AN APPROACH TO MODELING AND OPTIMIZATION OF INTEGRATED RENEWABLE ENERGY SYSTEMS (IRES)

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AN APPROACH TO MODELING AND OPTIMIZATION OF INTEGRATED RENEWABLE ENERGY SYSTEMS (IRES)

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Abstract: The purpose of this study was to cost optimize electrical part of IRES (Integrated Renewable Energy Systems) using HOMER and maximize the utilization of resources using MATLAB programming. IRES is an effective and a viable strategy that can be employed to harness renewable energy resources to energize remote rural areas of developing countries. The resource- need matching, which is the basis for IRES makes it possible to provide energy in an efficient and cost effective manner. Modeling and optimization of IRES for a selected study area makes IRES more advantageous when compared to hybrid concepts. A remote rural area with a population of 700 in 120 households and 450 cattle is considered as an example for cost analysis and optimization. Mathematical models for key components of IRES such as biogas generator, hydropower generator, wind turbine, PV system and battery banks are developed. A discussion of the size of water reservoir required is also presented. Modeling of IRES on the basis of need to resource and resource to need matching is pursued to help in optimum use of resources for the needs. Fixed resources such as biogas and water are used in prioritized order whereas movable resources such as wind and solar can be used simultaneously for different priorities. IRES is cost optimized for electricity demand using HOMER software that is developed by the NREL (National Renewable Energy Laboratory). HOMER optimizes configuration for electrical demand only and does not consider other demands such as biogas for cooking and water for domestic and irrigation purposes. Hence an optimization program based on the need-resource modeling of IRES is performed in MATLAB. Optimization of the utilization of resources for several needs is performed. Results obtained from MATLAB clearly show that the available resources can fulfill the demand of the rural areas. Introduction of IRES in rural communities has many socio-economic implications. It brings about improvement in living environment and community welfare by supplying the basic needs such as biogas for cooking, water for domestic and irrigation purposes and electrical energy for lighting, communication, cold storage, educational and small- scale industrial purposes.

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η_h- overall efficiency of hydropower generator

Q- discharge of water in m^3/sec

ρ- density of water= 1000 kg/m^3

h- height of the overhead tank (water head) in m

E_p – energy consumed to pump water (kWh)

η_{ps}- efficiency of the pumping system

I_T , I_b and I_d - total, direct normal and diffuse solar radiations respectively in kWh/m^2

R_b and R_d - tilt factors for diffused and reflected part of solar radiations

η_{pv} – efficiency of the PV system

A_{PV}- array area of the PV array in m^2

η_m is the module efficiency

η_{pc} is the power conditioning efficiency

P_f is the packing factor.

P_{wt} is wind power output (kW)

P_r is rated electrical power (kW)

v_c , v_r and v_f are cut-in, rated and cut-off wind speed respectively in m/s.

ρ_{wind} is the density of air in kg/m^3

A_w is the rotor area swept in $m^{2.}$

v_t is the average velocity of wind at time t in m/s.

C_p is the maximum power coefficient or Betz limit.

η_{WECS} is the efficiency of WECS.

t is the hours of operation of WECS per day.

D_a- Number of days of autonomy

B_{dis}- Maximum depth of discharge

T_c- Temperature correction

$E_{Bat}(t)$ and $E_{Bat}(t-1)$- Energy stored in battery at t and t-1 hour respectively.

$E_{ac-sur}(t) and\ E_{dc-sur}(t)$ - Amount of surplus energy of AC and DC respectively.

η_{inv}, η_{rec}, η_{cc} and η_{bat} - Efficiency of inverter, rectifier, charge controller and battery respectively.

σ- hourly self discharge rate of the battery

$E_{load}(t)$ - Energy required by the load at t hour

$E_{Bat}min$ and $E_{Bat}max$ - minimum and maximum charging quantities of the battery.

$E_b(t), E_h(t), E_w(t) and\ E_{pv}(t)$ - Energy produced by biogas generator, hydropower, wind turbine and PV array.

$E_{inv}(t)$ - Energy output of the inverter in kWh

u_{11}^k , u_{12}^k , u_{13}^k and u_{14}^k - Biogas used for cooking, stored biogas, biogas used to pump water, biogas used to generate electricity.

u_{25}^k , u_{24}^k , u_{26}^k and u_{27}^k – Water used for domestic need, generating electricity, irrigation need and storage in reservoir respectively.

u_{31}^k , u_{33}^k and u_{34}^k – Solar energy used for LGH and MGH, pump water and generate electricity respectively.

u_{43}^k and u_{44}^k – Wind energy used to pump water and generate electricity respectively.

x_{12}^{k-1}-total amount of biogas that is stored in the biogas tank till the previous hour k-1

δ_1^k- part of this stored biogas that is used to fulfill needs.

y_1- demand of biogas for cooking for an hour (m^3)

β_1^k- ratio of need for biogas for cooking demand to available biogas

y_2 - demand of water for domestic purposes (m^3) per hour.

x_{33}^k, x_{43}^k and x_{13}^k - water pumped for a duration of kth hour by PV powered water pump, wind powered water pump and biogas powered water pump respectively.

x_{27}^{k-1}- water available in reservoir at k-1 hour.

y_3 - demand of electricity (kWh) at every hour.

x_{34}^{k}, x_{44}^{k}, x_{24}^{k} and x_{14}^{k} - electricity generated by PV system, WECS, hydropower and biogas powered generator at kth hour respectively.

x_{5}^{k-1} - Electricity available in the batteries at (k-1)th hour.

y_4 - demand of water (m^3) for irrigation purposes at every hour.

x_{35}^{k}, x_{45}^{k} and x_{15}^{k} - water pumped by PV powered water pump, wind powered water pump and biogas powered water pump for irrigation purpose at kth hour.

x_{26}^{k-1} - water available in the reservoir at k-1 hour after domestic water need and electricity are fulfilled.

CHAPTER I

INTRODUCTION

I.1 Background

When electricity was first introduced in the late 19th century, the major resource that was used to produce electricity was non-renewable. Humans kept using these limited resources inefficiently without realizing that these resources will deplete to a small amount sometime in the future. With the ever growing economy of the world, it is nearly impossible to rely solely on these resources for a long-term duration, the reason being these resources are depleting rapidly.

The majority of our energy requirements presently are met by fossil fuels which, like many other resources, are becoming rare. At the current rate of depletion, known reserves of natural gas will be consumed in about 35 years and petroleum will be consumed completely in about 70 years and if these rates continue to grow exponentially, then natural gas will be exhausted within 14 years, and petroleum within 20 years. These figures should be modified in light of new technologies such as fracking that is becoming common place for extracting natural gas and petroleum resources. However fossil fuels are needed for many uses such as plastics, transportation, manufacturing and so on that it would be imprudent to depend on it for electrical energy. Recognition of this has led to the present emphasis on nuclear fission as a source of energy. However, the only naturally occurring and spontaneously fissionable source of energy is uranium

235 that is likely to be extinct by the end of the century [1]. Moreover nuclear energy produces spent fuel, which is extremely hazardous and can leak radiations if not stored properly.

Another major reason to look for alternate resources is that non-renewable sources are environmentally unfriendly. Global warming and high levels of CO_2 in the atmosphere have forced us to think about alternative for these resources. Figure I.1 shows the impact of various energy sources on the environment. Energy efficiency and the environmental performance differ substantially between various technologies. Primary energy is more efficiently used by renewable energy technologies such as hydropower, wind power, biogas, and photovoltaic [2].

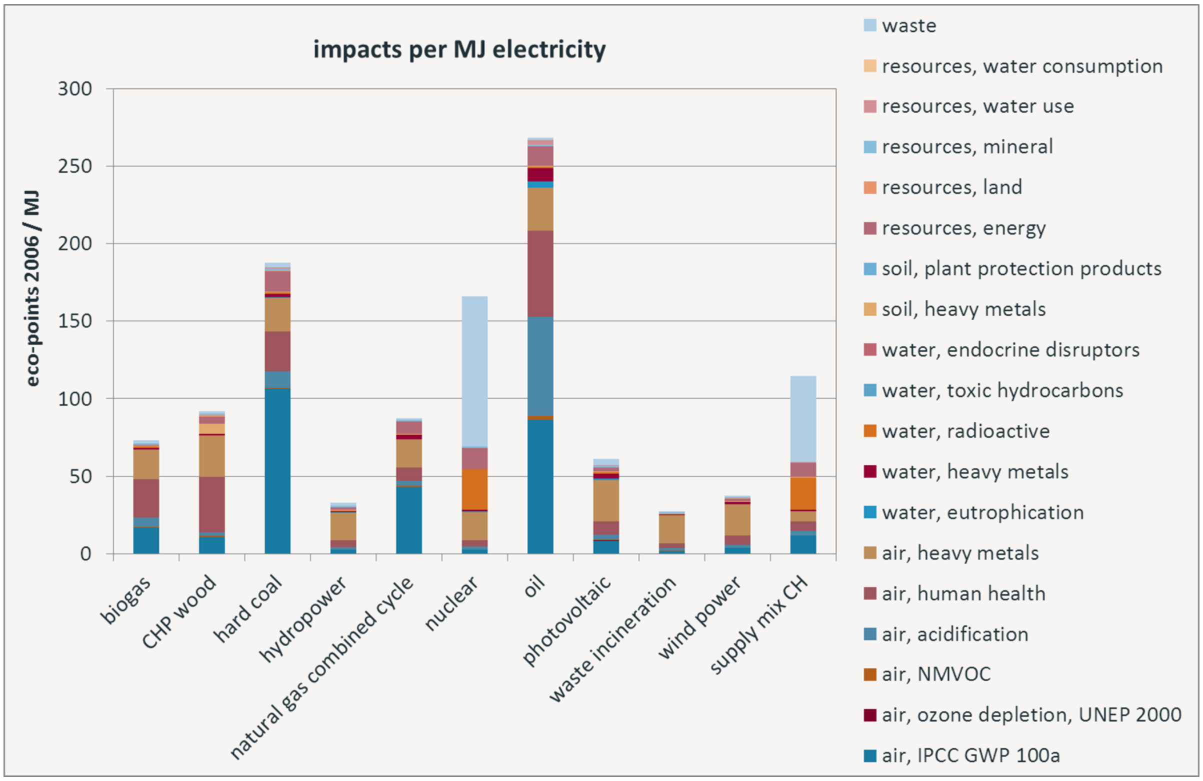
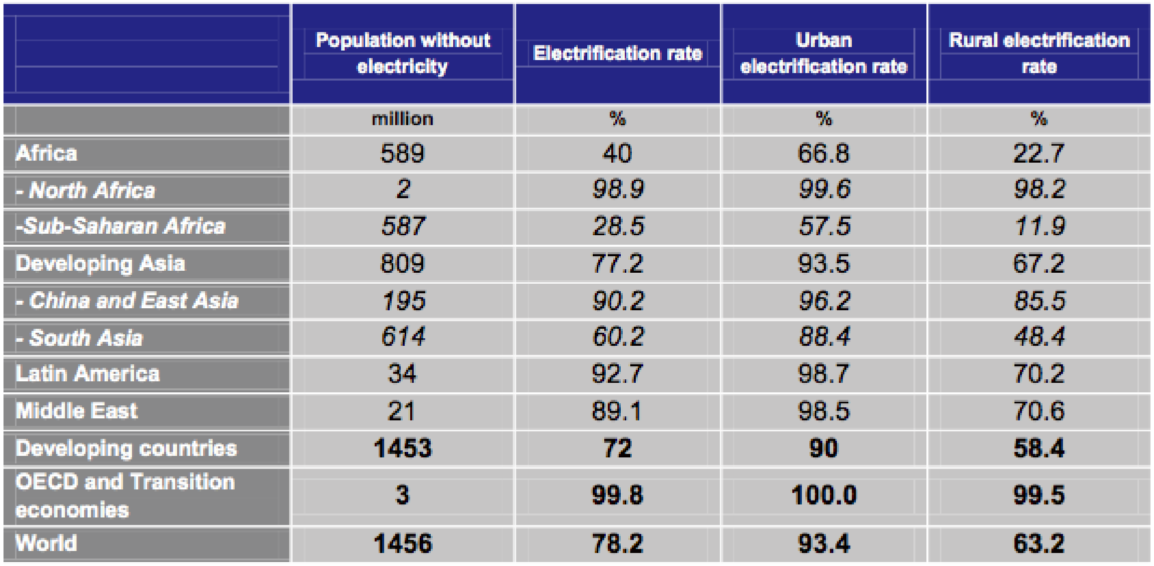


Figure I.1: Environmental assessment of energy systems based on life cycle assessment [2]

I.2 Urban Electrification versus Rural Electrification

The fact that developing countries are “developing” is that development takes place primarily in urban areas, whereas rural areas are highly under-developed. About one billion people are living in the remote scattered areas of developing countries all around 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. Hence, steps must be taken to improve the basic living environment and meet the energy and other necessities of the rural areas as a top priority [3].

According to International Energy Agency (IEA), in 2008, there were about 1.5 billion people around the world, i.e., about 22% of world population living without electricity out of which 85% live in rural areas [4]. A large number of private utility companies, who provide electricity to most of the consumers, are unwilling to electrify these isolated 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.



	Population without electricity	Electrification rate	Urban electrification rate	Rural electrification rate
	million	%	%	%
Africa	589	40	66.8	22.7
- North Africa	*2*	*98.9*	*99.6*	*98.2*
-Sub-Saharan Africa	*587*	*28.5*	*57.5*	*11.9*
Developing Asia	809	77.2	93.5	67.2
- China and East Asia	*195*	*90.2*	*96.2*	*85.5*
- South Asia	*614*	*60.2*	*88.4*	*48.4*
Latin America	34	92.7	98.7	70.2
Middle East	21	89.1	98.5	70.6
Developing countries	**1453**	**72**	**90**	**58.4**
OECD and Transition economies	**3**	**99.8**	**100.0**	**99.5**
World	**1456**	**78.2**	**93.4**	**63.2**

Table I.1: Electricity Access in 2008: Regional Aggregates [4]

I.3 Renewable energy 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 the rural electrification and funds for the development of these are limited. Hence, importing the needed resources will make the situation financially very untenable. Supplying electricity from a central grid is also inefficient and unfeasible because these areas are isolated with low loads and that leads to high transmission and distribution costs [5]. The difficult terrain in many rural regions also increases expansion costs significantly. Mountainous or forest areas, for instance will be difficult access for machinery, require more time and resources to install transmission lines.

The function of energy, and more particularly electricity, is of the essence for growth in rural areas. Installation of modern energy systems improves access to potable water through pumping and distribution system and lowers the malnutrition of the 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 and relieving women of fuel and water collecting tasks and significantly contributes to improving gender equity. With modern renewable energy systems, it is feasible to achieve ubiquitous access of electricity in the near future [6].

In recent years there has been a significant increase in the interest of 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 [7]. 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. Another essential comparative advantage of rural areas is open spaces that can be easily utilized to set up renewable energy systems. Hence, if it is possible to combine all these resources in an efficient manner to fulfill all their needs, then the problem of rural development can be effectively confronted.

I.4 Current Energy Scenario and Energy Crisis

The world economy is expanding to meet the aspirations of countries around the globe. This, in turn, will lead to an increase in energy demand, even if vigorous efforts are made to increase the efficiency of energy use and energy conservation. Renewable energy resources can meet most of the growing demand provided suitable approaches and requisite support are brought to bear. This is possible at prices lower than those usually forecasted for energy produced by fossil fuels and supplied to rural areas. By the middle of the 21st century, renewable resources could account for three-fifths of the world's electricity market as seen in Figure I.2.

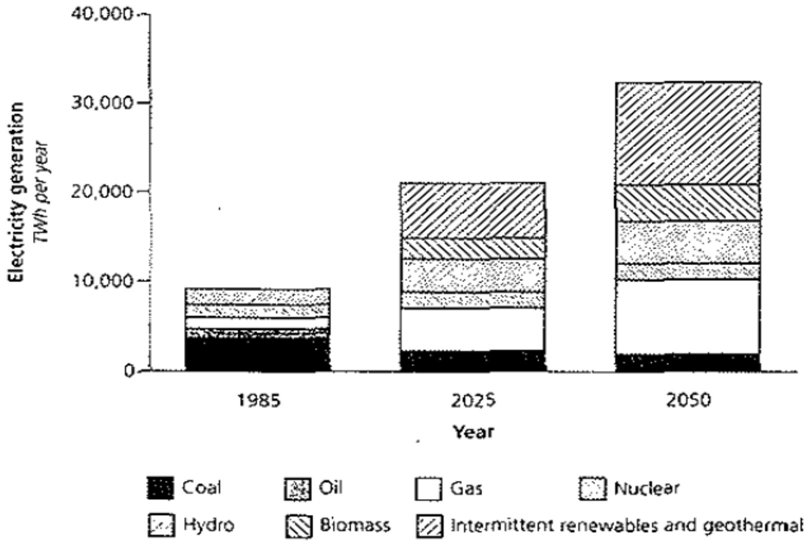


Figure I.2: Electricity Generation for the Renewables-Intensive Global Energy Scenario [8]

From this figure, it is clear that the use of renewables will increase from 20% in 1985 (mainly hydro power) to about 60% in 2025, which will primarily comprise of hydropower, solar, wind, and biomass. Moreover, making a transition to a renewables-intensive energy economy would provide environmental and other advantages, which cannot be measured in standard economic terms [8].

The historical evolution of rural electricity supply systems is shown in Figure I.3. In the past the function of distribution systems was limited to the distribution of electricity. It was very straight forward and passive. With the emergence of integrated systems, the function will turn from passive to active.

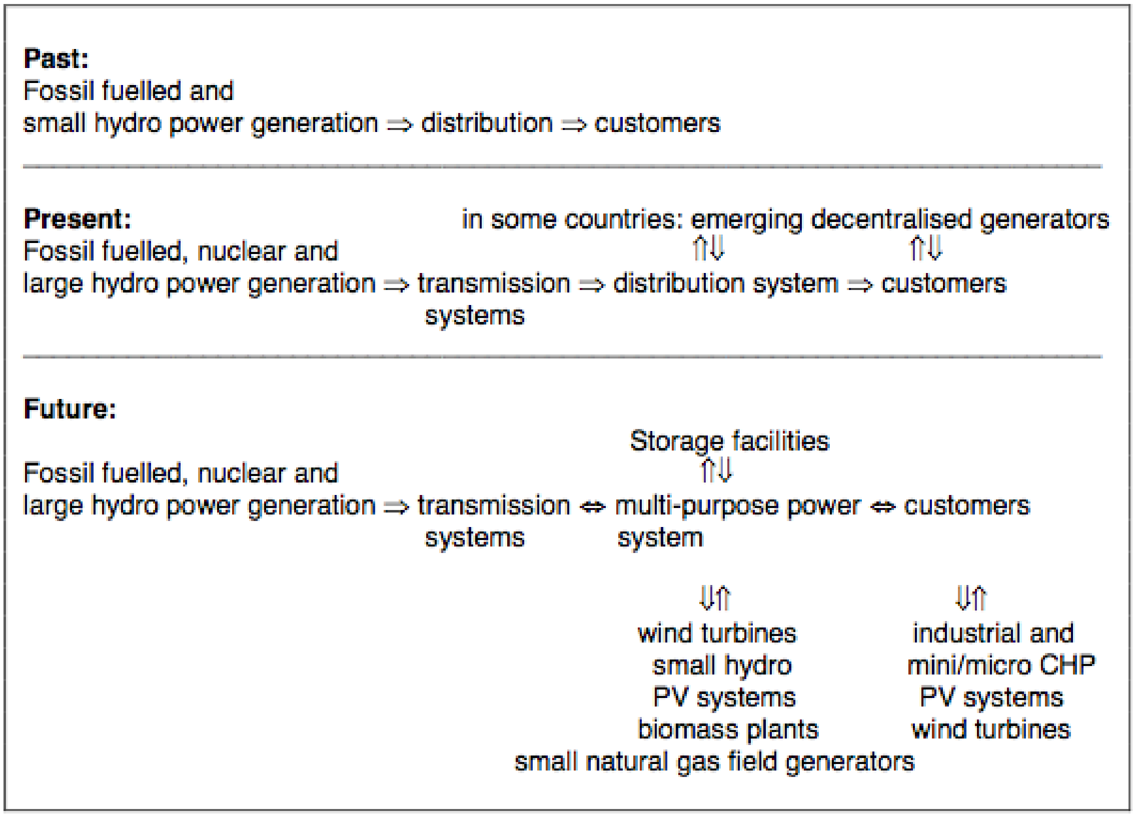


Fig I.3: Evolution of rural electricity systems [9]

I.5 Objective of the study

The ever-growing demand of increasing world population has inspired us to consider alternatives to supply quality energy in a sustainable manner. The need for sustainability has led to more and more research in the area of renewable energy. As an approach to use renewables resources in rural areas, the concept of integrated renewable energy system (IRES) has been proposed [23-24]. In this study the IRES concept is developed further in terms of modeling and optimization. A stand-alone system makes isolated rural areas self-sufficient for basic needs such as cooking, water needs and electricity in a cost effective and efficient manner, without the need of the central grid. Implementation of the IRES is proposed and the system is cost optimized using HOMER and need-resources combinations are optimized using MATLAB.

