

Microgrid Economy Through Optimal Design

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The Degree of Master of Technology



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Declaration

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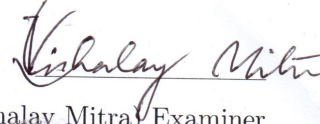
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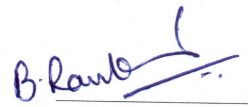
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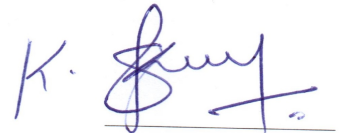
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Abstract

Nowadays fossil fuels are depleting and load demand is increasing rapidly. As a result, cost of power generation from conventional resources is increasing. On the other hand the power production cost from renewable resources like wind and solar energy is decreasing. The power generated from the renewable sources is now in marketable range. This increases the scope of microgrid and distributed generation. Power from only renewable resources is not reliable due to uncertainty in environmental conditions. It has to be coordinated with any of the other form of reliable power sources. The installment cost of solar and wind generation plants are very high. But, the maintenance and running costs are low. Installment cost of non-renewable energy source generation plants is low compared to renewable energy sources generation. But, the maintenance and running costs are high.

In present work questions, such as: What is the per unit cost of generation from a microgrid/renewable energy source? Can renewable energy generation attain grid parity? has been answered. Approach towards renewable sources is mostly driven by environmental concerns rather than economy. In this thesis work we also initiate a first step towards answering these questions and provide analysis of microgrid economy through optimal design approach. A framework for decision support system for sizing of distributed generators is provided. The objective function formulation involves costs (installation, maintenance and operational), economic factors (inflation and interest rate) as well as uncertainties (in the renewable generation and load demand). A few case studies involving a small manufacturing unit, commercial load, residential load and give some interesting insights into economy of microgrid and renewable generation sources. A detailed discussion on results obtained from these case studies are presented here.

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Chapter 1

Introduction

Electrical energy can be generated from both convention and non-conventional energy sources. Conventional sources such as coal, diesel, nuclear, hydel etc., are limited and depleting. The generation of power from conventional energy sources is becoming costly and also most of sources causes pollution. There are many renewable energy sources which can be converted into electrical energy. Solar, wind, tidal, geo-thermal, hydel, biomass and rain are some of such sources. Among the non-conventional resources solar, wind and biomass energies have enormous potential for power generation. The cost of purchase, installment of PV panels, Wind Turbines and implementation of technologies for biomass power generation is decreased and the power generated from these sources is eco-friendly.

Since, renewable power generation is uncertain. generally they are coordinated with dispatchable generators. Energy storage systems are such dispatchable generators. There are different kinds of electrical energy storage methods. Pumped-storage hydroelectricity, secondary batteries, flow batteries, compressed air energy storage, flywheel energy storage etc., In general secondary battery storage systems were extensively used for storage. It can be charged when excess power is generated from solar and wind power generating resources and delivers power when required. But, batteries are limited by their size. So, they can store/deliver energy up to their maximum capacity. It has to be recharged again to supply power to load.

1.1 Distributed Generation an Overview:

Generation of electrical energy in small scale grid connected or islanded is called as distributed generation or decentralized generation [1, 2]. In general centralized generating sources such as thermal, hydro, nuclear, large scale solar plants power must transmitted to distant places which includes

transmission losses. Recently, increase in load demand and advances in renewable energy power generation gives scope for distributed generation where generating sources will be placed near to load centers. Distributed generation not only limited renewable energy resources. It also includes small hydro, geothermal, diesel generation, electrical energy storage (EES) systems. Distributed generation enables to collect or store energy from different kinds of sources [3,4]. It may also reduce pollution. The following aspects gives rise to the development of distributed generation.

- The low cost of production of smaller units compared to the larger units.
- Reduction of total costs of tariff administration, metering, billing etc.,
- The increasing deterioration, age, capacity of constraints of transmission and distribution system.

A brief overview about few generators which can be incorporated in distributed generation has been discussed below

1.1.1 Solar Energy Conversion Systems

Solar Photo Voltaic Energy Conversion (SPVEC) system is the one of the fast growing renewable energy power generation. SPVEC systems are going to play major role in power generation industry and distributed generation in upcoming days. In solar power generation the energy from the photons is captured by PV panels and conversion into electrical energy will be done due to photo-voltaic effect.

There are numerous advantages of using PV panels for power generation and are listed below

- Solar energy is available everywhere
- PV panels can be installed in any terrain such as roof tops. It only needs rigid surface
- Solar power generation doesn't have environmental impacts
- Though the output power from PV panels is not always constant. However in tropical regions like India where peak loads occurs during summer (clear sky season). Comparatively peak output power PV panels occurs during this season for cooling

There is lot of potential for solar energy generation. PV cells operates in the presence of solar radiation. Solar radiation depends upon the weather conditions, time of the day and geographical conditions. Higher the radiation lesser the per unit power generation cost from SPVEC systems.

The solar power entering into the earth's atmosphere is enormous. Earth is receiving about 173 trillion Kwh per year. India has average 300 clear sky days. Length of average day is 11:45 *hours* in India. India is receiving 5 trillion Kwh energy from sun. The installed solar PV by 2013 in India is 2319 Mw . India is top in extracting power from the PV installed capacity termed as Kwh/Kw installed. Policies by the government of India is encouraging investment in solar energy generation. However, there are few limitations while using SPVEC systems along with their high capital cost. The maximum efficiency of solar power conversion by panels is 25% with presently available type of PV panels in market.

However, efficiency varies with different types of panels. To improve quality of power from SPVEC systems power electronics device is required which reduce efficiency and also when the panels are in operation efficiency of the panels will be decreased called as deration. The power output from PV panels decreases with increase in temperature. Uncertainty in solar irradiance etc., The irradiance from the sun over a surface normal to it is always constant. Due to the earth's rotation, axial tilt and atmosphere the irradiance entering into the surface is not from one direction at all time. Irradiance on a particular surface with clear sky can be estimated based upon latitude.

1.1.2 Wind Energy Conversion Systems

Wind energy conversion systems consists of turbine and generator system. Turbines convert the wind energy into mechanical energy and generators convert mechanical energy into electrical energy. Wind power is one of the oldest source of power that has been used by mankind. The world's first wind WEC (Wind Energy Conversion) system was built in late 19th century by Prof James Blyth. A group of wind turbines were placed in certain area and were called as wind farms. Wind farms were extent to large area and these areas mostly can also be used for farming. Wind speeds vary with heights from sea level, terrain of land and geographical position. Hence, wind turbines are often placed on-shore where wind energy availability is maximum.

Wind turbines can also be classified as Vertical and Horizontal axis turbines. Vertical axis turbines are less efficient than horizontal axis turbines. However, small scale wind turbines were developing using vertical axis. Wind turbines can also be classified by their small scale, medium scale and large scale wind turbines. The small scale wind turbines are of size less than 100 Kw , the medium size turbines size ranges from 100 Kw -250 Kw and large size wind turbine are of size more than 250 Kw . The total installed wind capacity in world is 369553 Mw . China is the largest producer of electrical energy from Wind resource. It produces almost half of the world wind power

generation. India had an installed capacity 22465Mw. India is the fifth largest country with wind installed capacity. Tamil Nadu state has largest installed capacity in India.

The following advantages made that it is economical to generate power from wind energy conversion systems (WECS)

- Wind energy is renewable source of power generation which is abundant in nature
- No pollution is associated with WECS systems
- Wind turbines can also be installed in farm lands

Few limitations were associated with power generation including capital cost. The maximum efficiency is always less than 58%. Power output from wind turbines have poor quality and it is not according to the power system standards. Power quality from these resources can be improved by using power electronic devices such as DC/DC converters, Inverters and Rectifiers based on load requirement AC or DC. Control techniques such as Model predictive control, PI control, Fuzzy logic control, Hysteresis control, Synchronous reference frame control were implemented for control of power electronic converters. With many power electronic components in the power system. It becomes more flexible. But, with increase in power electronic equipment the efficiency of the system decreases due to power losses in devices.

1.1.3 Biomass power conversion

Biomass is one of the renewable resources used for power generation. Biomass is produced from various natural and human activity sources such as agricultural crops, forests, house hold. Wood from forest a biomass is primary source of energy for heating for a thousand of years and also for power generation. The by-products from paper, pulp and timber industry can be used as biomass for power generation. Recently, biomass had attracted considerable attention for power generation due to the following advantages

- Biomass is carbon product generated due to natural process from carbon dioxide and water in environment. Hence, in overall no additional carbon dioxide is produced due to usage of biomass. It is an eco-friendly source for power generation.
- No harmful gases are emitted
- Biomass is abundant in nature and renewable

- Biogas produced from biomass can be used along with fossil fuels for power generation which reduces dependency on fossil fuels
- There were also by-products from biomass while processing such as ethanol and fertilizers etc.,
- Landfills can be reduced

There are also difficulties with power generation from biomass such as, feedstock must be transported from remote places to the generation station. Unwanted materials from biomass must be removed and needed further treatment before processing for power generation. Labor and capital costs are also involved in power generation from biomass.

1.1.4 Electrical Storage System

Electrical storage systems are devices which store energy when excess power is generated and deliver it when it is required. Storage of electricity is essential nowadays. Without any storage the generated electrical energy must be consumed at the same time when it is produced. Even a slight imbalance between generation and load causes power quality problems which may damage equipment. Batteries coupled with inverters are also used as backup sources when the grid fails and also due to the penetration of distributed generation surplus power may be produced when there is low loading. We can store this surplus power and use it for serving peak loads.

1.1.5 Diesel Generators

Diesel generators (DG) are a combination of a diesel engine and an electrical generator. The diesel engine converts fuel energy into mechanical energy and the generator converts mechanical energy into electrical energy. Diesel generators are used in support of the grid/microgrid. Diesel generators can also be used as backup sources when the grid fails and it is a reliable source. Diesel generators are incorporated in microgrids to supply power to critical loads when other power-generating sources fail or during times of bad weather conditions when wind and solar systems cannot produce power. It can also be used for load balancing. The cost of power generation from diesel generators is very high. However, there are few places like hospitals, schools where power is required for some critical loads. Installation of large-sized diesel generators increases capital cost and the generation of power from large-sized generators is costlier than the same power generated from a less-rated generator. However, diesel generators cannot generate power more than their rated capacity. Hence, low-rated diesel generators might not generate the

required power all the time. Hence, in order to avoid shortage of power and uneconomical capital, maintenance, and operational cost, generators must be critically sized.

1.2 Motivation

Nowadays distributed generation has attracted considerable attention in power generation. Fossil fuels are depleting and load demand is steadily increasing around the world. Traditionally most of the power is generated at a distant place from load centers by combustion of fossil fuel, which has raised a lot of environmental concerns due to emission of greenhouse gases. This necessitates lengthy transmission lines causing transmission power losses. These concerns have propelled recent technological advancements in renewable power generation and electrical energy storage system for distributed generation. In many countries attractive feed-in tariffs had motivated further investment in distributed generation. Distributed generation is an alternative solution in remote areas and islands where erection of transmission lines is either difficult or costly. Hence, in recent years design, control and operation of distributed generation, which includes solar, wind-turbines, biomass and storage devices to serve local load of designated area in distributed network has attracted considerable attention. Most of the distributed generation networks are grid-tied and research is mostly concentrated on stability, control, and integration with the grid. There has been a few studies on optimal operation of a given distributed generation [5–8]. However, the issue of optimal sizing and economics of distributed generators has received considerably less attention than they deserve. In fact, most PV and wind farm installations are large scale and are inspired by government policy/emphasis on renewable generation rather than economy. Present work conveys that installation of optimally sized renewable sources integrated with conventional generators is both economical and eco-friendly. Any algorithm for the selection of microgrid generators requires estimation of power generating from sources at any time and also cost involved in power generation. However, wind speeds and solar irradiance are uncertain which are sources for power generation from wind turbines and PV panels. Hence, the power generation from these sources requires estimation of solar irradiance and wind speeds.

Researchers proposed stochastic disaggregation procedure to estimate the irradiance from daily clearness index data [9–11]. Quasi-universal hourly clearness index is used for estimation hourly irradiance. In his work model hourly clearness index has been estimated instead of hourly irradiance. HCI has been estimated as with the analysis of meteorological records reveals that from the daily clearness index, estimation of hourly clearness index gives more accurate results and it is

independent of geographical position, at given location the solar irradiance outside atmosphere can be estimated accurately. Hence hourly irradiance entering into earths atmosphere can be estimated at any place, any time. Power output from the PV panel can be calculated from the estimated solar irradiance. Researchers were also proposed auto-correlation method to estimate hourly wind speeds from monthly average winds speeds [12–14]. In this technique wind speeds are assumed to follow weibull distribution which represents the range of wind speeds. Auto-correlation technique represents the dependence of wind speeds at present on previous wind speeds. So, estimation can be done on the output of the wind turbines.

James F. Manwell and Jon G. McGowan proposed kinetic energy battery model in which battery is modeled into two tanks, readily available energy tank and bounded energy tank [15]. This model is based on chemical kinetics. The model can be used for modeling charging and discharging. In kinetic energy battery model the battery capacity is defined based on charging and discharge rates. In his model temperature effects were also considered. Generators operation can be modeled using fuel cost curve. Hence, all the above work can lead us in optimal sizing of microgrid resources to serve load.

So, it is possible to optimally select the non-conventional power generating sources for a particular load distribution with co-ordination of any reliable sources or storage devices. Cost analysis can also be done which is an important aspect for microgrid design and also gives a decision analysis for a firm to involve in project or not.

1.3 Objectives

As mentioned earlier research work on optimal selection of microgrid has attracted considerable attention. Optimal design of microgrid with minimization of overall microgrid lifetime cost is required. Further, in interest of investors the objective function has to be modeled such that it can able to determine whether profits can be earned. With respect to these issues main objectives of this research are to achieve these objectives in view of various economical and environmental issues concerned with microgrid

- Propose a decision support system for optimal sizing of microgrid for a given load profile
- Estimate per unit cost of generation for the microgrid
- Include economic considerations, such as interest and inflation rates, in the problem formulation

- Profitability analysis for grid connected operation with feed-in tariff
- Sensitivity analysis w.r.t different parameters effect micro-grid per unit price
- Bootstrap analysis of micorgrid selection w.r.t various estimated parameters from random variables such as load, solar irradiance and wind speeds
- Analyzing the selection of microgrid for different kinds of loads and in different locations
- Developing an algorithm to select distributed generators with load forecasting and enabling installation of additional size of generators over project lifetime
- Designing an algorithm to optimally select distributed generators in concern of both economy and environmental issues
- Developing robust algorithm for optimal operation of microgrid
- Designing tool for selection and operation of microgrid generators

1.4 Scope of work

In present work various factors influencing micorgrid selection were analyzed and with case studies the mcirogrid dependency on various factors were discussed. The following objectives were discussed with results

- Modeling an objective function to optimally select microgrid configuration
- Determining overall microgrid cost and unit price
- Analyzing the results for different kinds of loads, weather conditions and different tariffs
- Sensitivity analysis of microgrid w.r.t different type of parameters influencing microgrid
- Bootstrap analysis of micorgrid selection w.r.t various estimated parameters had been done

1.5 Outline of chapters

This chapter presents an introduction about distributed generation and different power generation sources used in distributed generators. It also specifies the objectives of this project work in precise and orientation of the thesis.

- **Chapter 1:** This chapter includes the literature survey on existing algorithms for microgrid selection and also procedure to estimate solar irradiance and wind speeds. It also covers the calculation of power output from microgrid generators
- **Chapter 2:** In this chapter calculation of various costs involved in microgrid were discussed
- **Chapter 3:** This chapter deals with objective function and various constraints influencing the microgrid selection
- **Chapter 4:** This chapter discuss details about various cases studied for microgrid selection
- **Chapter 5:** Results for case studies were in present chapter
- **Chapter 6:** This chapter deals gives the the final conclusions on the basis of this study. Suggestions for future work are also given at the end of the thesis

Chapter 2

Literature Review

An introduction about the thesis work had given in the previous chapter. This chapter includes brief literature study, which contains the previous work had done on selection and cost analysis of microgrid.

HOMER is commercially available application to optimally select distributed resources. The following research work has been presented with HOMER optimization. Shervin Parvini Ahamdi et al discussed about the feasible combination of distributed generators for given load and proposed optimal operation of grid connected DC micro grid [16]. The configuration of microgrid includes PV panels, wind turbines, diesel generator, batteries, boilers and grid. Analysis about risk exposure, uncertainty, robustness and flexibility indices with respect to different parameters had been explained. Electrical and thermal loadings were analyzed. In this paper the author considered that the gasoline prices were uncertain and uncertainty analysis had discussed. Shujun Liu et al designed grid connected micro grid consists of PV panel, wind resources, battery for an average load of 500 Kw/h and peak load of 84 Kw [17]. They considered generic 10 Kw wind turbine. Both wind turbines and PV panels are connected to DC micro grid. In this paper they also discussed about the way HOMER optimally select DC micro grid. G Bhuvaneshwari and R Balasubramanian designed microgrid by optimally selecting distributed energy resources generation consists of PV panel, battery to DC link [18]. Wind, diesel generator, biomass gasifier, critical load of 55 Kwh/d and 7.5 Kw peak and Deferrable load 20 kwh/d and 5 Kw peak.

In all the above work selection of size of micro grid distributed resources had done using HOMER. However, HOMER assumes that load profile, environmental dependent factors such as wind speeds, solar irradiance etc.vary with time in a year and it repeats every year over project lifetime and also

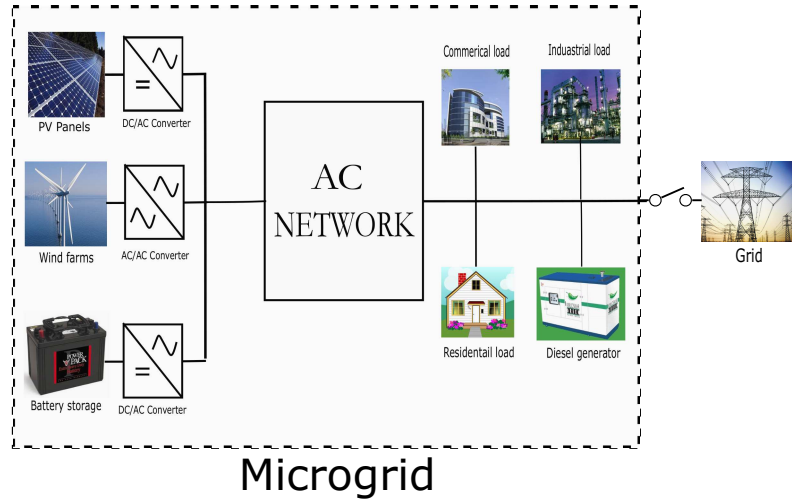


Figure 2.1: Schematic Diagram of Microgrid

capacity factor many of the renewable generation sources cannot be changed. In most of the practical situations these factors tend to change in project lifetime. With efficient forecasting techniques the changes in these parameters can be further predicted based on year in a project lifetime and previous data. In present thesis work the yearly change in parameters were considered over project lifetime project lifetime and also has flexibility to include different sensitive variable.

Fig. 2.1 represents the schematic diagram of microgrid. The power electronic devices represented fig2.1 such as, DC-DC converters,DC-AC converters can be multi-stage/ cascaded. The converters connected to microgrid generators are unidirectional and connected to battery is bi-directional. Since, in batteries power flows in both the directions.

Distributed generators may include renewable energy sources, such as, photo voltaic (PV) panels, wind mills etc as well as dispatchable generators, such as diesel generator (DG) and energy storage systems (EES). Most of the distributed generation networks are grid-tied and research is mostly concentrated on stability, control, and integration with the grid. There has been a few studies on optimal operation of a given distributed generation. However, the issue of optimal sizing and economics of distributed generators has received considerably less attention than they deserve. In fact, most PV and wind farm installations are large scale and are inspired by government policy/emphasis on renewable generation rather than economy.

In a recent study [19], optimal sizing of grid connected PV panels with battery storage for household load had been discussed. In this work [19],the researchers focused on whether trending decrease in capital costs of renewable resources can effect the conventional sources of power generation economically. He also discussed about death spiral a situation might arouse when the price of power

generation from PV panels might decrease below the price of power generation from conventional sources and users may get separated from grid.

The objective function and constraints for selection of PV panels and battery size are detailed below.

The number of PV panels selected must be less than maximum number of PV panels

$$\sum_{i=1}^I Y_i \leq N^{pv} \quad (2.1)$$

where Y_i is PV system i and N^{pv} is maximum number of PV systems can be selected.

The batteries also must be less than maximum number of storage system can be selected

$$\sum_{j=1}^J Y'_j \leq N^B \quad (2.2)$$

where Y'_j is PV system j and N^B is maximum number of battery systems can be selected.

If PV i is installed Y_i is 1 and 0 if PV panel is not installed and same follows for battery selection.

Here PV panels are considered are roof top of a particular house which is limited in area. Hence,

$$\sum_{i=1}^I Y_i A_i \leq A^m \quad (2.3)$$

where A_i is area occupied by PV system i and A^m is maximum area available

At any time p the power generated from PV panel must be greater than or equal to power sent to load and battery. The excess will be dumped. The load balancing for PV panel equation is formulated as follows serving

$$y_i \times A_i \times GHI_p \times \eta_i p^{pv} \leq X_{ip}^{PL} + \sum_{j=1}^J X_{ijp}^{PB} \quad (2.4)$$

where GHI_p is Global Horizontal Irradiance (GHI) during period p and η_i is efficiency of PV system i during period p , X_{ip}^{PL} is dc power sent to load from PV system i during period p and X_{ijp}^{PB} is dc power sent from PV system to battery during period p .

