Majithia, S.; Kiernan, L.; Hannan, J. Intelligent systems for demand forecasting. *In Artificial intelligence techniques in power systems* **March 1997**, 259-279. Institution of Electrical Engineers.

[96] Hagan, M.T.; Demuth, H.B.; Beale, M.H.; De Jess, O. Neural network design **2014**, PWS Publishing Co, Boston.

[97] Weng, G.; Zhang, Y.; Hu, Y. Application of Artificial Intelligence Technique in Distributed Generation System. *In International Symposium on Neural Networks* **May 2009**, 165-171. Springer, Berlin, Heidelberg.

[98] Lotfi, S.; Tarazouei, F. L.; Ghiamy, M. Optimal design of a hybrid solar-wind-diesel power system for rural electrification using imperialist competitive algorithm. *International Journal of Renewable Energy Research (IJRER)* **2013**, *3*, no.2, 403-411.

[99] Ramakumar, R. Engineering reliability: fundamentals and applications, **1993**, Prentice Hall.

[100] Negi, S.; Mathew, L. Hybrid renewable energy system: a review. *International Journal of Electronic and Electrical Engineering* **2014**, *7*, no.5, 535-542.

[101] Li, Z.; Yuan, Y.; Li, F. Evaluating the reliability of islanded microgrid in an emergency mode. *Universities Power Engineering Conference (UPEC)*, **2010** 45th International, IEEE, 1-5.

[102] Conti, S.; Nicolosi, R.; Rizzo, S. A. Generalized systematic approach to as-

sess distribution system reliability with renewable distributed generators and microgrids. *IEEE Transactions on Power Delivery* **2012**, *27*, no. 1, 261-270.

[103] Lovelady, D.; Yang, B.; Natti, S.; Mueller, H.; Tao, L. A scenario driven reliability assessment approach for microgrids. *Power and Energy Society General Meeting (PES)*, **2013** IEEE, 1-5.

[104] Wang, S.; Li, Z.; Wu, L.; Shahidehpour, M.; Li, Z.New metrics for assessing the reliability and economics of microgrids in distribution system. *IEEE transactions on power systems* **2013**, *28*, 3, 2852-2861.

[105] Maheshwari, Z; Ramakumar, R. Assessment of the Technical Effectiveness of SIRES in a Rural Setting. *In proceedings IEEE Technologies for Sustainability* **2017**, Arizona. (Accepted)

[106] Esau, Z.; Jayaweera, D. Reliability of active distribution networks with PV based strategic micro-grids. *In Power Engineering Conference (AUPEC)*, **September 2013** Australasian Universities, 1-6. IEEE.

[107] Shi, X.; Bazzi, A.M. Reliability modeling and analysis of a micro-grid with significant clean energy penetration. *In Power Electronics and ECCE Asia (ICPE-ECCE Asia)*,**June 2015** 9th International Conference on, 202-207. IEEE.

[108] Jiang, K.; Singh, C. New models and concepts for power system reliability evaluation including protection system failures. *IEEE Transactions on Power Systems* **2011**, *26*, no.4, 1845-1855.

[109] Song, J.; Bozchalui, M.C.; Kwasinski, A.; Sharma, R. Microgrids availability evaluation using a Markov chain energy storage model: a comparison study in system architectures. *In Transmission and Distribution Conference and Exposition (T& D)*, **May 2012** IEEE PES, 1-6. IEEE.

[110] Srinivasan, H.; Chinnaswarny, M.R.; Ramakumar, R. An approach to study the reliability of IRES using Markov models. *In Region 5 Conference: Annual Technical and Leadership Workshop*, **April 2004**, 11-20. IEEE.

[111] Vzquez, M.; ReyStolle, I. Photovoltaic module reliability model based on field degradation studies. *Progress in photovoltaics: Research and Applications* **2008**, *16*, no.5,419-433.

[112] Shi, X. Micro-grid Reliability Modeling and Analysis Approaches. Masters thesis, **August 2016**, University of Connecticut.

[113] Sheng, S. Improving component reliability through performance and condition monitoring data analysis. *Wind Farm Data Management & Analysis North America* **2015**, Houston, Texas, 25-26.

[114] Majeed, A.R.; Sadiq, N.M. Availability & Reliability evaluation of Dokan hydro power station. *In Transmission & Distribution Conference and Exposition: Latin America*, **August 2006**. TDC'06. IEEE/PES, 1-6. IEEE.

[115] Sapkota, D.; Bajracharya, T.R.; Luintel, M.C. Reliability and availability evaluation of Sunkoshi hydro power station. *In Proceedings of IOE Graduate Conference* **2014**, 197-202.

[116] Sumereder, C. Statistical lifetime of hydro generators and failure analysis. *IEEE Transactions on Dielectrics and Electrical Insulation* **2008**, *15*, no.3.

[117] Tesar, J.; Kirk, D.; Willard, J. Anaerobic digester system failure analysis, Corrective actions and BPMs. *Quanta Lux* **October 2012** Available online: `www.biocyclerefor.com/2012/presents_tuesday/Tesar_r_s.pdf`

[118] Kariko-Buhwezi, B.; Mwesigye, A.; Arinaitwe, J.; Colonna, G.P. Challenges to the sustainability of small scale biogas technologies in Uganda. *In Proceed-*

*ings of the Second International Conference on Advances in Engineering and Technology* **2011**, Entebbe, Uganda, *31.*

[119] Srinivasan, H. Probabilistic approach to assess the performance of Integrated Renewable Energy Systems (IRES) using Markov Models. Masters thesis, **December 2004**, Oklahoma State University.

[120] Huang, H.S.; Jao, J.C.; Yen, K.L.; Tsai, C.T. Performance and availability analyses of PV generation systems in Taiwan. *World Academy of Science, Engineering and Technology International Journal of Electrical* **2011**, Computer, Electronics and Communication Engineering, *5*, no.6, 36-40.

[121] Tanrioven, M. Reliability and costbenefits of adding alternate power sources to an independent micro-grid community. *Journal of power sources* **2005**, 150, 136-149.

VITA

Zeel Maheshwari

Candidate for the Degree of

Doctor of Philosophy

Dissertation: A STUDY OF SMART INTEGRATED RENEWABLE ENERGY SYSTEMS (SIRES)

Major Field: Electrical and Computer Engineering

Biographical:

Education:

Received the B.E. degree from Visvesvaraya Technological University, Hubli, Karnataka, India, 2011, in Electrical and Electronics Engineering

Received the M.S. degree from Oklahoma State University, Stillwater, Oklahoma, USA, 2013, in Electrical and Computer Engineering

Completed the requirements for the degree of Doctor of Philosophy with a major in Electrical and Computer Engineering, Oklahoma State University in September, 2017.

Experience:

Graduate Research Associate at Engineering Energy Laboratory, School of Electrical and Computer Engineering, Oklahoma State University from January 2014 to Present.

Graduate Research Assistant at Engineering Energy Laboratory, School of Electrical and Computer Engineering, Oklahoma State University from January 2012 to December 2013.

Professional Memberships:

Department Representative, Graduate and Professional Student Government Association (GPSGA)

Student Member, Institute of Electrical and Electronics Engineers (IEEE)