Chapter 2 : Literature review

In this chapter, a survey of literature on developing an energy management system for microgrid operations is presented. This chapter starts with a brief introduction to microgrid and energy management system. Next, the requirement of resource estimation is discussed. A review of literature on different techniques for estimation, modeling of energy resources at the local level and limitations associated with it are presented. This is followed by a discussion on wind farm and solar field layout for maximum utilization of these resources. Subsequently, various approaches and major issues related to the energy management system and microgrid are discussed in detail. Finally, research gaps are identified.

2.1 Introduction to microgrid

Microgrid is basically a small scale power generation system, which meets the local energy demand. According to Pike Research Report (Asmus *et al.*, 2009), the first "modern industrial microgrid in the United States was a 64 MW facility constructed in 1955 at the Whitling Refinery in Indiana", but the basic concept of microgrid is much older. The microgrid concept started in the late eighteenth century and has a small local power generation system to meet the demand in thousands of kW. Any typical microgrid should have decentralized power generation system and storage system, which are capable of balancing the supply and demand to maintain reliable service within its boundary. There is no universally accepted minimum or maximum size for a microgrid but it should be sufficient for a small community such as military group, universities, school or hospital. Nevertheless, any power generation system serving individual building either commercial, industrial or residential facility, referred as a single generation system or nano-grid.

The concept of microgrid started with a focus to overcome the energy shortage, enhance the integration of distributed renewable energy sources, and minimize environmental concern associated with conventional power generation system, such as carbon footprint and greenhouse gas emission. Additional motivations are to electrify the remote locations, to integrate Distributed Generation (DG) efficiently, and to reduce stress on transmission and distribution system by generating power where it is needed (Katiraei *et al*., 2008). It can be stated that microgrid is the transformation of the conventional power generation system to a more reliable, less carbon intensive and economical energy system by providing an effective platform for integrating and managing the DG sources. Microgrid being a smaller version of maingrid, it also provides closer proximity between power generation and its use, which improves the efficiency and reduces the transmission losses. Microgrid has the ability to integrate renewable energy sources such as solar, wind, small hydro, geothermal, waste-to-energy, and combined heat and power systems.

Microgrid technologies can be grouped into two types base on mode of operation: (i) grid-connected or centralized mode, and (ii) stand-alone or decentralized mode (Lopes *et al*., 2006). In centralized mode, microgrid is connected to the maingrid, while in a stand-alone mode, microgrid becomes a discrete energy system and local energy demand has to be met by only microgrid. In stand-alone mode, there must be a storage system and/or stand by diesel generation system integrated to microgrid, which will be operated at the time of non-availability of Renewable Energy Sources (RES). On the other hand, in grid-connected mode, the microgrid is connected to maingrid and is able to export and import energy according to the demand. In this mode, microgrid imports energy when there is shortfall and exports energy when generation is surplus.

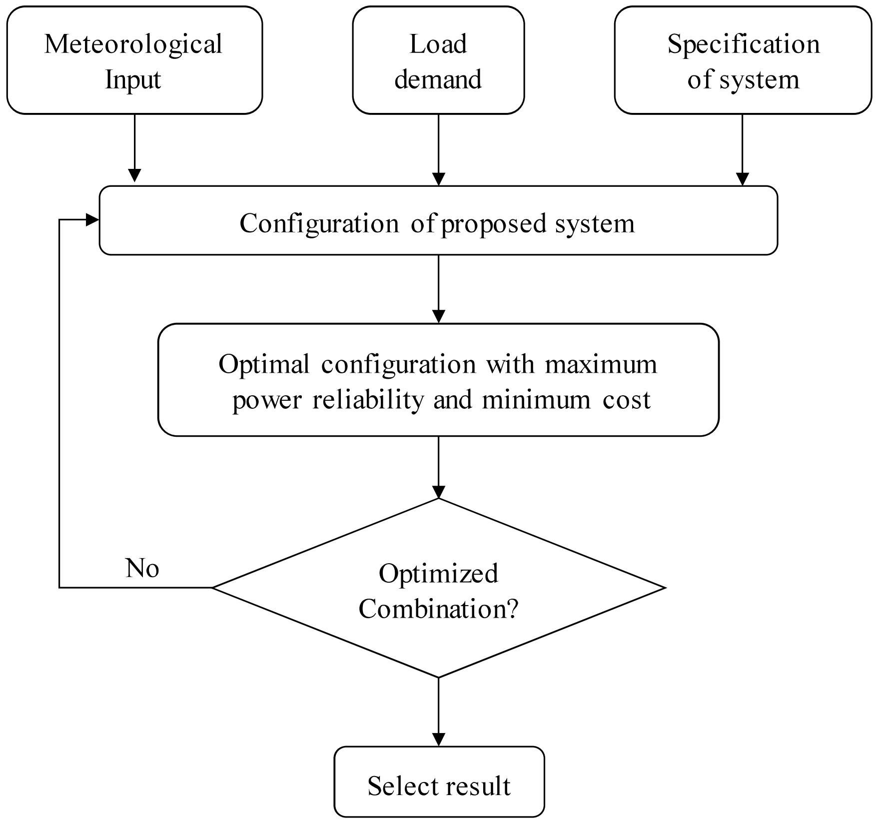

Figure 2.1. Typical approach adopted in sizing of energy management systems.

In both modes of operation, there is a need for optimal mix of the power generation from different generation sources, to minimize the cost of energy supply. Optimal mix of power generation is taken care by energy management system (EMS). Microgrid operates on EMS to ensure reliable and efficient operational planning. EMS for microgrid operations is not an easy task because of multiple operational objectives (running costs, energy efficiency, and emissions) and multiple time scales estimation (short term and long term). The EMS helps the operator on how the system power should be utilized in an efficient way to ensure reliability of energy supply. It is basically a supply-demand balance, which forms an optimization problem. When this problem takes into account real-world constraints, rather than just an abstract mathematical function, it becomes more complex (Shi *et al*., 2015). The size of microgrid varies with applications, however it is designed/operationalized to match the supply-demand requirements. The EMS works with respect to the power that is imported or exported from the maingrid along with the power required from different DGs, and the capacity of distributed storages (DSs) (Katiraei *et al*., 2008). Various optimization techniques have been proposed which may help to solve the supply-demand problem in the most suitable way according to the application. For efficient implementation of EMS, it would be beneficial to have a unified communication interface (Mashayekh *et al*., 2017; Saad *et al*., 2012; Kerdphol *et al*., 2014). Typical approach adopted in sizing of energy management systems is presented in Figure 2.1.

Stand-alone microgrid has wide scope in India. Around 34% of Indian population lives in urban areas and there is a requirement of independent microgrid to electrify the remote areas which are far away from the maingrid. As per the report of "The World Bank Data", in 2016, 15% of the total population do not have access to electricity at all. In terms of household, due to remote rural villages, more than 24.84 million households were unelectrified until October 2017 (Ministry of Power, 2017). In AP and TS alone, there are 0.613 million households which are not electrified. Moreover, renewable technology is not cost competitive enough to compete with maingrid power supply. Therefore, stand-alone microgrid is suitable to electrify the remote location with clean energy technologies as a DGs. The stand-alone microgrid has the ability to operate autonomously in emergency situations like a power disruption in the maingrid or in a remote location, not connected to the maingrid. Stand-alone microgrid operates independently with local available resources ensuring a continuous power supply to consumers, even when there are faults in the main power grid (Utsun *et al*., 2011; Lopes *et al*., 2006). General optimization problems will involve choosing the decision variable and formulating an objective function. The objective function is then solved by applying various system constraints using mathematical methods. The results achieved are compared with real-life scenarios and a profit/energy trend is plotted for the users (Minchala, 2015). Several case studies (with different microgrid) around the world have been undertaken to understand the benefits and limitations of each method.

The EMS for a microgrid operations is largely depended on the accuracy of input parameters, such as estimated energy potential and energy demand. Once potential and availability of DGs are estimated at the local level and corresponding demand is known, EMS will investigate for efficient and reliable strategy for microgrid operation. To estimate the availability of renewable energy based DGs, it is required to know the meteorological parameters, such as temperature, relative humidity, atmospheric pressure, solar radiation, and wind speed etc. at the local level. These meteorological parameters are available only at few locations in AP and TS. Thus, it limits feasibility study of microgrid across both the states. Hence, there is a need to develop a model to predict the resource potential based on meteorological parameters with high accuracy across both states.

