MODELING OF AN INTEGRATED RENEWABLE ENERGY SYSTEM (IRES) WITH HYDROGEN STORAGE

By

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MODELING OF AN INTEGRATED RENEWABLE ENERGY SYSTEM (IRES) WITH HYDROGEN STORAGE

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NOMENCLATURE

BI   Energy from biogas (kWh)

SC   Energy from solar thermal (kWh)

WECS   Energy from wind (kWh)

PV   Energy from PV panels (kWh)

MGH   Medium-grade heat requirements (kWh)

LGH   Low-grade heat requirements (kWh)

ELinit   Initial Electrical load (kWh)

EL   Total electrical load (kWh)

MGHBI   Medium-grade heat requirements met by biogas (kWh)

MGHEL   Medium-grade heat requirements added to electrical load (kWh)

LGHSC Low-grade heat requirements met by solar thermal energy (kWh)

LGHBI   Low-grade heat requirements met by leftover biogas (kWh)

LGHEL   Low-grade heat requirements added to electrical load (kWh)

ELWECSPV   Total electrical load met by energy from wind and PV panels (kWh)

ELFC   Total electrical load met by fuel cell energy (kWh)

ELunmet   Total electrical load that is unmet (kWh)

CHAPTER I

INTRODUCTION

1.1 Current Energy Scenarios

Today, most of the economies throughout the world reap the benefits of globalization and industrialization, and this has only led to a dramatic worldwide increase in total energy usage. Our extensive dependence on fossil fuels has taken a huge toll on the limited reserves of these energy resources and has also given rise to a number of environmental concerns. Developing countries have adopted fossil-fuel-driven energy models prevailing in industrialized countries only because fossil fuels enable faster economic growth and make modern lifestyles possible. However, the developed economies still remain the major contributor to the current CO_2 emission levels as a result of their high per-capita energy use. Also, the fact remains that the energy consumption patterns among the entire human population are highly uneven and consist of vast disparities between the rich and poor countries. Less than 25% of the world's population accounts for more than three quarters of the total energy usage and the number of people without access to electricity is about 22% of the world's population or about 1.4 billion people.

Fossil fuels still remain the dominant sources of energy worldwide and the certainty that they will progressively become scarcer and definitely more expensive as time goes by, has become an undisputable and well established trend. Given the current trends, our demand for fossil fuels is only going to increase further in the coming years (Figure 1.1). It is expected that by 2050, the

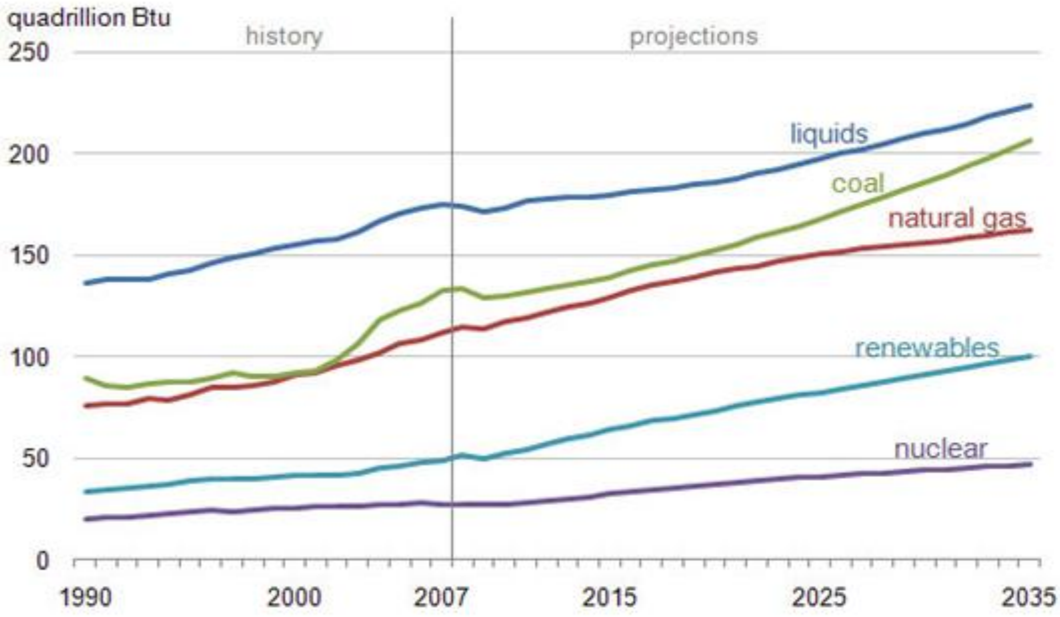


Figure 1.1 World marketed energy use by fuel type [1]

world population would saturate at around 9 billion people and such a population increase would only aggravate the problem of energy consumption further. As the cost of energy goes on increasing, our current reliance on oil, gas and coal requires replacement almost entirely by sustainable sources and technologies at some time in the not-too-distant future. This would definitely be an extraordinarily complex problem that would consume our efforts for next 40-50 years.

1.2 Energy Crisis and the core development challenge

Energy use is a fundamental aspect of human existence: it provides access to basic human needs such as food and water and it facilitates attainment of decent quality of life. The sun is the primary source of energy for life on earth and, through the ages, mankind has often found new methods and techniques to extract this energy of the sun. With the discovery of fire came the earliest forms of energy usage in the form of direct burning of firewood. The beginning of the industrial revolution in the eighteenth century was energized by mechanical wind mills and water

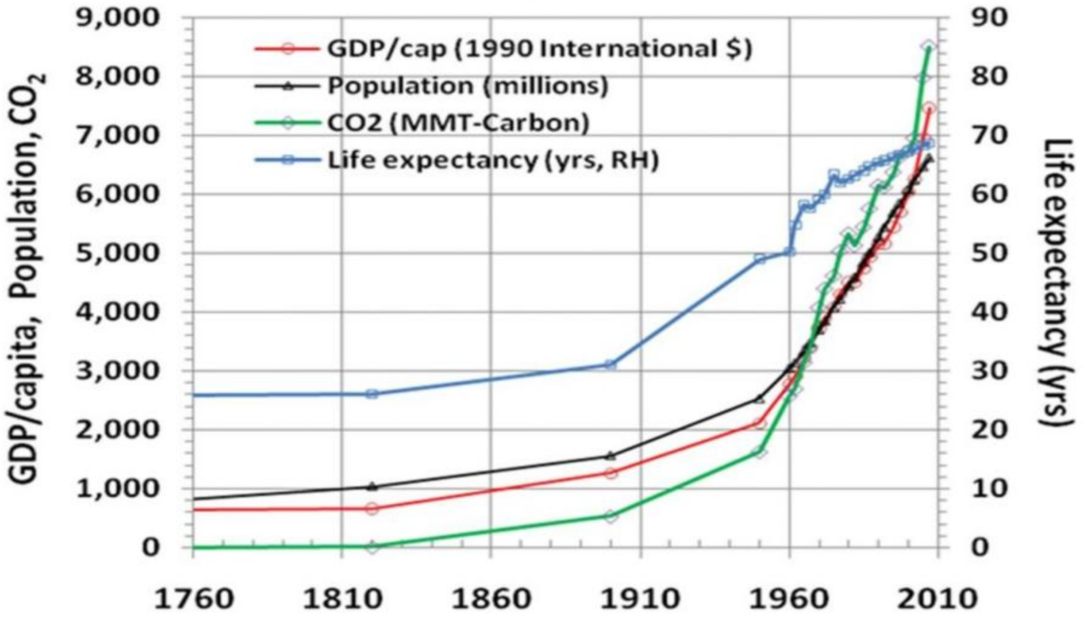


Figure 1.2 Global Population, Affluence, CO_2 emissions, and Life Expectancy, 1750–2007. Sources: Maddison (2010), CDIAC (2009), World Bank (2010)

wheels which were later followed by steam operated engines. The last century witnessed heavy dependence on coal, oil and natural gas which are concentrated forms of solar energy that has been stored for over 500 million years. As population and the pace of economic development increased, so did the consumption of these energy resources.

Figure 1.2 shows global trends from 1760 onward for population, affluence (GDP per capita), CO_2 emissions, and life expectancy (an indicator of human well-being). As illustrated in the figure, all the four indicators show exponentially increasing trends since the eighteenth century. As a direct benefit of increased economic activity, life expectancy more than doubled from 26 years to 69 years from the year 1760 to present day, although CO_2 emission levels increased by a factor of over 2000 during the same period. Figure 1.2 simply highlights the fact that there exists a strong correlation between the ever-increasing human population, its energy dependence and the environment as a whole.

Today, majority of the global population lives in developing countries, most of which are geographically concentrated in Latin America, Africa and southern Asia extending from 30° North to 30° South around the equator. The developing countries consist of densely populated regions and are characterized by slow moving economies that are heavily dependent on agriculture. In their efforts to attain improved standards of living and to catch up with the pace of economic development of the West, most developing countries have followed the energy production and consumption patterns set by some advanced industrialized nations. The developing nations maintain an opinion that the developed economies are driven by over-consumption and wasteful utilization of energy, while the developed nations accuse the developing nations of destroying the environment by over-population. The fact that both the opinions are right poses an immensely complex challenge to the developing world and the industrialized world that has no immediate solution.

The key drivers for change and transformation in the developing world are poverty eradication, education, environmental protection and sustained economic growth. Access to clean modern energy and water is a prerequisite to achieve these developmental goals. For a vast majority of people in developing countries, traditional biomass in the form of firewood, charcoal, harvest residues and animal wastes are the primary sources of energy. The direct burning of biomass is a major cause of health hazards among the people in rural areas and further, it’s unsustainable and poor use leads to environmental concerns such as deforestation and air pollution. Moreover, as said earlier, most developing nations resort to heavy imports of coal and oil to sustain rapid industrialization and economic growth. Undoubtedly, the bulk of climate change in the last 50 years is attributable to human activities that are related to fossil energy usage. The most recent statistics from IEA indicate that for the first time CO_2 emissions from developing countries (Non-annex I) surpassed those of the developed countries (Annex I). As shown in Figure 1.3, the CO_2 emissions in developing countries rose by almost 6% in 2008.

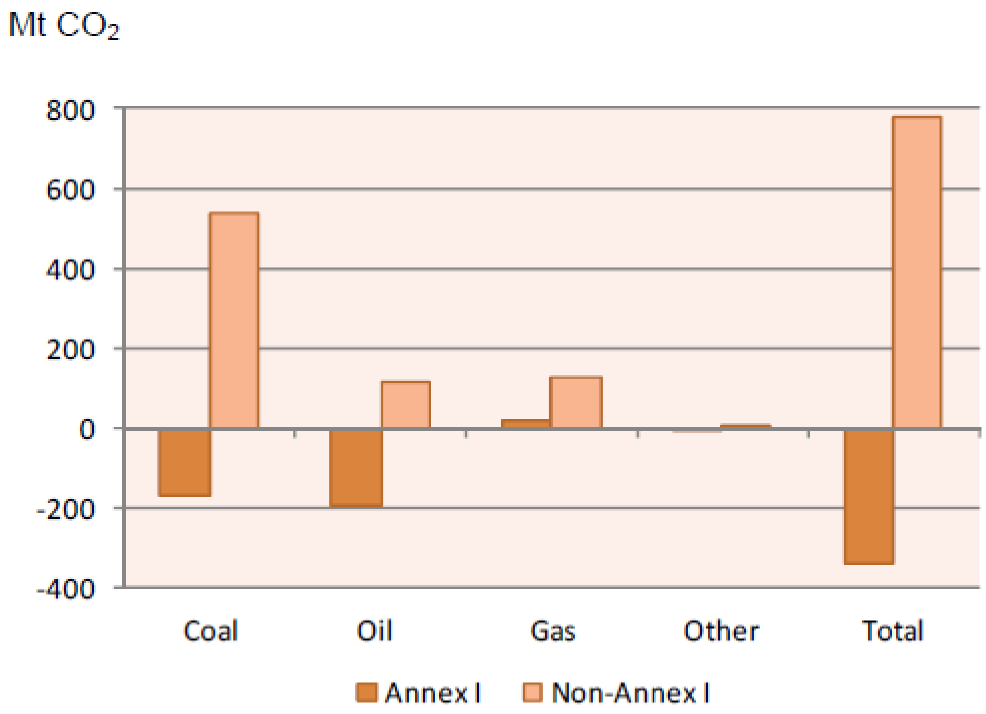


Figure 1.3 Global change in CO_2 emissions (2007-2008) [2]

We do need to realize that climate change would severely affect vital sectors such as agriculture, tourism and health, all of which form the economic life-blood of most developing nations. Moreover, conventional energy systems adopted by these countries are prone to risks related to price volatility, socio-political instability and technical failures. Rapidly deteriorating infrastructures and lack of basic amenities in rural areas are leading to mass migration of people to large urban areas that ultimately become marred by problems of high population densities, rapid rise of slums and inefficient sanitation leading to epidemics and various other health hazards. Expanding access to modern energy for the world's poor and a rapid transformation of energy efficiency remain a pressing matter that requires immediate collective action on the part of all countries.

The challenge of meeting this energy crisis may seem daunting and indeed, it is. In regards to this challenge, today the entire humankind as a whole needs to answer the following key questions that have local, national and global implications:

-Will the poor countries of the world be able to achieve sustainable growth without destabilizing social and environmental balance?

-Are the current patterns of economic growth based on fossil fuel consumption sustainable and if yes, then for how long?

-Can rural populations overcome poverty and improve their living environment through migration to large urban areas?

-Can the rapidly growing cities of developing countries be the engines of change and transformation as sought by those millions who still do not have access to basic amenities of food and health?

-Can our creativity and intelligence enable us to find ways and means for a more sustainable and uniform human development?

All the above questions are difficult to be answered, but are no less important. Later sections of this thesis make a sincere effort in identifying an approach and process that would generate more dialogue and creativity in finding answers to the above questions.

1.3 Renewable Energy: A Possible Solution

Today, humanity as a whole faces the greatest challenge of meeting its ever-increasing energy demands in a sustainable manner. More and more use of fossil fuels can accelerate the pace of economic development but definitely, this is not a sustainable solution to the energy problem on hand. Moreover, the option of extending electric grids to remote rural areas involves significant capital investments that cannot be justified in most of the cases. Given the low load factors and low income levels among the people in rural areas, the promise of grid electricity for all simply cannot be delivered. In developing countries, the priority of grid electricity should be for more productive purposes such as industry, business, health and communications rather than for electrification of individual rural homes. However, this would also require a significant increase in conventional generation capacities along with the addition of more nuclear energy. Generally, nuclear energy has a bad press because of the risks involved in operating a nuclear plant and moreover, the fuel required for nuclear power plants is an element from the Earth's crust that is in limited supply. Certainly, the practicability of nuclear energy is limited by fuel availability and technical, security, economic and ethical considerations. Thus, the option of harnessing nuclear energy would have limited justification in the developing world and is definitely not a long term solution to the problem of rural energization. Such models based on centralized generating systems, transmission and distribution grids and conventional energy resources would often rapidly reach their limits and would only deteriorate the global energy scenario further.

