Operational Optimization of

Integrated Renewable Energy System – Microgrid

A Thesis

Submitted by

DILRAJ MEENA

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THESIS CERTIFICATE

This is to certify that the thesis titled **Operational Optimization of Integrated Renewable Energy system – Microgrid** submitted by Dilraj Meena, to the Indian Institute of Technology, Madras, for the award of the dual degree, **Bachelor of Technology in Electrical Engineering and Master of Technology in Power systems and Power electronics**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Dr. Shanti K. Swarup
Project Guide
Dept. of Electrical Engineering
IIT-Madras, 600036

Place: Chennai

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ABSTRACT

Remote communities are in general not connected to the main power grid due to geographical conditions and this condition is severe in India. A hybrid microgrid using renewable energy as the main source can serve as a viable solution for this problem with considerable economical and environmental benefits. The focus of this project is to develop and study various microgrid used for different applications, especially for an off-grid community in India that combines Solar irradiation and Wind as a main renewable source of energy, and a storage system based on hydrogen, with zero load rejection policy, while minimizing the cost of installation of such hybrid system.

Three types of Microgrid, Residential Microgrid, Remote Area Microgrid and Microgrid Power has been developed and discussed in detail. Various comparative studies has been done for better understanding of different aspects of Microgrid.

Keywords: Cost Optimization, Hydrogen storage, Economic dispatch, Remote Area Microgrid, Industrial Microgrid, Residential Microgrid.

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ABBREVIATIONS

RES	Renewable energy sources
DERs	Distributed energy resources
GAMS	General Algebraic Modelling System
MIP	Mixed integer programming
NLP	Nonlinear Programming
HOMER	Hybrid Optimization Model for Electric Renewables
IRES-MG	Integrated Renewable Energy Sources – Microgrid
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
IMGs	Industrial microgrids
DG	Diesel generator
SHP	Small Hydro Power

Chapter 1

Introduction

1.1 Project Motivation

In spite of having an installed capacity of 214.63 GW as of February 2013, fifth largest in the world, over 300 million Indian citizens have no access to electricity with major chunk being formed by rural population. Of those in rural areas who did have access to electricity, the supply is intermittent and unreliable. [1]

Due to its unique geographical location India holds a certain advantage over countries to harness the potential of renewable energy, but India's significant and sustained economic growth is placing enormous demand on its energy resources. Apart from huge quantities of diesel and furnace oil used by all sectors – industrial, institutional, commercial and residential, lack of rural lighting is leading to large scale use of kerosene. This usage needs to be curtailed as it is leading to enormous costs in form of subsidies and increasing the countries import dependence. [2]

The wind-solar-diesel systems designed for remote communities include storage devices like hydrogen storage or battery. In order to have an economical operation of such systems, an initial step is to economically size the components in this system. The unit-sizing of components in a system including renewable resources, diesel units, and storage devices aims for economical design of the system, lower cost of electricity, and better environmental impacts.

1.2 Objective and Scope of the project

1.2.1 Objective

The main objective of this project is to devlop operational optimization models for Remote area microgrid, Residential microgrid and Industrial microgrid.

1.2.2 Scope

This project is related to operational optimization issues of remote area microgrid, residential microgrid and industrial microgrid. Optimal sizing of the system has been done in case of remote area and residential microgrid using General Algebraic Modelling system (GAMS) and Hybrid Optimization Model for Electric Renewables (HOMER) whereas in case of industrial microgrid emphasis has been on reduction of cost of operation of via inclusion of distributed energy resources in the system for which an optimal generation and dispatch model has been developed using quadratic optimization using GAMS. This project does not examine the dynamic behaviour of the microgrid, the system control algorithms, voltage and frequency stability analysis and response of the system when faults occur during its operation.

1.3 Thesis Structure

Chapter 2 is dedicated to historical background and literature survey. This chapter introduces the current state of renewable energy resources in India and their application in microgrid research keeping its application in off-grid areas in mind. In this chapter, a brief history of integration of renewable resources in traditional, systems is given. Optimization methods for unit-sizing purposes are discussed; pros. and cons. of each method are mentioned. A brief introduction has also been given regarding types of microgrid.

Chapter 3 discusses about Remote area microgrid and various components used in hydrogen based storage system. In the later part of the chapter problem formulation has been done to optimally size the hybrid system and a yearlong study of operation has been performed to check the reliability of the model.

Chapter 4 deals with issues related to Industrial microgrid and a comparative study has been done in the chapter where industrial load is being supplied only by fuel based power plants and in the second case where it is supplied by power plants in integration with distributed energy resources.

Chapter 5 is dedicated to residential microgrid where consumption of average household is calculated and a comparative study has been done between traditional battery bank storage system and hydrogen based storage system where pros and cons of each storage system has been discussed.

Chapter 6 summarizes the projects main points and contributions and proposes direction and suggestion for future work.

Chapter 2

Microgrid Planning and Operation

2.1. Overview: Renewable energy in India

Economic growth, increasing prosperity and urbanization, rise in per capita consumption and spread of energy are the key factors that are responsible for substantially increasing the total demand for electricity as show in figure below. Thus there is an emerging energy supply-demand imbalance.

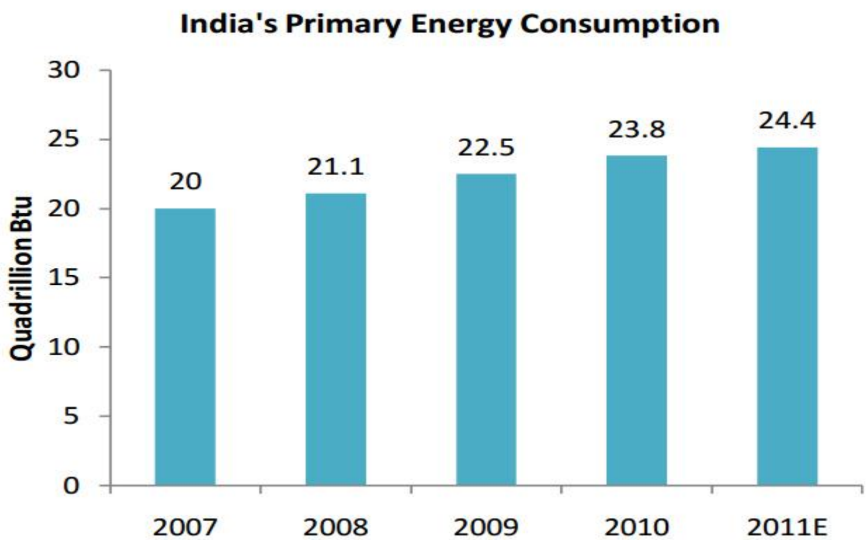

Fig. 2.1: India's Primary power consumption [Source: International Energy Outlook 2011]

Renewable energy can no longer be treated as "alternate energy" but is increasingly becoming a vital part of the solution to the nation's energy needs, as of march 31, 2012, installed capacity of renewable energy based power generation was 24,503 MW. The major renewable energy sources in India are wind energy, solar energy, biomass & waste energy, and small-hydro energy

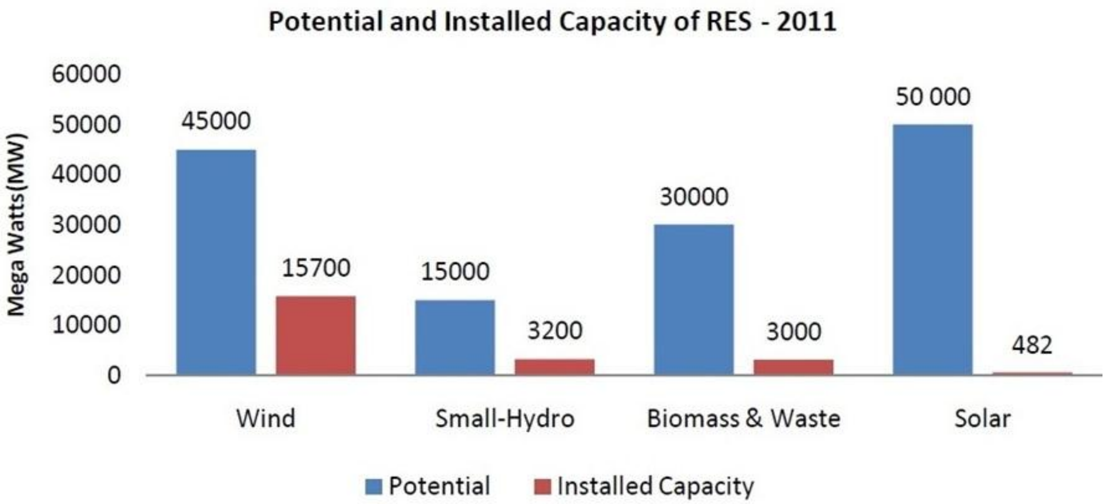

Fig. 2.2: India's Potential and Installed capacity of RES [Source: www.mnre.gov.in]

2.1.1. Wind Energy

Development of wind power began in the 1990's and has progressed significantly in the last few years and it accounts for 6% of India's total installed capacity. As of 31 Jan 2013 country's total wind power installed capacity is 18634.9 MW, mainly spread across Tamilnadu (7134 MW), Gujrat (3093 MW), Maharashtra (2310.7 MW), Karnataka (1730.1 MW), Rajasthan (1524.7 MW). [4]

2.1.2. Small-Hydro Energy

Hydro power projects with station capacity of 25 MW falls under the category of small hydro power capacity (SHP). Total installed capacity of small hydro projects as on March 31, 2012, was 3200 MW, however the estimated potential is more than 15000 MW. Most of the latent potential is in the Himalayan states. The SHP programme is largely private driven.

2.1.3. Solar Energy

India is densely populated and has high solar insolation, an ideal combination for using solar power in India, with about 300 clear sunny days in a year, India's theoretical solar power reception is about 5000 trillion kwh/yr. The daily average solar energy incident over India varies from 4 to 7 kwh/m2. For example assuming efficiency of PV modules were as low as 10% this would still be a thousand times greater than the domestic electricity demand projected for 2015 [5]. The grid connected solar power as of December 2010 was merely 10 MW but by July 2012 the installed grid connected photovoltaics had increased to 1040.6 MW. After realizing the potential of solar power Indian government unveiled the ambitious Jawaharlal Nehru National Solar Mission to produce 20GW of solar power by 2022.

2.1.4. Biomass and Waste energy

Owing to its virtues, biomass gasification can play a key role in the electrification of rural and remote communities as India's climatic conditions offer an ideal environment for biomass production. In spite of having a potential of over 30,000 MW of power from biomass but only 3000 MW was has been exploited leaving 90% of the potential capacity untapped.

2.2. Microgrid: Basic Introduction

A microgrid is a coordinated electrical system with multiple DERs and multiple loads, operation of the system can be autonomous/semiautonomous either in parallel or islanded mode which will be collectively treated by the grid as a controllable load or generator accordingly. It is connected to the grid at only one point, the point of common coupling (PCC). The main objective of its conception is to facilitate the penetration of distributed generation and provide high quality and reliable energy supply. The components that constitute the microgrid may be physically close to each other or distributed geographically.

The energy sources may be rotating generators or distributed energy (DE) sources directly connected to grid or interfaced by power electronic inverters. The installed DE may be wind, solar, fuel cells, geothermal, biomass, steam and gas turbines.

The connected loads may be critical or deferrable. Critical loads require reliable source of energy and demand stringent power quality. Non-critical loads may be shed during emergency situations and when required as set by the microgrid operating policies. The intermediate energy storage device is an inverter-interfaced battery bank, hydrogen storage, super capacitors or flywheel [3].

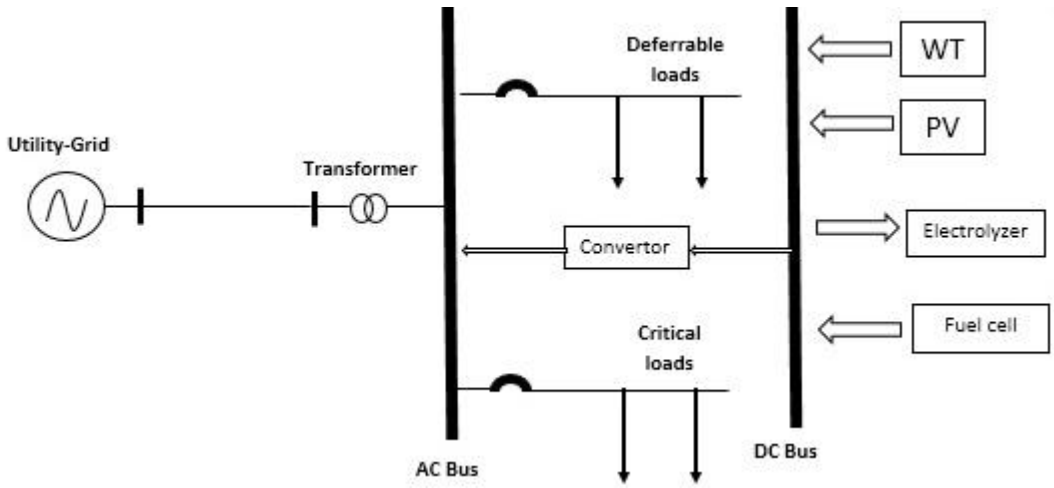

Fig. 2.3: Single line diagram of Microgrid

The microgrid can operate in grid-connected mode or in islanded mode. In grid-connected mode, the microgrid either draws or supplies power to the main grid. The microgrid components are controlled using a decentralized decision making process in order to balance demand and supply coming from the sources and the grid.

