ECONOMIC FEASIBILITY OF A HYBRID ENERGY SYSTEM FOR KALPITIYA PENINSULA FROM SELECTED TECHNOLOGIES

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Degree of Master of Engineering

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Thesis submitted in partial fulfillment of the requirements for the degree
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DECLARATION

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ABSRACT

Economic feasibility of having a grid connected hybrid energy system, consist of wind, solar, biomass (rice husk) & municipal solid waste (MSW) technologies for Kalpitiya peninsula was studied. Four (04) different microgrid configurations were simulated in HOMER Pro(Hybrid Optimization of Multiple Electric Renewables) for a project life time of 20 years and the economics of each case was compared with the base case, where Kalpitiya peninsula is fed from fossil fuel based (i.e.: diesel) power transmitted through main utility grid. Electricity demand data of Kalpitiya peninsula in every 30 minute interval throughout a day were obtained for the days in calendar year (2018) from Puttalam grid substation (feeder 03) to derive averaged hourly load profile and to study the daily, monthly variation. Average electricity demand in April was found to be the highest of all months in the year and average load in a typical day was 125056.52 kWh with a daily maximum of 8320.5 kW. Considering the recent global market costs trends of installation, operation and maintenance of renewable energy resources as well as the availability of resources, in Sri Lankan context four (04) different configurations of microgrids were simulated in HOMER Pro with the motive of ensuring 100% power supply throughout the project lifetime of 20 years. Most economical option in a private investors' perspective was a microgrid with wind, solar, biomass (rice husk) & municipal solid waste (MSW) in the system which has a discounted payback period of 2.68 years. However, in the perspective of Ceylon Electricity Board, the most economical microgrid consist of wind, solar & biomass (rice husk), where annual cost saving against the base case of LKR 350.5 Mn equivalent to 'stop running' a 1 MW diesel generator for 353 days per year. Sensitivity analysis was performed limiting the grid sales for each microgrid configuration proved that net energy purchase was lowest when the grid sale capacity was 10000 kW. Any of microgrid combinations was not possible to operate in island mode due to the intermittency of renewable resources. However, it was evident that none of the configurations considered solar energy is significant due to the high dominance in wind, biomass & MSW resources.

Key words: Kalpitiya, Microgrid, Renewable energy, HOMER Pro

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

Abbreviation	Description
AC	Alternating Current
AGC	Automatic Generation Control
AWLR	Average Weighted Lending Rate
CAIDI	Customer Average Interruption Duration Index
CAIFI	Customer Average Interruption Frequency Index
CEB	Ceylon Electricity Board
CCM	Continuous Conduction Mode
DCM	Discontinuous Conduction Mode
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generator / Distributed Generation
GHI	Global Horizontal Irradiation
GSC	Grid Side Convertor
HOMER	Hybrid Optimization of Multiple Electric Renewables
IEEE	Institute of Electrical and Electronics Engineers
IRENA	International Renewable Energy Agency
JICA	Japan International Cooperation Agency
LCLTGEP	Least Cost Long Term Generation Expansion Plan
LCOE	Levelised Cost of Energy
LDC	Load Duration Curve (LDC)
ERCOT	Electric Reliability Council of Texas
LSC	Load Side Converter
LVPP	Lakvijaya Power Plant
MEM	Microgrid Energy Manager

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPPT	Maximum Power Point Tracking
MSW	Municipal Solid Waste
NASA	National Aeronautics and Space Administration
NCRE	Non-Conventional Renewable Energy
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
NSSWM	National Strategy on Solid Waste Management
ORE	Other Renewable Energy
PC	Point of Connection
PCC	Point of Common Coupling
PI	Proportional Integral
PMS	Power Management Strategy
PUCSL	Public Utilities Commission of Sri Lanka
PV	Photovoltaic
PWM	Pulse Width Modulation
RDF	Refuse Derived Fuel
RSC	Renewable Side Converter
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control and Data Acquisition
SLSEA	Sri Lanka Sustainable Energy Authority
SSC	Storage Side Converter
SWM	Solid Waste Management
USA	United States of America
VSC	Voltage Sourced Converter

LIST OF APPENDICES

1 INTRODUCTION

1.1 Background

Energy is becoming a basic need for almost every human being in 21st century since the human needs have become more complex and sophisticated in this digital age. The demand for the energy is also increasing rapidly, as the population and economic activities achieved a significant growth across the world. The utilisation of energy from fossil fuel, dominantly for electricity generation, is expanded drastically as a quick response to cater this fast growing demand. Many countries provide continuous electricity supply using central electricity grids for their industries as well as for the general public in widely spread geographical areas, aiming increased economic development and improved community living standards. Therefore, the level of electrification has now become a key measuring index of a country's economic prosperity and social well-being.

Evolving trend in world economic sector is to align with the sustainable development principals mainly due to conservation of limited resources is now at prime importance. Therefore, the energy sector, which has a direct impact on economic activities, is essentially moving towards sustainability. Hence the renewable energy share in the energy mix of many countries are getting increased day by day. In Sri Lanka, both conventional energy sources, such as major hydro and non-conventional renewable energy sources such as solar power, wind power etc. are also utilised consistently in energy mix, which is positively influenced to the country's economic and environmental perspectives.

At present, 36% of primary energy supply in Sri Lanka is fulfilled from biomass, 44% from petroleum, 6% from hydro, 11% from coal and 3% from other renewable energy (ORE) sources. Level of the country's electrification is now over 99%, while ensuring 24 hours uninterrupted power supply and with acceptable power quality. This is a significant achievement of Sri Lankan government, where the government policies are also focussed on maintaining a balance between the economic development and the quality of life in rural and urban areas. Total installed power generation capacity of Sri Lanka is approximately 4,046 MW, with a composition of 900 MW of coal power, 1,575 MW of oil burning thermal power, 1,379 MW of hydro power and 544 MW of non-conventional renewable energy (NCRE) sources such as mini hydro, solar, wind and biomass power plants. The annual total electricity demand of the country is about 15,374 GWh and the expected annual demand growth is around 4-6%. Electricity end user categories, in terms of consumption, consists of a breakdown: 32.6% from industries, 27.9% from commercial enterprises, 37.8% from domestic users and the balance of 1.7% from street lighting, religious organizations etc. The estimated annual average expenditure of fossil fuel imports is nearly 25% of the Sri Lankan import expenditure and 50% of income earned from export. Therefore, the energy sector is obviously causing a huge impact on the balance of trade of the country and exchange rates as well.