There are other constraints such as of dumping of excess power and battery power interactions which are in common in all optimization algorithms. However, improved control techniques of power output from renewable sources limited the dumping of excess power.

The objective function is sum of all the capital, maintenance, operational costs, penalty costs

for unserved power and total cost price if the power is supplied from grid. Any cost occurred other than present year will be scaled to present year using discount factor. The objective function is formulated as follows

$$\begin{aligned}
NPV = & - \sum_{i=1}^I (Y_i \times CX_i^{pv}) - \sum_{j=1}^J (Y'_j \times CX_j^B) + \sum_{h=1}^H \left[\sum_{p=(h-1)p'+1}^{p=hp'} L_p \times EP_p + CF_p - \right. \\
& \left. \left(\sum_{i=1}^I (y_i \times FOM_{ip}^{pv}) + \sum_{i=1}^I (y'_j \times FOM_{jp}^B) \right) - USE_p \times FP_p \right] / (1 + RI)^h \quad (2.5)
\end{aligned}$$

where CX_i^{pv} is capex of PV panels, CX_j^B is capex of battery storage, $(L_p EP_p + CF_p)$ is sum of costs of grid electricity and grid supply charges. FOM_{ip}^{pv} is fixed operational and maintenance cost of PV panels at period p . FOM_{jp}^B is fixed operational and maintenance cost of battery at period p . $USE_p \times FP_p$ is unserved power penalty costs. L_p is electricity demand during period p . p' is number of periods per time segment h . The grid parity might change in time periods. EP_p is electricity price during period p .

The objective function is MILP. PV panels, batteries are termed in integer sizes. However, it makes objective function discrete and increased variables which requires more execution time than NLP. Similar, algorithm can be modeled as NLP objective function with fewer variable. However, there is no discussion about replacement and lifetime in this work. By doing optimal sizing and sensitivity analysis it was concluded that leaving the grid was not in economic interest of a household consumer.

In contrast, researchers at Hiroshima university studied the microgrid equipped with distributed generators, energy storage systems (ESS) and auxiliary sources of heat (ASH) and modeled an objective function for optimal operation of microgrid is proposed [20]. The researchers also discussed about selection of generators. The work is concentrated on whether it is economical or not to form autonomous independent network by the consumers itself. The objective function is sum of operational costs, microgrid construction cost and power interruption cost. The total operational costs is given as follows 2.6. The operational cost of DGs, ASHs and ESSs are formulated in first three terms of summation, the costs due to power interactions with grid is given in third and fourth

terms and last term is utility base rate of electricity

$$\begin{aligned}
z_1 = & \sum_{l=1}^n \sum_{i=1}^m S_j \sum_{i=1}^t [(f_{dg} + m_{dg})p_{dg}(i, j, l) + (f_{bl} + m_{bl})p_{bl}(i, j, l) + \\
& 2m_{st} \times pr_{st}(i, j, l) + e_e(i, j)p_e(i, j, l) - e_s(i, j)p_u(i, j, l)] \\
& + \sum_{l=1}^n [\alpha \times C_{gs} \times gs(l) + \beta \times C_{st} \times ss(l) + \gamma \times C_{bl} \times bs(l)] + 12e_b \times es
\end{aligned} \tag{2.6}$$

where i is time index, j is season index, m is the total number of seasons, t is the total number of time periods, S_j is number of days in particular season j , f_{dg} fuel cost distributed generators, l is consumer index, n is total number of consumers, $p_{dg}()$ distributed generators output, f_{bl} is fuel cost for ASHs, m_{dg} is maintenance cost of distributed generators, m_{bl} is maintenance cost of ASHs, m_{dg} is maintenance cost of distributed generators, p_{bl} is output power from ASHs, $e_e()$ is price of electricity purchase, p_e is purchase electric power, m_{st} is maintenance cost of EESSs, $pr_{st}()$ is discharged electric power, $e_s()$ is price at which electricity is sold, α , β , γ are depreciation rate of distributed generators, ESSs and ASHs, C_{gs} is capital costs of distributed generators, $gs()$ is installed capacity of DGs, C_{st} is initial cost of ESSs, $ss()$ is installed capacity of ESSs, C_{bl} is capital cost of ASHs, $bs()$ is installed capacity of ASHs, e_b is charge of power contract, e_s is contracted capacity, The cost of damages occurred to consumers due to power interruptions is termed as power interruption cost. The power interruption cost has been calculated as follows

$$z_2 = \sum_{l=1}^n \sum_{i=1}^m \sum_{i=1}^t [IC(i, j, l)prob(i)] \tag{2.7}$$

where $IC()$ is power interruption cost, $prob()$ is probability of power interruption

Construction of microgrid includes Energy Manager (EM), Circuit Breakers (CB), Separation Devices (SD) and installation of generators. The cost of microgrid construction is represented as follows

$$z_3 = \delta C_{SD} + \eta C_{EM} + \lambda C_{DL}(dl_{total}) + \sigma C_{SD}(cl_{total}) \tag{2.8}$$

where C_{SD} is installation of SD, C_{EM} is installation of EM, $C_{DL}()$ is distribution line construction cost, $C_{CL}()$ is communication line construction cost, dl_{total} is length of distribution line, cl_{total} is length of communication line, δ , η , λ , σ are depreciation rates of SD, EM, distribution line and communication lines respectively. By solving optimization function showed that it was more economical to operate distributed generators if consumers co-operated and it was concluded that network of microgrid hold a lot of promise.

There has also been some work on optimal sizing of PV units, wind turbines and energy storage system [21]. The researchers considered one year annual costs for optimization. The capital costs occur only in the year in which microgrid commenced. However, the researchers determined one year capital cost from generator lifetime and added to the operational costs and termed as construction cost and formulated as follows

$$C_c = \frac{C_I}{L} + C_o \quad (2.9)$$

where C_I is installment cost of generation systems, L is lifetime of generator and C_o is yearly operational costs.

It is assumed that operational lifetime is fixed and annual operating costs are proportional to the construction costs. The objective is formulated as follows

$$COST = Cost_{pv} \times n_{pv} + Cost_{wt} \times n_{wt} + Cost_{batt} \times C_{batt} \quad (2.10)$$

where $Cost_{pv}$ is price of unit PV panel, n_{pv} is number of PV panels, where $Cost_{wt}$ is price of unit wind turbine, n_{wt} is number of wind turbines, $Cost_{batt}$ is price of unit battery, C_{batt} is battery capacity. At any time total power output from microgrid must equal to load and at any time power generation capacity must greater than the demanded power. Hence, the objective is subjected to following constraints

- The power balance constraint

$$P_{pv} \times n_{pv} + P_{wt} \times n_{wt} + P_{batt} = P_{req} \quad (2.11)$$

- The electric quantity balance constraint

$$W_{pv} \times n_{pv} + W_{wt} \times n_{wt} + C_{batt} \times DOD \geq W_{req} \quad (2.12)$$

where P_{pv} is power output from each PV panel, P_{wt} is power output from each wind turbine, P_{batt} is power output from battery. It is positive when battery is discharging, negative when charging and P_{req} is load demand, W_{pv} is power generation capacity of each PV panel at particular time W_{wt} power generation capacity of each wind turbines at particular time and C_{batt} is battery capacity and DOD is depth of discharge. However, some important economic considerations, such as interest and inflation rates, were neglected. Further, there has been no study that could give optimal sizing of microgrid along with an estimate of per unit cost of generation.

2.1 Solar Photo-voltaic Energy Conversion System

A SPVEC system uses photo-voltaic panels to convert directly photon energy in sun-light into electrical energy by photo-voltaic (PV) effect. SPVEC systems be classified into Grid-connected and Stand-Alone systems. Gird connected SPVEC systems are more reliable than Stand-Alone systems.

2.1.1 Power Output from PV Panel

Power output from installed PV panel can be calculated from its ratings specified

$$P_{pv,output} = P_{pv,rated} D_{pv} \left(\frac{E}{E_{ref}} \right) (1 + \alpha_p (T - T_{ref})) \quad (2.13)$$

where $P_{pv,rated}$ is rated power output at standard test conditions, D_{pv} is PV derating factor, α_p is power co-efficient of temperature

Power output decreases with increase in temperature. Sometimes PV systems are designed with cooling systems [22]. Cooling of PV systems increases efficiency. PV panels can be cooled by using passive or active cooling. In active type cooling is done externally. An active cooling system contains blowers, or pumped water cooling. Active cooling systems are used when the gain of additional efficiency due to cooling is more than the power wasted due to cooling. In passive cooling PV panels are mounted with height of $2mts$ to allow air flow through them. The space between them is painted in white not absorb any heat.

Generally power output from a PV panel will be reduced after installation. It normally ranges from 80% to 90% of the rated capacity.

2.1.2 Estimation of irradiance incident on PV panel

The calculation of irradiance on PV panel includes two parts, calculation of extra-terrestrial irradiance and calculation of irradiance incident over a surface [9–11]. The formulae to find the total irradiance has been explained in steps below

Calculation of extra-terrestrial irradiance

Extra-terrestrial irradiance is the irradiance directly entering into earth's surface without any distraction due to earth's atmosphere. The direct irradiance over the earth's surface depends upon the longitude and latitude of the position. Now we go across some mathematical equations estimate

hourly irradiance and to convert irradiance measurement corresponding to sun angles into irradiance corresponding to local time.

- Time can be measured from sundials. However, there may be time mismatch between local time and time measured from sundials. In some situations time measured by sundial may be faster than local time and it is maximum of 16 min and 33 sec faster, happens during november. In some situations time measured by sundial may be slower than local time and it is maximum of 14 min 6 sec slower happens during february. It is due to earth's axial tilt during rotating around sun.

The equation of time measures the time mismatch due to the Earth's axial tilt.

$$EOT = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B) \quad (2.14)$$

where can be calculated as follows $B = \frac{360}{365}(d - 81)$ and d is day in a year starting from january 1st.

- In any country a standard longitude is selected to follow standard time across particular country and also globe has been marked as time zones to calculate standard time in each location. Indian standard time meridian is 82.58° E which passes through shankargarh fort. Local Standard Time Meridian is a reference meridian used for a particular time zone and it is represented as follows

$$LSTM = 15^{\circ}\Delta T_{GMT} \quad (2.15)$$

- Above two terms can be used to calculate exact time in a location by using Time Correction Factor. Time Correction Factor accounts the variation of the Local Solar Time within a given time zone due to the longitude variations and it is formulated as follows

$$TC = 4(Longitude - LSTM) + EOT \quad (2.16)$$

- Local Solar Time is the exact time corresponding to the exact location. It is an summation of local time corresponding to the meridian and Time Correction Factor

$$LST = LT + \frac{TC}{60} \quad (2.17)$$

- Simulations are done in terms of time and for calculation of irradiance from sun the angle at

which is incident over the location is needed. Hour Angle converts the local solar time into the number of degrees when the sun moves across the sky. Hence, by using Hour Angle we can determine the exact position of sun in terms of angles

$$HRA = 15^0(LST - 12) \quad (2.18)$$

- The Declination angle, denoted by δ , varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun. The earth tilted by an angle of 23.45^0 . The declination angle is zero if earth is not tilted. Only at the equinoxes the declination angle is zero and during solace the declination angle is 23.45^0 . However in between equinoxes and solaces the declination angle varies from 0 to 23.45^0 and can be calculated as follows

$$\delta = \sin^{-1} \left(\sin(23.45^0) \sin \frac{360}{365}(d - 81) \right) \quad (2.19)$$

- The Elevation angle is the angular height of the sun in the sky measured from the horizontal. It is 0^0 when sun is horizontal and 90^0 when sun is vertical. Elevation angle depends on time of a day and factors such as latitude, day in a year. It is denoted as α and it can be calculated as follows

$$\alpha = \sin^{-1}(\sin(\delta)\sin(\psi) + \cos(\delta)\cos(\psi)\cos(HRA)) \quad (2.20)$$

where ψ is latitude.

- Zenith angle is the angle between the sun and the vertical. Since, zenith angle is angle between sun and vertical, elevation angle is inclination between horizontal and sun. Zenith angle can be calculated same as elevation angle and formulated as follows

$$\theta_Z = 90 - \alpha \quad (2.21)$$

The time at which sunrise and sunset is calculated as follows by equating zenith angle to 90^0 and the simplified equation is given as follows

$$SUNRISE = 12 - \frac{1}{15^0} \cos^{-1}(-\tan(\psi)\tan(\delta)) - \frac{TC}{60} \quad (2.22)$$

$$SUNSET = 12 + \frac{1}{15^0} \cos^{-1}(-\tan(\psi)\tan(\delta)) - \frac{TC}{60} \quad (2.23)$$

- Azimuth angle is the compass direction from which the sunlight is coming. At Solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere

$$Azimuth = \text{Cos}^{-1} \left(\frac{(\sin(\delta)\cos(\psi) - \cos(\delta)\sin(\psi)\sin(HRA))}{\cos(\alpha)} \right) \quad (2.24)$$

Calculation of Irradiance on Inclined Surface

While installation of PV panels it is needed to know the amount of irradiance occurred in a particular location. The minimum value of irradiance is $0 \text{ kw}/\text{m}^2$ and maximum irradiance is $1 \text{ kw}/\text{m}^2$ at any time. Pyrheliometer is the instrument used to measure solar irradiance. The irradiance in a location can be represented in any of the form

- Daily, Monthly and Yearly average irradiance in a particular location
- Mean year data in a particular location
- Average sunshine hours data
- Sunshine hours

However, monthly average solar irradiance data can be easily obtained and researchers proposed algorithms for calculation of hourly irradiance data from monthly average data. The following set of equations describes procedure to calculate hourly irradiance data from daily average irradiance in month over a year

- Sun emits equal amount energy in all directions. Hence, the average solar energy entering into earth's atmosphere can be estimated accurately at any position (without interference of earth's atmosphere such as dust, gases and especially clouds). The solar power arriving at the top earth surface at particular point can be given as follows

$$G_{on} = G_{sc} \left(1 + 0.033 \cos \frac{360d}{365} \right) \quad (2.25)$$

G_{sc} is solar time constant $1.367 \text{ kw}/\text{m}^2$

- The extra-terrestrial horizontal radiation, defined as the amount of solar radiation striking a horizontal surface at the top of the atmosphere

$$G_o = G_{on} \cos(\theta_z) \quad (2.26)$$

- Due to earth's atmosphere comprising of clouds, gases and dirt. All the solar irradiance entering the earth's outer space can reach the ground. The clearness index ratio of the surface radiation to the extra-terrestrial radiation.

$$K_T = \frac{G}{G_0} \quad (2.27)$$

- A part of solar irradiance travels without any scattering and Beam radiation (G_b) is defined as solar radiation that travels from the sun to the earth's surface without any scattering by the atmosphere
- Diffuse radiation, defined as solar radiation whose direction has been changed by the earth's atmosphere

$$G = G_b + G_d \quad (2.28)$$

- The ratio of diffused radiation to the total radiation can be calculated from the clearness index. VA Graham, Hollands VGT, Unny TE proposed a time series model to estimate the hourly clearness index from the monthly clearness index data .So, hourly irradiance can be estimated as follows.

$$\frac{G_d}{G} = \begin{cases} 1 - 0.09K_T & \text{for } K_T < 0.22 \\ 0.9551 - 0.1604K_T + 4.388K_T^2 - 16.638K_T^3 + 12.336K_T^4 & \text{for } 0.22 \leq K_T \leq 0.80 \\ 0.165 & \text{for } 0.80 < K_T \end{cases} \quad (2.29)$$

- The direction at which solar irradiance occurs depends on the direction and angle at which panel is mounted. In order to extract maximum power from PV panels, tracking systems were also provided with both vertically and horizontally. In fixed PV panels the panels were mounted in north direction in southern hemisphere and south direction in northern hemisphere. The solar irradinace over a tilted panel can be estimated from the following equation

$$\begin{aligned} \cos(\theta) = & \sin(\delta)\sin(\psi)\cos(\beta) - \sin(\delta)\cos(\psi)\sin(\beta)\sin(\gamma) + \\ & \cos(\psi)\cos(\beta)\cos(\delta)\cos(\omega) + \cos(\delta)\cos(\beta)\sin(\gamma)\sin(\omega) \end{aligned} \quad (2.30)$$

where θ is the angle of incidence^[0], β is the slope of the surface ^[0], γ is the azimuth of the surface ^[0], ψ is latitude ^[0], δ is solar declination ^[0], ω is the hour angle ^[0].

- Beam radiation is defined as the ratio of radiance on the tilted surface to beam radiation on the horizontal surface. It is represented as R_b and formulated as follows

$$R_b = \frac{\cos(\theta)}{\cos(\theta_z)} \quad (2.31)$$

- Anisotropy index A_i , is a measure of the atmospheric transmittance of beam radiation

$$A_i = \frac{G_b}{G_0} \quad (2.32)$$

- Coefficient of Irradiation due to horizontal brightening

$$f = \sqrt{\frac{G_b}{G}} \quad (2.33)$$

- The total irradiance over an inclined plane can be calculated from the equation

$$G_T = (G_b + A_i G_d) R_b + G_d (1 - A_i) \left(\frac{1 + \cos\beta}{2} \right) \left(1 + f \sin^3 \frac{\beta}{2} \right) + G \rho_g \left(\frac{1 - \cos\beta}{2} \right) \quad (2.34)$$

Where β Slope of the surface [°] and ρ_g is ground reflectance, which is also called the albedo [%]

2.1.3 Different costs involved in SPVEC

SPVEC Capital Cost

The SPVEC installation includes the installation of the PV panels, Tracking system, Mounting hardware, Control system, inverter, Wiring and Installment.

- Commercially available PV panels

The type of PV panel installed determines the capital and performance of it. Some PV panels may be cost. But, have higher efficiency and some might be cheap and have poor performance.

The list of commercially available PV panels are given below

1. Mono-Crystalline : Mono-Crystalline solar panels are costliest of all the commercially available solar panels. The maximum efficiency of these panels are up to 18%. These require a rigid mounting frame. 36% of the PV Panels market share is held by mono crystalline.

2. Poly-Crystalline: The poly-Crystalline PV panels are costlier than thin film and cheaper than mono-Crystalline. The maximum efficiency of Poly-Crystalline PV panels is up to 16%. These panels require a rigid mounting frame. 52% of the PV panels market is held by poly-crystalline.
3. Thin-Film solar cells: The thin film solar cells are the cheapest of all the commercially available solar panels. These don't require any hardware to mount. The efficiency ranges from 6%-12%. 12% of the market share is held by thin-film solar cells.

- Tracking system

Tracking systems are provided to get maximum irradiance over a surface panel. The panels were mounted and adjusted horizontally, vertically along the direction of solar irradiance based upon sun azimuth and zenith angles. With incorporation of tracking systems the capital cost increases. However, tracking systems ensure maximum power extraction from panels.

- Control Systems

1. MPPT control of SPVECS: In MPPT control techniques the duty ratio of DC/DC is adjusted to get maximum output [23, 24]. There are commonly used techniques to track the maximum power in solar systems. There are many technically proven MPPT algorithms available. With variation in technology performance and costs may vary.
2. LPPT control of SPVECS: In LPPT control technique the duty ratio of DC/DC converter is adjusted to get the power required [25]. If P_{ref} is less than MPP. The output of DC/DC converter is the given reference power. If P_{ref} is greater than the MPP the output of DC/DC converter is Maximum Power. Sliding mode control is one of the existing LPPT techniques. P_{ref} is a signal representing power that is exactly needed from PV panel for user. There is a certain amount of research work on LPPT control of SPVEC systems.

However, in present work the selection of microgrid generators the economy is only a considerable factor and control techniques have little significance in selection. However, optimal operation requires the data of available control techniques.

Capital cost of PV panel system includes purchase and installation of all above devices. Despite of, in recent years the cost of PV panels decreased very rapidly due to technological advancements. The capital cost of PV panels is very high. It came in competition with wind power generation due to ease of their installation. Government policies in many countries also encourage the installation of clean energy sources and also PV panel's per Kw cost varies with installation size. Per Kw price

of PV Panel decreases with increase in size of the installment. For example the cost installing $1Kw$ plant is rupees one lakh fifty thousand. The cost of $100Kw$ plant is rupees one crore forty five lakhs and it tends Per Kw installment cost is rupees one lakh forty five thousand.

PV panel Maintenance Cost

PV panel maintenance cost includes

- Preventive Maintenance Cost: Preventive Maintenance cost includes cost due to servicing and inspection of equipment to prevent power loss and failure
- Corrective or Reactive Maintenance Cost: Corrective or Reactive Maintenance Cost is cost due to repair equipment breakdowns after the occurrence.

Without the maintenance of PV panels, the performance may decreases 8% and deration of 2% may occur every year. Hence, maintenance is an important factor. In our work, maintenance cost of PV panels is considered to be proportional to size of PV panels. If $1Kw$ yearly maintenance costs is Rs 1000. $10 K$ PV panel maintenance cost is Rs 10000. There is no operational cost for SPVEC.

2.2 Wind Energy Conversion Systems

WEC Systems convert kinetic energy wind into electrical energy with the help turbines and generators. The power output from Wind Turbines can be estimated from it's characteristics.