Microgrid can be classifies into various types depending upon the load it supplies, and thus has characteristics of its own. Majorly it is divided into three type's viz. Residential microgrid, Remote Area microgrid and Industrial Microgrid. Differences between the above mentioned microgrids are shown below in Table. 2.1:

Table 2.1: Comparison between different types of Microgrid

	Residential Microgrid	**Remote Area Microgrid**	**Industrial Microgrid**
Utility Connected	May be	No	Yes
Autonomous	May be	Yes	No
Emphasis on	Minimization of cost of supply of power	To supply power for a maximum period	Reliable power (zero load rejection) with minimum cost of operation
IRES components	PV/Wind	PV/Wind/Hydro/Biomass	Fuel based power plants

As shown above each microgrid has its own preferences, components depending on its type, location and demand. As in case of residential microgrid it can be autonomous or semi-autonomous in nature. Whereas remote area microgrids are autonomous in nature mostly due to geographical adverse conditions and aim of such microgrid is to supply power most of the time of the year with minimum cost. In case of industrial microgrid, due to critical nature of industrial load it should be ensured that load should be supplied at all time with no interruption in power supply thus conventional source of power generation viz. fuel based power plants are used to supply the major chunk of power of industrial load and distributed energy sources are used to supply a part of it to reduce the cost of operation.

2.3. Historical background and literature survey

Remote communities, are in general not connected to the main power grid and they get their power from diesel generators. Long geographical distances and lack of suitable means of transportation make the fuel transportation difficult and costly, resulting in increase in the generation cost of electricity. A hybrid microgrid using renewable energy as the main source can serve as a viable solution for this problem with considerable economical and environmental benefits.

Studies have shown that the integration of wind power into traditionally diesel-only remote area power supply (RAPS) systems can significantly reduce the harmful emissions and life-cycle costs. Due to the very high costs of installing and maintaining transmission lines, islands and small villages located away from main grids often have their own power supply system. These standalone systems are typically powered by conventional diesel generators as they have high reliability, low capital cost and are easily deployable. But in the recent years however, the cost of renewable energy sources is dropping and the diesel fuel price is increasing and its supply diminishing, hybrid systems are already an attractive option plus they have no harmful effects on the environments. [6]

Potential of unconventional sources to provide electricity to off-grid remote location can be understood several case studies. In addition to this if we add wind turbines and diesel generator as a back-up than we are looking a self-sustained reliable system capable of supplying the required power [7-8]

Various optimization techniques, such as probabilistic approach, graphical construction method and iterative technique, have been recommended for renewable energy system designs. Besides these optimization techniques for designing solar and/or wind systems, some diesel generator control strategies have been reported for the design of power generation systems including diesel generators [9].

Further research showed that, [10] use fuel cells and electrolyzer storage had clear advantage regarding portability and reliability, pollution though lacks in the aspects related to capital cost and efficiency. The problem regarding heat and efficiency can be targeted [11] using CHP generation system. New Technologies such as plastic micro-wind turbine [12] can also be incorporated for better which seems very promising and has very low capital cost and negligible O/M cost.

In [13], an energy-flow model developed for performance analysis and unit sizing of an autonomous wind-diesel microgrid has been introduced. A remote community is used as the study system, for which a wind power plant has been integrated at a medium penetration level into a system served by diesel generators. Lack of an energy storage component in this system is considered a disadvantage.

Reference [14] recommends a model for the design of stand-alone hybrid solar-wind diesel systems. The problem formulation makes sure that annual cost of the system is minimized, while using zero load rejection policy with minimum cost. The objective formulation has been solved using Genetic algorithm

The optimization of a hydro-solar-wind-battery hybrid system in context of minimizing the excess energy and cost of energy has been discussed in [15]. The configuration of the hybrid system is derived based on a theoretical domestic load at a remote location.

A method for calculation of the optimum size of a battery bank and the PV array for a standalone hybrid wind-PV system is developed in [16]. For a given load, the optimum number of batteries and PV modules were calculated based on the minimum cost of the system.

The hybrid system developed for remote area in this project uses a wind turbine/pv array, as the main source of energy, an electrolyser to absorb the excess power from the microsource, a hydrogen tank to store the hydrogen generated by the electrolyser, a fuel cell to supply the power deficit when the renewable resources is not adequate to meet the load, and a diesel generator as a backup. In case of industrial microgrid an attempt has been made to reduce the cost of operation while supplying industrial load by integration of renewable energy resources in the system.

2.4 Optimization tools GAMS and HOMER

2.4.1 GAMS

The General Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical programming and optimization. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows you to build large maintainable models that can be adapted quickly to new situations.

GAMS is especially useful for handling large, complex, one-of-a-kind problems which may require many revisions to establish an accurate model. The system models problems in a highly compact and natural way. The user can change the formulation quickly and easily, can change from one solver to another, and can even convert from linear to nonlinear with little trouble. GAMS provide solution to the problems much quicker than traditional platform used for programming such problems such as MATLAB due to compact nature of its modelling and avoidance of solving problems with running into loop each time for every indices.

In these project GAMS model has been built for all three microgrids discussed in chapter 2, viz. Residential microgrid, Remote area microgrid and Utility connected serving different purpose in each case which will be discussed in subsequent chapters.

2.4.2 HOMER

Hybrid Optimization Model for Electric Renewables is a computer model provided by NREL that simplifies the task of evaluating design options for both off-grid and grid connected power systems for remote, standalone and distributed generation (DG) applications.

HOMER optimization and sensitivity analysis algorithms allow the evaluation of the economic and technical feasibility for a large number of technology options and to account for variation in technology costs and energy resource availability. It models both conventional and renewable energy technologies by making energy balance calculations for each of the 8760 hours in a year. For each hour HOMER compares the electric demand of the system in that hour to the energy system can supply in that hour and calculate flow of energy from each component resulting in an optimal solution of installation cost and cost of project over its lifetime. The system cost calculations accounts for costs such as capital, replacement, operation and maintenance, fuel and interest rate.

In the project HOMER has been used as an analysis tool to conduct comparative studies between hydrogen based storage and traditional battery based storage in Chapter 4 while discussing Residential Microgrid.

Chapter 3

Remote Area Microgrid

3.1 Introduction

The microgrid proposed in Chapter 3 uses a solar array and wind turbine as the main source of energy, hydrogen storage device including electrolyser to absorb the excess power from the wind source, a fuel cell to supply the power deficit when the resources is not adequate to meet the demand, a hydrogen tank to store the hydrogen generated by electrolyser, and a diesel generator as a back-up source.

The two scenarios used for the purpose of unit-sizing are as follows:

1. **Diesel-only operation:** The system is operating in its traditional mode, and it uses diesel generators as power source. This scenario can be considered as the base operating mode. The advantages of this scenario are low capital cost, low maintenance, no dumped energy. The disadvantages are dependence on fuel and very high greenhouse gas emissions.

2. Hybrid Operation: In this scenario, all the demand will be met by the renewable energy sources (wind energy and solar energy). The flowchart of this scenario can be seen in Fig. 3.1, where the decision making algorithm is illustrated.

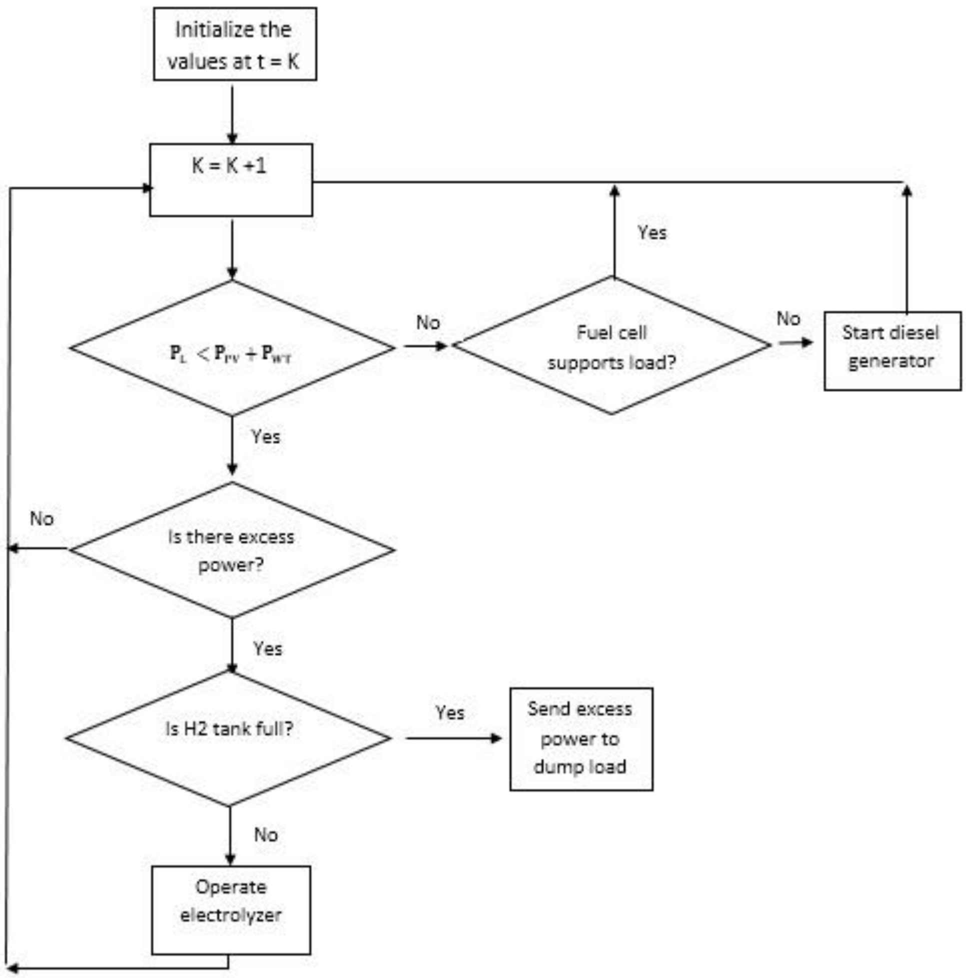

Fig. 3.1: Flow chart of operation of the remote area microgrid

In the case where wind and solar together cannot meet the demand, the algorithm goes to check the availability of power by fuel cell. If there is hydrogen in the tank, and the extra demand to be met is less than capacity of fuel cell, fuel cell will supply the demand. Otherwise, diesel generator will start to work, or will increase its power to meet the demand. It is assumed that there is no load shedding. The advantages of this scenario are very low operating cost, increased reliability due to hydrogen storage, very low emissions, and independence from fuel price variations. The disadvantages are intermittent nature of renewable energy and high capital cost of system.

3.2. Components of Microgrid

Microsources used to supply loads in the developed microgrid are wind power and solar power due to their yearlong availability in most of the parts of India as shown in the Fig. 2.3

3.2.1 PV Array

A number of solar cells connected to each other and mounted in a support structure or frame is called a photovoltaic module. Modules are designed to supply electricity at certain voltage, typically a 12 volt system. The current produced is directly dependent on how much light strikes the module. Multiple photovoltaic cells can be wired together to form an array. In general, the greater the surface area of a module or array, the more electricity will be produced. Photovoltaic arrays produce direct electricity. They can be connected in series and parallel electrical arrangements to produce and required voltage and current combination.

A bulk PV module consists of multiple individual solar cells connected, nearly always in series, to increase the power and voltage from that of single solar cell. Under optimum tilt conditions, the current density from a commercial solar cell is approximately is $30mA/cm^2$ to $36mA/cm^2$. Single crystal cells are often $100\,cm^2$, giving a current of about 3.5 ampere from a module. Multi crystalline modules have larger individual solar cells but a lower current density and hence the short-circuit current from these modules is often approximately 4A. However there is a large variation on the size of multi-crystalline silicon solar cells, and therefore this current may vary.

Insolation data is converted into power output from the photovoltaic array using the following equation [17]:

$$P_{PV}(t) = Ins(t) * A * Eff_{pv} \tag{3.1}$$

Where,

$Ins(t)$ = insolation time at time t (kW/m^2)

A = area of single PV module (m^2)

Eff_{pv} = Overall efficiency of the PV module and DC to DC boost convertor

Eqn (3.1) assumes temperature effects (on PV cells) are ignored.