However, sincere attempts to deal with these energy problems have sparked off a great deal of interest in renewable sources of energy- a readily available solution. They are non-polluting, inexhaustible and operate in stable harmony with the Earth's ecological systems. As a result, vast amount of research and development has been carried out in technologies involving renewable sources of energy, especially wind, biomass and solar. Hybrid and integrated technologies consisting of more than one form of renewable energy are fast becoming popular in both grid connected and off-grid/stand alone remote applications. Moreover, renewable energy resources are fairly and evenly distributed around the world (democratic) unlike coal, oil and natural gas. Most of the countries show a huge potential for untapped reserves of renewable energy resources and it is possible to harness this energy with the costs of off-grid technologies having come down significantly over the last few years. The rapid advancements of renewable energy technologies in the industrialized world can be combined with the vast potential of renewable energy resources in order to build up local capacities in developing countries. Renewable energies can reduce the pressure on fossil fuels and they could play an important role in realizing sustainable development for the entire planet.

1.4 Objective of the study

As discussed earlier, the task of meeting the growing energy needs of the ever-increasing global population has posed significant challenges on the entire humanity as a whole for decades. Today, most of the nations have fossil-fuel driven economies only because fossil fuels enable faster economic growth and make modern lifestyles possible. Definitely, this is not a sustainable option given the fact that fossil fuel reserves are limited and their heavy usage does take a huge toll on our environment. This study would present the concept of Integrated Renewable Energy Systems (IRES) as a means to harness renewable energy resources to cater to the energy needs of those millions in remote rural areas of developing countries who still do not have access to the basic amenities of health, water and education. Using the concept of IRES, it is possible to employ village energy centers in order to achieve sustainable development in a cost effective manner. A case study at the end of the study discusses the employment of IRES with hydrogen storage for a hypothetical remote rural community.

1.5 Organization of the thesis

This section provides a brief overview of the various topics discussed in the chapters that follow:

Chapter II: *Review of Literature*

This chapter evaluates the current status and potential of various renewable energy resources and also provides an insight into different types of approaches that can be adopted to harness renewable energy resources.

Chapter III: *Integrated Renewable Energy Systems (IRES)*

This chapter introduces the reader to the concept of integrated renewable energy systems in greater detail, thereby highlighting its various features, renewable energy technologies and different types of energy needs. This section also summarizes the current status of rural renewable energy generation.

Chapter IV: *Energy Storage Options for IRES*

This chapter identifies the various energy storage options that can be incorporated in IRES design process. The importance of hydrogen as an energy carrier of the future, is discussed in greater detail along with modeling of hydrogen storage technology for IRES.

Chapter V: *Case Study of a Hypothetical Remote Community*

This chapter presents a case study for implementation of IRES in a hypothetical remote community and discusses the simulation results thus obtained.

Chapter VI: *Summary and Concluding Remarks*

This chapter documents the concluding remarks and scope for future work.

CHAPTER II

REVIEW OF LITERATURE

2.1 Renewable Energy Resources: Current Status and Potential

Renewable energy resources can be defined as energy resources that are replaced periodically by natural processes and are practically inexhaustible so that their reserves are not depleted when used. Renewable energy is also called as clean energy or green energy because it does not pollute the environment in the manner that non-renewable energy resources do. All forms of renewable energies are derived directly or indirectly from sun’s energy and hence, renewable energy can be termed as infinite energy [3]. The sun’s energy has been the primary energy source for all life forms on earth. The process of photosynthesis which forms the fundamental life process in plants is energised by solar energy and plants form the basis of all biomass and organic material. Wind is the movement of air masses over the surface of the Earth resulting from uneven solar heating of the atmosphere that creates unequal air pressure distributions. The sun’s energy also drives the ocean currents in the form of waves and tides. Moreover, solar energy brings about the evaporation cycle to lift moisture in to the atmosphere to form rain clouds which are transported by winds and rains ultimately bring fresh water to plants and animals and add to the flowing waters of rivers, lakes and oceans. Thus, the replenishing source of hydropower is solar energy. Such natural resources based on solar energy are more evenly spread over the world and are freely available to all. However, capital costs of technologies and the space requirements to harness them in useful forms often pose barriers in realizing the full potential of these energy forms. The following sections provide brief overviews of the potential contributions of various forms of renewable energy towards energy sustainability.

2.1.1 Wind energy

Wind energy has shown rapid development and has become cost competitive with conventional energies over the last few years. The power density of a 40 kmph wind sweeeping through a square metre of intercepted area is almost equal to the power density of the bright sun (1000 watts/m^2). Small differences in wind speeds make huge differences in amount of energy that can be extracted, because the energy contained in wind increases as the cube of wind speed. Most of the developing countires show a great potential for very good wind sites that have still not been assessed. The current worldwide wind power capacity has exceeded 150,000 MW as shown in Figure 2.1. Presently, a little over 2% of the world's electrcity demand is met by wind energy. Individual nameplate ratings of the wind turbines have been steadily increasing and there has been a trend towards bigger turbines across all markets. Within last three decades, the mean rated capacities have grown from 30 kW to 3 MW, with 5 MW units in the offing. Improvements in wind turbine technologies that operate more efficiently in lower wind regimes and the siting of

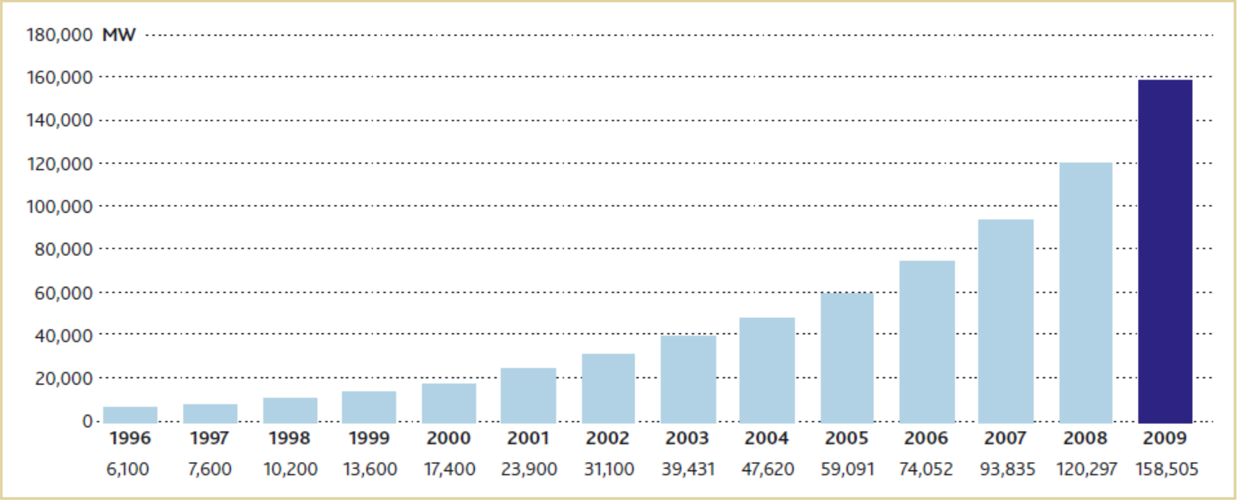


Figure 2.1 Wind power worldwide [4]

wind farms will help achieve capacity factors in excess of 25%. Winds over oceans are stronger and more constant, thereby resulting in higher capacity factors. As a result, the growing size of offshore wind installations would increase the average capacity factors throughout the world. Moreover, the fact that wind development has a small footprint and is fully compatible with farming and ranching activities has given rise to a range of new economic opportunites for rural economies. Wind turbines may displace less than 5% of the farmland, however these losses are greatly offset by economic benefits accruing to the land owner. Given these trends and the current growth rates, a goal of almost 10-12% of the world's electricity generation from wind power appears to be well within reach.

2.1.2 Bioenergy

Bioenergy is an important energy source for majority of the population in developing countries and it is presently the largest global contributor of renewable energy. However, it is primarily being harnessed in an environmentally unsustainable way that is detrimental to health. As shown in figure 2.2, biomass represents 10% of global annual primary energy consumption and this is mostly traditional biomass used for cooking and heating. This traditional use of biomass is bound to grow with increasing population, however there is a significant scope to improve the efficiences of biomass consumption patterns and make them environmental friendly. The current bioenergy resource potential is significantly greater than its present use and this potential can be further utilized in production of heat, electricity and fuels for transport. In industrialised countries, the contribution of biomass to the total primary energy usage is less than 3%. The efforts of various countries to increase their biomass usage had led to the deployment of community level combined heat and power (CHP) generation and dedicated electricity plants mainly confined to low cost feedstocks invovled in small scale applications such as use of biogas and waste treatment [5, 6]. In CHP applications, energy conversion efficiences are highly enhanced when top grade heat from biomass combustion is used for electricity production and

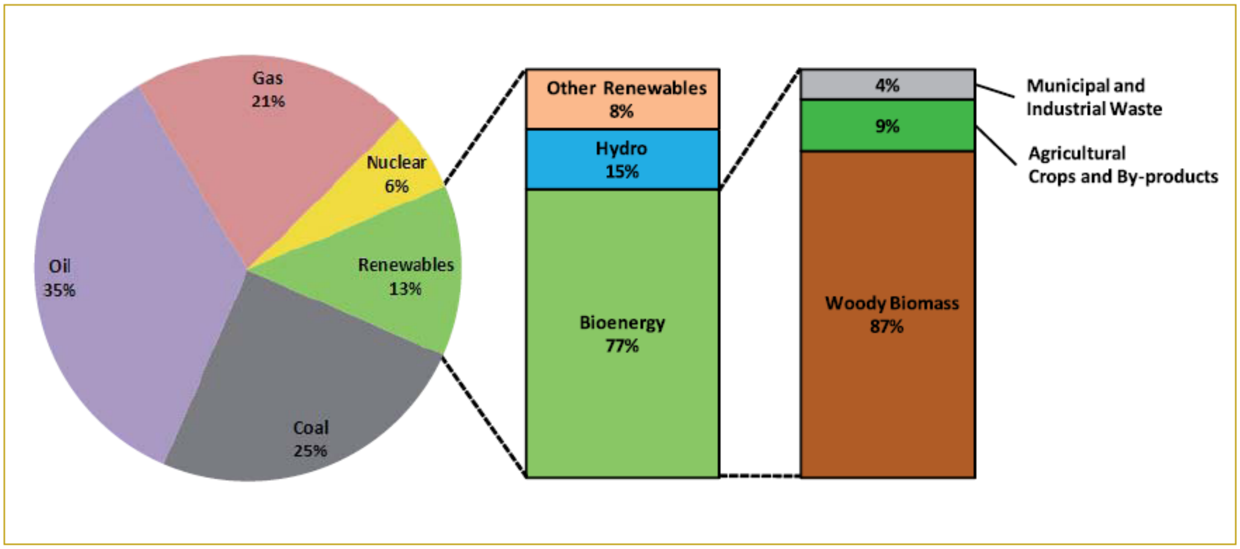


Figure 2.2 Share of Bioenergy in world primary energy mix. (Source: based on IEA 2006 and IPCC 2007)

low grade heat is used for thermal applications such as space heating. Analysis has shown that biomass combustion emits lesser green house gases as compared to combustion of fossil fuels. As a result, it is possible to mix biomass with coal to reduce environmental byproducts emitted by coal-fired plants. Attempts are made to meet the renewable energy targets through biomass usage in the form of conventional crops, after careful consideration of land availability and food demand. Global trades involving biomass feedstock and processed bioenergy carriers such as vegetable oils, ethanol, wood chips, agricultural residues etc., are showing increasing trends. Biomass can certainly make a substantial contribution to meet future energy demands of the increasing population in a sustainable way.

2.1.3 Hydropower

Hydropower is currently being utilised in some 150 countires with about 45,000 large dams being built worldwide for electricity generation. International Hydropower Association (IHA) estimates the total hydropower installed capacity to be about 860 GW (Figure 2.3 shows a regional breakdown of total installed capacity). Hydropower generates about one-fifth of the world's

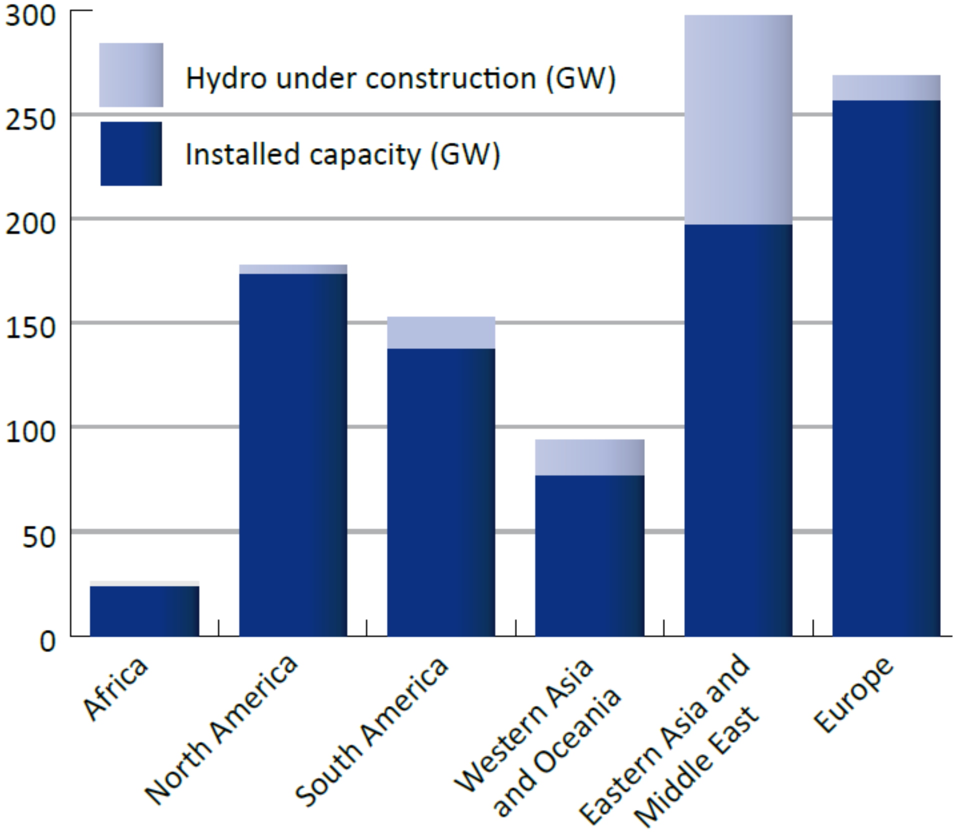


Figure 2.3 Total installed capacity (Hydro) by region (Source: IHA 2010 Activity Report)

electricty and is second only to fossil-generated electricity (coal, oil and gas). It is a mature and well advanced technology, with modern hydro power plants providing the most efficient energy conversion process as compared to other major types of power plants. The ability of hydroelectric plants to respond almost instantaneously to changing electricity demand makes them suitable for peak load applications. Moreover, they have the lowest operating costs and longest plant life as comapred to other large scale generation options. Some of the oldest hydropower plants are more than 100 years old and are still going strong. Hydropower resources are widely spread around the world, although much of the untapped potential hydropower is in developing countries. During the twentieth century, the industrialised nations developed much of their hydro power potential which accelerated their pace of economic development and contributed to their high levels of prosperity.

