A MICROGRID ENERGY MANAGEMENT SYSTEM IMPLEMENTSTION USING MIXED-INTEGER LINEAR PROGRAMMING

MSC THESIS

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JULY, 2020

DECLARATION

I hereby declare that this MSc thesis entitled "**A Microgrid Energy Management System Implementation using Mixed-Integer Linear Programming**" is my original work and has not been presented for a degree in any other university and all the sources of materials used for this thesis have been fully acknowledged.

SINTAYEHU TERBUSH ----------------------------------

Student Name **Signature**

Place and Date of Submission: ---------------------------------------

This MSc thesis has been submitted for examination with my approval as a thesis advisor.

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L/col. Dr.
Defence University, College of Engineering, Academic Dean.
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Name **Signature**

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Abstract

The ever continued growth and development of distributed generation (DG) in the electrical grid system led to the increasing expansion of microgrids across the world. Microgrid is distributed power generation units, energy storage devices, and controllable loads with the capability to operate in both grid-connected and island modes. Microgrid's economic operation is achieved through an energy management system that optimally schedules distributed generations and storage devices and continuously balances supply and demand. In this paper, a formulation of optimal unit commitment and dispatch scheduling of DGs in a grid-connected microgrid is presented. Mixed-integer linear programming (MILP) is used to carry out the optimal resource scheduling model. The goal is to reduce the overall operating cost of the system by optimally utilizing an energy storage device and a diesel generator unit by using load and renewable energy generation prediction. Operational constraints such as generation limits of DGs, battery charging/discharging limits, and state of charge (SOC) limits to be satisfied during all intervals of operation. Simulation results indicate that the operational cost of the system is effectively reduced through optimal scheduling of an energy storage system and a diesel Genset unit using the proposed strategy.

Keywords:Distributed generation (DG), Microgrids, Energy Management Systems,

Optimization, Mixed-integer linear programming (MILP).

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List of Abbreviations

AI	Artificial Intelligence
ANFIS	Adaptive Network Fuzzy Inference System
ANN	Artificial Neural Networks
ARIMA	Auto-Regressive Integrated Moving Average
ARMA	Auto-Regressive Moving Average
BP	Back-propagation
CHP	Combined Heat and Power
DER	Distributed Energy Resource
DFIG	Doubly-Fed Induction generator
DG	Distributed Generator
EMD	Empirical Mode Decomposition
EMS	Energy Management System
ESS	Energy Storage System
FC	Fuel Cell
GA	Genetic Algorithm
IMF	Intrinsic Mode Function
KW	KiloWatt
KWH	Kilo-Watt-Hour
KWp	Kilo-Watt-Peak
LF	Load Forecasting
MILP	Mixed Integer Linear Programming
MPPT	Maximum Power Point Tracking
PCC	Point of Common Coupling
PMDD	Permanent Magnet Direct Drive
PMSG	Permanent Magnet Synchronous Generator
PSO	Particle Swarm Optimization
PV	Photovoltaic

SOC	State of Charge
STLF	Short-Term Load Forecasting
SVM	Support Vector Machine
UPS	Uninterruptible Power Supply
WPF	Wind Power Forecasting
WT	Wind Turbine

CHAPTER ONE

INTRODUCTION

1.1 Background

Energy is still playing an increasingly significant part in developing the economy,advancing the technology as well as improving the industry of mankind. In recent years the world's electric power needis observed to be growing, this demand is anticipated to double in the coming 20years as well [1]. The fossil-fuels which have been utilized as the main source of power until now are quickly exhausting calling for us to find additional alternatives of energy source. Wind energy as well as photovoltaic solar panel are becoming the best for an energy source in the world [2].

The World Wind Energy Corporation (WWEC) estimates as of June 2017,gross installation of wind energy amount reached 486,661 MW worldwide by the end of 2016.Africa,pacific,oceania,Latin America ,North America, Europe &Asiahave increased their percentage of new wind energy installations to 53 %, 23.2 %, 16.2 %, 6.5 %, 0.8 % ,and 0.3 %, respectively, by the end of 2016. China (168, 730 MW, by the end of 2016) and USA (82,033 MW, by the end of 2016) are the top two leading countries in terms of installed wind power capacity. PVSolar is also a major source of renewable energy and the world has over 303,000 MW of installed solar power capacity by the end of 2016, according to Global Data's latest report. China (78.07 GW, by the end of 2016), Japan (42.75 GW, by the end of 2016), Germany (41.22 GW, by the end of 2016) and the USA (40.3 GW, by the end of 2016) are the top four leading countries in terms of installed PV power capacity.

According to their report, the United Statesgovernment has a plan to generate 20% of the grid electricity from wind energy by 2030[3] – [5]. China has also a strategic plan to remain a considerable influence on the global renewables market over the future, remaining the world's largest wind and solar installation market and increasing its share in the coming years. However, on the other hand, the U.S. depends onan aging power grid and pipeline distribution systems, some of which built in the 1880s. China has most of its generation sources at the west end of the country which is very far (more than 3000 km away) from large load centres (eastern region).

The development of renewable energy (RE) and distributed generations (DGs) will assist on improving usage of the presentelectricity systems decreases thepower consumption of the fossil based fuels &decreases transmission of power and distributions of power losses & reduces costs, increases the reliability of power supply and improve and guarantee power quality.However, the higher penetration of distributed generations results in the technical issues of which incorporate power management, power quality, reliability, power security and comprehensive power system efficiency, the interconnection of with grid and regulations etc. [6] [7]. The transmission of power and distributing of power greater than capacity and high cost to assure or to increase electric and fossil fuel gas costs instabilities, electric power quality, efficiency and consistency problems, cyber safety and the physical security attacks, ongoingpower systemrequirementissue, climate related actions and a imperfect maintenance care haveplayed a great role to a rising number power disturbances. These are a few of the driving forces to the present transfer of the global energy industry from huge connected and centralized electric power systems to the distributed small scale power systems so-called MG's [8]- [11]. Transmission controlsrequiring supplies closer to loads, technological innovations of renewable energy resources, energy efficiency, reliability, security, economic savings, and sustainability requirements are several other propulsiveforces for the concept of microgrids. The following subsections introduce the technologies, research and development of these emerging power systems.

1.1.1 Distributed Generation

The Distributed Generation mainly describes the small-sized power generators linked to the energy distribution grid characterized by measured powers starting from a few kW up to tens of MW powers. Several distributed generation technologies are currently broadly advanced, for instance including traditional power generators through diesel Genset plants and well-established RE systems, for example wind turbines and photovoltaic solar panels. Among a variation of distributed energy resources is well known renewable resources of energy that has an essential role in providing a sustainable energy source infrastructure, as they together exist in abundance & eco-friendly,but the intermittent nature & the uncertainties Corporates with renewable tools pose enough technological & financial challenges for system planners.

TheDistributed energy resources there are primary energy sources which are infrequent & fluctuating some extent such as WTs & PV. Their installation led to trends in developed MGs equipped with sufficient energy storage facilities & spinning reveres. In addition to fluctuation with the interruptions, energy storage systems play an essential role to decide optimum moments to purchase & sell electricity to the utility grid.

In the previous several years, the energy industry has seen significant shift towards renewable energy generation technologies in the face of rapidly depleting fossil fuel power generation, the rising of electricity demand and the strict policies of governments on decreasing of pollutant CO_2 across the world. The constant growth in renewable energy technologies has in turn paved the way for increased growth and application of distributed energy resources (DERs). Nowadays, several kinds of DGs for instance Wind turbine (WT) generators and PV solar installations are attracting more and more attention and these DGs are linked with low voltage power distribution networks [12]. DG is a small-scale electric power generation source meant to produce power at the location of consumption and linked with a distribution network or only supplies power for the local load as Uninterruptible power supply (UPS) systems. This approach brings power generation and control to the location of consumption and removesthe inefficiencies and complexity associated with congested long-distance transmission and distribution networks. Distributed generation bases suggest viable energy production opportunities as well as direct towards improved economy together with eminent consistency, decreased CO_2 emissions and eminent efficiency [13]. Reference [12] summarizes main advantages of distributed generation systems as follows:

- Extreme consistency of electricity supply; especially while service disruption is intolerable.
- DGs are variable to utilize RESs
- Extreme quality of power
- Better solutions for electricity supply across remote areas anywhere the utility grid not reachable to the consumers.

Detailed review paper on the DG realization using the microgrids was done recently [6] & [14].it touches upon many parts of DG&MG design. Several DERs as diesel engines, micro turbines, fuel cells, photovoltaic, small wind turbines etc. & their coordinated process & controller with controllable loads & storage devices such as capacitors, flywheels, batteries etc. are main effort of the MG design, operational plants for micro-grids grid-connected or islanded mode in [16]. Several case studies of microgrids around the world have been deliberated.

1.1.2 Microgrid

Microgrid (MG) is a set of interconnected loads and Distribution energy resources (DERs) at the power distribution level with classified electrical limitations that has black start capacity and can work both in isolated or non-isolated mode. RESs like wind, PV and regular generation sources like micro-gas turbine, fuel cells and Diesel powered engines (Des) are the chief power DGs resources in MG.

Microgrid can also express as a cluster of loads, DG units & ESSs controlled with reliable electricity source & can be coupled to main power system at the distribution level at a single point of connection, the point of common coupling (PCC) [17]. The forthcoming power grid could mainly produce electric power [18].MGs can also distribute financial benefits through small-scale renewable energy investments & implementation of suitable control & managing facilities [16]. Implementation of microgrids by way of the vast combination with DG would allow the technical challenges to be solved in a decentralized technique, decreasing the need for very ramified & complicated central coordination & enabling achievement of the smart grid [15].

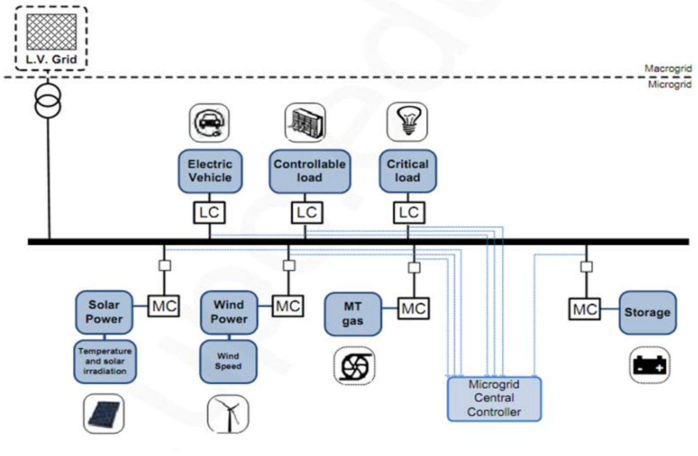

Figure 1.1 Microgrid Diagram

The main objectives of the MG concept include facilitating the speedily increasing penetration of DG systems into power networks & provision of reliable electricity supply [19], to critical local loads. MGs offer 3 main benefits above the traditional supply of electricity including central generation stations, long distance energy transmission over a network of high voltage lines, then distribution through medium voltage networks [20]:

- Implementation of combined heat & power technology
- Prospects to adapt to the quality of power distributed to enhance the constraints of end consumers
- Make more beneficial environment of energy efficiency and small-scale RE generation investments.

Coordinated operation of DERs as MGs has the potential to increase system reliability and power quality due to the decentralization of supply and control. Increase in reliability levels can be obtained as the distributed generation network can be allowed to operate autonomously in transient conditions, mainly if there is an outage or in case of disturbances upstream in the main electricity supply network. While grid connected process; distributed generations alongside the utility grid supplies power for the local load. Incase energy generated is bigger than the load use; the surplus power could either be stored in the energy storage unit or injected into the grid if there is demand. Conversely, incase energy generation is lesser than the load need; extra energy could be taken from the grid. For islanded control; the distributed generations must deliver secured voltage and frequency at the Point of common coupling (PCC) also accelerate the loads automatically. Furthermore, the MG must be reconnected to the utility grid faultlessly while the grid is made open again [12] [15].

MG systems usually integrate regular power generation units and RESs connected to energy storage facility. In order to successfully integrate renewable Distributed Energy Resources (DER) such as wind and PV, many technical challenges must be overcome to ensure that the present levels of reliability are not significantly affected, and the potential benefits of distributed generation are fully harnessed. Some of the main issues that need to be addressed include [21] [22]:

- Schedule and dispatch of units under supply and demand uncertainty, and determination of appropriate levels of reserves.
- Reliable and economical operation of microgrids with high penetration levels of intermittent generation in stand-alone mode of operation.
- Development of new voltage and frequency control techniques to account for the increase in power-electronics-interfaced distributed generation.

1.1.3 Energy Management Systems

Effective operation of a MG system wants an energy management system that plays a central role of monitoring flow of electricity in the system by optimum setting amount of power replaced between the microgrid & the utility grid, altering setting of dispatchable generation units & manageable loads depending on the current & forecast electricity tariff information, generation prediction, & load prediction in order to fulfil certain objectives & technical constraints [23]. This work is mainly focused on energy management in microgrid systems.

Microgrids accommodate a wide variety of distributed energy generation and storage options. The system is essential to accomplish a coordinated control & optimal management of energy resources while minimizing operational and maintenance rates. The concept of MG has increased the level of renewable energy penetration in to electric power supply networks, without a direct coupling with the conventional grid components. This is possible due to the unique feature of a microgrid, which allows both grid-connected operation and islanded operation in case of disturbances or power outages in the main grid. During grid-connected operation, the grid determines the voltage amplitude and frequency of the entire microgrid [24]. In this mode of operation, the DGs of the microgrid share its local loads with the grid supply. The main control objective is therefore to optimally set operating points for the dispatchable DGs and storage units to ensure economic operation and optimal scheduling of various sources. In stand-alone or islanded mode of operation, the microgrid operates as an independent entity. This mode of operation is significantly more challenging than the grid connected mode, because the critical demand-supply equilibrium requires the implementation of accurate load sharing mechanisms to balance sudden active power mismatches. In the absence of the main grid, voltages and frequency of the microgrid must be controlled by different DER units [24] [25].

From microgrid energy management point of view, unit commitment (UC) and economic dispatching generation devices, storage systems and loads within the system are crucial aspects. The intermittent nature of the renewable energy resources in the system poses a major challenge to ensure economic operation of the microgrid. Particularly wind & solar power plants cannot produce power steadily then wind speed & solar radiation change during the day and the seasonal of year [26]. Power system is however compelled for maintaining balances of the generally supplying as well as demands when operational in several practical as well as economic constrictions. Since loads as well as generating balances are very significant necessity on power networks, RESs such as wind power as well as solar' inconstant assimilation also unmanageable nature makes regulating power extra complicated, energy generation and demand predictions are consequently conducted for ensuring organized operating of renewable energy sources alongside several different source of energies and maintain operational stability within the microgrid. The accessibility for precise prediction of energy generation and demand some hour to time ahead allows the operators for planning UC, optimized power production program, schedule for maintaining of energy supplies as well as accessory, loads shed also several operation characteristics. Based on demand and generation prediction results and other operational information, optimal energy management strategies are employed to ensure economic and stable operation of the microgrid under both grid-connected and islanded modes. This study deals with a central energy management system for controlling an optimal scheduling of DGs as well as charging and discharging of an energy storage device in order to minimize the cost of electricity consumed in a microgrid. This is to be achieved by taking additional advantage of time-of-use pricing during grid-connected mode of operation.

1.1.3.1 Generation Power Forecasting

RESs, particularly PV solar power as well as wind power resources are among the best favorable power sources considered free, clean and abundantly available. For these reasons, they keep extending their share in electric power generation in the face of diminishing conventional fossil fuel energy sources and rising environmental protection concerns [27] [28]. Wind and solar energy resources are highly stochastic. Regarding wind energy source, its stochastics behavior appears by different aspects like seasonal changes, air pressure, landscape, temperatures, etc. [29]. Availability of solar energy also varies with time and weather conditions. MG techniques usually combine traditional power generating unit as well as RE source including power storing devices for powering locally controllable loads. It is therefore essential to accurately forecast the energy available from the intermittent renewable energy sources in order to overcome operational difficulties in management of microgrid systems and plan an optimal schedule of energy storage and other dispatchable distributed generation units. One day ahead power generation forecasting, known as short-term forecasting, in microgrids is particularly crucial to plan optimal unit commitment, economic generation scheduling, energy storage dispatch, load shedding and other aspects such as ensuring security and grid integration.

Concerning short-term wind power generation predicting(WPP), several methods have been reported in the literature. The wind power generation forecasting methods available by study are generally classified into 2 methods; Physical methods and statistical [30] [31]. The physical method wind prediction simulations use input variables derived from physical or meteorological data like pressure, temperature, terrain report and obstacles [25]. Many methods of physical prediction custom wind flow patterns around wind farms and turbine power curves to estimate wind energy output. Statistical methods are designed to identify interpretive input variables and to find out the relationship between variables and verified energy statistics to create wind generation forecast pattern [32]. The approaches could make use of various types of procedures and modeling techniques to create a correlation among the forecaster and energy production goal. The physical approaches are relatively beneficial for a long term prediction, whereas the statistical approach is better effective for short term predictions [30] [33]. Regards to time span for short term WPF is a few days or a range of predictions, from minutes to hours or time steps [34].

Over the past few years, researchers have come up with a wide range of predictive modeling strategies for various wind speeds and power. Time sequence consideration methods like autoregressive motion average, Autoregressive integral moving average (ARIMA) , artificial neural network approaches were mostly used [35] [36]. Different latest approaches like AI (artificial intelligence) and hybrid approaches, like support vector machine (SVM), NF (Fuzzy Logic, Neuro-fuzzy) network and future optimum approaches drawn a wide range of research interests in recent years. Wind speed and power field. [31] The application of short-term wind power forecast strategy based on artificial neural network is proved. Reference [37] using diverse kinds of neural networks to simulate the speed of wind and direction of wind in numerous time ranges, it is observed the FFNN has the greatest performance in wind speed forecast, while the influence of Elman network on short term wind direction is top predicted. In [38] A hybrid wind energy generation prediction method founded on neural network and wavelet transform is proposed. In research [39] a two-stage, fully statistical prediction method for wind power generation is proposed. In the first stage, the wavelet decomposition of wind speed time series is used to predict the wind speed, in the next few hours by using adaptive wavelet Neural Network (AWNN). The two-stage wind was predicted by using Feedforward NN. In [40], a short-term wind power prediction method based on support vector Machine (SVM) is proposed, and the performance of this method is better than that of persistence model and RBF-NN-based model. Study [41] labels fine tuning of the LS-SVM (least squares support vector machine) approach for the speed of wind prediction. It is considered that the least-squares method is superior to the one-step predictive persistence method. In [42], a method of short-term multi-step forward speed of wind and energy prediction employing a hybrid method of integrated density neural network is proposed. In reference [43], the ANFIS strategy was employed to apply a arithmetical time sequence speed of wind forecast model. [35] And [44] demonstrated the use of genetic algorithm and BP hybrid method in wind prediction training and neural network applications. A short term wind energy forecast method established on Elman NN training PSO scheme is proposed in [45]. The authors report that this method has achieved improved outcomes than the model centered on BP neural network. [25] In this paper, a hybrid wind power prediction method based on wavelet transform, PSO and ANFIS is introduced. Although it demonstrates the efficiency of this method relative to the different time series approaches, the method customs historic wind energy sequences in order to forecast upcoming rates in the system, regardless of various outer variables. Reference [46], the weighted factors of the hybrid wind prediction system composed of the persistent model BP neural network and RBF NN are optimized by using the enhanced particle swarm optimization (EPSO). It is reported that the performance of hybrid models is better than that of a single method.

The importance of the issue of solar resource forecasting has also drawn the focus of many studies worldwide. Substantial body of studies in the field is mainly concerned with forecasting solar radiation [45, 47-48], which is the single most important parameter in solar power production. Other studies have focused on forecasting of solar energy production directly [49-51]. Several forecasting techniques targeting different forecasting time horizons have been reported in the literature [52-54]. Application of time series modelling techniques for solar radiation and PV power generation forecasting has been demonstrated in references [50-51, 55]. Artificial neural networks-based PV power and solar radiation forecasting methodologies have been presented in references [56] and [57] respectively. Other techniques reported in the literature include forecast modelling approaches based on support vector machines (SVM) [58], adaptive neuro-fuzzy (NF) networks [59, 60], evolutionary optimization and other hybrid methods [61-65]. References [66-68] provide comprehensive review of various photovoltaic power forecasting techniques.

1.1.3.2 Electricity Demand Forecasting

Electricity demand or load forecasting (LF) is mostly described as the art of forecasting the future load on a given system for a specified period ahead [69].short-term load predicting in the order of a few hours to several days is a key issue for reliable & financial operation of power source. Several operational decisions such as dispatch scheduling, reliability analysis, security assessment, automatic generation control, load shedding & maintenance plan for generators are based on short-term load forecasting [70][71].MG load forecasting plays an important role to enhance management and usage of conventional and renewable energy mix within the microgrid. It also helps increase finances of energy exchange with other microgrids & the utility grid.