I.6 Organization of thesis

A brief overview of the various chapters is as follows.

Chapter II: Review of Literature

A review of the literature work close to this research is presented in this chapter. It discusses the various renewable energy sources and technologies along with their current status and potential. A brief discussion of the difference between energization and electrification is described. Methods used to harness these renewable sources are summarized briefly. Various proposed optimization techniques have been outlined.

Chapter III: Integrated Renewable Energy Systems (IRES)

A detailed description of Integrated Renewable Energy Systems (IRES) is given in this chapter. Components and features of IRES are discussed and resource- need combination is presented. A schematic diagram with the IRES components is illustrated.

Chapter IV: Modeling of IRES

Key components of IRES such as biogas generator, hydropower generator, wind turbine, PV system and battery banks are mathematically modeled. A discussion on size of the water reservoir is also presented. Modeling of IRES on the basis of need to resource and resource to need matching is pursued to help in optimum use of resources for the needs.

Chapter V: Optimization of IRES

IRES is cost optimized for electricity demand using HOMER software that is developed by the NREL (National Renewable Energy Laboratory). An optimization program based on the need-resource modeling of IRES is performed in MATLAB. Optimization of maximizing the utilization of resources for several needs is performed.

Chapter VI: Summary and Concluding Remarks

This chapter documents the work discussed in this thesis and summaries the scope and areas for further work.

CHAPTER II

REVIEW OF LITERATURE

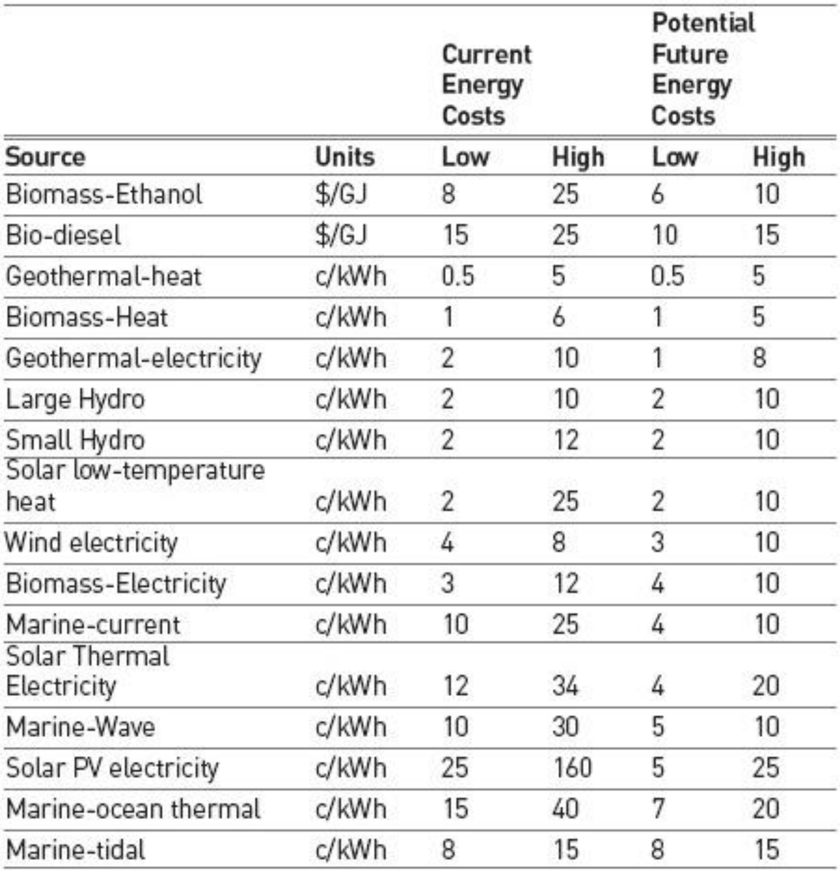
II.1 Renewable Energy Sources

The potential of renewable energy sources is vast and they can meet the world’s energy demand multiple times. Renewable energy sources such as biomass, wind, solar and hydropower can provide sustainable energy. The price of oil and gas continue to vary often and hence a transition to renewables-based energy systems is becoming attractive as their costs continue to decline. In the past three decades, solar and wind systems have experienced declining capital costs and rapid sales expansion. The cost of electricity generated has also decreased with increases in efficiencies of conversion. Presently, fossil fuel and renewable energy prices are moving in different directions, and so does their social and environmental costs. There is adequate dissemination and sustainable markets for renewable energy systems and the economic and policy aspects are aiding their development. In the coming years, it is possible that the growth in the energy sector will be predominantly in the area of renewable energy and not in conventional technologies. These developments are giving rise to market opportunities to formulate new ideas and exploit emerging markets to encourage renewable energy systems. The evolution and utilization of renewable energy can undoubtedly improve the variety in the energy supply markets and can be instrumental in gaining extended period and uninterrupted and sustainable energy supplies. In addition to

energy can undoubtedly improve the variety in the energy supply markets and can be instrumental in gaining extended period of and uninterrupted and sustainable energy supplies. In addition to

reducing global emissions, they will also aid in providing profit-oriented possibilities to meet targeted energy demands, specifically in the developing countries. They could help in creating unprecedented employment opportunities in rural areas besides leading to social and economic progress [10].

Significant cost reductions in the past few decades have made a number of renewable energy resources competitive with fossil fuels in various applications. Significant cost reductions can be achieved for most of the renewable energy resources as seen Table II.1. To make these resources competitive will require technology development and market deployments and an increase in production capacities to mass-production levels [11].



		Current Energy Costs		Potential Future Energy Costs	
Source	**Units**	**Low**	**High**	**Low**	**High**
Biomass-Ethanol	$/GJ	8	25	6	10
Bio-diesel	$/GJ	15	25	10	15
Geothermal-heat	c/kWh	0.5	5	0.5	5
Biomass-Heat	c/kWh	1	6	1	5
Geothermal-electricity	c/kWh	2	10	1	8
Large Hydro	c/kWh	2	10	2	10
Small Hydro	c/kWh	2	12	2	10
Solar low-temperature heat	c/kWh	2	25	2	10
Wind electricity	c/kWh	4	8	3	10
Biomass-Electricity	c/kWh	3	12	4	10
Marine-current	c/kWh	10	25	4	10
Solar Thermal Electricity	c/kWh	12	34	4	20
Marine-Wave	c/kWh	10	30	5	10
Solar PV electricity	c/kWh	25	160	5	25
Marine-ocean thermal	c/kWh	15	40	7	20
Marine-tidal	c/kWh	8	15	8	15

Table II.1 Current and Projected Future Costs of Renewable Energy Technologies. [11]

II.1.1 Solar Energy

Energy obtained from the sun is plentiful. If all the energy could be converted into useful forms, then it would be possible to fulfill more than the current world demand. However this does not happen because of the earth’s atmosphere that absorbs a fraction of the energy from reaching earth’s surface and earth’s rotation, which allows only half of the earth to be exposed to the sun at any time.

Solar energy can be converted to useful energy forms through a variety of demonstrated technologies. One way to convert the sunlight into heat is by using solar thermal technologies. Heat collected can be used for space heating or can be stored in a thermal medium such as water or molten salt. Need for electricity generating capacity can be reduced when solar energy replaces electricity in such applications. Another way of using solar energy is through solar photovoltaic (PV) technologies. Solar photovoltaic technologies directly absorb incident photons (particles of light that acting as individual units of energy) without complete conversion to heat. It is either converted to dc electricity as in a photovoltaic [PV] cell or stored as chemical energy through a chemical reaction such as dissociation of water into hydrogen and oxygen [12].

Concentrating Solar power (CSP) is one of the most promising technologies for harvesting solar energy. CSP technology is poised to take its place as one of the major contributors to future clean energy. CSP is a simple technology in which very large quantity of sunlight is focused onto a very small area, generating heat that can be transformed into electricity. CSP, unlike conventional solar photovoltaic technology, stores heat rather than electricity. This makes storage using CSP technology economical and more effective than solar photovoltaic, or PV technology. The storage capability allows CSP power plants to generate base-load power (minimum power that a utility must continuously supply to its customers to meet demand at a given time).

Using simple manufacturing processes, CSP technology capitalizes on conventional power generation cycles and meets the demand cost effectively [13].

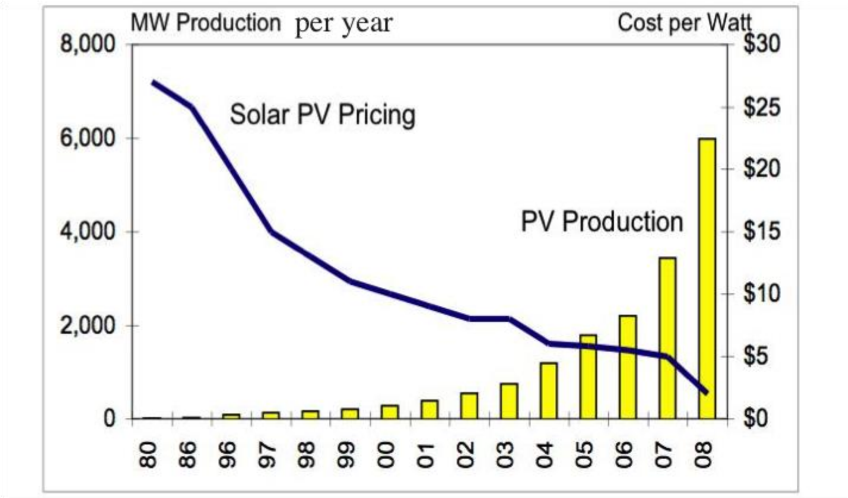


Fig II.1: Solar PV prices and global PV productions [14]

As seen in the figure II.1, photovoltaic production has grown rapidly. Several reasons such as material improvements and various government schemes have added to this growth. This has made PV and solar technologies, more acceptable as a source of energy for long-term considerations.

II.1.2 Wind Energy

Wind is air in motion in simple terms. Uneven heating of the Earth's surface causes it by radiant energy from the sun. People have harnessed wind energy since ancient times. Ancient Egyptians used wind to sail ships on the Nile River as early as 5000 B.C. Later, people built windmills to grind wheat and other grains. Early windmills looked like paddle wheels. Centuries later, people in Holland improved the windmill. They gave it propeller- type blades, still made with sails. By about the 19th century, windmills were used to pump water, grind grains and generate electricity. Although they lost their significance in 1950's because of cheap oil and low energy prices, they re-entered the market around the 1970's when there was oil crisis all around the world [15].

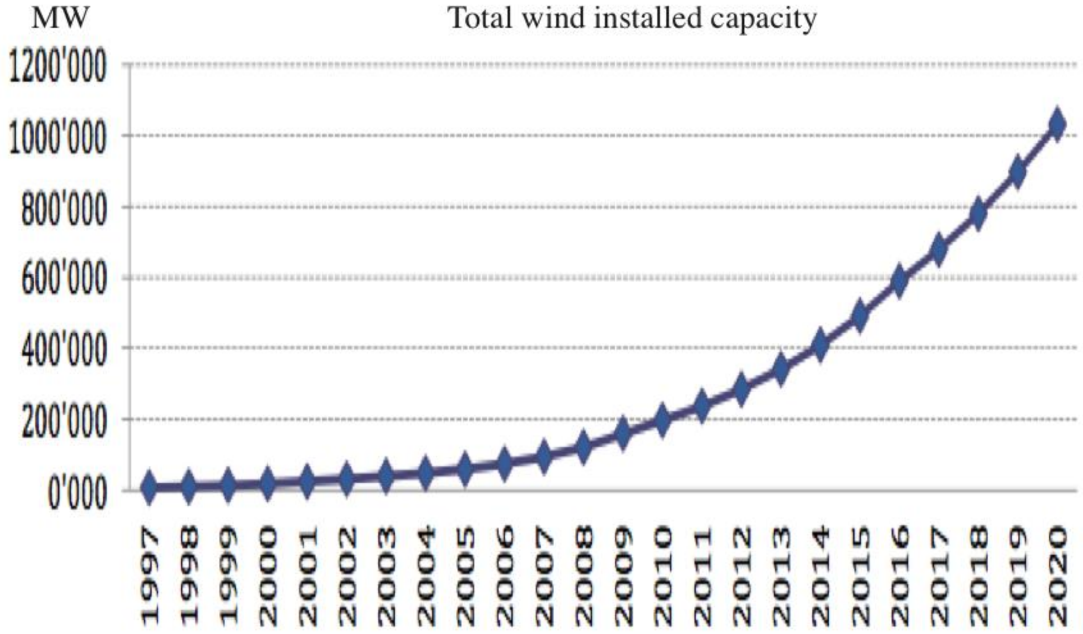


Fig II.2: Total wind Installed Capacity 1997-2020 [MW] [17]

Wind power has now established itself as a recognized electricity generation source, and is playing a dominant role in a rising number of countries' current and future energy plans. From 1995 to 2010 average cumulative growth rates in wind capacity were about 28%. Commercial wind power installations in about 80 countries at 2011 summed to about 240 GW, having increased by more than 40 times in that same period. Twenty-two countries have more than 1,000 MW installed [16]. Regardless of the necessity to promote policies throughout the globe and to expedite installation of wind power, it can be observed that appetite for investment in wind power is growing strong and there are plenty of projects yet to happen. In 2016, global wind capacity is expected increase to 500'000 MW and at least 1'000'000 MW capacity can be expected to be installed globally by the end of year 2020 [17].

It has been seen that utilization of wind energy can help to achieve a healthy ecosystem by significant reductions in the amount of CO_2 emitted to the atmosphere. Annual reductions in CO_2 from existing wind power plants were about 350 million tons in 2011. Under the IEA New

Policies scenario, this is expected to rise to 863 million tons annually by 2020 and up to 1447 tons per year by 2030 [16].

II.1.3 Hydro power

Water has always been one of the most indispensible and extensively used resource for humankind. Hydropower is a renewable energy source where power is obtained from the potential energy of water in higher elevations that flows and gets converted to kinetic energy at lower elevations. It is a proven, fully developed, anticipated, highly efficient and a price-competitive technology. Some of the early-recorded mentions of hydropower go back to over 2,000 years ago in ancient Greece and Egypt, where water wheels were connected to grindstones to turn wheat into flour. Invention of electrical generator in the late 1800's produced a new way to exploit hydropower for use by civilizations. By coupling water turbines to generators with belts and gears, a constant source of electricity was generated that could be used to power residences, commercial establishments and industries. Large supply of rivers and streams around the globe became readily available sources of energy which were quickly exploited. By using water for power generation, people have utilized nature to achieve a better lifestyle [18].

Although hydropower has low operation and maintenance cost, its capital cost is very high. It has a design life of more than a century, which is better than any other generating technology. Presently, hydropower is the only renewable source of energy that has been used on a large scale. Estimate of total global installed hydropower capacity reached 990 GW at average rate of growth of 3% per year by 2012. This accounts for about 16% of the total world's electricity [19].

Hydropower can be delivered through central and regional interconnected electric grids, through local mini-grids and isolated micro grids, and can also serve individual customers through captive plants. Classification of hydropower plants (HPP) is as shown on table II.2.

Hydropower plant Type	Energy and water management services
All	Renewable electricity generation Increased water management options
Run-of-river	Limited flexibility and increased variability in electricity generation output profile. Water quality (but no water quantity) management
Reservoir (Storage)	Storage capacity for energy and water. Flexible electricity generation output. Water quantity and quality management; groundwater stabilization; water supply and flood management
Multipurpose	As for reservoir HPPs; Dependent on water consumption for other uses
Pumped storage	Storage capacity for energy and water; net consumer of electricity due to pumping. No water management options

Table II.2 Different types of Hydropower plants [18]

Classification is done based on their operation and type of flow. Run-of-river, storage (reservoir) and pumped storage HPPs all vary from the very small to the very large scale, depending on hydrology and topography of watershed. In addition, there is a fourth category called in-stream technology, which is an emerging and less-developed technology [18].

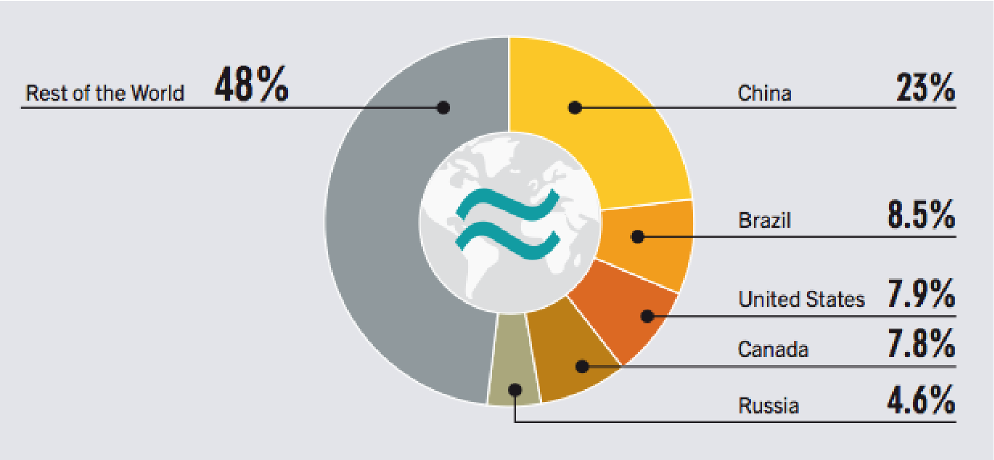


Figure II.3 Hydropower global capacity, shares of top five countries, 2012 [18]

II.1.4 Biomass Energy

The only natural, renewable carbon resource known that is large enough to be used as a substitute for fossil fuels is biomass. Biomass used for energy purposes is derived from a number of sources. Examples of biomass can be 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. Short-rotation energy crops, grown on agricultural land specifically for energy purposes, known as energy plantations, currently provide about 3–4% of the total biomass consumed annually. Biomass, often termed as bio energy, accounts for over 10% of global primary energy supply and is the world's fourth largest source of energy following oil, coal, and natural gas [19].

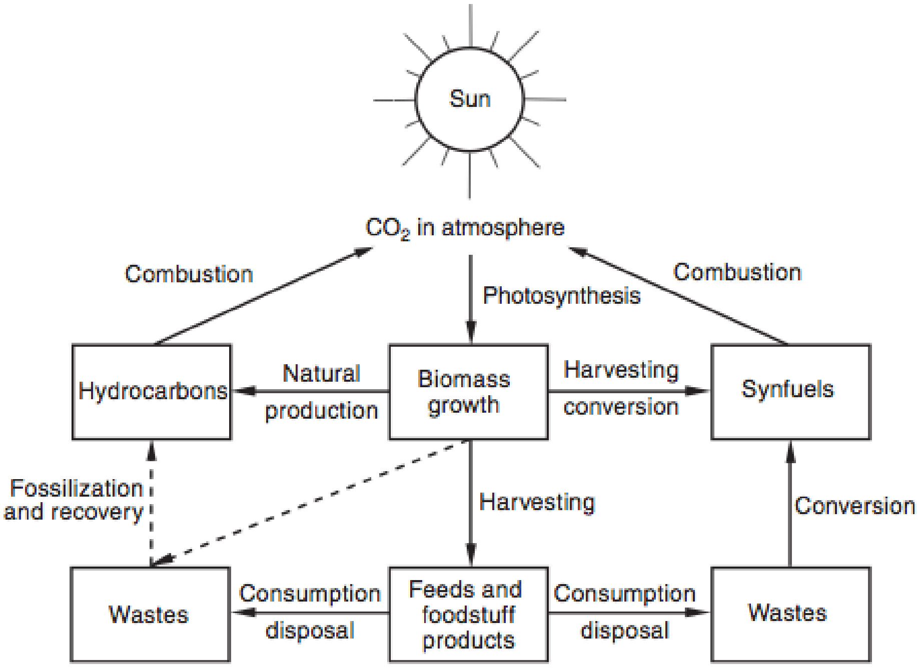


Figure II.4 Main features of biomass energy [20]

The striking feature of biomass is that it is widely and freely available, simple to use and low cost. Biomass is used largely and inefficiently in the rural areas for cooking and heating purposes.