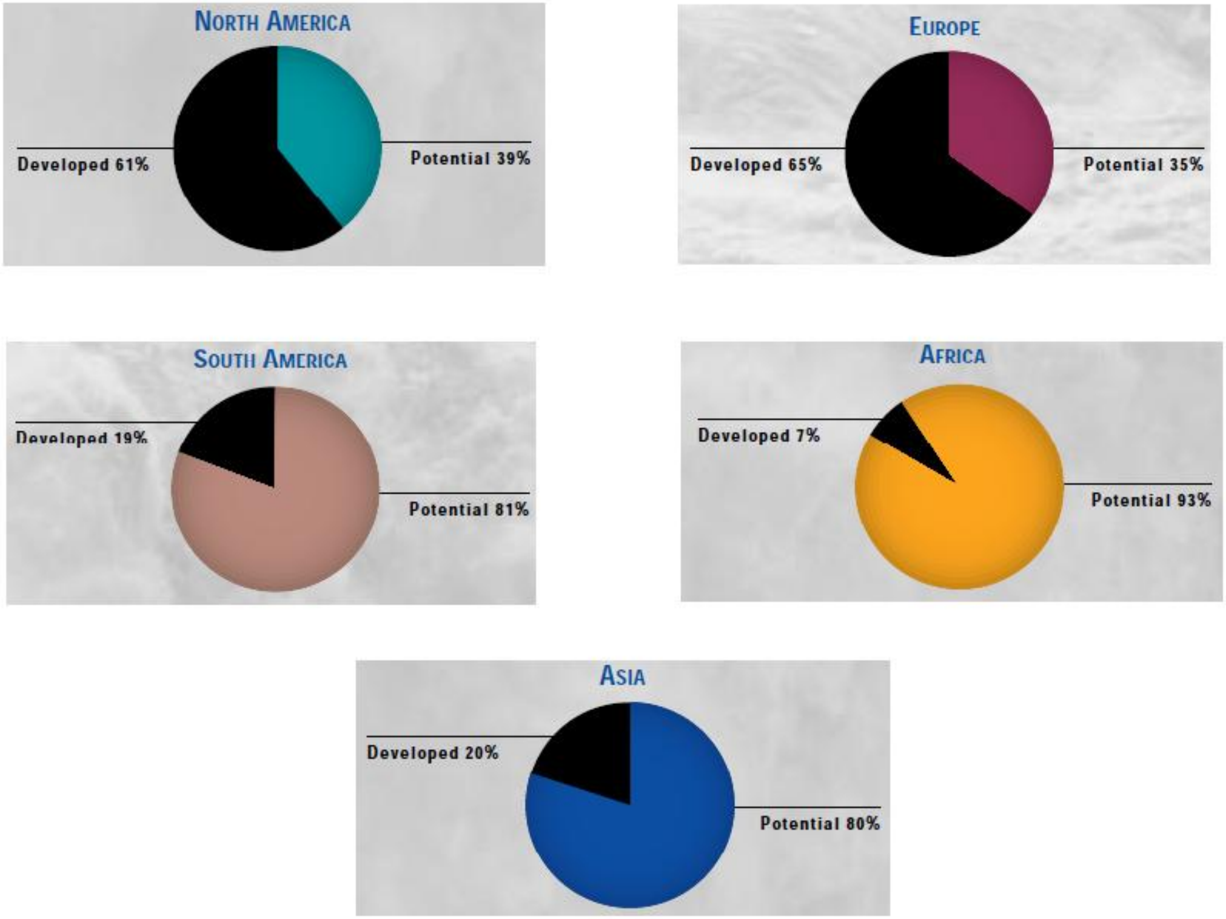


Figure 2.4 Hydropower potential in the developed and developing world [7]

As the pie charts in Figure 2.4 indicate, Europe and North America have already developed more than 60% of their hydropower potential while the emerging economies in Asia, South America and Africa still have vast reserves of untapped hydropower. Hydropower can be classified into three basic types:

-'Run of river' where power is generated through the daily flow of river

-'Reservoir' where power is generated through release of stored water

-'Pumped storage' where stored water used for power generation is recycled

Most hydropower projects were built to provide base load to the power system. However, the costs associated with shutting down thermal energy options resulted in them being kept running through periods of low demand. As a result, the concept of pumped storage has gained importance wherein energy is stored for use in periods of high demand by pumping water from a lower resevoir to an upper reservoir during off-peak periods. Currently, the worldwide total installed capacity for pumped storage is about 127 to 150 GW [7] and a significant portion of hydroelectric capacity would be further added to this in years to come. Moreover, it is possible to build tailor-made small, mini and micro hydropower projects that can become the best means for developing nations to improve access to electricity and improve living standards without incurring heavy environmental losses. As countries try to mitigate their greenhouse gas emissions, hydropower can perhaps provide the best solution since hydroelectric plants emit minimal amounts of air pollutants. The world's remaining hydroelectric potential needs to be considered in the energy mix of the future and this could assist the path of sustainable development.

2.1.4 Solar energy

Solar energy is a form of energy that can be considered to be practically unlimited in the long-term and is a very abundant resource globally. The fact that indirect uses of solar energy such as wind, hydropower and bioenergy are major contributors to renewable energy simply cannot undermine the potential of direct applications of radiant solar energy [8]. Solar energy can be directly used to heat or light buildings and to provide domestic hot water to meet basic thermal requirements of all households. The sun's radiant energy can also be used to produce industrial-grade heat that may be utilized to generate electricity employing conventional thermal-electric generators or to run heat engines. It can be used for cooking purposes, thus displacing the traditional methods of biomass utilization that lead to environmental concerns. It can be used to power water pumps in irrigation systems, to detoxify contaminated waters thereby addressing the

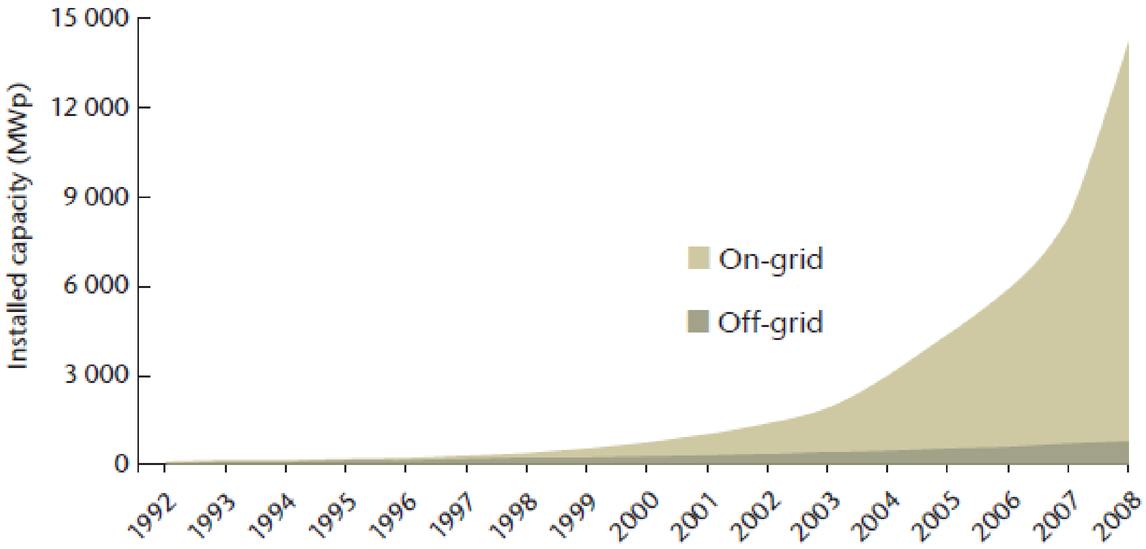


Figure 2.5 Cumulative installed global PV capacity [9]

issue of clean water and to refrigerate food and medicines for the populations that still have no access to electricity. Solar photovoltaics (PV) technology generates electricity through the direct conversion of sunlight. As shown in figure 2.5, grid-connected application is the fastest growing sector of photovoltaics. As a result of improvement in technology and decreasing costs of PV modules, the PV market worldwide has grown aggressively over the past decade with an annual average growth rate of 40%. Another direct application of solar energy is for solar heating and cooling technology (SHC) that uses the thermal energy directly from the sun to heat or cool domestic water or building spaces. In large markets, such as the United States and Australia, the major application of solar thermal energy is in the form of unglazed plastic absorbers for swimming pool heating. The solar thermal collector capacity in operation worldwide equaled 151.7 GW corresponding to 217 million square meters by the end of year 2008 (Source: Solar Heat Worldwide 2008). Advanced solar technologies, such as concentrating solar power systems (CSP) that use concentrated solar energy as a high temperature energy source to produce electrical power and drive chemical reactions, are fast gaining momentum. CSP technology produces cheaper centralized power than PV systems and is suitable for combined heat and power generation wherein supplementary power can be provided by gas or, preferably, by any other renewable energy. It is this diversity of opportunities that makes direct end-use and distributed utility applications of the sun’s energy an attractive option to solve the energy problems of the future.

2.1.5 Geothermal energy

Geothermal energy is a major global renewable energy resource with its most primitive usage being in the form of humans enjoying the benefits of natural hot springs for thousands of years. The main sources of geothermal energy are the heat flow from earth’s core and mantle and the decay of radioactive isotopes in the earths’ continental crust. The world’s geothermal heat resources are large but they are limited to only those areas that have access to this resource. Geothermal energy can be used both directly, as a source of heat and for electrical power generation. . Underground heat below 100 °C has a diverse range of end-use applications such as space heating (ground-source heat pump), domestic water and pool heating, agricultural drying, greenhouse heating, industrial uses, cooling/snow melting and a number of other small uses, while high temperature heat can be used for electricity generation. There are many other ways of utilizing geothermal energy for power generation and direct heat use, such as:

-binary generation utilizing hot water discharged from conventional plants and that available from low temperature geothermal resources

-geothermal energy potential within drilling depths of 3-10 km can be harnessed using enhanced geothermal systems technology

-hot water produced from oil and gas wells

-hot water present in deep sedimentary basins and off-shore locations along submarine rifts

-mature heat pump technology can be used for near surface applications of geothermal energy, thereby utilizing the ubiquitous shallow geothermal resources that are available almost anywhere on the earth's surface

Currently, more than 60 nations use geothermal energy with almost 24 among them producing electricity from geothermal resources. The total geothermal installed capacity in the world exceeds 10,400 MW with an estimate for worldwide geothermal energy generation of about 57,957 GWh/yr [10].

However, most of the technologies used to develop geothermal resources are evolving, extending capabilities and reducing costs so as to increase the technical and economic potential of these resources.

Nevertheless, even in areas with moderate amounts of geothermal resources, combining with bioenergy, can help balance a portfolio that includes large amounts of intermittent resources such as sun and wind. Clearly, the potential of geothermal resources to make a considerable contribution towards meeting world's current and future energy needs along with reduced future emissions and mitigation of climate change is promising.

2.2 Approaches to harness renewable energy

Various topologies and techniques can be used to harness renewable energy resources [11]. The renewable energy system configuration depends on the type of end-use application, energy conversion efficiencies and the capital costs involved in implementing the technology. A few basic approaches as far as utilization of renewable energy is concerned are discussed next.

2.2.1 One resource and one technology

One resource and one technology can be used to generate one form of energy to meet all the energy needs. Typical examples would be [12-15]:

-solar home system consisting of a PV array and a lead acid battery with charge controller supplying energy to individual household appliances

-stand-alone wind energy conversion systems

-solar thermal energy used for water heating

-biogas plant supplying energy for cooking

2.2.2 Hybrid systems

One of the main problems with solar and wind energy is their intermittent nature and the resulting discontinuity in delivery of power. Such problems can be mitigated by the use of hybrid technologies that involve utilization of more than one energy resource and converting all of them into a single energy form, typically electricity [16-23]. A few examples would be wind/PV electric systems, wind/diesel generator system, Wind/PV/Hydro system, PV/Wind/Biogas system etc. Figure 2.6 shows a typical hybrid system consisting of PV, wind and a diesel genset. A typical hybrid energy system for application in developing countries would consist of:

-a primary source of energy, typically a renewable energy resource

-a secondary source of energy for supplying power in case of shortages, i.e. a diesel genset

-a storage system for a stable power output, i.e. battery system

-a charge controller to regulate the current through the battery

2.2.3 Integrated Renewable Energy Systems

The two approaches stated above concentrate on just one final form of energy i.e. electricity and thus, fail to realize the value and significance of non-electricity producing renewable energy technologies. The third approach would be an implementation of an Integrated Renewable Energy

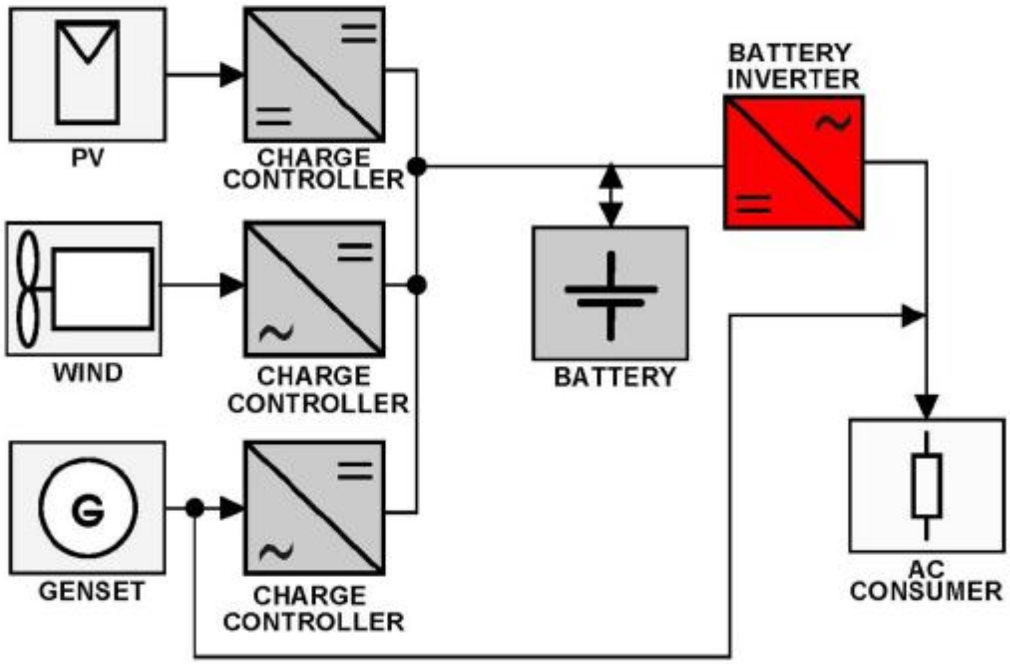


Figure 2.6 Hybrid Energy System

system (IRES) based on the fact that different types of energy needs require different forms and qualities of energy, unlike the first two approaches [24]. This concept of integrated approach involves the task of matching the energy needs and the available renewable energy resources a-priori so as to maximize end-use efficiencies of various energy conversion techniques and minimize cost. For example, biogas can be directly used for cooking instead of first converting it to electricity and then using it in electric stoves. Figure 2.7 shows one possible schematic representation of IRES employing multiple energy resources and multiple energy conversion techniques, which may vary depending on the energy needs and the availability of energy resources at a particular site. Thus, IRES has the potential to aggregate benefits resulting from the combination of renewable energy, energy efficiency and energy conservation.