1.2 Problem Identification

Kalpitiya peninsula is located in western costal belt in Sri Lanka and administratively it is located in Puttlam district in north western province. Electricity supply to the Kalpitiya peninsula is fed through the Puttalam grid substation as per the existing arrangement of the local power transmission network. Since the retirement of Heladhanvi diesel power plant, Puttalam grid substation is directly connected to New Anuradhapura & New Chilaw grid substations. These two substations are in 220 kV power transmission network, where each substation is located approximately 100 km away from Puttalam grid substation. Therefore, the generated power needs to be transmitted to a distance, more than 100 km, to cater the electricity demand of the end users in Kalpitiya peninsula where the transmission and distribution line losses generally accounts around 8% of generation. Therefore, it may be more economical to generate power locally with indigenous renewable energy and distribute–within Kalpitiya peninsula, where the renewable energy sources are abundantly available in the particular geographical area. It is a sustainable initiative to curtail unnecessary transmission and distribution losses and reduce or replace the usage of high cost diesel power, which leads to save considerable amount of carbon emission.

Substantial amount of wind power is being already generated and operated as grid connected systems in Kalpitiya peninsula. Puttalam district is recognized as a favourable part of the dry zone in Sri Lanka, where the solar power availability is high and consistently available throughout the year at an average intensity of 2000 kWh/m^2 of global horizontal irradiation (GHI). Apart from solar energy and wind energy, there are other indigenous renewable energy sources such as biomass and municipal solid waste (MSW), tidal energy. Those are available in ample amount in Kalpitiya peninsula, which are considered as promising sources of generating electricity.

It is quite difficult to predict the adequacy of available renewable energy resources to meet the electricity demand in Kalpitiya peninsula without studying the behaviour of each energy source. Conducting a proper analysis of seasonal and instantaneous variations of wind patterns, dominantly affects wind power generation. Environmental effects are also dominantly affects solar photovoltaic and tidal power generation. Also it is much important to perform a proper analysis on daily and monthly demand variation in Kalpitiya peninsula prior to such prediction. Therefore, it is really a challenging task to figure out the capability of meeting the electricity demand in Kalpitiya peninsula totally with self-generating renewable sources, as far as generation economics, uninterrupted supply of power and power quality is concerned.

1.3 Motivation

Electricity demand in Sri Lanka, is annually increased by about 4-6% in recent years. The capacity additions is being made continuously to the national grid to cater the increasing electricity demand of the country. These capacity additions were fulfilled from major hydro energy, fossil fuels such as diesel, coal and renewable energy sources such as solar energy, wind energy, mini hydro energy etc. However, the generation mix of the country is selected such that the electricity generation cost is kept at minimal which referred to as the least cost generation regime. Generation cost of an electricity unit from thermal energy sources heavily depends upon the cost of fuel and energy conversion technology. Since the world energy sector is currently facing a threat of depleting fossil fuel resources quite rapidly, the fuel prices of coal and diesel would start ramping up in near future which leads to increase the electricity generation cost significantly. In such situation, renewable energy would play a major role in power generation as it would be a more economical option over the conventional thermal energy generation.

Current energy policy in Sri Lanka is emphasized the target of becoming an energy independent nation by having 100% electricity generation from indigenous energy sources by 2050. In this scenario, solar power and wind power will be highly demanded since both energy sources are freely available in wide geographical areas of the country. Biomass energy is another promising option for electricity generation and have the advantage of non-intermittent electricity output compared to the solar energy and wind energy sources. However the energy conversion technology and type of the fuel used, plays key roles when selecting an appropriate bio energy source. To make the government policy of becoming an energy independence nation a reality, intermediate targets such as increasing the other renewable energy (ORE) portion of national energy mix up to 20% by 2037 is necessary as clearly explained in the least cost long term generation expansion plan (LCLTGEP) 2018-2037 published by the Ceylon electricity board.

Distributed generation is an attractive option to utilise the combined renewable energy sources such as solar energy, wind energy and biomass energy in the grid effectively as the effect of their resultant intermittent behaviour is possible to overcome with emerging technologies. On the other hand, the transmission losses also able to minimise as the energy generated is being utilised in close proximity to the power house without transmitting to the long distances.

Sri Lanka is a favourable country to harness solar energy very effectively due its location near the equator in Indian subcontinent which covers land area of 65,610 km^2 with approximately 1000 km long coastal belt all around the island. Sunshine is available throughout the year in adequate intensity in most parts of the country. As per the solar atlas developed by Sri Lanka Sustainable Energy Authority (SLSEA) and the solar maps developed by National Renewable Energy Laboratory (NREL), Department of Energy in United States of America (USA), it can be clearly identified that a substantial solar energy potential exists, especially in the dry zone of Sri Lanka.

Electricity generation technology from solar energy is still emerging. Once the technologies are sufficiently developed it is possible to extract solar energy more efficiently as the amount of solar energy receipt on the earth surface has a considerably high potential over energy demand. In future, solar energy would become one of the main energy sources connected to most power systems in the world. According to the solar resource maps developed by SLSEA, the annual GHI in Sri Lanka is estimated to be varied in between 1247 – 1903 kWh/m^2 in up country wet zone and 1904 – 2106 kWh/m^2 in mid, low country intermediate and dry zones. These estimations could be viewed more meaningfully on the daily basis where the solar energy potential of the country varied in between 3.4 $kWh/m^2/day$ to 5.7 $kWh/m^2/day$. This is clearly an adequate solar energy potential to harness solar energy with existing energy conversion technologies.

Harvest energy from the renewable energy sources such as wind energy and solar at its highest potential will reduce the commitment from the high cost fossil fuel fired power plants. However, the grid power integrated with such renewable energy is required to be optimised to select the most reliable and economically viable combination of energy sources. Power supply grids too expected to handle the intermittent nature of renewable energy technologies to a higher degree, which is the real challenge to overcome without compromising the reliability and quality of power supply in modern world.