Different STLF techniques have been suggested in the last decades. Traditional & timely predicting approaches include exponential smoothing [72] regression [73], autoreg ressive moving average 9ARMA), Kalman filter [74][61],& time – series methods [69].different artificial intelligence (AI) based methods such as artificial neural networks (ANN) [76], pattern recognition [77], expert system [78]-[80], radial basis functions (RBF) [81], fuzzy time-series [82], fuzzy neural networks [83][84] have also proposed. Application of support vector regression (SVR) for short-term load forecasting for office building is demonstrated in [85]. Reference [86] &[87] demonstrate effectiveness of combining wavelet transform & extreme learning machine for short term load forecast modelling. A hybrid STLF modelling technique that proposes a modified generalized regression neural network (GRNN) based on a multi-objective firefly algorithm (MOFA) aiming at enhancing forecasting accuracy and stability is presented in [88]. Other studies have also shown the effectiveness of NFNs for load forecasting [89]-[91]. Development of a new hybrid evolutionary fuzzy model for smart-grids load forecasting whose parameters are optimized using meta-heuristics is presented in [92]. Application of evolutionary optimizations such as genetic method (GM) & particle swarm optimization (PSO) & other hybrid forecast modeling algorithms have been demonstrated in [93-96]. Another useful technique known as empirical mode decomposition (EMD), has recently been applied in many studies in the field of forecasting [97-100].EMD is an adaptive nonlinear decomposition technique used in analysing nonlinear & non- stationary signals. The technique can decompose any complicated time –series signal into a finite number of constituent signals called IMFs which can be more suitably & precisely modelled & forecasted compared to the original signal [101].

1.1.3.3 Optimal Scheduling of Resources

Coordinated operation of DERs, load as well as energy store system in the form of microgrid has the potential to increase system reliability & power quality due to the decentralization of supply [102].MGs can also provide economic advantages through small-scale renewable energy investments & implementation of appropriate control & management facilities [16]. DERs that establish microgrid typically incorporate wind turbines & photovoltaic installations where the primary energy sources are infrequent & fluctuating. The continuous introduction of intermittent renewable energy resources and the constantly fluctuating price of electricity have led to trends to develop microgrids equipped with sufficient energy storage facilities. Efficient operation of microgrids needs the use of energy storage systems and other dispatchable units to maintain the balance between energy generation and demand in the system. Apart from dealing with the fluctuations, energy storage systems and dispatchable sources play an essential role to decide optimum moments to buying & sell electricity from to the utility grid. From to the operational requirements point of view, the MG system is required to accomplish an organized control & optimum management of energy resources while minimizing functional & repairs costs. Ensuring a smooth & reliable operation of a microgrid requires an efficient energy management system that dynamically fits the energy production to the consumption and ensures an optimal combination of DGs and energy storage units that accomplishes stable and economic operation.
The EMS which plays a central role of controlling flow of electricity in the system by optimum setting amount of power exchanged units & controllable loads depending on the current & forecast electricity tariff information, generation prediction,& load prediction in order to satisfy certain objectives & technical limitations [103].

In order to take full benefit of the financial & ecological advantage that come from optimal control of microgrid efforts have been made to develop & apply various optimization techniques & control strategies [140]. Stochastic program based plan is formulated in [105].with the aim of minimizing overall cost of electricity & natural gas usage in a building. Analysis of tough scheduling & unit commitment problems with penalty based costs for hesitation in generation is delivered in [106].application of neural networks to resolve the energy source optimization problem in power source networks has been demonstrated in [107-108]. Dynamic economic dispatch model for microgrids employing dynamic programming step by step procedure is presented in [109]. Reference [110]. Suggests a day-ahead battery scheduling for microgrids based on statistic optimization principle. A MG optimization plan based on linear programming is presented in [111]. Quantum-inspired evolutionary step by step procedure is employed in [112] to optimize operation of a MG in terms of reduction of operational cost & emissions.

1.2 Background of Energy in Africa

As stated by the World Health Organization (WHO) available data, approximately 3 billion populations use animal dung, burns firewood, use charcoal, crops and coal; in order to satisfy the day to day power supply needs in their life and amongst aforementioned 3 billion populations nearly 1.3 billion populations do not have access to electricity power. Further, 80% and more of the populations that don't have access to electricity and living in energy poverty are living in rural parts of third world countries. In spite of its energy resources wealth, the African continent is electricity inadequate zone on earth because of the not fully formed electricity infrastructure [113-115]. There is massive difference in rates of electrification among the African countries particularly in SSA. In SSA the standard per capita electricity use is at 488 kWh per annum, which is the smallest per capita electricity use on earth, when compared with the North African countries it is likely 1500 kWh per capita [116].

Household electrification rates vary widely in Sub-Sahara Africa; the electrification rates of households in countries such as; Senegal, Nigeria and Ghana are greater than of countries like South Sudan, Chad, Malawi and Liberia[117]. The rural parts of countries in SSA are regularly not connected with the country's national electricity grids, thus have very poor electrification rates. According to estimation by the World Bank, the 25 SSA countries are looking towards an energy catastrophe as it has been proved by continuing power cut [118] Almost part of nations in the Sub-Sahara Africa zone which is 24 of 50 nations has electricity access rates in single digits [118]. Nevertheless, connection to a grid would not assure a reliable and dependable electricity services since populations located in urban parts have some power grid connections that are defective, undependable and uncertain[119-125]. For example, country of Nigeria has numerous power shutdowns that the grid was labeled as "epileptic." In spite of improved electrification works worldwide; electrification efforts in SSA do not match with the rapid population growth, still the share of people with no access to electricity continues to be large [126]. Hence, Africa still confronts a great challenge which contains an electricity gap in two different scopes: an inequality between the supply of energy and demand around grid-connected areas, and energy access lack around off-grid areas [116].

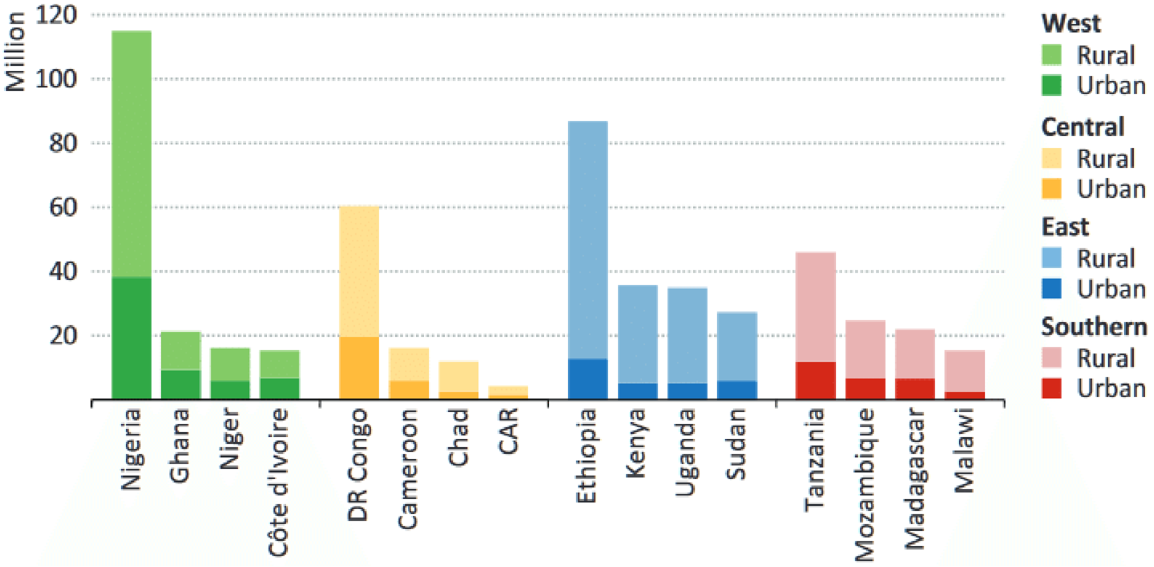

Figure 1.2Large population depending on the outdated use of biomass for cooking in Sub-Saharan Africa by sub-region, 2012 [128].

1.2.1 Africa’s Current Electricity Access

Total energy generation capacity of the 47 Sub-Sahara African countries without including South Africa is predicted to be at 45 gig watts (GW), which is smaller than of Turkey. Almost 25% of the generating capacity is inaccessible at present because of a huge lack in operations and poor maintenance actions [129]. Since year of 1990 to year 2013 the new generation capacity added was only 24.9 GW around Sub-Saharan Africa countries. Among these which South Africa added a capacity of 9.2 GW [130] [131]. Since year 2000, there seems to be comparatively significant growth, which nearly 13.8 GW of new generating size were enhanced across SSA, however several nations were behind generating capacity in the past years by consequence of weak maintenance efforts [132]. over the past decade in Sub-Saharan Africa countries, an average of 1to2 GW of energy generating volume were being added per annum, which shows a large gap that is behind the World Bank’s estimation of 8 GW generation capacity adding constraint over year 2015[131]. Besides, the progress of electrification through Sub-Sahara African countries is unequal; only a small number of countries like Ethiopia, Gabon, Ghana, and Kenya are in line to grasp universal access to electricity by year of 2030. Great number of Sub-Sahara African countries generation capacity possibly will collapse to keep pace with energy need run by continued population growth [133]. International Energy Agency estimates [134] that 90% of worldwide access to electricity shortage will be in the sub-Sahara African countries since the rest of the world countries are in line to reaching universal electricity access by year 2030.

Triggers and results for energy generation shortages in Sub-Sahara African countries have been widely explored in [135-139]. Overall triggers mentioned include low recovery of cost, the underselling of electricity power, losses of distribution, including other issues preventing investments in the industry. Nearly an amount of US$21 billion dollar of public funding which is 1.5% of regional GDP [136] goes to unproductive and inequitable energy funding for fossil fuel productions. Economic growth is being crippled by power sector ineffectiveness. Study by The World Bank predicts that Sub-Saharan Africa is losing US$8.2 billion dollars per annum [140]. Poor families endure the burden of this energy crisis since they need to pay about 20 times the amount spent by on-grid high-income households.

It has been estimated, over 50% of the sub-Sahara Africans are going to be residing in cities and nations' economy will increase roughly by 6 time by year 2050 [141]. Electricity need is consequently likely to follow the same path and Sub-Sahara African countries will have to increase access to energy percentages as to minimize the shortages of energy supply at present as well as to grasp energy increase in the future for demand of an environmental and economy development.

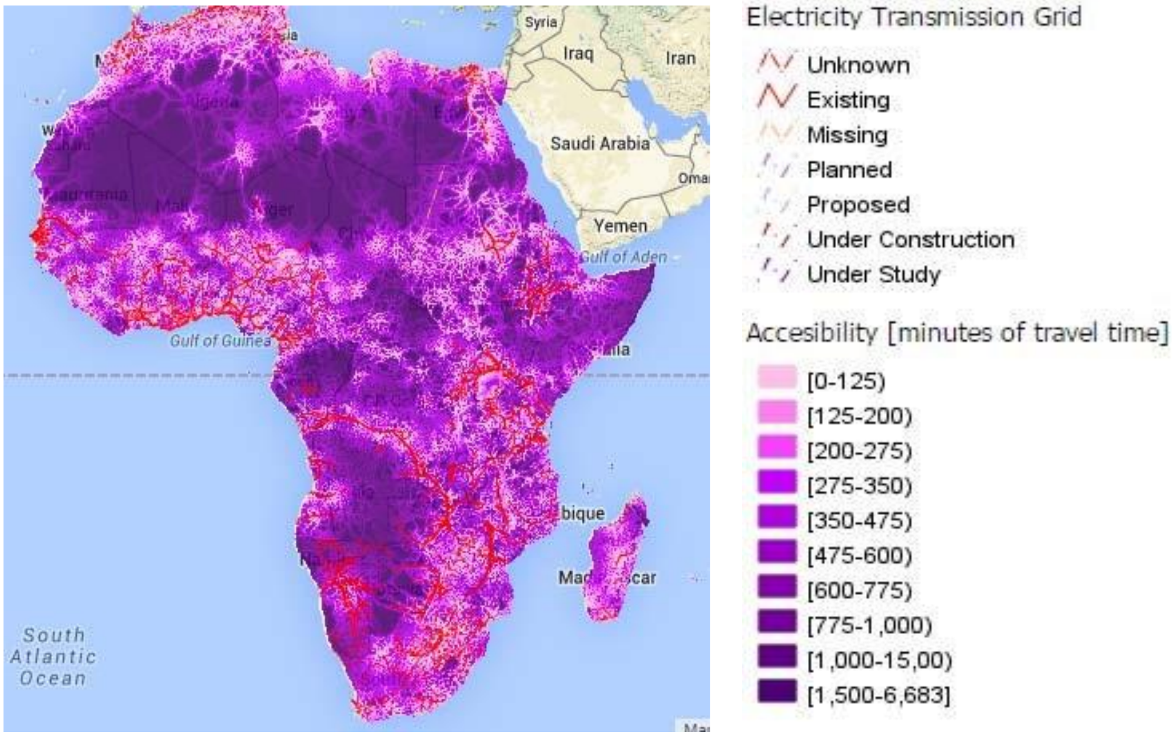

Figure 1.3Electrification and Accessibility of SSA, 2013[142]

1.2.2 Productive Use of Microgrids in Africa

MGs provide an inexpensive and consistent solution when put side by side with power grid extensions to parts that are far located from the grid. In several countries worldwide, the rural areas electrification is expected to be partially attained with micro power grids solutions, microgrids allows REs and also fossil-based fuel combination therefore helping as the best solution to tackling Sub-Saharan Africa’s energy sources, energy storage and load inter-connection demands. Falling in line with the COP21 conference call for MG energy systems that primarily build on REs sources, however supplying high power and ensuring quality service could be challenging to be achieved while MGs are based on variable RE sources.

Electrification of the rural partis expected to be achieved partially in years to come by deploying of off-grid systems and MGs. The IEA [143] estimates that among the 315 million of African populations presumed to gain electricity access by year 2040; about 80 million populations are expected to gain electricity access through off-grid systems, and population about 140 million are expected to have access through microgrids (MG). The expansion of microgrid brings up several questions, of which in recent years have been gaining even more devotion

[144].Including the technical and socioeconomic viability situations are the focus of some recent studies [145].

These recent studies regularly reflect hybrid MG, where virtual renewable energy productions such as solar, wind and /or hydraulic is enhanced by biomass or diesel generator [146-151]. The prospect towards advancing microgrids alone with renewable energy is yet an essential issue whether to subsidize to the serious de-carbonization trails needed to restrain climate change under 2°C [152], or to be capable to do it with no fossil fuels, energy source for which it is very challenging to guarantee a steady energy supply in remote parts worldwide and which might turn out to be more expensive in the midterm.

Although the direct cost of establishing renewable energy generating apparatus is very elevated compared to the implementation of fossil fuel generation; the issues including unreachability of countryside and isolated parts in sub-Saharan Africa coupled with increased fuel costs has led to long-term expected operating costs. The decline, which makes the scale rise, is conductive to the generation of renewable energy. Despite this, some renewable energy sources like hydropower and geothermal are discrete, while other sources of energy like wind and solar energy are essentially sporadic. Installing decentralized MGs near power generation and demand can prevent some of the economic and technical difficulties mentioned. In remote areas where grid expansion costs are very high, distributed generation, transmission power and distribution power are mostly the most cost-effective options. This can be achieved by handling the implementation of the RES and MGs.

Numbers of countries in Sub-Saharan Africa contain utility grids which span a minor topographical area supplying generally the populations located around urban areas. This is essentially credited to extreme direct capital expenses coupled with establishment of sufficient energy infrastructure. Furthermore, demand in rural parts of the region and remote areas is very low therefore reduces the effort of providing electricity access to rural areas as the duration over which the investing could be retrieved is unattractive [153]. The utility grids are subtle to energy production and load shifts as well, direct mixing of the power output from intermittent renewable energy source is unattractive since improper variations in grid voltage and frequency could trigger major system damage [154]. For frequency smoothing and voltage stabilization, installation of MGs with storage can help by increasing or decreasing power when needed [155].

The anticipated energy output can then be unified and combined into the grid through MG to grid interconnection. Regardless of having several RES, most societies in Sub-Sahara Africa remain with no access to electricity. At present the rural as well as remote areas community's electric power demands are delivered through 3 means: first; diesel powered or gas grid-connection, also renewable energies commonly locations that the grid is extended outside urban area; second; village/communities stage as well as industry minigrid or microgrid system powered by diesel, renewable energy, or powered by mix of diesel and RE. third; households stage; usually standalone devices also off grids device as well as system powered using diesels, old fashioned biomass and renewable energies for generating energy, to produce heat, for cooking, as well as for different beneficial consumptions [156] [157].

Still, to assure persistent social development along with growth of the economy in the SSA combined with demand to addressing rural areas access to electricity work and the overall electrification shortage, renewable energy sources and MG technologies are intended to lead the movement [158].

1.2.3 Energy Potentials of Sub-Sahara Africa

Even though electrification rate across Sub-Sahara Africa is poor, the region is gifted with plenty of energy potential in form of renewables such as wind energy, solar power, hydro power, biomass and other potential energy resources including fossil fuel, none sturdily displays the amount of energy potential Sub-Saharan Africa contains than the proportion of yearly output capacity to present day internal power use of REs for distinct nations [159]. The astonishing unexploited renewable energy potential is very large that even in Sub-Saharan Africa massive energy consumer countries such as Nigeria and South Africa, where the ratio is 2.0 and 1.3, respectively. The following Table 1:1 demonstrates how the renewable energy resources are spread throughout the SSA region [160].

Table 1-1Renewable Energy potentials per SSA regions, 2011, twh/year

SSA Regions	**Hydro**	**Solar**	**Wind Energy**	**Biomass**	**CSP**
Eastern Africa	578	2,195	309	642	1,758
Southern Africa	26	1,628	100	96	1,500
Central Africa	1,057	616	16	1,572	299
Western Africa	105	1,038	17	64	227
Total	**1,766**	**5,477**	**442**	**2,374**	**3,784**

The Rift Valley structure goes across the East Africa delivers extra power capacity for the nations around East Africa region. The energy potential across the region is anticipated to be 88 TWh per annum [160]. Besides, although majority of the African countries are net fossil fuels importers, Sub-Sahara Africa possesses substantial quantities of fossil fuels in its resources. In year 2011, the continents share in global oil production has been nearly 10% and 55% of the production that is around 67,519 million of tons' production is by the SSA nations [161]. Furthermore, 49% of the continents gross natural gas production that is 273,459 million of tons 8% of the global production is by the Sub-Sahara African nations as well [161]. Coal assets are largely condensed in South Africa, since South Africa possesses 95% of the entire Africa's coal in the country alone. In year 2009, fossil fuels were estimated to be approximately 50% of power generation of the whole African region, with biofuels, nuclear energy and additional renewable energy sources estimated for 47%, 0.5% and 1.5% respectively [161]. The segment of the renewable energy resource as energy production sources is decisively small which implies that plenty of chances in the area are available. Furthermore, it implies the problem of energy security in Sub-Sahara Africa is not yet appropriately directed as well. Power sectors economy reliance on fossil-fuels makes the economy susceptible to extreme and inconsistent costs of fuel. Highly prices become expensive energy prices and intermittent prices hamper the planning. Furthermore, in areas where accessibility is still a challenge such as in Sub-Sahara Africa shown in Figure. 1:3, the prices correspondingly depend on transportation expenses. Hence, difficulties which happen from fossil fuel reliance must act as spurs to drive Sub-Sahara Africa countries to grow energy security by taking advantage of the existing renewable energy means. According to IRENAs estimations; the global access to electricity in the continent could be simply reached by year

2030 if the appropriate policies are applied and that the activity will need to fully utilize renewable energy potential of Africa [160]. The RE capacity of Sub-Sahara Africa is a great advantage which could improve the mission of electrifying the SSA region, or else the mission may seem very challenging.