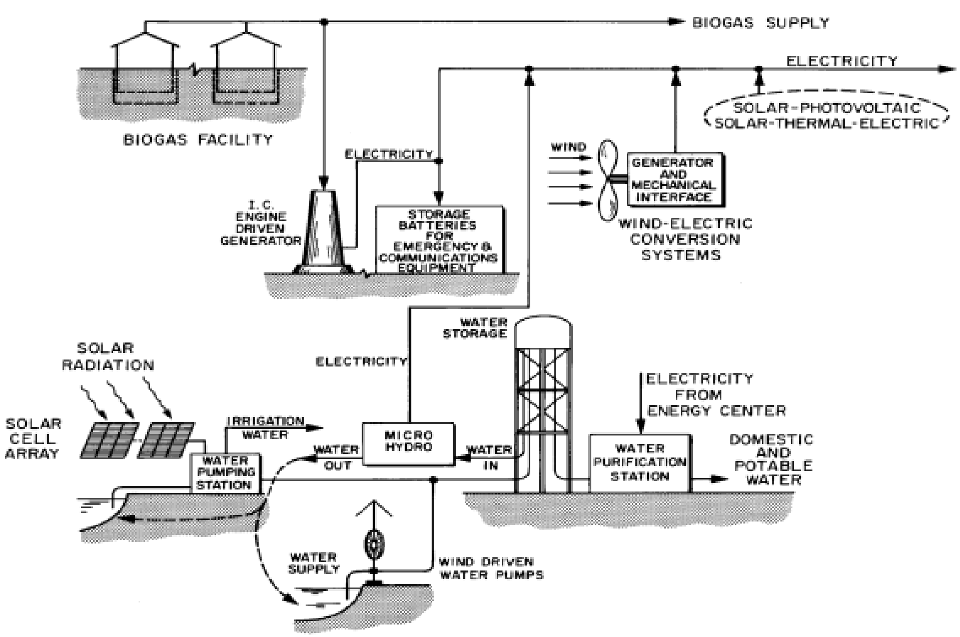


Figure 2.7 Schematic representation of IRES [24, 25]

CHAPTER III

INTEGRATED RENEWABLE ENERGY SYSTEMS (IRES)

3.1 Features of IRES

IRES involves harnessing a variety of locally available renewable energy resources and hence is more economical as compared to the option of grid extension to the rural communities. The IRES approach is based on the fact that some technologies are more efficient than others for supplying different forms of energy needs. The best application of IRES is its employment to “energize” remote rural areas in order to achieve sustainable development and improve quality of life for the people. Given the set of energy needs of the rural population and the available energy resources in the region, the concept of IRES involves matching energy needs with the available resources and technologies to maximize end-use efficiencies at minimum cost. Using this concept, it is possible to employ decentralized approach of establishing local mini-grid systems or village energy centers that involve technologies for utilization of multiple renewable energy resources. Such decentralized approaches can become competitive due to lower investments and maintenance costs as compared to grid electrification of remote rural areas.

As seen already, most of the hybrid energy systems concentrate on just one final form of energy and that is typically electricity. It is only for this reason that such systems make extensive use of diesel-power generating sets (diesel gensets) that act as a backup in case the energy generated from renewable energy resources falls short of the demand. However, non-continuous use of diesel generating sets involve frequent start-up and shut-down procedures and this results in reduction of the generator lifetime and also adds to the increasing maintenance costs. Most of the time diesel fuel has to be imported at the expense of valuable foreign exchange. IRES, on the other hand, involves extensive use of non-electrical technologies to minimize the use of diesel generating sets in the design process. Using the idea of resource-need matching between different types of energy needs and the non-electrical technologies, it is possible to completely exclude diesel generating sets from the IRES design, thereby saving major fuel costs.

The future climate change scenario will largely depend on the technology roadmaps that nations adopt in order to meet the growing energy demands of the populations that still do not have access to electricity. End-use energy efficiency will play a central role in reduction of CO_2 emissions and mitigation of climate change. The concept of resource-need matching largely takes into account the end-use efficiencies of various energy conversion techniques and thus IRES provides the best solution that can be effectively implemented for energizing the remote rural areas, in both developing and developed regions of the world.

3.2 Resources and Technologies for IRES

As mentioned earlier, nearly 1.4 Billion people worldwide still lack access to electricity and approximately one-third of the world's population relies on wood, straw, charcoal or dung for their daily cooking needs. For lighting purposes, kerosene lamps are extensively used that give very poor light output. Communication facilities consist of just radios that are powered by expensive dry cell batteries. Renewable energy technologies are playing an increasing role to bring about a transition from traditional to more modern forms of energy into households and small-scale industries in many countries. Renewable energy technologies consist of devices that convert renewable energy resources to useful forms of energy such as heat, electricity or mobility. The most prominent renewable energy resources and the related technologies that find ready applications in IRES design process are listed below:

Solar: Technologies that utilize solar energy are of two types, namely solar thermal technologies that utilize sun's thermal energy and solar photovoltaic technology that converts incident solar radiation (insolation) directly into dc electricity. The average solar radiation received by the earth's surface is about 1 kW/m^2. Although solar energy is a dilute resource, the range of its applications in IRES is very large. Solar cookers and solar water heaters are fast gaining momentum in remote rural areas of developing countries. Solar PV systems can be directly used to provide improved household lighting as compared to the use of kerosene lamps or candles. Such systems can also handle communication devices such as radios and televisions that require small amounts of power. Community level PV installations can be employed as a component of IRES in conjunction with other renewable energy technologies to generate electricity at the village level.

Biomass: Traditional methods of biomass utilization involve wasteful direct burning of biomass material generated from animal waste, agricultural, agro-industrial and forestry operations and such techniques are accompanied by problems of ill-health and environmental degradation. Today, a whole new generation of improved biomass stoves are available that provide better combustion efficiencies and reduce indoor air pollution. Methods such as biogas production by anaerobic digestion and biomass gasification are comparatively more environmental friendly [26]. Biogas can be produced from tree-based organic matter and animal wastes with cow dung being the most efficient resource. One pound of wet cow dung yields one cubic foot of biogas which typically is 50-75% methane. Biomass gasification technology involves production of producer gas and it can be integrated with gas turbines and internal combustion engines to generate electricity with reasonable overall conversion efficiencies [27].

Micro-hydro: Micro-hydroelectric generators are turbines that operate under low heads and low volumetric flow rate conditions. The energy from flowing water of the rivers and streams in rural areas can be harnessed using such micro-hydroelectric generators. Also, water can be pumped into small overhead tanks by use of wind pumps and/or PV operated pumps, which can later be used through micro-hydroelectric generators to generate electricity. Such a scheme can form an integral part of IRES.

Wind: Wind energy has been harnessed for centuries in the form of wind pumps to pump water. In off-grid rural areas where there is sufficient wind speed (3-5 m/s), such wind driven mechanical water pumps can be effectively incorporated into the IRES design, thus rendering a cost-effective solution for domestic water supply and small scale irrigation needs. Another way to utilize wind energy is through small-scale wind electric conversion systems (WECS) that require less wind to operate as compared to utility-scale wind energy applications.

Most of these technologies already exist and are continuously being improved with the aim of realizing lower capital costs, improved reliability and increased conversion efficiencies. IRES lays emphasis on the concept of resource-need matching so as to bring about the efficient utilization of these technologies. Table 3.1 lists the various possible combinations of different energy needs and renewable energy technologies that can be implemented through IRES design [28, 29].

3.3 Types of Energy needs

The concept of IRES is based on the fact that some technologies are more efficient than others for supplying some of the needs and this enables delivery of energy at a minimum cost in a sustainable manner. In order to add further value to the approach of resource-need matching, different needs can be categorized as follows depending on the type and quality of energy required [30, 31]:

-Medium-grade heat requirements (MGH) (100-300℃): primarily used for household cooking needs and also to supply thermal energy requirements of some small scale industries

Table 3.1 Resource - Need combinations

Needs	Resources
Cooking	-Improved cooking stoves (fuel wood, crop wastes) -Biogas from household-scale digester -Solar cooker
Lighting (domestic and community)	-Biogas from household-scale digester -Solar home systems -Electricity from IRES with multiple sources- PV, WECS, micro-hydro, biogas-fueled engine generator system, biomass gasifier coupled with gas engine
Water supply (domestic and community)	-Mechanical wind pumps -PV driven pumps -Biogas driven engine pump sets, biomass gasifier coupled with gas engine -Solar water desalination and purification -Solar water heaters
Water pumping for crop irrigation	-Mechanical wind pumps -PV driven pumps -Biogas driven engine pump sets
Heating and cooling (crop drying and other agricultural processing, hot water)	-Improved heating stoves -Solar crop dryers -Solar water heaters -Biogas from small and medium scale digesters

	-Fans operated by electricity from IRES
Communications (televisions, radios, cell phones) and educational activities	-Solar home systems - Electricity from IRES
Cold storage for perishables and vaccines	-Electricity from IRES -Solar refrigeration (community level)
Low grade heat requirements	-Flat plate solar collectors
Small-scale industries, drying units, bakeries etc.	-Solar drying -Biogas from small and medium scale digesters -Solar collectors for process heat -Electricity from IRES

-Low-grade heat requirements (LGH) (less than 100℃): domestic water heating, space heating, process heat for some small scale industries

-Electrical load (ELinit): domestic lighting and entertainment, street lighting, motor load, home appliances, educational and communication needs, flour mill, health centers and shops.

Figure 3.1 illustrates the concept of resource-need matching through utilization of multiple energy resources along with the option of energy storage in order to meet different types of energy needs.

3.4 Current Status of Rural Renewable Energy

Presently, renewable energy technologies such as solar PV, solar water heaters, biogas digesters, wind energy conversion systems, PV operated pumps and micro-hydro systems are providing different forms of energy to meet the basic necessities of modern life, including lighting, educational activites, communications, water purification, irrigation, and heating and cooling.

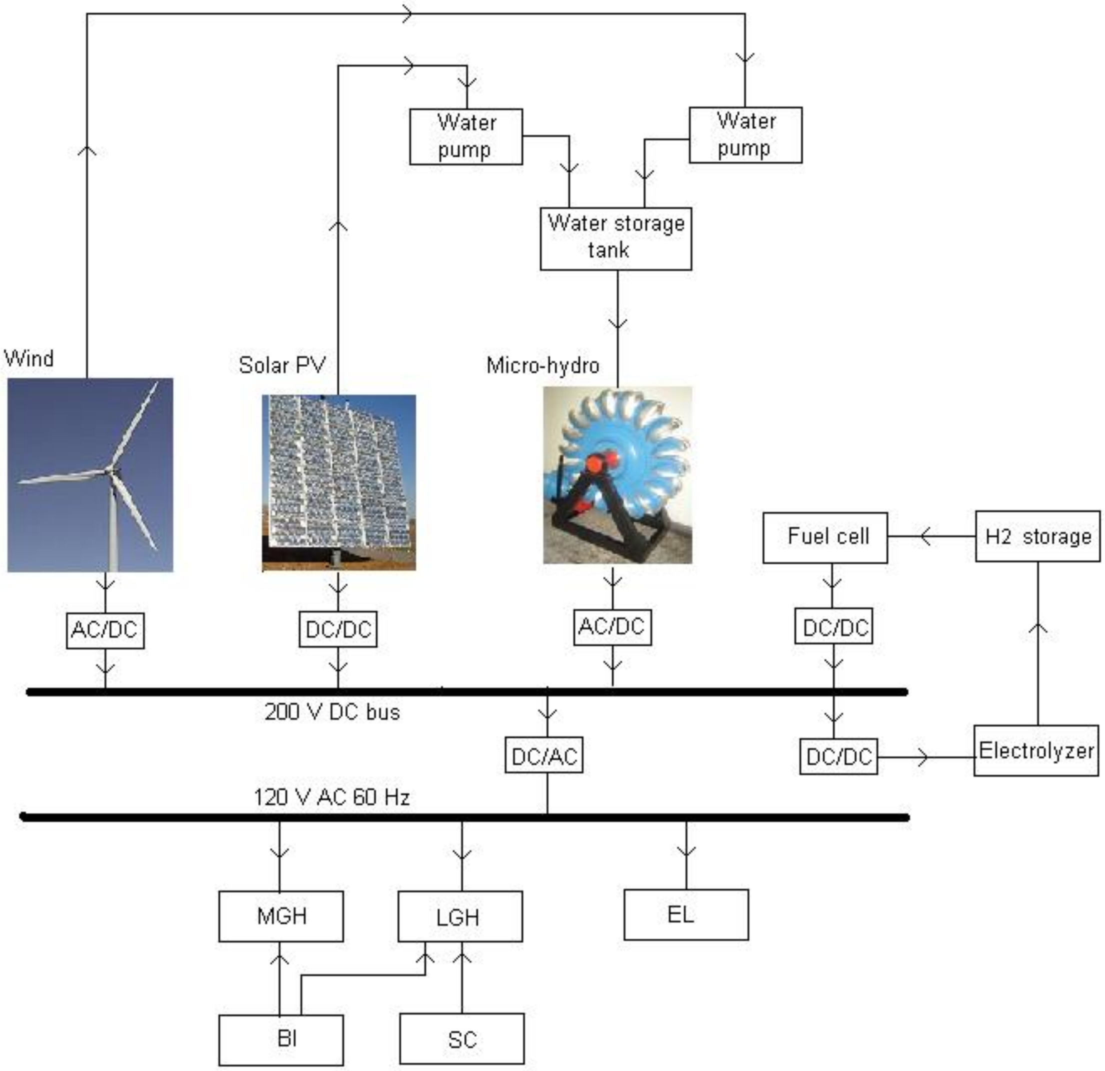


Figure 3.1 Schematic of an Integrated Renewable Energy System (IRES)

Millions of households throughout the world are benefitting from these technologies and so are schools, health centers and small-scale industries in rural areas.

Currently, over 50 million households are served by small-hydro village scale mini-grids (Table 1 in [28]). More than 30 million households worldwide employ biogas digesters to meet their cooking and lighting needs [32]. China is the biggest biogas producer in the world and has around 18 million household-scale biogas digesters. In Europe, Germany plays the leading role with almost 4000 biogas plants, most of them in farms for cogeneration. India has a total installation of more than 4 million biogas digesters. Biogas stoves are used by almost 40% of the world's population and more than 160 million households now use improved biomass cooking stoves.

Nearly 3 million rural homes get power from solar home systems (SHS) to meet their household lighting needs. In Bangladesh, a company named Grameen Shakti has reported an installation of around hundred thousand solar home systems [33]. Indonesian government created the 50 MW PV programme in 1997 in order to electrify one million homes within a period of ten years. Vietnam has approximately 2500 micro-hydro electric power stations (< 100 kW) that serve irrigation and drainage needs and produce electricity for about 200,000 households. In East Africa, traditional use of biomass forms the major component of primary energy usage and efforts are being made to increase the penetration of renewable energy technologies such as improved household stoves, biogas units and PV units. In China, government has implemented renewable energy projects to promote micro-hydro, small-scale wind power, small PV and hybrids of these technologies in order to provide electricity to the rural and poor communities in the country's western provinces.