1.4 Research gap

Hybrid energy systems or microgrids is a popular topic in research for electricity generation from renewable sources in the world. Mainly microgrids has been modelled, optimised & analysed for off grid rural electrification schemes such as small islands with a community where the grid connection is distant. Few research papers have discussed the optimisation techniques used to make the designed microgrids much economical replacing fossil fuel fired systems. It could be found that HOMER Pro (Hybrid Optimization of Multiple Electric Renewables) software tool, developed by NREL, Department of Energy in USA, is the microgrid modelling software used for the optimisation, sensitivity analysis where other software packages such as HYBRID2, IHOGA etc.

A hybrid energy system with wind turbines and diesel generator was modelled by K. Ratneswaran [1] for Eluvathiv island in Sri Lanka to run as an off grid system. HOMER Pro was used to model the most economical and reliable system with 02 nos. diesel generators of 45 kW & 15 kW capacities, 80 kW wind turbine and battery storage along with a 16 kW AC-DC converter which has a payback period of 07 years.

A grid connected wind-solar microgrid model was investigated by M. V. P. Geetha Udayakanthi [2] for a location selected in Kirinda, hambantota area after comparing the renewable energy potential of the particular site with the other parts of Sri Lanka. In that study southern coastal belt and north western coastal belt are identified as the best locations for microgrids in terms of renewable potential availability. The study finally has modelled a wind-solar hybrid energy system with a payback period of 3-4 years using HOMER Pro software tool.

Feasibility of having a hybrid energy system with solar PV-wind-diesel technologies for a rural area in Saudi Arabia was studied by S. Rehman, A.M. Mahbub, J. Meyer an L.M. Al-Hadhrami [3] It has concluded that, wind power generation would increase

5% for every 0.5m/s step increment of wind speed while the levelised cost of energy (LCOE) of the hybrid power system showed a linear declination.

A. Shezan, R. Saidur, K.R Ula, A. Hossain, W.T. Chong, S. Julai [4] of Department of Mechanical Engineering, University of Malaya has carried out a feasibility study of an off grid hybrid energy system model for 02 hotels in a remote area, Cameron highlands, consisting of wind-battery storage-diesel using HOMER Pro. The study was conducted as a step towards eco-tourism in remote villages where 15 nos. of 10 kW wind turbines, 4 kW diesel generator with 02 battery storage units became the most economical & eco-friendly system.

A research on performance & feasibility of a wind-solar PV-diesel microgrid in rural areas of Bangladesh was carried out by Mahabub Hasan and Oishe Binty Momin [5]. It was found that having a hybrid energy system with wind-solar PV-diesel has a total net present cost (NPC) less than diesel only system with less fuel consumption & reduces CO_2 emission by 60% rather than using utility grid energy.

Feasibility assessment of an off grid solar PV-diesel hybrid energy scheme for a catholic church was conducted by A.V. Anayochukwu [6]. Incorporation of solar PV to existing diesel generator system was the goal of this research & it was shown that a solar PV could be integrated to the system up to 53% where the generation from diesel could be reduced to 47%.

Hybrid energy system comprising of solar PV-wind-diesel-battery was proposed by M. Laidi, S. Hanini, B. Abbad, N. K. Merzouk and M. Abbas [7] to electrify the remotely located houses in southern Algeria. Microgrid with a renewable penetration of 47% was found to be the most economically viable alternative.

Technical & economic benefits of a hybrid energy system proposed for a rural area in Greece were studied by J. G. Fantidis, D. V. Bandekas and N. Vordos [8] as an alternative for diesel power generation. To identify the critical parameters, sensitivity analysis was carried out competitive technological scenarios in future were also discussed.

A review on optimal sizing techniques of hybrid energy systems done by Victor O. Okinda, Nichodemus A. Odero [9] proved that renewable generation is a viable option to consider in place of utility grid power supply or a replacement for off grid non fossil fuel based power generation for remote areas as well. Further, optimally sized components of hybrid energy system is important for supply reliability & financial viability.

Incorporation of renewable energy sources to a microgrid can be viewed in many perspectives. Ability to cater the electricity demand as much as possible from the microgrid with economic benefits as well as the technical improvements such as power supply reliability, less energy loss would make this financially & technically viable initiative. Most importantly the availability of renewable energy sources as well as the economics of the available energy sources would have to be concerned when a microgrid is to be connected to existing system. Therefore, it is important to evaluate the technical potential & economic feasibility of having a renewable energy based microgrid that could be employed for Puttalam, Kalpitiya peninsula as a pilot project.

1.5 Aim & Objectives

This research is aimed to evaluate the technical and economic feasibility of introducing a renewable energy based microgrid to Kalpitiya peninsula in Puttlam district as a pilot project. The possibility of isolate operation of the proposed microgrid from the national grid, called island mode is also to be evaluated. In this study, it is provided a detailed and optimised microgrid model to be implemented as a pilot project by using a globally accepted software tool expecting to achieve following objectives.

- To critically investigate the best combination of renewable energy sources to be integrated for the proposed microgrid in Kalpitiya peninsula where such microgrid is possible to operate in island mode without feeding power from the national electricity grid.

- To investigate the economic benefits of the proposed microgrid system for Kalpitiya peninsula over the conventional central grid electricity system.

- To make available this research work as a detailed study material about a viable microgrid system for the benefit of community & the country.

1.6 Methodology

The overall methodology and procedure of the research carried out is explained following.

Initially, a suitable location to implement a microgrid had to select based on the harness potential of renewable energy resources such as solar energy, wind energy, biomass energy etc. The distance of the utility grid connection is also concerned. In this perspective, Kalpitiya peninsula was selected as the area of interest to implement the proposed microgrid.

Then the actual hourly electrical load data set of Kalpitiya peninsula is collected for studying the variation of power consumption throughout the day and throughout the month. The derived hourly electrical load profile was used for the modelling of proposed microgrid. Modelling and optimisation of the microgrid was done using the widely accepted commercial microgrid modelling software called HOMER Pro.