3.2.2 Wind Turbine

Wind turbines make use of kinetic energy contained within the wind itself to turn a propellers of different kinds, which then turns a generator to create electricity. Important factor in determining wind power is the speed at which generator rotates. However since the generator rotation speed is directly affected by the rotation of the turbine we need to look at the factors that affect the turbine rotation, primary of these factors are wind speed and swept area by the blades of the wind turbine. In the developed case hourly wind data is evaluated and converted to wind turbine. If the speed is between the cut in and rated speed of turbine than the power output of wind turbine is defined as [18]:

$$P_{Wind}(t) = \frac{1}{2} * \rho * A * v^3(t) * C_p * Eff_{ad} \quad (3.2)$$

Where,

ρ = air density (kg/m^3)

A = area swept by the rotor (m^2)

v(t) = wind speed (m/s)

C_p = efficiency of the wind turbine

Eff_{ad} = efficiency of the AC to DC convertor

3.2.3 Hydrogen Storage

Hydrogen which has a specific energy of 143MJ/kg, about 40 kWH/kg requires about 50 to 60kWh of DC electricity in electrolyzer during electrolysis to generate 1kg of hydrogen which is then then again converted to DC current via Fuel cells.

In this project hydrogen storage has been used as an alternate source of energy when power from pv-wind hybrid system is lower than the demand. In this system excess power generated via wind turbines/solar panels (generally in the day) is converted into hydrogen via electrolyzer and hydrogen is stored in the hydrogen tanks for the use whenever there is deficit of power (generally in night) via fuel cells which convert the chemical energy of the fuel directly into electrical energy.

Solid oxide fuel cells (SOFC) is one of the types of fuel cells and use ceramic materials as their electrode and electrolyte. This allows SOFC to work at high temperatures. SOFC system also exhibit stable performance with varying load. In addition to it proton exchange fuel cell deliver high power density and offer the advantage of low volume and low weight compared with other fuel cells [19].

3.2.4 Diesel generator as backup

A diesel engine power generator is the combination of a diesel engine with an electrical generator to provide electricity. In the microgrid considered diesel generator is only used as back-up as depicted in Fig. 3.2, rather than in a parallel operation or in standalone. Though in the case study calculation has been done to determine the annual cost of the diesel used if the load was completely supplied by a standalone diesel generator set.

Diesel generator has several advantages over the other internal combustion engines such as, they have no high tension electrical ignition system to attend to resulting in high reliability and easy adaptation to damp environment, their lifetime is more due to increased strength of the parts used and they can deliver much more power of their rated power on continuous basis

3.2.5 Proposed Microgrid

The microgrid that will be developed and studied is shown in Fig. 3.2. It includes solar panel and wind turbine connected to the DC bus via a squirrel-cage induction generator, load of the area, and electrolyser-hydrogen storage-fuel cell system.

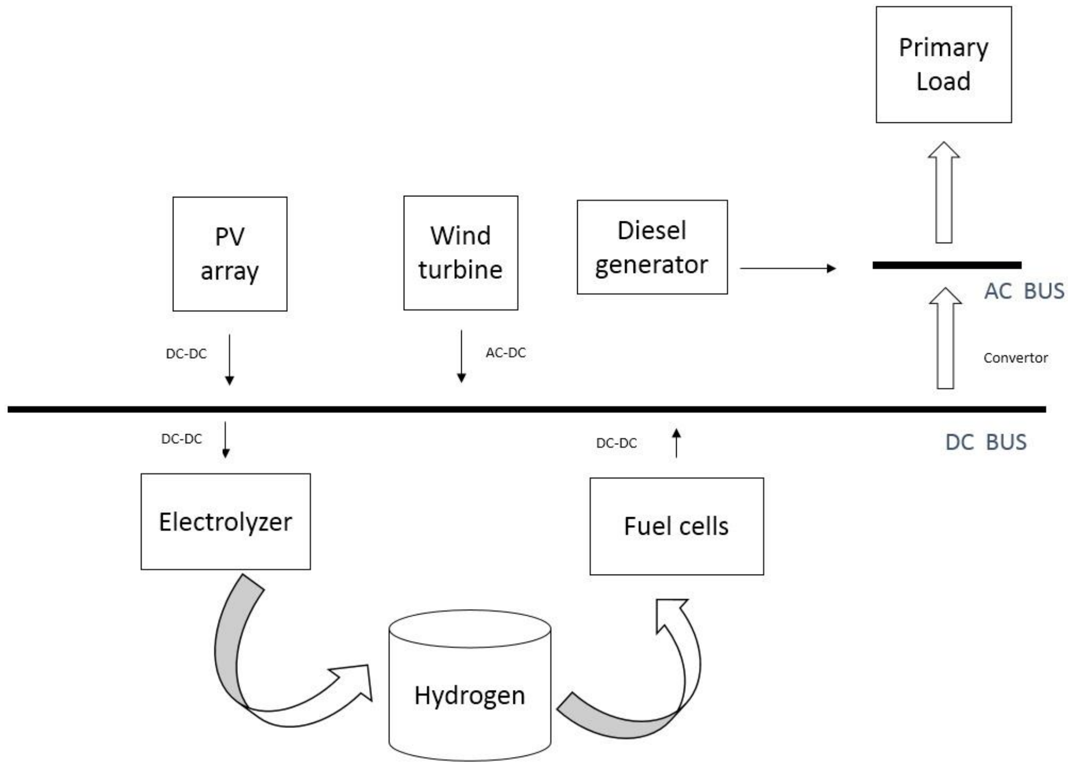

Fig. 3.2: Block diagram of the microgrid under study

Excess power generated at DC bus is converted into hydrogen via electrolyzer and hydrogen is stored in Hydrogen tanks. Whenever power from microsources is not able to supply is able to fulfill only partial demand Fuel cells comes into play and hydrogen stored is used to the load demand. A simple power management algorithm has been used to operate the system.

3.3 Optimization problem formulation

This section presents the optimization model of Remote area microgrid. Problem formulation has been done based on power dispatch algorithm presented in Fig-3.1. The mathematical formulation is described in (3.3)-(3.9). The model is formulated as MIP (mixed integer programming) in GAMS environment and the solver is BDMPL

A. Objective Function

The objective is to minimize the cost of electricity produced by the hybrid system. The cost of electricity depends on capital and operating costs of components. The sizes of units and the energy used by diesel generators reflect the cost of system. The simulation has been done for a year; so, the objective function can be described as follows [8]:

$$Cost = C_{fc} * afc + C_{elec} * alec + C_{wind} * awind + C_{solar} * asolar + C_{diesel,unit} \sum_{k=1}^{N} P_{diesel,\,k} + C \qquad (3.3)$$

Where,

C_{fc} = Capital cost of a fuel cell unit

C_{elec} = Capital cost of the electrolyzer unit

C_{wind} = Capital cost of Wind turbine unit

C_{solar} = Capital cost of PV module

$C_{diesel,unit}$ = Cost of generation of 1 Unit of power from diesel generator

C = Miscellaneous cost of the system

afc = number of fuel cell units

alec = number of electrolyzer units

N depends upon period of simulation and sampling time in the case study provided in the project samples are obtained once in a hour during a year, so N is 8760.

B. Constraints

1) Power flow equation constraint

$$P_{wind,k} + P_{solar,k} + P_{diesel,k} + P_{fc,k} - P_{elec,k} - P_{load,k} = 0 \quad (3.4)$$

$$\forall\, k = 1\ to\ N$$

2) Power flow from fuel cell and electrolyzer

$$P_{fc,k} - P_{fc,max} \leq 0 \quad (3.5)$$

$$P_{elec,k} - P_{elec,max} \leq 0 \quad (3.6)$$

$$\forall\, k = 1\ to\ N$$

3) Fuel cell and Electrolyzer sizing constraints

$$P_{fc,max} = a_{fc} * P_{fc,rated} \quad (3.7)$$

$$P_{elec,max} = a_{elec} * P_{elec,rated} \quad (3.8)$$

4) Hydrogen tank storage constraint

$$\sum_{k=1}^{N} (P_{elec.k} - P_{fc,k}) \leq C_{H2} \quad (3.9)$$

$$\forall\, k = 1\ to\ N$$

Where,

$P_{fc,max}$ and $P_{elec,max}$ are maximum rated capacity of the stack of fuel cells and stack of the electrolyzers,

C_{H2} = maximum capacity of hydrogen that can be stored in the hydrogen tank

$P_{fc,rated}$ and $P_{elec,rated}$ are the rated capacity of single unit of fuel cell and electrolyzers

3.4 Case study

In order to simulate and study the behaviour of microgrid over a long period of time a yearlong study has been done, the load profile of the remote area for the whole year is shown in Fig. 3.3

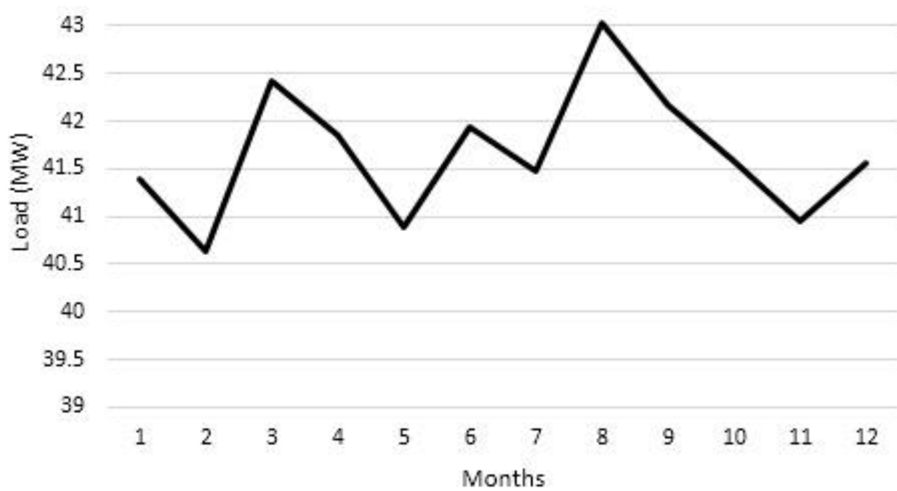

Fig. 3.3: Load data of a remote community

In the figure above load profile of a remote community has been shown which will be supplied via hydrogen based storage system as already discussed. 8760 samples with each sample of size 60min has been used for the purpose of power flow.

Yearlong solar and wind data of the place considered in study has been shown in Fig. 3.3 and Fig 3.4

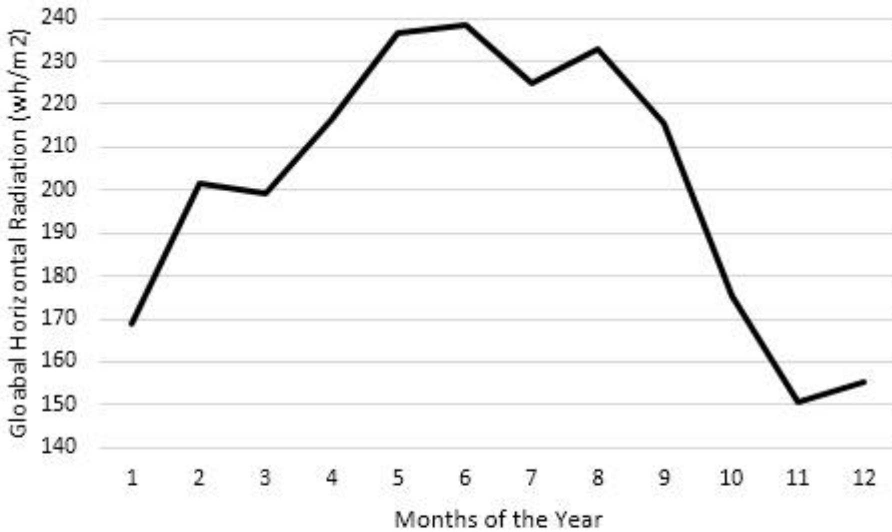

Fig. 3.4: Monthly average solar data of a remote community (wh/m^2)

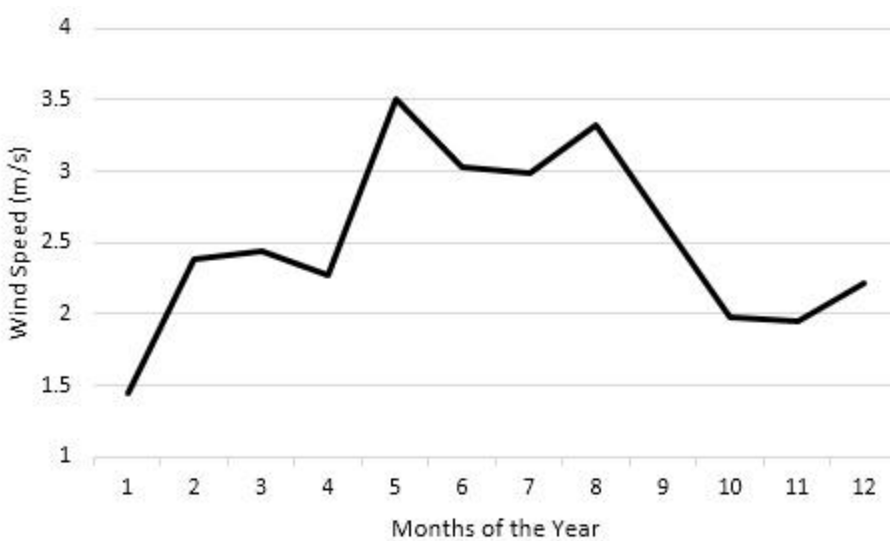

Fig. 3.5: Monthly average wind data of a remote community (m/s)

The information on microgrid components including wind turbine, fuel cell, electrolyser, hydrogen tank, is given in Table-3.1.