2.2.1 Wind Turbine Characteristics

The power According to BETZs law, wind turbines cannot convert more than 59.3% of the wind's kinetic energy. Most of the turbines will have maximum efficiency of 75% to 80% of BETZs limit. The efficiency of the wind turbines varies with speed.

The mathematical model of wind turbine:

Power output from wind turbine with wind speeds can be formulated as follows

$$P_{wind} = \frac{1}{2} \rho A v_w^3 C_p(\lambda, \beta) \quad (2.35)$$

where P_{wind} is power output from wind turbine, ρ is density of air, A is area swept by blade, v_w is velocity of wind

Turbine power co-efficient can be calculated from following equation

$$C_p = a_1 \left(\frac{a_2}{\lambda_i} - a_3\beta - a_4 \right) e^{\frac{-a_5}{\lambda_i}} \quad (2.36)$$

where a_1, a_2, a_3, a_4, a_5 are constants, λ is tip to speed ratio, β is Pitch angle.

Tip speed ratio λ can be calculated as follows

$$\lambda = \frac{w_r R}{v_w} \quad (2.37)$$

where R is radius of blade, w_r is rotor speed

Wind speeds varies with height.

However, wind speeds at heights different from anemometer height can be calculated from the equation below

$$\frac{U_{hub}}{U_{anemo}} = \frac{\ln(Z_{hub}/Z_0)}{\ln(Z_{anemo}/Z_0)} \quad (2.38)$$

where U_{hub} is speed at hub height of wind turbine in m/s , U_{anemo} is wind speed at anemometer height in m/s , Z_{hub} is hub height of wind turbine in m , Z_{anemo} is height at which wind speeds measured in m , Z_0 is surface roughness length in m , and \ln is natural logarithmic function.

Wind turbine power output at different different can be calculated from output at standard air density

$$P_{WTG} = \left(\frac{\rho}{\rho_0} \right) P_{WTG,STP} \quad (2.39)$$

where ρ is air-density, ρ_0 is air-density at standard test conditions and $P_{WTG,STP}$ is power output at standard test conditions.

2.2.2 Installation Costs of WEC Systems

Installation of wind energy conversion systems includes turbines, blades, generators, transformers, converters and wiring.

The wind turbines are equipped with control devices to control the power output. Different kind of control techniques

- MPPT control of WECS: In MPPT control the duty ratio of DC/DC is controlled in order to get maximum power [26].
- LPPT control of WECS: In LPPT control technique the duty ratio of DC/DC converter is

adjusted to get the power required [27]. If P_{ref} is less than MPP. The output of DC/DC converter is the given reference power. If P_{ref} is greater than the MPP output of DC/DC converter is MPP Power. Sliding mode control is one of the existing techniques.

Since, load balancing in optimal selection is generated power must greater than or equal to load. Type of control technique has little influence over the optimal sizing. However, type of available control techniques is an influential factor on optimal operation.

Wind power generation is one of the cheapest renewable source of power generation which is in use for decades and also many federal governments also encouraging clean energy sources of power generation by subsidies. Per Kw price of wind turbine decreases with increases in size of the installment. For example the cost installing $1Kw$ plant is rupees one lakh twenty thousand. The cost of $100Kw$ plant is rupees one crore ten lakhs which tends to Per Kw installment cost is rupees one lakh ten thousand.

2.2.3 Maintenance Cost of WECS

The maintenance cost of wind turbines is more than the maintenance cost of PV Panel because of moving parts. The maintenance cost includes cleaning to remove the debris and dirt over the blades. Changing the turbine bearings. Applying grease to the moving parts. The maintenance of wind turbines increases with increase in age of equipment. The newly installed wind turbines maintenance cost per year is around 2% of total installation cost and old wind turbines is 3% of total installation cost. In present work maintenance cost of wind turbines is considered to be proportional to their size.

2.3 Electrical Energy Storage Systems

Electrical energy storage systems convert electrical energy into other forms of energy, store it and convert back into electrical energy when needed.

2.3.1 Need of Electrical Energy Storage Systems

The penetration of renewable energy resources, increase in fuel costs and smart grid rises the need for Electrical Energy Storage (EES) systems. The following discussion explains the need of EES systems [28]. However, present discussion is mostly on batteries which can be easily incorporated into microgrid.

1. Off-grid areas:

Off-grid areas mostly consists of transportation and places where transmission lines cannot be constructed. Fossil fuel vehicles which are using in traditional transportation can be replaced by electrical vehicles and the power for these vehicles can be generated by using renewable energy sources. Off-grid areas can be electrified using Renewable resources. In all these systems there is need of batteries.

2. On-grid areas:

Penetration of renewable resources in on-grid areas increases difficulty in frequency control. If the fluctuations becomes more system performance may decrease. However, frequency control is mostly balanced by other conventional generation sources. These sources cannot be used at full load capacity without any storage. Batteries can mitigate the energy fluctuations and the sizing of generators can be also reduced.

3. Smart Grid applications:

Batteries are going to play prominent role in future smart-grids. Batteries on the distribution side can regulate power flow and also maintains voltage. The battery storage in electrical vehicles can also be used for load balancing during peak loads. Since, these loads can also be shifted. Batteries can also be used for energy management in homes and commercial buildings.

4. Power Quality Improvement:

Power distribution systems must provide electrical energy with minimum voltage and power fluctuations to the customers. Generally frequency is maintained using power generators. Battery Storage Systems (BSS) can provide required power to maintain frequency. Traditionally voltages are controlled using transformers. BSS can also maintain voltage when installed at user end.

5. Efficient use of network:

In power system network, congestion occurs when power lines cannot provide power when required in time to meet the increased load. Batteries installed at appropriate substations can solve congestion problem.

6. Shifting load timings:

Utilities must able to provide annually increasing peak load demand, in proportion generation should also increase. Batteries can provide an alternative solution by storing power at off peak

period running generators at maximum capacity and supplying during peak timings.

7. Islanded grids:

When network is stand-alone, power from all generating sources, like diesel generators, renewable resources must match the demand. With energy storing devices good quality power can be supplied.

8. Emergency power supply:

Batteries coupled with inverters can be used as emergency power supply during outage or power system failure.

2.4 Specifications of Batteries

There many kinds of commercially available batteries such as lead acid, lithium-ion, sodium sulphur batteries etc. The performance, lifetime and cost varies with different kinds of batteries. Lead acid are mostly used batteries for large power applications. These batteries are also used in vehicles. But, usage of lead is restricted. It is cheaper. Sodium Sulphur batteries are latest developed technologies for power applications. The batteries which are commercially available were provided with following specifications and these are using for power balance equations for battery [15]

- Nominal capacity:

The energy that can be withdrawn from fully charged battery at nominal discharge current when it is 100% charged. The units are A-h. Capacity of battery decreases with increase in discharge rate.

- Nominal voltage:

The battery terminal voltage varies with SOC, charge and discharge current and operating conditions around certain voltage called nominal voltage.

- Round Trip Efficiency:

Batteries are not 100% efficient due to internal resistance. Losses occurs during charging and discharging. Round trip efficiency is low for sodium type batteries due to heating requirements. The efficiency at which the energy charged to the battery can be discharged is called round trip efficiency. Typical efficiency is 80%.

- Battery Charge Efficiency:

The efficiency at which batteries can be charged. Normally it is calculated as square root of Round Trip Efficient.

- Minimum SOC:

The state of charge below which the battery should not discharge. Minimum state of charge is maintained for better lifetime and to supply power for critical loads. The influence of state of charge on battery cycles can be observed from lifetime curve.

- Float life:

When battery is limited in use. The charge and discharge cycles will have no effect on lifetime. Hence, batteries will be derated due to aging only which limits lifetime and it is the maximum life of a battery.

- Lifetime throughput:

Total amount of energy that can be cycled through the battery over life time at specified minimum SOC. Lifetime throughput can be calculated from lifetime curve.

- Maximum charge rate:

The maximum rate at which battery can be charged in an hour.

- Maximum charge current:

The maximum allowable charging current of battery at any time. If the battery is charged more than particular maximum charge current. Batteries may damage.

- Capacity Curve:

In addition to the above specifications the consumer will also provided capacity curve and lifetime curve. The absolute amount of charge available in the battery is called capacity of battery. Nominal capacity of battery is specified at nominal current. However, battery capacity depends upon temperature, discharge current and other factors. Generally capacity decreases with increase in discharge rate. The manufacturer will provide the capacity curve to represent the characteristics. Fig.2.2 represents the changes of capacity with changes in discharging current.

- Life time curve:

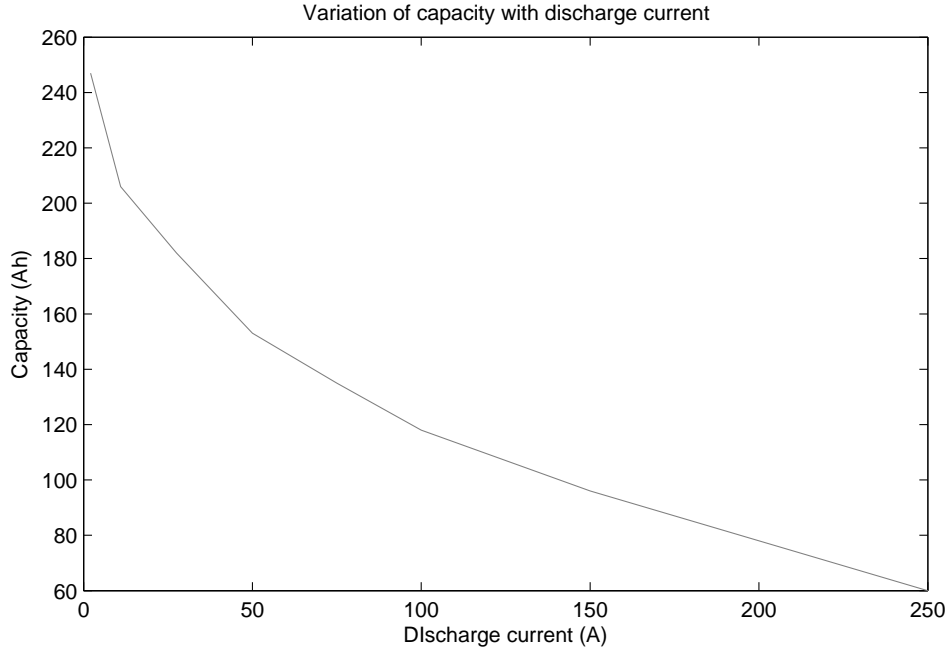


Figure 2.2: Battery Capacity Curve

This characteristics will give working life time of battery. Battery is fully charged and discharged to a certain value to determine the total cycles of charging and discharging in life time. The cycles of failure decreases with decrease in minimum state of discharge. Fig.2.3 represents the changes in cycles of lifetime of battery with changes in depth of charge.

2.4.1 Kinetic Battery Model

Manwell JF, McGowan JG proposed kinetic energy model for battery [15]. In kinetic battery model the battery is considered two tank system. The outer tank contains availabel energy, the energy availabel for power conversion and inner tank contains chemically bounded energy not readily availabel for conversion. The parameters used for kinetic battery model are maximum capacity, Capacity ratio is the ratio of size of availabel tank to the total tank size. Rate constant gives the conductance between two tanks. So, we can measure power interactions between two tanks.

- Total energy in the battery can be divided into
 - Availabel Energy The energy that is readily availabel for power conversion in present time step.
 - Bound Energy The energy which is chemically bounded and it is not availabel for power conversion at present time step.

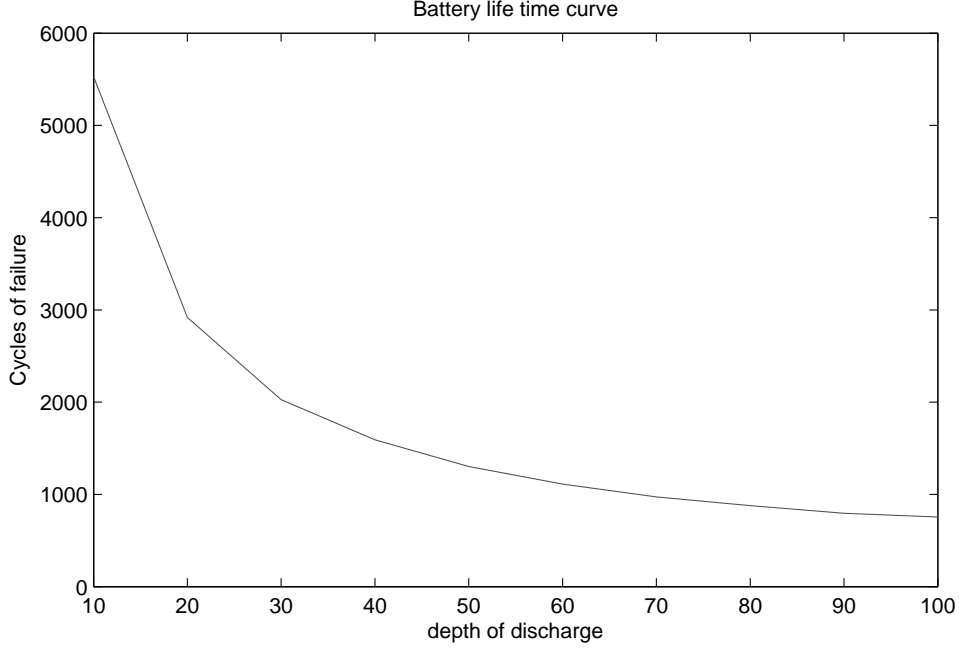


Figure 2.3: Lifetime Curve of Battery

Total energy is sum of availabel energy and bound energy

$$E_{T,t} = E_{a,t} + E_{b,t} \quad (2.40)$$

- The maximum amount of energy that can be discharged from the battery at particular time step t is formulated as follows

$$P_{dmax,t} = \frac{kE_{a,t}e^{-kt} + E_{T,t}kc(1 - e^{-kt})}{1 - e^{-kt} + c(kt - 1 + e^{-kt})} \quad (2.41)$$

- The maximum amount of energy that can be absorbed from the battery at particular time step t is formulated as follows

$$P_{cmax,t} = \frac{-kcE_{max} + kE_{a,t}e^{-kt} + E_{T,t}kc(1 - e^{-kt})}{1 - e^{-kt} + c(kt - 1 + e^{-kt})} \quad (2.42)$$

- The availabel energy at the end of time step t is given as follows

$$E_{a,t+1} = E_{a,t}e^{-kt} + \frac{(E_{T,t}kc + P)(1 - e^{-kt})}{k} + \frac{Pc(kt - 1 + e^{-kt})}{k} \quad (2.43)$$

- The bound energy at the end of time step t is given as follows

$$E_{b,t+1} = E_{b,t}e^{-kt} + E_{T,t}(1 - c)(1 - e^{-kt}) + \frac{P(1 - c)(kt - 1 + e^{-kt})}{k} \quad (2.44)$$

where $E_{a,t}$ is available energy, $E_{b,t}$ is bound energy, t is time step, P is power output, k is rate constant, c is capacity ratio. However in present work a simplified version of kinetic energy model has been used by neglecting the exponential terms. Simply considering the rate constant and capacity ratio.

2.5 Diesel Generator

A diesel compression-ignition engine often is designed to run on fuel oil. It can also be run for other liquid fuels or natural gas. Using of biogas mixed with fossil fuels to generate power are discussed in biomass section.

2.5.1 Diesel Generator Lifetime

Lifetime of Diesel Generator doesn't depend on number of years. It depends upon the number of working hours. The factors that influence generator lifetime are operating conditions, maintenance frequency, fuel quality, and other factors.

Estimation of Generator Lifetime

Lifetime of diesel generator can be estimated based on speed of operation. However, generator life

Table 2.1: Estimated generator life time based on speed of operation

Generator Type	Size(kw)	Estimated Life Time
High speed (3600 RPM) air-cooled gasoline, natural gas, or propane generator	1-10	250 - 1,000
High speed (3600 RPM) air-cooled diesel	4 - 20	6,000 - 10,000
Low speed (1800 RPM) liquid-cooled natural gas or propane generator	15 - 50	6,000 - 10,000
Prime power liquid-cooled diesel	7 - 10,000	20,000 - 80,000
Natural gas micro-turbine	25-500	50,000 - 80,000

can also be expressed in years with few mathematical calculations. The equation to convert generator lifetime into years is given as

$$R_{g,y} = \frac{R_{g,h}}{N_{g,h}} \quad (2.45)$$

Where $R_{g,h}$ represents generator lifetime in hours, $R_{g,y}$ generator lifetime in hours, $N_{g,h}$ operating hours in an year.

2.5.2 Minimum Load on Generator

In general optimal operation generator should not be operated below certain load and it is called minimum load on generator. Since, we are developing algorithm for optimal design. There is no need to consider this factor. The algorithm itself take care of it.

2.5.3 Fuel Curve

The fuel consumption of a generator depends upon the rated power and operation power at any hour [29]. Fuel consumption can be modeled as a straight line with intercept. It is characterized by intercept co-efficient and slope of a line which have physical meaning.

- Intercept co-efficient is the no-load fuel consumption of the generator divided by its rated capacity
- Slope is fuel consumption of the generator per Kw

Total fuel consumed can be given by the equation

$$F_T = F_0 P_{rated} + F_1 P_{gen}(t) \quad (2.46)$$

Where F_0 is intercept co-efficient, F_1 is slope, P_{rated} is rated power of diesel generator, $P_{gen}(t)$ is generating power at time instant t

Calculation of fuel intercept co-efficient and Slope

A generator consumes x_1 liters per hour for y_1 Kw generation and consumes x_2 liters per hour for y_2 Kw generation. The slope can be calculated with the following equation

$$F_1 = \frac{y_2 - y_1}{x_2 - x_1} \quad (2.47)$$

The intercept co-efficient can be calculated as

$$F_0 = x_1 - F_1 y_1 \quad (2.48)$$

Emissions Factors of generator

This section describes about the gaseous emission due combustion fuel from diesel generators

- Generator Carbon Monoxide Emissions Factor: Generator Carbon Monoxide Emissions Factor is the amount of carbon monoxide emitted per liter fuel consumed by generator
- Generator Unburned Hydrocarbons Emissions Factor: Generator Unburned Hydrocarbons Emissions Factor is the amount of unburned hydrocarbons emitted per liter fuel consumed by the generator
- Generator Particulate Matter: Emissions Factor Generator Particulate Matter Emissions Factor is the amount of particulate matter (smoke, soot, and liquid droplets) emitted per liter fuel consumed by the generator
- Generator Sulfur Emitted as Particulate Matter Factor Generator: Sulfur Emitted as Particulate Matter Factor is the fraction of the sulfur in the fuel that gets emitted as particulate matter.
- Generator Nitrogen Oxides Emissions Factor: Generator Nitrogen Oxides Emissions Factor is The amount of nitrogen oxides emitted per liter fuel consumed by the generator

The actual quantity of this pollutant produced by the generator will depend on engine design, operating conditions and power output of the generator. However, in present work reduction of emissions is not considered.

There are few other quantities which needed to be considered in optimal design

- Heat recovery ratio: Heat recovery ratio is the percentage of waste heat produced by the generator that can be used to serve the thermal load
- Substitution ratio: Substitution ratio is the ratio with which the biogas replaces fossil fuel in a co-fired generator
- Generator Minimum Fossil Fraction: Generator Minimum Fossil Fraction is the minimum allowable fossil fraction for a co-fired generator operating on a mixture of fossil fuel and biogas

2.6 Biomass Resources

Power can be generated from bio-mass by thermo- chemical process such as combustion, gasification and pyrolysis and also from bio-chemical process like anaerobic digestion [31]. There are many

advantages by replacing fossil fuels with biogas such as waste reduction / management, reduced emissions, cost savings and power reliability.

2.6.1 Power Generation From Biomass

Power generation from biomass essentially contains three stages:

- **Biomass feedstock:** Biomass in nature obtained in different forms and from different sources. The properties of biomass such as content of energy, ash, moisture content and homogeneity will have considerable impact on power generation. These properties will also have effect on storage, per unit, pre-treatment costs and generation techniques. The source and sustainability of biomass determines the economics and success of project. For an biomass power generation economics. The feed stock sources are listed below
 1. Rural : Livestock effluent, energy crops such as grasses and trees which are particularly grown for biomass, Agricultural wastes
 2. Urban: Wood Wastes such as trim, stumps, Pruned branches, shipping pallets, packing crates and wood debris from construction, demolition, grubbing and clearing activities. Waste from municipality solid and food processing units Waste water, sewage biogas
- **Biomass conversion:** The process by which biomass is converted into the energy form that can be used to generate electrical energy or heat.
- **Power generation technologies:** The process by which biomass energy is converted into electrical energy. There are wide range of commercially availabel technologies for power conversion.

Bioenergy can be converted into useful energy by following process

1. Thermo-chemical process:

The following technique is thermo chemical process which can be used for to convert bioenergy into useful energy for power generation

- (a) Gasification:

When biomass is partially combusted with low levels of oxygen environment producer gas and syn gas is produced. The other types of gasification techniques are allothermal or indirect gasification. The different type of gasifiers which can be used for gasification are fixedbed, fluidized bed and entrained flow. The products of these gasification methods

are a mixture of carbon-monoxide, char, tar, hydrogen, water and carbon dioxide. These products in turn used in combustion engines, fuel cells, gas turbines or micro-turbines. Power generation from gasification process has better efficient than combustion.