Many such pilot projects have been initiated throughout the world with the aim of contributing significantly to satisfy the energy needs of the poor. However, most of these projects concentrate on just one form of resource and/or one final form of energy, thus failing to realize the full potential of utilizing all the renewable energy resources available at a particular location in tandem. The concepts of "energization" instead of electrification, "integrated approach" and "resource need matching" as implemented by IRES, can definitely deliver the best solution when it comes to harnessing renewable energy resources.

CHAPTER IV

ENERGY STORAGE OPTIONS FOR IRES

4.1 Introduction

One of the major concerns related to renewable energy resources is their intermittent nature which may result in a mismatch between load demands and the renewable energy generation output. The widespread use of renewable energy technologies is hindered by their inability to provide power either when the wind is not blowing or the sun is not shining. It is possible to overcome or mitigate this problem with the use of energy storage devices incorporated in IRES, as shown in figure 11 (chapter 3). The output of renewable energy technologies can be levelled with the use of energy storage devices, which would allow storage of energy so that it can be dispatched at a later time. With the inclusion of energy storage systems, renewable energy technologies can become more competitive by reducing generation costs and delivering reliable power. Energy conversion from renewable energy resources with suitable energy storage options can play an important role in the development and operation of integrated renewable energy systems. Some of the energy storage options that are readily feasible for implementation in IRES are listed below.

4.1.1 Biomass storage

It is possible to harness the energy from biomass in a sustainable manner by using technologies such as improved stoves for direct combustion, biogas production by anaerobic digestion and biomass gasification. As already discussed, such technologies can be effectively implemented in rural areas through IRES design process.

The biomass consumed by these technologies can include a wide range of materials such as:

-Virgin wood: from forestry or from wood processing

-Energy crops: high yield crops grown specifically for energy applications

-Agricultural residues: residues from agriculture harvesting or processing

-Food waste: from food and drink manufacture, preparation and processing, and post-consumer waste

-Wastes and co-products from manufacturing and industrial processes in small-scale rural industries.

-animal wastes and residues

It is possible to store such biomass fuel in sufficient reserves at the point of usage, so that it can be utilized at a later time. However, solid and wet biomass fuels have relatively lower energy density as compared to fossil fuels and consequently, larger space volumes are required for their storage. Also, the fact needs to be considered that biomass cannot flow in pipes like oil or gas, and hence it requires arrangements for transportation of its bulk quantities to the storage facility or to the energy conversion equipment. Biomass can absorb moisture, and if not absolutely dry, can naturally degrade leading to loss of energy content. This may also lead to formation of moulds and spores that can be dangerous if inhaled. Therefore, biomass storage facility should be well-designed so as to keep the fuel in good condition, particularly protecting it from moisture, rain and groundwater. The energy from biomass can also be stored in the form of biogas in large storage tanks and the stored biogas can be later used for cooking and lighting needs or for electricity production.

Figure 4.1 Schematic for micro-hydro pumped storage

4.1.2 Hydro storage

A micro- hydro pumped storage configuration, as shown in figure 4.1, is a storage technology that is most capable of partnering with wind and solar energy, and can be easily incorporated into the village IRES. It is a mature technology and considered to be cost effective. Such a configuration would consist of water pumps driven by solar PV and wind generators, a water storage tank and a hydroelectric generator. Whenever there is excess renewable energy generation, energy can be stored in the form of potential energy by pumping water into the storage tank. In times of excess energy demands, stored water can be utilized through the hydroelectric generator to generate electric power. Moreover, the water in the storage tanks can also be used for domestic and irrigation purposes or to generate motive power. Such a micro-hydro pumped storage system has fast charging and discharging rates and the capability to keep up with the fluctuations in load demands. The system has high overall energy conversion efficiency and is completely clean, cheap and renewable in all respects.

4.1.3 Battery storage

Secondary batteries have long been utilized as a means to store energy for transportation systems as well as for stationary storage applications. In hybrid renewable energy systems, batteries are perhaps the most common and familiar energy storage device for smaller storage needs [34]. The technology is mature and batteries are inexpensive and have the ability to respond rapidly to power fluctuations. Batteries store energy in chemical form during charging and produce electrical power in DC form during discharge. For AC power applications, an inverter is required to convert the DC output of the batteries to AC form.

Conventional lead acid batteries have a wide range of applications because they are inexpensive with a round-trip efficiency of around 85-90%. It is possible to store significant amounts of energy using a battery bank consisting of several battery units in a battery bank. A charge controller is employed to control the performance of the battery bank which guarantees that the battery is neither over-charged nor discharged too deeply. However, batteries have limited durability, high maintenance costs and are highly dependent on temperature that can reduce the battery’s lifetime significantly. Such batteries are not appropriate for long-term energy storage because of their low energy density, self-discharge and leakage. Moreover, they also pose potential environmental hazards associated with their manufacture and disposal. But they are ideal for small-scale use for emergency communication and educational activities.

Recently, advanced battery storage systems have been developed primarily consisting of flow batteries such as zinc bromine (ZBB), nickel cadmium (NiCd) and sodium sulphur (NaS) batteries. Flow batteries employ a system consisting of external reservoirs for holding chemical reactants that flow into the battery stack containing electrodes. Such a configuration allows system power rating and the system energy storage capacity to be designed independently. As their costs decline over time, such advanced battery storage systems can find wide-spread applications in harnessing renewable energy resources.

4.1.4 Hydrogen storage

Recent advancements in hydrogen storage technologies have enabled long term energy storage wherein hydrogen plays the key role. Hydrogen is a clean and efficient medium of energy and it can be the energy carrier of the future because of its many advantages. Hydrogen can act as a fuel in almost all applications where fossil fuels are being used today [35]. Using renewable energy as a primary energy source, hydrogen as a fuel and electricity as a carrier, it is possible to produce and utilize hydrogen without any emissions. As a result of its high inherent mass energy density, the problem of leakage in hydrogen storage is insignificant as compared to that in batteries. Hydrogen can enable high capacity and long term seasonal energy storage and hence is well suited for IRES applications. Moreover, much like batteries, hydrogen storage technology has the ability to quickly respond to power fluctuations and is easy to install anywhere.

One of the major disadvantages is that hydrogen is not available in free form in nature and it needs to be produced by employing other sources of energy. Most of the commercially available hydrogen generation technologies are not free of carbon footprint. A system generating hydrogen from renewable sources of energy can be termed as a “maturing” technology which is characterized by nearly zero carbon footprint. The modeling of hydrogen storage technology for IRES is discussed in the next section.

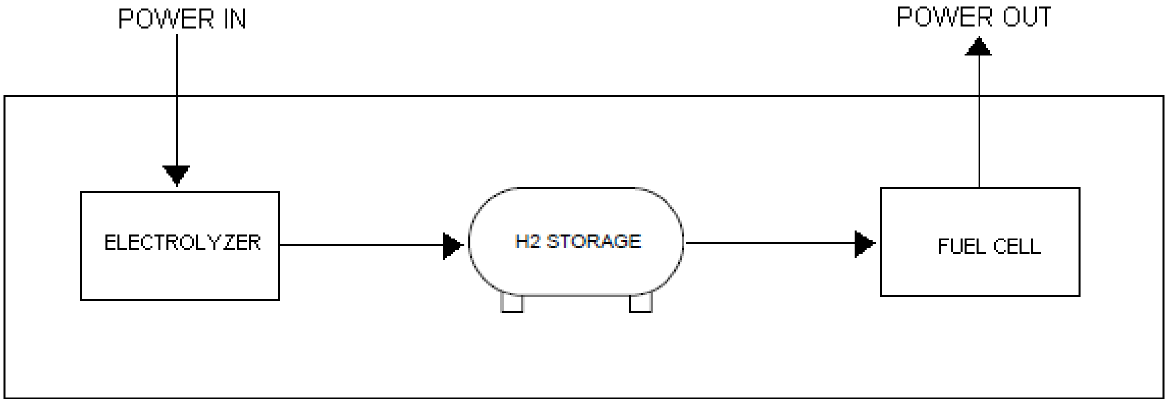


Figure 4.2 Hydrogen-based energy storage system

4.2 Hydrogen Generation and Utilization

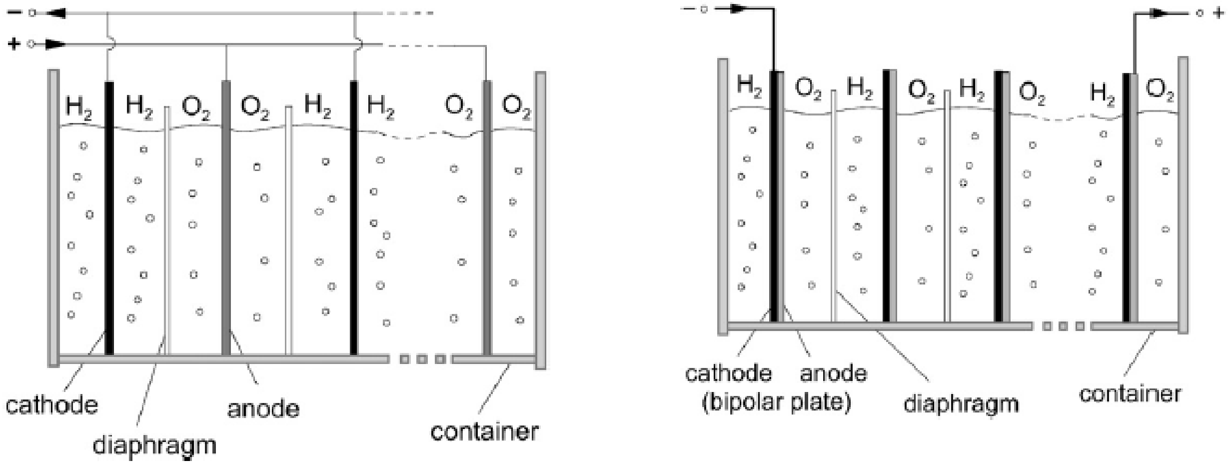
As shown in figure 4.2, the main components of hydrogen storage technology are the electrolyzer, gas storage tank and a fuel cell. The electrolyzer converts surplus energy generated from renewable energy resources into hydrogen that is stored in storage tanks in compressed gaseous form. Whenever renewable energy generated is less than the energy demand, stored hydrogen is converted back to electricity through a fuel cell to meet the excess demand. The following sections explain the process of hydrogen generation and utilization in greater detail.

4.2.1 Electrolyzer

The basic chemical reaction that governs the principle of electrolyzer operation is the decomposition of water into hydrogen and oxygen. The complete reaction is as follows:

$$\mathrm{H_2O + electrical\ energy\ \rightarrow\ H_2 + \frac{1}{2}\,O_2}$$

Conventional electrolyte used in water electrolyzers is an aqueous solution of potassium hydroxide (KOH). The electrolyzer stack consists of several electrolyzer cells connected electrically in series or parallel. In monopolar design (figure 4.3(a)), the cells are connected in series whereas bipolar design (figure 4.3(b)) employs parallel connection of cells. The advantage



(a) (b)

Figure 4.3 (a) Mono-polar electrolyte (b) Bi-polar electrolyte

of bipolar electrolyzer stacks is that they are more compact and have shorter current paths resulting in higher efficiency. However, compact design makes the construction of these stacks more complex which in turn adds to the manufacturing cost. Monopolar electrolyzers are relatively simpler in construction. However, most of the electrolyzers manufactured today are bipolar and alkaline [36, 37].

According to Faraday's law, hydrogen production rate is directly proportional to the transfer rate of electrons across the electrodes and is given by [38, 39],

$$\dot{\mathrm{n}} = \eta_{\mathrm{F}} \frac{\mathrm{N}}{2\mathrm{F}} \mathrm{I}_{\mathrm{elyz}} \tag{4.1}$$

where

$\dot{n}$ = hydrogen production rate (moles/sec)

N = number of electrolyzer cells

F = Faraday constant = 96485 C/mol

I_{elyz} = electrolyzer current (A)

η_F = Faraday efficiency given by,

$$\eta_F = \frac{I_{elyz} - I_{loss}}{I_{elyz}}$$

where I_{loss} is the internal current in amperes (typically, less than 1% of the operating current).

Equation 4.1 implies that higher operating current results in higher hydrogen production. Although most of the electrolyzers used in industry operate in the constant current mode, in case of IRES constant voltage mode would be preferred to allow the operating current to vary depending on the available excess power from wind and PV panels.

4.2.2 Types of Hydrogen storage

Several types of hydrogen storage techniques have been considered in the past [40]:

1. Compressed hydrogen
2. Liquid hydrogen
3. Metal hydrides
4. Carbon based materials (carbon nanotubes, activated carbon)

Of all the available options, compressed gas storage is the most widely used technology at present for large scale storage of hydrogen. For the sake of simplicity, the design of storage tank, compressor, piping, valves etc. is left for future work. The dynamics of compressed storage can be summarized by the use of ideal gas law, PV = nRT.

4.2.3 Fuel cell

A fuel cell is an electro-chemical device that converts the chemical energy of the fuel (H_2) directly and isothermally by employing an oxidant (O_2) in to electrical current (DC) and the only product is water. Thus, the basic chemical reaction that governs the fuel cell operation is exactly opposite to that of an electrolyzer. As shown in figure 4.4, hydrogen fuel is oxidized and

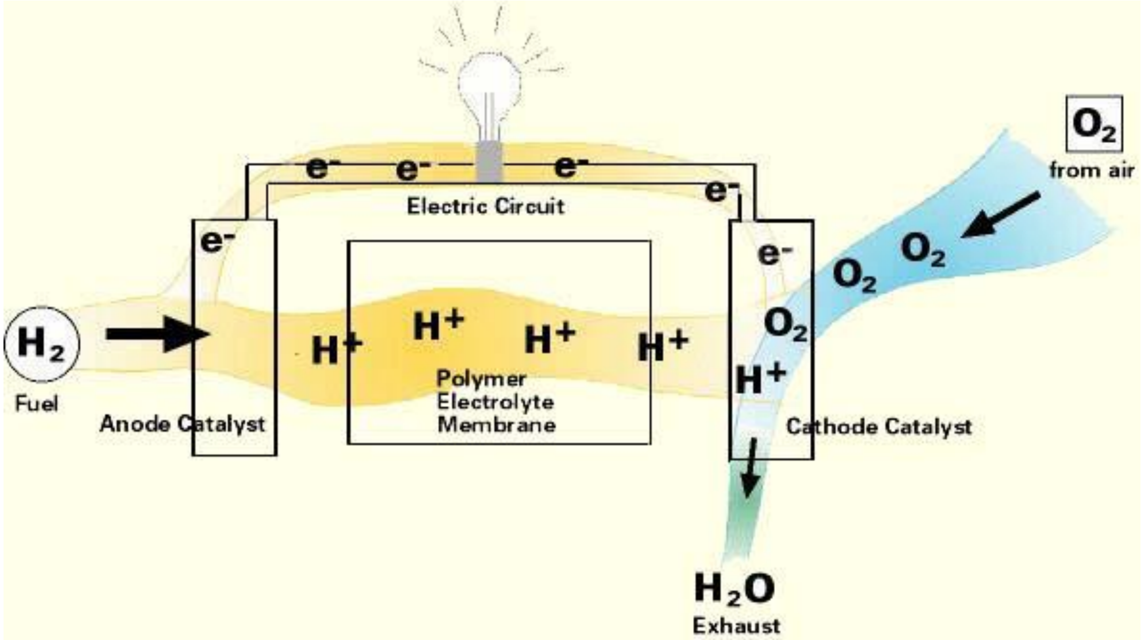


Figure 4.4 Fuel cell operation

electrons are released to the external circuit at the anode whereas at the cathode, oxygen is reduced and electrons are accepted from the external circuit.