In order to perform the simulations, wind resource data and solar resource data (published in NREL database or NASA surface meteorology and solar energy database) available in HOMER Pro software inbuilt libraries were used. Cost data of solar panels, wind turbines, biomass power generation and MSW power generation was manually included to the simulations. The particular global cost data trends was extracted from the data published in International Renewable Energy Agency (IRENA). Financial data such as inflation rate, nominal discount rate and exchange rate was extracted from recent publications of central bank of Sri Lanka to evaluate the economics of the optimised micro grid system configuration.
Evaluation of cost benefits for the proposed microgrid system was performed by compared with power supply from existing grid connection as the base case. Proposed microgrid scenarios were simulated to achieve the highest degree of autonomous control such that the whole microgrid is running in island mode.

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2 LITERATURE REVIEW

2.1 Microgrid System

2.1.1 What is a microgrid

The idea of a microgrid was initially introduced in the literature as a method to integrate the Distributed Energy Resources (DERs) together with Energy Storage Systems (ESSs) and controllable loads. Such microgrid could be viewed as a separate entity from the main electricity grid and it responds to control signals appropriately. There are several discussions regarding a detailed definition for microgrids among the technical forums. With referring to the topology, a microgrid could be recognised as a group of electrical loads, Distributed Energy Generators along with ESSs operated in coordination to supply electricity reliably and it is to the main power grid at the distribution level via the Point of Common Coupling (PCC). [10]

Rising of renewable energy generation continuously, has led the way to change the conventional top-down shape of electrical power grids to a network of smart, flexible power systems smaller in size, denoted as microgrids. Even though it is difficult, U.S. Department of Energy has given a more practical definition for a microgrid as a group of Distributed Energy Resources (DERs) and loads connected with clearly defined electrical boundaries that behaves as one controllable unit with respect to the power system. It can either be connected or disconnected from the power system to facilitate it to run on either on-grid or off-grid mode. However, microgrids would be considered as the building blocks when constructing the future power grid. [11]

Microgrid can also be described as a bunch of local electrical sources and electrical loads which are operated in a synchronised connection with a conventional power grid while it can also be functioned as an autonomous system in off-grid condition. [12]

Being a regionally limited power system, microgrid optimise the power quality and economic benefits while increasing the reliability, sustainability of power supply through operating in on-grid, off-grid or in dual modes continuously by changing the characteristic of the connection with the grid. [13].
According to the prevailing grid codes, all distributed generation should shut down during utility power outages whether it is renewable or fossil fuel. With reference to the definition, microgrid can maximise the benefits of distributed generators by utilising the power from distributed generation during utility power system outages. [13]

During the past decade, more small scale technologies used for the utilisation of DERs have shown a considerable growth as they have become economically feasible. Growth of utilising DERs has helped more communities and individual entities towards the operation of microgrids that allow consumers greater control over their energy resources. Most of the DERs which are employed in microgrids are renewable, intermittent generation such as wind power and solar power. [14]

2.1.1.1 DC Microgrid

The growing demand to employ more power from renewable energy sources such as solar energy has paved the way to a Direct Current (DC) microgrid. PV modules generate DC electric power and DC microgrid consists of interfacing converter such as grid-connected inverter, DC converter and bidirectional converter, voltage-balancer etc. If the microgrid is to be synchronized with available commercial grids, the power generated from DC microgrid should be converted to Alternating Current (AC). [12]

2.1.2 Components of a microgrid

With the development of power electronics and energy storage technology, microgrids had become more popular in power systems. As described in section 2.1.1, microgrid is a subunit of distribution consisting of distributed generators (DG), inverters, energy storage system, loads and monitor devices. [15]

As illustrated in figure 2.1, microgrids can have many distributed energy sources like solar PV, wind, hydro and controllable generation comprising of fossil fuel fired thermal power, biogas, hydro etc. including both non-dispatchable and dispatchable generating units. Apart from that the energy storage, consumers are also connected with microgrid where it connects to the main utility grid through common coupling as well. The status of the connection between the microgrid and main utility grid and microgrid is subjected to change comparing the generation from the microgrid and the power consumption by the loads at that particular time. [13]

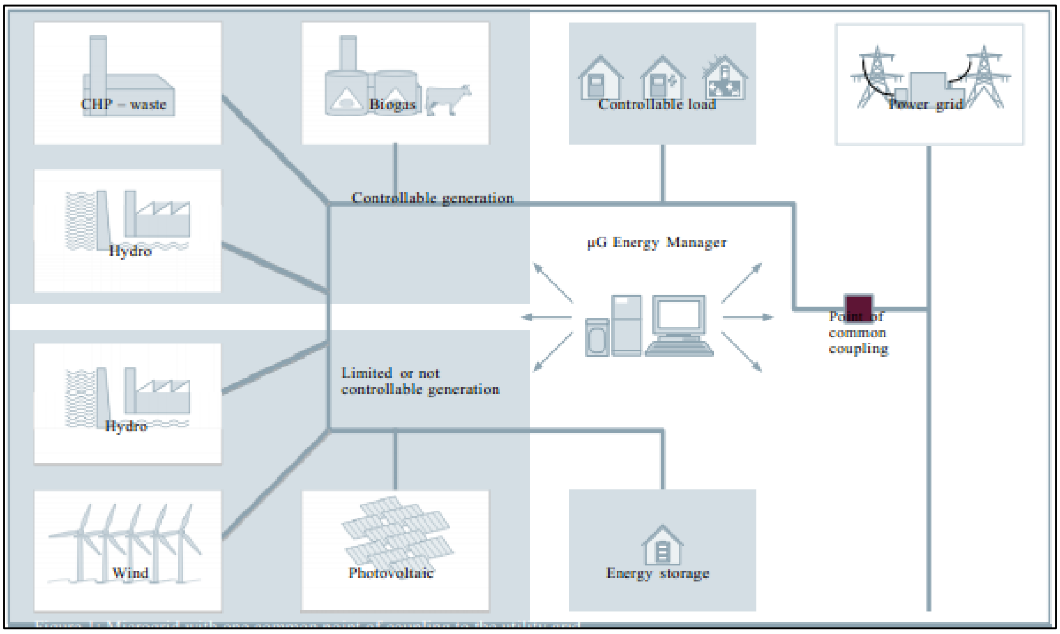


Figure 2.1: Microgrid with one common point of coupling to the utility grid [13]

Microgrid energy manager (MEM) indicated in figure 2.1 is a software for monitoring and control, that generally comprises of functions such as SCADA (Supervisory Control and Data Acquisition), energy management, generator and load management, system reconfiguration and black start [16]after a fault, system efficiency monitoring, carbon dioxide contribution analysis, system health monitoring and other functions. [13] Information flow and the functions of MEM could be illustrated as per the figure 2.2 below.