About one billion people in the world use biomass for cooking [21]. But biomass has significantly higher potential. Biomass can be converted into modern energy carriers such as gaseous and liquid fuels and electricity that can be widely used.

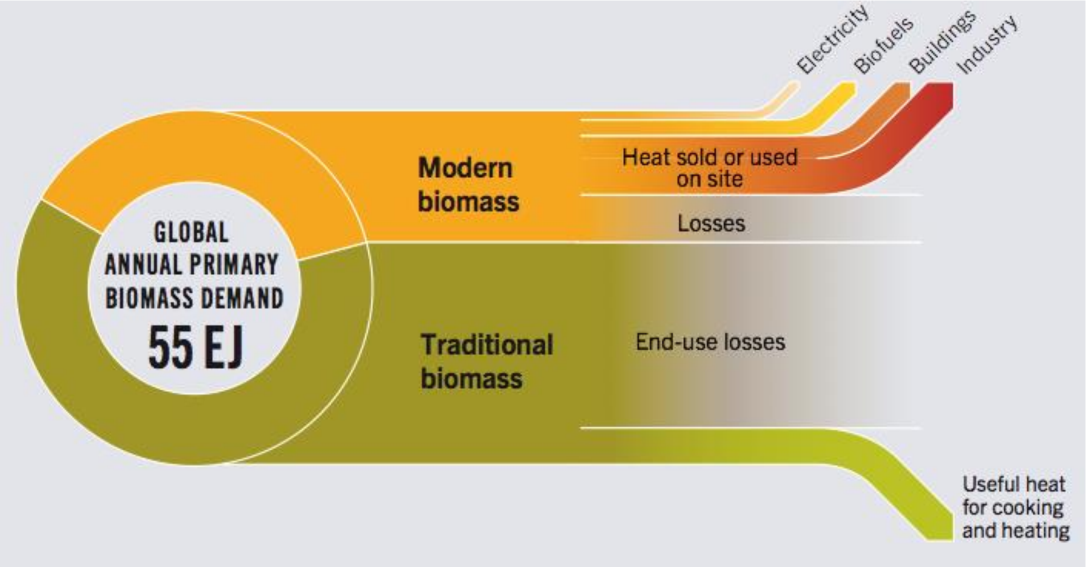


Figure II.5 Biomass to Energy Pathways [19]

It is clear from figure II.5 that, when biomass is used in traditional way, losses are high whereas when biomass is used for modern technologies, it can serve various purposes. Total primary energy supplied from biomass increased 2–3% in 2012 to reach approximately 55 EJ (1 EJ= 10^{18} Joules). Heating accounted for the vast majority of biomass use at about 46 EJ, including heat produced from modern biomass and traditional biomass. About 4.5 EJ was consumed for electricity generation, and a similar amount was used for biofuels [19].

Biogas is one of the most widely used and familiar form of biomass. It is produced when collected biomass undergoes an anaerobic fermentation in bio-digesters. Biogas contains about 55-70% methane by volume and rest of the composition includes carbon dioxide, nitrogen, hydrogen and sulphur. Heating value of biogas is about 4600-6000 kcal/m^3.

II.1.5 Energy storage

Energy storage, electricity energy storage in particular, is of key importance and a critical technology to have a reliable energy system, especially when electrical grid fails. In present electrical system where there are constant variations in the demand and price, energy storage can reduce electricity cost by storing energy produced in off –peak times when price is lower and supply it to the grid at peak times when prices are higher. In an era where renewable sources of energy are of high importance, energy storage plays a vital role in providing hassle free and continuous energy. The main reason is because; most of renewable resources such as solar and wind are stochastic by nature and weather dependent. There is increasing penetration of these resources in the main grid and they provide cost free- surplus energy whenever they are available. In such scenarios, energy storage system can store this low price electricity and provide it to consumers whenever there is a need for it.

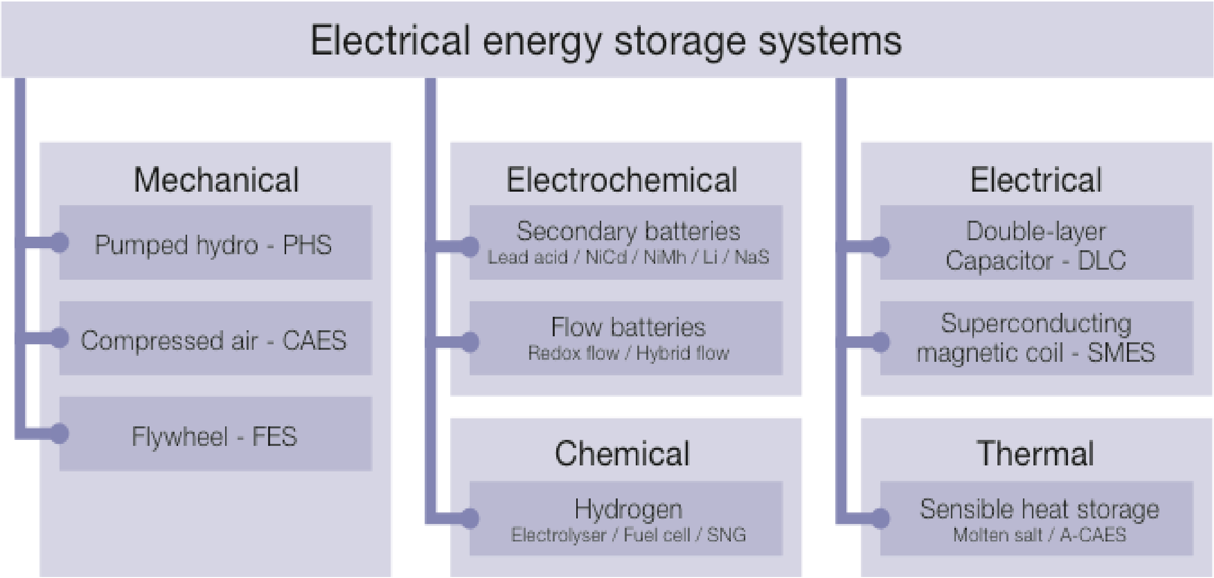


Figure II.6 Classification of electrical energy storage systems according to energy form [22]

Energy storage can be classified depending on the form of energy used. Energy storage systems are classified into mechanical, electrochemical, chemical, electrical and thermal energy storage systems. Figure II.6 shows the classification of energy storage system and a few examples under classification. Among all the classified categories, electrochemical energy storage is easily available and widely used.

II.2 Energization versus Electrification

Renewable energy sources such as solar, wind, hydro and biomass are easily harnessed and are bountiful in quantity. Energy obtained from these resources can be utilized in more than one way. Wind energy can be used to generate electricity as well as pumping up water. In a similar manner all these resources can be used in more than one way.

The most versatile form of energy used is electricity. End product electricity can be used to provide energy for needs such as heating, cooling, pumping water etc. in urban areas where electricity is easily available. However electricity that has been produced cannot be supplied to remote and isolated areas because of high transmission costs as discussed earlier. Major concern has always been providing electricity and other needs to remote rural areas. One way of providing electricity is through hybrid systems, which convert one or more forms of energy to electricity. But this “electrification” is not efficient and cost-effective since other demands such as cooking, water supply etc. are not met. Also, local energy needs for cooking and water supply are best met when supplied by alternate “relevant” energy sources instead of “flexible” electricity [23].

An efficient way of providing all the necessary energy needs is by using renewable energy resources in more than one way. For instance, biogas can serve the cooking demand and it can also serve purposes such as pumping water and providing electricity. Hydropower for example can fulfill the water needs as well as generate electricity. Although these needs can be fulfilled by electricity, it is not a cost effective. Hence there is a strong need for “energization” instead of “electrification” especially in remote rural areas. Energization involves harnessing all possible available renewable resources in such a way that several forms of energy of different quality and characteristics provide a variety of energy and other needs. To implement such a system, the key is to match needs with resources and hence maximize the efficiency and minimize cost [24].

II.3 Hybrid versus Integrated

A variety of systems may be used to harness renewable energy sources. These may be classified as Hybrid and Integrated renewable energy systems

II.3.1 Hybrid renewable energy systems

A hybrid energy system utilizes two or more energy resources, converts all of them into one form (typically electrical), energy storage and a distribution system. It combines renewable energy sources with fossil fuel powered diesel/petrol generator to provide electricity. It may or may not be connected to the central grid. They are generally independent of the larger centralized grids. Energy resources are usually converted into electrical energy either AC or DC and supplied to loads through a common bus. The primary intention of combining renewable energy is to save fossil fuel. Examples of renewable energy sources commonly used in hybrid configurations are small wind systems, photovoltaic systems, micro-hydro systems, biogas electric systems etc.

There are generally two accepted hybrid system configurations:

1) System mainly based on diesel generators with renewable sources used to reduce fuel consumption.
2) System mainly based on renewable energy sources and diesel generator used as a back up supply.

A typical stand-alone hybrid system is shown in figure II.7. It consists of a micro hydro generator, photovoltaic generator, biogas and biomass generator, a backup diesel generator, a convertor system and AC/DC buses [25].

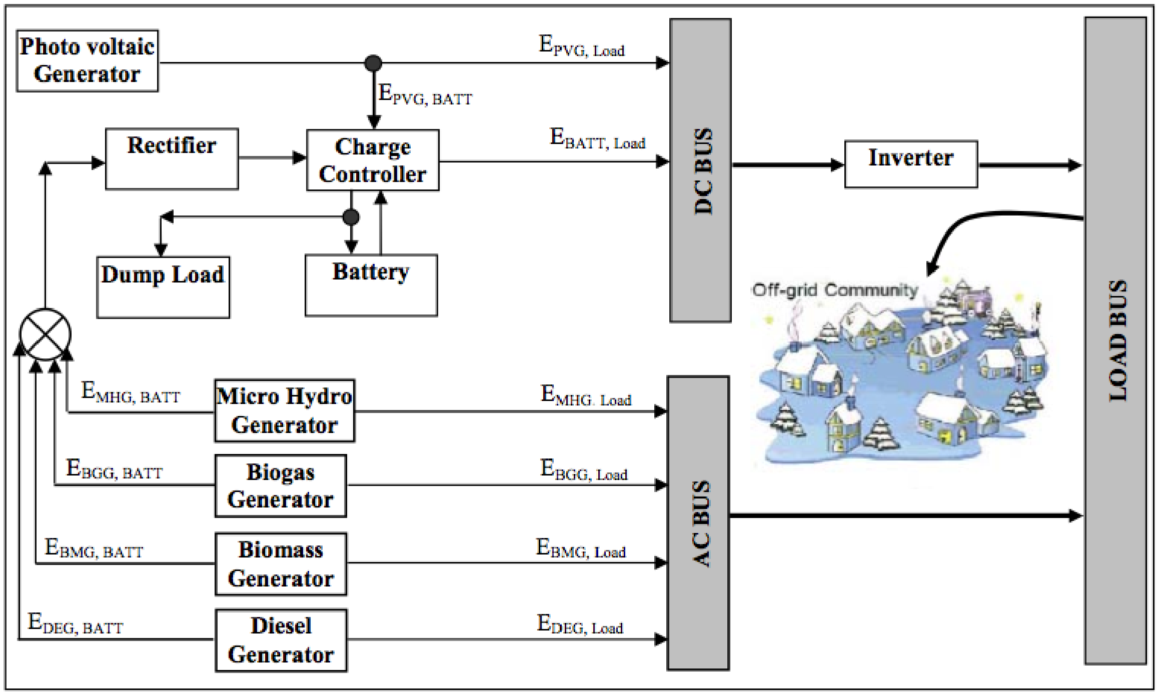


Figure II.7 Configuration of hybrid energy system [25]

II.3.2 Integrated renewable energy systems

The fundamental requirement of integrated renewable energy system (IRES) is to match various forms of energy to the needs of an isolated area in an efficient and economical manner. IRES utilizes two or more renewable energy sources, conversion technologies, and end-use technologies to provide a variety of needs. 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. Multiple inputs to IRES are of different forms and so are the multiple outputs. System may be connected to a central grid or can be stand-alone. The ultimate goal of IRES is to integrate the benefits at user end. One possible configuration of IRES employing multiple resources and needs at a particular site is shown in figure II.8 [26].

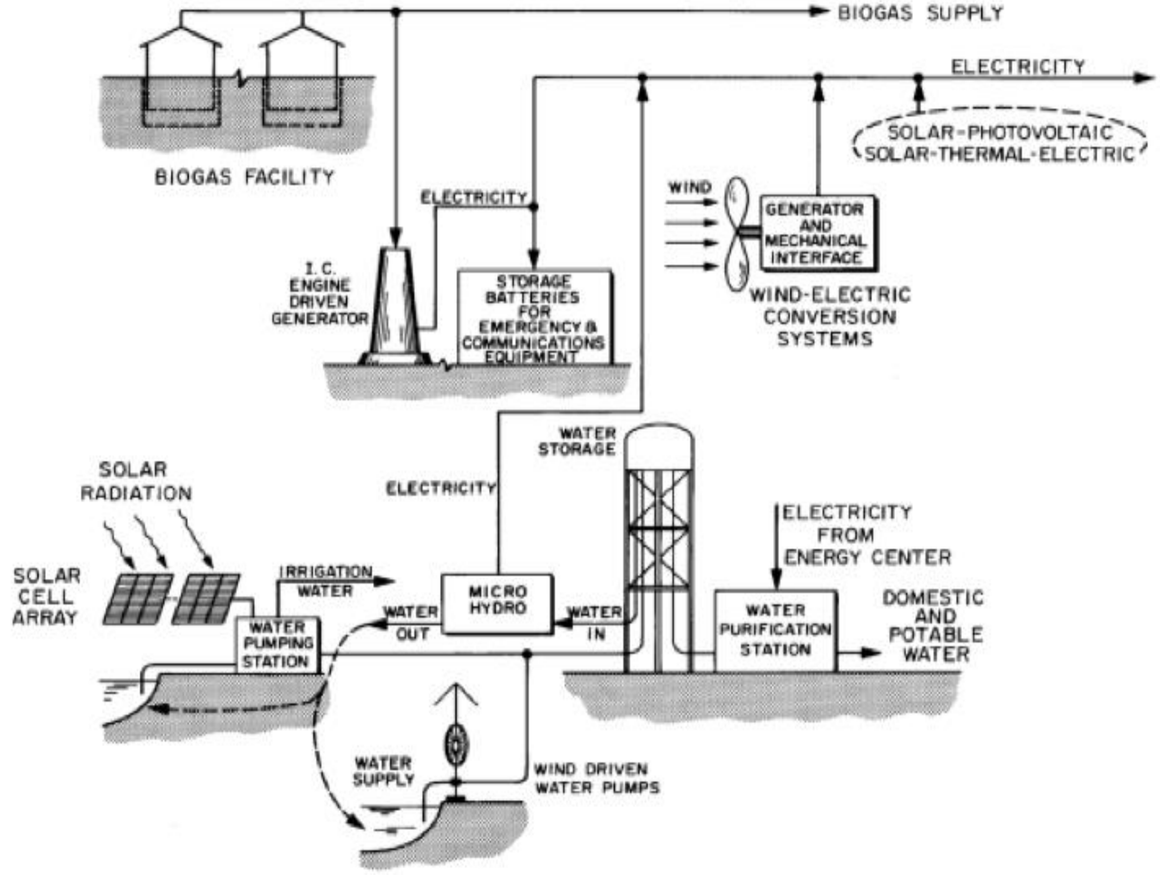
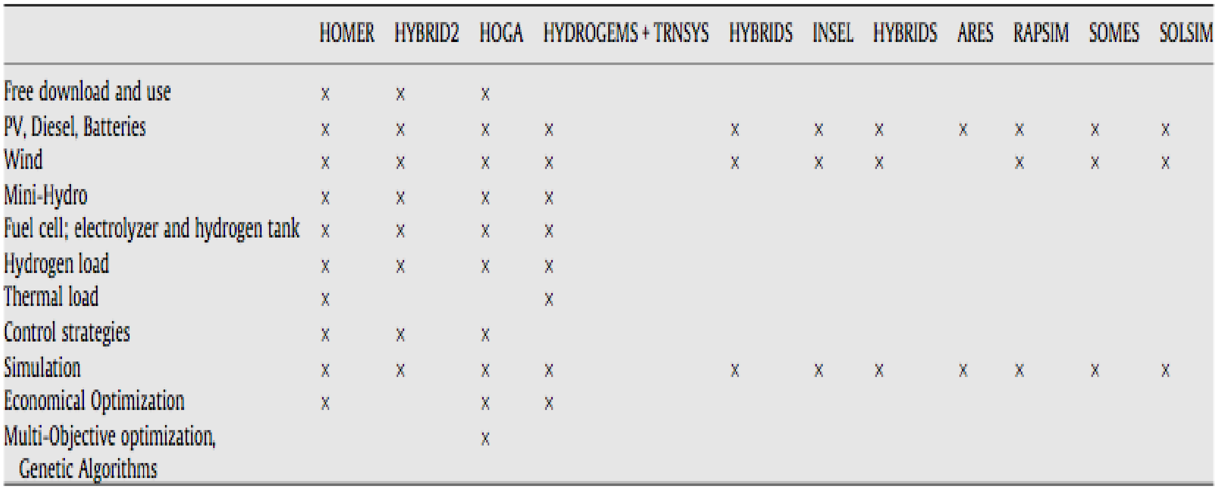


Figure II.8 Schematic of the IRES [26]

II.4 Proposed Optimization Techniques

Several optimization techniques have been proposed to optimize hybrid renewable systems as well as integrated renewable energy systems. There has been a fair amount of dedicated softwares to optimize renewable energy systems. By using computer simulation, optimum configuration can be found by comparing the performance and energy costs of different configurations. Some of the well-known softwares are HOMER, HYBRID2, HOGA, HYBRIDS, TRNSYS, HYDROGEMS, etc. The most commonly used software is HOMER that was developed by NREL (National Renewable Energy Laboratory). Table II.3 gives a comparison of these various softwares [27-28].