2.2 Resource estimation

Accurate estimation of DGs at the local level is a key step to development of any microgrid. Generally, the power generation from conventional technologies, such as diesel or gas, can be estimated from their governing equations or the performance characteristic curves. The estimation of solar or wind potential, however, is based on their mathematical representation (Kroposki *et al*., 2008) and these mathematical equations are dependent on data sets such as area available, insolation, cut-in/cut-out wind speed, material, efficiencies, etc (Deshmukh and Deshmukh, 2008). In a similar manner, performance of fuel cells, biomass gasifier can also be estimated (Chaiamarit and Nuchprayoon, 2013). It has to be noted that the accurate estimation of energy output from these DGs is purely dependent on the accuracy of data sets such as wind speed for wind power and solar radiation for solar power.

In India, meteorological data is measured and archived by Indian Meteorological Department (IMD), Pune. There are only a few locations where measuring instruments, such as barometer, cup counter anemometer, clock drum, sunshine recorder, wind vane, open pan evaporator, and thermometer are installed to record the meteorological data on temporal basis. In AP and TS, there are only 28 weather monitoring stations for the total area of 2,72,282 km^2, as shown in Figure 2.2.

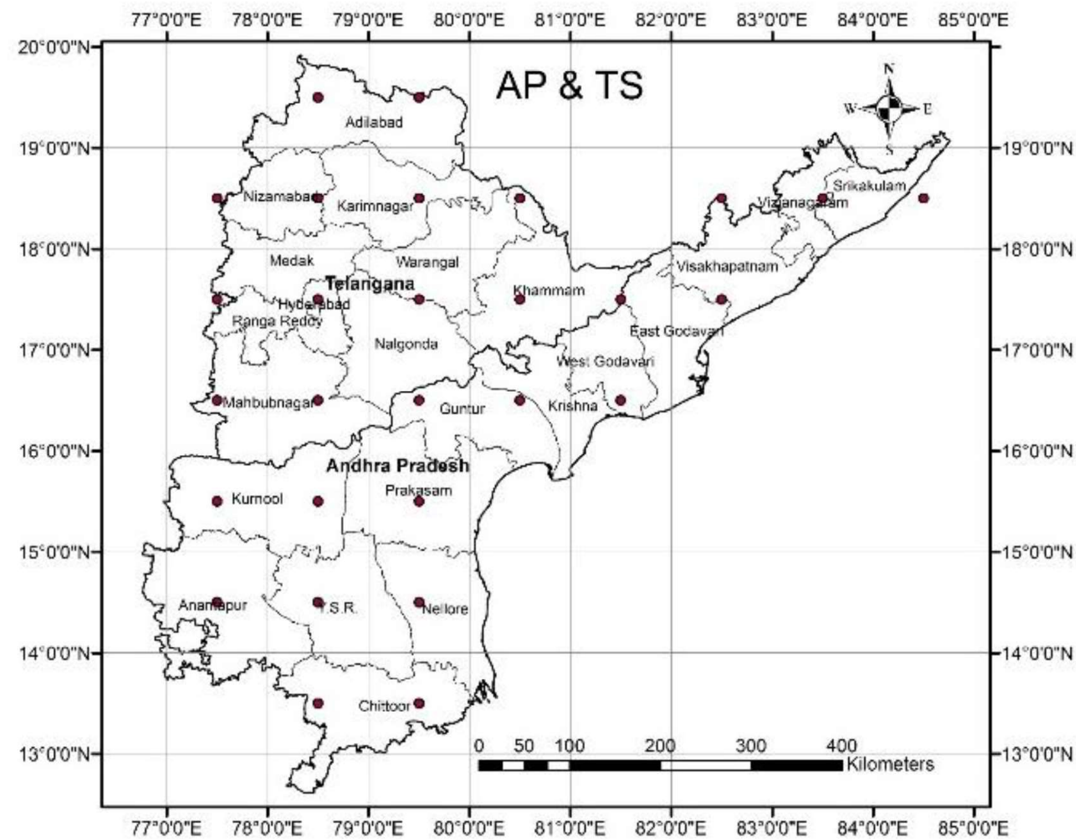

Figure 2.2. Map of AP and TS with locations at which data is measured by IMD, Pune.

Therefore, insufficient and inconsistent record of meteorological data is a key challenge to estimation and utilization of RES (Mahtta *et al.*, 2014). Non-availability of meteorological data has led to limited study and finally, utilization of RES. To investigate the feasibility and to size the RES at local/remote location, where the measured data is not available, researchers have to rely on data measured at the nearby weather monitoring stations. This way, estimation is not so accurate and can only be considered pre-feasibility analysis. On the other hand, for accurate estimation, the agencies need to install the instrument to measure the required meteorological parameters for at least one full year to record the data. Installation of new instrument and maintaining it for a long period is expensive and time-consuming activity, to initiate the feasibility study of microgrid operation. At the same time, the data recorded only for one year cannot give a reliable estimation of energy potential for a future due to climatic changes. Therefore, averaging of data for the previous few years is required for accurate estimation of renewable energy potential (Fadare, 2009; Celik and Kolhe, 2013). To overcome some of these limitations, researchers worldwide use different techniques to develop predictive models, which have the capability to predict the desired data at the local level. Remote sensing, Geographic Information Systems (GIS), and various mathematical techniques are adopted by researchers worldwide for prediction of energy potential at the local level.

Wong *et al*. (2016) used remote sensing and GIS to estimate the solar potential in Hong Kong. In the remote sensing approach, satellite detects and monitors the physical characteristics of focused area with the help of special cameras and sensors installed on satellite. The spatial cameras capture the image of large area, which helps researchers to analyze the local surface condition. Then the pixel-based analysis of the image is carried out for further evaluation, such as hydro and solar energy potential. The authors have used geostationary satellite data has been used to evaluate the cloud coverage. The distribution of possible cloud coverage and estimation of solar energy potential of roof-top have been studied and validated with ground-based observation. Finally, the authors have identified suitable locations for installation of a PV system. This study has observed an error of about 10% in estimation of solar potential versus the ground measured data. This error can further increase, if there is distortion in the data received from satellite or error in its processing. Moreover, resolution of data sources is a big challenge in data processing due to the variation of pixel size. At the same time, 3D variation with high resolution is difficult to capture and this data is not up-to-date due to the time taken by satellite to recapture the image of same location. Nevertheless, this approach can estimate the overall potential of a larger area/country and might not accurately estimate it at the microscale.

Mahtta *et al*. (2014) estimated solar potential in India using remote sensing. The district wise solar potential has been mapped. The study has been carried out based on the annual average value provided by NASA satellite. Authors analyzed the satellite data and reported the annual average solar potential state wise. Though this study is useful to evaluate the solar potential of state or a district, the authors have pointed out that high-resolution imaging is required for accurate estimation at the local level.

Yadav and Chandel (2015) used Artificial Neural Network (ANN) based J48 algorithm for estimation of solar potential in India. The authors have identified influencing input parameters, such as temperature, sunshine duration, latitude, longitude, clearness index and extraterrestrial radiation for prediction of solar potential. They have developed five ANN models and analyzed using different combinations of input parameters. The authors have used the mean absolute percentage error between actual and estimated value, as a basis to evaluate the accuracy of their ANN models. These predictive models are developed using NASA satellite data and validated with ground measured data. The best combination of input parameters (temperature, minimum temperature, maximum temperature, altitude and sunshine hours) has a maximum error of 6.89%. The authors have pointed out that for achieving higher accuracy in prediction, there is a need to further investigate these influencing parameters, as there is an error in the satellite data versus measured data at the ground location. It was observed that the satellite data has an error of 13 to 52% for given locations. A district wise map is presented by the authors to identify the districts that have maximum solar potential. This map shows the average value of solar potential at district level.

Recently, various researchers worldwide started using measured data at the ground station in their predictive models for achieving higher accuracy (Celik and Kolhe, 2013; Fadare, 2009; Mellit and Kalogirou, 2008). In India, district-wise average renewable energy potential maps for different resources (solar, wind, biomass, etc.) are available, but data and subsequent potential maps at the local level are not available. Therefore, accurate estimation and subsequent deployment of renewable energy technologies are big challenges. Hence, there is a need for developing such types of maps that helps studies on solar and wind energy resources.