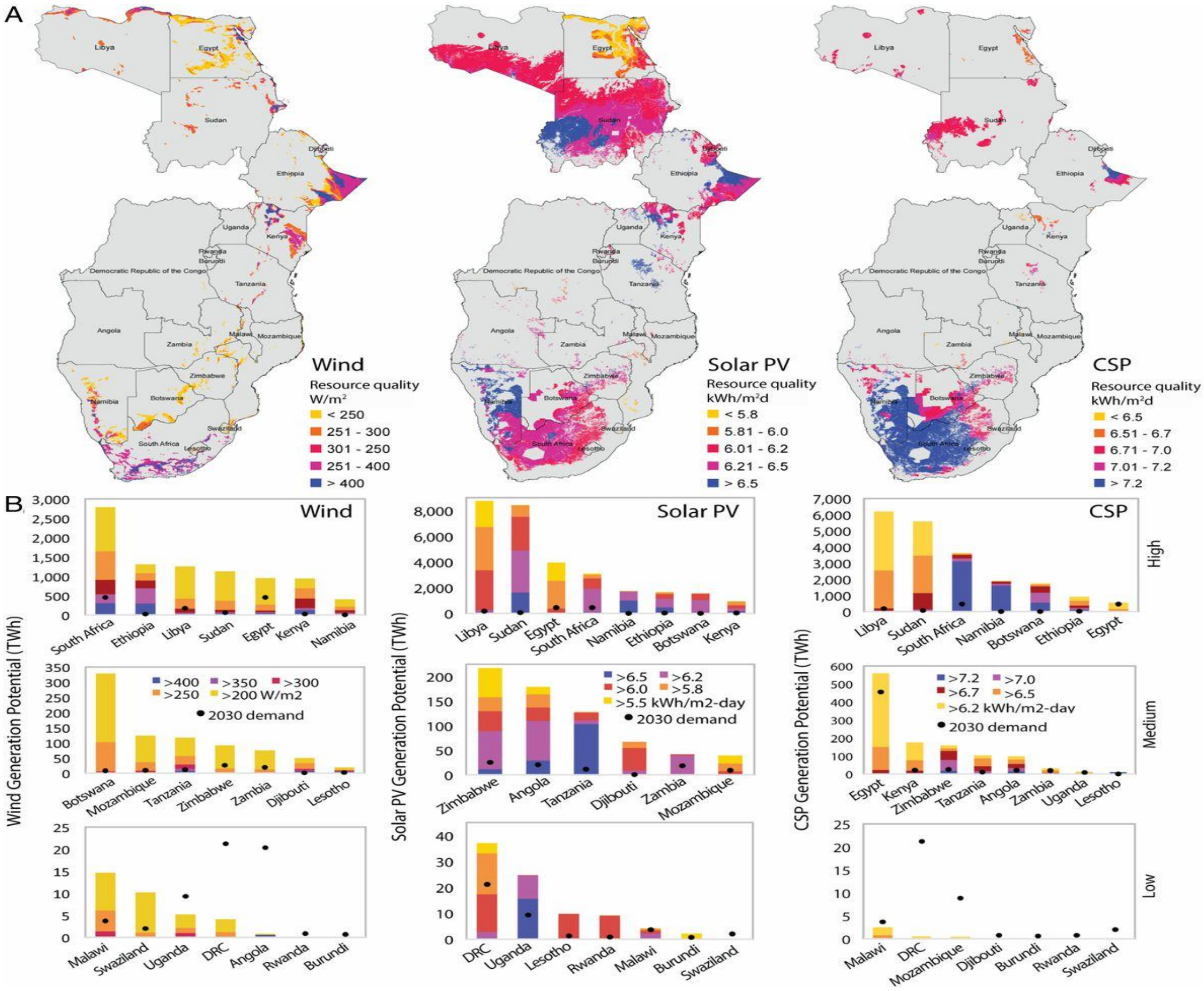

Figure 1.4Location and potential (TWh) of every nation’s RE resources inside the SAPP and EAPP. [162]

(A) Maps show the location and quality of renewable energy potential.

(B) Corresponding bar charts for each technology show the generation potential (TWh) of each resource quality range (in kWh·m−2 ·d −1 for insolation and m/s for wind speed) for each country. Countries are sorted by generation potential (high, medium, low). The 2030 demand for each country, as projected by the EAPP and SAPP Master Plans, is provided as a reference point (2, 3). [162]

1.2.4 Review on Development of Energy Mix in Africa

Regards Africa having both plenty of internal fossil-fuel assets and know-how in running the fossil fuel powered grids, power generation using fossil fuels are regularly considered as reliable and moderately reasonably priced. Furthermore, the small earnings rate of nations in Africa indicates that the government body place huge weight on preserving small power costs when implementing policy. On RESs there is only small experience if not none and some doubts if the low energy costs presented could be achieved in reality. A summary of model outcomes under this section although, do not indicate any inconsistency among fast development in power source and the energy system in line with 2015 agreement in Paris of 2°C direct for the global warming, the models take into account the combination of fossils with RESs as an ideal optimal approach.

The very latest drop in costs for REs, the fast acceptance of REs in Africa and the reevaluation of methodologies to address inconsistency did affect a turn more in favor of REs. several approaches believe it as achievable and reasonably priced to enhance nearly the entire new power for electricity generation from RESs. Considering, the harmful results of fossils on well-being, regional environmental quality, nation’s political constancy and corruption, along with the growing prices of power generation makes it very apprehensible that a modification from fossil-fuels to REs is very well lined up together with countries benefits. The first experimentations in Africa by means of strategies like auctions [163] indicates by what means a shift from fossil-fuel to REs could be realized and that costs for REs in the scale of fossils could be attained. The power generation assortment/combination of the time ahead might accordingly contain the fossil fuel parts that have previously been built along with a growing part of various RESs, like hydro, solar, wind powers and biomass.

Following that the cost REs going down, the price scale of REs overlies with the cost range of fossil-fuels, indicating that the REs are an appealing opportunity for investors for many reasons. Taking into account that the extra price of fossil-fuels obliged on the society could mark fossil-fuels as even less appealing.

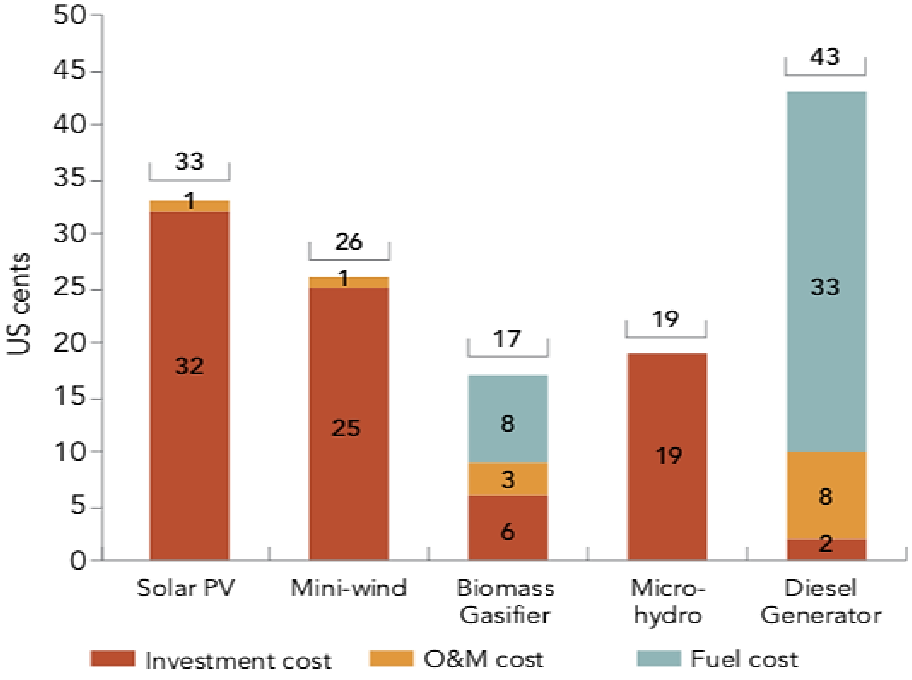

Figure1.5RE based mini grids being competitive (Cost of energy production from mini grids) [164].

As a first input, power generation mix situations for African continent by five very thorough, properly detailed energy economy simulations from reviewed publication are presented, the list of these models are illustrated in Figure 1:6. The assessment of shown model outcomes presents significant similarities and variances among them. Every model foresees a chance for the continent a quick economic growth including adequate power whilst obeying 2°C goal. The developed simulations presume that several diverse power supplies will be utilized as well, for the reasons that several power sources are complementary and since the ideal places are limited. The most significant energy contribution will be accessed from RESs, primarily solar, wind power, hydro and biomass. When the majority models reflect RE as the major methodology to climate change mitigation, the rest presume CCS (Carbon Capture and Storage) and/or nuclear power source being better choice.

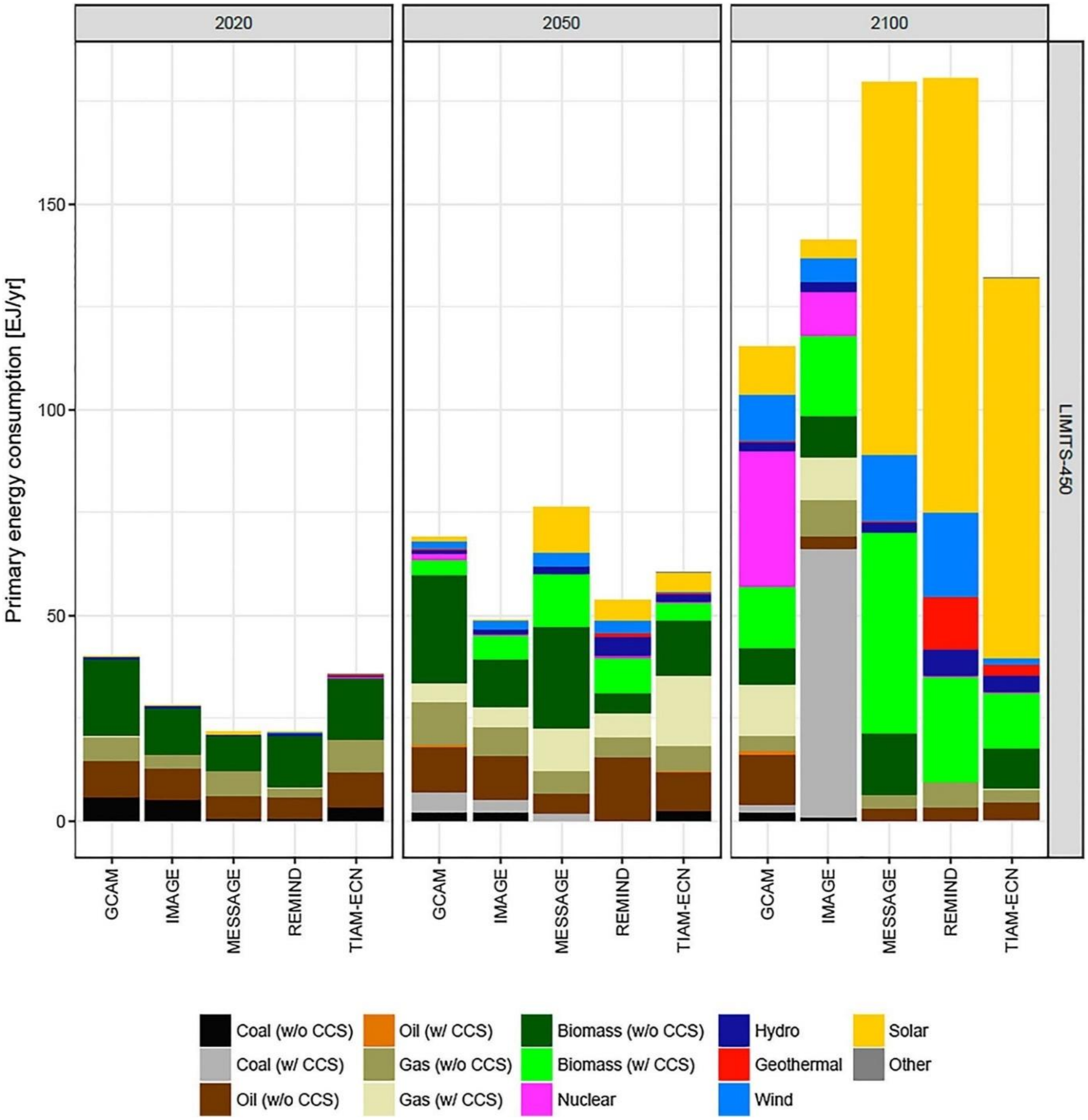

Figure 1.6Africa's Energy Mix. Sources: Writer's calculations applying LIMITS database [143] [165] [166].

Available literatures on the time-ahead advancement of energy mix in Africa explore to deliver the subject on precise goals for the climate mitigation could be achieved also to what point that the various technology sectors could provide contribution. Study [167] compares the outcomes from some IAMs (integrated assessment models). Their discovery indicates, achieving 2°C goal demands substantial further investments towards low CO_2 power. Regarding African continent, the research discovers the goal necessities a raise in investments towards REs from 1–3 to 13–72 billion US$ per annum, while leaving certain space for energy generation from fossil-fuels.

Latest researches aim on precise technical issues like the viability of climate mitigation through sub- optimum rules [168] and the methodical underestimation of PV power potential in early researches [169]. Compared to these studies, the following article focuses explicitly on the continent of Africa and policy selections for applying influential and environmental energy delivery.

1.2.5 Review of IAMs (Integrated-assessment-model)

The framework of the "Low Climate Impacts scenario and Implication of required tight emissions controlling Strategy, project (LIMITS)" [165] five major large range models are evaluated and the outcomes has become accessible on a public database. Depending on the result of this database, optimization for Africa's energy mix is evaluated and shown in Figure 1:6 among the models for a 450 ppm scenario. Limiting the carbon attentiveness in the atmosphere less than 450 ppm may possibly limit global warming under 2°C, respecting the direct of Paris Agreement 2015. Proposed simulations were developed autonomously so that outcomes differ to some scale. A citation has been described for thorough report on the applied simulations. Although the results vary in the details, they illustrate several significant resemblances.

1)Efficient climate change mitigation is considered as well-matching alongside fast growth in Africa. This is indicated in a numerous-fold growth in power generation all the way through the era. Although the improvement of the scenario demanded the simulation to keep with a CO2 plan and to produce economy development, the viability of this scenario is not specified with statement. Look [170] and [171] for researches studying the limits of viability in climate mitigation.

2) An extensive variability of energy sources is applied as per each five models. This wide variety indicates that the diverse energy potentials in the continent and also boundaries on all of the energy generation bases. For instance, biomass source exists inadequate throughout the entire lands accessible and for the need of making enough foods. Also, the wind powers as well as hydro are inadequate via the dimension of proper areas. Using energy from fossils resource is restricted by the higher destined on carbon releases.

3) Extreme consumption of biomass is a similarity among the models. A circumstance of increasing biomass is beneficial to the continent. The significant benefit of the biomass is; the carbon discharged while burning was earlier removed from atmosphere while the harvest's growing period, which indicates this technology is climate friendly.

4) CCS is used widely among the entire models. The carbon capture and storage is significant since it permits the sustained consumption of fossils deprived of rushing global warming. While mixing with biomass, carbon capture and storage is able to detach carbon from atmosphere therefore benefits steady the climate via 'negative emissions' [172]. The mix is named BECCS (bio-energy with carbon capture and storage).

The variances of models outcomes show diverse modeling assumptions. The following three models results; MESSAGE, REMIND and TIAM-ECN presume RESs to contribute a significant part. The solar power is a leading energy source among mentioned paradigms. A cost of the solar power is estimated to remain shrinking to turn out to be progressively affordable. Furthermore, environments for PV power source are tremendous in the continent since the sunlight is not only strong, but also far more dependable than rest of the world. Using another method, model named IMAGE is positive on costs and storage readiness for Carbon Capture and Storage so that it discovers it optimum to mix coal with Carbon Capture and Storage at big level. Correspondingly, the technique named GCAM is positive on nuclear power potentials.

1.2.6 Demand and Necessity of MG to Africa

Standing at a market viewpoint, the power shortage across the continent and energy demand guarantees huge commercial prospects in favor of industrialists as well as investing corporates. Large tendencies comprising geographical changes, urban expansion, development of economy, as well as transformation of technologies are established to advance and urge power demands within Africa [173] [174]. According to estimation, the annual market for energy household consumption costs in Sub-Sahara Africa amongst the poorest section of the people is estimated at US$10 billion [133]. The demand is primarily strong in the rural areas and remote areas of the region because of the shortage of grid expansion and low affordability [175]. However, the solar home systems market in Sub-Saharan Africa has been booming recently. Only in the first half of 2017, 1.77 million products of Pico photovoltaic (PV) and Solar Home Systems (SHS) have been sold in Sub-Saharan Africa, with corresponding cash sales revenues of 40.67 million USD

[176][177].

The necessity to solve and end lack of electricity power in the region as well as to the incentive on cutting down on global warming and CO_2 emission is a key. Therefore, RESs and MGs are expected to contribute extensively to the anticipated green as well as environmental time ahead. All nations, especially to the Sub-Sahara Africa it is essential to fully utilize the potential energy of RESs as to guarantee the upcoming times power reliability. In an attempt to improve the access to electricity around remote areas and rural locations across the region, affordable MG solutions offer hopeful solutions to solve energy the power shortage in Africa.

1.3 Statement of the problem

A MG is a cluster of electricity sources& loads in one or more locations that may or may not be connected to traditional wider power systems. The most intriguing feature of a MG is its ability for local control allowing it to operate reliably as an island. The achievement of such distributed microgrid will depend heavily on the availability of renewable resources & the economics of the DERs.

Although there have been continuous improvements in the research and development regarding the energy management of microgrids, there still exist many limitations on the previous and current researches and developments. This thesis is motivated by these limitations (research problems) presented below:

- Less consideration of renewable uncertainties and load fluctuations in the research and development of energy management systems.
- Limited consideration of electricity price variations in the research and development of energy management systems.
- Inadequate consideration of energy storage options in the research and development of energy management systems.
- High computational burdens for solving energy management optimization problems
- Inefficient & ineffective utilization of energy storage systems for the whole optimization (scheduling) horizon.

1.4. Scope of the work

This thesis aims to optimally manage the power outputs of the dispatchable micro sources in microgrids considering the uncertainties in renewable generations and load demands, main grid electricity prices, and energy storage options.

1.5. Objectives

1.5.1 General objective

A Microgrid energy management system implementation using mixed- integer linear programming

1.5.2 Specific Objectives

The thesisSpecific objectives are summarized as follows:

- To study the concept of microgrids and the role of EMSs for optimal control of microgrids.
- To establish optimization models for optimal (economic) unit commitment, scheduling, and dispatching of energy resources in microgrids
- To implement EMS optimization problem solver
- To analyze and characterize the short-term (day-ahead) operation of microgrids from economic optimality (maximum profit and/or minimum cost) perspectives.

1.6 Significance of the Thesis

The successful completion and finding of this thesis have the following main contribution:

- Implementation of an optimal energy management system for a microgrid that can be operated either in the islanded or grid-connected mode of operation.
- Development of an optimization model for a microgrid containing renewable energy generations, conventional generations, and energy storage devices.
- Implementation of an energy management system optimization solver for a microgridcontaining renewable energy generations, conventional generations, and energy storage devices.

1.7 Methodology

To accomplish the overall work of this thesis will follow the following methods.The optimal unit commitment and resource scheduling strategy are formulated and implemented using mixed-integer linear programming approach. A microgrid network with a mix of renewable and conventional energy resources will be modeled to serve as a test platform for the microgrid energy management strategy to be developed in this study. Matlab software will be used throughout this work for the implementation of the microgrid optimization model.

The EMS relates the estimated power produced by the renewable generators and other conventional DGs with the estimated load demand & determines the unit commitment plan and dispatch scheduling of the dissimilar energy storage devices & conventional generators for 24 hours into the future, thereby minimizing the daily operating cost of the overall microgrid system.

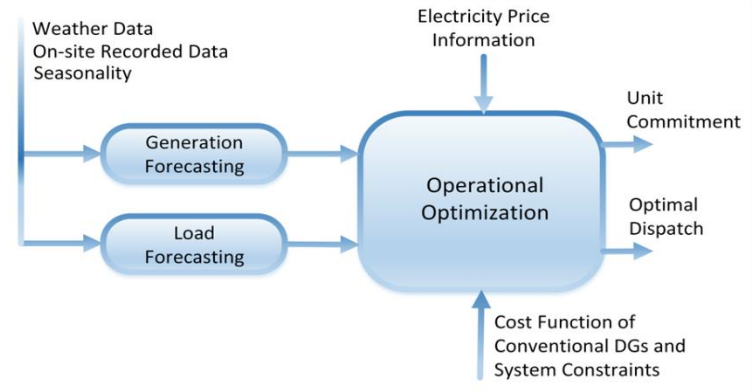

Figure 1.7General schematic of MG energy management system

An optimization tool will be developed which takes into account the results of one-day-ahead prediction of the renewable energy generation and load demand. Various network-specific constraints and next day energy buying and selling tariffs will be considered to set up the optimization problem. The overall goal of the optimization process is to schedule the energy resources in the system for the next 24 hours so that the minimum cost of operation is achieved without violating operational constraints. For simple of implementation & rapid computation, the optimization model will make use of a mixed-integer linear programming method to solve the optimization problem.

1.8 Organization of the Thesis

The thesis is organized include the following:

Chapter 2 presents a literature review of distributed generation, EMS for MGs, It also presents the related previous research and development works relevant to this thesis.