Depending on the type of electrolyte used in the cells, they are classified as Phosphoric acid fuel cell (PAFC), Alkaline fuel cell (AFC), Proton exchange membrane fuel cell (PEMFC), Solid oxide fuel cell (SOFC) and Molten carbonate fuel cell (MCFC). Among these, PEMFCs generate the highest power density and they operate at low temperatures (less than 100℃). PEMFC running on hydrogen is commercially available for stationary and portable applications [41].

The open circuit voltage of the fuel cell stack depends on the ideal standard Nernst potential generated by the cell which in turn depends on the utilization factor of the hydrogen fuel. The utilization factor of hydrogen in the fuel cell is given by [42]:

$$U_f = \frac{60000RTI_{fc}}{2FP_{fuel}V_{fuel}x} \tag{4.2}$$

where

R = 8.3145 J/(mol K)

T = temperature of operation (K)

I_{fc}= fuel cell current (A)

F= 96485 C/mol

P_{fuel} = fuel pressure (atm)

V_{fuel} = fuel flow rate (lpm)

x = percentage of hydrogen in the fuel (%)

Like electrolyzer, fuel cell is operated in variable current mode depending on the load requirement. Thus the hydrogen utilization factor can be kept constant at its nominal value. Keeping the utilization factor constant, equation 4.2 gives the fuel flow rate required for a particular load requirement.

The electrolyzer and the fuel cell models discussed in the preceding sections can be incorporated into the IRES design algorithm, so as to store excess renewable energy in the form of hydrogen that can be utilized later in case of energy shortfall. Hydrogen has the potential to be a long term candidate for sustainable energy development because of its characteristic of being an environmentally friendly energy carrier that can effectively bridge intermittent renewable energy resources with energy storage. With such ability, hydrogen technology can certainly gain a strong foothold in IRES applications. However, at present such systems face steep economic issues.

CHAPTER V

CASE STUDY OF A HYPOTHETICAL REMOTE COMMUNITY

5.1 System considerations:

For our design of IRES, we consider energy needs of a typical hypothetical remote area community with a human population of 700 and a livestock population of 450 cattle with no access to the electric grid [43, 44].

5.1.1 Energy needs:

The energy needs are categorized into medium-grade heat requirements (MGH), low-grade heat requirements (LGH) and electrical needs (ELinit) as discussed in Chapter III. We assume the total energy requirements and the maximum rates of energy consumption for the remote area community under consideration as given below:

MGH needs: 700 kWh/day (P_{max}= 100 kW, P_{min}= 0 kW)

LGH needs: 400 kWh/day (P_{max}= 65 kW, P_{min}= 0 kW)

ELinit needs: 450 kWh/day (P_{max}= 30 kW, P_{min}= 5 kW)

5.1.2 Renewable energy resources and technologies:

We consider an integrated renewable energy system consisting of biogas, solar thermal, solar PV and wind electric conversion system aided by hydrogen storage technology. The assumptions for various energy resources and technologies are as follows:

Biogas:

Assuming an average yield of 10 kg of wet dung collected per animal per day, total amount of wet dung collected from 450 cattle is 4500 kg per day. With one pound of wet cow dung yielding approximately one cubic foot of biogas [45], the resultant biogas generation is 280 m^3/day. Assuming an energy equivalent of 5.55 kWh/m^3 for biogas, the total amount of energy generated from biogas is 1540 kWh/day. If the biogas plant operates on full power for 5-6 hours on a daily basis, the maximum power generated by the plant would be approximately around 300 kW.

Solar thermal:

Solar thermal collectors are used to meet low-grade heat energy requirements as they have the capability to deliver end-use efficiencies of about 50-70% as against PV panels which have efficiencies of about 10-20% in meeting the same energy needs. To meet the LGH requirements of 400 kWh/day for the rural community under consideration, the maximum rate of solar thermal energy generation (assuming a capacity factor in the range of 22-24%) can be calculated as follows:

$$P_{\max} = \frac{400\ \mathrm{kWh}}{24\mathrm{hrs} * 0.238} = 70\ \mathrm{kW}$$

Solar PV and Wind energy conversion system (WECS):

To supply all the electrical energy requirements, we consider solar PV panels with total rated output of 10 kW_P and a WECS rated at 30 kW. Considering the fact that the capacity factors for PV and WECS are in the range of 12-20% and 20-40% respectively, the rated output of 10 kW_P PV and 30 kW WECS would be insufficient to meet the electrical needs of 450 kWh/day for the remote rural community under consideration, as stated earlier. The sole purpose to underrate PV and WECS is to highlight the importance of hydrogen storage that is implemented in our IRES design, as discussed later.

Table 5.1 Minimum and maximum power for energy needs and resources

Energy needs:	***P*min (kW)**	***P*max (kW)**
MGH needs	0	100
LGH needs	0	65
Electrical load	5	30
Resources:	***P*min (kW)**	***P*max (kW)**
Biogas	0	300
Solar thermal energy	0	70
WECS	0	30
PV	0	10

Table 5.1 summarizes the maximum and minimum power ratings considered for all energy needs and resources.

5.1.3 Hydrogen Generation and Utilization

As discussed earlier, we consider a hydrogen storage technology consisting of an electrolyzer, a gas storage tank and a fuel cell. From the economic point of view and to avoid oversizing, the choice of electrolyzer rating is subjected to the following constraints:

Capacity of the electrolyzer, $P_{\text{elyz}} \leq$ (maximum power generated from PV and WECS – minimum load)

$$\therefore \quad P_{\text{elyz}} \leq (30+10-5)\ \text{kW}$$

$$\therefore \quad P_{\text{elyz}} \leq 35\ \text{kW}$$

Table 5.2 shows the specifications of the electrolyzer used for the IRES design under consideration [46].

Table 5.2 Details of electrolyzer used in IRES

Power	26 kW
Voltage	35-37 VDC
Operational temperature	80 ℃
Operational pressure	7 bar
Number of cells	21
Electrolyte	KOH (40wt.%)

Table 5.3 Details of fuel cell stack used in IRES

Power	6 kW
Voltage	45-60VDC
Operational temperature	65 ℃
Operational pressure	1.5 atm
Nominal composition of hydrogen	99.99%

The fuel cell is rated so as to supply the minimum electrical load.

$$\therefore \quad P_{\mathrm{FC}} \geq 5 \text{ kW}$$

Table 5.3 shows the specifications of the fuel cell stack used for IRES design under consideration [42].

As discussed in chapter 4, electrolyzer is operated in variable current mode so as to maximize the hydrogen production and in case of fuel cell, hydrogen utilization factor is kept constant at 99.56% through variable current operation.

The hydrogen generated by the electrolyzer is stored in the gas storage tank in compressed form. The dynamics of compressed gas storage can be summarized by assuming with little error that hydrogen is an ideal gas and thus, the application of ideal gas law PV = nRT is justified. We assume hydrogen storage at a maximum of 120 bar pressure for our design of IRES.

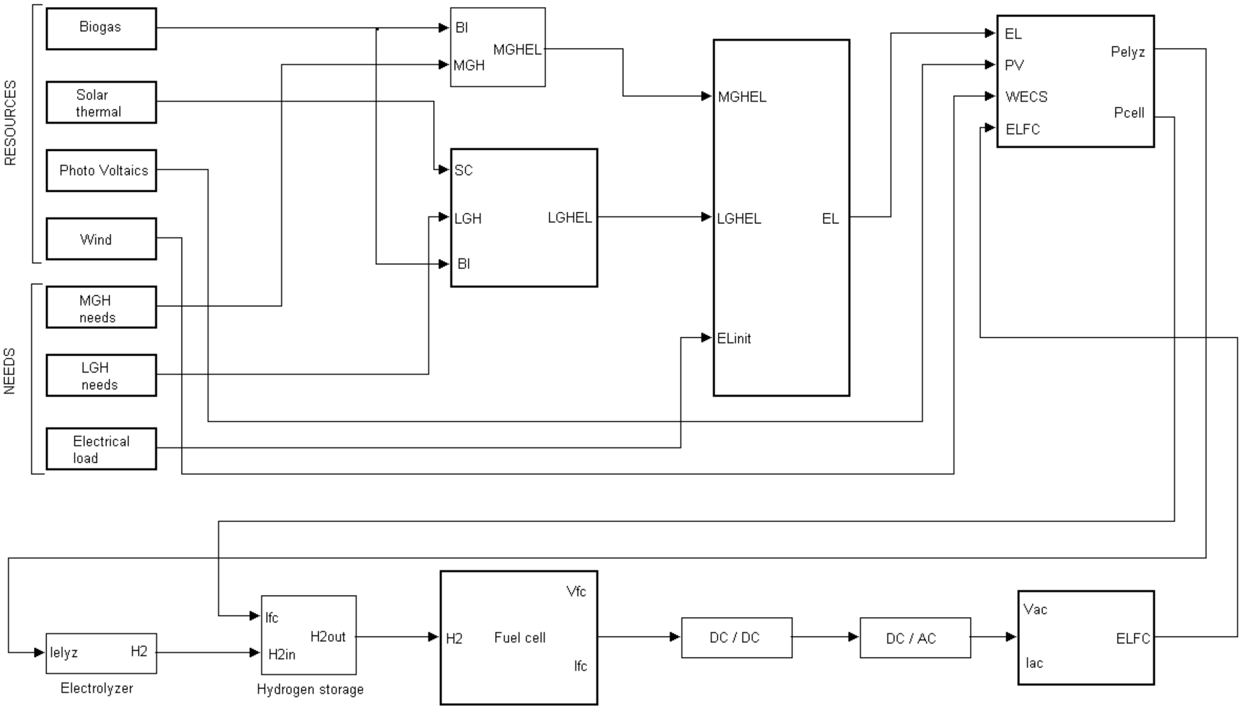


Figure 5.1 Block diagram for implementation of IRES

5.1.4 Algorithm for IRES operation

IRES operation is based on the concept of 'resource-need' matching so as to maximize the various end-use energy conversion efficiencies. Medium-grade heat requirements (MGH) are first met by available biogas(BI) and the leftover MGH requirement is added to electrical load (EL). Solar thermal energy caters to low-grade heating (LGH) energy needs with the highest end-use efficiency. Hence, LGH needs are first met by solar thermal (SC) energy, then by leftover biogas (if any) and the rest is added to EL. The energy from the wind electric conversion system (WECS) and photovoltaics (PV) is used to meet the total electrical load (EL). Hydrogen is produced by an electrolyzer whenever there is excess energy from wind and PV panels. Likewise, the stored hydrogen is utilized in a fuel cell to supply the electrical load in case of a shortfall in energy generated from WECS and PV.

As illustrated in figure 5.1, the current reference I_{elyz} is generated for the electrolyzer in case of excess energy available from wind and PV panels, and current reference I_{fc} is generated for fuel cell in case of energy shortfall from wind and PV panels. Electrolyzer and fuel cell operation are discussed further in the following sections.

5.1.5 Electrolyzer operation

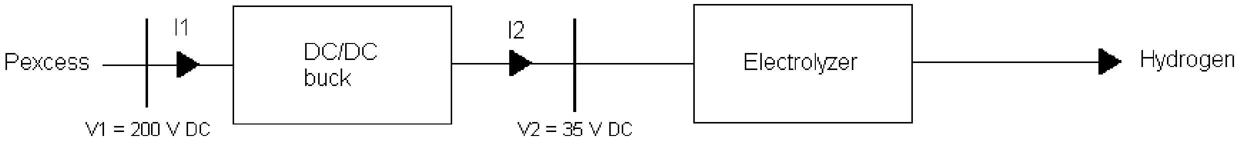


Figure 5.2 Electrolyzer operation

As shown in Fig. 5.2, excess renewable energy (Pexcess) is given as input to the electrolyzer through a DC/DC buck converter. Current I1 is calculated as follows,

$$I1 = \frac{Pexcess}{200\,V}$$

For a lossless buck converter, $I2 = I1 * \frac{V1}{V2} = I_{elyz}$

Using equation 4.1, we can calculate the amount of hydrogen generated by the electrolyzer current I_{elyz}.

5.1.6 Fuel cell operation

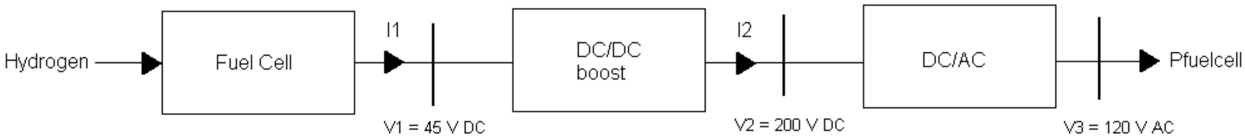


Figure 5.3 Fuel cell operation

As shown in Fig. 5.3, Pfuelcell is the power required to be supplied by the fuel cell given by,

$$Pfuelcell = \eta_{Inverter} * 200\,V * I2$$

where $\eta_{Inverter}$ is the efficiency of DC/AC inverter which is assumed to be 0.8 for simulation in this case.

$$\therefore I2 = \frac{Pfuelcell}{\eta_{Inverter} * 200\,V}$$

For a lossless boost converter, $I1 = I2 * \frac{V2}{V1}$ = I_{fc}

Using equation 4.2 and by keeping the utilization factor constant at 99.56%, we can calculate the amount of hydrogen required for fuel cell operation with current I_{fc}.

5.2 Simulation of Results

We consider a time step of one hour for our analysis which includes variations of needs and resources. The time step of one hour is considered sufficient since the cumulative renewable energy resources do not change significantly over one single hour.

The energy needs and the availability of resources (in kWh) are varied randomly on an hourly basis. Simulations may be generated for any number of time steps, although in our case we generate simulations for 10 time steps for the sake of clarity in figures, as seen in figures 5.4-5.11.

Figures 5.4 to 5.7 show the variations of available energy resources: biogas, solar thermal energy, WECS output and PV output respectively on an hourly basis for duration of 10 hours (10 time steps).

Figures 5.8 to 5.11 show the results obtained from IRES operation for the same duration.