2.2.1 Prediction and mapping of wind potential

Accurate prediction of wind potential is one of the important steps to develop any stand-alone or integrated wind power system. There is a large coastal area in southern states of India possessing relatively high wind density. Taking this into consideration, the Government of India aims at generating up to 40% of electricity from renewable energy resources by 2020 (MoP, 2018). Under these circumstances, sufficient information about wind energy potential is crucial to design wind farms and identify locations to install. Wind energy data is available at very few locations (28 locations in AP and TS). Wind speed exhibits variable profiles with respect to space and time. Prediction and mapping of wind energy potential at a given site are critical for the development of any wind farm. Hence, wind characteristics of the site are needed for effective utilization of the wind potential (Akpinar and Akpinar, 2004; Genc *et al.*, 2005). In developed countries, analysis of wind characteristics and assessment of wind energy potential have gained the attention of researchers (Bekele and Palm, 2009; Riahy and Abedi, 2008). Nevertheless, this type of information and in-depth investigation are not available in developing countries. Apart from estimation of wind energy potential, the study of wind speed distribution characteristics and parametric study for estimation of wind energy potential are also important for assessing turbine output performance, analyzing loading effect on the wind turbine structure and wind energy conversion systems (Elhadidy and Shaahid, 2000; Mathew *et al.*, 2002). The prediction of wind speed depends on various meteorological parameters, such as relative humidity, pressure, temperature, etc. Investigations on the effects of these meteorological parameters can be carried out through a parametric study. However, this type of parametric studies is not widely available in published literature. Hence, the present work focuses on identifying the most influencing meteorological parameters that affect the prediction of wind speed.

There are several numerical techniques used for estimation of energy potential. A detailed review of numerical techniques used by researchers for wind power estimation in various geographical location is presented by Foley *et al.* (2012). These methods are categorized as physical, statistical, hybrid and hybrid statistical. Authors have discussed calculation of standard error in all these methods. A similar approach has been adopted by Qahwaji and Colak (2007) using three different machine learning algorithm for prediction of solar flare. Authors compared Cascade-Correlation Neural Networks, Support Vector Machines and Radial Basis Function Networks, and recommended a combination of Support Vector Machines and Cascade-Correlation Neural Networks.

Among all numerical techniques, the neural network approach is widely used by researchers worldwide for prediction of meteorological parameters (Carolin Mabel and Fernandez, 2008; Celik and Kolhe, 2013; Mellit and Kalogirou, 2008a; Ramirez-Rosado *et al.*, 2009; Sözen *et al.*, 2004a). The ANN model is widely considered an alternative method, which can handle complex and undefined problems (Kalogirou, 2001). The ANN model is capable of learning from samples and can handle random and inadequate data. The ANN model can also handle non-linear problems. Once trained with sufficient input data, ANN can predict the target output with greater accuracy. The ANN approach has diverse applications in various engineering and science fields, such as automation, pattern recognition, predicting, computer science, industrial, optimization, and medical sciences.

Kalogirou (2001) presented a detailed overview of ANN applications in renewable energy area. This model may have either one or multiple hidden layers based on the nature of problems to achieve higher accuracy. The ANN approach is widely used in the renewable energy system, such as solar steam generator and photovoltaic system (Kalogirou, 2001). The ANN approach is also used for building service system, forecasting of energy demand, prediction of tariff, etc. Researchers have also used this approach for prediction of energy potential in developing countries (solar energy prediction in Nigeria (Fadare, 2009), and wind energy prediction in Turkey (Celik and Kolhe, 2013).

Geographic Information System (GIS) approach was also used by the researchers to develop maps based on predicted energy potential from ANN models. These maps give a better visualization of available wind potential, which helps the decision maker in site selection as well as in designing of wind farm. GIS approach is also useful for superimposing various energy potential maps over one another for design of hybrid energy systems. In India, wind energy potential map has been presented by Ramachandra and Shruthi (2005) using GIS approach. In Thailand, the wind energy potential estimated using atmospheric mesoscale model and represented using GIS approach by Janjai *et al.* (2014). It can be observed that researchers worldwide are researching in predictive models for estimation of wind energy potential using available measured data. Estimation and mapping of wind potential at local level can increase the utilization of RES more effectively. Simultaneously, it can also help to study of feasibility of microgrid at given location.

2.2.2 Prediction and mapping of solar potential

Solar energy is another renewable energy source available across the globe, which needs to be estimated accurately at local level for better and effective utilization. Tropical countries like

India are blessed with adequate solar energy potential (Muneer *et al.*, 2005). Major parts of India get about three hundred sunshine days in a year with about/more than eight hours' sunshine per day and solar radiation in the range of 4 to 7 kWh/m^2/day. Currently, India is one of the precursors in the renewable energy markets globally. The solar power generation in India is rapidly increasing; it was 3 MW in 2008 and reached over 21.18 GW in 2019. In 2015 the government of India increased its solar generation capacity, aiming at a huge investment with a target of 20 GW by 2020. To achieve the target, lack of and inconsistent data are pointed out as one of the key barriers to capacity expansion (World Bank, 2010). In these situations, quality information about solar energy potential at local level is vital, so that it can be efficiently utilized. Presently in India, there are only limited locations with measuring instruments, which have solar energy potential data. Solar radiations modelling and mapping at a specific site are prerequisites in designing and planning of solar power generation (Chendo, 2001; Sözen *et al.*, 2004b). Hence, measuring or predicting solar potential is a crucial step in development and assessment of solar power generation at specific location. IMD records and archive the meteorological data in India. Nevertheless, while IMD records other parameters for various sites, there are a few locations where pyrometers are installed for recording solar radiation intensities. Therefore, it is required to develop a model to estimate solar potential at local scale to overcome some of these limitations by taking geographical and meteorological information as input parameters.

The ANN has been considered in the modelling of complex systems and applied for forecasting solar potential around the world by various researchers. In Turkey, ANN model has been used to forecast solar radiation (Sözen *et al.*, 2004b). Daily solar radiation has been predicted and efficacy of photovoltaic system was investigated using ANN (Heidari, 2016; Kumar *et al.*, 2017; Kumar *et al.*, 2016). The ANN with computational fluid dynamics has been studied to predict wind power in hilly areas (Burlando and Meissner, 2017). An adaptive wavelet network model for predicting daily total solar potential in Algeria was reported by Mellit *et al*. (2006). Kalogirou presented a detailed overview of the application of ANN model (Kalogirou, 2001). A comparison between ANN model and another simpler model like regression has been studied by Mellit and Kalogirou (2008b). Authors have suggested that the ANN models are fast and efficient in solving a complex problem. ANN has become popular among researchers to tackle this type of problems due to its capability to handle nonlinear conditions. This approach can help researchers to estimate/utilize the solar potential in an efficient way. Prediction of solar/wind potential using these numerical tools is accurate, less time consuming and avoids the installation/monitoring of measuring equipment at the study locations.

2.3 Resources optimization

Optimal use and mix of renewable energy resources, such as wind and solar, for meeting the energy demand at minimum cost is a crucial step for efficient operations of a microgrid. In the case of wind power harvesting, the number of wind turbines as well as their positioning is an important step for maximum utilization of wind potential available at the study locations. Wind turbine extracts energy from the approaching wind, which enters the turbine blades from its front side. The wind speed on the downstream side (after the work is done on the turbine blades) reduces due to the wake effect. If wind turbines are placed closer to one another or one behind the other, effective approaching wind speed reduces drastically due to the wake effect. On the other hand, if the turbines are placed far from each other to avoid this wake effect, the wind farm power output reduces due to improper use of available wind farm land. Similarly, for maximizing solar power generation at a site, it is important to estimate number of solar panels and their positioning based on its geographical location, solar elevation angle, shading effect, etc.

2.3.1 Wind farm layout optimization

Optimal positioning of wind turbines in a wind farm is an important step for achieving maximum power generation. Therefore, researchers use various numerical techniques with high-end computing systems for wind farm layout optimization. This problem becomes more complex and nonlinear due to uncertainties associated with wind speed and aerodynamic behaviour of the wind.