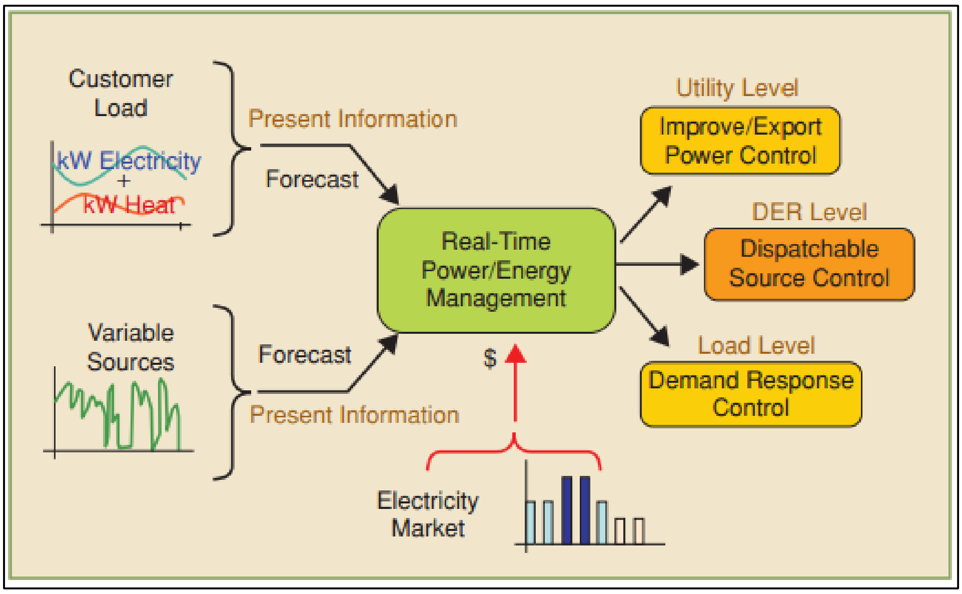


Figure 2.2 : Functions & information flow of Microgrid Energy Manager (MEM) [16]

As shown in Figure 2.2, MEM receives the real-time and the projected values of electrical load, generation, as well as the market information to offer the appropriate control directives on power flow, generation output and energy consumption level from the utility grid, controllable loads, and dispatchable sources respectively.

2.1.2.1 Configuration of a DC microgrid

In a DC microgrid, DERs, electrical loads, battery storage are connected to DC bus through various converters such as Load Side Converter (LSC), Storage Side Converter (SSC), Renewable Side Converter (RSC) and other required devices. Connecting of DC microgrid with main AC grid power grid is done via Grid Side Converter (GSC). Diesel generator is connected to AC grid side power directly as the generated power is in AC form. GSC is capable of handling reverse power flow. SSC has a DC-DC converter which is in between DC bus and storage equipment such as flywheel, battery storage, super capacitor and EDLC (Electric Double Layer Capacitors) etc. Renewable energy sources or DERs such as solar PV cells, fuel cells, wind turbine, etc. has an interface RSC to connect with DC bus. General arrangement of a typical DC microgrid is illustrated in figure 2.3. [12]

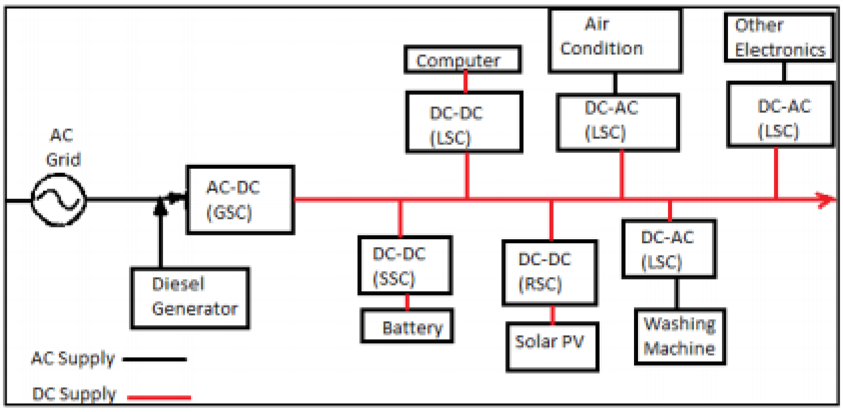


Figure 2.3 : Layout of a DC microgrid [12]

Unlike in AC microgrids, issues like voltage, frequency and synchronisation does not encounter in DC microgrids. It also reduces energy loss resulting from AC/DC converters so that it reduces the utility cost which in return improves the system efficiency. [12]

2.1.3 Operation modes of microgrids

Basically a microgrid can be operated in two modes. They are on-grid mode and the off-grid mode. When the microgrid is connected to the grid, it assists to reduce the load of the grid and save the energy from fossil fuel as well. In the off-grid or islanding mode, electricity will be supplied for critical loads only which make the critical loads operate without a power shortage during the main power grid failures. Switching between the two operating modes is actuated automatically. Control technology of microgrids has to be studied to realize the effects such as fluctuations, when accessing microgrids into main power grids. [15]

As shown in the figure 2.4, the microgrid covers 03 feeders, A, B, C and load in a radial network structure. Power from the microgrid can be solar PV power generation, fuel cells, micro gas turbines, and all other forms. If the micro power sources is placed near a heat demand, it can become a heat source for the local utilisation, thus make maximum use of the heat and power. [15]