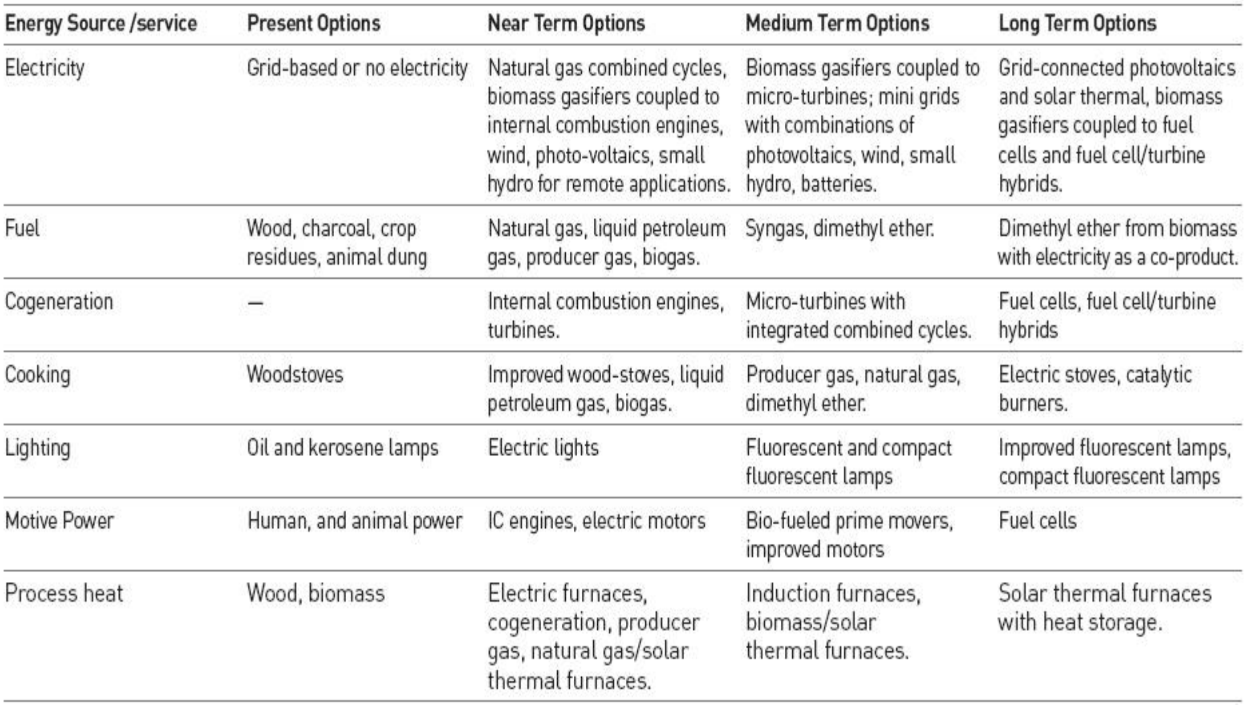
	HOMER	HYBRID2	HOGA	HYDROGEMS + TRNSYS	HYBRIDS	INSEL	HYBRIDS	ARES	RAPSIM	SOMES	SOLSIM
Free download and use	x	x	x								
PV, Diesel, Batteries	x	x	x	x	x	x	x	x	x	x	x
Wind	x	x	x	x	x	x	x		x	x	x
Mini-Hydro	x	x	x	x							
Fuel cell; electrolyzer and hydrogen tank	x	x	x	x							
Hydrogen load	x	x	x	x							
Thermal load	x			x							
Control strategies	x	x	x								
Simulation	x	x	x	x	x	x	x	x	x	x	x
Economical Optimization	x		x	x							
Multi-Objective optimization, Genetic Algorithms			x								

Table II.3 Comparison of various Software [28]

Apart from these software, many multi-objective algorithms have also been used to optimize the system. Among them, commonly used algorithms are Multi-objective evolutionary algorithm (MOEA), simulated annealing, artificial neural networks, multi-objective particle swarm optimization algorithm (MOPSO), non-dominated sorting genetic algorithm (NSGA-II) and so on [29-31].

II.5 Current Status of Rural Electrification

Currently, about 1.6 billion people, or about 22% of the world's population, live without electricity and this number hasn't changed much since 1970. Yet, electricity required for people to light their homes, pump a nominal quantity of potable water, watch television and listen to radio would amount to less than 1 percent of overall global energy demand. Developing nations hence encounter a critical energy challenge in this century. It is mandatory to satisfy the essentials of billions of people who stay in these developing countries and lack access to basic and modern energy services. Progress towards increased efficiency, large fuel diversity and lower pollutant emissions need to be expedited at the same time. Table II.4 suggests technological options to energize rural areas [32].



Energy Source /service	Present Options	Near Term Options	Medium Term Options	Long Term Options
Electricity	Grid-based or no electricity	Natural gas combined cycles, biomass gasifiers coupled to internal combustion engines, wind, photo-voltaics, small hydro for remote applications.	Biomass gasifiers coupled to micro-turbines; mini grids with combinations of photovoltaics, wind, small hydro, batteries.	Grid-connected photovoltaics and solar thermal, biomass gasifiers coupled to fuel cells and fuel cell/turbine hybrids.
Fuel	Wood, charcoal, crop residues, animal dung	Natural gas, liquid petroleum gas, producer gas, biogas.	Syngas, dimethyl ether.	Dimethyl ether from biomass with electricity as a co-product.
Cogeneration	—	Internal combustion engines, turbines.	Micro-turbines with integrated combined cycles.	Fuel cells, fuel cell/turbine hybrids
Cooking	Woodstoves	Improved wood-stoves, liquid petroleum gas, biogas.	Producer gas, natural gas, dimethyl ether.	Electric stoves, catalytic burners.
Lighting	Oil and kerosene lamps	Electric lights	Fluorescent and compact fluorescent lamps	Improved fluorescent lamps, compact fluorescent lamps
Motive Power	Human, and animal power	IC engines, electric motors	Bio-fueled prime movers, improved motors	Fuel cells
Process heat	Wood, biomass	Electric furnaces, cogeneration, producer gas, natural gas/solar thermal furnaces.	Induction furnaces, biomass/solar thermal furnaces.	Solar thermal furnaces with heat storage.

Table II.4 Technological options in rural areas [32]

Local and national governments of developing countries are playing a crucial role in promoting and supplying “green” energy to rural areas. This can be achieved through various projects, series of measures and schemes. Presently, in developing countries, about 48,000 MW of installed capacity mainly comes from small hydro, biomass and a part of it from geothermal and wind. Small hydro plants, biomass, solar home systems and community-scale wind power provide lighting to about 65 million households in the rural areas of these countries. Wind turbines power about 1 million water pumps, while solar panels power about 20,000 pumps [33].

Often the purpose of using renewable energy is to reduce carbon emissions at national and global levels. This, in turn, can be implemented with the support of national and international organizations that promote renewable energy. Incentives such as Clean Development Mechanism (CDM) in the framework of United Nations Framework Convention on Climate Change

(UNFCCC) has helped large developing nations such as Brazil, India and China to get support for numerous of small projects. China leads the world with 7.5 million household biogas digesters installed followed by India with about 3 million household biogas digesters. There are over 170,000 household biogas plants in Nepal, which were supported by the Biogas Support Partnership (BSP). Renewable Energy Development Project (REDP), launched by China's National Development and Reform Commission (NDRC), subsidized the installation of 402,000 solar home systems. Beginning in the 1980s, a long-standing government program of subsidy, tax, and financial incentives has driven India's PV market and has paved the path for India to have the largest market for solar home systems with about half a million such houses to have PV systems. Household-scale wind power (sized 100–5000 watts) has been examined in a few countries, with most installations globally (about 140,000 small wind turbines) taking place in Inner Mongolia in China. About 500,000 to one million wind-powered water pumps are in use in Argentina, which is followed by years of development of a local manufacturing unit for small wind turbines [33-34].

Most of the present projects focus on one renewable resource with one form of energy as output. The current need of the world is a combination of several renewable resources to produce various energy outputs to fulfill a variety of demands in rural areas. This concept is the foundation for Integrated Renewable Energy Systems (IRES).

CHAPTER III

INTEGRATED RENEWABLE ENERGY SYSTEMS (IRES)

III.1 Introduction

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 the most efficient, cost effective and practical way, with the ultimate goal of amalgamating the advantages at the user end. IRES technique is appropriate in view of the fact that some technologies are more efficient than others for serving distinct energy needs of rural communities. Such systems can operate well in both stand-alone mode as well as when connected to a centralized grid. The prime significance of IRES is its focus to “energize” remote rural areas rather than “electrify” these areas promoted by hybrid systems, in order to achieve sustainable development and improve the basic living environment of rural masses.

When a set of energy and other needs of rural area and available energy resources in the region are known, the first step in the introduction of IRES involves matching the needs with the available resources to increase end-use efficiencies at low cost. Decentralization can be achieved by establishing micro-grid systems or centers that encourage the use of renewable energy using this concept. In addition, decentralized approach can be a competitor to grid electrification of remote rural areas, primarily because of reduced capital and maintenance costs.

Renewable energy resources are highly site-specific, stochastic in nature and are fairly evenly distributed around the world with little or no costs. They are greatly dependent on the climatic conditions, geographical factors and seasons of the site under consideration. Furthermore these energy resources have no or minimal impact on environment when compared to non-renewable resources. Utilization of these resources will significantly reduce CO_2 emissions and hence play a vital role in diminishing global warming. Since renewable resources are random in nature, integration of these resources will aid in to overcoming the shortcomings of one resource by the strengths of other resources. Another noteworthy point of integrated systems is that it helps to minimize energy storage requirements to a great extent. Besides energization, IRES provides job opportunities, which ultimately could lead to socio-economic upgrade of rural areas. Consequently, IRES provides a solution par excellence that can be beneficial when put into practice for energizing the rural areas.

III.2 Need and Resources

Given a set of needs and resources, a match is made between one or more resources to satisfy needs. Estimates of rural consumption and needs can differ extensively from one community to the other. For overall development of rural areas, it is important to provide energy for three main types of needs:

1. Energy required to improve the basic living environment
2. Energy required to make progress in the agriculture production and increase field fertility
3. Energy needed to set up small-scale industries and hence expand job opportunities in the rural area.

All the above types of needs should be fulfilled in order to improve the social and economic standards of the rural sector. Both domestic and community surroundings must be considered in calculating the energy required for improving basic living needs. In the domestic area, cooking accounts for about 60-90% of the total energy consumption. Lighting, drinking and domestic water supply constitute the rest. In the community sector, energy is required for streetlights, space heating or cooling (depending on the weather conditions), communications, cold storage of medical supplies, educational, community and sanitation purposes [3].

III.2.1 Types of resources

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

1. Biomass
2. Hydro
3. Solar
4. Wind

As discussed earlier, it is more effective to use biomass in the converted form such as biogas, biofuel or biodiesel rather than directly using biomass as fuel. Biofuel or biodiesel can be used to fuel vehicles whereas biogas can be directly used for cooking, producing electricity, pumping water or supplying thermal loads. Water in rivers and streams can be stored in overhead reservoir, which becomes potential energy storage. The potential energy of water can be used to generate electricity through a small hydro power station or can supply water for domestic and irrigational purposes. Grinding grains and milling is also possible using mechanical aspect of hydropower plant. To pump up river or stream water to a high head reservoir, a wind powered water pump or a PV powered pump can be employed. Along with this, wind and solar energy can also be used to generate electricity. Solar energy can also be used for cooking with solar cookers, low-grade water heating using solar water heaters and to dry crops using solar dryers.

III.2.2 Types of energy needs

Basis of IRES is that some resources are more cost effective to supply some energy needs. For example, biogas can be used for cooking more efficiently than using electricity for cooking. In a similar manner, using biogas powered water pump is less efficient than wind powered or solar powered. Needs can be classified into four main types:

Medium grade thermal energy needs:

Medium grade heat (MGH) can be described as the thermal loads with temperatures ranging from 100° to 300° C. Thermal loads for MGH include cooking, industrial process heating and crop processing. Concentrated solar collectors and biogas can fulfill the medium grade heating requirements.

Low grade thermal energy needs:

Low grade heating (LGH) can be described as thermal loads, which require temperatures less than 100° C. Thermal loads for LGH include water and space heating, drying the crops and process heating. Solar flat plate collector can be used for the same.

Electrical needs:

Electrical needs can be fulfilled using the electricity generated by various components of IRES such as hydropower plant, wind electric conversion system (WECS), PV panels and biogas-driven generator. Electrical loads are domestic and commercial lighting, communication, cold storage, educational purposes such as computers and schools, small-scale industry, shops, hospital and medical needs, milling and grinding machines and so on.

Water supply needs:

Water is required for drinking, cooking, domestic and irrigational purposes. Water can be supplied through wind or PV powered pumps to pump water from streams or rivers in addition to water available in the reservoir. Various possible combinations of available resources and corresponding needs is presented in Table III.1

Needs	Resources and Technologies
Cooking	Biogas obtained from biogas digesters and household digesters Solar Cooker Improved cooking stoves
Water (drinking, domestic and community purpose)	Wind turbines powered water pumps PV powered water pumps Water available in reservoir Biogas driven water pumps
Lighting (domestic and community including street lighting)	PV cells Electricity from IRES with several sources like micro-hydro power, WECS, PV, biogas fueled generator
Small- scale industries, shops, educational institutions, cold storage, hospitals	Electricity from IRES
Communications (radio, television sets, cell phone chargers)	Solar home systems Electricity from IRES
Low grade heating (space and water heating, crop drying)	Flat plate solar collectors Solar crop dryers
Medium grade heating (industrial process heating, crop processing)	Concentrated solar collectors Electricity from IRES
Water (irrigational purpose)	Wind turbines powered water pumps PV powered water pumps
Energy Storage	Biomass and biogas energy storage Potential energy in form of water Battery storage

Table III.1: Need- Resource Combination [35]

III.3 Components of IRES

Figure III.1 shows a possible schematic diagram for IRES. It constitutes a micro hydro generator, biogas digesters, solar flat plate collectors, wind powered and PV powered water pumps, wind electric conversion systems (WECS), photovoltaic (PV) systems, biogas driven pumps and generators, energy storage devices, rectifiers and converters.

Biomass collected from organic wastes are fermented anaerobically to produce biogas which is used to fuel the water pump as well as generate electricity through the biogas driven generators. Biogas can also be used and stored for cooking purposes. Water from rivers and streams can be pumped up by using the wind powered and PV powered water pumps into the overhead reservoir. It can be used to fulfill demands of domestic and irrigation water needs of rural areas. In addition to water supply, water stored in the reservoir can be used to generate electricity. Wind electric conversion systems utilizing by wind energy and solar photovoltaic arrays utilizing insolation (incident solar radiation) are used to generate electricity. Solar flat plate collectors can fulfill the low-grade thermal demands of rural areas. Electricity can be 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 computers and laptops, domestic and street LED lighting etc.

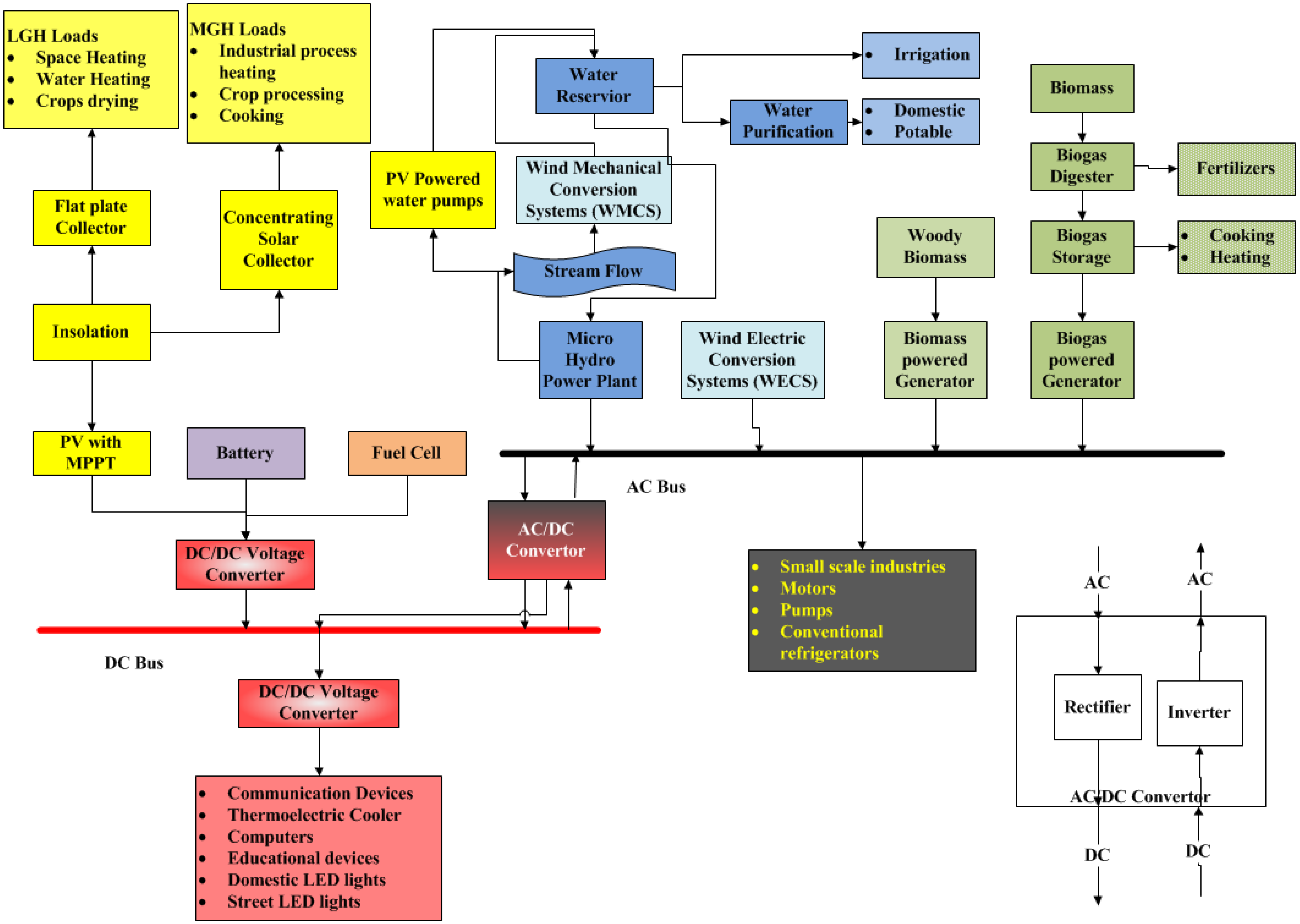


Figure III.1: A possible schematic diagram for IRES.

CHAPTER IV

MODELING OF IRES

All the models presented in the chapter are based on the hourly values of the quantities of interest and hence can be classified as hourly models.

IV.1 Modeling of 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. 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). Energy in kWh produced by a biogas generator can be represented as follows:

$$\text{Energy from biogas (kWh)} = \text{Biogas Volume } (m^3) * \text{ Energy equivalent of biogas } (kWh/m^3)$$

Energy equivalent of biogas is typically taken as 5.6 kWh/m^3. It can be seen 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].

IV.2 Modeling of Hydropower generator

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. Energy obtained from hydropower generator can be given as [37]

$$\text{Energy obtained from hydropower (kWh)} = \eta_h * (g * Q * \rho * h)/1000 \quad \ldots(\text{IV.1})$$

OR

$$\text{Energy obtained from hydropower (kWh)} = \eta_h * (g * h * \text{volume of water } (m^3))/3600 \ \ldots(\text{IV.2})$$

Where η_h- overall efficiency of hydropower generator

Q- discharge of water in m^3/sec

ρ- density of water= 1000 kg/m^3

h- Height of the overhead tank in m

g- acceleration due to gravity in m/s^2

A water pump is needed to pump up water to store in an overhead reservoir. Wind powered water pump or PV powered water pump can be used to pump water and store in the overhead reservoir. Amount of water pumped can be given by,

$$\text{Amount of water pumped } (m^3) = E_p * \eta_{ps} / (\rho * g * h) \quad \ldots (\text{IV.3})$$

Where E_p – energy consumed to pump up the water (kWh)

η_{ps}- efficiency of the pumping system

IV.3 Modeling of PV system

Incident solar radiation (insolation) is the input to the PV system. Total solar radiation on an inclined surface can be given as,

$$I_T = I_b * R_b + I_d * R_d + (I_b + I_d) * R_r \qquad \text{… (IV.4)}$$

where I_T , I_b and I_d are total, direct normal and diffuse solar radiations respectively in kWh/m^2

R_b and R_d are tilt factors for diffused and reflected part of solar radiations [38].

This clearly indicates that total solar radiation depends on the position of sun, which varies from month to month. Hourly energy output can be expressed as,

$$\text{Energy obtained from PV array (kWh)} = \eta_{pv} * I_T * A_{PV} \qquad \text{…(IV.5)}$$

Where, η_{pv} – efficiency of the PV system

A_{PV}- array area of the PV array in m^2

The system efficiency η_{pv} can be given as,

$$\eta_{pv} = \eta_m * \eta_{pc} * P_f \qquad \text{…(IV.6)}$$

where η_m is the module efficiency

η_{pc} is the power conditioning efficiency

P_f is the packing factor.