Chapter 3 provides the configuration and components of general microgrid architecture and the case study microgrid of this thesis. It gives the detail working mechanisms and models of the main components of the case study MG.

Chapter 4 presents the optimal energy management of microgrids, which is the main focus of this thesis. It presents the architecture (configuration) of the proposed energy management system (EMS), the different input variables for the proposed EMS optimization model, the EMS optimization objective function and constraints, the proposed EMS optimization solver, the EMS optimization solutions.

Chapter 6 summarizes the thesis and concludes. It also provides some suggestions for future works related to the thesis topic.

CHAPTER TWO

LITERATURE REVIEW

2.1 Related Previous Research Works

Study directed in [123] is expected to be an ideal EMS designed for a grid coupled photovoltaic cell hybrid technique through manageable loads with DSM apparatus. The goal of energy management systems is to reduce the cost of generating electricity, thereby affecting the thinking limits of battery capacity, solar production and power balance. The demand side management method was employed in opened loop technique for programing above 24-hour hybrid system energy movement. Demand-side management is centered on the time of use (TOU) platform that has a higher power expense at peaking load times and lower at off-peak hours. In this case, the method measured the purchase expenses of power from grids, the price amount of energy sold to the power grid, and bearing expenses of the hybrids technique. With the purpose of transmitting energy motion simultaneously, the variable interrupt is invalidated and the MPC is adopted. It is worthy to point out; range of the simulation is limited to system control. Therefore, installation expenses have not been taken into account under simulation. A 28.8 kWh batteries and 7kW photovoltaic were comprised in assessment of the hybrid system. Considering power demands and climate change amongst the season of wintertime plus season of summertime, also among week-days plus/weekends 4 paradigms have been assessed, week-days/weekends in summertime as well as wintertime. Without applying model predictive control during simulations of optimization controlling, prediction of the two load demands as well as the photovoltaic production has been presumed to become average rate for the wintertime or summertime. While employing the model predictive control, linear state space simulation has been established including distributing suiting technique for executing insecurity. The test time is 1 hour under mentioned case, including forecast time of 24 hours for optimized programming of 5 weekdays during wintertime. Under optimized controlling subject, hybrid technique operating method reached the highest utilization of solar power as well as batteries storage. In addition, electricity purchasers demanded small quantity of energy generated by the grid as for usage therefore managed to decrease regular service payment/month. The development of these changes suggests that daily energy expenses have fallen from 58% percent to 65% percent and net of gained by consumers is 1.23 to $1.83 daily. Under the practical condition of model predictive control, two cases have been assessed. As for incident of the progressive instabilities in photovoltaic production, incomes were raised by 27% competed with optimized controlling. While progressive instabilities of the load demands were observed, incomes rose by 31%. As a result, the researchers decided model predictive controlling delivered best controlling operation as per precision as well as heftiness, attaining better expense saving compared with optimized controlling technique.

In study [131] the researchers advanced an EMS prototype in support of an inaccessible renewable-based microgrid, which encompassed controlling of energy bases and supple scheduling of energy expenditure via sculpting convenient and uncontrollable masses. A deterministic administration consummate model was devised and thenceforth assimilated into a RH (Rolling Horizon) control regulator approach as to diminish the ambiguity appearing in both generation bulk capacity and power demand beside cogitating updatable predictions.The purpose of the EM is boosting the profitable efficient operation of the method. Demand side management has been employed by methods of loads shift to manageable load as to diminish the operational expenses. Additionally, drawbacks were pertained for not linking the load demand or else if the use began ahead of its initial origin bound after its most recent attach. Diesel intake of the diesel powered generators is demonstrated as mixed-integer linear program by way of altering the non-linear feature into line fragments. The researchers pondered an instance review through a solar panel energy production system, diesel powered generators, an ESS and collections of loads, among these five are manageable. The microgrid performance survived paralleled with and devoid of demand side management representing a prognostication prospect of 24 hours including period separations of 1 hour pro a programming horizon of 30 day periods. In favor of the setup along DMS the operational fee of diesel was abridged by 11.3% direct towards an improved manipulation of renewable energy sources, that directed to 27% reduced usage of non-renewable energy sources energy. Furthermore, the ecological influence was lowered by precluding the production of 1.62 tons of CO2 per annum, connected with diesel fuel which is not disbursed. Lastly, researchers purported as upcoming outlook task the weight of distinct sorts of energy foundations, the assembly to the utility grid and the integration of climate as well as demands ambiguity.

The authors in [132] established an energy management system applying UC alongside a RH approach for RE based microgrid. MILP which is centered on projecting simulations as to instigate forecast horizons for two days was the problem created. Microgrid pondered in this research comprised one diesel powered generator, one wind energy turbine, two solar PV systems, one ESSs and various load, comprising of water providing system that is. Diesel powered generators' oil usage has been symbolized thru none convex method, also guesstimated as piece-wise linear sections for mixed-integer linear program design. The energy management system has been devised to postulate optimizing online points pro apiece energy generating units, also indicators for purchasers founded on DSM apparatus. The instigators executed an economic analogy among the Rolling Horizon and the standard unit commitment (UC). The propose of the energy management system is to abate operating costs. As to do that, quite a lot of objectives had to be attained: curtail the consumption of diesel; provide effective power production points for the diesel powered generator, Energy Storage System inverter and Photovoltaic panel plant; turning on and turning off water pumps as for keeping high water storage container levels in intended parameters as well as directing signs toward end users with the purpose of endorsing performance vicissitudes ensuing the demand side management apparatus. Completely all the interactions of the microgrid were grounded on Guiding Control and Data Acquisition and numerous measurement apparatuses. Three developments were inspected in the study. The first one cogitated Photovoltaic panels, an energy storage system, a diesel powered generator and no demand side management apparatus. It was verified that the unit commitment–rolling horizon approach abridged the predictable overall costs by 18% during the summer and by 27% during the winter precisely to deplete startups as well as diesel powered generation expenses. Next, scenario 2nd; the wind power has been enhanced on the structure. Effects indicated drop of overall cost with regard to the first scenario for both unit commitment and unit commitment–rolling horizon approach. In the unit commitment–rolling horizon case, the cost decrease of the second scenario with respect to the first is 20%. Lastly, scenario 3 applied demand side management apparatus and attested extra cost declines by carrying out demand altering coefficients and heightening the water pumps activations by way of flexed loads throughout the times with power overage.

The mixed-integer linear program design to cope the power generation plus necessitate of a power grid-connected MG contained by responsive planning method has been propositioned [133]. Suggest of this energy management system is to increase the profitability of the system while promoting demand side management through a profile of plasticity requirements and penalties. In addition, a rolling deadline approach has been adopted to address impossibility associated with renewable energy generation and utilization. The optimization group must reveal the power range that should be generated as well as the generation method: economy dispatches as well as UC, optimization accommodation storing levels; loads transfer plan, as well as main grids energy buying/selling range after the function. Overall operating function cost takes into account manufacturing cost, storage cost and penalty cost. Subsequent advent reveals the same function of satisfying the interruption of each energy last pass. The revenue or revenue of the system approach is assumed to be electricity retailed to the service utility grid. The RH method can still be enhanced by several features of the commitment unit's commitment difficulty, like slope restrictions and small rise and fall time restrictions, also non-convex generation expenses and time-reliant start expenses that might make nonlinearity familiar in simulation. Researchers didn’t take into account permanent expenses assorted including, installation and investment ordination of power generator, in role of the invent design of the energy schmoose was not reflected, plus a short term assessments have been directed. Furthermore, the flexible costs linked to the power generation from solar energy as well as the wind energy were deemed zero. The rationale review was purposeful on a power grid-connected microgrid amid photovoltaic panel, micro wind turbines, energy storage as well as 30 distinct power users. The energy management system cogitated a control over 15 min horizon and a scheduling over 24 hours’ horizon period. The mixed-integer linear program archetypal was effected on the GAMS 24.1 and resolved operating on CPLEX 12 resulting 0 optimization. Researchers determined that lengthier estimation horizons directed to a substantial diminution concerning the utility of grid energy to mollify the demand beneath the postulation of precise demand expectations, while farther prospect material is established in the direction to explain the optimization setback. Consequently, the revenue is augmented. In contrast, when load-shifting is not deliberated, the return revenue of the system is reduced. Besides, handling power demand permitted improving the suppleness and self-sufficiency of the microgrid. As an upcoming future work, the authors projected the contemplation of dissimilar dynamics, similar to environmental influence, across the application of multipurpose optimum methodologies and amalgamation of reorganizing action penalizations to evade chief vicissitudes concerning the primary schedule following the incidence of an unforeseen event.

Study [134] advanced an Energy management system (EMS) for a standalone MG arranged by an energy storage system (ESS), diesel generator (DG), wind turbine (WT) and a sea water desalination system. The energy management system contained the distributed generators, that is; the wind-turbines and the diesel powered generators and the ESS and a hierarchy controlling has been employed, including synchronization controlling level as well as EMS level. The objective finction is to exploit utilization of the wind power generation as well as decreasing diesel generator usage, safeguarding a steady process. Coordinated controlling for microgrid has been functioned under the following operating stages, at which one or the other; the energy storage system or the DG functioned as a focal energy foundation to postulate quotation merits for the voltage and frequency. The energy management system built the demanded remote controlling, regulating, gesturing and measuring of mechanisms on SCADA model programming. Furthermore, the rolling horizon approaches has been employed on EMS for controlling intermittent as well as uncertainty of wind turbine energy generation and dominate the power variations. Thus, wind energy was estimated by genetic algorithms that is BP neural network centered speed of wind prediction technique. Effectiveness of recommended technique has been verified through examinations in real time digital simulation method. Assessments measured MG of 500 kWh energy storage systems, DG of 1250 kVA as well as 2MWwind turbine generators. The researchers settled; energy management system can distinguish the system management method online and effectively attain the switch joining operation modes conferring to SOC of the energy storage system as well as estimated speed of wind.

The constituent unit allegiance developed by [135], which is claimed to be developed by the generic mixed integer linear program (MILP), reduces the operating costs of residential MGs that are coupled with the main grid. PV, thermals solar panel, DGs, like controllable household appliances, cogeneration units, thermal and energy storage devices, and electric vehicles constitute a carefully inspected residential MG. The optimization problems have been developed to meet the supplying plus demands of electricity as well as heat load.

2.2 Comparative Summary

The main idea for literature reviewing is to have an understanding the notions of distributed generation, microgrids, and energy optimization, with particular attention to EMS for MGs. Hence, the most important focus of this literature review is the organization of EMS and optimization approaches towards MGs.

As shown above literatures most of researches focused on either in unit commitment or optimal dispatching model to minimize the cost and they have not considered renewable uncertainty and load fluctuation. But, in this thesis both unit commitment and optimal dispatching were used and also considers the fluctuations in renewable energy and load demand in the microgrid and using suitable day-ahead forecasts (typical generation profiles at the location selected for the study) to overcome these fluctuations in this thesis work.Mixed integer linear programing algorithm was used to manage the microgrid.

The simulation outcomes show the success and possible advantages of the applied EMS strategy:

- Minimize power generation fuel costs and grid energy purchase costs.
- Maximize energy sales profit.
- Maximize the economic use of energy storage systems.
- Increase the utilization of renewable energy in the microgrid.

CHAPTER THREE

Configuration and Components of Microgrids

The microgrid is a small-scale power system which is a group of interconnected loads and distributed energy resources (DERs) with defined electrical boundaries forming a local electric power system at distribution voltage levels, that acts as a single controllable entity and can operate in either grid-connected or island mode of operation. It has a black start capability. The DER includes distributed generator (DG) (photovoltaic solar, wind turbines, internal combustion generators, fuel cells, microturbines, etc.) and distributed energy storage (DS) (flywheels, superconductor inductors, and capacitors, batteries, etc.). MG could be divided into AC/DC microgrid. When the two groups occur coupled, it is said hybrids AC-DC MGs. The focus of this thesis is the AC MG which operates in either grid-connected or island mode.

The MG DGs can be classified into two main groups: (i) conventional rotating machine-based DG (RM-DG) (e.g., internal combustion generators, induction generators are driven by a fixed-speed wind turbine), and (ii) power electronic converter-interfaced DG (PEC-DG) (e.g. photovoltaic solar, fuel cells, permanent magnet synchronous generators driven by variable-speed wind turbines, microturbines, etc.). The DSS can be charged with the excess power from the renewables and/or cheaper power from the main utility grid and discharge to cover the power shortage and/or for economic system operation. Hence, they assist to improve the reliability of the microgrid system and making it efficient and economical as well. Moreover, energy storage devices are known for their fast response. Thus, they also suppress transient and dynamic instabilities and contribute to control microgrid system voltage and frequency by providing the desired power balance reserve ranging for a short time.

A microgrid can be connected to the upstream distribution network at the point of common coupling (PCC) through a substation transformer. It can operate in two modes: either in grid-connected or island mode. In the grid-connected mode, the PCC switch is turned on and the microgrid is coupled with the main utility grid. In this case, the microgrid participates in the energy exchange or trading with the main utility grid. When the upstream distribution network gets disturbance or faulted, the PCC static switch can be opened to separate the MG form the main utility grid. Hence, the MG can persist to operate in the so-called islanded mode of operation.

The typical AC MG configuration has been illustrated in Fig. 3-1 that contains renewable energy sources, energy storage system, load as well as supplementary units which are entirely coupled on general AC bus together with a microgrid central controller (MGCC) as well as static-transfer-switch (STS). The supplementary unit is illustrated as a microturbine here nonetheless; the supplementary unit can either be a diesel generator, fuel cell (FC), or different storage unit. The photovoltaic as well as ESS units are coupled via double-step DC/DC and DC/AC power electronics converter while the microturbine and the wind turbine units are coupled via double-step AC/DC and DC/AC power electronics converter. The AC output voltage from each DG via its converter is combined also coupled in general AC bus to deliver power to the load and/or to the main utility grid. The output voltage and current of each DG and DS are operated separately. Nonetheless, communications among static transfer switch and various DG and DS unit is yet needed to understand the condition of the static transfer switch and decide the relevant control action in real-time for the dispatchable DG and DS units. With the purpose of disconnect/reconnect the MG from/to the main grid perfectly, the static transfer switch is employed at the PCC that can be monitored and controlled by the MGCC. Loads are coupled to the microgrid side of the static transfer switch to guarantee they are constantly getting power whether the microgrid is functioning in islanded mode or grid-connected mode, i.e. despite the STS condition [129].

While the grid coupled operating method, the renewable energy source’s units operate as a current source and send energy straight to the AC bus. The main grid is referring to the AC bus voltages and frequencies, and the renewable energy source unit manages the energy course. ESS is linked with multi-maneuvering converters. This could be able to charge/discharge according to power production circumstances, loads as well as the SOC status. Though, while the islanded method; renewable energy source operates as a current source providing straight the load and the storage units operate as voltages sources managing the AC bus voltages through charge/discharge operation. The storage unit’s DC/AC converters control the magnitudes as well as frequencies of AC bus voltages. Renewable Energy Source unit function on Maximum Power Point Tracking (MPPT) while grid coupled operation method to extract the maximum possible renewable energy available. The same is applicable in the islanded mode of operation assuming produced energy could either be utilized by the loads or utilized to charging the DS units [131].

In an islanded mode, the DS energy storage system (ESS) is employed as making grid element controlling AC bus, whereas renewable energy source is utilized as supplying grid element adding powers to AC bus [132].

Though the AC MGs are very prominent as researches studies as well as installations over DC MGs, DC MGs have begun gaining further attention also a concern for DC MGs improved efficacy, natured/straight coupling of RESs as well as several extra advantages. Moreover, several problems that have encountered on AC MGs, such as reactive energy flows, frequency control, and energy qualities don't appear on DC MGs. That is makes the associated primary-controlling remarkably lesser complicated than of counterpart AC type [130.

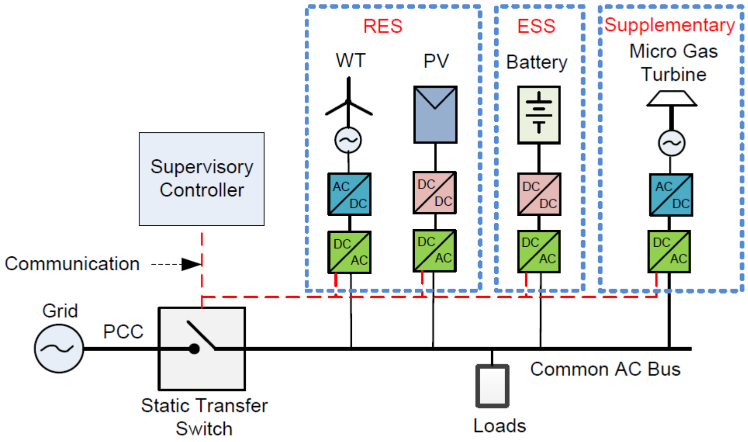

Figure3.1General AC microgrid structure

The following subsections will present the configuration and the components of the case study microgrid in this thesis. The detailed working mechanisms and modeling aspects of the components will be covered.

3.1 Microgrid Configuration

The case study AC microgrid consists of wind and PV based renewable energy sources (RESs), energy storage system (ESS), diesel generation system, and distributed loads. The microgrid consists of typical distributed generation components and industrial load. It is assumed that the microgrid network supplies the energy demands of an industrial facility. Henceforth, this typical microgrid is said to be the "*case study microgrid*."

3.2 Microgrid Components

3.2.1 Wind Turbines

The wind is a clean and sustainable source of electrical energy. Wind resource is an abundantly available renewable energy resource and with steadily lowering the cost of electrical energy production. Advances in power electronics technology and favorable policies that promote clean energy development have enabled wind energy to extend its contribution to electric power generation systems in the last decades. Wind energy production technologies are nowadays becoming increasingly important in the operation of electric power systems and represent a significant share of the growing green energy market across the world [28] [131]. Global wind power installed capacity has increased from 120,696MW in 2008 to 486,790MW in 2016. It is expected to exceed 1,260,000MW by the end of 2020 [142].

Wind turbines (WTs) are used to convert kinetic energy carried by wind into mechanical form through aerodynamic rotor blades, and againinto electrical energy through a generator. The mass of electrical power that can be achieved from WTs depends on the surrounding air density, wind speed, turbine blade area, & wind energy conversion efficiency. The power generated by a horizontal axis wind turbine is given by:-

$$P_G = \frac{1}{2} C_p \rho A V^3 \quad (3.1)$$

The generated power is express by P_G, $\rho$is the density of air,$A$is turbine blade area,Vexpress wind speed$C_p$is wind energy charge over efficiency which is known as the power coefficient. The power coefficient can be defined as the actual turbine power in proportion with the theoretical wind power & is similar to aerodynamic virtue of the turbine blades[133]. It is a function of the turbine blade tip speed ratio λ and the turbine blade pitch angle β. The tip speed ratio λ is given by:

$$\lambda = \frac{\omega}{V} R \qquad (3.2)$$

Where R is the radius of the turbine rotor and ω is the angular speed of the rotor; the power coefficient C_p and hence the output power of the turbine is maximized at some specific value of λ. The maximum power point tracking (MPPT) function is required to regulate the rotational speed of the turbine rotor to achieve maximum power generation.

A wide range of wind turbine generator technologies is in operation today. Wind turbines can be broadly categorized as fixed-speed and variable-speed turbines.

A. Fixed Speed Wind turbines

Fixed-speed wind turbines operate at nearly constant rotor speed controlled by grid frequency regardless of the variations in wind speed. These wind turbine technologies typically employ squirrel-cage induction generators directly connected to the main grid via a transformer, as shown in Fig. 3.2. If the wind speed increases above the rated value, the system must be disconnected from the grid to avoid mechanical damage to its structures. Despite the relative simplicity, low cost, and robustness of fixed-speed wind turbines, the power conversion efficiency is degraded at operating speeds different from a given value. The capacitor bank is required to provide reactive power compensation [134, 135].

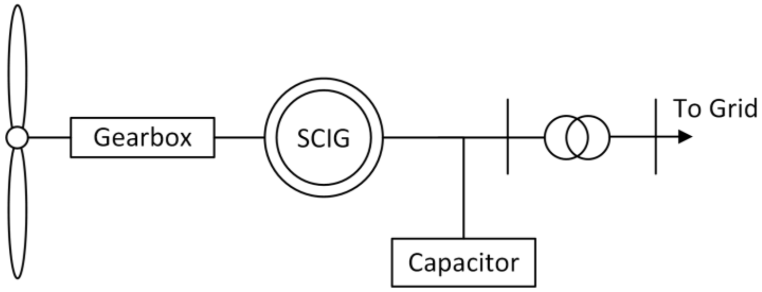

Figure3.2fixed speed wind turbine

A. Variable-Speed Wind Turbines

Variable-speed wind turbine systems are designed to operate at a wide range of rotor speeds. Their ability to operate at various speeds and control flexibility allows them to extract more energy from wind compared to fixed-speed wind turbines [134]. Two dominant variable-speed wind turbine technologies, namely the doubly-fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG) based wind systems are introduced below.