Researchers worldwide are investigating various techniques, such as Genetic Algorithm (GA), Gaussian model algorithm and Jensen's wake decay model for wind farm layout optimization to maximize the power generation (Abbes and Allagui, 2016; Gao *et al.*, 2015; Montoya *et al.*, 2014; Turner *et al.*, 2014). Montoya *et. al.* (2014) addressed the need for choosing two dissimilar wind turbines to minimize standard deviation of energy generated within a day while maximizing the total energy generated by the wind farm. A method based on multi-population GA was presented for wind turbine layout optimization, in which the algorithm was developed for extraction of the highest power in the minimum cost (Gao *et al.*, 2015). The algorithm has been applied to a 2 km × 2 km wind farm allowing different wind speeds. Grady *et al*. (2005) used a GA approach to obtain ideal locations of wind turbines for maximizing power generation and at the same time reducing the number of turbines required. Turner *et al.* (2014) have worked on Jensen's wake decay model to characterize multi-turbine effects and improves mixed optimization constructions. An area rotation technique, where the highest area would be exposed to the free velocity stream was proposed by Shakoor *et al.*, (2016) to find the best proportions of the wind farm contour. In this, a technique called definite point selection was developed and implemented to locate the position of turbines to maximize the power output while considering minimum spacing required between the turbines for operational safety. Parada *et al.* (2017) used Gaussian wake wind turbine model for the wind farm layout optimization. The Gaussian model algorithm has an exponential function, which is used for determining the drift in the wind speed. Chowdhury *et al.* (2013) proposed unrestricted wind farm layout optimization method, which simultaneously identifies the location and the selection of wind turbines for wind farms, that face variable wind conditions. Gonzalez *et al.* (2010) proposed an algorithm to calculate annual income from a wind farm considering the loss of power generation in an individual wind turbine due to wake decay effects. Lee *et. al.* (2010) used GA for positioning wind turbines in a wind farm. A dispersed genetic algorithm is used by Katic *et al.*, (1987) to find the maximum number of wind turbines and their location in a large wind farm. It is pointed out that the wind farm layout optimization approach needs to be extended further for complex terrains and for real-time wind scenarios to maximize the generation capacity of a wind farm.

2.3.2 Solar field layout optimization

To maximize cost-effective power generation at a given site, the placement of solar panels and its tilt angle need to be investigated considering shading effect of the adjacent solar panels. Solar panels cast their shadow on surrounding panels due to sun path, which reduces the amount of incident energy and hence its output. There are two ways of installing the solar panels in a solar field: tracking and fixed position. Tracking system yields higher power for a given field, but it is associated with cost and maintenance of tracking mechanism. Hence, fixed position is generally preferred for large solar fields. In fixed position, the sufficient spacing and tilt angle between the adjacent panels meant to avoid the shading effect affects the power output from a solar field. Considering these factors, there is a need to maximize the power generation from a given solar field. If the solar panels of amorphous silicon solar cells, instead of crystalline silicon solar cells is used, the effect of shading can be minimized. However, this type of solar panel is not manufactured in India. According to the current policy of the Government of India, subsidy is provided only on such solar panels (monocrystalline, polycrystalline, etc.) that are manufactured in India. Hence for reducing the cost of power generation, it is suggested to use locally manufactured solar panels. Another parameter which maximizes solar power generation is its tilt angle.

Hong *et al*. (2017) presented roof-top PV potential for hill-shade effect. They proposed a method to estimate the PV potential for available rooftop area surrounded by high-rise buildings. The proposed method has a hierarchical approach: calculation of (i) physical potential, (ii) geographic potential and (iii) technical potential. Typically, the researchers worldwide analyzed and estimated rooftop solar PV potential in different geographic environments using various methods. One of the method commonly used is based on approximation of certain percentage of available rooftop area for solar PV installation. IEA (2002) has expressed the available rooftop area considering its use in solar PV installation, as a percentage of ground floor area in European counties. Peng and Lu (2013) have also approximated the available rooftop area using architectural and solar suitability factors, expressed in the percentage of the ground floor area, to estimate the rooftop solar PV potential in Hong Kong. This type of approach is simple to adopt at the regional level for theoretical estimation of solar PV potential. However, it is required to be validated using architectural constraints.

Some researchers have also used an approach based on various social factors (i.e., population, land uses, and building footprint) to estimate rooftop solar PV potential of a region. Izquierdo *et al.* (2008) estimated the available rooftop area by integrating information on population, number of buildings and land uses with various coefficients (e.g. shadow) to estimate the rooftop solar PV potential in Spain. Wiginton *et al.* (2010) estimated the available rooftop area for a region by extrapolating the calculated rooftop area of a sample locality using the population data in Canada. This method may be useful if building rooftop data is not available. It does not consider the localized rooftop characteristics of a region and hence the results can only be approximated.

Furthermore, researchers have also estimated rooftop solar PV potential of a region by computing the available rooftop area using a GIS approach, which involves the localized rooftop characteristics. Ko *et al.* (2015) computed the shaded areas on rooftops by conducting hill-shade analysis with the sampled building data. However, the authors approximated the available rooftop area for a region based on the sampled building data to estimate the rooftop solar PV potential in Taiwan. Strzalka *et al.* (2012) computed the shaded areas on rooftops using the CityGML model with all buildings in the study area. Authors have extrapolated the estimated electricity generation of the rooftop solar PV system for similar regions in Germany. These methods can consider the localized rooftop characteristics for more realistic results, but still have a few limitations, such as (i) sample buildings or partial areas are taken into account for GIS simulation, (ii) sun path and relevant local conditions are not considered on hourly, monthly, and annual basis, and (iii) the methods can be time-consuming and sometimes inefficient due to requirement of large data. Therefore, it is pointed out that accurate estimation of PV potential in a realistic way at the local level is necessary for its integration for microgrid operations.

2.4 Energy management techniques for microgrid operations

Microgrid integrates the RES along with storage system at local level. It also requires Energy Management System (EMS) for its efficient operations and optimal use of DGs. The optimal use of energy sources should ensure that the carbon footprint is kept within the accepted levels (Kroposki *et al.,* 2008). Thus, there are many parameters to be considered, including economics of the system for efficient EMS (Wang *et al*., 2015). EMS aims at optimizing microgrid for maximum utilization of DGs at minimum cost with high reliability (Lopes *et al*., 2006). However, managing a microgrid with high reliability becomes more challenging due to geographical diversity, availability of DGs and their seasonal as well as intra-day variations.

Even though, several methods have been developed for energy management system, there are some challenges that need to be addressed for achieving higher reliability of energy supply in microgrid operations and optimum utilization of DGs for minimizing the cost of energy supply. Different techniques used for energy management system are discussed below:

2.4.1 Model predictive control

Researchers have used Model Predictive Control (MPC) optimization technique for energy management in microgrid operations by optimizing various system components of a microgrid. This technique involves a heuristics mathematical programming and priority rules. The main objective of MPC technique is to control the storage system, such that electricity transfer from the microgrid is reduced. MPC optimizes the dispatch power in microgrid operations using short term weather forecasts and past energy demand pattern (McLarty *et al*., 2015). This technique works on real-time feedback of energy demand and storage system to optimize the power supply from microgrid according to the dispatch strategies. MPC basically defines the future control action using past and current information to improve the capacity of storage system, increase the utilization of RES and decrease the dependency on maingrid (Hooshmanda *et al*., 2012; Parisio *et al.*, 2014).

Prodan and Zio (2013) have introduced an MPC based optimization approach for a microgrid considering uncertainty factor. In framework propose by authors, the authors have considered cost values, energy generation profiles, power consumption, and functional constraints, such as the battery charge that should be within the limits and maximum battery capacity that should be equal to the rated value. Efficiency of this approach was validated through simulations and compared using real data for a test system. The authors have used MPC technique to control battery storage operations in such a manner that minimum capacity battery system will be required in microgrid. Authors have suggested that MPC approach could control microgrid component with the stated constraints to improve the performance conditions of microgrid.

Parisio *et al.* (2014) presented a case study in Athens, Greece using MPC. The authors have used MPC approach to achieve economic efficiency of microgrid operations. Least-square support vector machines for regression with a moving time-frame window was applied to forecast the power generation daily, by renewable energy sources based on the previous data. Three experiments have been performed for microgrid operations with different levels of MPC-MILP (Mixed Integer Linear Programming) method: (i) without high-level control, (ii) considering MPC–MILP control with a planning level of 24 steps and (iii) considering the MPC–MILP control with a planning horizon of 72 steps. The authors observed substantial reduction (28 to 35%) in maintenance cost when battery storage use was minimized.

Bifarettia *et al.* (2017) applied the MPC to a residential level microgrid system. A layout of the rule-based control algorithm is given in Figure 2.3. Their methodology includes deciding the control actions for various component of microgrid (i.e. fuel cell operation, storage system, charge & discharge cycles, and appliances used) based on a cost function, which takes into account both present state of the system and a logical prediction of weather. The authors have reported that MPC strategy was able to match with the reference grid profile, minimizing use of fuel cell and maximizing photovoltaic utilization.