IV.4 Modeling of Wind Electric Conversion System (WECS)

Power output from wind system is expressed as a function of wind speed. A simple model for the wind system output can be expressed as follows [39],

$$P_{wt} = \begin{cases} P_r \frac{v_t - v_c}{v_r - v_c} & v_c \le v_t \le v_r \\ P_r & v_r \le v_t \le v_f \\ 0 & else \end{cases} \qquad \ldots\text{(IV.7)}$$

Where P_{wt} is wind power output at time t (kW)

P_r is rated electrical power (kW)

v_c , v_r and v_f are cut-in, rated and cut-off wind speed respectively in m/s.

Typical output characteristic of a wind-electric conversion system (WECS) is as shown in figure IV.1.

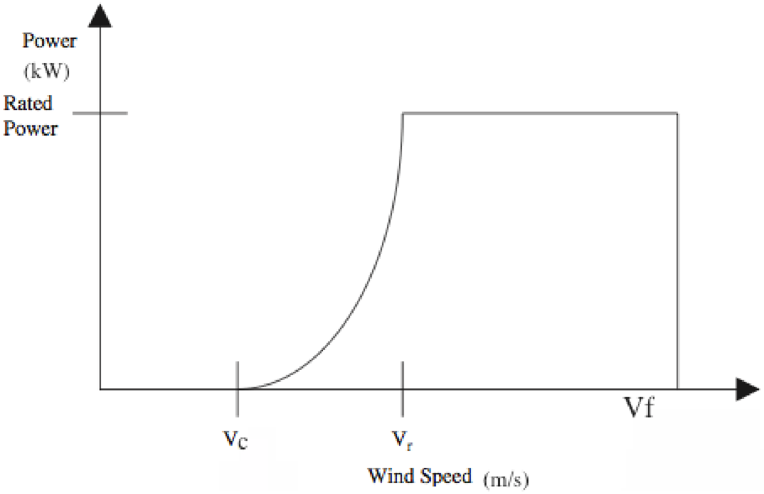


Figure IV.1 Typical Characteristic of a WECS.

Another way of calculating wind energy is by considering area swept by wind turbine blades. Considering the Weibull shape parameter to be k=2, energy obtained can be given by the following equation [40],

$$\text{Energy obtained from WECS (kWh)} = \frac{1}{2} \times \rho_{wind} \times A_w \times v_t^3 \times C_p \times \eta_{WECS} \times t \quad \text{…(IV.8)}$$

Where ρ_{wind} is the density of air in kg/m^3

A_w is the rotor area swept in m$^{2.}$

v_t is the average velocity of wind at time t in m/s.

C_p is the maximum power coefficient or Betz limit, which has a theoretical maximum value of 0.59.

η_{WECS} is the efficiency of WECS.

t is the hours of operation of WECS per day.

IV.5 Modeling of Battery bank

Battery bank is required to store and provide energy when there is a load demand and the renewables are not able to fulfill the requirements of electricity demand, commonly referred as days of autonomy. Size of battery depends on number of days of autonomy (D_a), rated battery capacity, maximum depth of discharge (B_{dis}), temperature correction (T_c) and life of the battery. Required battery capacity in ampere-hour is given as [38],

$$\text{Required battery capacity } (B_c) = \frac{Load\ in\ Ah \times D_a}{B_{dis} \times T_c} \quad \text{…(IV.9)}$$

Battery state of charge (SOC) is the result of the cumulative sum of daily charge/discharge transfers. The difference between load and power generated determines whether battery is charging or discharging. If battery is charging then power generated is greater than load and vice versa when battery is discharging. At any hour t, battery state depends on its previous state of charge and energy stored and consumed during the previous hour (t-1) and current hour (t). The available battery bank capacity, when input is greater than the load at time t can be expressed as,

$$E_{Bat}(t) = E_{Bat}(t-1) \times (1-\sigma) + [E_{ac-sur}(t) + E_{dc-sur}(t)] \times \eta_{Bat} \quad \ldots \text{(IV.10)}$$

$$E_{ac-sur}(t) = [E_b(t) + E_h(t) + E_w(t) - E_{load}(t)] \times \eta_{rec} \times \eta_{cc} \quad \ldots \text{(IV.11)}$$

OR

$$E_{ac-sur}(t) = [E_{ac}(t) - E_{load}(t)] \times \eta_{rec} \times \eta_{cc}$$

$$E_{dc-sur}(t) = [E_{pv}(t) - (E_{load}(t) - E_{ac}(t))/\eta_{inv}] \times \eta_{cc}$$

…(IV.12)

When load is greater than the input, then available battery capacity at time t can be expressed as,

$$E_{Bat}(t) = [E_{Bat}(t-1) - E_{netload}(t)]/\eta_{inv} \quad \ldots \text{(IV.13)}$$

where $E_{Bat}(t)$ and $E_{Bat}(t-1)$- Energy stored in battery at t and t-1 hour respectively.

$E_{ac-sur}(t) and\ E_{dc-sur}(t)$ are amount of surplus energy of AC and DC respectively.

σ - Self discharge rate of the battery

η_{inv}, η_{rec}, η_{cc} and η_{bat} are the efficiencies of inverter, rectifier, charge controller and battery respectively. [37- 38]

Energy stored in the battery is subject to the following constraint,

$$E_{Bat}min \leq E_{Bat}(t) \leq E_{Bat}max$$

$E_{Bat}min$ and $E_{Bat}max$ are the minimum and maximum values of charge storage capability of the battery.

$E_b(t), E_h(t), E_w(t) and\ E_{pv}(t)$ are energy produced by biogas generator, hydropower, wind turbine and PV array.

IV.6 Modeling of Inverter

The photovoltaic system generates DC power and the output of the battery bank is DC. Therefore there is a need for the inverter to convert DC power to AC power whenever there is a need for AC power in the IRES system. The inverter is characterized by a power dependent efficiency and the role of the inverter is to keep the AC bus at a constant voltage and convert DC power to AC power with best possible efficiency. The associated relationship is [37]

$$E_{inv}(t) = (E_{Bat}(t) + E_{pv}(t)) \times \eta_{inv} \qquad \ldots \text{(IV.14)}$$

$E_{inv}(t)$ is the energy output of the inverter in kWh

$E_{Bat}(t)$ and $E_{pv}(t)$ are energy stored in battery bank and energy generated by PV array

IV.7 Size of Water reservoir

Water storage is an essential part of IRES. Water may be stored in reservoirs, tanks and towers. Water distribution system should have storage so that it is capable of providing continuous water supply for basic domestic purposes, commercial and industrial uses, and emergencies such as firefighting. Size of water reservoir depends on its functions such as operating, equalizing, fire and/or emergency and dead-storage volumes. All these individual volume components must be considered in combination to determine the total volume of storage capacity that is required for any system. The total storage required is typically the sum of all these functions. Different segments of water storage are illustrated in figure IV.2

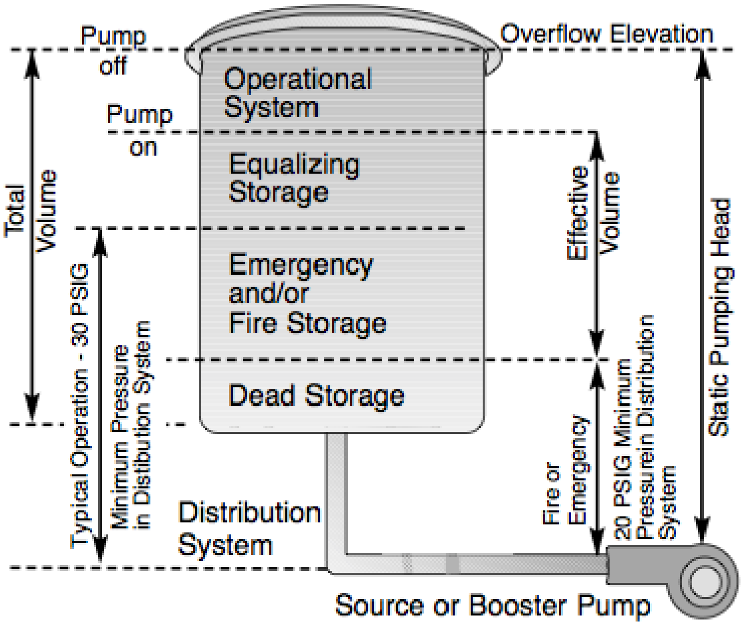


Figure IV.2 Components of water storage [52]

IV.8 Modeling of IRES

As discussed earlier, renewable energy resources are to be matched to the various tasks or needs to fulfill all the demands of a rural area. Table IV.1 shows resource numbering used in this study and Table IV.2 shows the task numbering used in this study.

Denoted as i	**Resource**
1	Biogas
2	Water
3	Solar
4	Wind

Table IV.1 Resource numbering

Denoted as j	**Task Numbering**
1	Cooking, MGH, LGH
2	Storage of biogas
3	Pumping water
4	Electricity
5	Domestic water
6	Irrigation water
7	Water storage

Table IV.2 Task numbering

There are two ways of modeling IRES: one is to match resource to various needs in the order of priority and other is to match need to various resources, again in order of priority. Figure IV.3 shows a matching of resource to need in the order of priority.

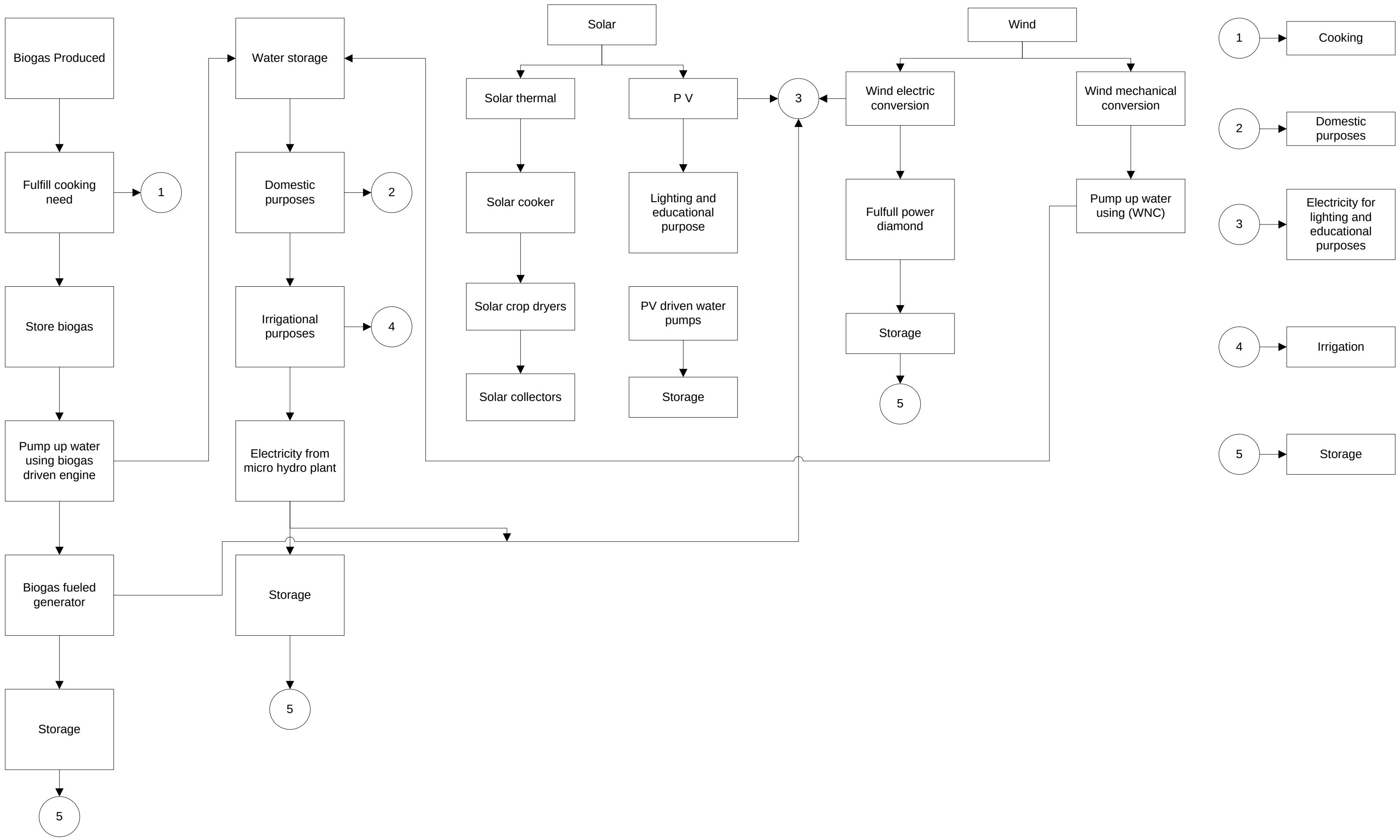


Figure IV.3 Resource to Need Match Approach

IV.8.1 Method 1: Resource- Need Matching

In IRES, renewable energy resources such as biogas, water, solar and wind are used. Wind and solar resources can fulfill various needs simultaneously whenever they are available and hence need not be prioritized. The quantity of resources such as biogas and water are fixed and needs to be matched in order of priority. This priority order is based on important 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. It is to be noted that not every resource is used to satisfy all needs. Resources are used only if they can efficiently satisfy a particular need. Each of the resource listed is used for one or more tasks. For a given resource u_i, a portion of this resource u_{ij} (required or allotted) will be used for the j^{th} task. This remaining portion of resource z_{ij} i.e. (u_i- u_{ij}), is used for the next task in the order of priority.

<u>Biogas resource (i=1)</u>

Biogas is used for various needs such as cooking, storage for future use, pumping water and producing electricity in the order of priority. Following notations are used to express total biogas used in a day.

Symbol	Description	Unit
u_1	Total biogas used for an hour	m^3
u_{11}	Biogas is used for cooking	m^3
u_{12}	Biogas stored	m^3
u_{13}	Biogas used to pump water	m^3
u_{14}	Biogas used to generate electricity	m^3
z_{11}	Biogas remaining after fulfilling cooking need	m^3
z_{12}	Biogas remaining after storing biogas	m^3
z_{13}	Biogas remaining after fulfilling pumping water need	m^3

During the k^{th} hour, biogas is first used for cooking (u_{11}^k); whatever remains ($z_{11}^k = u_1^k - u_{11}^k$) after fulfilling the cooking need is stored (u_{12}^k). After storing biogas in tank, remaining biogas

($z_{12}^k = z_{11}^k - u_{12}^k$) can be used to pump water (u_{13}^k). If biogas is still left ($z_{13}^k = z_{12}^k - u_{13}^k$), then it is used to generate electricity (u_{14}^k). Total biogas at k^th hour can be represented by the following equation,

$$u_1^k = u_{11}^k + \alpha_{12}^k (u_1^k - u_{11}^k) + \alpha_{13}^k (u_1^k - u_{11}^k - u_{12}^k) + \alpha_{14}^k (u_1^k - u_{11}^k - u_{12}^k - u_{13}^k)$$

$$u_1^k = u_{11}^k + \alpha_{12}^k\left(z_{11}^k\right) + \alpha_{13}^k\left(z_{11}^k - u_{12}^k\right) + \alpha_{14}^k\left(z_{12}^k - u_{13}^k\right)\}$$

From above equation it can be seen that the total biogas resource u_1 (m^3) is the cumulative sum of the portions of biogas used for various tasks at the k^{th} hour. The coefficient α_{ij} is the ratio of the total biogas resource to the portion of biogas resource used for j^{th} task. If the coefficient α_{ij} is greater than 1, then biogas is used for the next prioritized task. For instance, if total biogas available is greater than biogas used for cooking u_{11} (m^3) then remaining biogas z_{11}, i.e. ($u_1 - u_{11}$) amount of biogas (u_{12}) can be stored for future use. Similarly, if biogas storage tank is full then the remaining biogas ($z_{12}^k = u_1^k - u_{11}^k - u_{12}^k$) can be used for pumping the water.

Constraints:

$$If\ \alpha_{11}^k = \frac{u_1^k}{u_{11}^k} > 1 \qquad \text{, Then} \quad \alpha_{12}^k = 1$$

$$else = 0$$

$$If\ \alpha_{12}^k = \frac{z_{11}^k}{u_{12}^k} > 1 \qquad \text{, Then} \quad \alpha_{13}^k = 1$$

$$else = 0$$

$$If\ \alpha_{13}^k = \frac{z_{12}^k}{u_{13}^k} > 1 \qquad \text{, Then} \quad \alpha_{14}^k = 1$$

$$else = 0$$

For one day, i.e. k=1 to 24, the total resource U_1 for a day can be expressed as follows,

$$U_1 = \sum_{k=1}^{24}\{u_{11}^k + \alpha_{12}^k(z_{11}^k) + \alpha_{13}^k(z_{11}^k - u_{12}^k) + \alpha_{14}^k(z_{12}^k - u_{13}^k)\} \qquad \ldots\text{(IV.15)}$$

$$U_1 = \sum_{k=1}^{24}\{u_{11}^k + \alpha_{12}^k(z_{11}^k) + \alpha_{13}^k(z_{12}^k) + \alpha_{14}^k(z_{13}^k)\}$$

$$U_1 = \sum_{k=1}^{24}\{u_{11}^k + \sum_{j=2}^{4}[\alpha_{1j}(z_{1(j-1)}^k)]\}$$

Water resource (i=2)

Water must be first used for domestic purposes and then for electricity generation. If water still remains in reservoir, then it can be used for irrigation purposes and stored for future use. Following notations are used to represent total water resource used in a day.

Symbol	Description	Unit
u_2	Total water used for an hour	m^3
u_{25}	Water is used for domestic purpose	m^3
u_{24}	Water used to generate electricity	m^3
u_{26}	Water is used for irrigation purpose	m^3
u_{27}	Water stored in overhead reservoir	m^3
z_{25}	Water remaining after fulfilling domestic need	m^3
z_{24}	Water remaining after generating electricity	m^3
z_{26}	Water remaining after fulfilling irrigation need	m^3

Accordingly,

$$U_2 = \sum_{k=1}^{24}\{u_{25}^k + \alpha_{22}^k(z_{25}^k) + \alpha_{23}^k(z_{25}^k - u_{24}^k) + \alpha_{24}^k(z_{24}^k - u_{26}^k)\}$$

$$U_2 = \sum_{k=1}^{24}\{u_{25}^k + \alpha_{22}^k(z_{25}^k) + \alpha_{23}^k(z_{24}^k) + \alpha_{24}^k(z_{26}^k)\} \qquad \ldots\text{(IV.16)}$$

From above equation it can be seen that total water resource U_2 (m^3) for a day is the cumulative sum of portions of water that are used for various tasks. The coefficient α_{21} is ratio of the total water resource to the portion of water resource used for the domestic purpose (u_{25}^k). If the coefficient α_{21} is greater than 1, then water is used for next prioritized task i.e. electricity generation. If the remaining water resource ($z_{25}= u_2- u_{25}$) after fulfilling domestic water demand, is greater than water used for electricity u_{24}, then the remaining water i.e. z_{24} ($u_2- u_{25}-u_{24}$), can be used for irrigation water. After using water for irrigation purpose, remaining water (z_{26}) can be stored in overhead reservoir.

Constraints:

$$If\ \alpha_{21}^k = \frac{u_2^k}{u_{25}^k} > 1 \qquad \text{, Then} \quad \alpha_{22}^k = 1$$

$$else = 0$$

$$If\ \alpha_{22}^k = \frac{z_{25}^k}{u_{24}^k} > 1 \qquad \text{, Then} \quad \alpha_{23}^k = 1$$

$$else = 0$$

$$If\ \alpha_{23}^k = \frac{z_{24}^k}{u_{26}^k} > 1 \qquad \text{, Then} \quad \alpha_{24}^k = 1$$

$$else = 0$$

Solar resource (PV systems) i=3:

As mentioned earlier, solar energy can be used simultaneously for various purposes such as electricity generation (u_{34}^k in kWh), pumping water (u_{33}^k in kWh) and low and medium grade heating($u_{31}^k\ in\ kWh$). The total solar resource used U_3(kWh) for one day is given by following equation,

$$U_3 = \sum_{k=1}^{24}\{u_{31}^k + u_{33}^k + u_{34}^k\} \qquad \text{... (IV.17)}$$

Wind Systems i=4:

Wind energy is not resource limited and can be used simultaneously for various purposes such as electricity generation (u_{44}^k in kWh) and pumping water (u_{43}^k in kWh). The total wind resource used U_4(kWh) for one day is given by the following equation,

$$U_4 = \sum_{k=1}^{24}\{u_{43}^k + u_{44}^k\} \qquad \text{...(IV.18)}$$

Alternately,

$$U_4 = \sum_{k=1}^{24}\{\sum_{j=3}^{4} u_{4j}^k\}$$

IV.8.2 Method 2: Need- Resource Matching

Another method of modeling IRES is to match needs to available resources. In this method, demand of a resource for a particular task is known and available resources at that hour are known. Needs such as cooking, domestic water, electricity and irrigation water to fulfill the needs of a rural area are denoted as y_1, y_2, y_3 and y_4 respectively. Resources are matched to these needs in the best possible and efficient manner to fulfill demands.