- ***DFIG***

In wind turbines based on DFIG, the stator winding of the generator is directly connected to the grid whereas the rotor winding is connected to the grid via a back to back converter consisting of a rotor side converter, a DC link capacitor bank, and a grid-side converter. The architecture is shown in Fig. 3.3. The rating of the converters is typically about 30% of the rated power of the generator. This configuration makes it possible to control a large amount of power flowing through the stator by injecting a small amount of power into the rotor circuit. The converter on the rotor side is usually configured with a controller that regulates the electromechanical torque and the desired excitation of the machine. The converter on the grid side controls the power factor and maintains the DC link voltage at a constant value [136].

When the generator operates above synchronous speed, both the rotor and stator supply power to the grid. On the other hand, when the generator runs slower than synchronous speed, the rotor absorbs a fraction of the power produced by the stator.

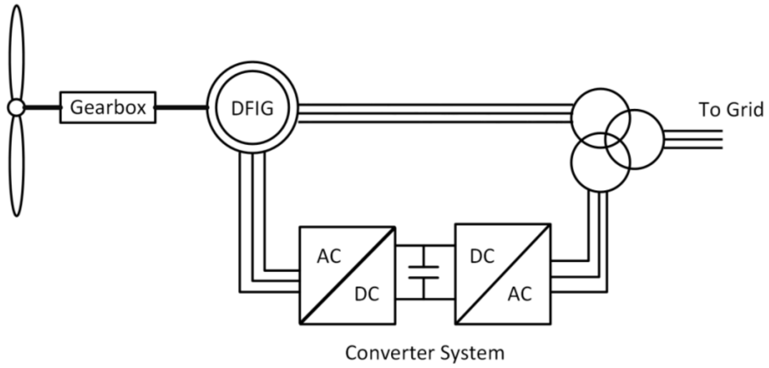

Figure 3.3Doubly-fed induction generator

- ***PMSG***

Permanent magnet synchronous generators have recently become increasingly common in the wind power industry. The presence of gearbox in wind turbine systems causes problems as the gearbox is prone to frequent faults and requires regular maintenance. The reliability of variable speed wind turbines can be greatly improved by making use of direct-drive permanent magnet synchronous generators (PMSG) [137]. As shown in Fig. 3.4, a PMSG based wind turbine system mainly consists of a rotor, a synchronous generator and a back to back power electronic converter. The rotor of the synchronous generator is made from permanent magnet materials and hence avoids the need for a supply of magnetizing current from the stator. This improves the machine’s capability to operate at a higher power factor and enhances efficiency. The main disadvantage of PMDD wind turbine technology is the relatively high cost of permanent magnet material.

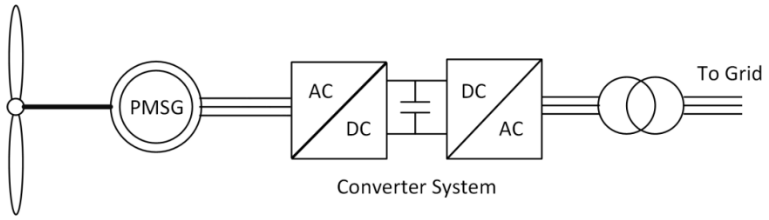

Figure3.4PMSG based wind turbine system

The wind turbine considered in the case study microgrid system is a 1.5MW rated wind turbine selected from the Homer component library.

3.2.2 PV Solar Systems

Solar energy is the most abundant and one of the most dominant renewable energy resources. It is a neat source of energy with no noise pollution. Photovoltaic (PV) systems directly convert the energy in solar irradiation into electrical energy utilizing solar cells made from semiconductor materials. Solar radiation landing on the surface of the solar cells causes the flow of electric current proportional to the amount of the radiation and emergence of potential difference in the material, a phenomenon known as the photovoltaic effect. Solar cells are usually combined to form modules during manufacture. Solar modules typically contain 36 to 72 cells. Modules are grouped into arrays in various patterns to achieve the desired voltage and current requirements.

PV power generation has gained increasing usage in various applications such as battery charging, pump station power supply, satellite stations, and supplying power to remote homes. Its share of power generation in electric power systems is increasing. The main advantages of PV installations are that they are pollution-free and require very little maintenance. The installation costs are however relatively expensive due to the high cost of the semiconductor materials and requirement of interfacing power electronic converter systems.

Solar cells exhibit non-linear I-V characteristics. Radiation strength, temperature, and shading affect the performance of PV systems. The most important factor which affects the characteristics of PV systems is solar irradiation. Fig. 3.5 shows the outcome of variation in solar irradiation on the current and voltage outputs of a solar cell. Fig. 3.6 shows the current and voltage values in the characteristic curve at which the maximum possible power is extracted from the cell for solar irradiation. PV systems are usually equipped with power electronic maximum power point tracking (MPPT) devices which continuously adjust the output voltage and current to ensure the transfer of maximum power.

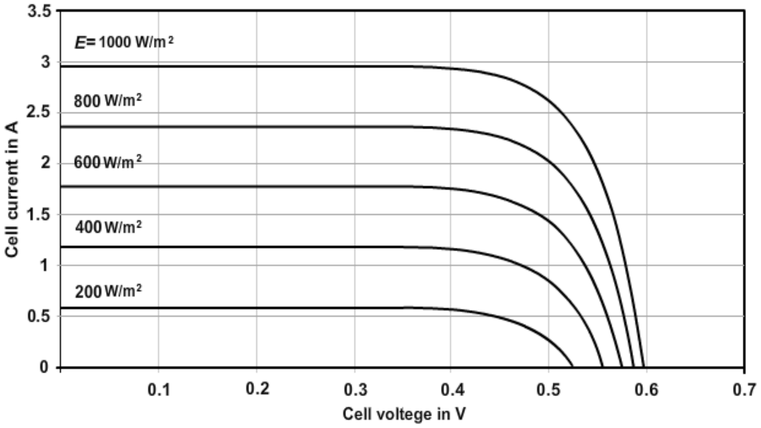

Figure 3.5I-V characteristics of a solar cell [138]

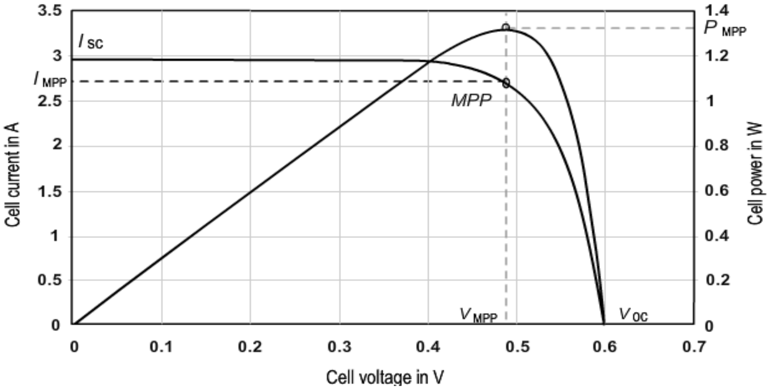

Figure 3.6MPP of a solar cell [138]

The equivalent circuit of a PV cell representing its electrical characteristics is shown in Fig. 3.7it is represented by a constant current source in parallel with a diode and a resistor. The shunt and series resistors are used to represent the losses in the PV cell while the diode represents the characteristics of the PN junction created between the positively and negatively doped regions of the cell.

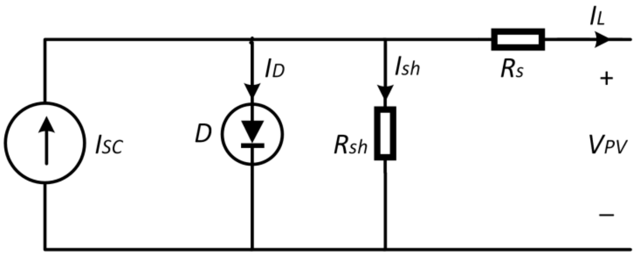

Figure3.7Equivalent circuit diagram of a PV cell

The output current I_L is given by:

$I_L=I_{SC}-I_d-I_{sh}$ (3.3)

The current through the diode I_d and the shunt resistance current I_{sh} can be expressed by equation 3.4 & equation 3.5 respectively.

$I_d=I_o[e^{\frac{V_{PV}-R_sI_L}{V_T}}-1]$ (3.4)

$I_{sh}=\frac{V_{PV}-R_sI_L}{R_{sh}}$ (3.5)

Where,

I_o: Current created by photovoltaic effect;

I_o: Reverse saturation current;

V_{PV}: Cell output voltage;

R_s: Series resistance representing material resistance;

I_L: Output current;

V_T: A thermal voltage which is a function of temperature;

R_{sh}: Shunt resistance representing current that doesn't reach the external circuit.

The PV system considered in the case study microgrid system for this study is rated 500kWat Standard Test Conditions (STC).

3.2.3 Diesel Generators

Diesel generators convert fuel energy into mechanical energy utilizing an internal combustion engine and then into electric energy employing an electric generator. Thus a diesel generator belongs to the internal combustion engines. Its name is linked to the type of fuel it uses to produce electricity. A diesel generator (also known as diesel Genset) is the combination of a diesel engine with an electric generator (often an alternator) to generate electrical energy. Diesel generators generally have high operating costs and generate electricity on demand when compared with renewable DERs. The rating of the diesel generator considered in this study is 400kW.

3.2.4 Energy Storage Systems

Energy storage systems (ESS) are used to store energy during periods where energy production exceeds the demand and deliver energy when demand exceeds production. They are becoming increasingly important in integrated power systems with the growing penetration of renewable energy. Energy storage systems provide many advantages including reduction of energy losses, improving the reliability of supply, and enhancing operational economics of power systems.

A wide range of energy storage technologies is available today. Power intensive energy storage systems are used in applications that are generally demanding in terms of step response performances and with frequent transitions between charge and discharge phases. These kinds of storage devices are used to deal with transient situations characterized by short durations but can cause sudden instability problems. Batteries, flywheel systems, and supercapacitors are suited for this application due to the rapid response characteristics they provide. The use of supercapacitors as auxiliary supply in power systems can complement the slower response of main sources and energy storage systems through their very fast power response and high specific power. The main advantage of supercapacitors is that energy can be taken from the device at a very high rate which a battery of the same size cannot supply in the same period. A supercapacitor can also be charged at a high charging rate in a short duration [143].

Energy storage devices with high energy density are used for energy-intensive applications which are not very demanding in terms of response performances but with frequent and long charge and discharge cycles at variable rates. They are used to deal with daily variations of renewable energy resources and load demand. Many kinds of different batteries are available in the industry for this purpose. The most commonly used type of batteries is electrochemical batteries such as lead-acid batteries, lithium-ion batteries, and vanadium redox batteries (VRB) which convert electrical energy into chemical energy and vice versa. An electrochemical battery contains varies electrolytic cells connected in series & parallel. Each cell is made up of a pair of half cells in series connected by a conductive electrolyte material which contains positively charged ions (cations) and negatively charged ions (anions). The anions move to the half-cell containing the positive electrode called the cathode. The cations move to the other half cell containing the negative electrode called the anode. Vanadium redox batteries make use of sulphuric acid electrolyte solution in two tanks containing vanadium species in different oxidation states: V^{4+}/V^{5+} redox couple (positive) and V^{2+}/V^{3+} redox couple (negative). The stack consists of several cells where the half-cells are separated by a proton exchange membrane (PEM) [144]. The main electrochemical reactions occur at the cells' inert electrode. The electrolytes are circulated from the external tanks to the stacks through pumps. The general schematic of a VRB is shown in Fig. 3.8.

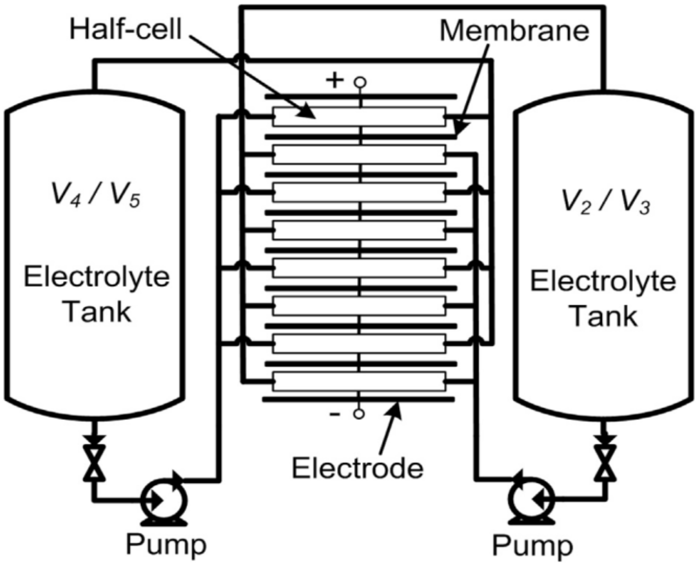

Figure 3.8General scheme of a VRB [144]

During discharging, electrons are removed from the negative electrolyte (anolyte) and moved to the positive electrolyte (catholyte) through the external circuit. During charging, the flow of electrons is in the reverse direction; reduction reaction occurs in the anolyte and oxidation reaction occurs in the catholyte [145].The case study microgrid system is considered to be configured with ESS devices with a storage capacity of 200kW*4h. Thus, an energy storage system with a storage capacity of 800kWh and a charge/discharge rate of 200kW is employed for the steady-state energy management system model in this thesis**.**

CHAPTER FOUR

Optimal Energy Management for Microgrids

4.1 Introduction

It has been pointed out that, now the previous insufficient periods. Foremost financial&ecological strategy modifications need caused in amplified usage of circulated bearing systems. That haveconveyed main topological variations towards the rechargeable power plants & released active universe aimed by the enlargement a MGs. The efficient operation of distributed energy resources and microgrids is realized through energy usage optimization strategies, taking into account generation and demand uncertainties, cost of electricity production, and other operational requirements.

The purpose of optimal scheduling of generation units of microgrids is to determine the output power of dispatchable power sources and the charging/discharging power of energy storage systems through affecting overall impartial a minimizing the overall operating prices whereas maintaining essential constraints intact. The objective function for unit commitment and optimal dispatch problem of a grid-connected microgrid could be defined as:

$$C= \sum_{t=1}^{k}\left\{T^{grid}(t)*P^{grid}(t)+\sum_{j=1}^{n}\left(S^{j}(t)*f^{j}(P^{j}(t))+SC^{j}(t)\right)\right\} \qquad (4.1)$$

Where

C	Operational cost of microgrid
t	Time interval (time step)
P^{Grid}	Power supplied by the utility grid to the microgrid
T^{Grid}	Utility electricity tariff
$P^{j}(t)$	The output power of j^{th}conventional unit at interval t
$f^{j}(P^{j}(t))$	The cost function of the j^{th}conventional unit
$SC^{j}(t)$	Starting cost of j^{th}conventional unit at interval$t$
$S^{j}(t)$	Situation (commitment ~ 0 or 1) of thej^{th}conventional unit at intervalt
n	Number of dispatchable generation units
k	Number of time intervals in the designated optimization horizon.

Equation (4.1) shows the cost minimization objective function in a microgrid regards the prices energy bought since through effectiveness grid along with a cost of manufacturing get-up- and-go with a microgrid using unadventurous origination.

The basic technical constraints that must be satisfied during every time interval are:

$$P_{min}^{Grid} \leq P^{Grid}(t) \leq P_{max}^{Grid} \qquad (4.2)$$

$$P_{min}^{j} \leq P^{j}(t) \leq P_{max}^{j} \qquad (4.3)$$

$$-P_{max}^{ES} \leq P^{ES}(t) \leq P_{max}^{ES} \qquad (4.4)$$

$$SOC^{min} \leq SOC(t) \leq SOC^{max} (4.5)$$

Where

P_{min}^{j}	Minimum generating limit of the j^{th} conventional unit
P_{max}^{j}	Maximum generating limit of the j^{th} conventional unit
P_{min}^{Grid}	Minimum allowed grid power
P_{max}^{Grid}	Maximum allowed grid power
$P^{ES}(t)$	Charging or discharging power of energy storage at interval t
P_{max}^{ES}	Maximum charging/discharging power of energy storage
SOC^{min}	Minimum state of charge of energy storage
SOC^{max}	Maximum state of charge of energy storage.

Equation (4.2) defines the minimum and maximum power exchange limits with the main grid. Equation (4.3) express the constraint associated to minimum & maximum generation limits of conventional generation units in the microgrid system.Battery charging/discharging rate limits & allowable battery state of charge range are handled by constraint equations (4.4) and (4.5) respectively. In addition to the constraints defined above, the total power balance equation in the microgrid should be satisfied in each interval. The power balance equation can be described as:

$$\sum_{j=1}^{n} P^{j}(t)=P^{load}(t)-\sum_{i=1}^{m} P_{Ren}^{i}(t) -P^{ES}(t)-P^{grid}(t) \qquad (4.6)$$

Where P^{load} means total load demand in the microgrid and $P_{Ren}^{i}(t)$ represents power supplied by the i^{th} uncontrollable source in the microgrid at interval t.

The target of the energy management system is to assure day-ahead decisions for the financial operation of the microgrid. The suggested optimization model considers the intermittent nature of renewable generation, fluctuations in load demand, fuel costs for power generation, technical constraints and capacity constraints, time-varying grid tariffs, and the likelihood of energy trading to and from the main grid.

Figure 4.1 shows a general schematic of an EMS, with EMS, commands for optimal charge/discharge power of the energy storage system, DG power output, main grids input/output power, and demand control. Decisions are based primarily on REpower generation and load demand forecasts, power generation diesel costs, and electricity prices in the main grid. The decisions will generate a time range of one day based on one-hour intervals in this thesis.

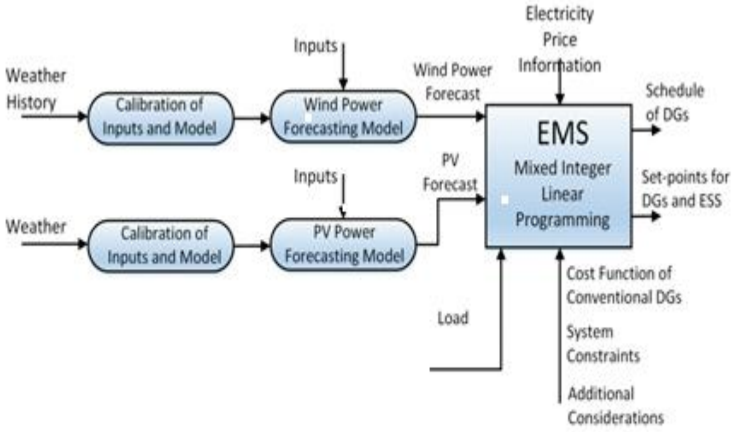

Figure 4.1Schematic of the proposed EMS

In the following sections, I present an optimal energy management system proposed as part of this thesis work. The suggestedoptimum unit commitment and dispatch scheme take the results of one-day-ahead prediction of RE production as well as load demand into account to optimally schedule the dispatchable units. The renewable energy generation forecasts are substituted by a typical generation profile from a wind turbine and a PV system obtained from Homer software at the geographical location selected for this study. A typical hourly load profile of an industrial facility is considered as the load profile for modeling in the study. Various constraints and next day energy buying and selling tariffs are considered to setup the optimization problem. The overall target for the optimization process is to optimally schedule the energy resources in the system for the next 24 hours so that the minimum cost of operation is succeeded without violating operational constraints. A straightforwardness of application & reckless calculation, through optimization model makes use of mixed-integer linear programming (MILP) method to solve the unit commitment and optimal scheduling problem. The outputs of the optimization model are:

- The guarantee & dispatch plan of conventional power generation units for 24 hours.
- Plan of hourly influence operation among a microgrid & the foremost grid aimed at 24 hours.
- Power charging convicting & sustaining line-up 24 hours.

A general microgrid system consisting of the type distributed generation resourcesthat were described in previous sections are used as the case study. The policy are intended at accomplishing optimum scheduling of distributed energy resources although assembly numerous working restrictions scheduled a foundation of projected yield control after renewable get-up-and-go properties; i.e. wind turbine and PV system estimated load demand profile, cost of electricity production from conventional energy generation system, i.e. diesel generator unit with a maximum generation capacity of 400kW, an energy storage system with a storage capacity of 800 kWh, hourly utility electricity tariff and other basic information.