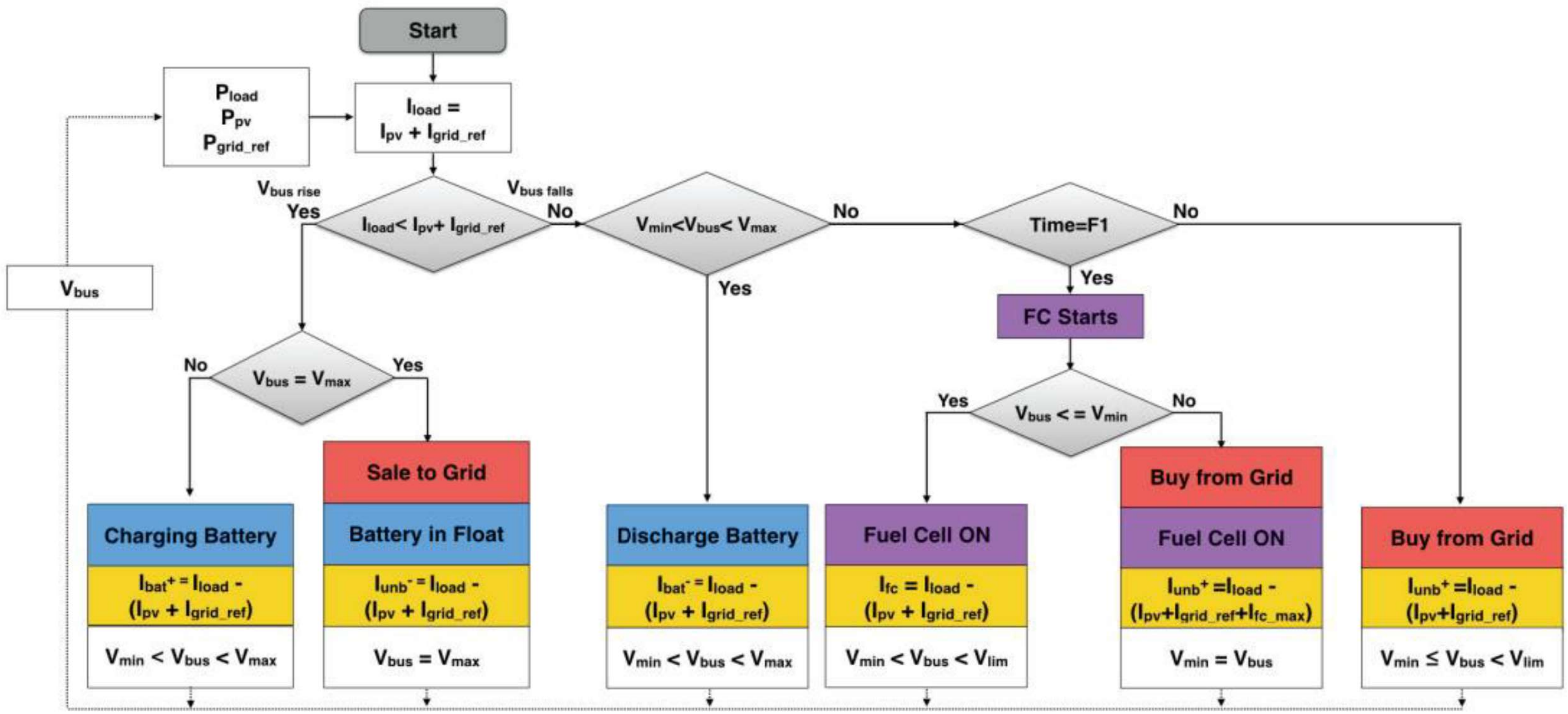

Figure 2.3. Scheme of rule-based control algorithm (Ref: Bifarettia *et al.,* 2017).

Pan *et al*., (2015) have done a case study of an industrial park in Beijing, China using MPC based EMS. Authors have developed the microgrid consisting of dispatchable generation units (diesel generators and micro turbines), non-dispatchable units (photovoltaic and wind), energy storage units (super-capacitors and battery systems) and non-controllable local loads. The authors have used Beijing Electricity Tariffs as per the “time of use scheme”. Application of MPC approach, improved operation strategy and planning of dispatchable units is achieved to enhanced energy efficiency. MPC technique adjusts any error in prediction of the load and renewable generation within the next iteration, enhancing the system stability. It allows larger penetration of intermittent renewable energy sources and thus results in economic benefits to both end users and grid operators. The authors have also reported that the MPC technique has some limitations in tackling real-life situation, especially with respect to frequency of demand and supply. A realistic model with addition of such type of constraints can be investigated for long term planning.

2.4.2 Mixed integer linear programming

Mixed Integer Linear Programming (MILP) method is an integrated design approach which considers electrical, heating and cooling loads. In the MILP method, some constrains are considered to be integer and some non-integer. Therefore, each component of microgrid can be modelled separately in MILP for enhancing the overall system efficiency. Parisio and Glielmo (2011) investigated microgrid operations to meet the time-varying energy demand with operational constraints to minimize the cost of energy supply and the energy imported from the maingrid. The authors have not used any complex heuristics or decompositions approach in this technique. A commercial solver, ILOG’s CPLEX 11.0, has been used to solve the entire model efficiently. The authors have pointed out that MILP improves the scheduling quality and reduces computational work. MILP is more suitable to online applications, such as smart grid. The authors have reported that the classical mathematical programming techniques cannot be directly integrated with the MILP, thereby limiting its use.

Morais *et. al.* (2010) have used MILP along with general algebraic modelling systems for a hybrid energy system consisting wind turbine, fuel cell, solar units and storage battery units. A proposed microgrid is presented in Figure 2.4. The authors have used the objective function as total marginal cost for a period of 24 hours. The converging rate was found to be as good as 0.09 seconds with 30 iterations. This technique gives the advantage to the researchers to minimize the operational cost of generating units while considering reliability of power supply.

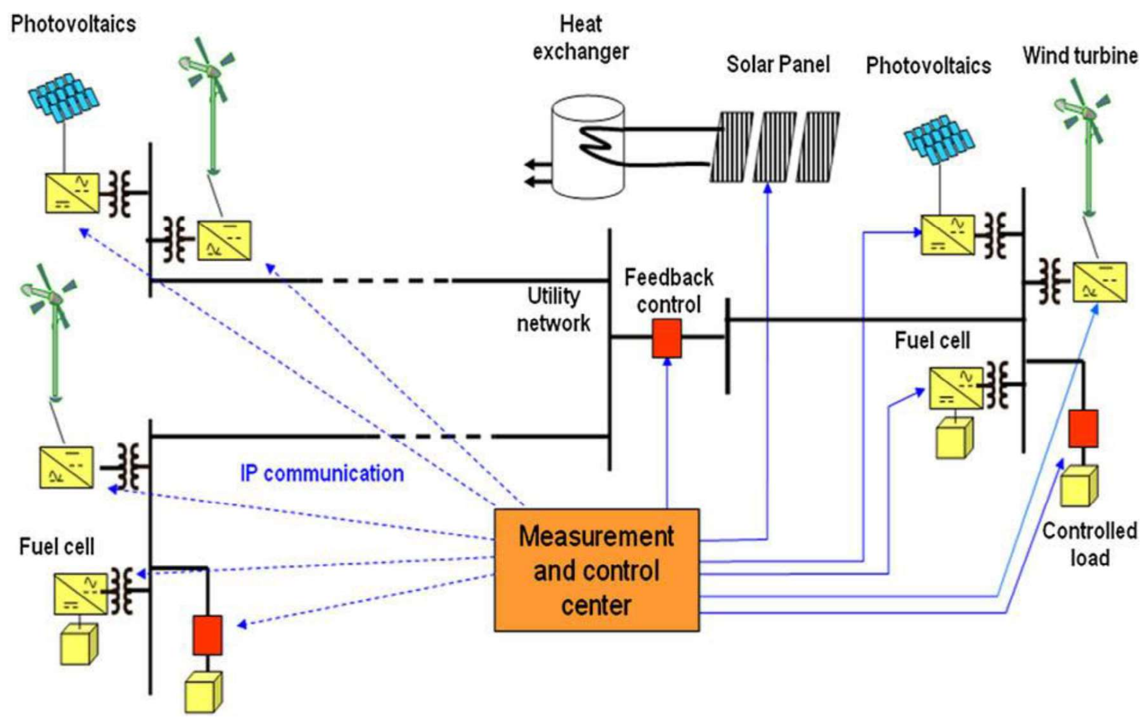

Figure 2.4. Proposed microgrid with control system (Ref: Morais *et. al*., 2010).