- (b) Pyrolysis: Pyrolysis is a process in which biomass is heated to 450 to 600 without the presence of oxygen which produces a liquid called bio-oil and also solid, gaseous products. The bio-oil can be used for power generation

2. Bio- Chemical Process:

Bio-gas is produced from feedstock through anaerobic digestion. The feedstock must be pre-treated before digested. Useless materials such as plastic, mud, stones and etc. must be removed. The biomass should be mixed with water and other type of feedstock. Mesomeric and thermophilic digesters were commonly used. In multi-stage digesters control of process in each stage and optimal digestion is possible. Multi-stage digesters are not much in use

Anaerobic digestion occurs at two different range of temperatures:

- (a) Between $20^{\circ}C - 45^{\circ}C$, usually $35^{\circ}C$ called as mesomeric conditions
- (b) Between $50^{\circ}C - 65^{\circ}C$, usually $55^{\circ}C$ called as thermophilic conditions

The by-product of digestion is digestate which can be used as fertilizer. Biogas is upgraded by removing water and carbon-dioxide which can be used as fuel for vehicles and power generation. Biogas contains major quantities of methane and carbon-dioxide and small quantities of ammonia, sulphur dioxide, hydrogen sulphide, hydrogen and water. Certain types of digesters should be used for different kinds of biomass.

power can be generated from these products by the following methods

1. Direct combustion: Conventional Rankine cycle is used in this process. Biomass will be oxidized i.e. is burnt to generate heat which in turn boils water and generates steam in a high pressure boiler. The steam is used to rotate turbines for generation power through electro-mechanical conversion. The overall efficiency is 23%-25%. The exhausted steam is condensed and can be again used to generate steam or for any other heating purpose
2. Co-firing with fossil fuels: Co-firing of bio-mass with fossil fuels for power generation is generally in use. Changes in burners, mills and dryers is required for co-fired generators. In co-fired boilers for 10% of biomass or 50%-80% of pre-treated biomass can be used with minimum modification in plant design. Else, it requires much changes in plant design

2.6.2 Cost of Biomass Power

Generation of electricity from biomass requires a feedstock which must be produced, collected, stored and transported. 40%-50% of the total electrical generation is comprised of feedstock purchase and maintenance. The price of feedstock depends on energy content, moisture contents, transportation, storage and cost of handling at the plant.

2.6.3 Biomass power generation technology costs

The technology used for power generation varies with type of feedstock, environment and energy conversion methods. The cost of power generation varies with technology. The different costs for biomass power generation technologies is given. However, power generation from biomass through co-fired engine only is discussed in this work.

2.6.4 Operation of CO-fired Engine

Definitions

- Biogas Substitution Ratio: The ratio by which biogas has be replaced with fossil fuels to generate same amount power from co-fired engine. For example if 6 liters of biogas is needed to generate power which consumes 1 liter of fossil fuel. Then substitution ration is 6. For liquid fuels the substation ratio is little more than the ratios of LHV's of biogas and fossil fuel. For gaseous generators the substitution ratio is equal to LHV's of biogas and gaseous fossil fuel.
- Gasification percentage: The percentage by which biogas is produced from biomass feedstock.

Calculation of Power Output from Co-fired Generator

The following assumptions were made while calculating the power output from fossil fuel [32]

- The substitution ratio is independent of power output from generator and fuel mixture
- The co-fired engine is considered such that maximize the use of biogas
- There is minimum limit in fossil fuel fraction

The fuel curve of curve of co-fired engine can be derived from fuel curve when only fossil fuel is used. The mathematical equations to find power output from co-fired engine can be calculated as follows

$$\dot{m}_0 = \rho_{fossil}(F_0 P_{rated} + F_1 P_{gen}(t)) \quad (2.49)$$

from assumption 1,

$$\dot{m}_0 = \dot{m}_{fossil} + \frac{\dot{m}_{gas}}{z_{gas}}; \quad \dot{m}_{gas} = z_{gas}(\dot{m}_0 - \dot{m}_{fossil}) \quad (2.50)$$

Where ρ_{fossil} is density of fossil fuel in kg/l , \dot{m}_0 is fossil fuel rate in pure fossil fuel mode, \dot{m}_{fossil} is fossil fuel rate in cofired mode, \dot{m}_{gas} is biogas flow rate, z_{gas} is biogas substitution ratio. Biogas substitution ratio. Now the fossil fuel fraction can be defined as

$$\chi_{fossil} = \frac{\dot{m}_{fossil}}{\dot{m}_0} \quad (2.51)$$

From the above equations

$$\dot{m}_{gas} = z_{gas}(\dot{m}_0 - \chi_{fossil}\dot{m}_0); \quad \dot{m}_{gas} = z_{gas}\dot{m}_0(1 - \chi_{fossil}) \quad (2.52)$$

The fossil fuel substitution ration must be greater than minimum fraction

$$\chi_{fossil,min} \leq \chi_{fossil} \leq 1 \quad (2.53)$$

Due to cofired engines rated capacity reduces and it is defined as follows

$$P_{rated,der} = \tau P_{rated} \quad (2.54)$$

τ is deration factor of rated power.

2.7 Grid

Grid can considered to be a dispatchable generator. Power can be sold and bought from the grid. The cost of power purchased from the grid is proportional to the power bought at any time instant t . The cost of power sold to grid is proportional to power delivered at any time instant t . Cost of

power interactions with grid can be represented as

$$c_{grid,p}(t) = R_{grid,p} p_{grid,p}(t) \quad (2.55)$$

$$c_{grid,s}(t) = R_{grid,s} p_{grid,s}(t) \quad (2.56)$$

$$p_{grid}(t) = p_{grid,p}(t) + p_{grid,s}(t) \quad (2.57)$$

where, $p_{grid,p}(t)$ is power bought from grid at time t and it is always positive, $c_{grid,p}(t)$ is cost corresponding to power bought, $p_{grid,s}(t)$ is power delivered to grid at time t and it is always negative, $c_{grid,s}(t)$ is cost corresponding to power delivered to grid. At any instant power can be either sold or bought from grid. The unit price for power bought and delivered to grid is given by $R_{grid,p}(t)$ and $R_{grid,s}(t)$, respectively.

Hence, grid cost at time t is given as follows

$$c_{grid}(t) = c_{grid,p}(t) + c_{grid,s}(t) \quad (2.58)$$

Annual grid cost can be represented as

$$C_{grid-ann} = \sum_{t=0}^{8759} c_{grid}(t) \quad (2.59)$$

2.8 Summary

In this chapter we provided literature review about previous work done on microgrid economy and design. We also discussed about previous work done with HOMER a commercial tool which is used for selection of microgrid. Mathematical equations for power output, cost corresponding to output power and constraints over storage and power output was provided in this chapter. Formulae for calculation of solar irradiance and wind speeds were also discussed.

Chapter 3

Microgrid Generators: Cost Formulation and Microgrid Configuration

This chapter discuss about a mathematical formulation for cost estimation of microgrid generators over microgrid lifetime. These cost estimates are later used in an optimization problem to determine optimal sizing of the generators.

3.1 Important definitions

In this section important definitions of parameters which are used in microgrid

- Project Life:

Project Life is time up to which the system costs and cost analysis will be done. Salvage value of all the installed equipments will be considered at the end of the project

- Discount factor:

It is the ratio to calculate the present value of cost or cash occurred in any year. It can be expressed as follows

$$df = \frac{1}{(1 + Ri)^y} \quad (3.1)$$

- Real Interest Rate:

It is actual interest rate imposed over money borrowed after considering the inflation effect.

$$Ri = \frac{N_i - I_f}{(1 + I_f)} \quad (3.2)$$

Various types of generators and sizes are involved in a microgrid. To calculate the total cost of power generation from a particular generator during entire project lifetime, effect of interest rate should be considered. Therefore, any cost incurred during project lifetime has to be expressed in terms of present time (year in which microgrid commenced) and this can be achieved using present value function [30]. The present value function is formulated as:

$$pvf(Ri, y) = \frac{1}{(1 + Ri)^y} \quad (3.3)$$

where, Ri is annual real interest rate and y is year in which cost occurred. df and $pvf(Ri, y)$ defines the term. The net present value, expressing equivalent present day cost for expense to be incurred in year y , is given as a function of (3.3) by

$$C_{npv}(y) = C_y pvf(Ri, y) \quad (3.4)$$

Where C_y is cost incurred in year y .

To consider economy of microgrid over its lifetime, capital, maintenance and operational costs of distributed generators should be included.

3.2 Capital Cost of Generating systems

The total capital cost or total installation cost is sum of the capital cost and replacement cost in project lifetime. The generating system installed costs is considered that it will not change with time. The installation cost initial capital cost of Generators varies with sizes. Generally per Kw cost decreases with increase in size. In optimal selection if the size of generating system is between two sizes which we considered the capital cost for installation will be interpolate between the costs of sizes which we considered. If the optimally size of generator is more than the largest size we considered. We will consider the Per Kw size of the largest size considered for capital costs. The variation of capital cost can be explained with installation of PV panel. If the cost of 1Kw of PV panel is Rs.150000 and the per Kw cost of 2Kw is Rs.148000. If the optimally selected size is 1.5Kw the Per Kw cost of the PV panel installed is Rs.149000.If the optimally size is 5Kw per Kw considered will be Rs.148000.

The generating system lifetime is the time upto which an installed generator can be in operation. The generators must be replaced with same size after the end their lifetime. The replacement cost might be less than the capital cost. However, the scrap value is not considered at the end of the generator lifetime in present work. The number of times generators must be replaced depends on the generator lifetime and project lifetime. It can explained with an example of wind system. If the project life time is 25 years and the wind system life time is 20 years. The installation should be done twice. At the starting of the project and at 21 year of the project. The cost is same at the both times. But, the installed costs occurred other than present time will be scaled to the present value i.e., the first year using discount factor/ present value function.

The generator total project lifetime can be mathematically formulated as follows

$$C_{ic} = f_i(P_i, l_i, l) \quad (3.5)$$

where, f_i is non-linear function which can be modeled with c_{ic} , an array of capital costs corresponding to different sizes belonging to generator i . P_i is installed capacity of generator i , l_i is generator lifetime, l is total project lifetime. Total capital cost c_{ic} is always positive.

These series of equations explains about calculation of total capital cost

$$C_{ic} = S_{ic} c_{ic}^P \quad (3.6)$$

S_{ic} is sum of all the generator installed years discount factors or values present value function scaled to the present year given as follows

$$S_{ic} = \sum_{y=1}^{g_{time}} pvf(Ri, (y-1)g_{life}) \quad (3.7)$$

where g_{time} is number of times generator has to be replaced, Ri is real interest rate.

Calculation of number of times generator to be replaced in project lifetime is formulated as follows

$$g_{time} = \left[\frac{l}{g_{life}} \right] + 1 \quad (3.8)$$

where $\left[\frac{l}{g_{life}} \right]$ is an integer function, l is project lifetime, g_{life} is lifetime of generators, c_{ic}^P is capital cost polynomial function. It also includes the reserve capacity of the particular generator.

The calculation of capital cost can explained with an example. Consider the table 3.1 which shows the array of capital costs of generator corresponding to different sizes i.e, c_{ic} and the per unit

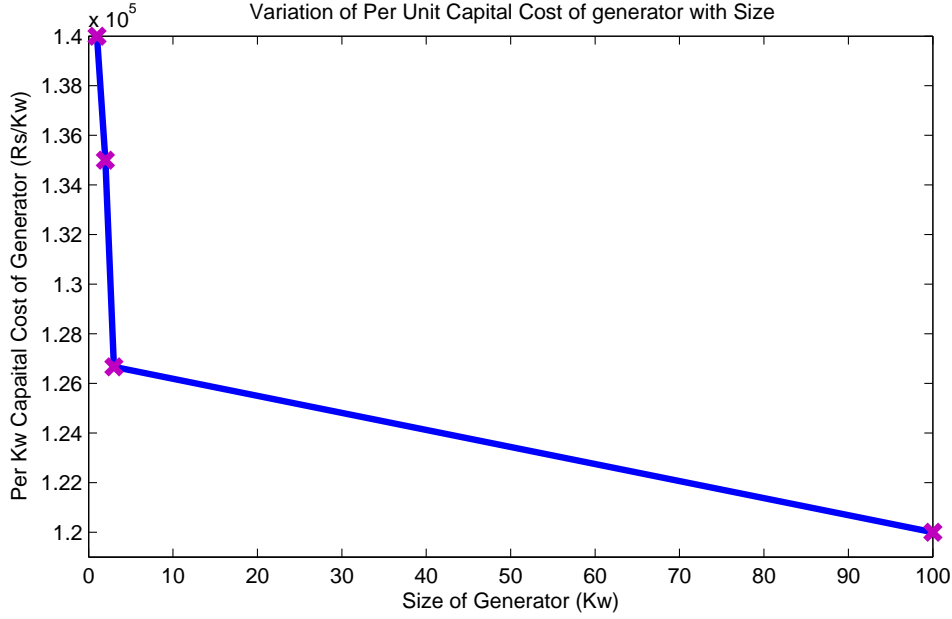


Figure 3.1: Per Unit Capital Cost of Generator with Variation in size

cost corresponding to different sizes is given in figure 3.1. It can be fitted to an second polynomial function which can be represented as $c_{ic}^P = 0.0024P_g^2 + 1.1976 \times 10^5 P_g + 2.3808 \times 10^4$. The per unit cost variation with size of generator calculated from derived polynomial function is represented in fig 3.2.

Table 3.1: Generator Capital Cost of Different Sizes

Generator Size	Capital Cost
1	140000
2	270000
3	380000
100	12000000

3.3 Maintenance Cost of Generating systems

The total maintenance cost of generating systems is the expenditure due to the maintenance of generator occurred during project lifetime. Since, maintenance of generators will be given to an firm as annual maintenance contract. Maintenance cost of generators will be considered annually in present work. The maintenance cost occurred in any year during project lifetime is scaled to the present value and summed to the total maintenance cost using net present value function. The total

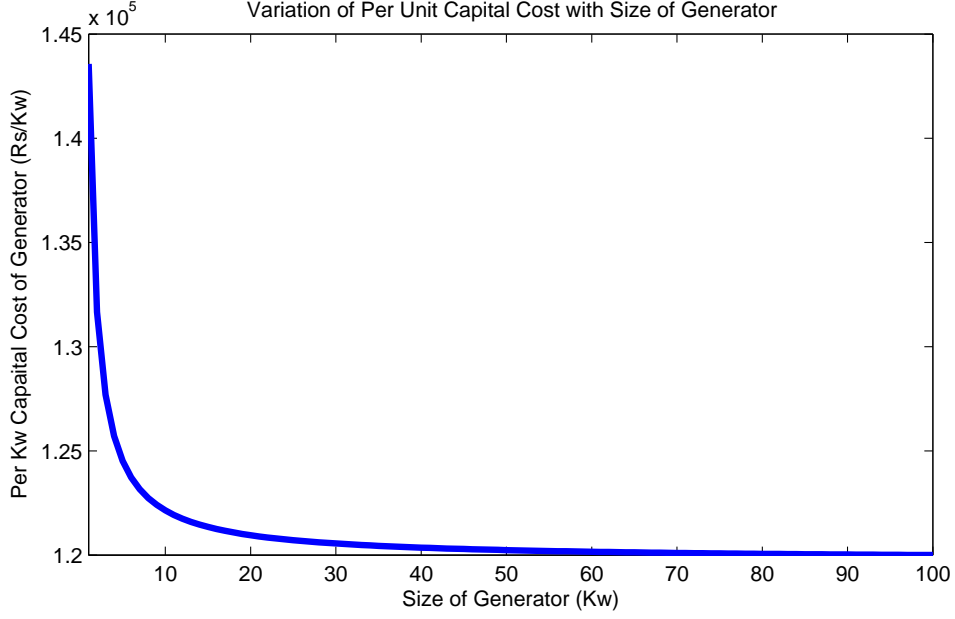


Figure 3.2: Per Unit Capital Cost of Generator with Variation in size Calculated from Derived Polynomial Function

maintenance cost of a generating system occurred in project lifetime is expressed as follows

$$C_{im} = g_i(P_i, l) \quad (3.9)$$

The maintenance cost is a function of installed capacity. The nonlinear function can be determined with c_{im} , which is an array of maintenance costs corresponding to different sizes of generator i .

These series of equations explains about calculation of total maintenance cost

$$C_{im} = S_{im}c_{im}^p \quad (3.10)$$

S_{im} is sum of all the discounted factors of every year's in project lifetime

$$S_{im} = \sum_{k=0}^{l-1} pvf(Ri, k) \quad (3.11)$$

c_{im}^p is maintenance cost of generator i in year of installation. It also includes the maintenance of reserve capacity of the particular generator. c_{im}^p is always positive. However, in present work $g_i(P_i, l)$ is considered as linear function.

3.4 Operational Cost of Generating systems

Operational cost of a generator depends on both size and power generated at particular time instant. It can be formulated as follows

$$c_{io}(t) = R_{io} h(P_i, p_i(t)) \quad (3.12)$$

Where $p_i(t)$ denotes power generated at particular time instant t by generator i and R_{io} is fuel cost. The cost $c_{io}(t)$ is always positive. Annual operation cost of i^{th} distributed generating system can be represented as follows

$$c_{io,ann} = \sum_{t=0}^{8759} c_{io}(t) \quad (3.13)$$

It is assumed that load profile and all environmental dependent factors repeat with certain variability every year throughout project lifetime. Power output from generators and load demand is considered to be constant in each time step. However, power balancing and cost calculations are modeled for one hour time step.

Since, the time step in present work is one hour and in an year total of 8760 hours are present (not considering Leap Year). Total operational cost can be formulated similarly as maintenance cost and represented as C_{io}

$$C_{io} = \sum_{i=0}^{l-1} pvf(Ri, i) \sum_{t=0}^{8759} c_{io}(t) \quad (3.14)$$

3.5 Total Cost of Generating Systems

Total generator cost is sum of capital, maintenance and operational cost during project lifetime. It is represented as

$$C_i = C_{ic} + C_{im} + C_{io} \quad (3.15)$$

Total generator cost is always positive. Any generator cost can be formulated in the cost framework provided in this section. Storage systems capital and maintenance costs can be formulated similarly as generating systems. However, there is no operation cost involved. Grid lifetime cost contains only operational cost. Costs corresponding to grid can also be negative while power is being sold to grid. These cost formulation for some example generators are explained in the next section.

3.6 Optimal Microgrid configuration

The optimal selection of microgrid is defined as the process of determining the size of distributed generators and storage systems ($P_1, P_2, \dots, P_N, P_{bat}$) in such a way that the following objective function is minimized.

$$C_{life} = \sum_{k=1}^N \alpha_i C_k + \alpha_{bat} C_{bat} + \alpha_{grid} C_{grid} \quad (3.16)$$

where, C_{life} is the total microgrid lifetime cost which includes capital, maintenance and operational cost of all generators in project lifetime. The total cost of generator k during project lifetime is denoted as C_k , C_{bat} is lifetime cost of corresponding storage systems (battery), C_{grid} is cost of power exchange with grid over project lifetime. Weights (denoted as $\alpha_i, \alpha_{bat}, \alpha_{grid}$) can also be imposed based on priority of generating systems in the microgrid. Formulation C_k the total cost of k^{th} generator using the equations in section 3 has been discussed in detail here.

3.7 Constraints Over Optimal Selection of Microgrid

The objective function is subjected to the following constraints. Power generation from microgrid must be sufficient to cater to loads and losses at each time instant.

$$\sum_{i=1}^N p_i(t) + p_{bat}(t) + p_{grid}(t) \geq p_{load}(t) + p_{loss}(t) \quad (3.17)$$

where, $p_i(t)$ represents power output from i^{th} generator at time instant t and it is always positive. $p_{bat}(t)$ and $p_{grid}(t)$ are power exchanges with battery and grid, respectively. p_{bat} and p_{grid} are positive, when power is drawn from them and negative otherwise. $p_{load}(t)$ and $p_{loss}(t)$ are load and loss occurred at time t , respectively. $p_{loss}(t)$ doesn't include power loss of generating systems. constraints can also be imposed on minimum and maximum installation sizes of generators The output power from any generator should be greater than minimum permissible power and less than maximum power.

$$p_{imin} \leq p_i(t) \leq p_{imax} \quad (3.18)$$

For most of the generating systems p_{imin} is zero and p_{imax} is rated power. However, for renewable generator, p_{imax} is maximum available power and it varies at each time instant.

The constraints over the battery storage system are

$$E(t) = E(t-1) + \eta_c p_{batc}(t) - \eta_d p_{batd}(t) \quad (3.19)$$

$$E_{min} \leq E(t) \leq E_{max} \quad (3.20)$$

$$p_{bat}(t) = p_{batd}(t) - p_{batc}(t) \quad (3.21)$$

$$p_{batc}(t) \leq p_{batc,max}; p_{batd}(t) \leq p_{batd,max} \quad (3.22)$$

where, $E(t)$ is energy stored in battery at time t , E_{min} is minimum state of charge, E_{max} is maximum state of charge, η_c battery charging efficiency, η_d battery discharging efficiency, $p_{batc}(t)$ is battery charging power at time instant t , $p_{batd}(t)$ is battery discharging power at time t , $p_{batc,max}$ is the maximum charging power, $p_{batd,max}$ is the maximum discharging power. Charging and discharging powers are always positive. For batteries parameters were specified in terms of current. The above equations were derived based on assumption that the battery terminal voltage is constant at nominal voltage and initially the battery is considered to be 90% charged. At any time battery can be charged or discharged. Hence, at any time either $p_{batc}(t)$ or $p_{batd}(t)$ is zero.