Table-3.1: Microgrid components specifications

	Wind turbine	**Fuel cell**	**Electrolyser**	**PV panel**	**Power Converter**	**Diesel generator**
Manufacture	Hikochi Electronics Limited	Horizon fuel cell technologies	HySolGenics M2	Reliance	Luminous	
Rated output power per unit (kW)	10	5	5	7	5	120
Cut-in speed (m/s)	2.5	NA	NA	NA	NA	NA
Cut-out speed (m/s)	25	NA	NA	NA	NA	NA
Rated speed	12 (m/s)	NA	NA	NA	NA	NA
Swept area (m2)	50.24	NA	NA	NA	NA	NA
Capital cost (Rs)	624000	780000	468000	1060000	2,000	NA
Efficiency (%)	25	50	75	12.5	95	90
Lifetime (year)	20	6	7	20	5	20
Fuel consumption (litre/hour)	NA	NA	NA		NA	15

3.4.1. Scenarios

Two main scenarios has been considered in this, project first one is traditional diesel based system in which power at all time is supplied via diesel generator and second one which is a hybrid pv-wind system

A. Only Diesel

In this scenario, the system is operated in its traditional mode, where diesel generators are used as the only power source. The diesel generator considered for this project is 140kw diesel generator which consumes 14-16 litre of diesel while supplying power at the efficiency of 75 to 85%, which is ideal for the load profile considered in this case, but as the load demand may vary over a large range, efficiency of the generator From the above information cost of diesel for generation of 1 unit can be calculated as:

Total annual load to be supplied via DG	=	364.9 MW
Amount of diesel consumed to generate 1 unit of power	=	1-1.5 litre
Cost of diesel to generate 1 unit of power	=	50-75 Rs.

Total cost to supply the load demand throughout the year = 364900*70 = 27367500 Rs

B. Fully-renewable

To show proper functioning of the model a test simulation has been done for hourly data of load wind power and solar power starting from midnight for 24 hours, results are shown in Fig. 3.6

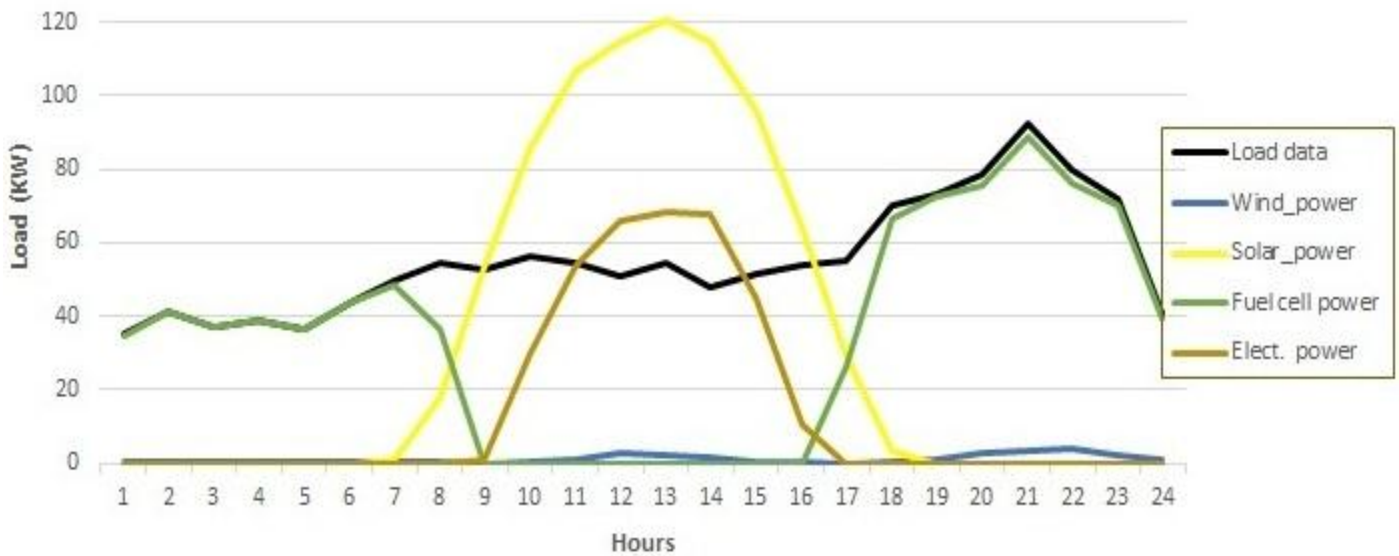

Fig. 3.6: Power share between Solar, Wind, Fuel cell and Electrolyzer

It can be seen from the result that during night time from 12 am to 7am when there is no power generation from solar and wind power so required amount of load is supplied by fuel cell. Solar panels starts generation of power from 7am till 6pm as the system realizes that there is no power from renewable sources during the night so it stores the extra hydrogen via electrolyzer in the hydrogen tank keeping the load demand during night in mind.

The GAMS model, as explained before, is based on power share of the components with the objectives of satisfying the demand of the area and minimizing the operating cost of the system that results in minimum cost of electricity.

In this case simulation has been done for a yearlong hourly data of the wind speed, solar irradiation and load data of the remote community. In spite of promising developments in the field related to efficiencies of wind turbine, solar cells, fuel cells and electrolyzers, assumptions which has been taken in this project are only of proven technology which has been listed below:

Table-3.2: Efficiency of Various components of the microgrid

	Component	**Efficiency (%)**	**Conversion of power**
1.	Solar panels	12.5	From Solar panels to DC to DC boost convertor
2.	Wind turbine	25	From Wind turbine to DC bus
3.	DC to DC boost convertor	85	DC to DC boost convertor to Invertor
4.	Invertor	85	Invertor to AC load
5.	Electrolyzer and DC to DC buck convertor	75	From DC bus to Hydrogen tank
6.	Fuel cells and DC to DC boost convertor	50	From hydrogen to Invertor

3.5 Results and discussion

3.5.1 Optimization results

In the hybrid scenario, sizing of renewable components (solar panels and wind turbines) is done keeping in zero rejection policy of Eqn. (3.4) that at every point of time throughout the year load should be supplied with hybrid system of Solar-Wind-H_2, result of the simulation which has been done for samples 8760 samples (no. of hours in the year) is shown below in Fig. 3.7

```
                         LOWER     LEVEL     UPPER    MARGINAL

---- VAR cost            -INF  1.3260E+8     +INF       .
---- VAR a_solar           .      64.000     +INF  1.0600E+6
---- VAR a_fc              .      42.000     +INF  7.8000E+5
---- VAR a_elec            .      47.000     +INF  4.6800E+5
---- VAR a_wind            .        .        +INF  6.2400E+5

  cost  cost of system
  a_solar  integer varible for the pv size
  a_fc  integer varible for fc size
  a_elec  integer variable for elec size
  a_wind  integer variable for wind size


**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
```

Fig. 3.7: Screenshot of GAMS showing optimal sizing result for the Remote area microgrid

According to result shown in Fig. 3.6, no of solar panels required to supply the load profile throughout the year are 64 and as each panel is considered to be of 7 KW making the rated capacity of the PV system to be 448 KW and number of fuel cells required to supply the load in absence of solar power are 42 making its total rating of fuel cell system to be 210 KW as the rating of single fuel cell is considered to be of 5 KW, similarly no. of electrolyzers required to store hydrogen during the peak season of solar power to supply power in lean season are 47 making total electrolyzer system rating to be 235 as rating of single electrolyzer is 5 KW. Cost distribution of the proposed microgrid is show below in Table 3-3:

Table-3.3: Cost distribution of the Remote area microgrid

Component	**Rating of single module (KW)**	**No. of modules required**	**Cost of single component**	**Cost of total component**
Solar Panels	7	64	1060000	67840000
Wind turbine	10	0	624000	0
Fuel cell	5	42	780000	32760000
Electrolyzer	5	47	468000	21996000
Miscellaneous	NA	NA	NA	10000000
Total cost		132596000 Rs.		

In the table shown above other than the capital cost of the components of optimally sized microgrid, miscellaneous cost has been also considered keeping in mind the cost of uncounted components of microgrid.

Hydrogen storage which is used as an intermediate storage, is the main focus of this project, as rather than the traditional storage system viz. stack of batteries a hydrogen based storage system is used, status of hydrogen in the hydrogen in the tank starting with is show in the Fig. 3.7

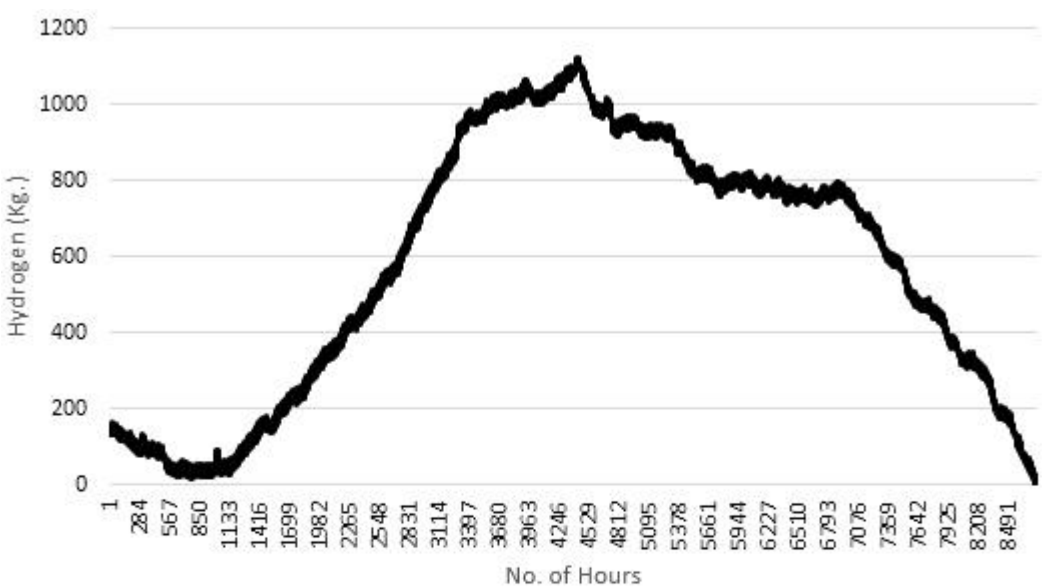

Fig. 3.8: Hydrogen tank storage throughout the year (kg)

Starting with a hydrogen storage of 150 kg as expected hydrogen storage goes up during the peak months of solar irradiation, which are May, June and July as shown in Fig. 3.4 to compensate for the poor supply of solar power in the months of October, November and December shown in the Fig. 3.4. Thus keeping this in mind hybrid system generates extra hydrogen than required during the night time and keeps increasing hydrogen storage to an optimal sufficient level without oversizing the system to supply the deficit power generation in months of lean solar power generation.