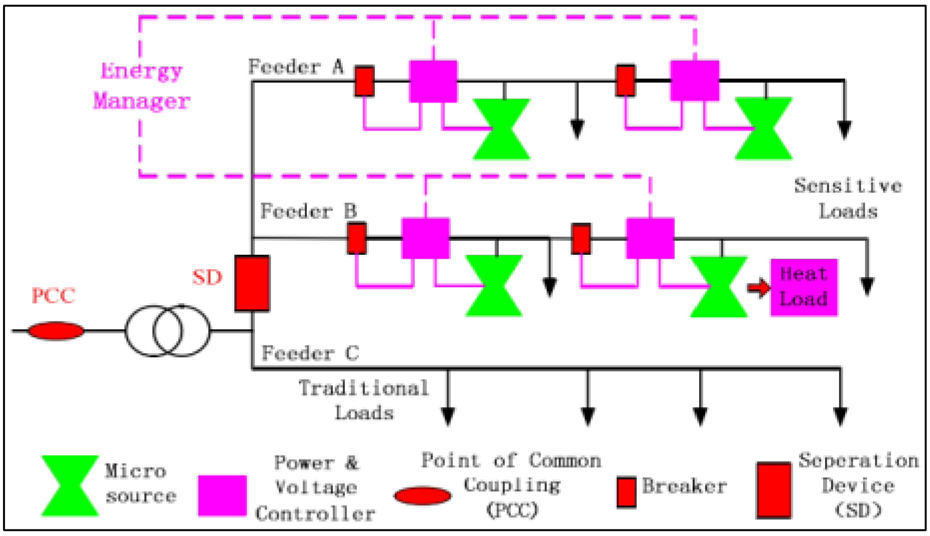


Figure 2.4 : Basic structure of a microgrid [15]

2.1.3.1 Grid connected mode

During the grid-tied mode, the microgrid operator or MEM could decide whether to sellback or purchase energy considering the operating energy cost, generation capability on-site, and the prevailing prices on the energy market to operate the system more economically. [13]

The DER units produce prescribed amount of power which would minimise power purchasing from the grid (peak shaving). Each DER unit is controlled to represent either a (real/reactive power) PQ-bus or a (real-power/voltage) PV-bus. Therefore, the main power grid should be able to absorb the difference in supply and demand of real/reactive power within the microgrid. [16] Sometimes grid tied systems can switch to islanded mode (referred to as emergency mode) where they maintain a connection with the grid and will typically consume power from the grid when there is a high internal demand and no adequate generation while exporting power into the grid when internal generation is higher than internal demand. When the system is on-grid, it is less strict regarding the necessity for power generation and energy storage, the power from the grid compensate during any power shortfalls. Once it is economically favourable microgrid would import energy straight away from the grid. [14].

2.1.3.2 Off-grid mode

An on-grid microgrid can switch to islanded mode only when the main utility grid has a failure where no power is supplied to the microgrid. [14] In the case of main power grid outage, the breaker at the PCC will open automatically and own generating units within the microgrid will keep uninterrupted power supply to loads. [13] Islanded systems have no connection with any national or regional power grids and it must generate all the necessary power on its own. [14]
However, in the islanding mode, the power output of DER units should match the total load demand within the microgrid. Otherwise, the microgrid shall implement a load-shedding process to match the actual power output against the demand. [16]

2.2 Controlling of Microgrids

2.2.1 Need to control a microgrid

Within any power system, generated power must tally with the real-time consumer demand as electricity is a perishable (it must be used immediately upon creation) commodity. However, consumer demand can vary even within a short timescale such as seconds, minutes and actual power demand requirement is generally met by generating power in excess of actual demand. ESSs can help to get a relief from the perishable property of electricity. Short term energy storage is already employed within an electricity grid named as spinning reserve as flywheels with large inertia and other methods such as battery backup. It helps to maintain the grid robust, flexible and compensate the excess capacity requirements. Short term storage will discharge most of its stored energy within 15 minutes due to friction and kinetic losses. Energy storage is significant in an electricity grid and microgrids in terms of system regulation (frequency and voltage), spinning reserve, peak shaving, peak shifting, load levelling, and transmission support. [14]

Efficient and effective functioning of a microgrid that has multiple DER units requires a power management strategy (PMS) or an energy management strategy (EMS) especially for islanding operation. Quick response of the PMS/EMS is very critical for a microgrid in comparison with a conventional power grid. The reasons are,

1) Consisting of many DER units with different characteristics and generation capacities
2) Unavailability of potentially dominant source of power generation to operate in island mode (i.e.: lack of infinite bus)
3) Fast response of connected DER units which can affect voltage/angle stability adversely in the absence of appropriate provisions [16]

When a microgrid switches to islanding mode from the grid connected mode, frequency of microgrid can be affected severely due to the unbalance between power demand and power generation. In that particular moment, DERs may react slowly to balance the situation. In order to operate the microgrid steadily without any interruptions, storage systems with quick response such as Battery Energy Storage Systems are needed. [17]

Microgrids and integration of DER units, introduce a number of operational challenges that has to be addressed in the design of control, protection systems so as to ensure the reliability levels are not affected significantly and the potential benefits of DG are fully utilised. Unrealistic assumptions which are only applicable to conventional distribution systems make new operational challenges, while some of them result in stability issues generally observed only at a transmission network level. [10]

2.2.2 Variables to control in microgrids

Voltage, frequency, and active and reactive power are the most important variables to control the operation of a microgrid. In grid connected operation mode, frequency of the microgrid and the voltage at PCC are dominantly determined by the main utility grid. The main task of microgrid control is to utilise the active and reactive power generated by the DER units and serve the load demand. Reactive power generated by a DER unit can be used for voltage control, reactive power supply, or power factor correction at the corresponding Point of Connection (PC). In grid-connected mode, regulation or control the voltage by DER units close to the PCC may not allowed by the main utility grid to avoid any interference (determined by the electrical distance and Short Circuit MVA of the grid) as the same functionality provided by the grid itself. [10]

The standalone mode of operation is more challenging than the on-grid mode, because the equilibrium of demand and supply of electricity is critical. Then voltages and frequency regulation of the microgrid are not assisted by the main power grid, those variables should be controlled by different DER units. Accurate load sharing mechanisms should be implemented to balance the sudden active power mismatches in order to control the voltage and frequency. Power balance is ensured either by a MEM which communicates appropriate set points to local controllers of different DER units and also to controllable loads or by local controllers utilising local measurements directly. Purpose of power balancing strategy is to make sure that all DER units engage in serving the load demand in a pre-specified manner. [10]