The constraints over the biomass power generation system are

$$E_{bio,sto}(t) = E_{bio,sto}(t-1) + E_{bio}(t) - \rho F_1 P_{gen}(t) \quad (3.23)$$

$$E_{bio,min} \leq E_{bio}(t) \leq E_{bio,max} \quad (3.24)$$

where E_{bio} is biogas capacity, $E_{biom}(t)$ is energy converted from biogas at time t , $E_{bio,min}$ is biogas reserve for backup and $E_{bio,max}$ is maximum storage available for biogas. Among all possible generators combination, distributed generators with lowest microgrid lifetime cost is considered as optimal combination. Constraints can be also imposed on generators configuration. Further, configurations with only one particular generation type is possible.

3.8 Summary

Formulation of capital, maintenance and operational costs of generator is discussed in this chapter. Objective function to optimally select different generators and various constraints over battery and biomass power generation was also provided in this chapter.

Chapter 4

Case Studies and Parameters

In this thesis work selection of microgrid in different locations and with different microgrid combinations has been discussed. Details about sensitivity analysis and bootstrapping also had discussed. In all the case studies power loss is assumed to be 10%. Since, solar irradiance and wind speeds are uncertain. 20% reserve capacity is considered both in installation of PV Panels and wind turbines. 20% reserve capacity also considered for biomass power generation. Dispatchable generators should have higher reserve capacity to ensure reliability and availability of sufficient power all times. For the microgrid considered in the case studies, battery and diesel generator are the only dispatch able generators and hence reserve capacity for them is kept at 30 % and 50%, respectively. Different reserve capacities were considered for profitability analysis which will be discussed later. Efficiency of PV Panels decrease after installation over a period of time. The factor by which it decreases is called derating factor. The derating factor of 0.8 is considered in the case studies presented in this paper.

4.1 Case Studies

4.1.1 Study about Effects of Load Variation on Microgrid Economy

The loads profile will have considerable influence on microgrid lifetime cost and unit price. For islanded systems with poor load factor systems microgrid lifetime is more than the grid connected systems and also systems with good load factors. In present thesis work we also discuss about the effects of load profile on microgrid lifetime with certain examples. Various case studies involving a small manufacturing load and a commercial load [33] are considered for this optimal microgrid

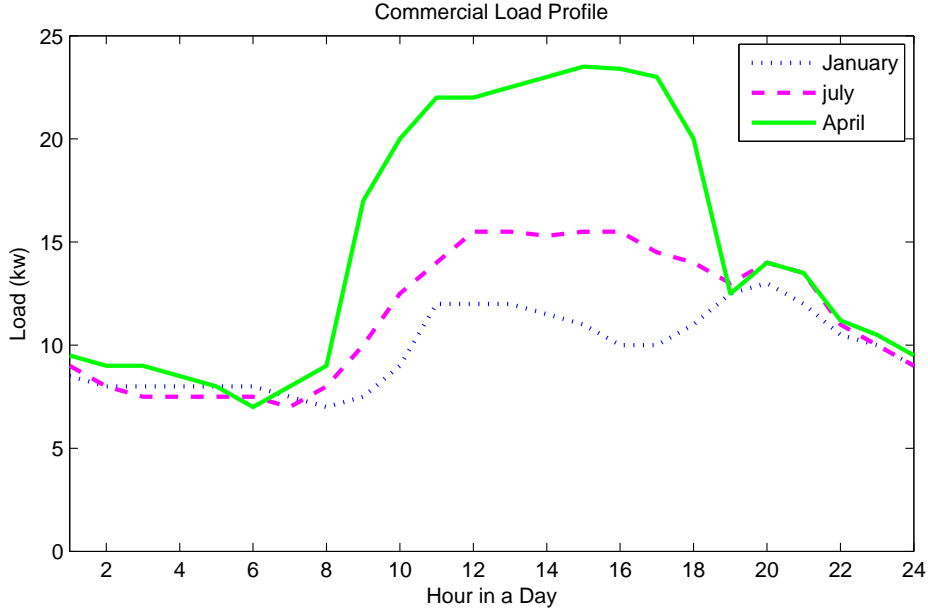


Figure 4.1: Hourly Electrical Load Profile of Study Commercial Load

sizing study. Subsequently optimal PV units, Wind turbine units, diesel generator, biomass power generators, battery storage units installed capacity are obtained and estimates of per unit cost for power generation is obtained. Assuming that the loads are currently electrified by grid only. The electrical power consumption of loads specified is measured hourly over 24 hrs in three different seasons. Fig. 4.1, shows the commercial load profile. The peak load of commercial unit is 30 Kw, average load is 306 Kw/day. Fig. 4.2, shows the Small manufacturing unit load profile. The small manufacturing unit peak load is 250 kw and average load of 2.485 Mw/day. Commercial load profile mostly contains air-conditioning and lighting loads. Whereas small manufacturing load contains mainly production units. During summer season (April), it can be observed that power consumption drastically increases for commercial load due to air-conditioning. Small manufacturing unit power consumption doesn't vary much over a year. This is because air conditioning is only a small percentage of overall load. A comparative results for selection of microgrid generators and microgrid economy for small manufacturing and commercial loads were provided in chapter 5 section 5.2

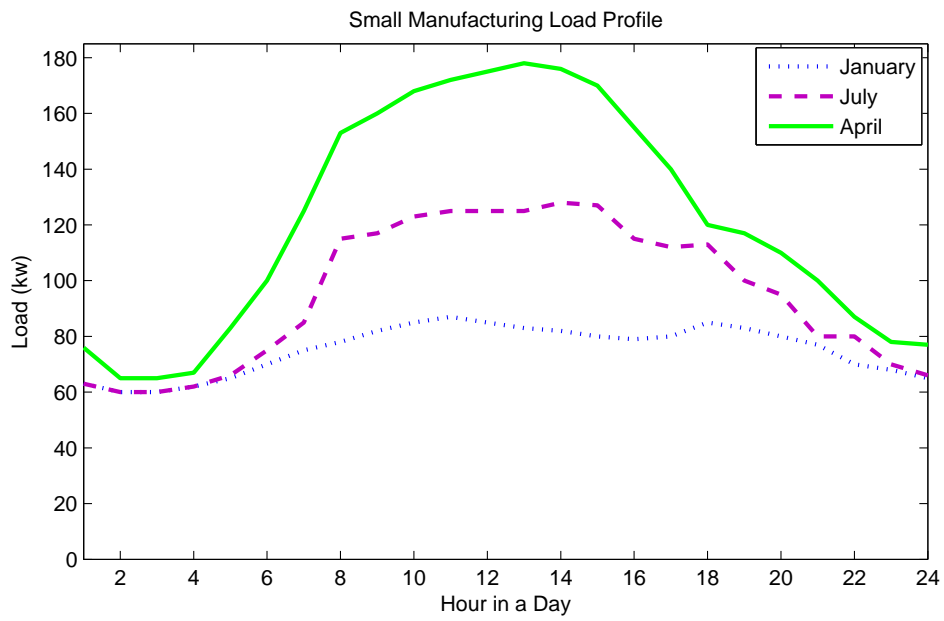


Figure 4.2: Hourly Electrical Load Profile of Study Small Manufacturing Load

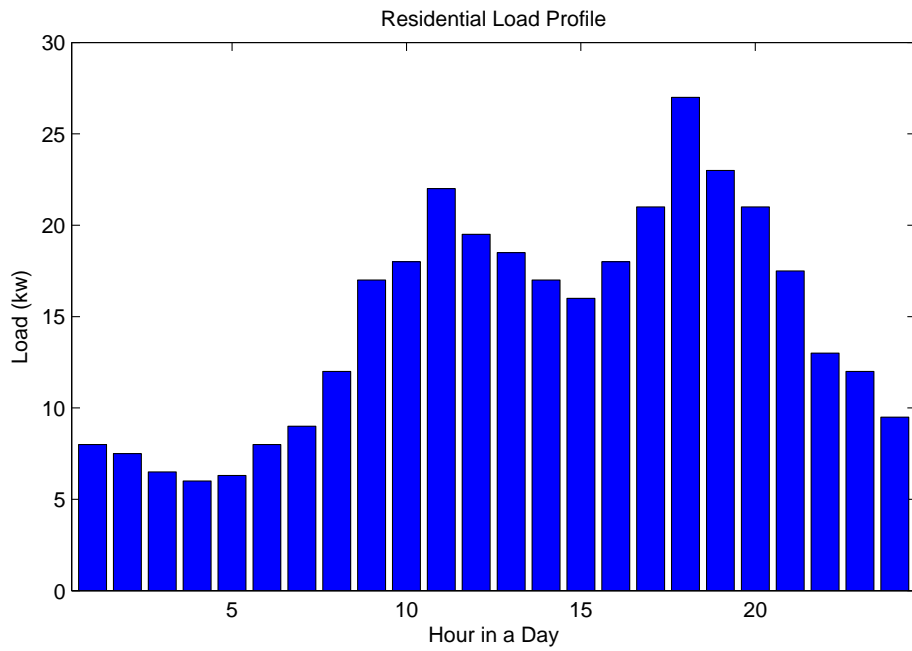


Figure 4.3: Hourly Electrical Load Profile of Study Small Manufacturing Load

4.1.2 Study about Selection of Microgrid Generators in Different Locations

The weather conditions varies with geographical conditions. Wind speeds and solar irradiance changes from location to location. However, Power output from PV panels not only depends on irradiance. It also depends on temperate and surface properties (Very limited influence due to reflexion). Power output from wind systems also depends on air density. Onshore places will have good wind speeds than offshore places. Even wind speeds vary with seasons. Monsoon months will be clouded and also have good wind speeds. Monsoons generally occurs from the months of June to December. Other than monsoon months the days will be clear sky. However, in some years monsoons may fail. Hence, power output from PV systems and wind systems depends on both location and time. Hence, microgrid generators selection and unit price varies with location even for identical load with change in loaction. It is not economical to install a wind turbine in poor wind speeds locations and also PV panels in places with poor irradiance. In section 5.1 of chapter 5. we discuss about optimal selection of microgrid generators and the changes in total microgrid lifetime cost and unit price with change in environmental conditions.

4.1.3 Study of Microgrid Economy with Biomass

So, far microgrid selection in any/ present work discussed about generation of power from renewable source included wind and solar systems. However, biomass is availabel at lowest cost and power generation from biomass is also reliable. In rural areas large amouts biomass is generated from animal husbandry and agriculture which can be used to generate biogas. Biogas can be used to generate power from co-fired engines. In chapter 5, section 5.3 we discuss about selection of microgrid generators along with biomass in a rural village called Quedantang Village. Fig. 4.3, shows the residential load profile of Quedantang Village. The peak load of residential unit is 45 *Kw*, average load is 353 *Kw/day*. The one day load profile of residential unit is considered in whole year and it is assumed that it won't vary with seasons and it has two peaks during morning and evening.

4.1.4 Microgrid Economy Sensitivity w.r.t Operational Costs

Power generated from distributed generators depends on both renewable and conventional sources. Mostly power generation from renewable resources doesn't have any operational costs which vary time, demand and many other factors. However, power output from conventional will have operational cost and also which varies with time over project lifetime. Diesel generator and grid are

the dispatchable generators. Diesel generators work on fuel. Grid prices will have both feedin and feedout tariffs. The fuel cost and grid prices varies with time to time. In chapter 5 and section 5.4 results for the variation of microgrid lifetime cost with changes in all three parameters. We will analyze the results from surface plot by changing any two parameters. Hence, the results were displayed for following studies

1. Change in microgrid lifetime cost with variation in grid feedin and feedout tariffs
2. Change in microgrid lifetime cost with variation in fuel price and feedin tariff
3. Change in microgrid lifetime cost with variation in fuel price and feedout tariff

4.1.5 Bootstrap Analysis of Microgrid w.r.t Load Data

The Hourly load data in a year is generated by randomizing the load profile of a day in different seasons or in a particular month. 20% variance for the daily load profile and 15% variance will be added to time to time load over a year. However, the effectiveness of algorithm depends on the generated load data. In present work we are going to generate set of hourly load data by randomizing the load profile of a day in a particular month with different initial seed values. The average load for each set of data remains constant. These set of generated hourly load data will be processed to select the microgrid generators for serving load and per unit cost will be estimated for grid connected systems. The results were displayed in chapter 5 and section 5.5.

4.1.6 Profitability Analysis

So, far we discussed about the selection of microgrid generators on the basis of reliability. However, many firms are interested in earning profits from microgrid. For profitability analysis the objective function is modified with decrease in reserve capacity and not installing any backup generators for grid connected systems with feedin tariff. There by reduced total cost. In present study we select distributed generators for just serving the required load and the excess power is sent to grid. Thus, we can earn the profits. However, we are really not sacrificing much of reliability. Even the grid failed, we can serve the load with PV systems, wind systems and battery. In chapter 5 and section 5.6 we are providing the results for possibility of profits from grid connected microgrid with feedin tariff.

4.2 Parameters

In this section various parameters considered for optimal design of microgrid were tabulated. Table 4.1 provides the generic wind turbine power output at various wind speeds.

Table 4.1: Wind Turbine Power Output at Different Speeds

Wind Speed	Power output
0	0.000
3	0.000
4	0.020
5	0.040
6	0.090
7	0.190
8	0.30
9	0.520
10	0.700
11	0.85
12	0.940
13	0.960
14	0.980
15	1
16	0.96
17	0.890
18	0.890
19	0.720
20	0.690
24	0.670

Fig. 4.4, illustrates wind turbine output profile fitted to an third order polynomial equation for the data of turbine power output at different speeds given table. 4.1. Cut-in wind speed is 3 m/s , cut-out speed is 24 m/s and rated wind speed is 11 m/s . Below the wind speed 3 m/s the wind turbine doesn't give any output power.

Table. 4.2 explains the prices of solar panels of different sizes. It can easily noted from the table that per KW prices are declining with increase size of PV panels and it is assumed that for panels sized more that 100 Kw the per Kw cost remains same as the 100 Kw panels per Kw cost. The above

Table 4.2: Solar Capital Cost of Different Sizes

PV Panel Size	Cost
1	150000
2	290000
3	430000
100	14000000

capital cost has fitted to an second order polynomial equation $0.0102P_s^2 + 1.399 * 10^5 P_s + 1.0205 * 10^4$ where P_s is size of PV panel.

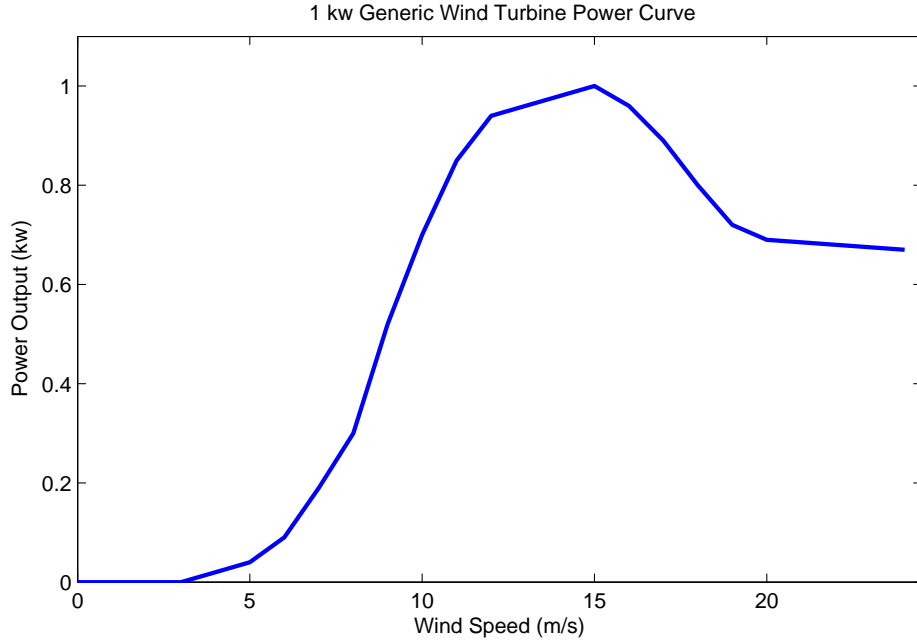


Figure 4.4: 1 kw Generic Wind Turbine Power Output at different Wind Speeds

Table. 4.3 explains the prices of wind turbines of different sizes. It can easily noted from the table that per *Kw* prices are declining with increase size of wind turbines and it is assumed that for turbines sized more that 100 *Kw* the per *Kw* cost remains same as the 100 *Kw* panels per *Kw* cost. The above

Table 4.3: Wind Capital Cost of Different Sizes

Wind Turbines Size	Cost
1	140000
2	270000
3	380000
100	12000000

capital cost has fitted to an second order polynomial equation $0.0024P_w^2 + 1.1976 \times 10^5 P_w + 2.3808 \times 10^4$ where P_w is wind turbine size.

The other parameters of different generators used in microgrid selection were listed in Table-4.4

4.3 Summary

Discussion about various cases considered for microgrid study was explained in this chapter. These case studies provides view about the influence of factors such as location, type of loads, operational costs on the microgrid economy and selection of microgrid. It also explains the reliability of algorithm. We can also know about whether profits can be earned from microgrid ?. The Capital cost

Table 4.4: Parameters

Parameter	Value	Units
c_{1m} (PV)	1000	$Rs/kwyear$
c_{2m} (Wind)	800	$Rs/kwyear$
c_{3m} (DG)	800	$Rs/kwyear$
c_{4m} (Bat.)	400	$Rs/kwyear$
l	25	$year$
l_1 (PV)	20	$year$
l_2 (Wind)	18	$year$
l_3 (DG)	15000	$hour$
l_4 (Bat.)	3422	kwh
f_{03} (DG)	0.08	m^3/kwh
f_{13} (DG)	0.25	m^3/kwh
R_3 (DG)	60	Rs/kwh
$R_{s,grid}$	4	Rs/kwh
$R_{p,grid}$	10	Rs/kwh
Derating Factor	0.8	-
SOC_{min}	30	%
SOC_{max}	90	%
η_c	90	%
η_d	90	%
$p_{batc,max}$	400	w
$p_{batd,max}$	400	w
Ri	5	%
Battery nominal voltage	2	v
χ_{fossil}	2	-
z_{gas}	4	-
τ	4	-

corresponding to different sizes of generators, maintenance cost and parameters were listed in tables.

Chapter 5

Results and Discussions

5.1 Selection of Microgrid Generators in Different Locations

In this section selection of microgrid in different locations across INDIA has been discussed. India is a tropical country with vast geographical extent. Details about the changes of microgrid selection with the changes in terrain has been included. The studies were done with the solar irradiance and wind speeds data of Chennai, Mumbai, Hyderabad, Delhi and Bangalore. These are the metropolitan cities across INDIA. Chennai and Mumbai are metropolitan in coastal areas, Hyderabad and Bangalore are cities in SOUTH INDIA. Delhi is a city in NORTH INDIA where winters have long nights. All the cities in INDIA are polluted. Microgrid is an hope to reduce it. The load considered in present section is small manufacturing. Following generators as well as microgrid configurations are considered for the case studies presented

- Case 1: Islanded operation with PV panels, wind turbines, DG and battery
- Case 2: Islanded operation with PV panels, DG and battery
- Case 3: Islanded operation with wind turbines, DG and battery
- Case 4: Grid connected operation with PV panels, wind turbines, DG and battery with feed-in tariff
- Case 5: Grid connection operation with PV panels, wind turbines, DG and battery without feed-in tariff

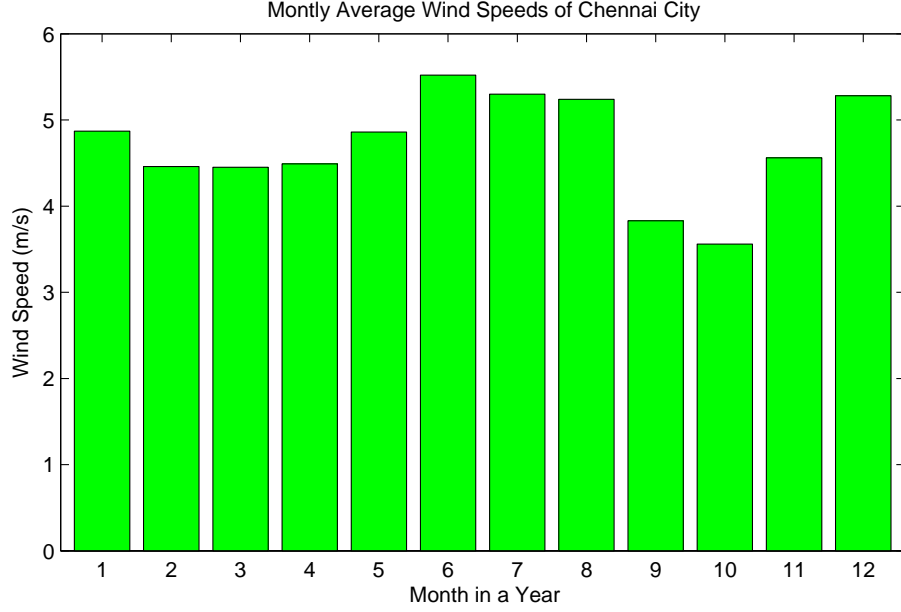


Figure 5.1: Monthly Average Wind Speeds of Chennai City

5.1.1 Study of Microgrid Selection in Chennai City

Chennai is coastal city with abundance of wind and solar resources. Chennai city Latitude is 13.00° N. Longitude is 80.18° E. and Elevation is 16 m. .It has more than 12hrs of daylight. Fig. 5.1 shows the wind speeds and Fig. 5.2 shows the solar irradiance of chennai city [34]. It is clear that from Fig. 5.1 chennai has good potential for wind generation. Hence, it made tamilnadu as the largest installed capacity of Windmills in INDIA.