One of the most forcing result of the simulation is non-inclusion of the wind turbine in the final optimal result despite having considerable wind speed throughout the year, answers to this question can be answered after looking at the solar irradiation and wind speed data simultaneously as shown in the Fig. 3.9

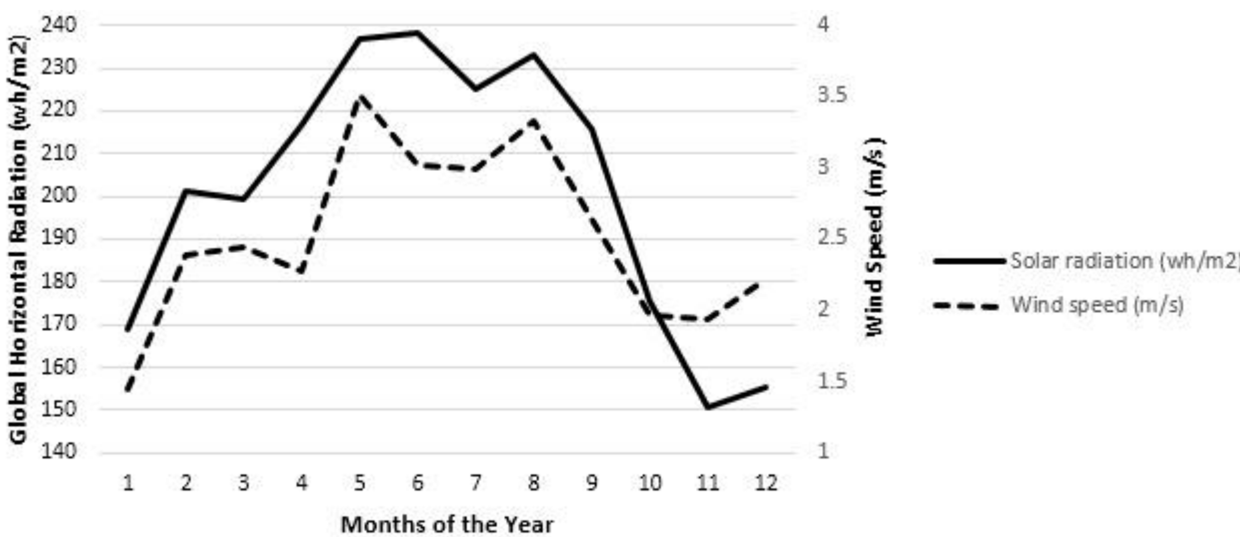

Fig. 3.9: Monthly data of wind speed (m/s) and Solar insolation (wh/m^2)

Thing that should be noticed from the above shown graph is that wind power generation is high at the same time when the solar insolation data is high, meaning that both solar panels and wind turbine both are generating power at the same time, but as the $\frac{generation\ (Kw)}{Cost\ (Rs.)}$ ratio of the pv panels is lower than that of wind turbine module thus resulting in the optimal solution of microgrid without any wind turbine.

3.5.2 Comparative study of different scenarios

To compare the two considered scenario for the longer period of the time following assumptions have been made, which are shown below:

Table. 3.4: Operation and maintenance cost of various components of Microgrid

	Fuel cell	**Electrolyser**	**Photovoltaic Panels**	**Diesel generator**
Capital cost (Rs)	32760000	21996000	67840000	NA
O&M cost/yr (Rs.)	4000	4000	12000	3000
Replacement cost (Rs.)	32760000	21996000	64000000	1200000
Lifetime (year)	5	5	20	20

After calculating the project cost for both the scenarios, diesel only and hybrid system results of the Project cost for a time period of 20 years are shown below in Fig. 3.10:

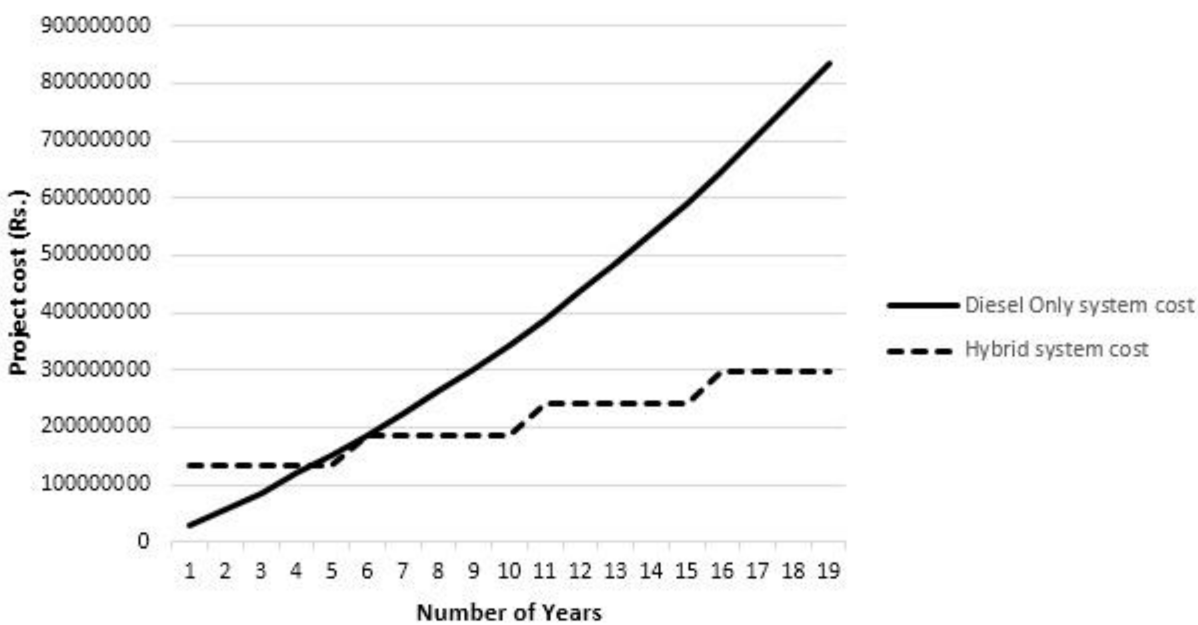

Fig. 3.10: Estimated cost of the project over the years

3.6 Summary

It can be concluded from the study that optimally sized microgrids can be used in India to supply reliable power supply to remote areas where power supply via utility grid is not possible. Yearlong operation of microgrid to supply the given load profile in Fig. 3.3 suggests that PV module of rating 448 KW, fuel cell configuration of 210 KW and electrolyzer system of rating 235 is required to supply the load with zero rejection policy throughout the year.

A comparative study has been done between standalone diesel based model and hybrid model to compare the cost of the project for a lifetime of 20 years. It is easily visible from the Fig-3.10 that in spite of low installation cost of diesel operated system after few initial years, difference between costs of operation of hybrid system and diesel based system keeps widening.

Chapter 4

Industrial Microgrid

4.1 Introduction

Industrial Microgrid are typically formed by the corpoaration of power plant and distributed energy resources. Industrial Microgrid differs from residential microgrid in various ways as already discussed in chapter 2, few characteristics which sets them apart from residential and remote area microgrid are:

1. Scale of operation of Industrial microgrid is much larger than residential and remote area microgrid.
2. Industrial microgrid loads are considered critical in nature thus power supplied should not intermittent in nature.
3. Under normal operation of Industrial microgrid major chunk of power is supplied via conventional fuel based power plants.

In certain cases industrial microgrid can be connected or disconnected from the power grid, during standalone operation IMGs must generate their own required energy to feed the electric loads through the cooperation of DG unit.

4.1.1 PV generation system in IMGs

PV systems are being accepted as suitable alternatives to the conventional energy resources due to environmental concerns and transmission congestion management issues. PV power currently represents a low percentage of global electricity production. However, its application in industrial networks is expected to grow rapidly since the peaks of most industrial loads coincide with maximum power output of the power modules [22].

In this project it has been shown that industrial microgrid can utilize the energy generated by PV plants to minimize the cost associated with the operation of fuel based power plants.

4.2 Case study 1: Only utility dependent Industrial grid

In utility dependent industrial grid transmission system is used for the delivery of bulk power over considerable distances and a distribution system is used for local deliveries. The transmission networks are interconnected through ties so that utilities can exchange power, share reserves and render assistance to one another in times of need. For an interconnected system, the fundamental problem is one of minimizing source expenses. The economic dispatching problem is to define the production level of each plant so that the total cost of generation and transmission is minimum for a prescribed schedule of loads.

The economic dispatch problem has been solved via many traditional optimization methods including [20]:

- Gradient based method
- Newton methods
- Linear programming
- Quadratic programming, and
- Dynamic Programming

Quadratic programming is a special type of mathematical optimization problem. It is a problem of optimizing (minimizing or maximizing) a quadratic function of several variables subject to linear constraints on these variables.

4.2.1 Problem formulation

The objective of the classical economic dispatch is to minimize the total system cost (Eqn. 5.1) by adjusting the power output of each of the generators connected to the grid. The total system cost is modeled as the sum of the cost function of each generator [21].

A. Objective formulation

$$min \sum_{i=1}^{N_g} F_i(P_{G_i}) \tag{5.1}$$

Where,

$F_i(P_{G_i})$ = Cost function of i^{th} generating unit,

P_{G_i} = Real power output of the i^{th} unit,

N_g = The total number of generators connected to the power system

The cost function of each generator establishes the relationship between the power injected to the system by the generator and the cost incurred to load the machine to that capacity. Generators are typically modeled by smooth quadratic functions such as Eqn. (5.2), in order to simplify the corresponding optimization problem as well as to facilitate the application of classical techniques

$$F_i(P_{G_i}) = a_i + b_i P_{G_i} + c_i P^2{}_{G_i} \tag{5.2}$$

Where,

a_i, b_i and c_i are known as the cost coefficients of the i^{th} generating unit.

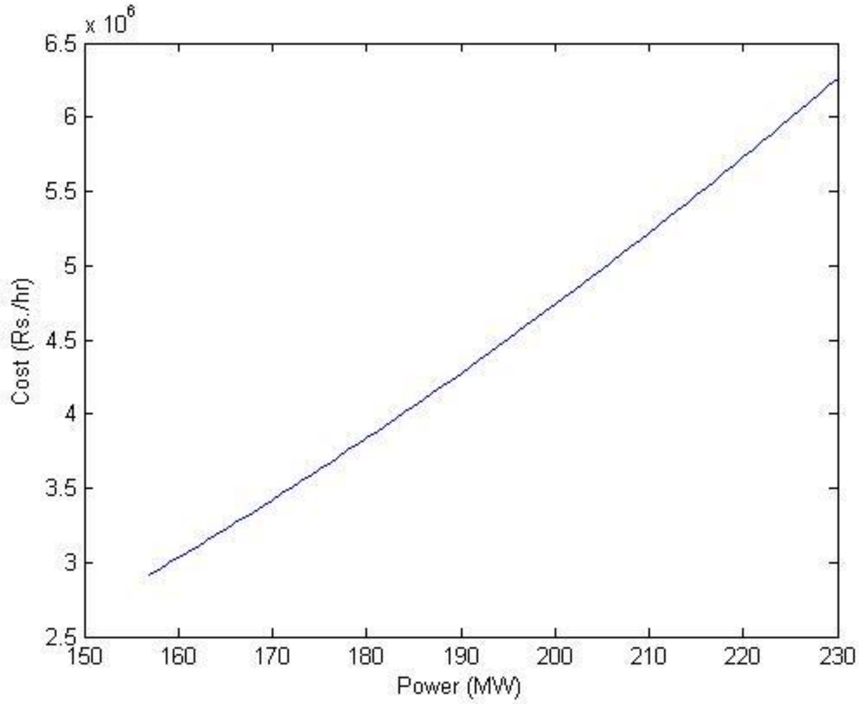

Fig. 4.1: Typical fuel cost function of a thermal generating unit

B. Equality constraint

The power balance is an equality constraint that reduces the power system to a basic principle of equilibrium between total system generation and total system loads. Equilibrium is only met when the total system generation ($\sum P_G$) equals the total system load (P_D) plus the system losses (P_L) as it is stated in Eqn. (12)

$$\sum_{i=1}^{N_G} P_{G_i} = P_D + P_L \quad (5.3)$$

The exact value of the system losses can only be determined by means of a power flow solution. The most popular approach for finding an approximate value of the losses is by the way of Kron's loss formula [21] Eqn (5.4), which represents the losses as a function of the output level of the system generators.

$$P_L = \sum_{i=1}^{N_G} \sum_{j=1}^{N_G} P_{G_i} B_{ij} P_{G_j} + \sum_{i=1}^{N_G} P_{G_i} B_{i0} P_{G_j} + B_{00} \quad (5.4)$$

Where B_{ij}, B_{i0} and B_{00} are known as the loss or B-coefficients.