Problem of high circulating current could initiate as a result of a minute difference of amplitude, frequency or phase angle of the output voltage of any DER unit in the microgrid. In the technical literature this issue is investigated extensively and various types of control strategies were introduced to overcome the issue. One such strategy is to control one of the inverters to operate as a dominant master unit so that it regulates the voltage of the microgrid where the same unit is capable of controlling frequency in open loop with the help of an internal crystal oscillator. DER unit connected with the master inverter can be viewed as a synchronous generator with a typical reactive power-voltage droop characteristic and other DER units can export active, reactive power following the set points determined by the secondary controller. DC microgrid can also be controlled in a similar approach with a master DER unit to control the voltage level of the microgrid by compensating for sudden active power mismatches. Rest of the DER units can handle any active power mismatches in a shared manner using active power-voltage droop characteristics. [10]

2.2.3 Control strategy of microgrid with multi DERs

Considering the desired functions and realistic possible operational scenarios, control strategies could be selected for DER units in a microgrid. DER unit controls can also be determined by the way it deals with other DER units within the system. Controlling active-reactive power and/or voltage-frequency of a DER unit are the main control functions. [16]

Table 2.1 provides a general categorisation of the main control functions of a DER unit and the strategies are divided into major control approaches as the grid-following and grid-forming controls.

Table 2.1 : Categories of major functions of a DER in a microgrid [16]

	Primary Energy Source (PES)	Interface/Inversion	Power Flow Control
Conventional DG	Reciprocating engines	Synchronous generator	AVR & Governer control (+P, ± Q)
	Small hydro		
	Fixed-sped wind turbine	Induction generator	Stall or pitch control of turbine (+P, - Q)
Nonconventional DG	Variable-speed wind turbine	Power electronic converter (AC-DC-AC conversion)	Turbine speed and DC Link voltage controls (+P, ± Q)
	Microturbine		
	Solar PV	Power electronic converter (DC-DC-AC conversion)	MPPT and DC Link voltage controls (+P, ± Q)
	Fuel cell		
Long-term storage (DS)	Battery storage	Power electronic converter (DC-DC-AC conversion)	State-of-charge and/or output voltage/frequency controls (+P, ± Q)
Short-term storage (DS)	Super capacitor	Power electronic converter (DC-	State-of-charge (+P, ± Q)

		DC-AC conversion)	
	Flywheel	Power electronic converter (AC-DC-AC conversion)	Speed control (+P, ± Q)

As summarised in table 2.2 each control approach can be divided further into non-interactive and interactive strategies referring to the communication with main utility grid. When the direct control of voltage and/or frequency at the PC is not required grid-following approach is adopted. If the output power of the unit is controlled independent of the other units or loads (non-dispatchable DER unit), then it constitutes a grid non-interactive strategy. An example of grid non-interactive strategy is the Maximum Power Point Tracking (MPPT) control of a solar-PV unit. However, grid-interactive control strategy is based on specifying set points for active/reactive power output. Power output set points are specified according to a power dispatch strategy or else active/reactive power compensation of the load or the feeder. [16]

Table 2.2 : Control Approaches [16]

	Grid-Following Controls	Grid-Forming Controls
Non-interactive Control Methods	Power export (with/without MPPT)	Voltage and frequency control
Interactive Control Methods	Power dispatch Active and reactive power support	Load sharing (droop control)

2.2.3.1 Grid-following control

The grid-following power export control strategy is commonly used to control the DER power output within the pre-determined voltage and frequency limits by the microgrid. If the coupling converter is a voltage-sourced converter (VSC), a current controlled strategy can be used to determine the reference voltage waveforms for the pulse-width modulation (PWM) of the VSC. The reference signals are also synchronised to the microgrid frequency by tracking the PC voltage waveform. [16]

Figure 2.5 shows a control block for grid-following power export strategy with a DC link voltage controller (VDC Control) and a reactive power controller (Q Control). Power extracted from a DER is fed into the DC link, so that it increases the DC link voltage. Then the voltage controller acts by specifying an adequate value of the d-axis inverter current (i_d (ref) – active component of current) in order to balance the power flow at the dc link.

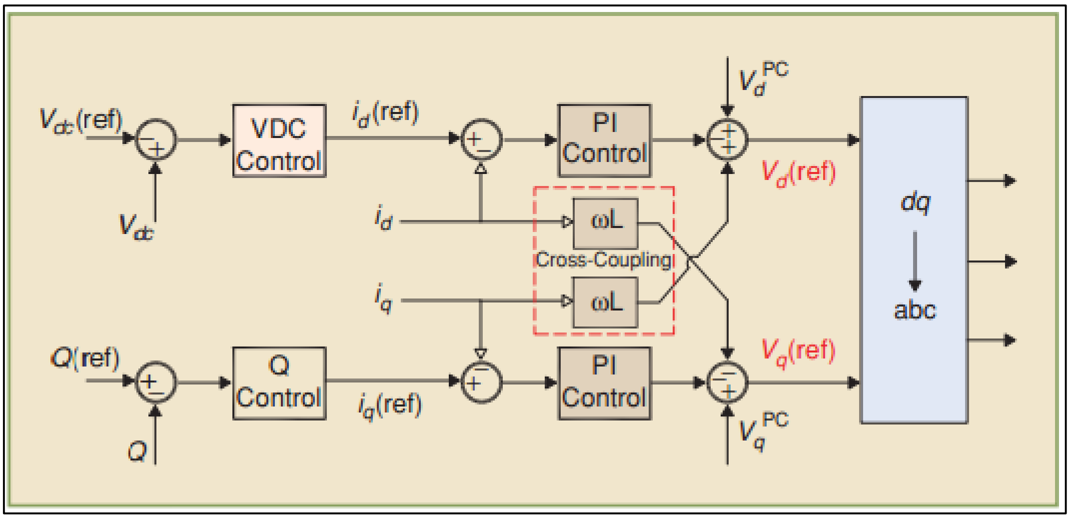


Figure 2.5 : Grid-following power export control diagram [16]