4.2 Power Output Modelling of Components

4.2.1 Wind Turbine

A wind turbine is recycled to transform kinetic energy accepted through the wind addicted to powered method & formerly interested in electrical energy. The total of electrical power. The that tin attitude attained after current of air turbines be contingent happening adjacent mid-flight density, current of air rapidity, turbine blade expanse, & wind get-up-and-go adaptation competence.

$$\mathrm{P_G} = \frac{1}{2}\mathrm{C_p}\rho \mathrm{A}\mathrm{V}^3 \qquad (4.7)$$

A created power is represented by $\mathrm{P_G}$, ρ are the concentration a air, A are turbine blade area, V signifies wind speed &$\mathrm{C_p}$ are wind energy adaptation effectiveness which can be designated as a turbine power in amount within wind power & are connected to aerodynamic features of a turbine blades. Wind turbines within a rated power producing capacity of 1.5MW are measured. The characteristic day-to-day power group distinguishing of a 1.5MW wind turbine at Adama wind farm's position is used for this work. Homer software is used to estimate the hourly generation profile of the 1.5MW wind turbine using at the wind farm location for one month on an hourly basis. The hourly wind power generation profile of a typical day for the simulation is obtained by averaging the values of corresponding hours for one month. Homer software uses weather condition data obtained from NASA to calculate expected electrical power generation from the wind turbine at the selected location.

4.2.2 PV System

Photovoltaic classifications electricity produce by changing sunlight interested in electrical energy. PV schemes don't produce air-pollution or whichever thoughtful of discharges although operational. Revolving masses is essential to produce electricity using PV collections, later negligible conservation are essential. The yield power $\mathrm{P_G}$ of a PV connection are assumed by [146]:

$$\mathrm{P_G} = \begin{cases} \mathrm{P_{STC}} \frac{(\mathrm{G})^2}{\mathrm{G_{STC}}\ \mathrm{R_C}}, & 0 < G < \mathrm{R_C} \\ \mathrm{P_{STC}} \frac{\mathrm{G}}{\mathrm{G_{STC}}\ \mathrm{R_C}}, & \mathrm{G} > \mathrm{R_C} \end{cases} \tag{4.8}$$

$$\mathrm{P_G} = \begin{cases} \mathrm{P_{STC}} \frac{(\mathrm{G})^2}{\mathrm{G_{STC}}\ \mathrm{R_C}}, & 0 < G < \mathrm{R_C} \\ \mathrm{P_{STC}} \frac{\mathrm{G}}{\mathrm{G_{STC}}\ \mathrm{R_C}}, & \mathrm{G} > \mathrm{R_C} \end{cases} \tag{4.8}$$

Where $\mathrm{P_{STC}}$ symbolizes a thoroughgoing generation capability of a organization at ordinary assessment situations (STC), G are expected solar energy, $\mathrm{R_C}$ are the confident radiation argument set as 150W/m^2, and $\mathrm{G_{STC}}$ are situation irradiance which are 1000W/m^2, a peak generation capability of a PV scheme deliberated in this education is 500kW. In this study, $Homer\ software$ is recycled to approximation the characteristic generation outline of a 500kW PV arrangement at the designated location (Adama) in a comparable method to that of wind power generation estimation.

4.2.3 Diesel Generator

Diesel generators convert fuel energy into mechanical energy employing an internal combustion engine and then into electric energy employing an electric generator. Thus a diesel generator belongs to the internal combustion engines. Its name is linked to the type of fuel it uses to produce electricity. A diesel generator (also known as diesel Genset) is the combination of a diesel engine with an electric generator (often an alternator) to generate electrical energy. Diesel generators generally have high operating costs and generate electricity on demand when compared with renewable DERs. The rating of the diesel generator considered in this study is 400kW. Based on fuel consumption and power generation profile of a typical diesel generator as provided in Homer software and assuming the cost of fuel to be 0.4USD/L, the cost function of the 400kW rated diesel generator can be approximated as follows:

$$C_{DG}(\Delta t) = 0.106 * P^{DG}(\Delta t) + 3.6 \qquad (4.9)$$

Where$C_{DG}(\Delta t)$ and $P^{DG}(\Delta t)$ separately attitude aimed the energy price in USD & the control manufactured through the diesel generator now kilowatts at the time intermissionΔt.

$$0 \leq P^{DG}(t) \leq 400 \qquad (4.10)$$

4.2.4 Energy Storage System

In an environment with inconsistent renewable energy generation, varying load, and electricity price, vigor storing systems can piece an significant part happening optimizing the operation of microgrids. Trendy this study, we have modeled a battery-operated energy storing scheme by a size of 800kWh, & accusing & settling control rating of 200kW. SOC of the battery on the end of the t^{th} intermission (twitch of the $(t + 1)^{th}$) intermission remains given by:

$$SOC(t + 1) = SOC(t) - \frac{\eta_t P^{ES}(t)}{W^{ES}} \qquad (4.11)$$

Where η_t remains the indicting efficiency, $P^{ES}(t)$is indicting control on the t^{th} intermission &W^{ES} remains the vigor storing volume of the battery. Toward evade deep release of the battery, the optimization scheme necessity content the next constrictions during any interval of the day.

$$-200 \leq P^{ES}(t) \leq 200 \qquad (4.12)$$

$$10 \leq \mathrm{SOC(t)} \leq 100 \qquad (4.13)$$

4.2.5 Main Utility Grid

Excess control shaped in the microgrid determination stand both traded toward the key net afore stowed cutting-edge the battery-operated built proceeding the choice of the EMS. Likewise, the energy storing determination discharge, & the usefulness grid-iron determination inject power-driven control hooked on the microgrid once around stays additional request than the control formed trendy the microgrid. The general group & request control equilibrium calculation duty be contented throughout all intermissions of process.

$$\mathrm{P^{grid}\,(t) = P^{load}\,(t) - P^{PV}\,(t) - P^{wind}\,(t) - P^{ES}\,(t) - P^{DG}\,(t)} \qquad (4.14)$$

4.3 EMS Optimization Problem Formulation

This work applies mixed $-$ integer rectilinear program strategy to begin a component guarantee & optimal transmitting prototypical aimed at microgrids within mixed properties & an energy loading organization. Assumed trajectories f, lb, &ub, matrices A, &Aeq, & equivalent directions b&beq, & a established of catalogues *intcon*, MILP inventions a vector x that diminishes the impartial purpose $\mathrm{f^T x}$.

$$\text{Minimize } f^T x \text{ subject to } \begin{cases} x\ (intcon)\ is\ \ integers \\ A \cdot x \leq b \\ Aeq \cdot x \leq beq \\ lb \leq x \leq ub \end{cases} \qquad (4.15)$$

A policy stay aimed at achieving optimal scheduling of distributed energy resources but assembly many active limits proceeding the sources of projected yield control after renewable vigor resources, likely cargo request details, price of power manufacture after conventional vigor group systems, current tariff, & additional needed information. The crops of the microgrid piece promise & optimal dispatching typical are:

- The status (commitment) and communication calendar of the diesel generator unit, which stands the first conformist control group part hip the event training microgrid structure

- Calendar of hourly control deal amid the microgrid & the chief net for 24 hours

- Vigor loading accusing & clearing schedule for 24 hours.

There are important constraints that need to be fulfilled. The optimization process is conducted subject to the constraints:

- Overall supply and demand balance equation,
- Power generating capacity limits of a diesel generator unit,
- Accusing &satisfying amount restrictions of a energy storage component,&
- State of Charge (SOC) limits of energy storage.

The EMS equates the predictable power fashioned through a renewable generators & within the predictable weight request & regulates a unit commitment and optimal scheduling of the diesel generator & get-up-and-go loading device 24 hours addicted to the forthcoming, which decreases the operational price of the total microgrid. Consequently, the impartial are to attain the lowermost price of group & decrease the price of energy obtained on or subsequently the utility. Scientifically, equations (4.1) through (4.6) can be modified to describe the objective function and constraints relevant to the case study microgrid as:

Minimize

$$C = \sum_{t=1}^{k} \{ T^{grid}(t) * P^{grid}(t) + (S(t) * f(P^{DG}(t)) + SC^{DG}(t)) \} \qquad (4.16)$$

Subject to

$$0 \leq P^{DG}(t) \leq 400 \qquad (4.17)$$

$$-200 \leq P^{ES}(t) \leq 200 \qquad (4.18)$$

$$10 \leq SOC(t) \leq 100 \qquad (4.19)$$

$$P^{DG}(t) = P^{load}(t) - P^{PV}(t) - P^{wind}(t) - P^{ES}(t) - P^{grid}(t) \qquad (4.20)$$

Where

C	Day forward working price a microgrid
f	Operational price purpose of diesel generator
S	Status (commitment) of diesel generator
P^{DG}	The output power of diesel generator
P^{Wnd}	The yield control ofthe wind turbine
P^{PV}	The yield power of the PV scheme
$SC^{DG}(t)$	Preliminary price of a diesel generator component by intreval t
k	Number of time intervals, which is 24 hours in this study

Two integer variables are used. One integer variable are recycled to designate a status (commitment) of a diesel generator component at each interval i (1 if the diesel generator unit is running and 0 otherwise). The second integer variable is used to indicate whether the diesel generator unit has changed state from OFF to ON at a particular time interval.

CHAPTER FIVE

RESULT AND DISCUSSIONS

Twenty-four hours ahead of unit commitment and optimal dispatch scheduling are measured in this thesis work. Expected time.0.ly normal weight request & a power generation expected from the 1.5MW wind turbine and 500kWp PV system is publicized in Figure. 5.1 The intermission are one hour &, consequently, nearby is 24 rests in a day. Once are imitation surprises, it is assumed for this simulation that the state of charge of the energy storage system is 20 percent. The hourly price of grid electricity assumed in this work is shown in Fig. 5.2

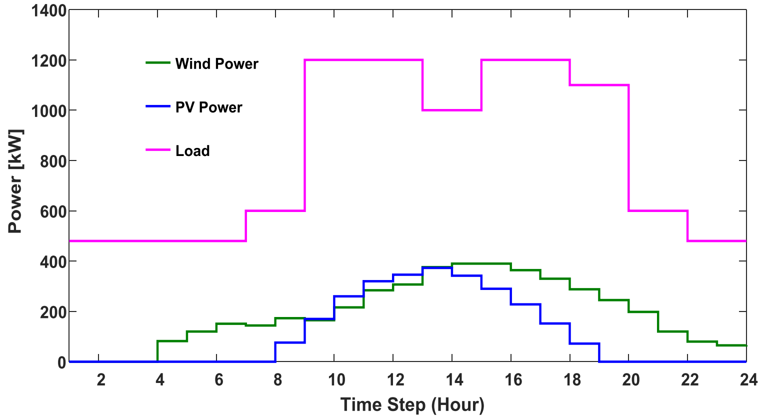

Figure5.1Load and renewables profile during simulation day

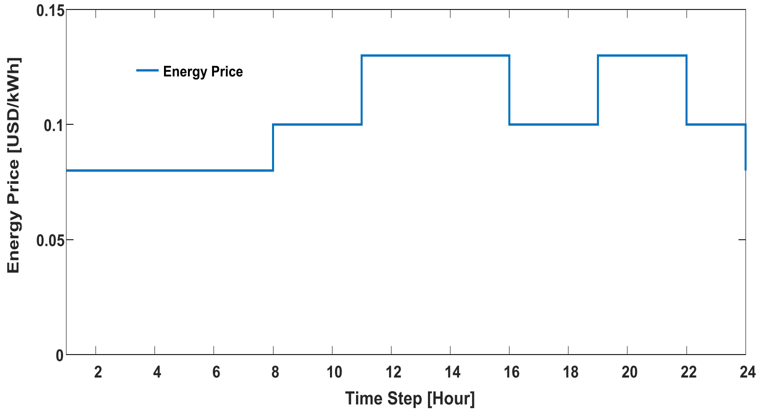

Figure5.2Hourly prices of electricity

Taking into account the hourly normal renewable-energy-generation & weight outlines providing in an overhead figures, smearing a projected MILP grounded microgrid working optimization policy products an optimal scheduling of resources in case of learning microgrid for 24 hours' dated as revealed in Fig. 5.3. It confirmations an optimal practice of the get-up-and-go packing, diesel generator, and utility supply aimed at the simulation day on an hourly foundation. Positive standards of grid power designate the utility grid materials control to the microgrid, although negative standards specify power disseminate to utility grid. Regarding the energy packing organization, positive standards of power resemble to satisfying periods however negative standards match to alleging periods. The state of responsibility of the energy loading scheme at changed interval of the imitation period for the specific simulation situation is shown in Fig. 5.4. It can be practical that the diesel generator unit originates addicted to procedure throughout the pauses somewhere the electricity value of the utility grid develops developed, modifying that manufacturing power by fuel develops additional cost-effective through hours of peak electricity price from the grid. It can also be seen in the results that a microgrid importations power after the utility grid throughout furthermost of the breaks of the imitation day to gratify the local electricity demand which exceeds the local supply. The microgrid exports power to the grid during periods when the energy price is higher, thereby utilizing cheaper locally produced energy and making additional revenue from energy export at higher rates. Without making use of the energy storage unit and the optimal resource scheduling strategy, the cost of operation during the 24 hours is 1263.3 USD. With the usage of the optimal scheduling of charging/discharging of the energy storage system and optimal scheduling of the diesel generator, the functioning price for the identical period is concentrated to 1150.2 USD. This shows the effectiveness of the proposed optimal scheduling strategy applied in the simulation in terms of achieving the economic operation of the case study microgrid system.

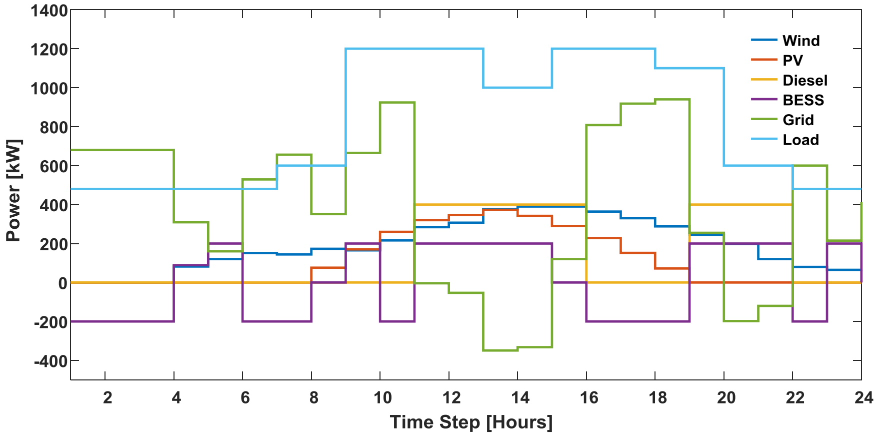

Figure5.3 Outputs of optimal scheduling in simulation

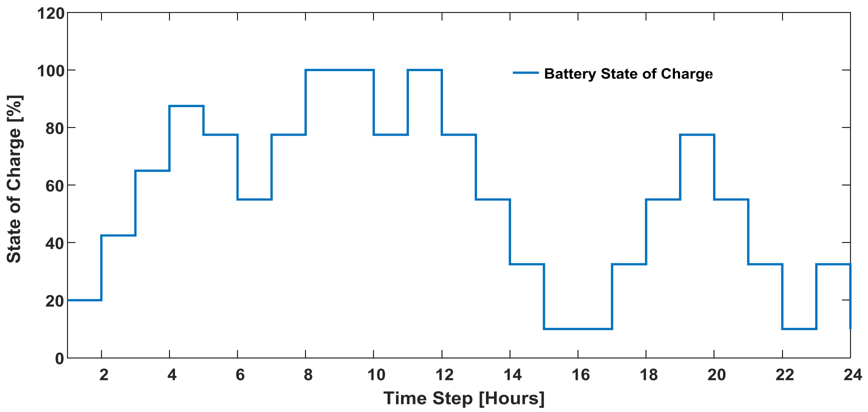

Figure5.4 State of charge of VRB in simulation case 1

The results demonstration the energy packing charges during recesses anywhere electricity amount is little, and discharges throughout phases of great value. Additional get-up-and-go produced inside a microgrid throughout little amount eras could be recycled to responsibility the BESS and sold to the grid throughout high cost stages. Consequently, optimal scheduling of a energy packing & diesel generator allows microgrid to minimize operational costs or maximize revenue from energy export to the utility grid. The status schedule of the diesel generator component at changed period intermissions aimed at an imitation day during a 24-hour imitation historical is obtainable in Figure 5.5. Visual comparison of Fig 5.5 and Fig 5.2 indicates that the diesel generator functions throughout an intermission of an extraordinary network electricity value to decrease energy bills. It residues off when grid prices go little to decrease fuel feasting.

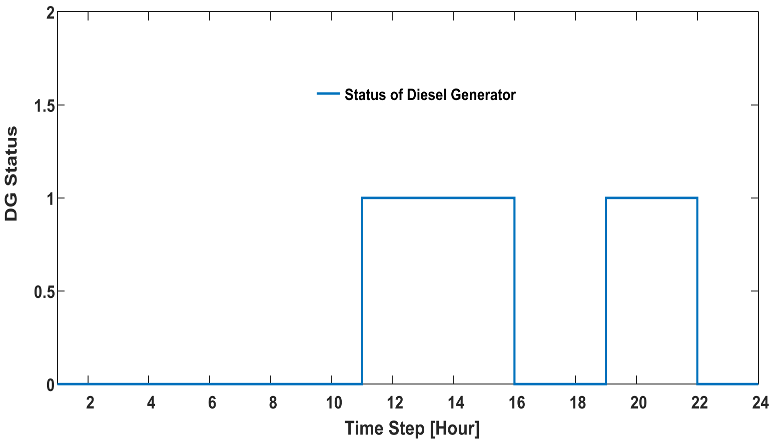

Figure 5.5**Commitment schedule of the diesel generator unit**

The baseload of a microgrid is altered due to the battery charging and discharging operations at different time intervals. The ESS plays an important role in lowering the expected daily minimum load in the microgrid as seen from the generation side. This is because the energy storage system could supply a portion of the local consumption, thereby reducing the daily minimum load seen from the generation side.

To summarize the findings of this chapter, the optimal scheduling of energy resources in a Wind-PV-Diesel generator-ESS microgrid was performed using the MILP optimization algorithm. The proposed energy management optimization algorithm considers the fluctuations in renewable energy and load demand in the microgrid and using suitable day-ahead forecasts (typical generation profiles at the location selected for the study) to overcome these fluctuations in this thesis work. The simulation outcomes show the effectiveness and possible advantages of the applied EMS strategy:

- Minimize power generation fuel costs and grid energy purchase costs.
- Maximize energy sales profit.
- Maximize the economic use of energy storage systems.
- Increase the utilization of renewable energy in the microgrid.

Furthermore, the proposed EMS optimization method is fast convergence and produces a globally optimal solution in an acceptable short computation period.

CHAPTER SIX

CONCULUSION AND FUTURE WORKS

6.1 Conclusions

In the growth & enlargement of a distributed group, efficient energy management systems show significant character in the system of microgrid schemes. The availability accurate generation and demand prediction and efficient resource scheduling strategies are key aspects for optimal management of microgrids. The addition of more distributed energy resources, particularly a renewables, & resulting expansion of microgrid systems requires efficient energy management systems. An EMS plays a central role of managing power flow in the system by deciding the optimal amount of power exchanged between the microgrid and the utility grid, adjusting outputs of dispatchable generation units and controllable loads considering the current and predicted electricity tariff information, generation forecast, and demand forecast to accomplish certain objectives while satisfying operational constraints. The efficient process of microgrids is recognized through optimum scheduling of energy storage and other dispatchable units in the system. Stored energy is useful for matching the intermittent nature of renewable energy generation units to accomplish stable and optimum operation. This thesis dealt with optimum energy management in microgrids under demand and resource uncertainties. The purpose is to develop an optimal hourly resource scheduling plan for the next day to minimize fuel costs and increase overall operational efficiency. In this thesis, the microgrid energy management system has been developed and implemented using the Matlab software environment. To sum up, the following conclusions can be drawn from this thesis.

Optimal operational scheduling of the energy resources in a microgrid operation has been performed using the MILP in Matlab. The proposed energy management optimization algorithm considers the fluctuations of REs and load demand in the microgrid, and uses typical day-ahead generation and load profiles to overcome these fluctuations in this thesis work. The developed EMS optimization model has also considered other several factors such as the energy storage options, grid electricity price variations, energy trading with the utility grid, and fuel consumption of a diesel generator.

The model result shows that the applied energy management strategy is used to minimize the diesel cost of power generation, power purchase cost of the grid, maximize the energy sales profit, maximize the economic utilization rate of ESS, and improve efficiency and utilization REs within MG. The experimental simulation outcome provided the effectiveness of the proposed Mixed Integer Linear Program based EMS strategy to achieve potentially low power generation diesel costs and grid power purchase costs for the MG. Furthermore, the proposed method is fast convergence and produces a globally optimal solution within an acceptable short computation period.