C. Inequality constraint

Generating units have lower ($P_{G_i}{}^{min}$) and upper ($P_{G_i}{}^{max}$) production limits, which are directly related to the design of the machine. These bounds can be defined as a pair of inequality constraints as follows:

$$P_{G_i}{}^{min} \leq P_{G_i} \leq P_{G_i}{}^{max}, \quad i = 1,2 \ldots N_G \qquad (5.5)$$

To show the functioning of model of optimal dispatch developed in GAMS a standard problem has been taken from the book, Power generation, operation and control by Allen J wood and B.F. Wollenberg,

Fuel cost curve for the three units has been shown below

$$F_1(P_1) = 213.1 + 11.669P_1 + 0.00533{P_1}^2 Rs/h$$

$$F_1(P_1) = 200.0 + 10.333P_1 + 0.00889{P_2}^2 Rs/h$$

$$F_1(P_1) = 240.0 + 10.833P_1 + 0.00741{P_3}^2 Rs/h$$

With unit dispatch limits

$$50.0\, Mw \leq P_1 \leq 200Mw$$

$$37.5\, Mw \leq P_1 \leq 150Mw$$

$$45.0\, Mw \leq P_1 \leq 180Mw$$

And a load demand of 210 MW

Using Kron's formula, Eqn (5.4) a model has been developed in GAMS for a three bus system for which fuel cost curve, constraint on power generation and load demand are shown above and B coefficients of which are already calculated and given in the problem which are shown below:

$$P_{G_i} = [1.079 \quad 0.5 \quad 0.6]$$

$$B_{ij} = \begin{matrix} 0.0676 & 0.00953 & -0.00507 \\ 0.00953 & 0.0521 & 0.00901 \\ -0.00507 & 0.00901 & 0.0294 \end{matrix}$$

$$P_{G_j} = \begin{matrix} 1.079 \\ 0.5 \\ 0.6 \end{matrix}$$

$$B_{i0} = -0.0766 \quad -0.00342 \quad 0.0189$$

$$B_{00} = 0.0040357$$

Note: All P_i values must be per unit on 100MW base which will result in P_{loss} in per unit on 100MW base

4.2.2 Results

In the model developed in GAMS two optimal solutions have been obtained, 1st one based on minimum cost of the fuel to suffice the demand.

```
---- VAR p  power generation level in MW

      LOWER     LEVEL     UPPER    MARGINAL

p1    50.000    50.000   200.000     0.094
p2    37.500    75.486   150.000      EPS
p3    45.000    93.262   180.000       .

                       LOWER     LEVEL     UPPER    MARGINAL

---- VAR loss           -INF      8.748     +INF       .
---- VAR cost           -INF   3155.288     +INF       .

  loss  total transmission loss in MW
  cost  total generation cost - the objective function


**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
                             0     ERRORS
```

Fig. 4-2: Screenshot result of GAMS showing power distribution between generators to achieve minimum cost

As shown in the above result to achieve minimum cost of operation generator (P_1) should supply 50MW, generator (P_2) should supply 75.486MW and generator (P_3) should supply 93.262MW which would leads to minimum cost of the system viz. 3155.288 Rs/hr.

Second optimal solution aims to achieve minimization of the losses in the system as shown in the (Fig. 4.3).

```
---- VAR p  power generation level in MW

        LOWER     LEVEL     UPPER    MARGINAL

p1      50.000    58.107   200.000      .
p2      37.500    38.155   150.000 5.561E-11
p3      45.000   121.692   180.000 4.151E-10

                         LOWER     LEVEL     UPPER    MARGINAL

---- VAR loss            -INF      7.955     +INF       .
---- VAR cost            -INF   3184.376     +INF       .

  loss  total transmission loss in MW
  cost  total generation cost - the objective function


**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
                             0     ERRORS
```

Fig. 4-3: Screenshot of result of GAMS showing power distribution between generators to achieve minimum losses

It can be observed from the above result that to achieve minimum loss viz. 7.955MW generator (P_1) should supply 58.107MW, generator (P_2) should supply 38.155MW and generator (P_3) should supply 121.692MW. Results obtained above have been summarized below in the Table 4.1:

Table-4.1: Summary of the different cases solved above

Aim	P_1 (MW)	P_2 (MW)	P_3 (MW)	Loss (MW)	Cost(Rs/hr)
To minimize Cost	50	75.486	93.262	8.748	3155.288
To minimizes losses	58.107	38.155	121.692	7.955	3184.756

It can be observed from the above results that there is certain trade-off between achieving minimum cost and minimum lossess in the system, as minimization of cost comes at a certain expenses viz. increase in the lossess of the system and vice versa.

To understand the trade-off clearly, third part of the optimal dispatch model deals to achieve different various intermediate solutions to see the change in loss values with respect to the cost of the system and vice versa. The result of the trade-off are shown below in the Fig.4.4:

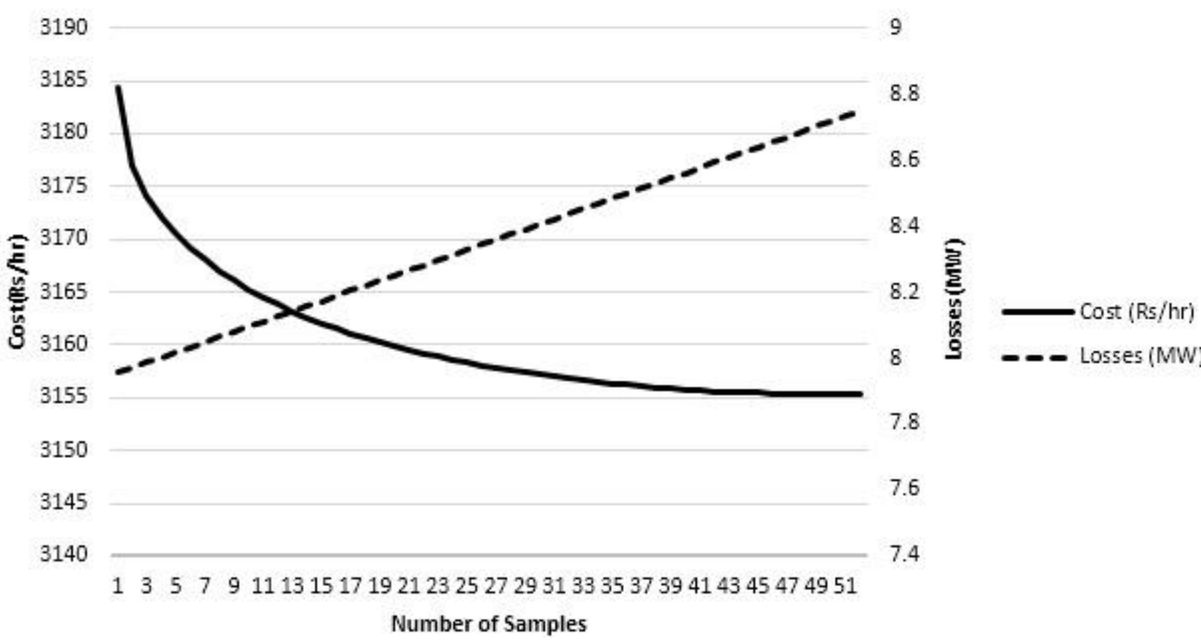

Fig. 4.4: Curve showing Inverse relation between Fuel Cost and Losses of the system

Case study solved above has been done for only for Industrial load of a single hour, thus to study a day long operation of the microgrid a 24 hour load has been chosen which is shown in Fig 4.5

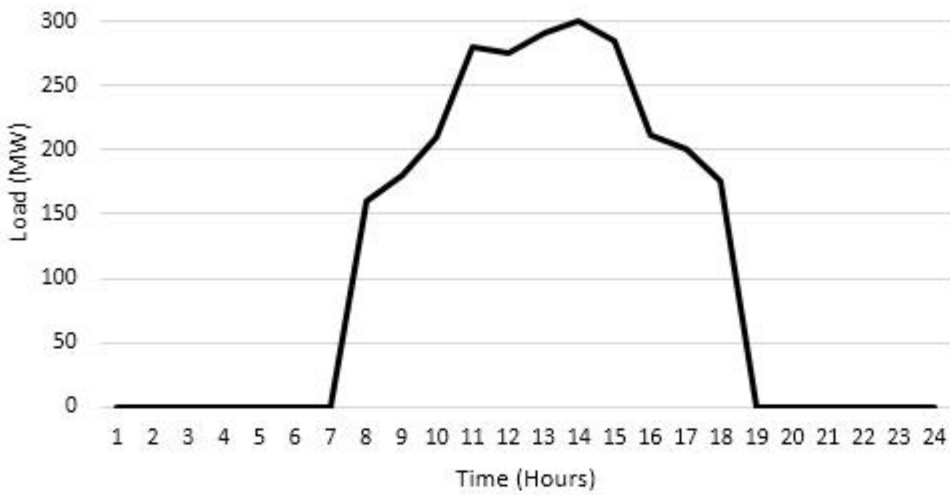

Fig. 4.5 Industrial Load data

For the given load data simulation optimal dispatching has been found to achieve minimum cost of operation which has been shown in Table-5.1

Table. 4-2: Results of optimal dispatch operation of power plants for a day

Time	Load	P_1 (MW)	P_2 (MW)	P_3 (MW)	Cost of Operation (Rs/hour)
7-8 AM	160	50	54.112	61.011	2523.559
8-9 AM	180	50	62.619	73.784	2771.414
9-10 AM	210	50	75.486	93.262	3155.288
10-11 AM	280	73.648	94.588	127.418	4098.947
11-12 AM	275	71.788	93.288	125.011	4029.608
12-1 PM	290	77.377	97.194	132.256	4238.546
1-2 PM	300	81.113	99.808	137.127	4379.386
2-3 PM	285	75.512	95.89	129.832	4168.562
3-4 PM	212	50	76.348	94.575	3181.41
4-5 PM	200	50	71.182	86.727	3025.683
5-6 PM	175	50	60.487	70.575	2708.856
Total					38281.259

4.3 Case study 2: Utility and DERs based Industrial grid: IMGs

In the case study 1 we have found cost of operation of industrial grid which is supplied by utility power. In the case study 2 a part of industrial load will be supplied by DERs in our case viz. PV module of 50 MW is used to supply the load. Solar power generation for a 50 MW solar plant near Industrial area is shown in below Fig. 4.6

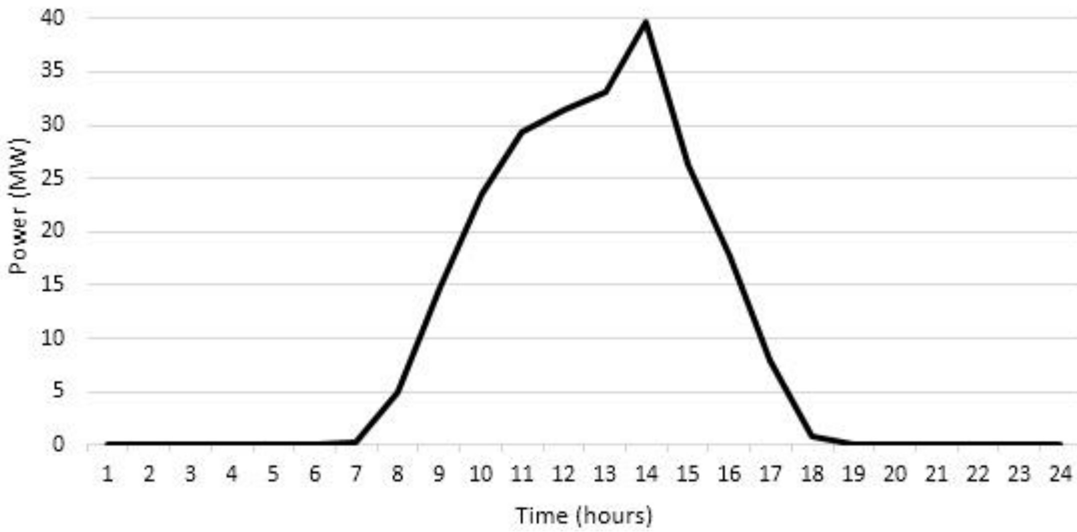

Fig. 4.6 Power generation of PV based Microgrid

As we can see that power supplied by PV based microgrid is correlated to peak demand of the Industrial load. Net load which is yet to be supplied by the Utility grid is shown below in Fig. 4.7

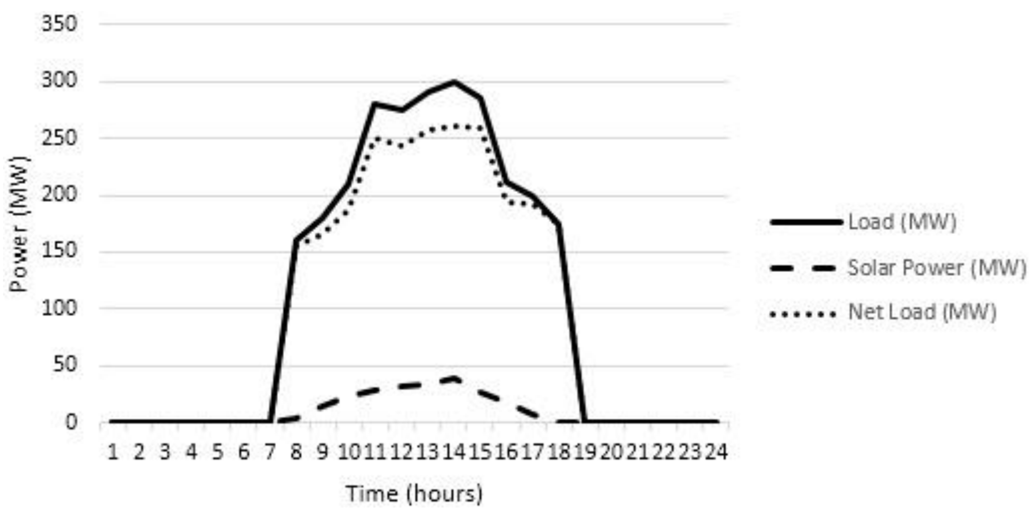

Fig. 4.7 Net Industrial load

Net Industrial load calculated after subtracting power generated by 50 MW module of PV will be supplied from power plants following optimal dispatching strategy to result in minimum cost of operation while supplying the required load.