Wouters *et al*. (2015) presented a new approach based on the principle of cost minimization for MILP in order to design residential distributed energy systems. The proposed energy system was designed by considering annual demands and available DGs. The DGs were integrated into the form of network. The authors have considered location specific input data related to weather, cost and regulations. The microgrid was evaluated for its performance at the local level, where it is implemented. Zaree and Vahidinasab (2016) have formulated a new approach using MILP for EMS and investigated both stand-alone as well as grid-connected microgrid. The authors have pointed out that the constraints leading to the formulation of nonlinear programming are difficult to solve using MILP approach. Therefore, the nonlinear constraints can be simplified by linearization methods before applied to MILP. It has been reported that the MILP method does not involve complicated decompositions or heuristics approach, which leads to decrease in computational time and to improve the scheduling quality. It was also pointed out that MILP method is effective in unpredictable situations involving varying forecast of weather and energy demands. However, it is difficult to integrate the classical techniques of mathematical programming with MILP, which limits the use of MILP in specific as well as complex problem.

2.4.3 Game theory

Game theory is a mathematical framework using analytical tools to study the interaction among the system parameters (referred as players). It is used in integrating interdisciplinary systems like power systems, networking, communication and control. Applications of game theory include economics, politics, psychology and more recently design and analysis of communication systems. The challenges, which were addressed using game theory are: (i) requirement of distribution of operations for effective communication and control of each node in the microgrid, (ii) requirement of simple formulae and algorithms which can efficiently model the state of the players or parameters and (iii) finally, the need to integrate these algorithms in different sectors likes power and communication system. One of the most important techniques used for game theory is Nash equilibrium. The Nash equilibrium state is considered as the solution to the game, where two or more players participate. In the Nash equilibrium, "if each player has chosen a strategy, and no player can benefit by changing strategies while the other players keep theirs unchanged, the current set of strategy choices is the optimal outcome of a game”. Hence, every player wins because everyone gets the outcome they desire. In game theory, there may be multiple Nash equilibria or none at all. Saad *et al*. (2012) have used game theory with fixed heuristics approach to reduce power loss from a microgrid and reported a 31% reduction in loss of power.

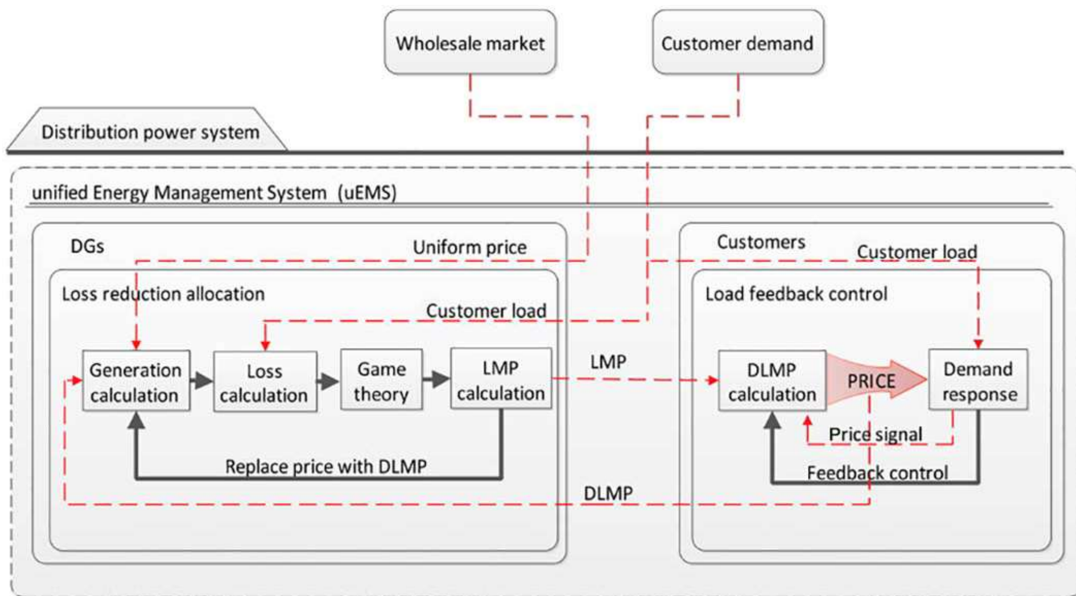

Figure 2.5. Unified energy management system model (Wang *et al*., 2015).

Wang *et al*. (2015) have applied game theory using an iterative method to achieve an optimal loss reduction for each DGs of a microgrid. The authors have used a unified energy management system model, as shown in Figure 2.5. It has been reported that the overall profit of all DGs is increased by using this model. This is very important in microgrid as distributed devices generate and transmit power to microgrid, which generally has substantial power losses. Wang *et al*. (2014) used game theory for solving long-range algorithms in distributed power systems, where each DG was viewed as a player, which could interact with other players and also individually affect the entire system’s loss. The authors have reported that the application of game theory has shown a reduction in total power losses. It has been pointed out that this analysis has demonstrated positive results proving that game theory can save a lot of power in each DG of microgrid. Authors have suggested that game theory is beneficial when situations are of conflicting nature. In microgrid operations, the game theory can help in maximizing economic benefits, while using RES effectively. The game theory can be used for microgrid operations to arrive at an optimal strategy so that both consumers and suppliers get benefited from it. However, game theory is most useful when the microgrid is operated interdependently by various operators. On the other hand, game theory considers only a finite number of the possible outcomes of any action; while there can be an infinite number of possibilities.

2.4.4 Particle swarm optimization

Particle Swarm Optimization (PSO) method is based on the social behaviour of flocking and schooling patterns of fishes and birds. Holkar and Waghmare (2010) have used the PSO for grid-connected microgrid to minimize the operating costs. The authors have used the modified version of PSO along with genetic algorithm, due to the inadequate searchability of old PSO for global maxima or minima. Their new algorithm helped the particles (i.e. parameters of the problem) to exchange information with each other to increase their ability to search for global optimal condition. This approach not only helped to cut operational costs but also increased the reliability of the system.

Kerdphol *et al.* (2014) used the PSO for integrating and optimizing the size of Battery Energy Storage system (BESS) into a microgrid. Authors have suggested that the stability of the microgrid is significantly dependent on the optimal size of BESS. The microgrid system investigated by the authors is shown in Figure 2.6. The authors have pointed out that inefficient BESS leads to various system and operating losses with an increased cost of microgrid operations. The performance of BESS has been evaluated and compared with other storage technologies available. The authors have reported that BESS based on polysulfide-bromine has proved to be the most efficient storage system; size of BESS was reduced by approximately 19% and the total cost saved on BESS was 0.46 million USD. It has been observed that application of the PSO technique has shown significant improvement in grid security, power stability, and economic profitability along with improvement in high-frequency control.

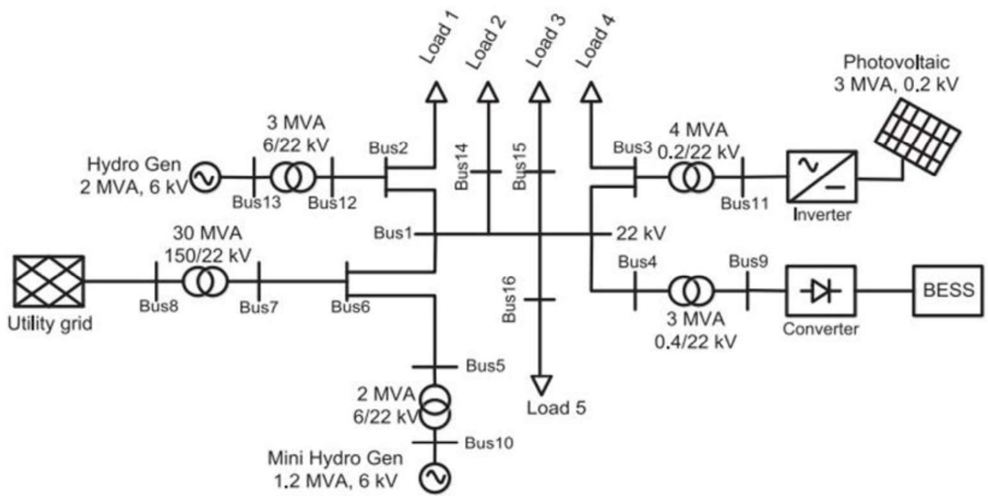

Figure 2.6. Microgrid system for analysis (Ref: Kerdphol *et al*., 2014).