Cooking need (y_1):

Demand of biogas for cooking for an hour (m^3) is represented by y_1^k. It should be noted that y_1^k should not be mistaken with u_{11}^k, which is the part of biogas that has been used for cooking. In other words, when u_{11}^k is equal to y_1^k at kth hour then we say that the need has been fulfilled completely.

In general, β^k is the ratio of need to available resource. β^k is termed as need-to-availability ratio.

$$\beta_1^k = \frac{y_1^k}{x_1^k} = \frac{need\ at\ k^{th}\ hour}{available\ biogas\ at\ k^{th}\ hour}$$

The following notations are used to represent the need of biogas at k^{th} hour

Symbol	Description	Unit
x_1^k	Biogas produced at k^{th} hour	m^3
x_{12}^{k-1}	Biogas stored at (k-1) hour	m^3
y_1^k	Biogas need for cooking at k^{th} hour	m^3
δ_1^k	Fraction of stored biogas used to fulfill needs	
β_1^k	Cooking need-to-biogas availability ratio	

When $\beta_1^k \leq 1$, then y_1^k can be given as,

$$y_1^k = \beta_1^k x_1^k \qquad \text{… (IV.19)}$$

Otherwise $\beta_1^k > 1$, then y_1^k can be expressed as,

$$y_1^k = x_1^k + \delta_1^k * x_{12}^{k-1} \qquad \text{…(IV.20)}$$

Domestic water needs (y_2):

The following notations are used to express an equation for domestic water needs.

Symbol	Description	Unit
x_{33}^k	Water pumped at k^{th} hour by PV powered pump	m^3
x_{43}^k	Water pumped at k^{th} hour by wind powered pump	m^3
x_{13}^k	Water pumped at k^{th} hour by biogas powered pump	m^3
x_{27}^{k-1}	Water available in reservoir at (k-1) hour	m^3
y_2^k	Demand of water for domestic purpose	m^3
δ_{21}^k	Fraction of water stored in the reservoir used to fulfill needs	
δ_{22}^k	Fraction of biogas used to pump water	
β_2^k	Domestic water need-to-pumped water availability ratio	

The need-to-availability ratio β^k in this case is given as,

$$\beta_2^k = \frac{y_2^k}{x_{33}^k + x_{43}^k}$$

As seen in the above equation, preference is first given to water pumped by PV pumps and wind water pump; reason being they are freely available and can be used simultaneously for various purposes.

When $\beta_2^k \leq 1$, then y_2^k can be given as,

$$y_2^k = \beta_2^k (x_{33}^k + x_{43}^k) \qquad \ldots \text{(IV.21)}$$

Otherwise $\beta_2^k > 1$, then y_2^k can be given as,

$$y_2^k = x_{33}^k + x_{43}^k + \delta_{21}^k * x_{27}^{k-1} \qquad \ldots \text{(IV.22)}$$

If $\delta_{21}^k > 1$, then biogas powered water pump is used to provide water for domestic purpose.

$$y_2^k = x_{33}^k + x_{43}^k + x_{27}^{k-1} + \delta_{22}^k * x_{13}^k \qquad \ldots \text{(IV.23)}$$

Electricity needs (y_3):

The following notations are used to express an equation for electrical needs.

Symbol	Description	Unit
x_{34}^k	Electricity generated at k^{th} hour by PV array	kWh
x_{44}^k	Electricity generated at k^{th} hour by wind turbine	kWh
x_{24}^k	Electricity generated at k^{th} hour by hydropower	kWh
x_{14}^k	Electricity generated at k^{th} hour by biogas driven generator	kWh
x_5^{k-1}	Electrical energy available in battery bank at (k-1) hour	kWh
y_3^k	Demand of electrical energy need	kWh
δ_{31}^k	Fraction of water stored in the reservoir used for electrical energy needs	
δ_{32}^k	Fraction of energy in battery bank used for electrical energy needs	
δ_{33}^k	Fraction of biogas was to generate electricity.	
β_3^k	Electricity need-to-generated electricity ratio	

The need-to-availability ratio β^k in this case is given as,

$$\beta_3^k = \frac{y_3^k}{x_{34}^k + x_{44}^k}$$

As seen in the above equation, preference is first given to electricity generated by PV system and wind turbine; reason being they are freely available and can be used simultaneously for various purposes.

When $\beta_3^k \leq 1$, then y_3^k can be given as,

$$y_3^k = \beta_3^k (x_{34}^k + x_{44}^k) \quad \dots \text{(IV.24)}$$

Otherwise $\beta_3^k > 1$, then y_3^k can be given as,

$$y_3^k = x_{34}^k + x_{44}^k + \delta_{31}^k * x_{24}^k \quad \dots \text{(IV.25)}$$

If $\delta_{31}^k > 1$, then energy stored in batteries is used to provide electricity.

$$y_3^k = x_{34}^k + x_{44}^k + x_{24}^k + \delta_{32}^k * x_5^{k-1} \quad \dots \text{(IV.26)}$$

If $\delta_{32}^k > 1$, then biogas powered generator is used to provide electricity.

$$y_3^k = x_{34}^k + x_{44}^k + x_{24}^k + x_5^{k-1} + \delta_{33}^k * x_{14}^k \quad \dots \text{(IV.27)}$$

Irrigation water needs (y_4):

The following notations are used to express an equation for irrigation water demand.

Symbol	Description	Unit
x_{36}^k	Water pumped at k^{th} hour by PV powered pump	m^3
x_{46}^k	Water pumped at k^{th} hour by wind powered pump	m^3
x_{16}^k	Water pumped at k^{th} hour by biogas powered pump	m^3
x_{26}^{k-1}	Water available in reservoir at (k-1) hour for irrigation purpose	m^3
y_4^k	Demand of water for irrigation purpose	m^3
δ_{41}^k	Fraction of water stored in the reservoir used to fulfill irrigation need	

δ_{42}^{k}	Fraction of biogas used to pump water for irrigation purpose
β_{4}^{k}	Irrigation water need-to-pumped water availability ratio

The need-to-availability ratio β^{k} in this case is given as,

$$\beta_{4}^{k} = \frac{y_{4}^{k}}{x_{36}^{k} + x_{46}^{k}}$$

As seen in the above equation, preference is first given to water pumped by PV pumps and wind water pump for irrigation need; reason being they are freely available and can be used simultaneously for various purposes.

When $\beta_{4}^{k} \leq 1$, then y_4^k can be given as,

$$y_{4}^{k} = \beta_{4}^{k}(x_{36}^{k} + x_{46}^{k}) \qquad \ldots \text{(IV.28)}$$

Otherwise $\beta_{4}^{k} > 1$, then y_4^k can be given as,

$$y_{4}^{k} = x_{36}^{k} + x_{46}^{k} + \delta_{41}^{k} * x_{26}^{k-1} \qquad \ldots \text{(IV.29)}$$

If $\delta_{41}^{k} > 1$, then biogas powered water pump is used to provide water for irrigation purpose.

$$y_{4}^{k} = x_{35}^{k} + x_{45}^{k} + x_{26}^{k-1} + \delta_{42}^{k} * x_{16}^{k} \qquad \ldots \text{(IV.30)}$$

CHAPTER V

OPTIMIZATION OF IRES

V.1 Introduction

Optimization of IRES is undertaken in two parts. Cost of electricity is optimized using HOMER and optimization of the utilization of resources for various needs is done using MATLAB programming. A typical rural area that consists of population of 700 in 120 households and 450 cattle is considered for cost analysis and optimization of IRES. This area is assumed to have adequate supply of resources such as water, wind, solar and biogas resource. Most of the people have agriculture as their occupation and hence a significant amount of agricultural waste is produced that can be used as biomass. Every animal is considered to yield an average of 10 kg of wet dung everyday, which also constitutes biomass. All told, biomass can produce a minimum of 280 m^3 of biogas everyday. Each household needs about 1.5 m^3 of biogas everyday for cooking and therefore about 180 m^3 is required for cooking daily. The remaining 100 m^3 is used for other purposes such as generating electricity and pumping water [41]. Average daily water use per person for domestic purposes is about 80-100 gallons i.e. about 0.3409 m^3. Therefore about 240 m^3 of water is needed per day for the rural area for the domestic purpose. Average household electricity consumption is estimated to be about 9.5 kWh/day, according to the World Energy Council (WEC) [48]. Therefore for 120 households, about 1141 kWh is needed per day. For irrigation purposes, about 120 to 140 m^3 of water is needed for 4 to 5 acres of land [44]. A total of

200 acres of agricultural land is considered. Table V.1 gives a summary of the requirements of the rural area for various purposes.

Sl no.	Purpose/Need	Quantity per day
1	Biogas for cooking	180 m^3
2	Domestic water	240 m^3
3	AC load	696 kWh
4	DC load	445 kWh
5	Irrigation water	4800 m^3

Table V.1 Summary of energy and other requirements

V.2 Cost optimization electrical part of IRES

Cost optimization for electricity of IRES is done using the software called HOMER. HOMER stands for Hybrid Optimization Model for Electric Renewable and is developed by the National Renewable Energy Laboratory (NREL), Golden Colorado. HOMER optimizes the system by randomly selecting size of generating system in order to obtain the most optimal solution for IRES with lowest possible capital and electricity cost.

A system can be a stand-alone or it can be connected to the central grid when being optimized by HOMER. It requires information such as available resources, capital, operational and maintenance costs for the components used, component types, load profile, weather conditions and economic constraint. After considering all these factors, HOMER displays a list of all possible configurations in the order of increasing cost of electricity (COE). Electrical energy requirements needed to fulfill the needs of the rural areas are given as inputs to the HOMER software. As mentioned earlier table V.1 lists all the electrical loads, both AC and DC. Other details of the components used to optimize the system are presented next.

V.2.1 Biomass and Biogas Generator

A mathematical model of the biogas component was discussed earlier. Average biomass available in study area is 4.5 tons. Capital cost of the biogas generator is $1000/kW with a replacement cost of $850/kW. The operational and maintenance (O&M) cost is given as $0.01/kW [42]. Monthly average biomass resource in tons/day is assumed and shown in figure V.1. Sizes of biogas generator considered in HOMER are 80 kW, 85 kW, 90 kW and 100kW.

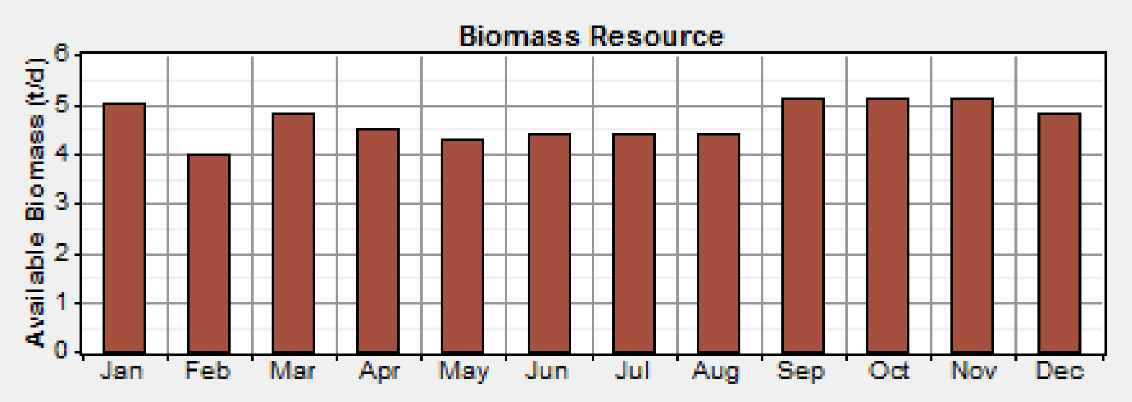


Figure V.1 Average Monthly Biomass Resource

V.2.2 Hydropower generator

The study area considered has a monthly average water flow of 45 L/s. Hydro generator is considered to have 70% efficiency and a head of 50m. Rated capacity of hydro generator is calculated using the formula discussed earlier and it works out to be 15.5 kW. Capital cost of the hydropower generator is taken as, as $25,000 and its replacement and O & M cost are $20,000 and $500 per year respectively. Its lifetime is given as 25 years [43]. Figure V.2 gives the average water flow in L/s over a period of one year.

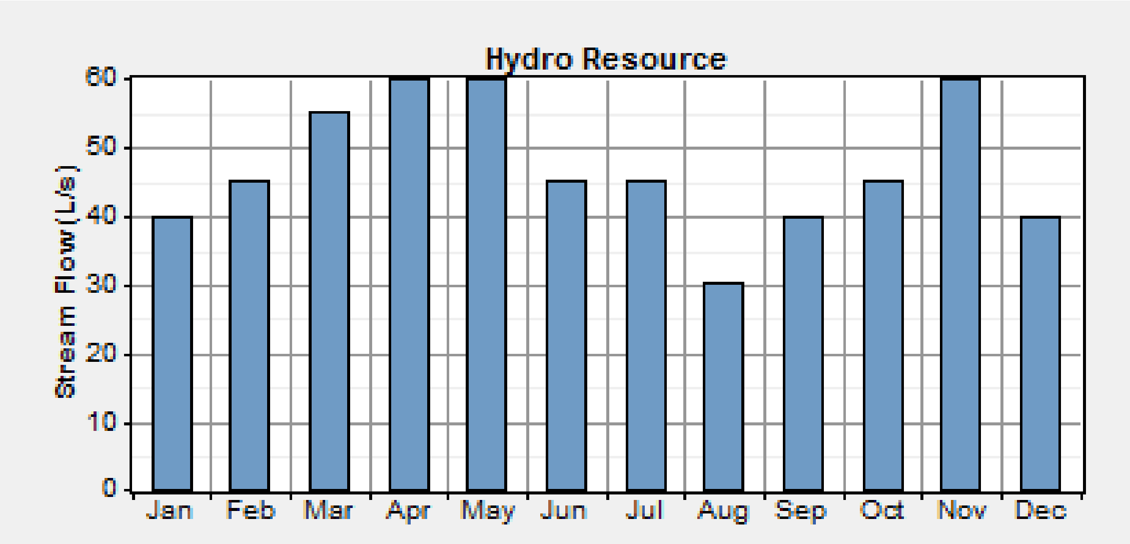


Figure V.2 Average Monthly Stream flow.

V.2.3 Solar resource and PV system

Solar radiation for the study area is obtained from the official NASA surface meteorology and solar energy website which is a feature of the HOMER tool while gathering solar data. HOMER asks for latitude and longitude input to provide solar data, which are given as 36.12° N and 97.06° W respectively. It is seen that, daily average solar radiation is about 5.5 kWh/m^2 and average clearness index is 0.6. Capital cost and replacement cost are $3500/kW and $3000/kW respectively. The O & M cost is practically zero and its lifetime is considered to be 25 years [40]. Figure V.3 shows monthly average solar radiation and clearness index. A derating factor of 80% is taken for each panel to account the factors caused by parameters such as shading, temperature, tilt etc. Different sizes of PV system considered for HOMER simulation are 5kW, 10 kW, 11kW and 12 kW.

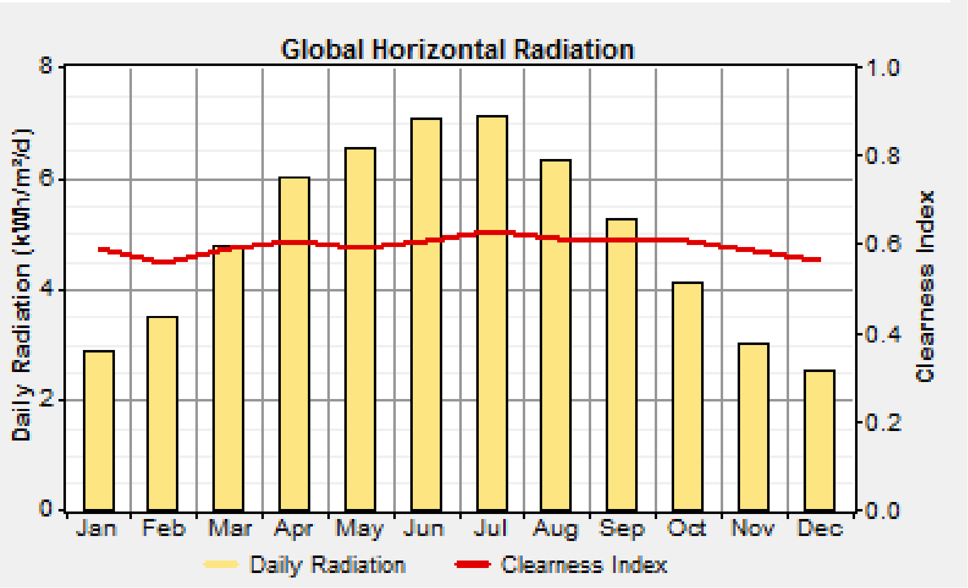


Figure V.3 Average Monthly solar radiation and clearness index.

V.2.4 Wind Electric conversion system

Average wind speed at the study area is assumed to be 6.2 m/s. The wind turbine type considered is BWC Excel S that is manufactured by Bergey Wind Power. Its power rating is 10 kW AC and the rotor diameter is 7 m. Capital and replacement costs are $31,770 and $28,000 respectively. It has an O & M cost of $65 per year [45]. Figure V.4 shows monthly average wind speed in m/s. Various units of wind turbines considered are 1, 2 and 3 for HOMER simulation.

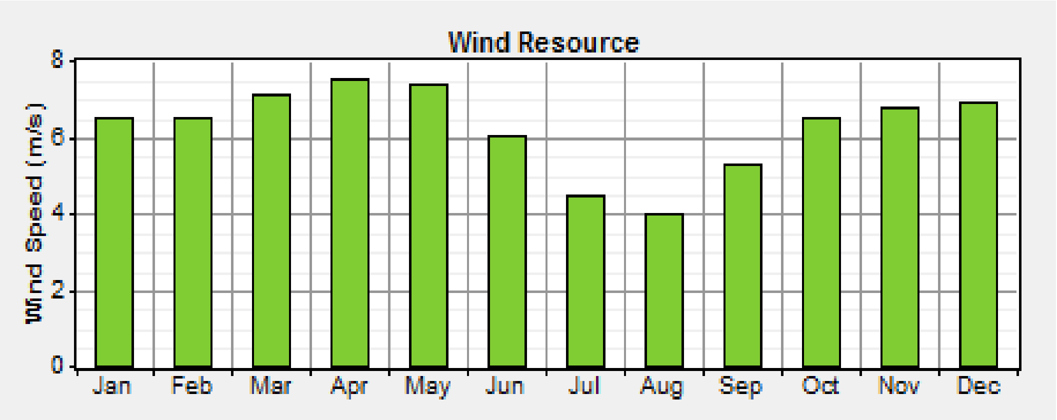


Figure V.4 Monthly average wind speed

V.2.5 Battery bank and Converter

Battery type used is Surrette 4KS25PS, which is a 4-volt, 2 cell high capacity lead-acid and deep cycle battery. It is used commonly for stand by applications and renewable energy application. Its nominal capacity is 7.6kWh (1900 Ah). Capital and replacement cost are \$1300 and \$1100 respectively and O & M costs are \$15 per year [46]. The numbers of batteries considered for the battery bank are 30, 35, 40 and 45 for HOMER simulation.

Capital cost of a bidirectional converter is \$800/kW. Its replacement cost is \$750 per kW and \$15 per year O & M costs. The inverter and rectifier efficiency is 90% and 85% respectively [40].

V.2.6 HOMER simulation model and results

A total electrical load of 1141 kWh per day is needed to completely satisfy electrical energy requirements of the rural area under study. Average AC load demand is 696 kWh/day and average DC load is 445 kWh/day. Figure V.5 shows daily electrical load profile of the rural area considered.