6.2 Future Works

This thesis dealt with efficient energy management in microgrids under generation and demand uncertainties. The research on microgrids has been just a few decades, and as a new energy system, there are still many problems open for research on microgrids. Below are some of the further researches recommended to be extended from the contribution of this work:-

- Optimal energy management for microgrids considering customers' interaction in the microgrid (taking into account demand response).
- Optimal energy management for microgrids with multiple objectives and more operational scenarios.
- Ultra-short-term or online optimal dispatching.
- Hardware and/or application software implementation of the energy management systems.
- Consideration of more advanced microgrid architectures having more number of DGs, ESS devices, and flexible load demands.
- Extending the concept of the thesis to DC microgrids.

This work can be further improved to be able to handle more complex optimization problems in a more generic microgrid system including other forms of energy sources not considered in this study such as microturbines. As more diverse generation systems are incorporated, the issue of emission minimization, cost of battery charge/discharge cycles, etc. also becomes an important aspect to consider. Therefore, this work can be upgraded in future works to develop an EMS with enhanced functionalities able to handle multi-objective optimization problem with nonlinear characteristics of various types of power generation systems. Also, a microgrid control strategy should be in the place that enforces the decisions of the central EMS and ensures stable operation by maintaining system voltage and frequency within a preset range.

This work will be further extended in future research works to include model predictive control (MPC) based optimal energy management and control strategy in microgrids.

7. REFERANCES

[1] F. Blaabjerg, Z. Chen, and S. B. Kjaer. ”Power electronics as efficient interface in dispersed power generation systems”. IEEE Transactions on Power Electronics, 19(5):1184 – 1194, 2004.

[2] T. Degner, J. Schmid, and P. Strauss. ”Distributed Generation with High Penetration of Renewable Energy Sources Final Public Report of Dispower Project”. ISBN 3-00-016584-3, 2006.

[3] “AWEA US wind industry annual market report year ending 2010”. Available: http://awea.org.

[4] U.S. Department of Energy. ‘20% Wind Energy by 2030. Increasing Wind Energy’s Contribution to U.S. Electricity.

[5] American Wind Energy Association. ”U.S. Wind Industry: Market Update”. Available: http://awea.org.

[6] J. Huang, C. Jiang, and R. Xu. ”A review on distributed energy resources and microgrid”. Renewable Sustainable Energy Rev., 12(9):2472 – 2483, 2008.

[7] N. Saito, T. Niimura, K. Koyanagi, and R. Yokoyama. ”Trade-off analysis of autonomous microgrid sizing with pv, diesel, and battery storage”. In Proc. IEEE Power Energy Soc. Gen. Meet, 2009.

[8] R. H. Lasseter and P. Paigi. ”Microgrid: a conceptual solution”. In Proc. Power Electronics Specialist Conference, volume 6, pages 4285 – 4290, 2004.

[9] P. Paigi and R. H. Lasseter. ”Autonomous control of microgrids”. In Proc. IEEE Power Energy Soc. Gen. Meet, 2006.

[10] J. Eto, R. Lasseter, B. Schenkman, J. Stevens, D. Klapp, H. Volkommer, E. Linton, H. Hurtado, and R. Roy. Overview of the certs microgrid laboratory test bed”. In CIGRE/IEEE PES Joint Symposium Integration of Wide-Scale Renewable Resources into the Power Delivery System, 2009.

[11] R. H. Lasseter. ”Extended CERTS microgrid”. In Proc. IEEE Power Energy Soc. Gen. Meet - Conversion and Delivery of Electrical Energy in the 21st Century, pages 1–5, 2008.

[12] J.F. Hu, “Advanced control in smart microgrids”, Ph.D. dissertation, School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney, Australia, 2013.

[13] J.M. Guerrero, F. Blaabjerg, T. Zhelev, K. Hemmes, E. Monmasson, S. Jemei. M. P. Comech, R. Granadino, and J. I. Frau, "Distributed generation: Toward a new energy paradigm," IEEE Magazine Ind. Electron., vol. 4, no. 1, pp. 52-64, March 2010.

[14] T.S. Ustun, C. Ozansoy and A. Zayegh, "Recent developments in microgrids and example cases around the world: A review," Renewable and Sustainable Energy Reviews, vol. 15, pp. 4030-4041, Oct. 2011.

[15] D. E. Olivares et al., "Trends in microgrid control," IEEE Tran. On Smart Grid, vol. 5, no. 4, pp. 1905-1919, 2014.

[16] Z. Zhang, G. Li, and M. Zhou, "Application of microgrid in distributed generation together with the benefit research", IEEE PES General Meeting, Minnesota, USA, 2010.

[17] D. E. Olivares et al., "Trends in microgrid control," IEEE Tran. On Smart Grid, vol. 5, no. 4, pp. 1905-1919, 2014.

[18] G. Celli, F. Pilo, G. Pisano, V. Allegranza, R. Cicoria and A. Iaria, "Meshed vs. radial MV distribution network in presence of large amount of DG", IEEE PES Power Systems Conference and Exposition, 2004.

[19] C. Marnay, F. Rubio, and A. Siddiqui, "Shape of the microgrid", IEEE PES Winter Meeting, Columbus, Ohio, USA, 2001.

[20] C. Marnay and G. Venkatarmanan, "Microgrids in the evolving electricity generation and delivery infrastructure," in IEEE Power Engineering Society General Meeting, pp. 1-5, 2006.

[21] Dondi, D. Bayoumi, C. Haederli, D. Julian, and M. Suter, "Network integration of distributed power generation," J. of Power Sources, vol. 106, no. 1–2, pp. 1–9, 2002.

[22] J.P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," Electric Power Syst. Research, vol. 77, no. 9, pp. 1189–1203, 2007.

[23] K. Kimura, "Neural networks approach for wind-solar energy system with complex networks," IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS), 2013.

[24] A. Mukherjee, "A case study of islanded microgrid control", M. S. thesis, Department of Electrical Engineering, The Florida State Univ., Florida, USA, 2012.

[25] Catalão, João & Pousinho, H.M.I. & Mendes, V.M.F. (2011). Hybrid wavelet-PSO-ANFIS approach for short-term wind power forecasting in Portugal. Sustainable Energy, IEEE Transactions on. 2. 50 - 59. 10.1109/TSTE.2010.2076359.

[26] Petrollese, Mario & Cau, Giorgio & Cocco, Daniele & Lucariello, Marialaura. (2014). Optimal generation scheduling for a hybrid stand-alone power system using renewable energy sources and hydrogen storage.

[27] Oliver, M. and T. Jackson, 1999. The market for solar photovoltaics. Energy Policy, 27: 371–385.

[28] Gomes, Pedro & Castro, Rui. (2012). Wind Speed and Wind Power Forecasting using Statistical Models: AutoRegressive Moving Average (ARMA) and Artificial Neural Networks (ANN). International Journal of Sustainable Energy Development. 1. 10.20533/ijsed.2046.3707.2012.0007.

[29] Chang, Wen-Yeau. (2014). A Literature Review of Wind Forecasting Methods. Journal of Power and Energy Engineering. 02. 161-168. 10.4236/jpee.2014.24023.

[30] Sideratos, George & Hatziargyriou, Nikos. (2007). an Advanced Statistical Method for Wind Power Forecasting. Power Systems, IEEE Transactions on. 22. 258 - 265. 10.1109/TPWRS.2006.889078.

[31] Catalão, João & Pousinho, H.M.I. & Mendes, V.M.F. (2009). An Artificial Neural Network Approach for Short-Term Wind Power Forecasting in Portugal. Engineering Intelligent Systems. 17. 1 - 5. 10.1109/ISAP.2009.5352853.

[32] Foley, Aoife & Leahy, Paul & Marvuglia, Antonino & Mckeogh, Eamon. (2012). Current methods in adVances in forecasting of wind power generation. Renewable Energy. 37. 1-8. 10.1016/j.renene.2011.05.033.

[33] Lei, Ma & Shiyan, Luan & Chuanwen, Jiang & Hongling, Liu & Yan, Zhang. (2009). A review on the forecasting of wind speed and generated power. Renewable and Sustainable Energy Reviews. 13. 915-920. 10.1016/j.rser.2008.02.002.

[34] Costa, Alexandre & Crespo, Antonio & Navarro, J & Lizcano, Gil & Madsen, Henrik & Feitosa, Everaldo. (2008). A review on the young history of the wind power short-term prediction. Renewable and Sustainable Energy Reviews. 12. 1725-1744. 10.1016/j.rser.2007.01.015.

[35] M.K.Deshmulh & Moorthy, Balakrishna. (2010). Application of Genetic Algorithm to Neural Network Model for Estimation of Wind Power Potential. Journal of Engineering, Science and Management Education. 2. 42-48.

[36] Li, Lingling & Wang, Minghui & Zhu, Fenfen & Wang, Chengshan. (2009). Wind Power Forecasting Based on Time Series and Neural Network.

[37] Rotich, Nicolus K., Jari Backman, Lassi Linnanen i Perfilieve Daniil. "Wind Resource Assessment and Forecast Planning with Neural Networks." Journal of Sustainable Development of Energy, Water and Environment Systems 2, br. 2 (2014): 174-190. https://doi.org/10.13044/j.sdewes.2014.02.0015

[38] Catalão, João & Pousinho, H.M.I. & Mendes, V.M.F. (2011). Short-term wind power forecasting in Portugal by neural networks and wavelet transform. Renewable Energy. 36. 1245-1251. 10.1016/j.renene.2010.09.016.

[39] K. Bhaskar and , S.N. Singh, "AWNN-assisted wind power forecasting using feed-forward neural network", IEEE Transactions on Sustainable Energy, 3(2), pp. 306-315, 2012.

[40] J.W. Zeng, and W. Qiao, "Support vector machine-based short-term wind power forecasting", Proc. of the IEEE/PES Power Systems Conf. and Exposition, Phoenix, pp. 1-8, 2011.

[41] J.Y. Zhou, J. Shi, and G. Li,: "Fine tuning support vector machines for short-term wind speed forecasting", Energy Conversion and Management, 52, pp. 1990-1998, 2011.

[42] Z.X. Men, E. Yee, F.S. Lien, D.Y. Wen and Y.S. Chen, "Short-term wind speed and power forecasting using an ensemble of mixture density neural networks", Renewable Energy, 87, pp. 203-211, 2015.

[43] F. Castellanos and N. James, "Average hourly wind speed forecasting with ANFIS". 11th Americas Conference on Wind Engineering, San Juan, Puerto Rico, 2009

[44] R.L. Xu, et al., "A prediction model for wind farm power generation based on genetic-neural network", Journal of Convergence Information Technology, 7(14), pp. 11-19, 2012.

[45] A. Mellit and A. MassiPavan, "A 24-h forecast of solar irradiance using artificial neural network: Application for performance prediction of a grid-connected PV plant at Trieste, Italy", Solar Energy, 84(5), pp. 807-821, 2010.

[46] W. Y. Chang, "Short-term wind power forecasting using the enhanced particle swarm optimization based hybrid method", Energies, September, 2013.

[47] Azadeh, Ali & Maghsoudi, amir & Sohrabkhani, S. (2009). An integrated artificial neural networks approach for predicting global radiation. Energy Conversion and Management. 50. 1497-1505. 10.1016/j.enconman.2009.02.019.

[48] R. Marquez and C.F.M. Coimbra, "Forecasting of global and direct solar irradiance using stochastic learning methods, ground experiments and the NWS database", Solar Energy, 85(5), pp. 746-756, 2011.

[49] P. Larson, David & Nonnenmacher, Lukas & F.M. Coimbra, Carlos. (2016). Day-ahead forecasting of solar power output from photovoltaic plants in the American Southwest. Renewable Energy. 91. 11-20. 10.1016/j.renene.2016.01.039.

[50] P. Bacher, H. Madsen and H. Nielsen, "Online short-term solar power forecasting", Solar Energy, Vol. 83, pp. 1772–1783, 2009.

[51] Li, Yanting & Su, Yan & Shu, Lianjie. (2014). An ARMAX model for forecasting the power output of a grid connected photovoltaic system. Renewable Energy. 66. 78–89. 10.1016/j.renene.2013.11.067.

[52] Perez, Richard & Kivalov, Sergey & Schlemmer, James & Jr. Hemker, Karl & Renné, David & Hoff, Thomas. (2010). Validation of short and medium term operational solar radiation forecasts in the US. Solar Energy - SOLAR ENERG. 84. 10.1016/J.SOLENER.2010.08.014.

[53] Wang, Fei & Mi, Zengqiang & Su, Shi & Zhao, Hongshan. (2012). Short-Term Solar Irradiance Forecasting Model Based on Artificial Neural Network Using Statistical Feature Parameters. Energies. 5. 1355-1370. 10.3390/en5051355.

[54] C.W. Chow, B. Urquhart, M. Lave, A. Dominguez, J. Kleissl, J. Shields and B. Washom, "Intra-hour forecasting with a total sky imager at the UC San Diego solar energy tested", Solar Energy, 85 (11) , pp. 2881-2893, 2011.

[55] Y. Chu., B. Urguhart, S. Gohari, H. Pedro, J. Kleissl and C. Coimbra, "Short-term reforecasting of power output from a 48MWe solar PV plant", Solar Energy, Vol. 112, pp. 68–77, 2015.

[56] F. Almonacid, P. Perez-Higueras, E. Fernandez and L. Hontoria, "A methodology based on dynamic artificial neural network for short-term forecasting of the power output of a PV generator", Energy Conversion and Management, Vol. 85, pp. 389–398, 2014.

[57] Kashyap, Yashwant & Bansal, Ankit & Sao, Anil. (2015). Solar radiation forecasting with multiple parameters neural networks. Renewable and Sustainable Energy Reviews. 49. 825-835. 10.1016/j.rser.2015.04.077.

[58] M. Rana, I. Koprinska and V. Agelidis, “2D-interval forecasts for solar powerproduction.” Solar Energy, Vol. 122, pp. 191–203, 2015.

[59] A. Mellit and S. A. Kalogirou, “ANFIS-based modelling for photovoltaic power supply system: A case study”, Renewable Energy, 36(1), 250-256, 2015.

[60] Chauvin, Rémi & Nou, Julien & Thil, Stéphane & Grieu, Stéphane. (2014). Intra-day DNI forecasting under clear sky conditions using ANFIS. IFAC Proceedings Volumes (IFAC-PapersOnline). 19.

[61] Bouzerdoum, M & Mellit, Adel & Massi Pavan, Alessandro. (2013). A hybrid model (SARIMA–SVM) for short-term power forecasting of a small-scale grid-connected photovoltaic plant. Solar Energy. 98. 226–235. 10.1016/j.solener.2013.10.002.

[62] Vaz, A.G.R. & Elsinga, Boudewijn & van Sark, Wilfried & Brito, M. (2016). An artificial neural network to assess the impact of neighbouring photovoltaic systems in power forecasting in Utrecht, the Netherlands. Renewable Energy. 85. 631-641. 10.1016/j.renene.2015.06.061.

[63] Lin, Kuo-Ping & Pai, Ping-Feng. (2015). Solar power output forecasting using evolutionary seasonal decomposition least-square support vector regression. Journal of Cleaner Production. 134. 10.1016/j.jclepro.2015.08.099.

[64] Sanchez-Garcia, Jose & Espinosa-Juarez, E & Flores, Juan. (2016). Short term photovoltaic power production using a hybrid of nearest neighbor and artificial neural networks. 1-6. 10.1109/TDC-LA.2016.7805658.

[65] A. Dolara, F. Grimaccia, S. Leva, M. Mussetta and E. Ogliari, “A physical hybrid artificial neural network for short term forecasting of PV plant power output”, Energies, vol. 8, pp. 1138 – 1153, 2015.

[66] J. Antonanzas, N. Osorio, R. Escobar, R. Urraca, F.J. Martinez-de-Pison and F. Antonanzas-Torres, “Review of photovoltaic power forecasting”, Solar Energy, Vol. 136, pp. 78-111, 2016.

[67] Ye Ren, P.N. Suganthan and N.Srikanth, “Ensemble methods for wind and solar power forecasting-A state-of-the-art review”, Renewable and Sustainable Energy Reviews, Vol. 50, pp. 82-91, 2015.

[68] R. H. Inman, H. T.C. Pedro and C. F.M. Coimbra, “Solar forecasting methods for renewable energy integration”, Progress in Energy and Combustion Science, Vol. 39, pp. 535-576, 2013.

[69] E.E. Elattar, J. Goulermas and Q.H. Wu, “Electric load forecasting based on locally weighted support vector regression”, IEEE Transactions on Systems, Man, and Cybernetics-Part Applications and Reviews, 40(4), pp.438-447, 2010.

[70] B.U.I. Islam, “Comparison of conventional and modern load forecasting techniques based on artificial intelligence and expert systems”, International Journal of Computer Science Issues, 8(5/3), pp.504-513, 2011.

[71] N. Amjady, “Short-term hourly load forecasting using time series modeling with peak load estimation capability”, IEEE Transactions on Power Systems, 16(4), pp. 798–805, 2001.

[72] W.R. Christiaanse, “Short term load forecasting using general exponential smoothing”, IEEE Transactions on Power Apparatus and Systems, 90, pp. 900-911, 1971.

[73] A.D. Papalexopoulos and T.C. Hesterberg, “A regression based approach to short term system load forecasting”, Proceedings of PICA conference, 3, pp. 414–423, 1989.

[74] G.D. Irisarri, S.E. Widergren and P.D. Yehsakul. “On-line load forecasting for energy control center application”, IEEE Transactions on Power Apparatus and Systems, 101, pp.71–78, 1982.

[75] J. W. Taylor, L. M. de Menezes, and P. E. McSharry, “A comparison of univariate methods for forecasting electricity demand up to a day ahead,” International Journal of Forecasting, 22(1), pp. 1–16, 2006.

[76] H.S. Hippert, C.E. Pedreira and R.C. Souza, “Neural networks for short-term load forecasting: A review and evaluation”, IEEE Transactions on Power Systems, 16(1), pp. 44–55, 2001.

[77] A.S. Dehdashti, J.R. Tudor, and M.C. Smith, “Forecasting of hourly load by pattern recognition-a deterministic approach”, IEEE Transactions on Power Apparatus and Systems, 101, pp. 3290–3294, 1982.

[78] S. Rahman and R. Bhatnagar, “An expert system based algorithm for short term load forecast”, IEEE Transactions on Power Systems, 3(2), pp. 392–399, 1988.

[79] S. Rahman, “Generalized knowledge-based short-term load forecasting technique”, IEEE Transactions on Power Systems, 8(2), 508–514, 1993.

[80] K.L Ho, Y.Y. Hsu, C.F. Chen, T.E. Lee, C.C. Liang, T.S. Lai, and K.K. Chen, “Short term load forecasting of Taiwan power system using a knowledge-based expert system”, IEEE Transactions on Power Systems, 5(4), pp. 1214–1221, 1990.

[81] S.Q. Sheng and C. Wang, “Integrating radial basis function neural network with fuzzy control for load forecasting in power system,” Proceedings of Transmission and Distribution Conference and Exhibition: Asia and Pacific, pp. 1–5, 2005

[82] H.T. Yang and C.M. Huang, “A new short-term load forecasting approach using self-organizing fuzzy ARMAX models”, IEEE Transactions on Power Systems,13(1), pp. 217–225, 1998.

[83] D. Srinivasan, D.S. Chang and A.C. Liew, “Demand forecasting using fuzzy neural computation, with special emphasis on weekend and public holiday forecasting”, IEEE Transactions on Power Systems, 10(4), pp. 1897–1903, 1995

[84] A. G. Bakirtzis, J.B. Theocharis, S.J. Kiartzis and K.J. Satsois, “Short term load forecasting using fuzzy neural networks”, IEEE Transactions on Power Systems,10(3), pp. 1518–1524, 1995.

[85] Y.B. Chen, P. Xu, Y.Y. Chu, W.L. Li, Y.T. Wu, L.Z. Ni, Y. Bao, and K. Wang, “Short-term electrical load forecasting using the support vector regression (SVR) model to calculate the demand response baseline for office buildings”, Applied Energy, 195, pp. 659-670, 2017.

[86] S. Li, L. Goel and P. Wang, “An ensemble approach for short-term load forecasting by extreme learning machine”, Applied Energy, 170, pp. 22-29, 2016.

[87] S. Li, P. Wang and L. Goel, “Short-term load forecasting by wavelet transform and evolutionary extreme learning machine”, Electric Power Systems Research, 122, pp. 96-103, 2015.

[88] L.Y Xiao, W. Shao, C. Wang, K.Q Zhang and H.Y. Lu, “Research and application of a hybrid model based on multi-objective optimization for electrical load forecasting”, Applied Energy, 180, pp. 213-233, 2016.

[89] M. Figueiredo, R. Ballini, S. Soares, M. Andrade and F. Gomide, “Learning algorithms for a class of neurofuzzy network and application,” IEEE Trans. Syst., Man, Cyber. C, Appl. Rev., 34(3), pp. 293–301, 2004.

[90] C. J. Lin, C. H. Chen and C. T. Lin, “A hybrid of cooperative particle swarm optimization and cultural algorithm for neural fuzzy networks and its prediction applications,” IEEE Trans. Syst, Man, Cyber. C, Appl. Rev., 39(1), pp. 55–68, 2009.