Al-Saedi *et al*. (2011) have used PSO technique to find optimal energy management solutions for a stand-alone microgrid consisting of wind and micro turbines. They compared their results with Successive Quadratic Programming (SQP) optimization technique. The objective function of both the algorithms (i.e. SQP and PSO) was updated every three minutes keeping the load and generation constant. At each step, the optimum balance between wind energy conversion systems and micro turbines was determined. SQP was applied to increase the accuracy and faster convergence in PSO. The convergence speeds and convincing simulations show the potential of this technique for real-time energy management system with multiple energy sources. The authors have observed that the PSO can solve an extensive solution space, while considering the objectives function, such as cost minimization of generated electricity, efficiency maximization of micro turbines and environmental emission reduction. It has been reported that PSO method is flexible in terms of integration with other optimization techniques and forms a hybrid optimization tool. The PSO method requires relatively less number of parameters compared to other optimization techniques and has the ability to escape local minima. Moreover, the PSO method has derivative free algorithm unlike other techniques available and can start the iteration process even without the availability of an initial solution. The PSO method has some limitations also to solve multi-dimensional problems, as no general theory of convergence is applicable. Hence different parameters of PSO method need to be improved to address the multidimensional problems.

2.4.5 Hybrid optimization model for electric renewable

The most efficient way of developing microgrid is by using the Integrated Renewable Energy Systems (IRES) approach. This approach takes into account multiple renewable energy sources for minimizing the cost of energy supply while meeting the energy demand. The Hybrid Optimization Model for Electric Renewable (HOMER) software is one such tool developed by the National Renewable Energy Laboratory, Department of Energy, USA to analyze microgrid design. It can be applied for designing of a microgrid, either in stand-alone or in grid-connected mode. Schematic of HOMER software is given in Figure 2.7. HOMER software carries out hybrid optimization while considering multiple DG sources and multiple storage systems simultaneously. Kanase-Patil *et al.* (2010) have investigated integrated renewable energy system for remote location in India. The authors have used HOMER software to simulate various IRES configurations and compared the results with LINGO software results. The microgrid has been modeled and optimized to ensure the reliability by considering two parameters: energy index ratio and expected energy not supplied. The authors have reported that the best configuration consists of micro hydropower, biomass, biogas, solar energy and wind in their study region.

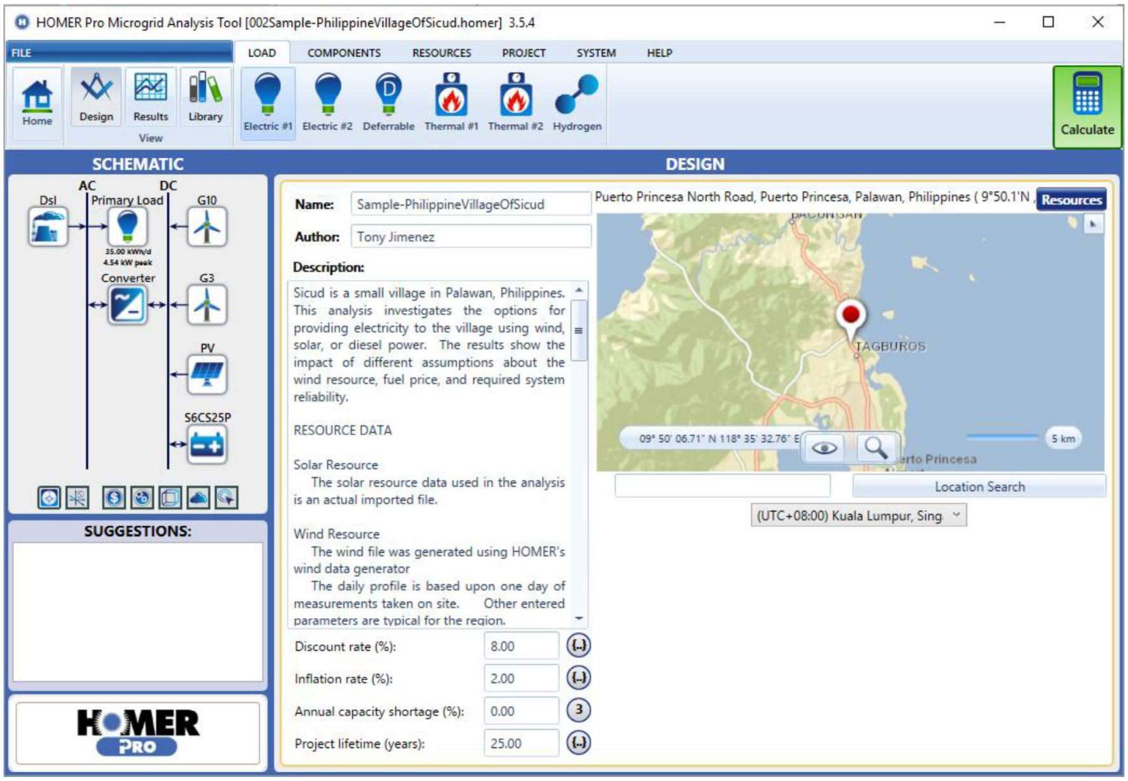

Figure 2.7. Schematic and design of HOMER software.

Hafez and Bhattacharya (2012) have investigated optimal IRES for grid-connected microgrid, consisting of PV, wind, micro-hydro and diesel generator. They have compared grid-connected microgrid with stand-alone diesel-based microgrid. The authors have analyzed the economic aspects of different scenarios using HOMER software. It has been found that the microgrid with 100% renewable energy fraction has the least carbon foot-print but net present cost is substantially high compared to diesel-renewable mixed microgrid. The authors have pointed out that further investigations should be carried out for various combinations of conventional and renewable energy systems to minimize the cost for power generation at a local scale in different regions.

Castellanos *et al*. (2015) have investigated IRES of PV and anaerobic digestion for stand-alone power system in India. The authors have designed the IRES to meet the energy demand of a rural village with an electrical requirement of 22 MWh per year. Seven different combinations of energy generation units and storage units (batteries, water electrolyzer and hydrogen storage with fuel cell) have been modeled and simulated using HOMER software. The authors have used PV system to meet the daytime energy demand, and to store the power using battery system to meet the night energy demand. They have used a biogas based "combined heat and power" system to meet peak and variable energy demand.

Halabi *et al*. (2017) have done a case study for performance analysis of a hybrid energy system in Malaysia using HOMER software. The authors have considered PV and diesel generator along with battery system for stand-alone microgrid operations. Three different scenarios, such as diesel alone, PV/diesel with battery and PV with battery have been investigated to meet the energy demand with minimum net present cost and cost of energy. The authors have also carried out a sensitivity analysis on the effect of variation in fuel, PV and battery cost along with the variation in energy demand on the performance of energy system. The authors have observed that 100% RE system exhibited the best environmental characteristics, while having highest costs. However, the hybrid system consists of PV, diesel and battery showed the best technical performance as well as gave good economic and environmental performance. It has been observed that integration of RES enhances the performance of the systems and reduces energy storage requirements. The authors have pointed out that there is a need to investigate the different hybrid energy system at the local scales to improve the performance of microgrid in different regions. However, the performance and cost of PV, as well as battery technologies, are improving day by day, which will finally reduce the cost of power supply in the near future. Recently, HOMER software became popular amongst researchers worldwide, due to its ability to optimize IRES and its capability to integrate and investigate various technologies, such as PV, wind, hydro, fuel cells, and boilers. HOMER software is capable of evaluating multiple design options for grid-connected and stand-alone power systems. It can also perform the sensitivity analysis for possible variation in energy demand, power generation unit and power storage units.

2.5 Research gaps identified

The literature review indicates that researchers worldwide are investigating EMS for microgrid to effectively integrate renewable energy systems. This will enable to achieve higher efficiency and will attract investments for faster penetration of renewable energy in supply system. The main objective of microgrid development is to estimate and utilize locally available energy sources for meeting energy demand with higher reliability, minimum cost of energy supply and associated carbon emissions. The microgrid development becomes more complex due to geographically dispersed, limited location of distributed resources and seasonal as well as intra-day variability in renewable resources. In a developing country like India, where the energy supply-demand gap is more, the microgrid development has a huge scope. The main challenges for researchers and decision makers are insufficient and inaccurately measured data of local renewable energy sources to develop microgrid. Based on the literature survey, following research gaps have been identified:

- Prediction and mapping of renewable energy potential at local level is required.
- A generalized methodology is required to be developed for accurate estimation of power generation from renewable energy sources at local level.
- There is a need to investigate integration of available renewable energy sources, as a part of microgrid operations, at local level for their maximum utilization.

2.6 Objectives of the study

This research work aims at evaluating the potential of renewable energy sources (wind and solar) at local level and proposes an integrated energy management system for microgrid operations with least operating cost and high reliability. In order to achieve this, following objectives are defined:

I. Develop a model for predicting and mapping the wind and solar energy potential at local level using available meteorological data.

II. Estimate ideal land available in the regions with higher renewable energy potential for installation of solar fields and wind farms and develop a generalized methodology for solar field and wind farm layout to maximize the power generation.