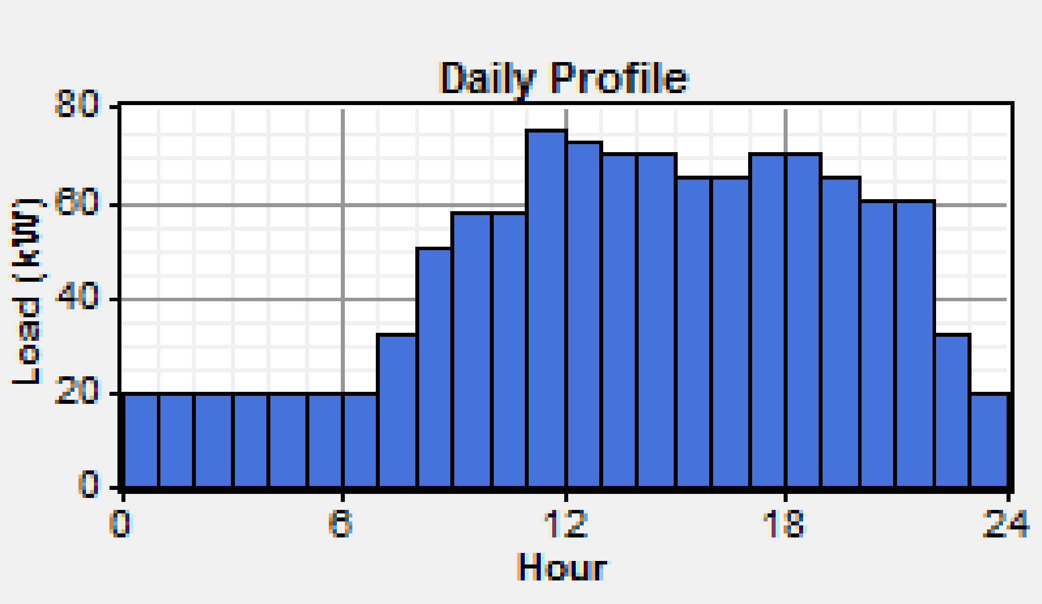


Figure V.5 Average daily electrical load profile

IRES for electrical demand is considered to be a stand-alone system in HOMER simulation and its lifetime is considered to be 25 years with an annual interest rate of 8%. Figure V.6 shows the proposed model for electrical demand of IRES for cost optimization and it consists of PV array, hydro generator, wind turbine, biogas generator, battery bank, a bidirectional converter, AC and DC loads.

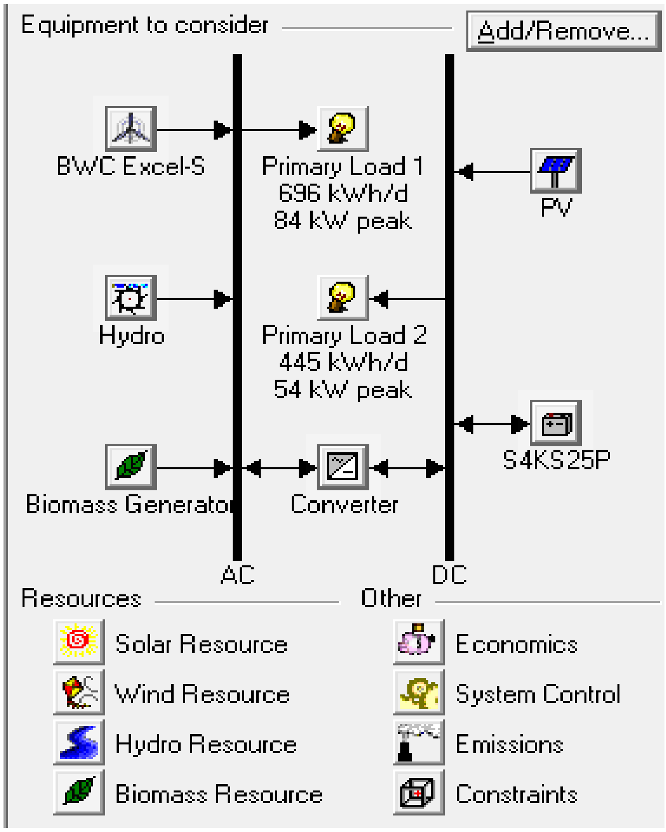
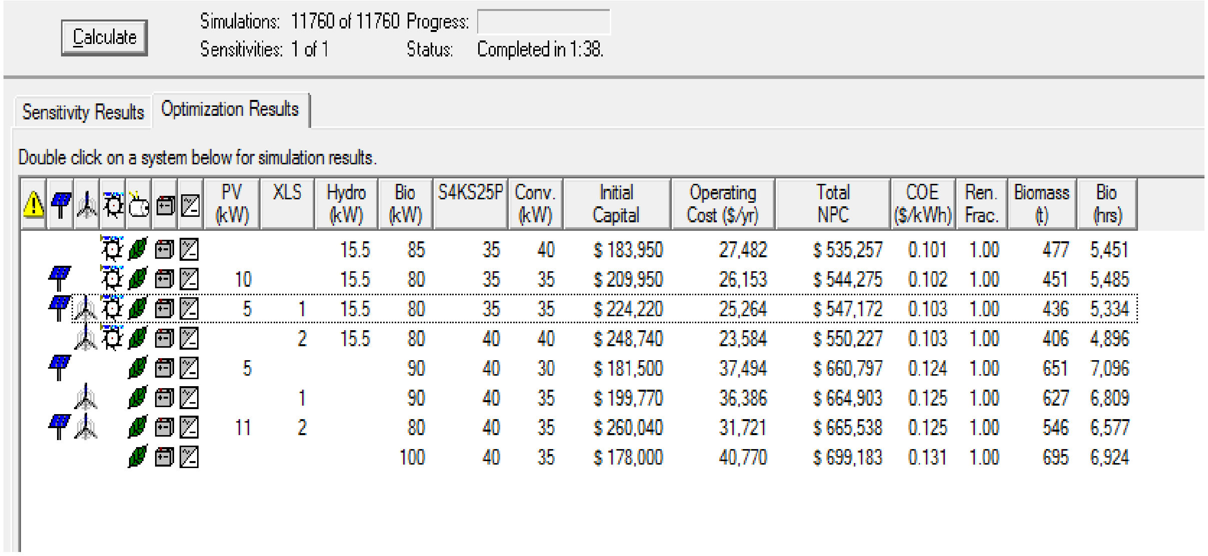


Figure V.6 the proposed model for IRES for cost optimization in HOMER

For simulation purposes, different sizes of the components are considered as discussed earlier. Adding more number of sizes for each simulation to find the most optimal system configuration can maximize the search space. HOMER lists all the possible system configurations for electrical part of IRES. Figure V.7 shows the simulation results obtained by HOMER

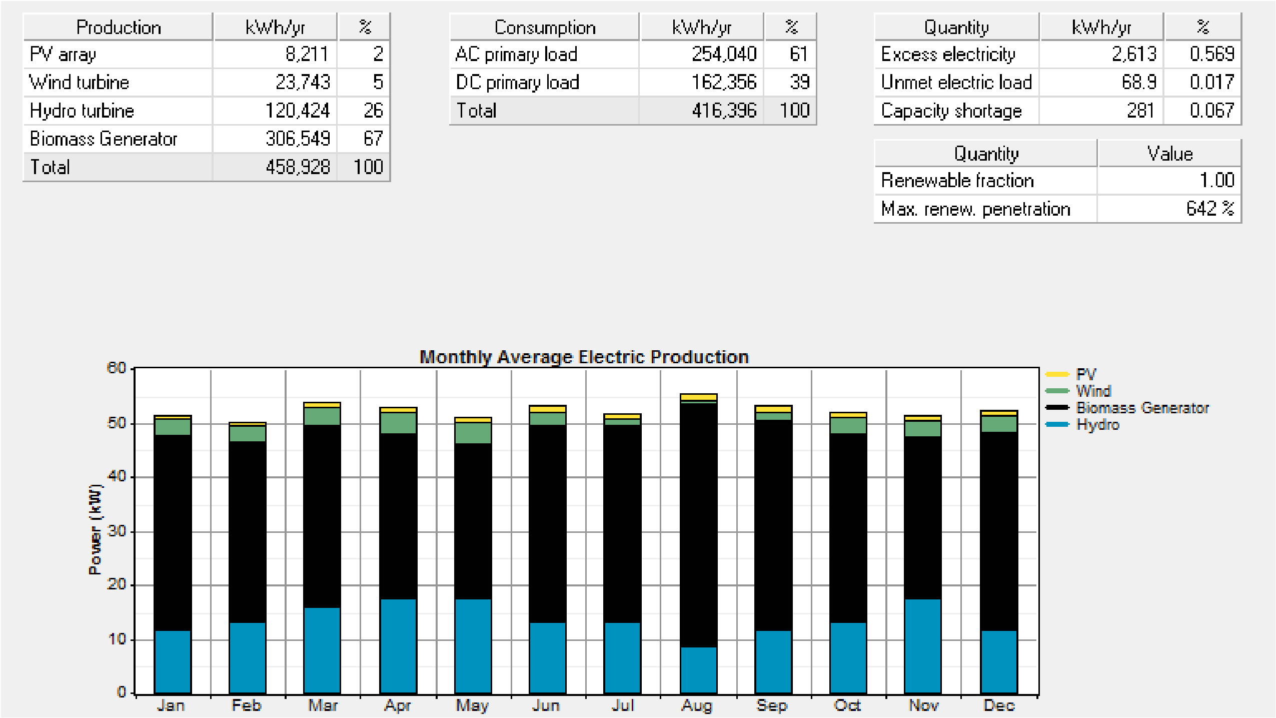


Double click on a system below for simulation results.

PV (kW)	XLS	Hydro (kW)	Bio (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Bio (hrs)
		15.5	85	35	40	$ 183,950	27,482	$ 535,257	0.101	1.00	477	5,451
10		15.5	80	35	35	$ 209,950	26,153	$ 544,275	0.102	1.00	451	5,485
5	1	15.5	80	35	35	$ 224,220	25,264	$ 547,172	0.103	1.00	436	5,334
	2	15.5	80	40	40	$ 248,740	23,584	$ 550,227	0.103	1.00	406	4,896
5			90	40	30	$ 181,500	37,494	$ 660,797	0.124	1.00	651	7,096
	1		90	40	35	$ 199,770	36,386	$ 664,903	0.125	1.00	627	6,809
11	2		80	40	35	$ 260,040	31,721	$ 665,538	0.125	1.00	546	6,577
			100	40	35	$ 178,000	40,770	$ 699,183	0.131	1.00	695	6,924

Figure V.7 Cost optimization results in HOMER for electrical part of IRES

It is seen from the results obtained by HOMER that the optimal configuration of electrical part of IRES is given by 5kW of PV, one wind turbine of 10kW AC BWC Excel S, 15.5kW rated hydropower generator, 80 kW of biogas generator, 35 Surrette S4KS25P battery bank and 35kW of bidirectional converter. The simulation result also provides the cost of optimal IRES for electricity demand for the given configuration. The total initial capital cost for the system is $224,220 and operating cost is about $25.264 every year. The total net present cost (NPC) over the lifetime period is given as $547,172. The cost of electrical energy (COE) is 10.3¢ per kWh, which is less than 11.6¢ per kWh for the USA residential customers [47]. It is also seen that price of electricity obtained from IRES is less than that of PV, CSP, and natural gas. Figure V.8 shows how electricity demand is fulfilled by renewable resources and percentages of each resource used to fulfill the electricity demand over a period of one year.



Production	kWh/yr	%
PV array	8,211	2
Wind turbine	23,743	5
Hydro turbine	120,424	26
Biomass Generator	306,549	67
Total	458,928	100

Consumption	kWh/yr	%
AC primary load	254,040	61
DC primary load	162,356	39
Total	416,396	100

Quantity	kWh/yr	%
Excess electricity	2,613	0.569
Unmet electric load	68.9	0.017
Capacity shortage	281	0.067

Quantity	Value
Renewable fraction	1.00
Max. renew. penetration	642 %

Figure V.8: Electricity demand fulfill by various resources

V.3 Optimization of IRES using MATLAB

HOMER optimizes cost with respect to only electricity whereas it does not optimize energy and other outputs of IRES such as cooking demand, water demand and heating demands. Hence a program in MATLAB is developed using the mathematical modeling concept of IRES discussed earlier. Programming in MATLAB is a way to validate these mathematical models. The optimum utilization of resources can be maximized using the MATLAB program. The following assumptions are made in developing the optimization procedure.

- Size of water reservoir, battery bank and biogas tank are assumed to be large enough to store the water and biogas respectively
- Output obtained from MATLAB is valid for the study area only and can change with geographical and weather conditions for other areas.

- Domestic water demand for a day is assumed for all 24 hours and irrigation water demand is assumed to be constant at 200m^3 per hour.
- Hourly biogas produced and hourly cooking demand is assumed for duration of one day.
- It is assumed that renewable resources do not change significantly over an hour.

V.3.1 Input Data to IRES

Input data to IRES for an hour are biogas available, wind speed data, solar data, cooking demand, domestic water demand, electrical energy demand and irrigation water demand. Optimization of IRES is carried out for one day. Hourly biogas produced is assumed to be as in figure V.9.

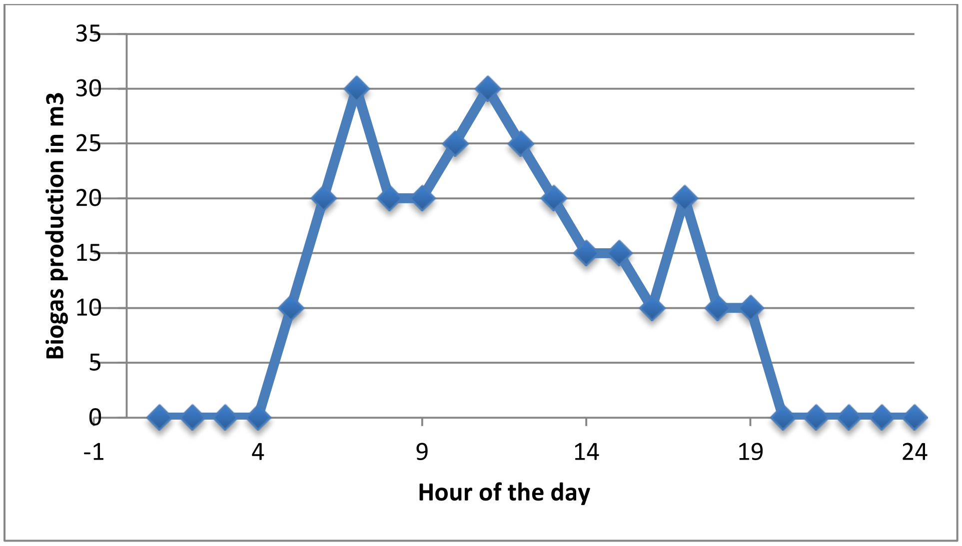


Figure V.9 Estimated biogas production per day

It is to be noted that there is a possibility that the study area might have low wind regimes or low solar irradiation depending on the season. However for this study, the following hourly wind speed in m/s and hourly solar irradiation in kWh/m^2 for a particular day are shown in figure V.10 and figure V.11 respectively.

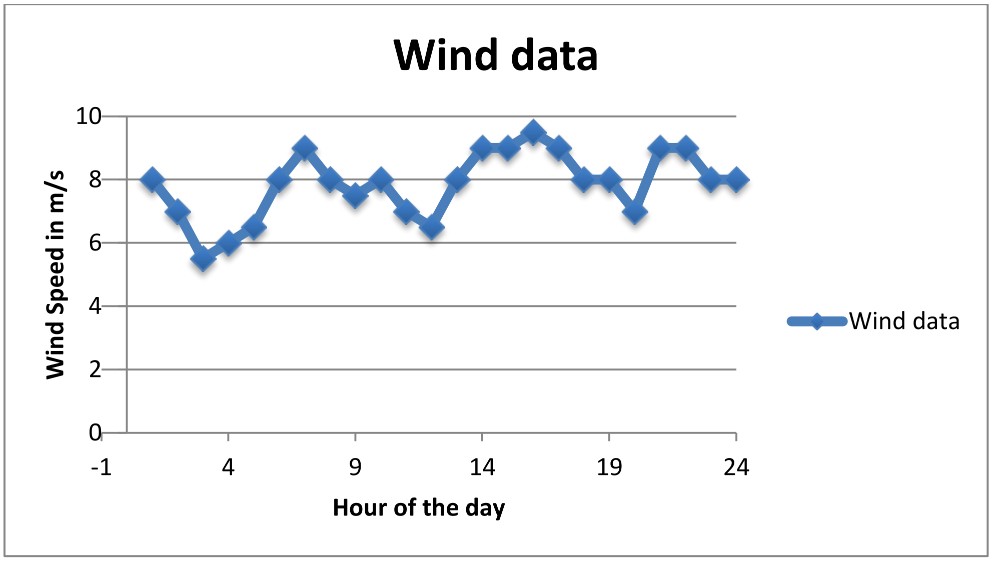


Figure V.10 Hourly wind speed [39]

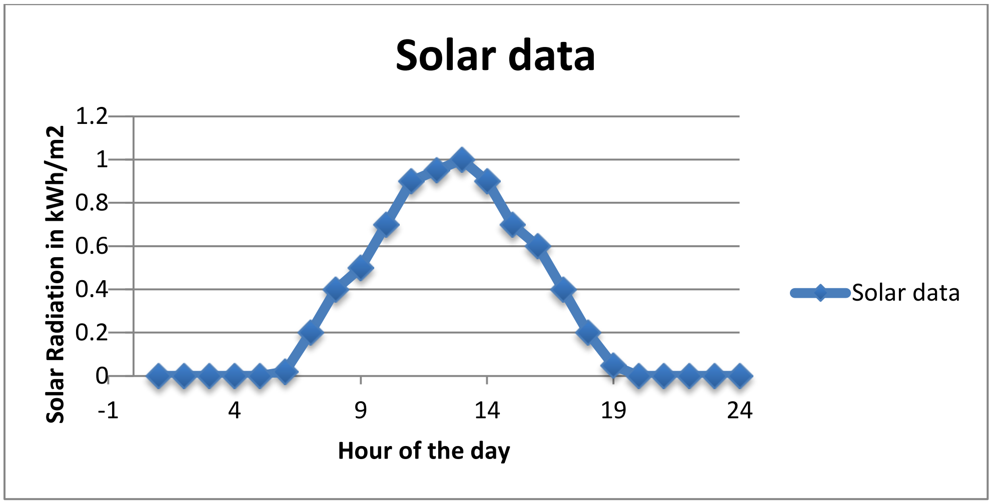


Figure V.11 Hourly solar radiation [44]

V.3.2 Pumping Capacity of Wind water pump and Solar pump

Pumping capacity of a wind water pump or windmill depends on the pump diameter, wind speed, pumping elevation and diameter of the wind wheel. Depending on speed, wind is classified into three categories.

1) Light Winds- Wind speed ranging from 3.6 to 10 mph or 1.6 to 4.5 m/s can be called as light winds. Pumping capacity of windmills when light wind blows is about 25%.
2) Medium Winds- Wind speed ranging from 11 to 17 mph or 4.6 to 7.6 m/s can be called as medium winds. Pumping capacity of windmills when medium wind blows is about 55%.
3) Strong Winds- Wind speed ranging from 18 to 20 mph or 7.7 to 8.9 m/s can be called as strong winds. Pumping capacity of windmills when strong wind blows is about 100%.

A windmill with a pump diameter of 6 inches and a 5m diameter wind wheel is considered. Its full pumping capacity is 1875 gallons of water per hour or 7.1 m^3 of water per hour [49]. Six such windmills are considered.

Solar pumps often referred as PV powered water pumps can also be to used to pump water. A 140-volt, 640 W 6SQF-2 Grundfos PV powered water pump is considered. 30 such PV panels are considered to fulfill water need of rural area. Table V.2 shows amount of water pumped for different solar irradiance by one PV- powered water pump [50].