[91] Y. Bodyanskiy, S. Popov, and T. Rybalchenko, “Multilayer neuro-fuzzy network for short term electric load forecasting,” Lecture Notes in Computer Science, 5010, pp. 339–348, 2008.

[92] N. Coelho, I.M. Coelho, B.N. Coelho, A.J.R. Reis, R. Enayatifar, M.J.F. Souza and F.G. Guimarães, “A self-adaptive evolutionary fuzzy model for load forecasting problems on smart grid environment”, Applied Energy, 169, pp. 567-584, 2016.

[93] X. Sun, P. B. Luh, K. W. Cheung, W. Guan, L. D. Michel, S. S. Venkata et al., “An efficient approach to short-term load forecasting at the distribution level”, IEEE Transactions on Power Systems, 31(4), pp.526-2537, 2016.

[94] M. S. Kiran, E. O¨zceylan, M. GU¨ndu¨z and T. Paksoy, “A novel hybrid approach based on particle swarm optimization and ant colony algorithm to forecast energy demand of Turkey”, Energy Conversion and Management, 53, pp.75–83, 2012.

[95] N. Amjady, F. Keynia, and H. Zareipour, “Short-term load forecasting of power systems by combination of wavelet transform and neuro-evolutionary algorithm”, Energy, 34, pp.46-57, 2009.

[96] S. Mishra and S. K. Patra, “Short term load forecasting using neural network trained with genetic algorithm & particle swarm optimization”, First International Conference on Emerging Trends in Engineering and Technology, 2008.

[97] S. Q Guo, L.Ruan, H.H. Dong, Z.G. Li, F.H. Liu and R. Cao, “EMD-based short-term load forecasting”, International Conference on Automatic Control Theory and Application, pp. 141-145, 2014.

[98] N. Liu, Q.F. Tang, J.H. Zhang, W. Fan and J. Liu, “A hybrid forecasting model with parameter optimization for short-term load forecasting of micro-grids”, Applied Energy, 129, pp. 336-345, 2014.

[99] C.F. Chen, M.C. Lai and C.C. Yeh, “Forecasting tourism demand based on empirical mode decomposition and neural network”, Knowledge-Based Systems, 26, pp. 281–287, 2012.

[100] Z. H. Zhu, Y. L. Sun and H. Q. Li, “Hybrid of EMD and SVMs for short-term load forecasting”, IEEE International Conference on Control and Automation, 2007.

[101] N.E. Huang, Z. Shen, S.R. Long, M.C. Wu, H.H. Shih and Q. Zheng, “The empirical mode decomposition and the Hilbert spectrum for nonlinear and nonstationary time series analysis”, Proceedings of the royal society of London series a–mathematical physical and engineering sciences, series A, 454, pp. 903–995, 1998.

[102] C. Marnay, F. Rubio, and A. Siddiqui, “Shape of the microgrid”, IEEE PES Winter Meeting, Columbus, Ohio, USA, 2001.

[103] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas, “Microgrids management,” IEEE Power & Energy Magazine, vol. 6, pp. 54-65, 2008.

[104] A. Parisio, E. Rikos, and L. Glielmo, “A Model Predictive Control Approach to Microgrid Operation Optimization,” IEEE Transactions on Control Systems Technology, vol. 22, pp. 1813–1827, 2014.

[105] X. Guan, Z. Xu, and Q.-S. Jia, “Energy-efficient buildings facilitated by microgrid,” IEEE Transactions Smart Grid, vol. 1, pp. 243–252, Dec. 2010.

[106] D. Bertsimas, E. Litvinov, X. Sun, J. Zhao, and T. Zheng, “Adaptive robust optimization for the security constrained unit commitment problem,” IEEE Transactions in Power Systems, vol. 28, pp. 52–63, 2013.

[107] K. Kimura, “Neural networks approach for wind-solar energy system with complex networks,” IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS), 2013.

[108] R. Aquino and M. Carvalho, “Recurrent neural networks solving a real large scale mid-term scheduling for power plants,” International Joint Conference on Neural Networks (IJCNN), 2010.

[109] X.P. Liu, M. Ding, J.H. Han, and P.P. Han, “Dynamic economic dispatch for microgrids including battery energy storage”, Journal of Energy and Power Engineering, vol. 5, pp. 461-465, 2011.

[110] Q.Y. Xu, N. Zhang, C.Q. Kang, R.Y. Wang, J.R. Wang, Z.P. Cui, and Z.G. Yang, "Day-ahead battery scheduling in microgrid considering wind power uncertainty using ordinal optimization", North American Power Symposium (NAPS), 2014.

[111] R. Rigo-Mariani, B. Sareni, and X. Roboam, "A fast optimization strategy for power dispatching in a microgrid with storage", 39th Annual Conference of the IEEE Industrial Electronics Society, IECON, 2013.

[112] E. Z. juybari and S. M. Hosseini, "Optimization of microgrid using quantum inspired evolutionary algorithm", I.J. Intelligent Systems and Applications, 2014

[113] Grace C. Wu, Ranjit Deshmukh, Kudakwashe Ndhlukula, Tijana Radojicic, Jessica Reilly Moman, Amol Phadke, Daniel M. Kammen, Duncan S.Callaway Strategic siting and regional grid interconnections key to low-carbon futures in African countries PNAS April 11, 2017 114 (15) E3004-E3012; first published March 27, 2017 https://doi.org/10.1073/pnas.1611845114

[114] Bazilian, Morgan & Nussbaumer, Patrick & Rogner, Holger & Brew-Hammond, Abeeku & Foster, Vivien & Pachauri, Shonali & Williams, Eric & Howells, Mark & Niyongabo, Philippe & Musaba, Lawrence & O Gallachoir, Brian & Radka, Mark & Kammen, Daniel. (2012). Energy access scenarios to 2030 for the power sector in sub-Saharan Africa. Utilities Policy. 20. 1 - 16. 10.1016/j.jup.2011.11.002.

[115] Nadia, Ouedraogo. (2017). Modeling sustainable long-term electricity supply-demand in Africa. Applied Energy. 190. 1047-1067. 10.1016/j.apenergy.2016.12.162.

[116] Nkiruka Avila, Juan Pablo Carvallo, Brittany Shaw, and Daniel M. Kammen The energy challenge in sub-Saharan Africa: A guide for advocates and policy makers Part 1: Generating energy for sustainable and equitable development. Oxfam America Report.

[117] Bos, Kristine & Chaplin, Duncan & Mamun, Arif. (2018). Benefits and challenges of expanding grid electricity in Africa: A review of rigorous evidence on household impacts in developing countries. Energy for Sustainable Development. 44. 64-77. 10.1016/j.esd.2018.02.007.

[118] Hancock, Kathleen. (2015). The expanding horizon of renewable energy in sub-Saharan Africa: Leading research in the social sciences. Energy Research & Social Science. 16. 10.1016/j.erss.2014.12.021.

[119] Cole, Matthew & Elliott, Robert & Occhiali, Giovanni & Strobl, Eric. (2018). Power outages and firm performance in Sub-Saharan Africa. Journal of Development Economics. 134. 10.1016/j.jdeveco.2018.05.003.

[120] Lenz, Luciane & Munyehirwe, A & Peters, Jörg & Sievert, Maximiliane. (2016). Does Large-Scale Infrastructure Investment Alleviate Poverty? Impacts of Rwanda's Electricity Access Roll-Out Program. 10.1016/j.worlddev.2016.08.003.

[121] González-Eguino, Mikel. (2015). Energy poverty: An overview. Renewable and Sustainable Energy Reviews. 47. 10.1016/j.rser.2015.03.013.

[122] Panos, Vangelis & Turton, Hal & Densing, Martin & Volkart, Kathrin. (2015). Powering the growth of Sub-Saharan Africa: The Jazz and Symphony scenarios of World Energy Council. Energy for Sustainable Development. 26. 10.1016/j.esd.2015.01.004.

[123] G. Dagnachew, Anteneh & Lucas, Paul & Hof, Andries & Gernaat, David & De Boer, Harmen Sytze & Vuuren, Detlef. (2017). The role of decentralized systems in providing universal electricity access in Sub-Saharan Africa – A model-based approach. Energy. 139. 10.1016/j.energy.2017.07.144.

[124] Nadia, Ouedraogo. (2017). Africa energy future: Alternative scenarios and their implications for sustainable development strategies. Energy Policy. 106. 10.1016/j.enpol.2017.03.021.

[125] Deichmann, Uwe & Meisner, Craig & Murray, Siobhan & Wheeler, David. (2010). Public Disclosure Authorized Public Disclosure Authorized The Economics of Renewable Energy Expansion in Rural Sub-Saharan Africa. The World Bank, Policy Research Working Paper Series. 39. 10.1016/j.enpol.2010.09.034.

[126] Daly, Hannah & A Walton, Molly. (2017). Energy Access Outlook: from Poverty to Prosperity, World Energy Outlook-2017 Special Report.

[127] Eberhard, Anton & Gratwick, Katharine & Morella, Elvira & Antmann, Pedro. (2017). Independent Power Projects in Sub-Saharan Africa: Investment trends and policy lessons. Energy Policy. 108. 390-424. 10.1016/j.enpol.2017.05.023.

[128] International Energy Agency, " Africa Energy Outlook: A Focus on Energy Prospects in sub - Saharan Africa", IEA (2014).

[129] AREI, A framework for transforming Africa towards a renewable energy powered future with access for all. Publication date: 2015, October,

http://www.africanpowerplatform.org/resources/620-a-framework-for-transforming-africa-towards-a-renewable-energy-powered-future-with-access-for-all.html.

[130] Eberhard, Anton & Gratwick, Katharine & Morella, Elvira & Antmann, Pedro. (2017). Independent Power Projects in Sub-Saharan Africa: Investment trends and policy lessons. Energy Policy. 108. 390-424. 10.1016/j.enpol.2017.05.023.

[131] Eberhard, Anton; Gratwick, Katharine; Morella, Elvira; Antmann, Pedro. 2016. *Independent Power Projects in Sub-Saharan Africa : Lessons from Five Key Countries*. Directions in Development--Energy and Mining;. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/23970 License: CC BY 3.0 IGO.

[132] Eberhard, Anton & Gratwick, Katharine & Morello, Elvira & Antmann, Pedro. (2017). Accelerating investments in power in sub-Saharan Africa. Nature Energy. 2. 17005. 10.1038/nenergy.2017.5.

[133] Africa Progress Report 2015 - Power, People, Planet: Seizing Africa's energy and climate opportunities – World Report Published on 05 Jun 2015

[134] Tracking SDG7: The Energy Progress Report 2018 International Bank for Reconstruction and Development / The World Bank full report on the Tracking SDG7 website.

[135] Whitley, S. and van der Burg, L., 2015. Fossil Fuel Subsidy Reform: From Rhetoric to Reality. New Climate Economy, London and Washington, DC. Available at http://newclimateeconomy.report/misc/working-papers.

[136] Energy policy— Case studies. 2. Fuel— Prices. 3. Electric utilities— Government policy. I. Clements, Benedict. II. Coady, David. III. Fabrizio, Stefania. IV. Gupta, Sanjeev. V. Alleyne, Trevor. VI. Sdralevich, Carlo. VII. International Monetary Fund.

[137] Whitley S. Time to change the game: fossil fuel subsidies and climate. London: Overseas Development Institute; 2015. http://www. odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/ 8668.pdf.

[138] Ighobor K. Light at the end of the tunnel: much ado over Africa’s power sector. Africa Renewal; 2014. http://www.un.org/ africarenewal/magazine/april-2014/light-end-tunnel.

[139] Jean Arlet, Electricity Tariffs, Power Outages and Firm Performance: A Comparative Analysis, Global Indicators Group, Development Economics. The World Bank March, 2017.

[140] Anton Eberhard, Orvika Rosnes, Maria Shkaratan, Haakon Vennemo. Africa's power infrastructure: investment, integration, efficiency. The World Bank, 2011. https://doi.org/10.1596/978-0-8213-8455-8

[141] IRENA (2011), Prospects for the African power Sector: Scenarios and Strategies for Africa Project

[142] P. Buchana, and T.S. Ustun "The role of microgrids & renewable energy in addressing sus-sahara Africa's current and future energy needs", 2015.

[143] A. E. O. IEA, "A focus on the energy prospects in sub-saharan africa, world energy outlook special report," International Energy Agency Publication, pp. 1–237, 2014.

[144] N. Lidula and A. Rajapakse, "Microgrids research: A review of experimental microgrids and test systems," Renewable and Sustainable Energy Reviews, vol. 15, no. 1, pp. 186–202, 2011.

[145] P. Basak, S. Chowdhury, S. H. nee Dey, and S. Chowdhury, "A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid,"Renewable and Sustainable Energy Reviews, vol. 16, no. 8, pp. 5545–5556, 2012.

[146] M. D. Al-Falahi, S. Jayasinghe, and H. Enshaei, "A review on recent size optimization methodologies for standalone solar and wind hybrid renewable energy system," Energy Conversion and Management, vol. 143, pp. 252–274, 2017.

[147] C. Cader, P. Bertheau, P. Blechinger, H. Huyskens, and C. Breyer, "Global cost advantages of autonomous solar–battery–diesel systems compared to diesel-only systems," Energy for Sustainable Development, vol. 31, pp. 14–23, 2016.

[148] Ghorbani, Narges & Kasaeian, Alibakhsh & Toopshekan, Ashkan & Bahrami, Leyli & Maghami, Amin. (2017). Optimizing a hybrid wind-PV-battery system using GA-PSO and MOPSO for reducing cost and increasing reliability. Energy. 154. 10.1016/j.energy.2017.12.057.

[149] Hosseinalizadeh R, Shakouri HG, Amalnick MS, Taghipour P. Economic sizing of a hybrid (PV-WT-FC) renewable energy system (HRES) for stand-alone usages by an optimization-simulation model: Case study of iran. Renew Sust Energ Rev. 2016;54;139-150.

[150] C. Wang, Y. Liu, X. Li, L. Guo, L. Qiao, and H. Lu, “Energy management system for stand-alone diesel-wind-biomass microgrid with energy storage system,” Energy, vol. 97, pp. 90–104, 2016.

[151] Coo, Linney & Lee, Dong-Jing & Chen, Long-Yi & Yu, Jyun-Ying & Jan, Shen-Rong & Chen, Su-Jen & Lee, Wei-Jen & Tsai, Ming-Hua & Lin, Wei-Taw & Li, Yuan-Chung & Blyden, Bai. (2009). A micro hydro power generation system for sustainable microgrid development in rural electrification of Africa. 2009 IEEE Power and Energy Society General Meeting, PES '09. 1 - 8. 10.1109/PES.2009.5275244.

[152] A. G. Dagnachew, P. L. Lucas, A. F. Hof, and D. P. van Vuuren, “Trade-offs and synergies between universal electricity access and climate change mitigation in sub-saharan africa,” Energy Policy, vol. 114, pp. 355–366, 2018.

[153] Fabini, Douglas & Barido, Diego & Omu, Akomeno & Taneja, Jay. (2014). Mapping Induced Residential Demand for Electricity in Kenya. ACM DEV 2014 - Proceedings of the 2014 Annual Symposium on Computing for Development. 43-52. 10.1145/2674377.2674390.

[154] Woyte, Achim & Van Thong, Vu & Belmans, Ronnie & Nijs, Johan. (2006). Voltage Fluctuations on Distribution Level Introduced by Photovoltaic Systems. Energy Conversion, IEEE Transactions on. 21. 202 - 209. 10.1109/TEC.2005.845454.

[155] L. Dusonchet, M. G. Ippolito, E. Telaretti, G. Zizzo and G. Graditi, "An optimal operating strategy for combined RES-based generators and electric storage systems for load shifting applications," 4th International Conference on Power Engineering, Energy and Electrical Drives, Istanbul, 2013, pp. 552-557.doi: 10.1109/PowerEng.2013.6635668

[156] Henner, Dagmar. (2017). REN21. 2017. Renewables 2017 Global Status Report.

[157] Africa Energy Outlook, A FOCUS ON ENERGY PROSPECTS IN SUB-SAHARAN AFRICA, World Energy Outlook Special Report. OECD/IEA, 2014. International Energy Agency.

[158] “Economic Issues No. 23--Promoting Growth in Sub-Saharan Africa.” [Online]. Available: http://bit.ly/QZne9l. [Accessed: 17-Nov-2014].

[159] Piet Buys, et al. "Country Stakes in Climate Change Negotiations: Two Dimensions of Vulnerability. “Climate Policy 9.3 (2009): 288-305.

[160] IRENA (2011), Prospects for the African power Sector: Scenarios and Strategies for Africa Project

[161] African Development Bank (AfDB) (2011). Advisory: African Private Investment Guidance. Oil and Gas Strategy. Tunis: AfDB.

[162] Grace C. Wu, Ranjit Deshmukh, Kudakwashe Ndhlukula, Tijana Radojicic, Jessica Reilly-Moman, Amol Phadke, Daniel M. Kammen, and Duncan S. Callaway. PNAS April 11, 2017 114 (15) E3004-E3012; published ahead of print March 27, 2017

[163] IRENA. (2017). Renewable energy auctions: Analysing 2016. Abu Dhabi: Author.

[164] World Bank, “Sate of Electricity Access report 2017”, 2017.

[165] Kriegler E, Tavoni M, Aboumahboub T, Luderer G, Calvin K, De Maere G, Krey V, Riahi K, et al. (2013). *What Does the 2 Degree C Target Imply for a Global Climate Agreement in 2020? The LIMITS Study on Durban Platform Scenarios.*LIMITS Special Issue, FP7 LIMITS Project

[166] Jessica Jewell et al. Comparison and interactions between the long-term pursuit of energy independence and climate policies, *Nature Energy* (2016). DOI: 10.1038/nenergy.2016.73

[167] McCollum, D., Nagai, Y., Riahi, K., Marangoni, G., Calvin, K., Pietzcker, R., … van der Zwaan, B. (2013). Energy investments under climate policy: A comparison of global models. Climate Change Economics, 4(4), 1340010.

[168] Bertram, Christoph & Luderer, Gunnar & Pietzcker, Robert & Schmid, Eva & Kriegler, Elmar & Edenhofer, Ottmar. (2015). Complementing carbon prices with technology policies to keep climate targets within reach. Nature Climate Change. 5. 235-239. 10.1038/nclimate2514.

[169] Creutzig, Felix & Agoston, Peter & Goldschmidt, Jan Christoph & Luderer, Gunnar & Nemet, Gregory & Pietzcker, Robert. (2017). The underestimated potential of solar energy to mitigate climate change. Nature Energy. 2. 10.1038/nenergy.2017.140.

[170] Rogelj, Joeri & Luderer, Gunnar & Pietzcker, Robert & Kriegler, Elmar & Schaeffer, Michiel & Krey, Volker & Riahi, Keywan. (2015). Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nature Climate Change. 5. 519-527. 10.1038/nclimate2572.

[171] Riahi, Keywan & Kriegler, Elmar & Johnson, Nils & Bertram, Christoph & Elzen, Michel & Eom, Jiyong & Schaeffer, Michiel & Edmonds, Jae & Isaac, Morna & Krey, Volker.

(2013). Locked into Copenhagen Pledges—Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change.

[172] P. Peters, Glen & M. Andrew, Robbie & Boden, Tom & G. Canadell, Josep & Ciais, Philippe & Le Quéré, Corinne & Marland, Gregg & Raupach, Michael & Wilson, Charlie. (2013). COMMENTARY: The challenge to keep global warming below 2 degrees C. Nature Climate Change. 3. 10.1038/nclimate1783.

[173] Paul Lamontagne. Johannesburg, Africa’s gigantic growth prospects to benefit entrepreneurs, investors, Business Report, 5 October 2017, https://www.iol.co.za/business-report/opinion/africas-gigantic-growth-prospects-to-benefit-entrepreneurs-investors-11493909

[174] Gielen, Dolf. (2018). GLOBAL ENERGY TRANSFORMATION - a roadmap to 2050.

[175] Foster, Vivien & Azuela, Gabriela & Bazilian, Morgan & Sinton, Jonathan & Banergee, Sudeshna & de Wit, Joeri & Ahmed, Asad & Portale, Elisa & Angelou, Nicolina & Liu , Jiemei. (2015). Sustainable Energy for All 2015: Progress toward Sustainable Energy. 10.1596/978-1-4648-0690-2.

[176] Global Off-Grid Lighting Association (GOGLA). Global Off-Grid Solar Market Report Semi-Annual Sales and Impact Data; GOGLA: Utrecht, the Netherlands, 2017.

[177] Semero, Yordanos Kassa, Jianhua Zhang, and Dehua Zheng. "Optimal energy management strategy in microgrids with mixed energy resources and energy storage system." *IET Cyber-Physical Systems: Theory & Applications* 5.1 (2020): 80-84.

8. APPENDIX