Hourly wind speeds generated from monthly average wind speeds are shown in fig. 5.3. Hourly solar irradiance generated from monthly average solar irradiance data are shown in fig. 5.4. All the hourly data in present section were represented with continuous time plot.

Table 5.1: Comparative Results for Various Case Studies for Selection of Microgrid in Chennai

Case	$P_1(kw)$ Solar	$P_2(kw)$ Wind	$P_3(kw)$ DG	$P_4(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/kw)
Islanded	246	356	246	429	306450000	13.512
Islanded without Wind	396	0	262	390	324020000	14.2
Islanded without Solar	0	588	249	335	246900000	13.99
Grid Connected with Feedin	257	660	75	33	207570000	9.59
Grid Connected without Feedin	162	328	75	33	256900000	12.52

Table 5.1 indicates the results corresponding to different optimal distributed generators configurations possible for a serving small manufacturing load in chennai city.

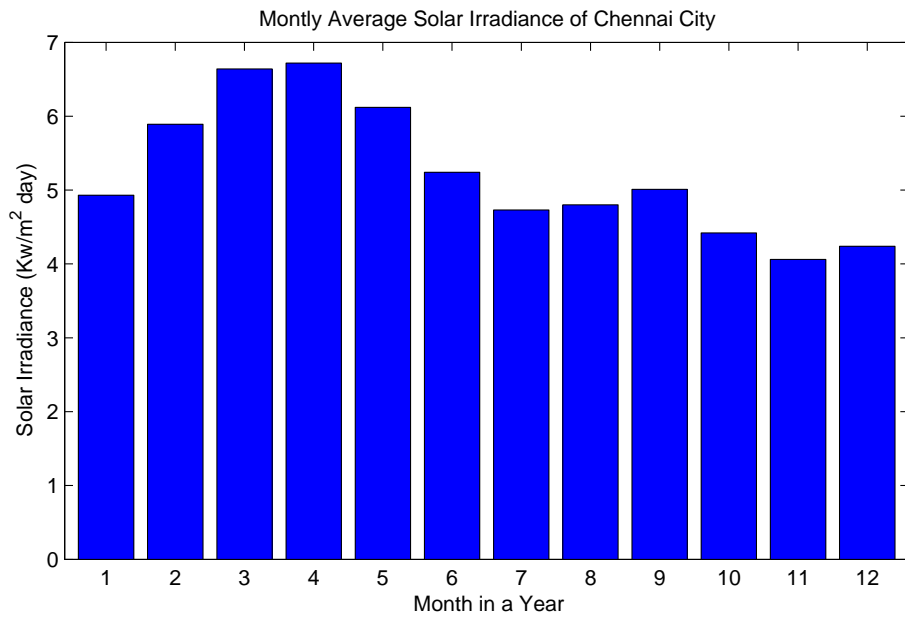


Figure 5.2: Monthly Average Wind Speeds of Chennai City

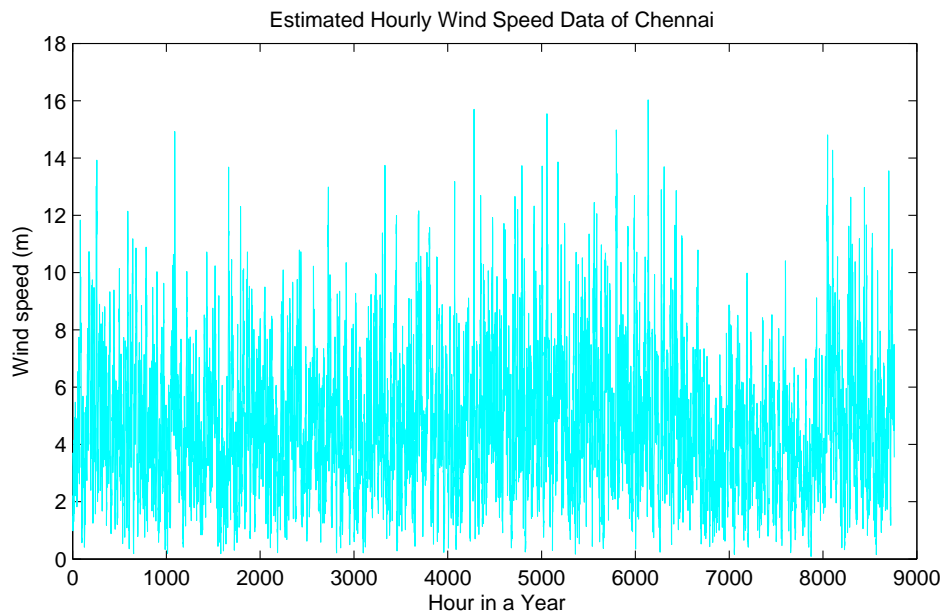


Figure 5.3: Estimated Hourly Wind Speeds of Chennai City

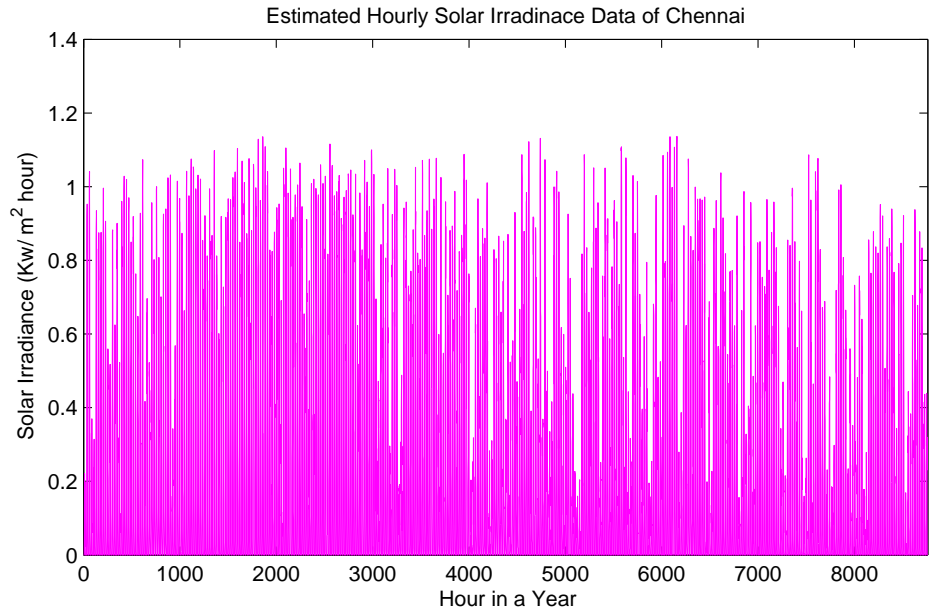


Figure 5.4: Estimated Hourly Solar Irradiance of Chennai City

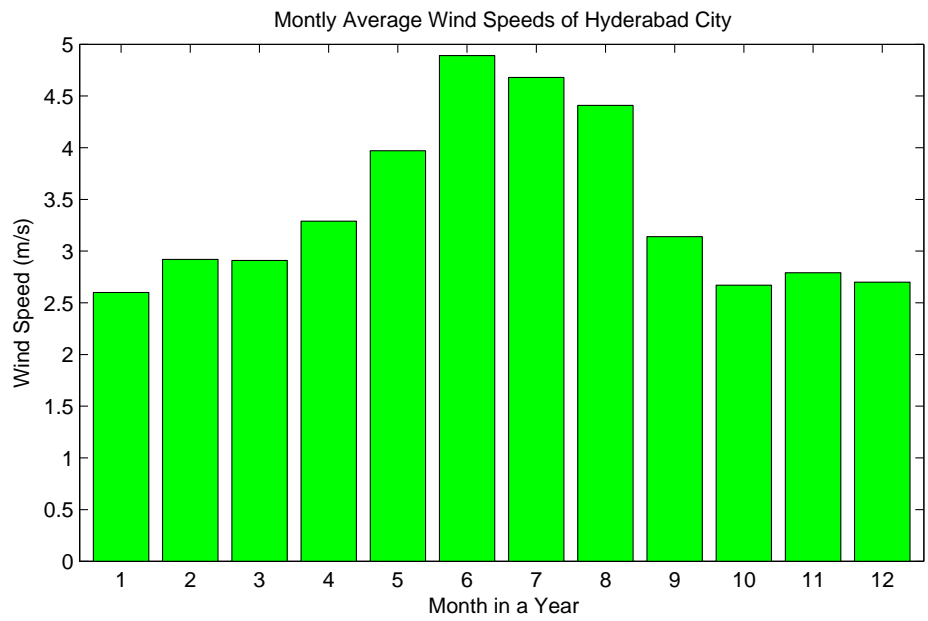


Figure 5.5: Monthly Average Wind Speeds of Hyderabad City

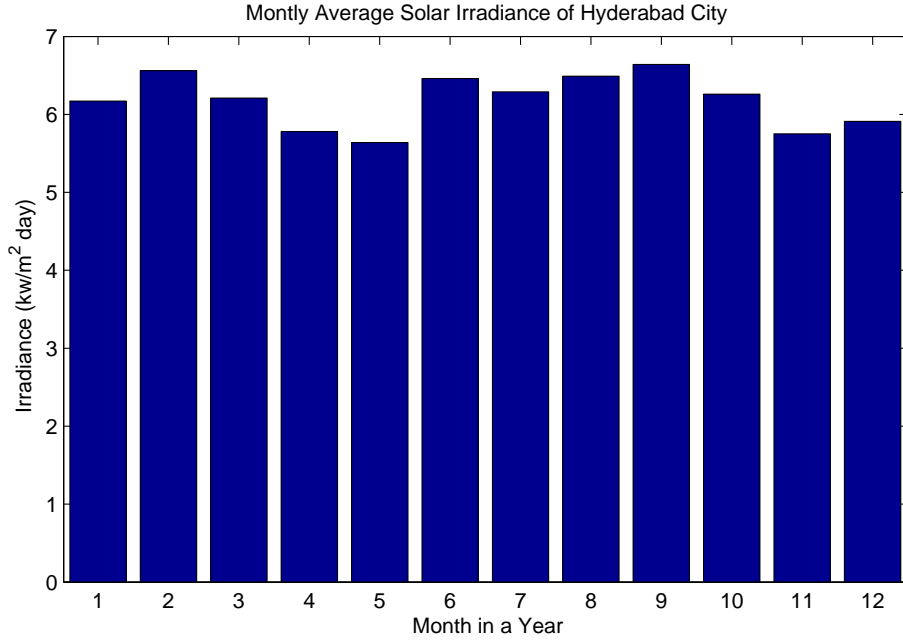


Figure 5.6: Monthly Average Solar Irradiance of Hyderabad City

5.1.2 Microgrid Selection in Hyderabad City

The present section discuss about the effects of Hyderabad terrain in selection of microgrid Hyderabad city. It is located at 17.385^0 N, 78.4866^0 E and average height of 536 m from sea level as it located in deccan plateau region. Hyderabad is a metropolitan City in SOUTH INDIA. It has good potential for solar energy. Since, it is located in plateau region. It has poor wind potential. So, far telengana state is producing power mostly from conventional sources and it is planning for new installation of renewable sources. Fig. 5.5 shows the monthly average wind speeds in a day and Fig. 5.6 shows the solar monthly average irradiance of hyderabad city in day [34]. Estimated hourly wind speeds from monthly data is shown in fig. 5.7. Estimated hourly solar irradiance from monthly data is shown in fig. 5.8.

Table 5.2: Comparative Results for Various Case Studies for Selection of Microgrid in Hyderabad

Case	$P_1(kw)$ Solar	$P_2(kw)$ Wind	$P_3(kw)$ DG	$P_4(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/kw)
Islanded	401	0	262	392	345030000	14.17
Grid Connected with Feedin	524	0	75	33	267360000	11.78
Grid Connected without Feedin	300	0	75	33	283980000	12.52

Table 5.6 indicates the results corresponding to different optimal distributed generators configurations possible for a serving small manufacturing load in hyderabad city.

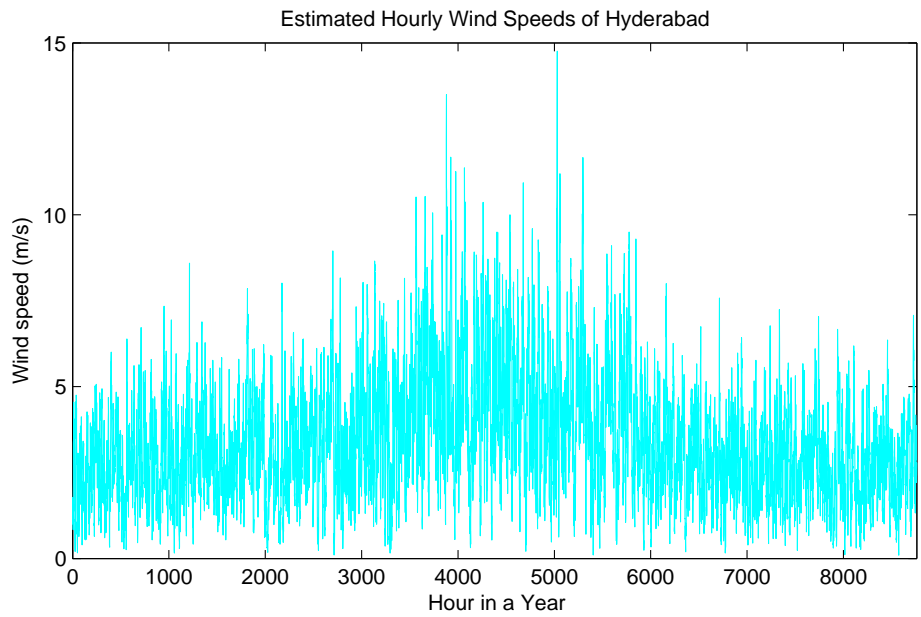


Figure 5.7: Estimated Hourly Wind Speeds of Hyderabad City

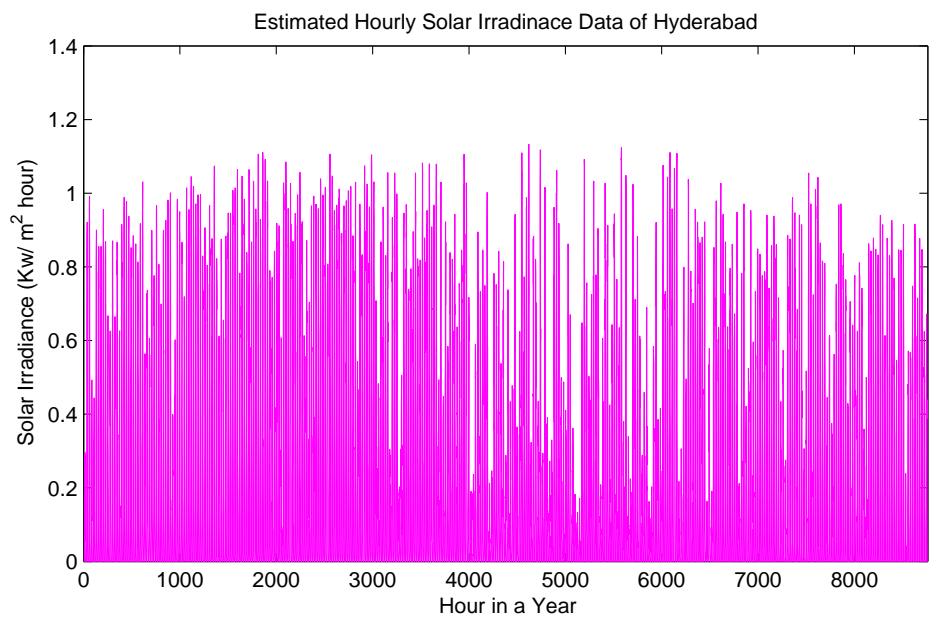


Figure 5.8: Estimated Hourly Solar Irradiance of Hyderabad City

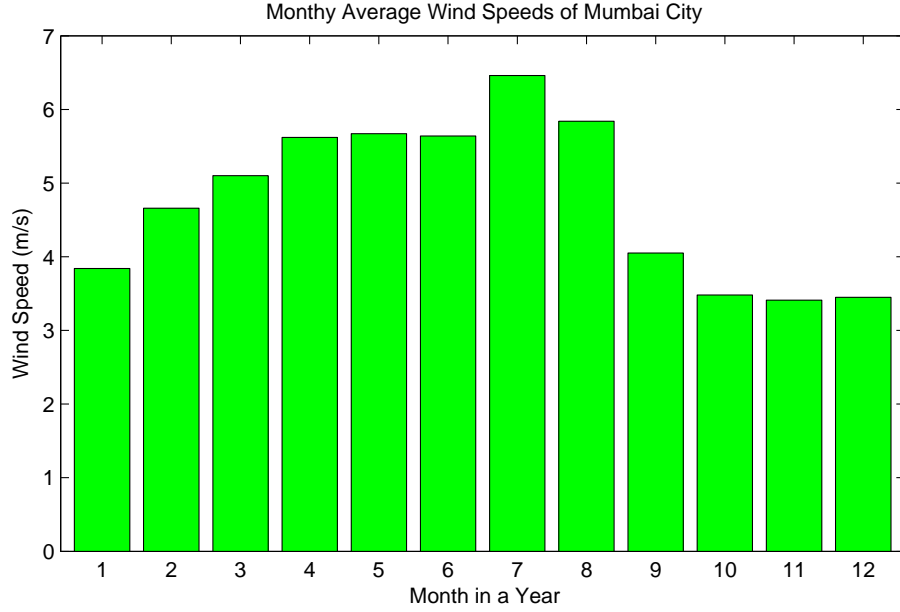


Figure 5.9: Monthly Average Wind Speeds of Mumbai City

5.1.3 Microgrid Selection in Mumbai City

Mumbai is commercial capital of INDIA. It lies on the east coast of INDIA. It is highly industrialized area which has good wind and solar potential. So, the unused land in industrialized area can be used for power generation where load is stationed. Mumbai city is less frequently effected from Strom than Chennai city which ensures safety of wind mills. The location of mumbai city is 18.9750° N, 72.8258° E and it is 15 m above sea level. Fig. 5.9 shows the monthly average wind speeds in a day and Fig. 5.10 shows the solar monthly average irradiance of Mumbai city in day [34]. Estimated hourly wind speeds from monthly data is shown in fig. 5.11. Estimated hourly solar irradiance from monthly data is shown in fig. 5.12. Table 5.3 indicates the results corresponding to different optimal distributed generators configurations possible for a serving small manufacturing load in Mumbai city.