Solar Irradiance (watts/m^2)	Water pumped (liters per hour)
200	240
400	660
500	840
600	1020
700	1080
800	1080
900	1140
1000	1200

Table V.2 Amount of water pumped by PV array[50]

Amount of water pumped by biogas powered water pump can be given as [51],

$$Volume\ of\ water(m^3) = \frac{amount\ of\ biogas(m^3) * 5.6 * 367}{head\ (m)}$$

The number 5.6 denotes kWh energy value produced by 1m^3 of biogas.

V.3.3 Results of optimization of IRES

Resources are optimized for a period of one day and time step of 1 hour. Water needs and cooking need are in m^3/hr whereas electricity need is in kWh. Figure V.12 shows the flow chart of the algorithm used in MATLAB. Order of priority for needs is cooking need, domestic water need, electricity need and irrigation water need.

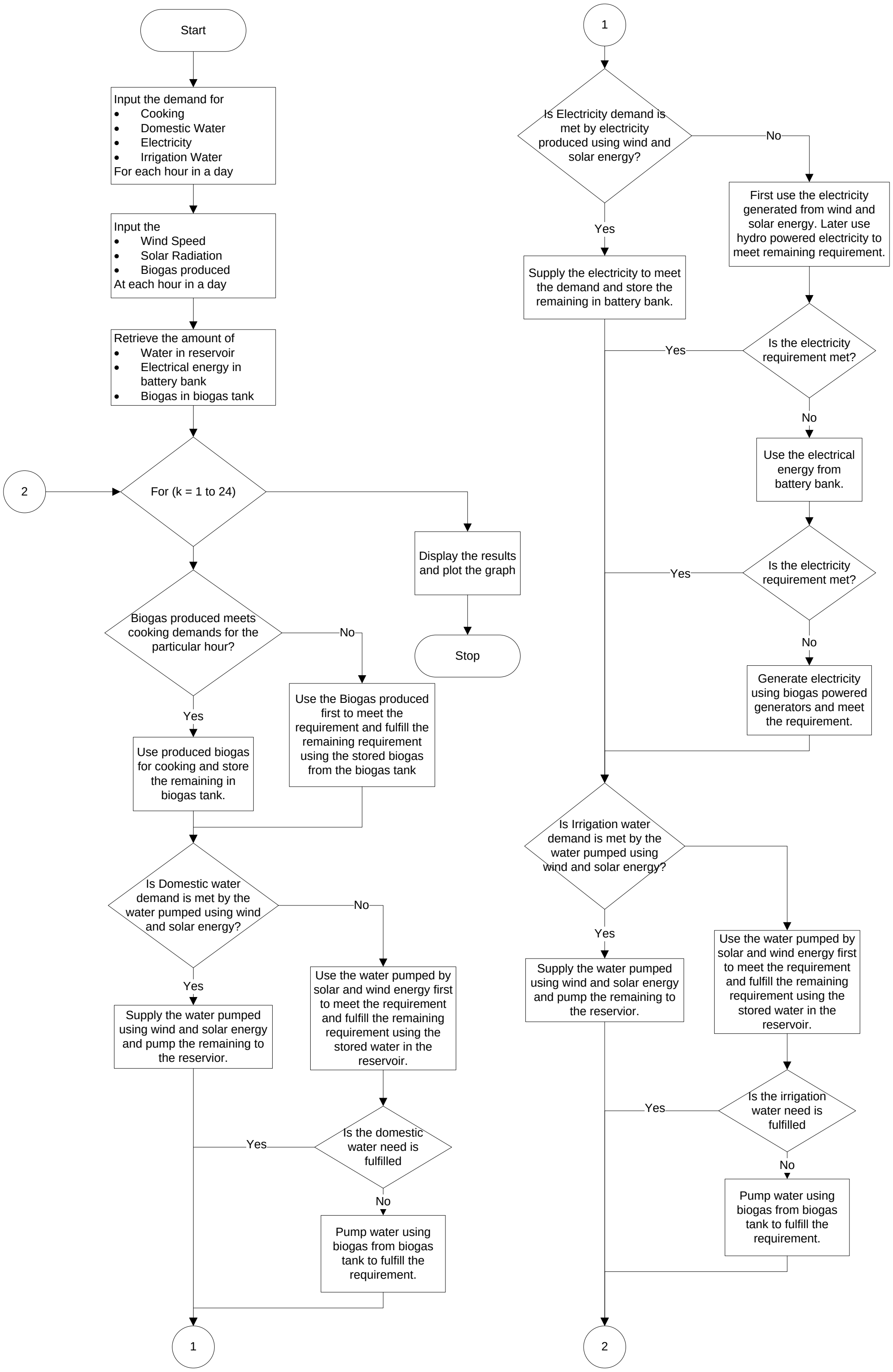


Figure V.12 Flowchart of optimization of utilization of resources

Figure V.12 shows the flowchart of the optimization of the utilization of resources in MATLAB. Figure V.13 to figure V.16 shows the optimization results. It is to be noted that the summation of cooking need, domestic water need, electrical energy need and irrigation need over a period of one day is 180m^3, 240 m^3, 1141 kWh and 4800 m^3 respectively which are equal to the earlier mentioned need values.

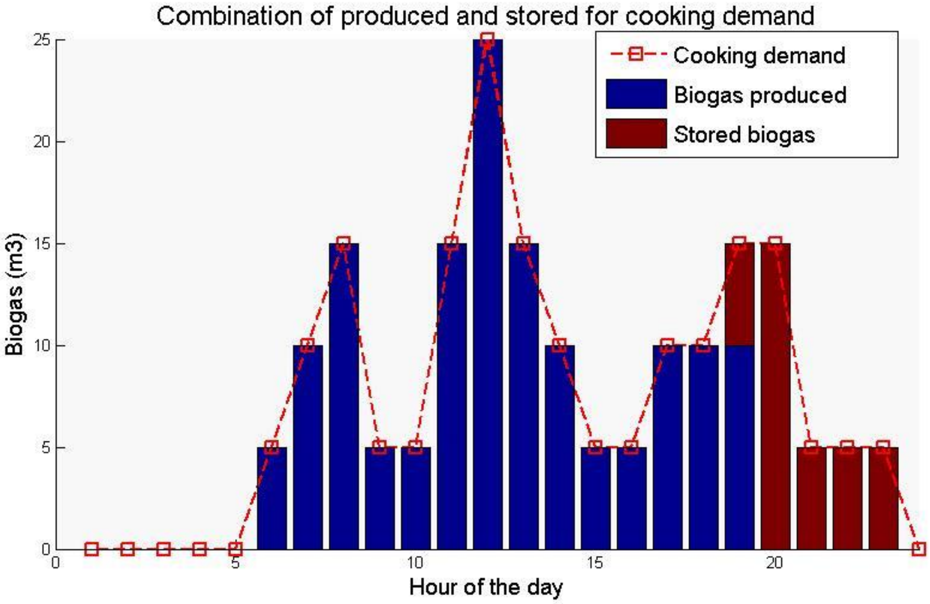


Figure V.13 Cooking demand.

At 6 am demand for biogas for cooking need begins and reaches its peak at 12 pm when the demand for biogas is high. Biogas produced at every hour fulfills most of the demand for cooking as seen in the figure V.13. At 7 pm when biogas produced is less than cooking demand, then biogas which is stored before 7 pm is used. After 7pm production of biogas stops and cooking need is fulfilled by the stored biogas.

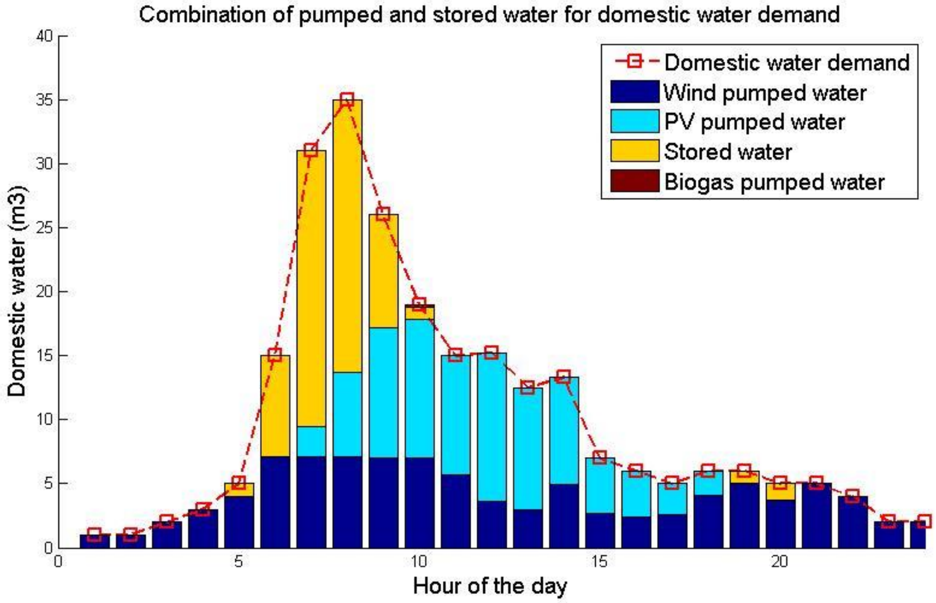


Figure V.14 Domestic water demand.

There is a need for domestic water throughout the day as seen in the figure V.14. Water used for bathing, drinking, cooking, washing vessels and clothes and toilet can be referred as domestic water. A high demand of domestic water is seen from 6 am to 9 am mainly because of bathing, washing vessels and toilet purposes. Majority of the domestic water demand can be fulfilled by wind powered pumps and PV powered pumps. Rest of the demand can be fulfilled by water stored in the reservoir. A small part of domestic water demand is fulfilled by biogas powered water pump at 10 am.

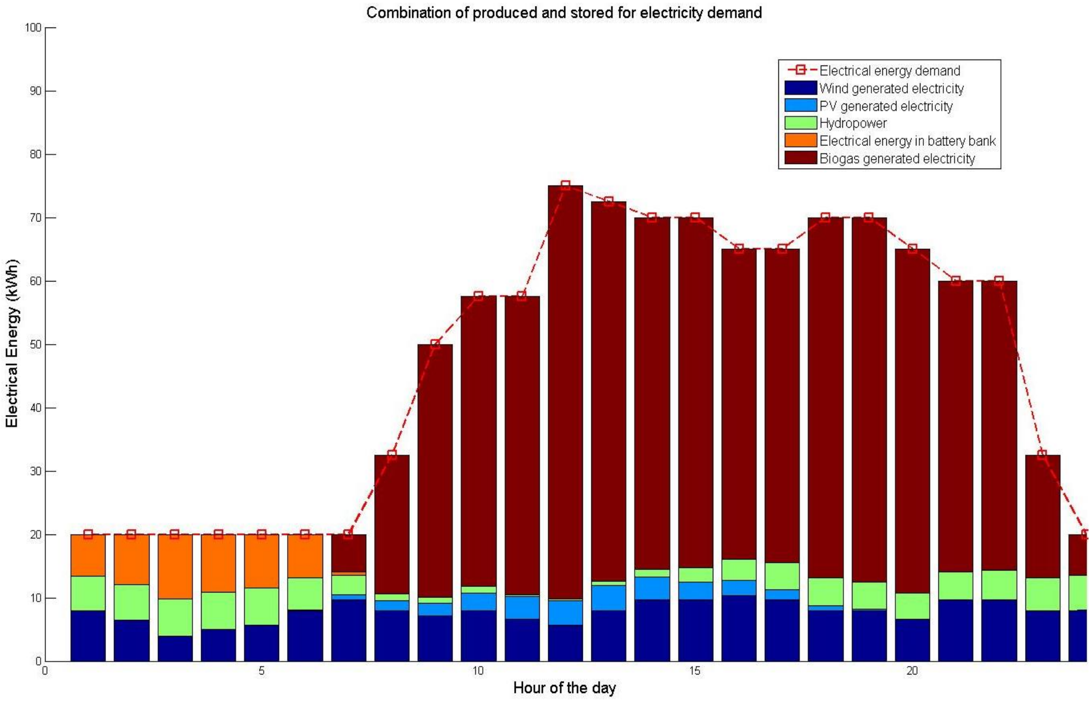


Figure V. 15 Electrical energy demand

Electrical energy demand is at peak at noon and in evening when lights are turned on. Electrical demand is fulfilled electricity generated by wind turbines, PV array, hydropower and biogas generator and electrical energy in the battery bank. Preference is first given to electricity generated by wind turbine and PV array. If demand is not fulfilled, then hydropower, electrical energy from battery bank and biogas generator is used to fulfill the electrical demand.

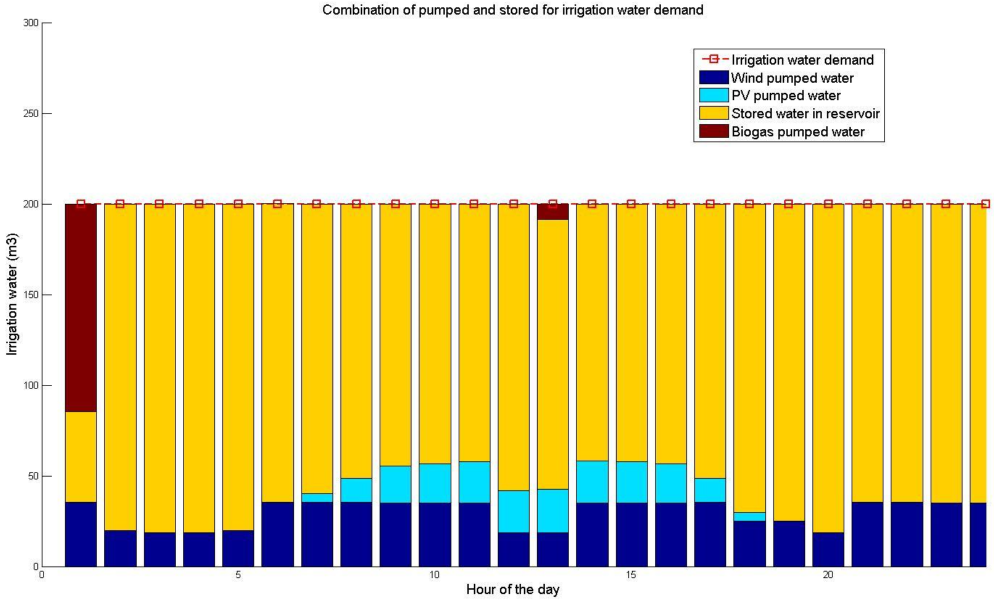


Figure V. 16 Irrigation water demand

Irrigation water demand is assumed to be constant throughout the day. The purpose of irrigation water used even in night is because water is quickly evaporated in daytime. 5 units of wind systems with pump diameter 6 inches and diameter of wind wheel 5m is considered and 20 units of PV water pumps rated at 140-volt, 640 W 6SQF-2 Grundfos PV powered water pump, must be installed to fulfill domestic and irrigation water need. At 1 am, biogas powered water pump is used to pump water for irrigation. It pumps water sufficient to fulfill the irrigation demand till noon. At noon, biogas powered water pump is again used to pump sufficient water for the rest of the day.

CHAPTER VI

SUMMARY AND CONCLUDING REMARKS

VI.1 Summary

Harnessing renewable energy resources has gained prominence in the last few decades. IRES is an effective and a viable strategy that can be employed to harness renewable energy resources to energize remote rural areas of developing countries. The resource- need matching, which is the basis for IRES, makes it possible to provide energy in an efficient and cost effective manner. Modeling and optimization of IRES for a selected study area makes IRES more advantageous when compared to hybrid concepts.

A remote rural area with a population of 700 in 120 households and 450 cattle is considered as an example for cost analysis and optimization. It is located at 36.12° N latitude and 97.06° W longitude. It has ample biogas obtained from organic waste and water resource from rivers and streams. It has adequate sunshine and medium to high wind speeds around the year.

Mathematical models for key components of IRES such as biogas generator, hydropower generator, wind turbine, PV system and battery banks are developed. A discussion of the size of water reservoir required is also presented. Modeling of IRES on the basis of need to resource and resource to need matching is pursued to help achieve optimum use of resources for the needs.

Fixed resources such as biogas and water are used in prioritized order whereas flexible resources such as wind and solar can be used simultaneously for different priorities.

Electrical components of IRES are cost optimized for electricity demand using HOMER software that is developed by the NREL (National Renewable Energy Laboratory). The optimal design yielded by HOMER is listed below

- PV array system rated at 5kW
- Wind turbine rated at 10kW AC BWC Excel S
- Hydropower generator rated at 15.5kW
- Biogas generator rated at 80 kW
- 35 units of Surrette S4KS25P battery bank rated at 1900 Ah
- Bidirectional converter rated at 35kW.

Total capital cost for optimal IRES configuration is $224,220 and operating cost is about $25.264 per year. Total net present cost (NPC) over the lifetime period is given as $547,172. The cost of electrical energy (COE) is estimated to be 10.3¢ per kWh.

HOMER optimizes configuration for electrical demand only and does not consider other demands such as biogas for cooking and water for domestic and irrigation purposes. Hence an optimization program based on the need-resource modeling (presented in chapter 4) of IRES is performed in MATLAB. Optimization of the utilization of resources for several needs is performed. 6 units of wind systems with pump diameter 6 inches and diameter of wind wheel 5m is considered and 30 units of PV water pumps rated at 140-volt, 640 W 6SQF-2 Grundfos PV powered water pump, must be installed to fulfill domestic and irrigation water need. Results obtained from MATLAB are presented in chapter 5, which clearly show that the available resources can fulfill the demand of the rural areas.

Introduction of IRES in rural communities has many socio-economic implications. It brings about improvements in living environment and community welfare by supplying the basic needs such as biogas for cooking, water for domestic and irrigation purposes and electrical energy for lighting, communication, cold storage, educational and small- scale industrial purposes. IRES is flexible in implementation and is easily adaptable. Its configuration can be modified depending on available resources and needs of the rural area under consideration. Along with social and economic improvements in the rural community, implementation of IRES can provide employment opportunities to the local people. Necessary political steps and support from society are required in order to realize the promise of sustainable development facilitated by IRES.

VI.2 Scope of future work

The biggest hurdle in implementing IRES is the fact that its design is site specific. Collection of detailed data for needs and available resources plays a crucial rule in installing IRES. Hence a comprehensive study must be undertaken in each case to make IRES viable. There is a need for further analysis and optimization of the cost of energy supplied and components of IRES. Optimization techniques such as MATLAB optimization toolbox and genetic algorithm can be used in the future to carry out detailed optimization. Modeling and optimization of power electronic components such as inverter and rectifier must be done for a complete analysis of IRES. In addition, a load flow analysis, voltage regulation, power quality, power factor, stability and unbalanced loads (in case of three phase operation) must be studied in depth to effectively energize remote and rural areas.

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APPENDICES

Hour	Wind data (m/s)	Solar data (kw/ m2)	Water pumped by wind (x43)	Water pumped by solar (x33)	Electricity demand (y3)	Domestic water demand (y25)	Biogas production (x1)	Cooking demand (y11)
1	8	0	7.1	0	20	1	0	0
2	7	0	4	0	20	1	0	0
3	5.5	0	3.7	0	20	2	0	0
4	6	0	3.7	0	20	3	0	0
5	6.5	0	4	0	20	5	10	0
6	8	0.02	7.1	0	20	15	20	5
7	9	0.2	7.1	2.4	20	31	30	10
8	8	0.4	7.1	6.6	32.5	35	20	15
9	7.5	0.5	7	10.2	50	26	20	5
10	8	0.7	7	10.8	57.5	19	25	5
11	7	0.9	7	11.4	57.5	15	30	15
12	6.5	0.95	3.7	11.7	75	15.2	25	25
13	8	1	3.7	12	72.5	12.5	20	15
14	9	0.9	7	11.7	70	13.3	15	10
15	9	0.7	7	11.5	70	7	15	5
16	9.5	0.6	7	10.8	65	6	10	5
17	9	0.4	7.1	6.6	65	5	20	10
18	8	0.2	5	2.4	70	6	10	10
19	8	0.05	5	0	70	6	10	15
20	7	0	3.7	0	65	5	0	15
21	9	0	7.1	0	60	5	0	5
22	9	0	7.1	0	60	4	0	5
23	8	0	7	0	32.5	2	0	5
24	8	0	7	0	20	2	0	0

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