Results of model developed in GAMS using quadratic optimization are shown in Table-4.3

Table. 4.3. Net optimal dispatch operation of power plants

Time	**Net Load**	**P_1 (MW)**	**P_2 (MW)**	**P_3 (MW)**	**Cost of Operation (Rs/hour)**
7-8 AM	155.09	50	52.032	57.901	2463.668
8-9 AM	165.27	50	56.348	64.361	2588.258
9-10 AM	186.43	50	65.366	77.926	3155.288
10-11 AM	250.58	62.728	86.964	113.373	3695.292
11-12 AM	243.53	60.121	85.147	110.049	3600.093
12-1 PM	256.88	65.06	88.591	116.357	3780.859
1-2 PM	260.26	66.313	89.465	117.963	3826.96
2-3 PM	258.66	65.72	89.05	117.203	3805.120
3-4 PM	194.36	50	68.761	83.059	2953.317
4-5 PM	192	50	67.75	81.529	2923.192
5-6 PM	174	50	60.061	69.935	2696.393
Total					35488.44

After calculating cost of operation for both cases viz. where industrial load is supplied only via utility grid and in second case where it is supplied via utility grid in cooperation with PV module. A decrease in cost of operation is clearly visible in case study 2 where PV module was employed in cooperation with Utility. The reduction in cost of operation has been summarized in the Table-4.4

Table-4.4: Cost of operation comparison of Case studies 1 and 2

	Utility based supply	**Utility and PV module based supply**
Cost of Operation/day (Rs.)	38281.259	35488.44
Reduction in cost (%)		7.3%

4.4 Summary

In case of Industrial load it can be observed that inclusion of distributed energy resources into the main power grid supplied by fuel based power plants results in reduction in cost of operation upto a significant amount as in the case study solved above we have observe a reduction in cost of operation during for a day by 7.3% which is quite significant in nature considering the scale of cost operation of such power plants.

Thus it can be concluded that a generation scheduling method coordinated with PV module system can reduce the cost of operation of industrial microgrid and can also serve as a source backup in case of blackout or brownout to supply the critical industrial load.

Chapter 5

Residential Microgrid

5.1 Introduction

Utility systems vulnerability to multiple failure is well known and chances of such failures will increase as demand grows. Thus residential microgrids have the advantage of allowing better recovery form disasters as well as to boost utility system performance. By being placed closed to the load, residential microgrid can be switched into and out of transmission system. It can also operate independently from the rest of the system for a period of time.

Residential microgrid developed in this project has been developed in both Optimization tools GAMS and HOMER. A hydrogen based storage system has been developed with a zero rejection policy in GAMS and a battery bank storage system has been developed in HOMER. Finally a grid connected semi-autonomous residential has been developed for better understanding of functioning of residential microgrids

5.2 Case study 1: Traditional Storage system (battery bank)

In this case to develop a traditional storage system HOMER has been used where and chosen renewable energy sources are wind power and solar power and excess power generated throughout the day will be stored to supply the load during non-availability of microsources during time

In order to simulate and study the behaviour of microgrid over a long period of time a yearlong study has been done, the load profile of the area for the whole year is shown in Fig. 5.1

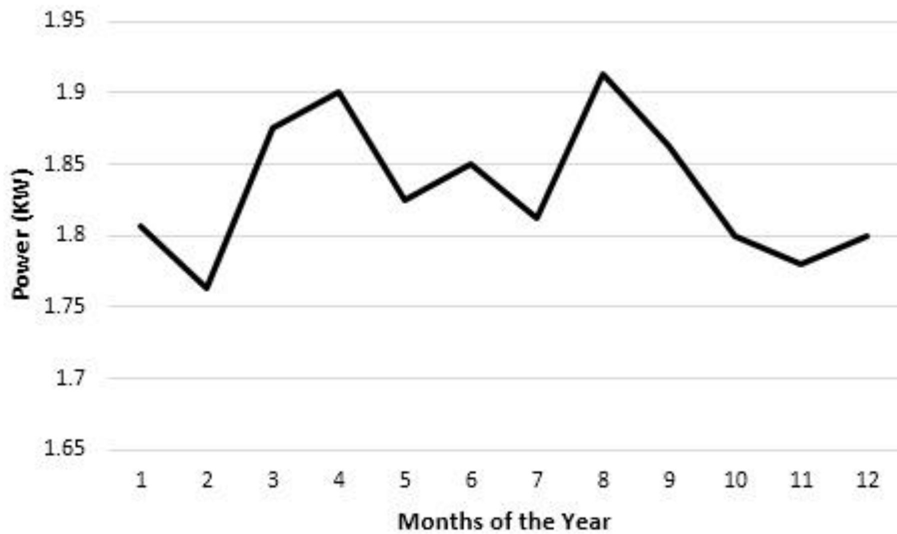

Fig. 5.1: Load data of a Residential community

In the figure above load profile of a residential community has been shown which will be supplied via hydrogen based storage system as already discussed. 8760 samples with each sample of size 60min has been used for the purpose of power flow

Yearlong solar and wind data of the place considered in study has been shown in Fig. 3.4 and Fig 3.5 in chapter 3.

Information regarding components of microgrid which has been use is given in the Table-5.1 shown below

Table-5.1: Residential Microgrid components specifications

	Wind Turbine 2	**Wind Turbine 2**	**Battery1**	**Battery 2**	**PV panel**	**Power Converter**
Manufacture	SW AIRX(8)	Generic 3KW	Trojan-105	Surrette 6CS25P	RS210 (Reliance)	Luminous
Rated output power per unit (kW)	0.55 KW	3 KW	225		7 KW	5 KW
Rated capacity (ah)	NA	NA	225	1156	NA	NA
Output	DC	DC	DC	DC	DC	AC
Cut-in speed (m/s)	2.5	4	NA	NA	NA	NA
Cut-out speed (m/s)	20	24	NA	NA	NA	NA
Rated speed	14 (m/s)	12.5 (m/s)	NA	NA	NA	NA
Capital cost (Rs)	40500	190000	7830	62000	1060000	35000
Replacement Cost (RS)	35000	150000	7000	50000	100000	30000
O&M cost/yr (Rs.)	800	5000	500	900	500	500
Efficiency (%)	25	25	NA	NA	12.5	85
Lifetime (year)	15	15	10 (float life)	12 (float life)	20	5

As shown in table above different types of two type of batteries and wind turbine has been considered such that resulting solution has best optimal solution

5.2.1 Results and discussion

After simulating the developed model sizing of the optimally viable solution has been shown below in Table-5.2

Table-5.2: Residential Microgrid components cost distribution

Component	Size of single module	No. of modules required	Cost of single module	Replacement cost	Total Capital cost
Solar Panels capacity	7 kW	2	1060000	1000000	2120000
SW AIRX	0.55 KW	0	40500	40000	0
Generic Wind turbine	3 KW	0	624000	600000	0
Trojan-105	NA	0	7614	7500	0
Surrette6CS25P	NA	25	62000	50000	1550000
Luminous Inv.	5 kW	1	35000	30000	35000
Miscellaneous	NA	NA	NA	NA	500000
Total cost (Rs.)					4205000

According to result shown in Table-5.2, no of solar panels required to supply the load profile throughout the year are 2 which makes the total rating of the PV module system as 14 KW and no. deep cycle batteries required for successful operation of the Microgrid are 25 and 1 Invertor is required to convert the stored power in batteries to supply the AC load.

5.3 Case study 2: Hydrogen based storage system

In this model a solar array and wind turbine as the main source of energy, hydrogen storage device including electrolyser to absorb the excess power from the wind source, a fuel cell to supply the power deficit when the resources is not adequate to meet the demand, a hydrogen tank to store the hydrogen generated by electrolyser, and a diesel generator as a back-up source.

This section presents the optimization model of Remote area microgrid. Problem formulation has been done based on power dispatch algorithm presented in Fig-3.1. The mathematical formulation is already described in (3.3)-(3.9). The model is formulated as MIP (mixed integer programming) in GAMS environment and the solver is BDMPL.

In order to simulate and study the behaviour of microgrid over a long period of time a yearlong study has been done, the load profile of the area for the whole year is shown in Fig-5.1 in the earlier part of the this chapter.

Yearlong solar and wind data of the place considered in study has been shown in Fig. 3.4 and Fig 3.5 in the chapter 3. The information on microgrid components and their efficiencies including wind turbine, fuel cell, electrolyser, hydrogen tank, has been already given in Table-3.1. And Table-3.2 in chapter 3.

5.3.1 Results and discussion

In the hybrid scenario, sizing of renewable components (solar panels and wind turbines) is done keeping in zero rejection policy of Eqn. (3.4) that at every point of time throughout the year load should be supplied with hybrid system of Solar-Wind-H_2, result of the simulation which has been done for samples 8760 samples (no. of hours in the year) is shown below in Fig 5.2

```
                          LOWER     LEVEL     UPPER    MARGINAL

---- VAR cost              -INF  7.4590E+6    +INF        .
---- VAR a_solar             .       3.000    +INF  1.0600E+6
---- VAR a_fc                .       3.000    +INF  7.8000E+5
---- VAR a_elec              .       3.000    +INF  4.6800E+5
---- VAR a_wind              .        .       +INF  6.2400E+5

  cost  cost of system
  a_solar  integer varible for the pv size
  a_fc  integer varible for fc size
  a_elec  integer variable for elec size
  a_wind  integer variable for wind size
```

Fig. 5.2: Screenshot of GAMS showing optimal sizing result for the residential microgrid

According to result shown in Fig.5.6, no of solar panels each with a rating of 7 KW required to supply the load profile throughout the year are 3 and number of fuel cells required to supply the load in absence of solar power are 3, similarly no. of electrolyzers required to store hydrogen during the peak season of solar power to supply power in lean season are also 3. Cost distribution of the proposed microgrid is show below in Table 5-3:

Table 5-3: Cost distribution of the hydrogen based residential Microgrid

Component	**Rating of single component (KW)**	**No. of components required**	**Cost of single component**	**Cost of total component**
Solar Panels	7	3	1060000	3180000
Wind turbine	10	0	624000	0
Fuel cell	5	3	780000	2340000
Electrolyzer	5	3	468000	1404000
Invertor	5	1	35000	35000
Miscellaneous		NA	NA	500000
Total cost				7459000

Hydrogen storage which is used as an intermediate storage, is the main focus of this project, as rather than the traditional storage system viz. stack of batteries a hydrogen based storage system is used, status of hydrogen in the hydrogen in the tank starting with is show in the Fig. 5.3

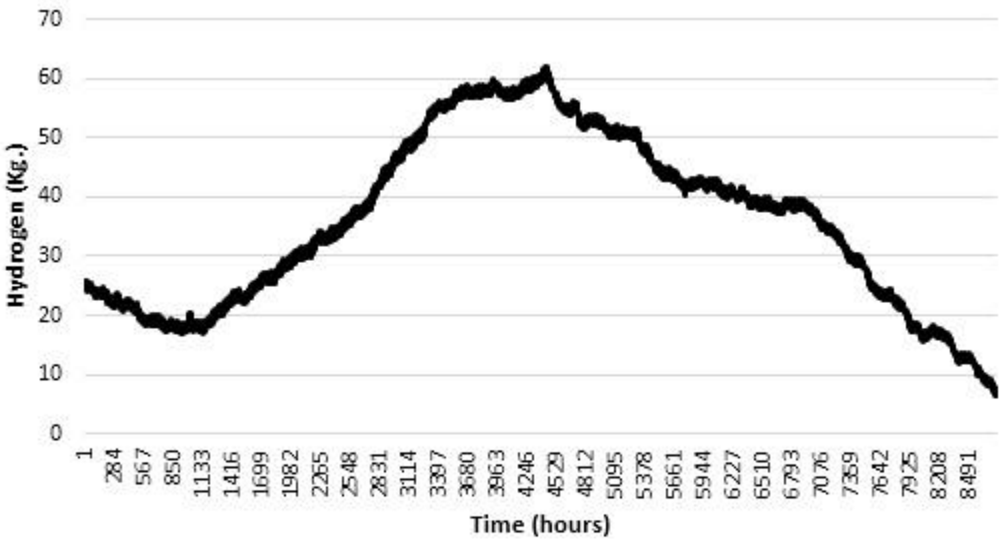

Fig. 5.3: Hydrogen tank storage throughout the year (kg)

Starting with a hydrogen storage of 24 kg as expected hydrogen storage goes up during the peak months of solar irradiation, which are May, June and July as shown in Fig. 3.4 to compensate for the poor supply of solar power in the months of October, November and December shown in the Fig. 3.4. Thus keeping this in mind hybrid system generates extra hydrogen than required during the night time and keeps increasing hydrogen storage to an optimal sufficient level without oversizing the system to supply the deficit power generation in months of lean solar power generation.