Table 5.3: Comparative Results for Various Case Studies for Selection of Microgrid in Mumbai

Case	$P_1(kw)$ Solar	$P_2(kw)$ Wind	$P_3(kw)$ DG	$P_4(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/kw)
Islanded	318	329	173	425	282650000	12.46
Islanded without Wind	416	0	248	266	315340000	13.9
Islanded without Solar	0	490	219	1054	246900000	14.6
Gird Connected with Feedin	417	596	75	33	213420000	9.41
Grid Connected without Feedin	204	263	75	33	207570000	11.15

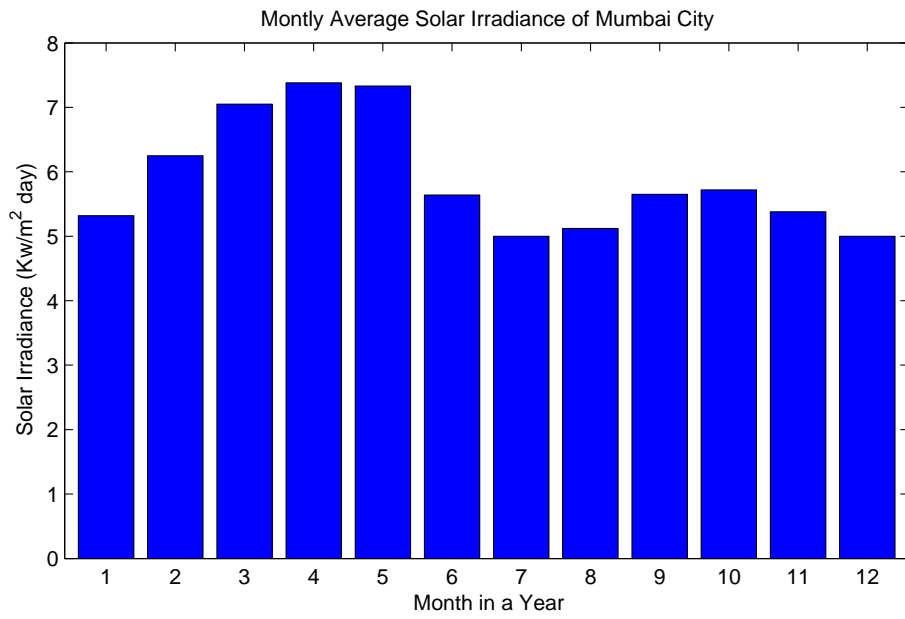


Figure 5.10: Monthly Average Solar Irradiance of Mumbai City

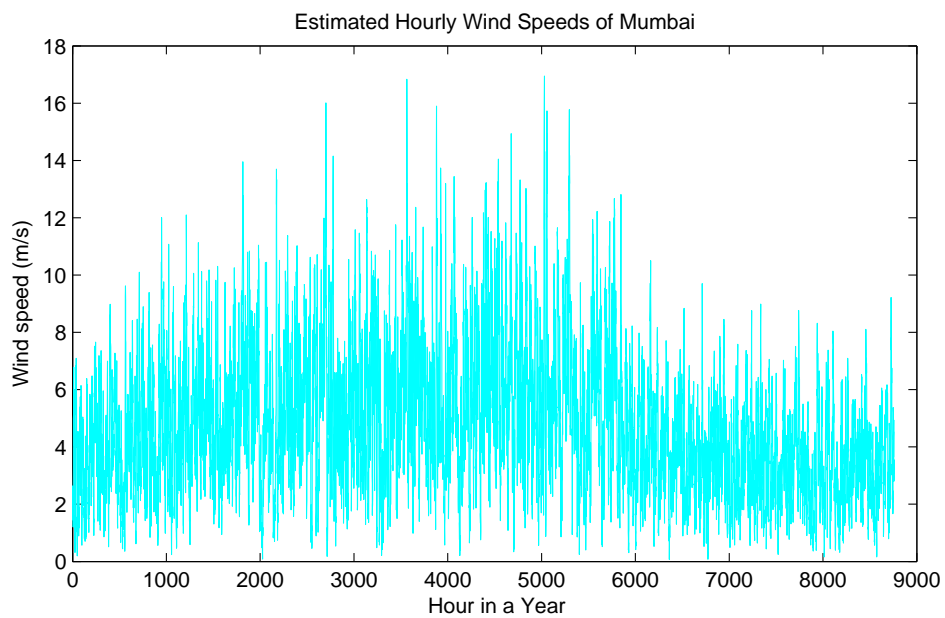


Figure 5.11: Estimated Hourly Wind Speeds of Mumbai City

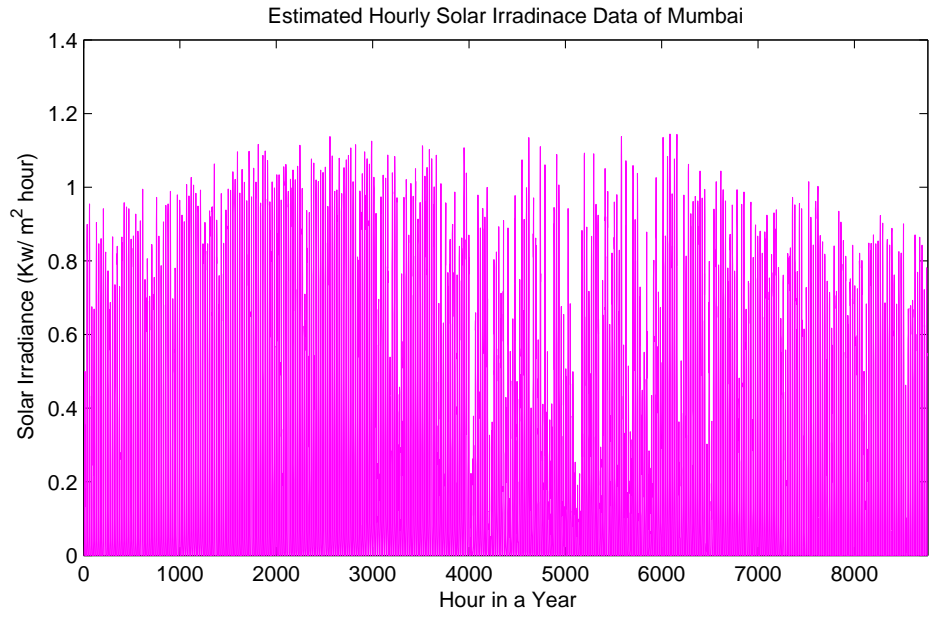


Figure 5.12: Estimated Hourly Solar Irradiance of Mumbai City

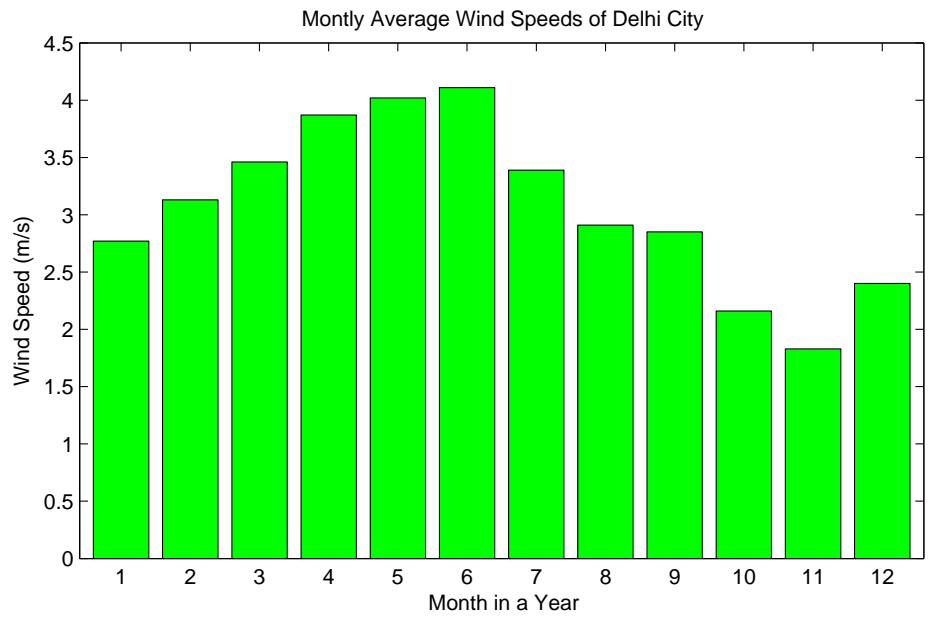


Figure 5.13: Monthly Average Wind Speeds of Delhi City

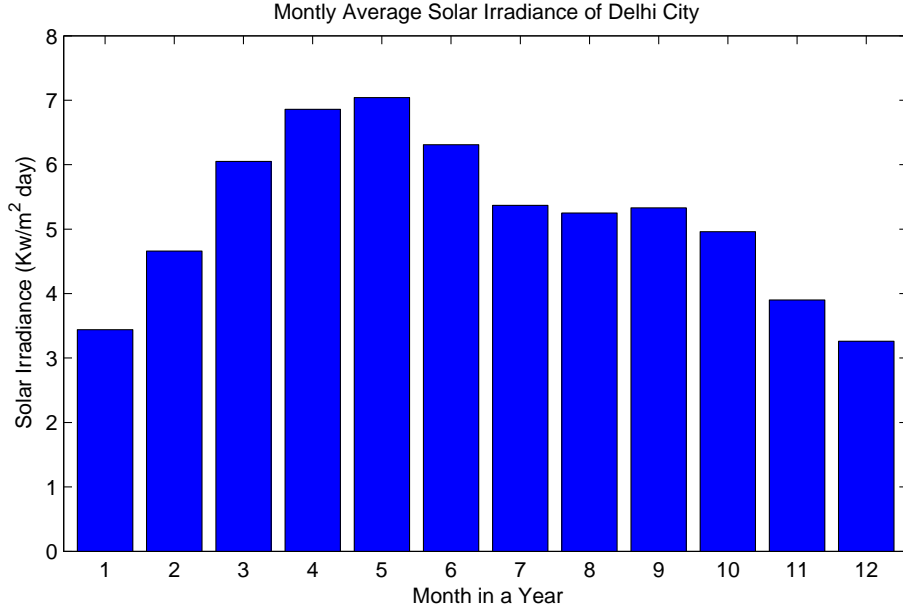


Figure 5.14: Monthly Average Solar Irradiance of Delhi City

5.1.4 Microgrid Selection in Delhi

In this section we study about microgrid selection in delhi. Delhi is the capital city of INDIA situated in NORTH INDIA where poor wind speeds and extreme whether condition occurs. specially we are discussing about effects of poor solar power generation during winter over microgrid selection. Delhi latitude $28.58^{\circ}N$, longitude $77.2^{\circ} E$ and 216 m above sea level. Fig. 5.13 shows the monthly average wind speeds in a day and Fig. 5.14 shows the solar monthly average irradiance of Delhi city in day [34].

Estimated hourly wind speeds from monthly data is shown in fig. 5.15. Estimated hourly solar irradiance from monthly data is shown in fig. 5.16.

Table 5.4: Comparative Results for Various Case Studies for Selection of Microgrid in Delhi City

Case	$P_1(kw)$ Solar	$P_2(kw)$ Wind	$P_3(kw)$ DG	$P_4(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/kw)
Islanded	617	0	200	779	356100000	15.7
Grid Connected with Feedin	538	0	75	33	267360000	12.1
Grid Connected Without Feedin	315	0	75	33	290970000	12.8

Table 5.4 indicates the results corresponding to different optimal distributed generators configurations possible for a serving small manufacturing load in Delhi city.

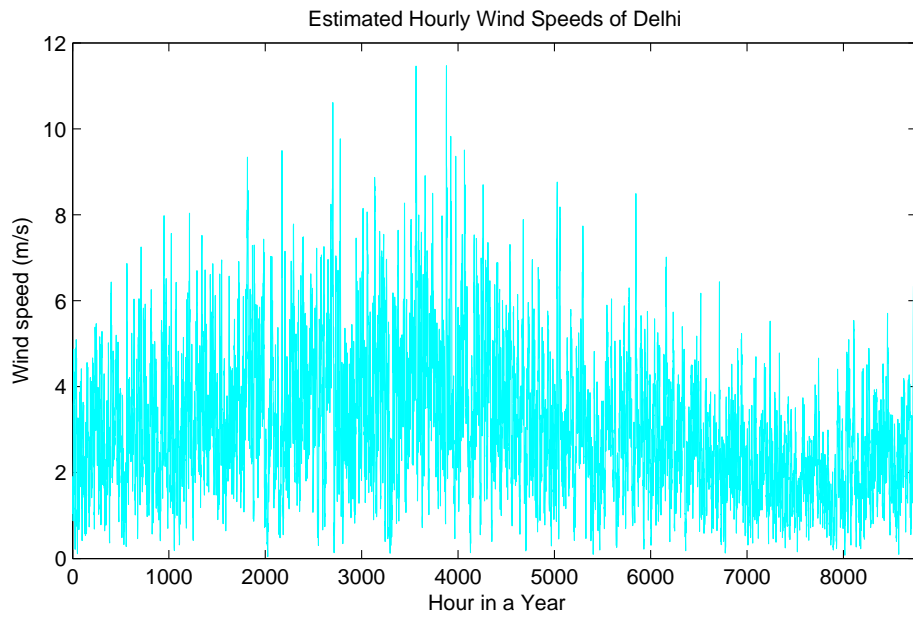


Figure 5.15: Estimated Hourly Wind Speeds of Delhi City

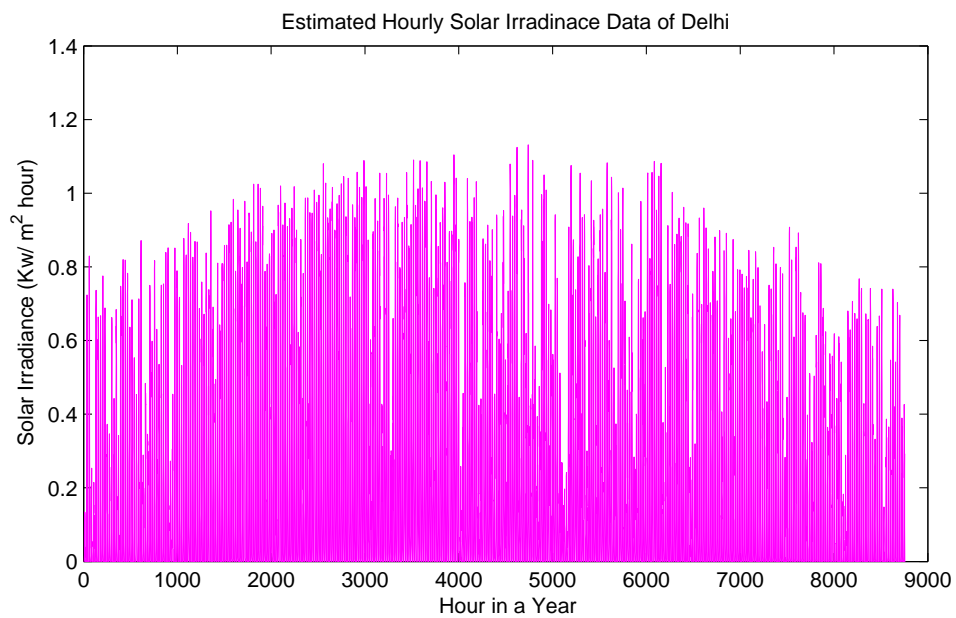


Figure 5.16: Estimated Hourly Solar Irradiance of Delhi City

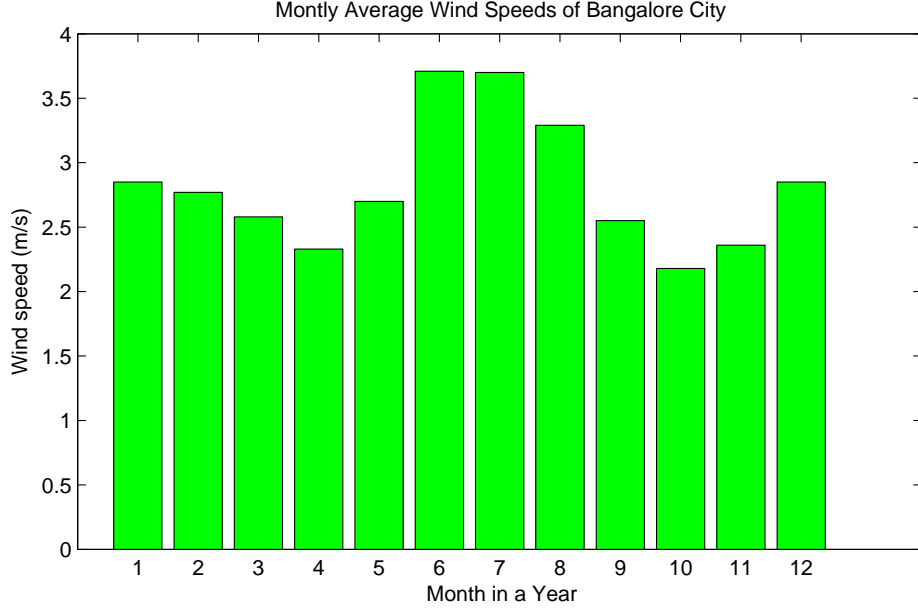


Figure 5.17: Monthly Average Wind Speeds of Bangalore City

5.1.5 Microgrid Selection in Bangalore

Bangalore is a metropolitan city in South corner of INDIA. Bangalore is a pleasant city. It is most polluted city in INDIA. The location of Bangalore is 12.9667° N, 77.5667° E and it is 300 m above sea level. Its elevation is the highest among the major large cities of India. Fig. 5.17 shows the monthly average wind speeds in a day and Fig. 5.18 shows the solar monthly average irradiance of Bangalore city in day [34]. Estimated hourly wind speeds from monthly data is shown in fig. 5.19. Estimated hourly solar irradiance from monthly data is shown in fig. 5.20.

Table 5.5: Comparative Results for Various Case Studies for Selection of Microgrid in Bangalore City

Case	$P_1(kw)$ Solar	$P_2(kw)$ Wind	$P_3(kw)$ DG	$P_4(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/kw)
Islanded	413	0	255	375	335310000	14.78
Grid Connected with Feedin	540	0	75	33	265750000	11.7
Grid Connected without Feedin	301	0	75	33	283290000	12.5

Table 5.5 indicates the results corresponding to different optimal distributed generators configurations possible for a serving small manufacturing load in Bangalore city.

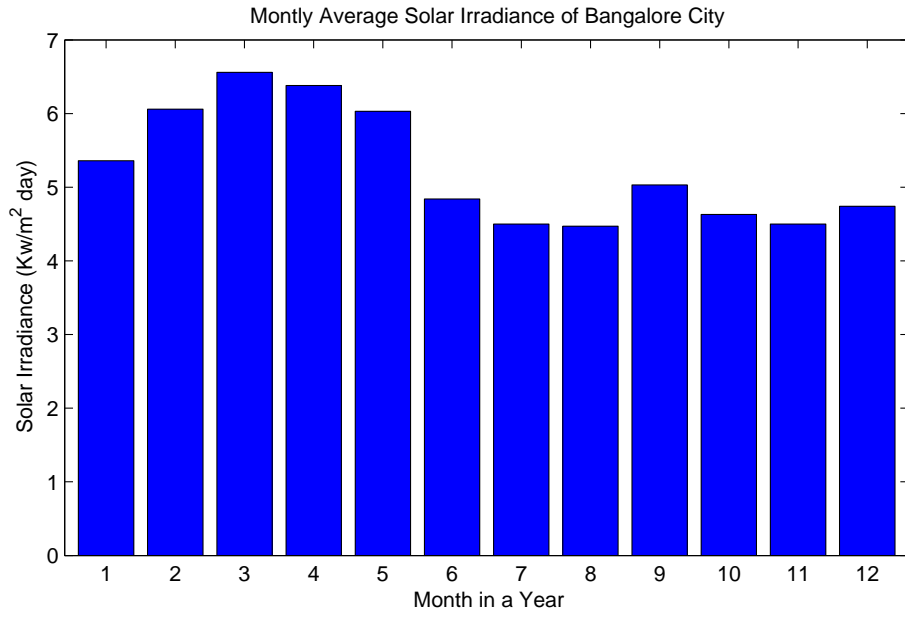


Figure 5.18: Monthly Average Solar Irradiance of Bangalore City

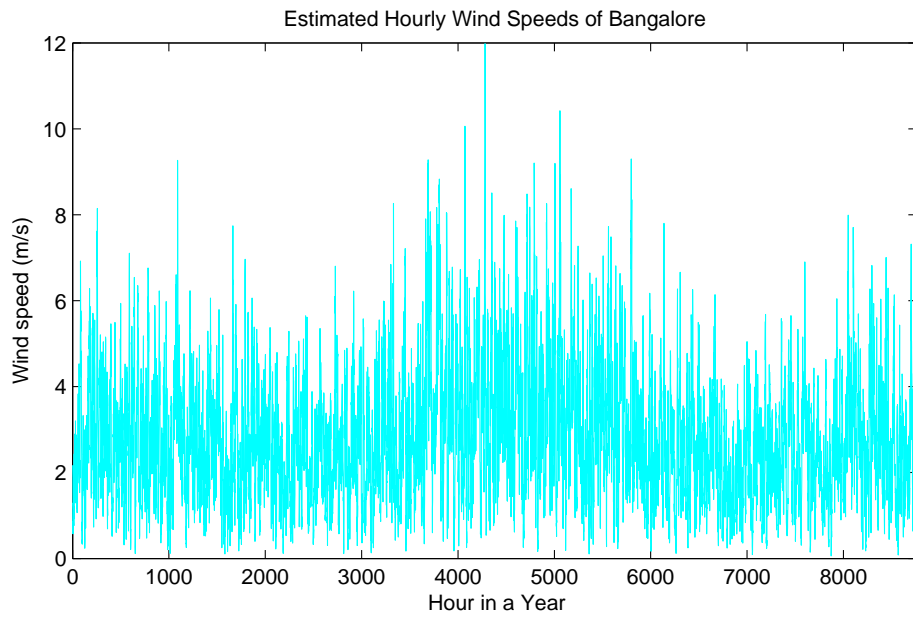


Figure 5.19: Estimated Hourly Wind Speeds of Bangalore City

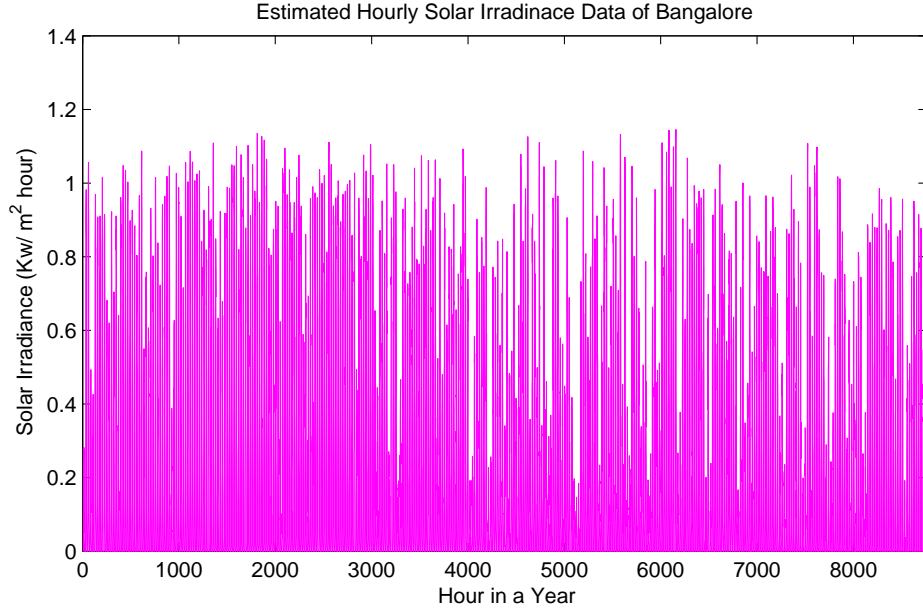


Figure 5.20: Estimated Hourly Solar Irradiance of Bangalore City

5.1.6 Observation

Discussion on Results of Microgrid Selection with Different Distributed Generator Configurations

From hourly wind speed distribution it can be easily observed that most of the time wind speeds in off-coastal areas are around cutin wind speeds. Hence, case 1 and case 3 were not considered for off-coastal cities. Based on the results obtained, following observations can be made.