III. Investigate an integrated renewable energy system for stand-alone microgrid operations.

2.7 Scope of the study

The study is about development of energy management system for microgrid operations at local scale by considering locally available renewable energy resources. The objective of microgrid development is to meet the present as well as future energy demand with high reliability and minimum cost while reducing the greenhouse gas emission. The renewable energy resources as well as needs vary from region to region. These parameters are used to define an appropriate region to develop IRES at local level. The IRES requires to fulfill the energy demand subject to certain limit or constrains with high penetration of renewable energy. The study describes the methodology to accurately predict the renewable energy potential, to identify the ideal location for installation of energy system and to maximize the use of the energy resources. The methodology adopted in the present study can also be applied to other regions, which have locally available renewable energy resources and energy demand; new region can be defined for implementation of IRES.

2.7 Methodology adopted for the study

The overall methodology adopted to achieve the defined objectives of the study is shown in Figure 2.8. To carry out this study, meteorological data has been obtained from various Government agencies. The entire data was measured at the weather monitoring station. The measured data is then used to develop a model which can predict the wind and solar potential at any given location where measured data is not available. The measured and predicted data are used to develop a map of solar and wind potential using GIS approach in the study region. Based on the maps, regions with higher resource potential are identified and ideal land available within these regions for installing wind farm and solar filed are estimated. Thereafter, for optimal use of available solar and wind potential, wind farm and solar field optimizations are carried out for placement of wind turbine and solar panel. Finally, an integrated renewable energy system is proposed based on local energy demand and resources available. The energy system is simulated and optimized for real-life scenario at Thumkunta, (a village in Ranga Reddy district, TS).

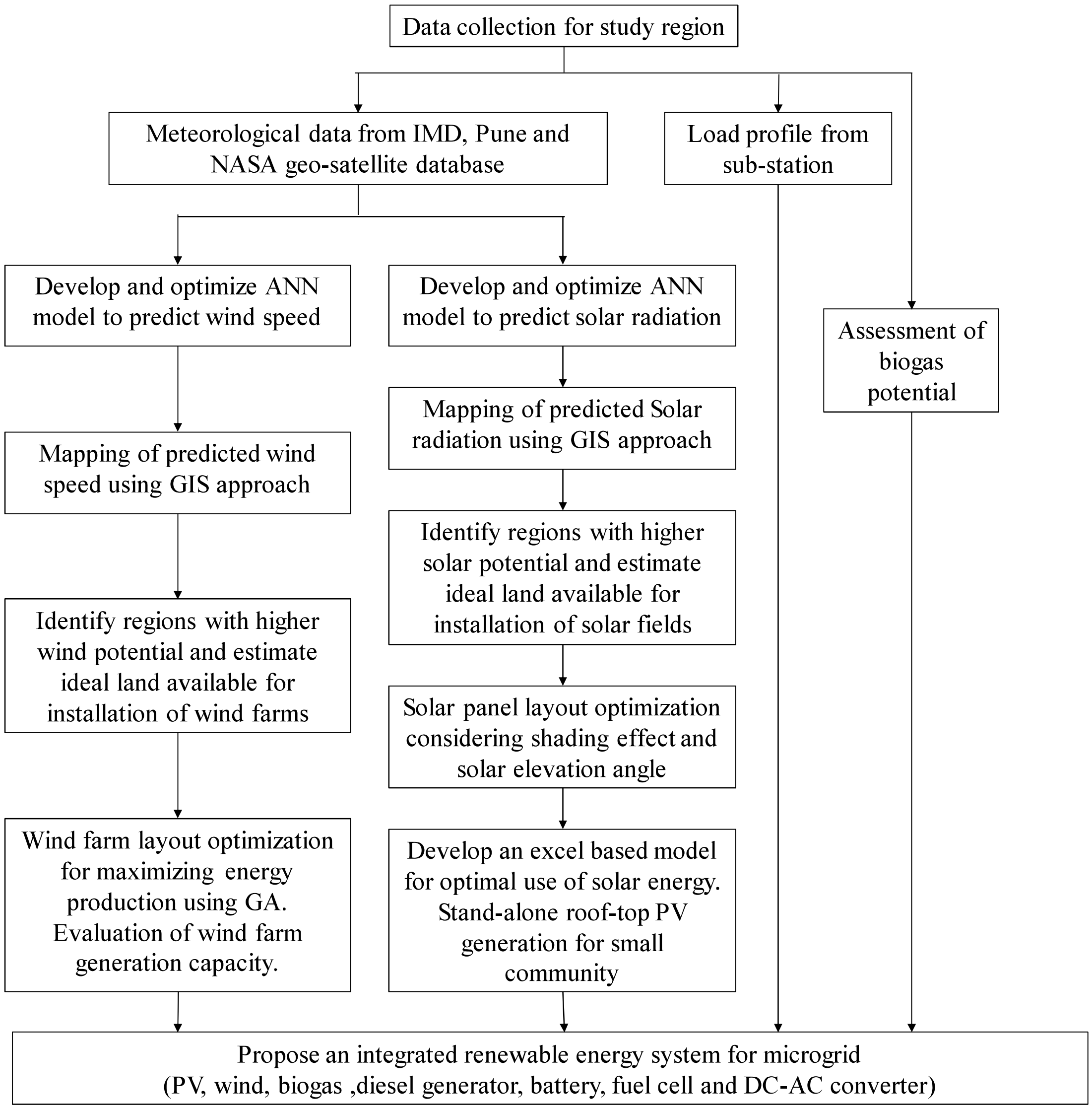

Figure 2.8. Flow chart of methodology adopted for the present work**.**

Phase I: In this phase, the meteorological data is collected and analyzed for study region (AP and TS) from Indian Meteorological Department (IMD), Pune, for estimation of the wind speed. All these data are measured at the weather monitoring station and archived by IMD, Pune. Meteorological parameters such as temperature, station level pressure, relative humidity and wind speed are considered for wind speed prediction. Wind speed was measured at a height of 10 meters. This data is used as a reference data point for developing a model, which can predict wind speed at any location within AP and TS.

Phase II: In this phase, a study is carried out to find the most influencing parameter for predicting the wind speed using ANN. Considering the most influencing parameter, an ANN model is developed and optimized to predict wind speed with higher accuracy. The developed model can be used to predict wind speed at any location within AP and TS. Predicted wind speed is analyzed and mapped in the form of contour over AP and TS using GIS approach for better visualization of wind potential. Regions with higher wind potential are identified based on wind potential maps. Land Use and Land Cover (LULC) analysis is carried out to evaluate the availability of suitable types of land areas within the study region.

Phase III: In this phase, the meteorological data is collected and analyzed for study region (AP and TS) from IMD, Pune and NASA geo-satellite database for estimation of solar radiation. Meteorological parameters such as temperature, sunshine duration, relative humidity, precipitation and solar radiation at various reference locations are used to develop the predictive model.

Phase IV: In this phase, an ANN model is developed, trained and optimized for prediction of solar radiation in AP and TS using the available meteorological data. Optimized model is then used to predict the solar radiation. Predicted solar radiation is analyzed and mapped in the form of contour over AP and TS using GIS approach for better visualization of solar potential. Based on the developed solar potential maps, regions with higher solar potential are identified. The LULC analysis is carried out to estimate ideal types of land for solar fields within the regions of higher solar potential.

Phase V: In this phase, Wind Farm Layout Optimization (WFLO) is carried out for positioning the wind turbine using genetic algorithm. The wake model is considered to maximize the wind power generation. The number of wind turbines and their position in wind farm are found out for maximum power generation. The cost-effective power generation is then calculated for a given wind farm. Effects of wind speed and direction of wind on WFLO are also investigated.

Phase VI: In this phase, an excel based model is developed for maximum utilization of solar energy, considering shading effect of solar panel, solar elevation angle and panel dimension. Roof-top solar power generation is investigated for a small community, which can be operated in a stand-alone mode.

Phase VII: Finally, an integrated energy management system is proposed to meet the energy demand for a community. Hourly demand for a community is estimated by taking real-time supply data from sub-station. The proposed IRES is considered as stand-alone microgrid. Different components integrated into microgrid includes DG sources (PV, wind, biogas and diesel generator), storage systems (battery and fuel-cell) and DC-AC converter. Seven different scenarios (realistic and futuristic) with different combinations of DGs and storage system were investigated using Hybrid Optimization Model for Electric Renewable (HOMER). The cost-effective and reliable IRES is thereby proposed for microgrid operations. Some possible policy intervention is suggested for the IRES.

The next chapter presents the development of model to predict wind speed using measured meteorological data and mapping of wind potential using GIS approach.