5.4 Comparison: Hydrogen vs Traditional battery bank storage system

A comparative study has been done between traditional battery bank storage system and hydrogen based storage system. Long term study has been done assuming the project life to be of 20 years and pros and cons of each storage system has been discussed

5.4.1 Project life calculation of Traditional system

Project cost calculation has been done assuming the life cycle of project to be 20 years is shown in Table-5.4

Table-5.4: Residential Microgrid project life calculation

Component	Capital cost	Lifecycle	Total Replacement cost (Rs.)	Total O&M cost	Total(Rs.)
PV module	2120000	20	0	20000	2140000
Surrette 6CS25p	1550000	4	6000000	450000	8000000
Convertor	35000	7	60000	10000	105000
Miscellaneous	500000	NA	NA	NA	500000
System	4205000	NA	6060000	480000	10745000

After optimally sizing the battery storage based microgrid project life cost calculation has been done for 20 years with replacement and operation and maintenance cost of the components shown above in Table-5.4. Apart from the cost mentioned above, miscellaneous cost has also been considered for unaccounted components and expenses of microgrid.

5.4.2 Project life calculation of Hydrogen based storage system

Project life calculation for hydrogen based hybrid has been done for 20 years of operation of microgrid shown below in Table-5.5

Table-5.5: Hydrogen storage based project life calculation

Component	Capital cost	Lifecycle	Total Replacement cost (Rs.)	Total O&M cost	Total(Rs.)
PV module	3180000	20	0	30000	3210000
Fuel cell	2340000	5	6000000	240000	8580000
Electrolyzer	1404000	5	4062000	240000	5706000
Convertor	35000	7	60000	10000	105000
Miscellaneous	500000	NA	NA	NA	500000
System	7459000	NA	10122000	520000	18101000

After calculating project life of both systems for a period of 20 years, it can be seen that project cost of battery based storage system is less than the hydrogen based storage system which is also shown in Fig. 5.4

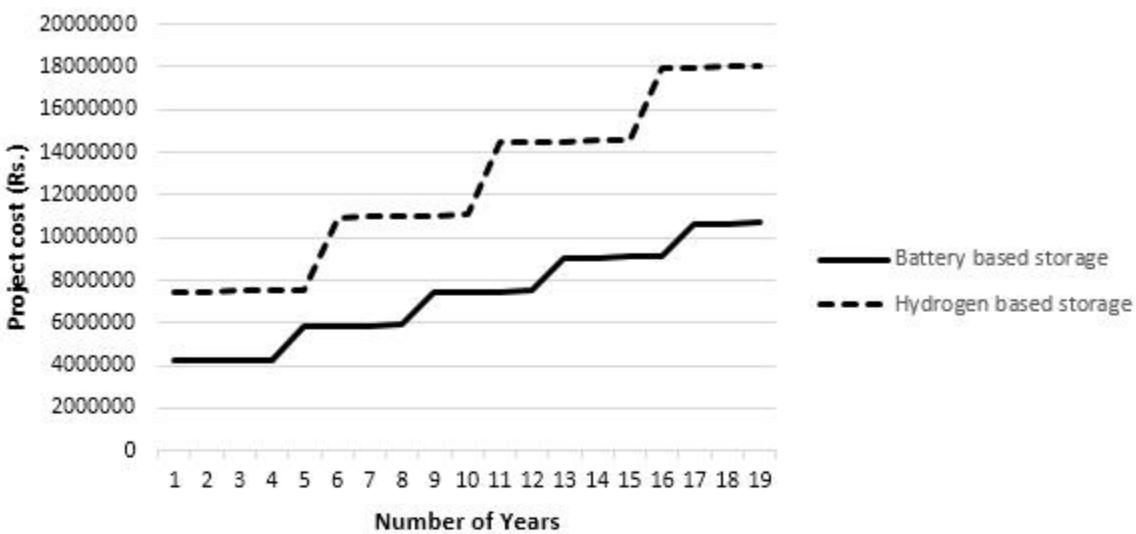

Fig. 5.4: Estimated cost of projects

5.5 summary

After calculating project life of both systems for a period of 20 years, it can be seen that project cost of battery based project is less than the hydrogen based project by 7356000 Rs. Both type of storage system has its own advantages and disadvantages which are discussed below in Table-5.6:

Table-5.6: Comparison between battery bank storage system and hydrogen based storage system

	Advantages	**Disadvantages**
Hydrogen based storage	Hydrogen is easily portable in case storage is low No leakage energy Smaller footprint Environment friendly Cost of increasing the size of storage is low	Low round trip efficiency – results in a higher number of PV panels needed for a given load Higher capital cost and project life cost.
Battery bank storage	High round trip efficiency Lower installation and project life cost	Adverse impact on the environment Increasing storage size is expensive

It can be summarized from the results above that more no. of panels will be required to supply a load profile to compensate for the losses in electrolyzer and fuel cell. In the case study solved in this chapter that in case of battery based storage we have seen that solar module of total capacity 14 KW in combination of 24 batteries is required to supply the load profile but as the power losses are higher in the hydrogen based storage system, solar module of total capacity 21 KW in combination with fuel cells and electrolyzers is required to supply the load with zero rejection policy.

Chapter 6

Conclusions

6.1 Summary and conclusions

In this project operational optimization has been done for remote area, residential and industrial microgrid. In case of remote area microgrid and residential microgrid aim was to supply reliable power throughout the year with zero rejection of load and in case of industrial microgrid aim was to reduce the cost of operation via distributed energy resources in this project viz. PV based power.

In Chapter 2 historical background and literature survey. This chapter introduces the current state of renewable energy resources in India and their application in microgrid research keeping its application in off-grid areas in mind. In this chapter, a brief history of integration of renewable resources in traditional, systems is given. Optimization methods for unit-sizing purposes are discussed; pros. and cons. of each method are mentioned. A brief introduction has also been given regarding types of microgrid.

In Chapter 3 deals with the issues of remote area microgrid. After yearlong study of the model developed in GAMS for remote hydrogen based microgrid it can be concluded that hydrogen based storage can be used to supply to reliable power to the remote community at adequate cost of operation.

Industrial loads are considered critical in nature thus in Chapter 4 a comparative study has been done between only utility based power supply and utility in integration with renewable resources, a significant reduction in price has been observed after optimally scheduling the power generation and distribution of power from fuel based plants and supplying a part of industrial load via PV module.

Chapter 5 is related to residential load where a comparative study has been performed between traditional battery bank storage system and hydrogen based storage system. Cost figures of both cases show a clear advantage of traditional battery storage based system, indicating a need for research and technological advances in the hydrogen based storage system

6.2 Project contribution

In this project different operational optimization models have been developed for three types of microgrid remote area, industrial and residential microgrid. Advanced mathematical model GAMS is used to develop the model for a remote area microgrid which has been solved using MIP. In case residential load both optimization tools GAMS and HOMER are used for comparative study of traditional battery bank storage system and hydrogen based storage system.

In case of industrial load an optimal dispatch model of a fuel based power plant has been developed using quadratic optimization in GAMS, where optimal generation and scheduling is done to ensure minimum cost of operation of system. A comparative study has also been done to analysis the impact of inclusion of renewable energy resources to supply a chunk of power via PV module.

6.3 Suggestions for future work

- **Alternate Renewable Resources**

  Biomass, hydropower, geothermal energy, and other renewable resources already discussed in the chapter 2 need to be studied and implemented as some of them may be economically viable for implementation in remote communities India. Technologies such as plastic micro wind turbine should be included in future studies as their field trails has been very promising due to their low capital cost and power generation even at very low speed which is the case with India.

- **Microgrid dynamics**

  To examine the dynamic behaviour of the microgrid, the system control algorithms could be studied. The power flow analysis, the voltage and frequency stability analysis, the islanding operating mode, and the response of the system when faults occur are all challenging issues.

References

1. "*All India region-wise generating installed capacity of power*" Central Electricity Authority, Ministry of Power, Government of India. February 2013.
2. "*The potential of renewable energy in India*" Gyan research and analytics 2011
3. M. A. Pedrasa, and T. Spooner, "*A Survey of Techniques Used to Control Microgrid Generation and Storage during Island Operation*".
4. http://www.mnre.gov.in/mission-and-vision-2/achievements/ - Ministry of Renewable Energy
5. http://thesolarity.wordpress.com/2010/09/25/status-of-solar-energy-in-inida-2010/ "*Status of solar in India* -2010"
6. D. Edwards and M.Negnevitsky, *"Designing a Wind-Diesel Hybrid Remote Area Power Supply System*", senior member IEEE 2008.
7. Tapan K. Bose, Kodjo Agbossou, Mohan Kolhe, Jean Hamelin , "*Stand-alone renewable energy system based on hydrogen production*" 2004 IEEE Transaction on Energy conversion
8. M.Vafaei, and M.Kazerani, *Optimal Unit-Sizing of a Wind-Hydrogen-Diesel Microgrid System for a Remote Community*, IEEE, 2011
9. Z. Wei, and Y. Hongxing, "*One optimal sizing method for designing hybrid solar-wind-diesel power generation systems*", Proceeding of ISES Solar World Congress 2007: Solar Energy and Human Settlement.
10. D.B. Nelson, M.H. Nehrir, and C. Wang, *"Unit Sizing of Stand-Alone Hybrid Wind/PV/Fuel Cell Power Generation Systems"* PES.2005.1489286 pp.2116 - 2122 Vol. 3 In proceeding of: Power Engineering Society General Meeting, 2005. IEEE
11. Aitor Milo, Haizea Gaztanaga, "*Optimization of an experimental hybrid microgrid Operation: Reliability and Economic Issues"* 2009 IEEE Bucharest power tech conference June 28th – July 2nd Romania.
12. http://www.motorwavegroup.com/new/motorwind/product.html

13. F. Katiraei, and C. Abbey, "*Diesel plant sizing and performance analysis of a remote wind-diesel microgrid*", Proceeding of the IEEE-PES 2007 General meeting.

14. Z. Wei, and Y. Hongxing, "*One optimal sizing method for designing hybrid solar-wind-diesel power generation systems*", Proceeding of ISES Solar World Congress 2007: Solar Energy and Human Settlement.

15. J.A. Razak, K. Sopian, Y. Ali, M.A. Alghoul, A. Zaharim, and I. Ahmad, *"Optimization of PV-Wind-Hydro-Diesel Hybrid System by Minimizing Excess Capacity*", European Journal of Scientific Research, Vol.25 No.4 2009.

16. H. Suryoatmojo, T.H. Member, A.A. Elbaset, and M. Ashari, "*Optimal design of wind-PVdiesel-battery system using genetic algorithm*", IEEJ Trans. PE, Vol.129 No.3, 2009.

17. R. Chedid, H. Akiki and Saifur Rahman, "*A decision support technique for the design of hybrid solar-wind power system*" IEEE Transactions on Energy conversion, Vol. 13, No. 1, March 1998

18. Patel MR. Wind and solar power systems. Boca Raton: CRC Press; 1999.

19. Shin'ya Obaraand Abeer Galal El-Sayed: "*Compound Micro-grid Installation Operation Planning of PEFC and Photovoltaics with Prediction of Electricity Production using GA and Numerical Weather Information*", International Journal of Hydrogen Energy, Vol. 34,No. 19,pp. 8213-8222, (2009).

20. Raul E. Perez-Guerrero and Jose R. Cedenio-Maldonado, "*Economic Power dispatch with the Non-smooth cost functions Using Differential Evolution*" Member IEEE

21. A. Wood, B. Wollenberg, *Power generation, Operational and control*. New York: Wiley, 1996.

22. S.Y. Derakhshandeh, Amir S., Sara Deilami, Mohammad A. S. Masoum and M.E Hamedani *"Coordination of generation scheduling with PEVs Charging in Industrial Microgrids"* IEEE Transaction in Power system

Bio-data

NAME	:	Dilraj Meena
DATE OF BIRTH	:	11th Dec 1990
ADDRESS	:	62, MAHAVEER NAGAR, NEAR HAMMIR BRIDGE, RANTHAMBHORE ROAD, SAWAI MADHOPUR, RAJASTHAN - 322001
EDUCATION	:	BTECH IN ELECTRICAL ENGINEERING AND MTECH IN POWER SYSTEMS AND POWER ELECTRONICS
EMAIL	:	dilraj90@gmail.com