In case 1, Though power generation cost from diesel generator is high, considerable size has been installed. This is counter intuitive from economic stand point but expected from reliability stand point as diesel generator is the only dispatchable generator, which can supply power to load at any instant. Optimal size of batteries maximize the usage of renewable source generation, in particular PV panels. In Case 2, without wind turbine units there is a drastic increase in PV panels installation capacity. In spite of higher installation of PV panels, per unit cost of power generation is high. The high per unit cost is due to increased DG operating time. Thus going for increased solar panel installations without due economic consideration may actually increase per unit cost of microgrid operation. In case 3 with only wind renewable source power generation also led to increased size of wind turbines and diesel generator operational time. As, a result per unit cost also is increased in the same way in solar generators alone. To take maximum advantage of microgrid all generating systems must be selected coordinately. In Case 4 and Case 5 grid can serve

as dispatchable generator with lower per unit cost. In ideal situation with 24 *hrs* grid power supply there is no need to install other dispatchable generators. Control of such microgrid configuration was proposed in [25]. However, for reliability and continuous operation during outages, an additional constraint on minimum installation size of dispatchable generators is introduced. For grid connected system, total microgrid per unit cost is less compared to islanded microgrid and more compared to grid parity. To ensure reliable and uninterrupted power, the increased per unit cost compared to grid parity may be acceptable for many critical loads. In Case 5, it can be observed that without feed-in tariff the sizes of PV panels and Wind turbines also decreased. It can also be noted that in coastal regions grid connected microgrid with all resources the unit power generation cost is less than grid parity.

Discussion on Results of Microgrid Selection in Different Locations

From the above results it can be observed that selection of distributed resources for supplying power to an ideal load profile in any location around INDIA, demanded almost same size of solar panels, diesel generators and battery Islanded or grid connected without wind energy installations. It can be realized that it is possible because indian peninsula has almost uniform solar irradiance. The cities along coastal lines have good wind resources where installation of wind turbines can compete the solar energy generation costs. In comparison of case 2 and case 3 results for coastal cities where installation of wind and solar are considered separately in powering the load. Power generation from only solar resources costs less than power generation from wind resources . Since, peak load occurs during day time which demands reduced battery sizes. Subsequently, results in reduced total cost/per unit cost of islanded. However, in overall more power is generated from turbines than solar panels in a year. Hence, in grid connected cases i.e., case 4 and case 5 where the role of conventional resources are limited wind installation in coastal regions had an absolute domination over solar installation.

5.2 Comparative Study of Microgrid Economy for Small Manufacturing and Commercial loads

Small manufacturing loads occurs in sub-urban places. Commercial loads were mostly occur in urban sites and daily average load is small for commercial load, therefore installation of wind turbines is not considered in this comparative studies. Hyderabad city's weather conditions were considered

and hourly data was generated for optimal sizing. A detailed description about loads were given in

The case studies considered for microgrid selection are listed below

- Case 1: Islanded operation with PV panels, DG and battery
- Case 2: Grid connected operation with PV panels, wind turbines, DG and battery with feed-in tariff
- Case 3: Grid connection operation with PV panels, wind turbines, DG and battery without feed-in tariff

Table 5.7 represents the results for various case studies analyzed for commercial load and Table 5.7 provides the results for various case studies analyzed for commercial load.

Table 5.6: Comparative Results of Microgrid Economy for Various Case Studies for Small Manufacturing Load in Hyderabad

Case	$P_1(kw)$ Solar	$P_2(kw)$ DG	$P_3(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/kw)
Islanded	401	262	392	345030000	14.17
Grid Connected with Feedin	524	75	33	267360000	11.78
Grid Connected without Feedin	300	75	33	283980000	12.52

Table 5.7: Comparative Results of Microgrid Economy for Various Case Studies For Commercial Load in Hyderabad

Case	$P_1(Kw)$ Solar	$P_2(Kw)$ DG	$P_3(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/Kw)
Islanded	55	30	66	41765645	14.94
Grid Connected with Feedin	56	13	7	34253758	12.0684
Grid Connected without Feedin	35	13	7	35901587	12.6587

In all the cases the installation of generators follow the same trend such as manufacturing loads. Unit price of power serving to commercial load is more when compared to small manufacturing due to poor load factor and power demand during evening times. During these times solar energy cannot be generated which demands large sized batteries or selling power at lower cost during sunny day and purchasing during evenings at higher costs.

5.3 Microgrid Economy with Biogas

Biogas is one of the renewable sources. The parameters used were given in table 4.4. In present work load profile of a village with 98 houses are is in fig 4.3. It assumed that biomass is mainly produced from animal husbandry. Hourly average biomass produced in a day considered. 20%

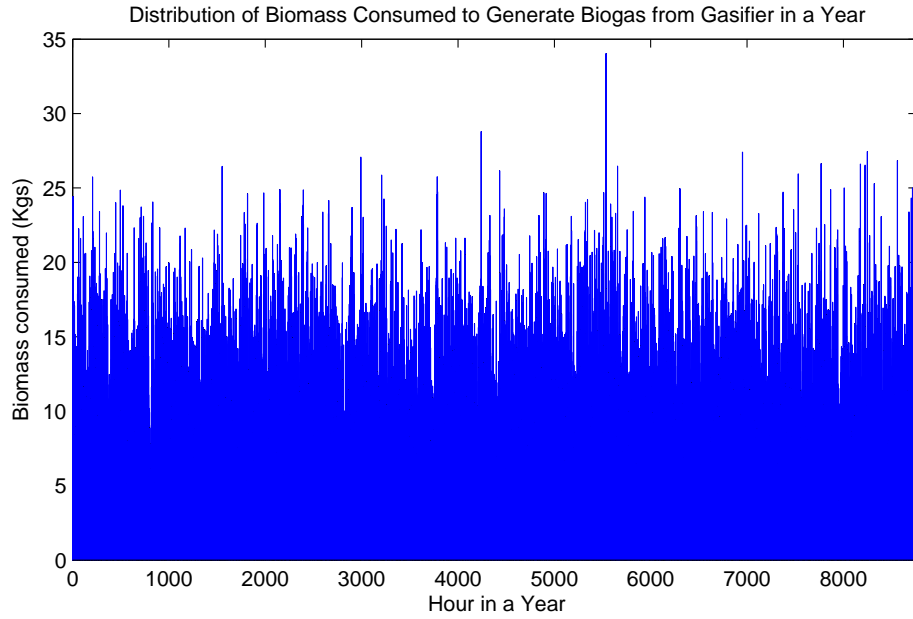


Figure 5.21: Hourly Distribution of Biomass Consumed for Biogas Generation in a Year

day to day, 15% time to time variation has been introduced for more realistic approach and the hourly biomass consumed to generate biogas is presented in fig 5.21 with bar graph representation. Geographical factors were considered to be identical to hyderabad city. Hence, installation of wind is not considered. Biogas fueled generators are substitution for diesel generators.

Different case studies presented for microgrid selection are listed below

- Case 1: Islanded operation with PV panels, bio-fueled generators and battery
- Case 2: Grid connected operation with PV panels, bio-fueled generators and battery with feed-in tariff
- Case 3: Grid connection operation with PV panels, bio-fueled generators and battery without feed-in tariff

Results were presented in table 5.8

Table 5.8: Comparative Results of Various Case Studies for Selection of Microgrid with Biomass

Case	$P_1(kw)$ Solar	$P_2(kw)$ Biomass	$P_4(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/kw)
Islanded	43	12	71	38929000	12.07
Grid Connected with Feedin	48	12	9	30108000	9.34766
Grid Connected without Feedin	31	12	9	30935000	11.7

From the studies we can conclude that running of biogas fueled diesel generator can replace the

presently using fossil fuel generators. Using biogas fueled generator is both economical and eco-friendly. Since, in present work it is assumed that biomass is free of cost. The objective function selected the biogas fueled generators such that all the available bioenergy is converted into electrical energy. The biofueled generators are also running for whole project lifetime and most of the time with rated capacity. Hence, here biofueled generators are working as base load generators. The biofueled generators role for load balancing is very limited compared to diesel generators in other studies. Even it is profitable for generating power from biofueled generators with grid connected and cost of power generation with biomass is lowest of all other generators and also controllable in present case.

5.4 Sensitivity Analysis of Microgrid Economy w.r.t Operational Costs

In this section effects of variation in different prices on grid connected microgrid selection in Chennai city has been discussed. The sensitivity parameters are fuel prices, grid tariffs both feed in and feed out. The following cases were considered in present study

- Case 1: Sensitivity analysis of microgrid with changes in grid tariff
- Case 2: Sensitivity analysis of microgrid with changes in grid feed in tariff and fuel prices
- Case 3: Sensitivity analysis of microgrid with changes in grid feed out tariff and fuel prices

The output results for case 1 is shown in fig 5.22. The feedout tariff ranges from Rs 6 to Rs 10.5, feedin tariff ranges from Rs 2 to Rs 6.5 and fuel price is kept constant at Rs 60. From the fig 5.22, it can be observed that with increase in grid feedout tariff total microgrid cost also increases. But, it has very little effect on microgrid total cost. Since, the highest price considered for grid feedout tariff is still less than the per unit cost of generation from any other conventional sources. Increase in grid feedin until Rs 4.5 tariff led to increase in PV panels and wind generator sizes. It also reduces the total power bought from grid which eventually leads in small decrease of total microgrid cost. However, with increase in grid feedin more than Rs 4.5 there is dramatic change in total cost, installation of PV panels and wind turbines. When feedin price is more than Rs 5 profits can be also earned by selling power to grid only. However, we assumed that power can be sold to grid at any time which is not realistic.

The output results for case 2 is shown in fig 5.23. The purpose of generators and battery is grid

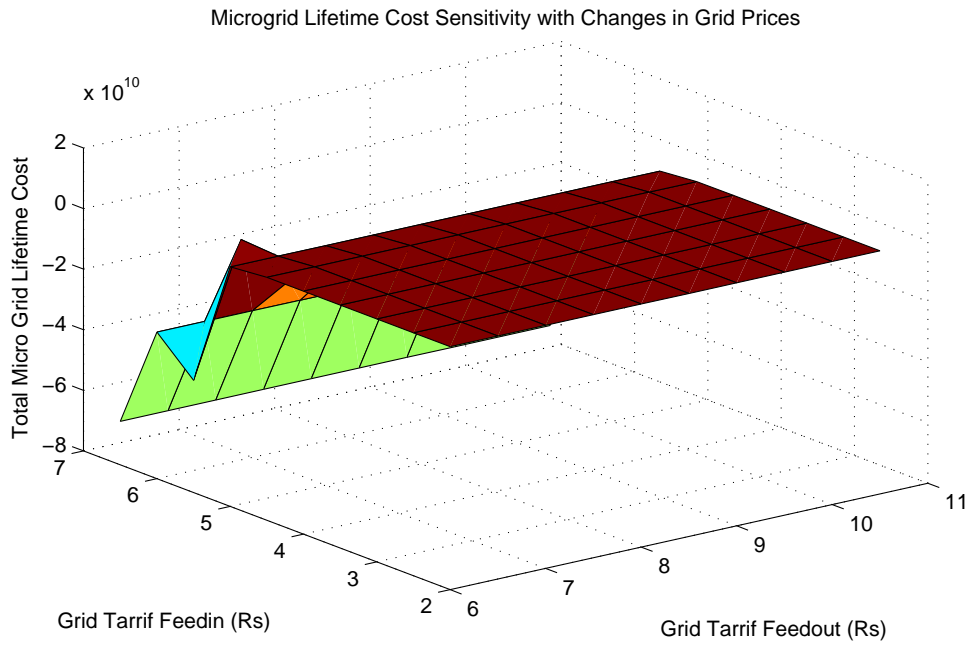


Figure 5.22: Variation of Microgrid Total Cost with Changes in Grid Feedin and Feedout Tariff

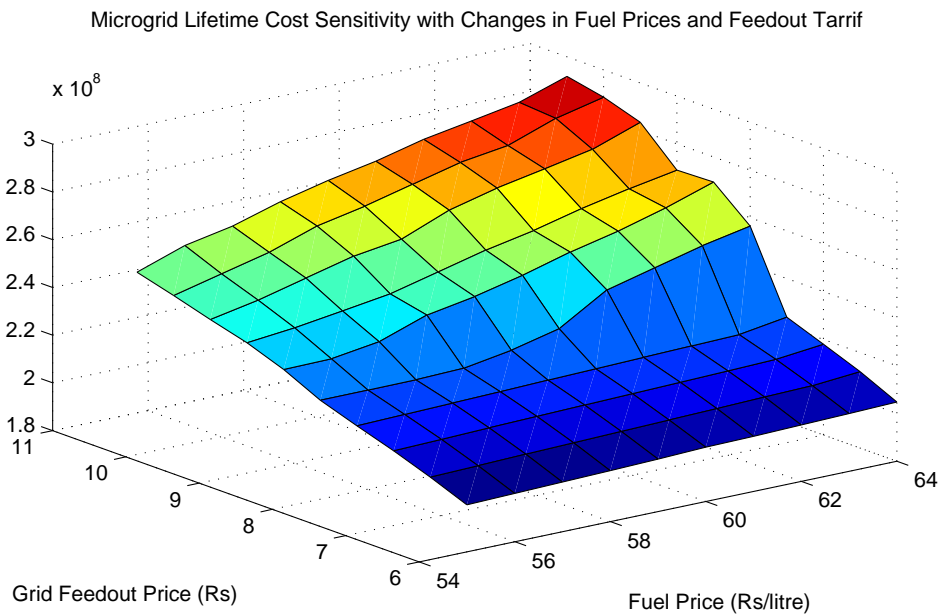


Figure 5.23: Variation of Microgrid Total Cost with Changes in Diesel Generator Fuel Price and Grid Feedout Tariff

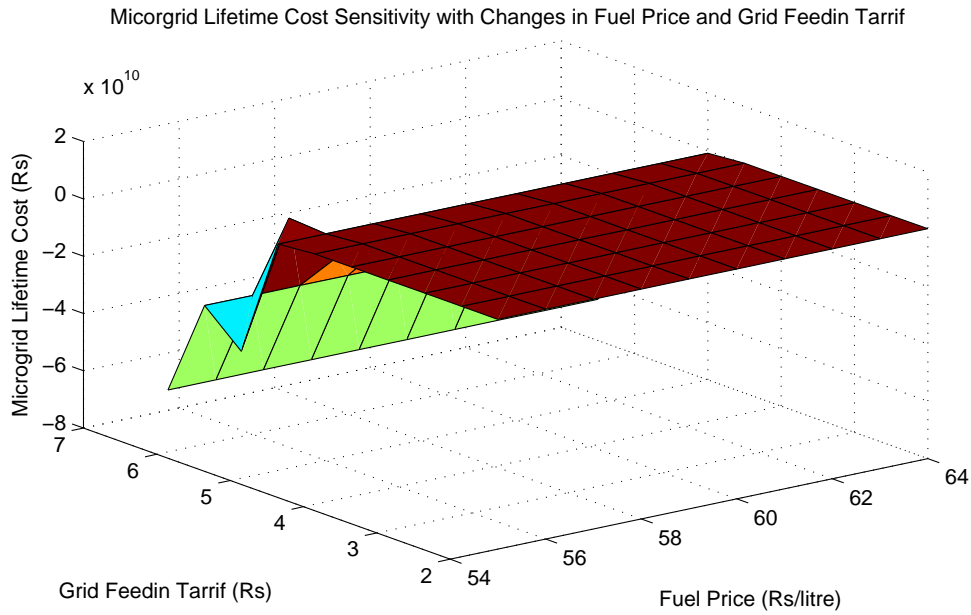


Figure 5.24: Variation of Microgrid Total Cost with Changes in Grid Feed in Tariff and Diesel Generator Fuel Prices

connected mode is for backup and also the minimum unit price for power generation is ranged from Rs 18 to Rs 19.4 which far greater than the grid parity considered. Hence, very limited power is drawn from diesel generator. From fig 5.23 the following observations can be made. With increase in grid feedout prices the microgrid lifetime cost increased same as in case 1. With increase in fuel prices the microgrid lifetime cost increasing in very slow rate (almost negligible). Since, as mentioned earlier the installation size of diesel generator is fixed and power is generated from it very few hours and at rated capacity. Hence, for grid connected systems using of diesel generators as main generators rather than backup is always not economical.

The output results for case 3 is shown in fig 5.24. From case 3 results it can be observed that changes in grid feedin tariff has considerable effect on microgrid lifetime cost than the changes of fuel price. The reason is mentioned in case 2. With increase in grid feedin tariff the microgrid lifetime cost decreased until Rs 5. However, further increase in feedin tariff reduces microgrid costs very rapidly and can also make profits only by selling power to the grid while supplying to the load also. It can be clearly observed in fig 5.24.

5.5 Bootstrap Analysis of Microgrid with Changes in Load Estimation

In this section we are studying the effects of randomly estimated load on microgrid selection and lifetime cost. In present work chennai weather conditions were considered and only july one day's load profile of small manufacturing is considered and hourly load profile in a year is estimated as mentioned. The average daily load over the year is kept constant 1.804 *Mw*. However each time the initial seed to generate random data has been changed. Hence, the yearly load pattern will also change for each set of data. We examine the results of economy and selection of generators for grid connected microgrid for 100 sets of load data generated as explained above for selected load profile. The average load is constant 1.804 *Mw*, the peak load is varying between 100 *Kw* to 105 *Kw*. However, any two load pattern will not be identical.

The per unit cost of system varies from *Rs* 9.998 to *Rs* 10.02, The selection of PV systems ranged from 112 *Kw* to 116 *Kw*, selection of wind systems varied from 397 *Kw* to 403 *Kw*. Diesel generators and battery are installed only for backup. Hence, there will not be much influence of load on selection of these systems. From the above results we state that the algorithm is reliable for grid connected systems. Since, avg load is constant. The timely variation in load can be compensated by sending or receiving power from grid. However, in islanded cases power can be served only by the installed generators and also batteries will have limited storage. Hence, mismatch in estimated data will considerably effects the unit price of power served by the grid. However with accurate load data measured at different small interval of times in a year this problem can be solved.

5.6 Profitability Analysis

For profitability analysis weather conditions of chennai and small manufacturing load were considered. Case a and Case b in Table 5.9 explains grid connected microgrid configuration with renewable of source generation and limited sized battery storage system for small manufacturing load. Only 10% reserve capacity was considered both in installation of PV panels and wind turbines. Since, objective in present study is to make profit from microgrid. The unit power costs *Rs* 7.695 in Case a and *Rs* 8.831 in Case b, which is less than grid parity. In Case b power cannot be sold to grid.

Table 5.9: Comparative Results for Various Case Studies

Case	$P_1(kw)$ Solar	$P_2(kw)$ Wind	$P_3(kw)$ DG	$P_4(Kah)$ Bat.	$C_{life}(Rs)$	Unit Price (Rs/kw)
Grid Connected with Feedin	214	874	0	10	174523561	7.695
Grid Connected without Feedin	142	327	0	10	207476213	8.831

5.7 Summary

In this chapter results of different case studies described in previous section considered for study of microgrid selection and economy were provided. The results provide an example about the effects of terrain, load profile and operational prices of microgrid on microgrid economy. We also discussed that by sacrificing reliability we can earn profits from microgrid. Results providing reliability of algorithm also included in this chapter.

Chapter 6

Conclusions and Suggestions for Further work

6.1 Conclusion

The present work has been mainly focused on optimal design of microgrid with various distributed generators for a given load data. It includes the mathematical formulation for calculation of power output from these distributed resources such as PV units, wind turbines, Diesel Generators, Biomass Resources and battery storage. The objective function is formulated as an NLP equation. Various real time constraints over different generators were also implemented. The algorithm proposed can also be applied under real time weather conditions where wind speeds and solar irradiance are estimated yearly using forecasting techniques and also forecasted yearly load data can also be used for microgrid selection.

Thorough various case studies the following observations were made

- Installation of wind energy sources is economical only in coastal regions. Because, coastal regions will have wind speeds above cutin speeds most of the time
- For an identical load the installation of microgrid in INDIA without wind resources demands almost identical sizes of distributed generators. Since, the average solar irradiance across INDIA Peninsula is almost same
- Per unit cost of microgrid also varies with type of load. Hence, while serving different kinds of loads. Tariffs must be set based on peak and average load

- In grid connected systems using of Diesel Generators as base load generators is always uneconomical. However, it can be used as backup sources
- Using of biomass for power generation is always economical and eco-friendly and it is cheapest source of power generation among all renewable sources
- With grid feedin tariff's the changes in feedout and fuel prices will have less effect on microgrid lifetime compared to changes in feedin tariff
- variation of estimated load data considerably effects the microgrid generators selection and also unit price
- Profits can also obtained from microgrid when grid connected with feedin tariff

6.2 Future Work

- Modeling an objective function to optimally select distributed generators with concerns of both environmental and economy issues
- Bootstrap analysis of microgrid w.r.t estimated solar irradiance and wind speeds
- Studying microgrid selection with yearly forecasted data of wind speeds, solar irradiance and load data
- Designing a robust tool for optimal selection microgrid considering various factors such as tracking system in solar, height of wind turbines, load scheduling e.t.c,

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