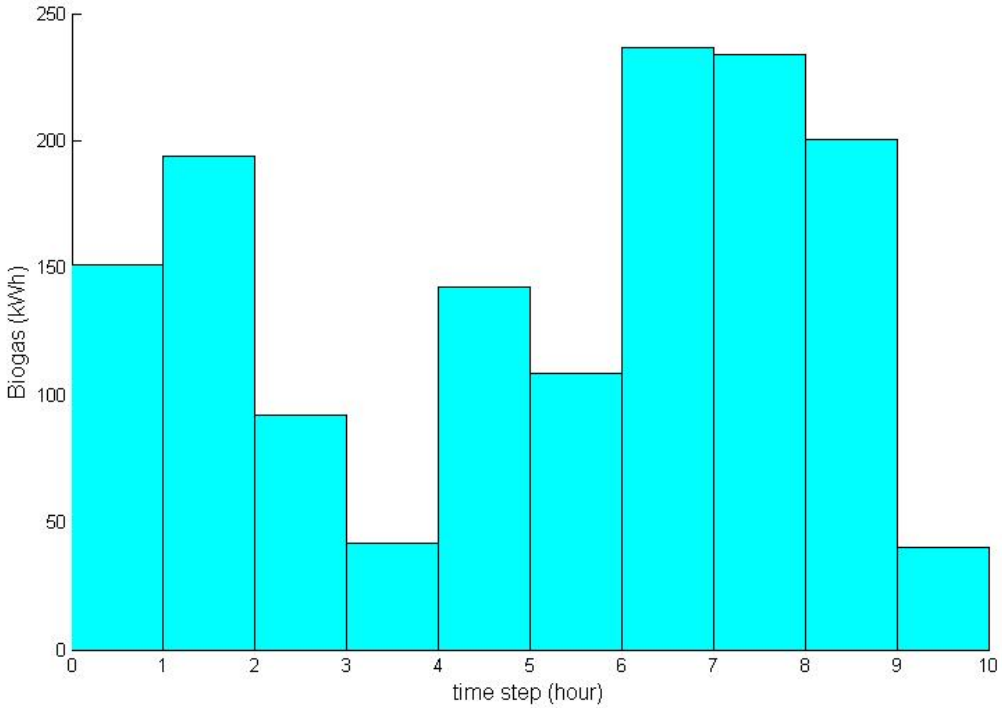


Figure 5.4 Biogas production in kWh

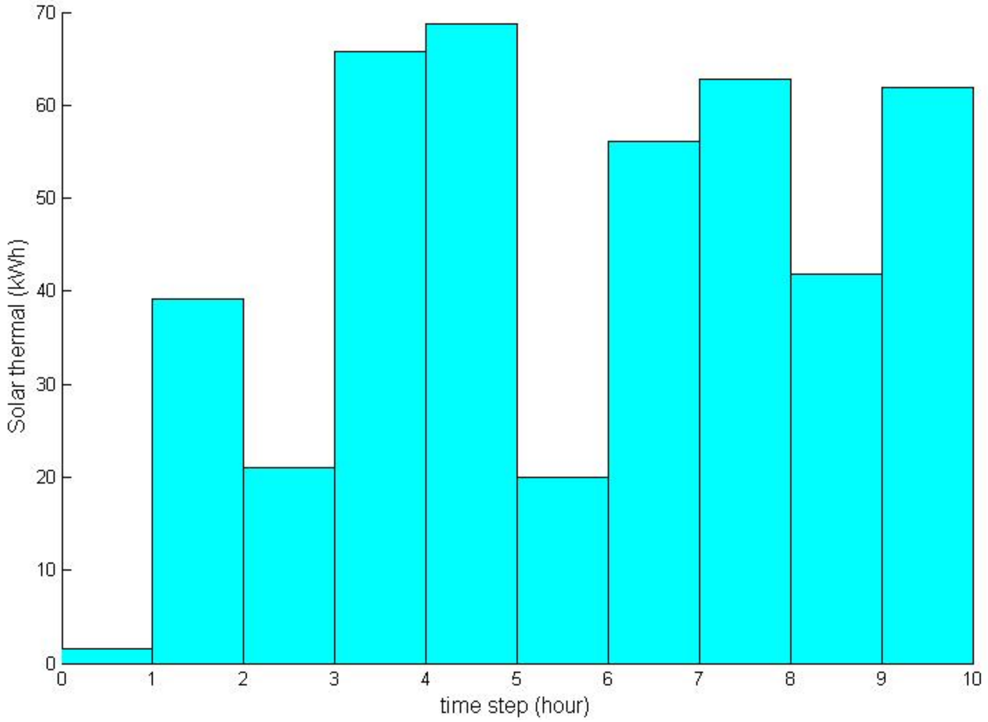


Figure 5.5 Solar thermal energy in kWh

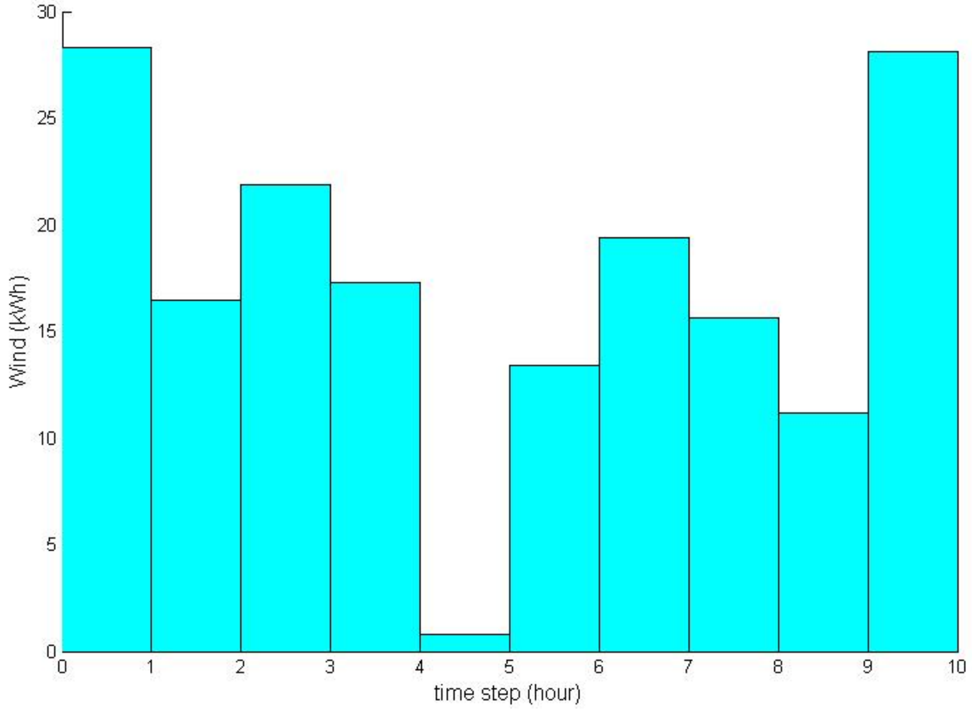


Figure 5.6 Wind energy generated in kWh

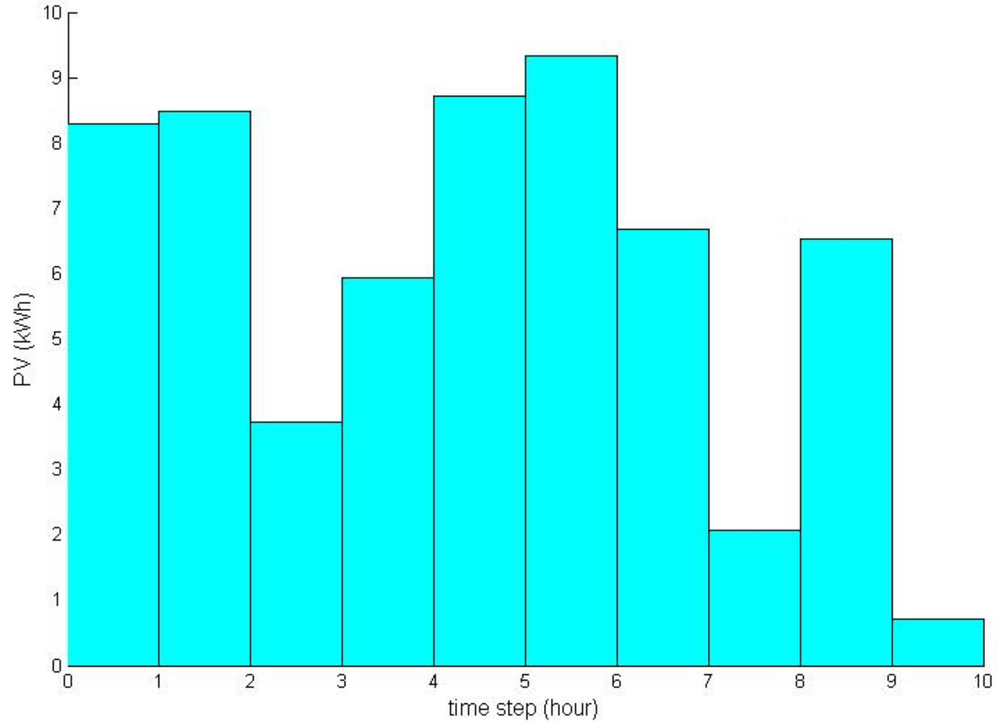


Figure 5.7 Solar PV energy in kWh

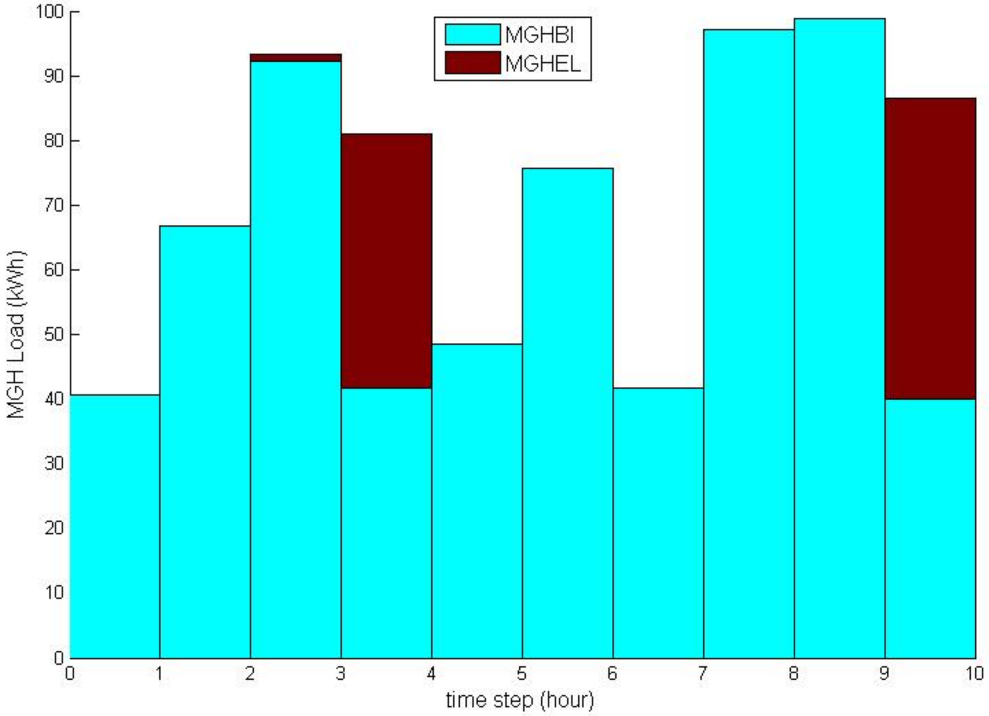


Figure 5.8 MGH needs

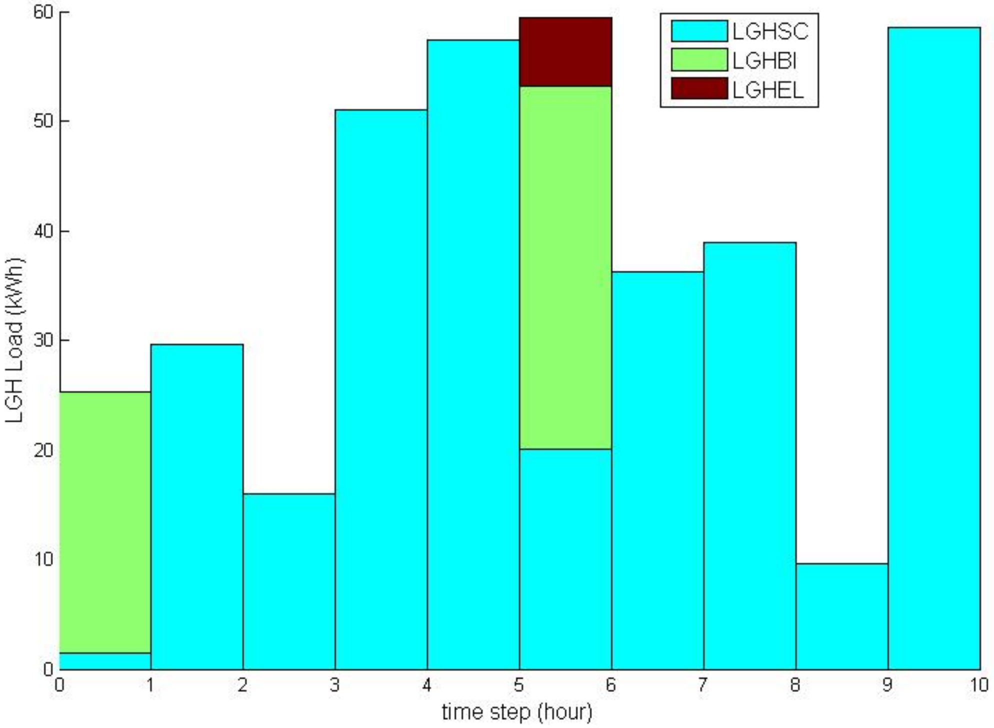


Figure 5.9 LGH needs

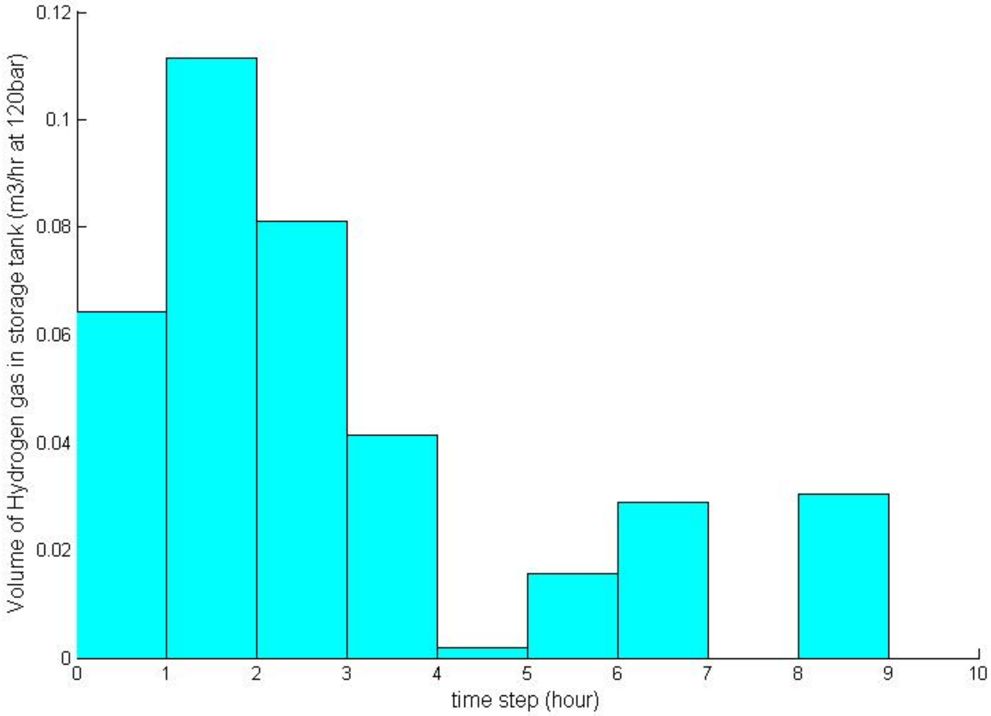


Figure 5.10 Hydrogen production in m^3/hr at 120 bar pressure

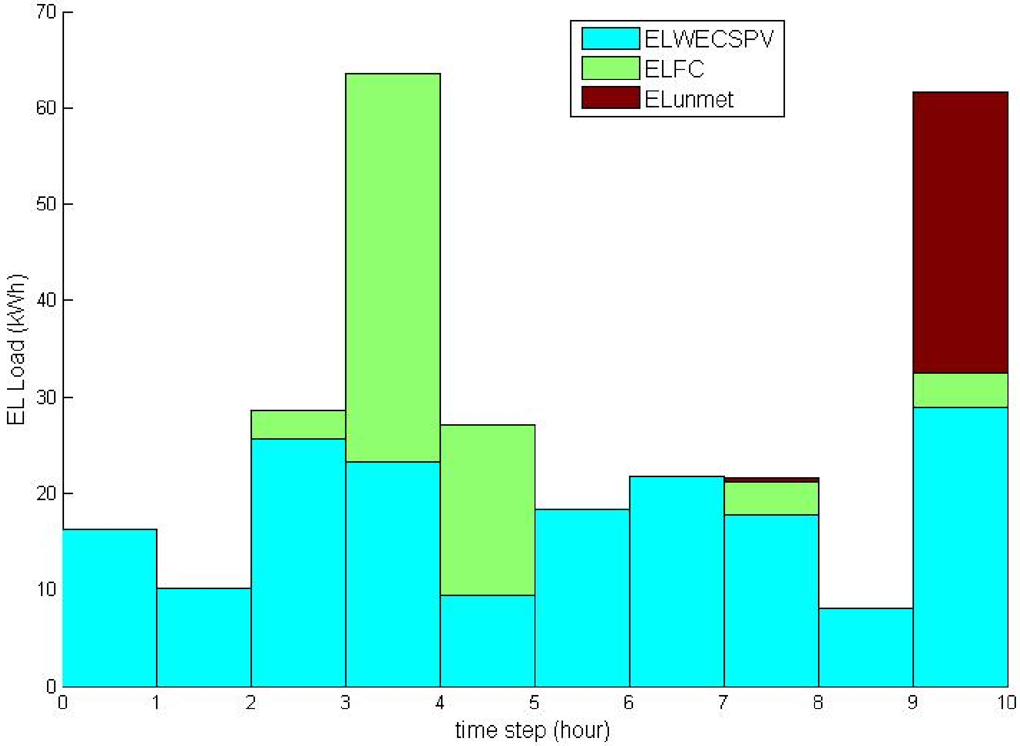


Figure 5.11 Electrical energy needs

5.3 Discussion of Results

As seen from Fig. 5.8, MGH needs are first met by available biogas at each time step. In case of a biogas shortfall, the leftover MGH needs are added to the electrical load to be met by wind and PV panels. Fig. 5.9 shows that LGH needs are first met by available solar thermal energy, then by any leftover biogas and the rest is added to the electrical load.

The electrical load is met by energy generated from wind and PV panels (Fig. 5.11). In case of a shortfall, the leftover electrical load is supplied from fuel cell depending on the availability of hydrogen stored in the previous time step (Fig. 5.10).

From Fig. 5.11, we observe that the fuel cell operates at time steps t = 3,4,5,8,10. Fig. 5.10 shows the amount of hydrogen available in storage at each time step, and this is tied to the operation of electrolyzer.

Whenever renewable energy generated in electrical form is more than the electrical needs, hydrogen is generated by the electrolyzer and stored inside the storage tank in compressed gaseous form whereas in case of energy shortfall, the stored hydrogen is utilized through the fuel cell to cater to the excess demand.

Hence, we consider the following two scenarios:

Scenario 1: Fuel cell operation at time instant t = 8, when energy from WECS and PV is less than the total electrical demand (EL)

Scenario 2: Electrolyzer operation at time instant t = 9, when energy from WECS and PV is more than the total electrical demand (EL)

Table 5.4 Energy Needs and Resources for Scenarios 1 and 2

Needs/Resources (in kWh)	**Scenario 1** (time instant t = 8 hrs)	**Scenario 2** (time instant t = 9 hrs)
BI	234.0887	200.5537
SC	62.7278	41.8269
WECS	15.6361	11.1694
PV	2.0678	6.5385
MGH	97.1786	98.7975
LGH	38.9264	9.6770
ELinit	21.6070	8.0704
MGHBI	97.1786	98.7975
MGHEL	0	0
LGHSC	38.9264	9.6770
LGHBI	0	0
LGHEL	0	0
EL	21.6070	8.0704
WECS + PV	17.7039	17.7079
Is WECS + PV > EL ?	No	Yes
Fuel cell/Electrolyzer operation ?	Fuel cell operation	Electrolyzer operation
ELWECSPV	17.7039	8.0704
ELFC	3.5109	0
ELunmet	0.3922	0

5.3.1 Scenario 1

Time instant t = 8 represents scenario 1.

As shown in table 5.4, medium-grade heat (MGH) requirements are completely met by available biogas and low-grade heat (LGH) requirements are completely met by available solar thermal energy. The total electrical demand (EL) during this instant is 21.6070 kWh and the total energy generated from wind energy conversion system (WECS) and photovoltaic panels (PV) is (15.6361 + 2.0678) = 17.7039 kWh.

Therefore, in this case (WECS + PV) < EL and the excess energy is supplied by the fuel cell.

Fuel cell utilizes the amount of hydrogen stored in the previous time step t = 7, as shown in figure 5.10.

Hence, as illustrated in figure 5.11, at t = 8:

amount of electrical load met by WECS and PV = ELWECSPV = 17.7039 kWh

amount of electrical load supplied by fuel cell = ELFC = 3.5109 kWh

amount of electrical load unmet = ELunmet = 17.7039 – 3.5109 = 0.3922 kWh

In this case, the amount of hydrogen available in the previous time step t = 7 is not able to completely satisfy the electrical needs at t = 8. Since the available hydrogen is completely utilized, no hydrogen is left in the storage at the end of t = 8, as seen in figure 5.10.

5.3.2 Scenario 2

Time instant t = 9 represents scenario 2.

As shown in table 5.4, medium-grade heat (MGH) requirements are completely met by available biogas and low-grade heat (LGH) requirements are completely met by available solar thermal

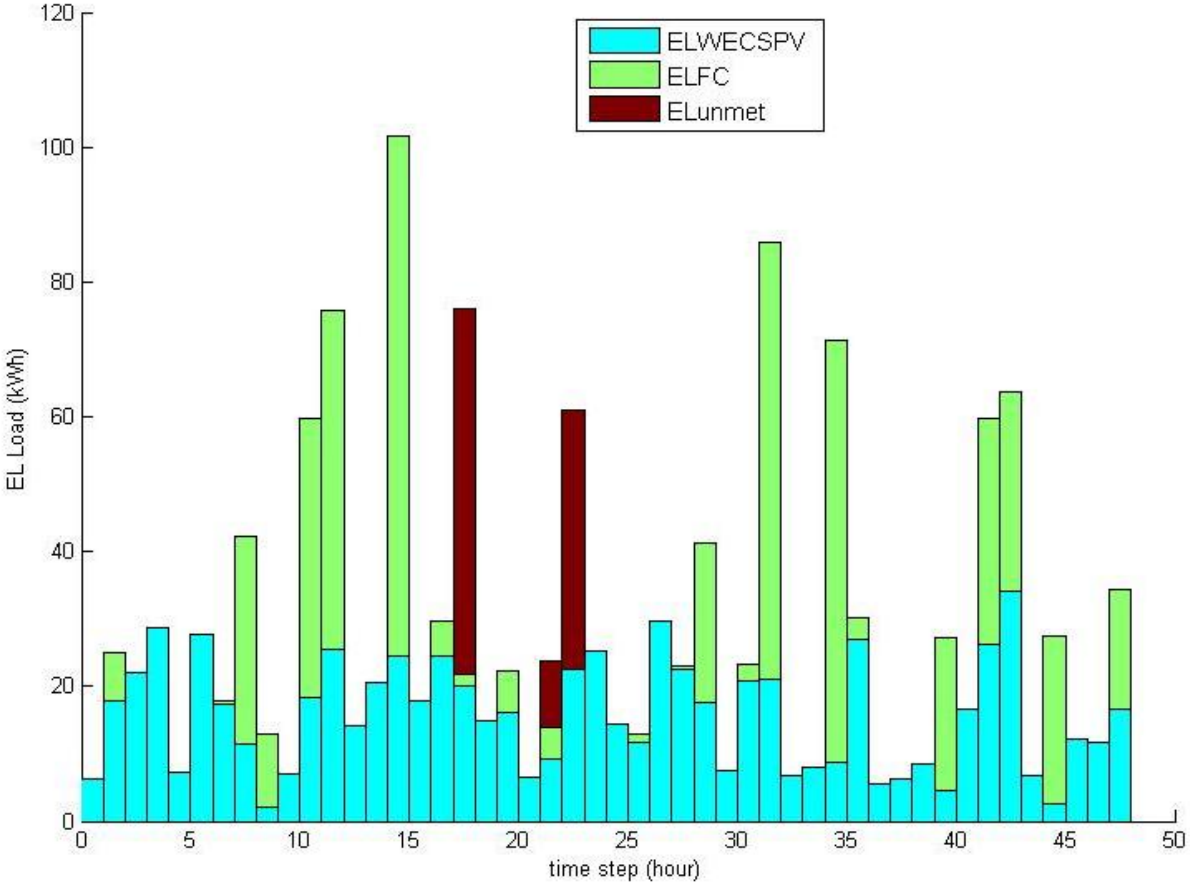


Figure 5.12 Electrical energy needs for 48 time steps

energy. The total electrical demand (EL) during this instant is 8.0704 kWh and the total energy generated from wind energy conversion system (WECS) and photovoltaic panels (PV) is (11.1694 + 6.5385) = 17.7079 kWh.

Therefore, in this case (WECS + PV) > EL and the excess renewable energy is converted to hydrogen by the electrolyzer, as seen in figure 5.10 at t = 9.

Hence at t = 9, all the electrical load is met by energy from WECS and PV, and fuel cell does not operate in this case, as illustrated in figure 5.11.

Moreover, results in Figure 5.11 show that fuel cell operates at instants t = 3,4,5,8,10 by utilizing the hydrogen available in the preceding time steps respectively (Figure 5.10). The results justify the use of hydrogen storage in order to meet the electrical load requirements at a later time.

Also, it is possible to generate simulations over ‘n’ time steps. Figure 5.12 shows one such simulation of electrical load met over duration of 48 time steps.

CHAPTER VI

SUMMARY AND CONCLUDING REMARKS

IRES is an effective, smart and viable strategy that can be implemented for remote area applications, in both developed and developing regions of the world. The concept of resource-need matching employed by IRES enables effective and economic utilization of locally available renewable energy sources. Case study of a hypothetical village indicates that the overall operation of IRES can be enhanced further by inclusion of an energy storage technology such as hydrogen storage. As other energy storage technologies become viable, they could be incorporated in the overall strategy. Hydrogen, a clean energy source when burned, generated from clean energy resources can constitute a process for energy generation that would be sustainable and almost emission-free. However, as far as electrolyzer-fuel cell combination is concerned, further work is needed to investigate its dependence on temperature and pressure. Even other dynamic aspects of compressed gas storage technology such as compressor, piping, auxiliary power and other accessories can be studied further. The synergy between hydrogen development and renewable energy technologies will be significant in the future and has the potential to address global issues concerning energy. Above all, cost must come down before wide spread use can be realized.

Also, we need to realize that implementation of IRES can bring about significant socio-economic benefits such as improved community welfare and quality of life, which include lighting for children’s night studies, street lighting, evening cottage industry as well as educational activities name a few. Case studies of rural areas that have high penetration of improved biogas operated stoves have shown clear results of improved women's health in addition to spending less time and labor for fuel wood collection and cooking. With the availability of reliable power supply, rural small scale industries can flourish, thereby creating local employment opportunities. Access to television and radio can facilitate dissemination of information on commodity prices, weather and new farming methods and practices. All such benefits can justify the use of renewable energy technologies in rural areas, although these costs may not be as high as those involved in extension of electric grids.

Further, it is necessary to develop political will and commitment to realize the promise of sustainable development facilitated by IRES. Public policies supported by both public and private sectors need to be formulated to facilitate technical know-how transfer among the developed and developing nations. The development of IRES can be used as a tool to generate jobs and promote local industry through innovative, sustainable and replicable business models for both small-scale equipment manufacturing and consumptive uses of renewable energy technologies. Research and development of such technologies and concepts should be coordinated on a global level through available databases matching rural populations, their energy requirements, income levels and distribution of energy resources.

The design of IRES would be area-specific, thus making it even harder to generalize the procedure [47]. Proper consultation with the rural communities forms an essential part of IRES design procedure to learn about their exact energy needs and the available resources. Failure to do so may result in a mismatch between what is installed and what is required. Moreover, an efficient design would ensure minimal installation of electricity-producing technologies as compared to non-electrical technologies and this would help in further reducing the overall costs. Each of the resource-need combinations may be separately studied and modeled in order to derive conclusions on efficiency and the cost of its implementation [31, 48]. IRES design simulations can then be carried out by including only those components required as per the needs and the available resources at a particular site. The essence of IRES lies in its efficient design and the fact that it involves harnessing locally available renewable energy resources to “energize” remote areas. In all these regards, the concept of IRES will prove to be more economical and smart as compared to other options for remote communities.

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VITA

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Scope and Method of Study: The purpose of the study was to consider the integration of hydrogen storage technology as means of energy storage with renewable sources of energy. Hydrogen storage technology consists of an alkaline electrolyzer, gas storage tank and a fuel cell. The Integrated Renewable Energy System (IRES) under consideration includes wind energy, solar energy from photovoltaics, solar thermal energy and biomass energy in the form of biogas. Energy needs are categorized depending on the type and quality of the energy requirements. After meeting all the energy needs, any excess energy available from wind and PVs is converted into hydrogen using an electrolyzer for later use in a fuel cell. Similarly, when renewable energy generation is not able to supply the actual load demand, the stored hydrogen is utilized through fuel cell to fulfill load demand. Analysis of how IRES operates in order to satisfy different types of energy needs is discussed.

Findings and Conclusions: All simulations are performed using MATLAB software. Hydrogen storage technology consisting of an electrolyzer, gas storage tank and a fuel cell is incorporated in the IRES design process for a hypothetical remote community. Results show that whenever renewable energy generated is greater than the electrical demand, excess energy is stored in the form of hydrogen and in case of energy shortfall, the stored hydrogen is utilized through the fuel cell to supply to excess power demand. The overall operation of IRES is enhanced as a result of energy storage in the form of hydrogen. Hydrogen has immense potential to be the energy carrier of the future because of its clean character and the model of hydrogen storage discussed here can form an integral part of IRES for remote area applications.

ADVISER’S APPROVAL: Dr. R. Ramakumar