The reactive power controller of Figure 2.5 specifies the reference value for the q-component of the converter current (i_q (ref) – reactive component of current). The Q (ref) value is get close to zero if the power factor improves towards to unity. It also shows two proportional-integral (PI) controllers for the d-axis and q-axis current controls, the voltage feed-forward terms, and the cross-coupling elimination terms. The outputs from the current controllers, after transformation, constitute the reference voltages for the PWM signal generator. One of the main features of the current control strategy is its inherent capability to limit the converter output current during a microgrid fault and thus provide over current protection for the converter and reduce the fault current contribution of the unit. [16]

2.2.3.2 Grid-forming control

In this control approach behaviour of a “swing source” is emulated during an autonomous operation of microgrid. A DER unit within a microgrid could be assigned to regulate the voltage at the PCC and stabilise system frequency effectively. The DER unit must be having adequate reserve capacity to compensate for the balance power. If two or more DER units actively participate in the grid stabilisation and voltage regulation, then typical frequency-droop and voltage-droop control strategies are used to share real and reactive power components. In this case, the actual voltage and frequency within the microgrid could deviate from the rated values, but still within acceptable limits, in relation to the load level and the droop characteristics. [16]

Figure 2.6 shows frequency-droop (f-P) and voltage-droop (v-Q) characteristics where each is specified by its slope (K_{fP} or K_{vQ}) and a base point representing either the rated frequency (f_o, P_o) or the nominal voltage (V_o, Q_o), respectively. The droop coefficients and the base-points can be controlled through a restoration process to dynamically adjust the operating points of the units. This is achieved by dynamically changing the power sharing levels to set the frequency and voltages at new values. The restoration action is normally imposed very slowly and may also be exploited during resynchronisation of an autonomous microgrid. [16]

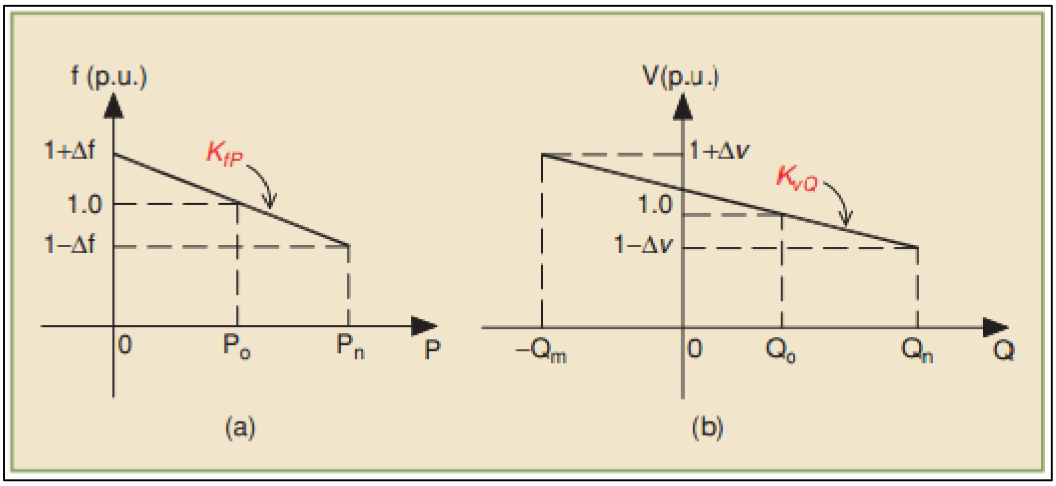


Figure 2.6 : Droop characteristics for load sharing in multi DERs. (a) f – P droop (b) V-Q droop [16]

A block diagram of a droop control strategy is shown in Figure 2.7. The inputs to the controller are the locally measured deviations in the frequency and the terminal voltage of the unit. If DER units have different capacities, the slope of each droop characteristic is selected proportional to the rated capacity of the corresponding unit to prevent overloading. [16]

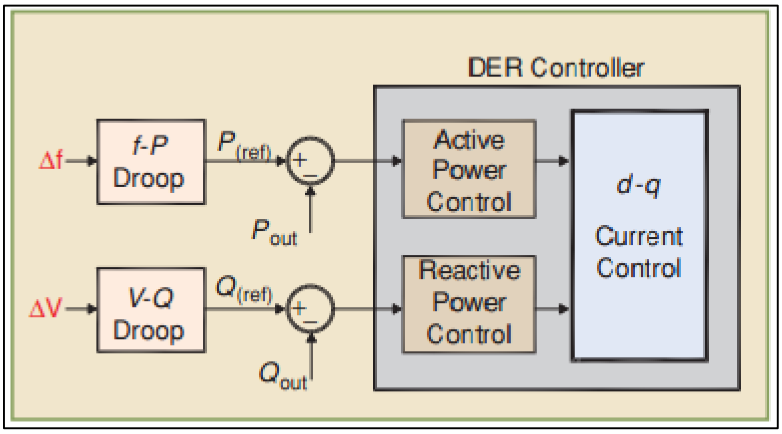


Figure 2.7 : Droop control strategy [16]

2.2.4 Active power & reactive power control

Quick responsive and flexible active, reactive power control strategies are required to minimise the impact of microgrid dynamics such as islanding transients, damp out power and frequency oscillations. Generally, these control strategies are used for output power control of dispatchable DER units, using prescribed reference values for real power dispatch and reactive power compensation. The control structure is conceptually similar to that of Figure 5.7. The main differences are in the methods used to generate the reference values. [16]

As illustrated in the control block diagram in figure 2.8, output active power and reactive power of a DER unit is controlled with reference to a specified set point. P(ref), Q(ref) are the active power, reactive power set points and P_{out} and Q_{out} are the feedbacks of calculated active power, reactive power outputs using the measured actual output voltages and currents of DER. Setting of values for P(ref) and Q(ref) shall be done by a supervisory power management unit (i.e. : microgrid energy manager – MEM) or it could be calculated locally according to a given load profile in order to export optimal active, reactive power from the unit. Commonly applied other methods are based on compensating variations in the local load, peak shaving profiles, and/or smoothing out fluctuations in the feeder power flow. Two specific cases of reactive power compensation are based on voltage regulation of the unit at the PC and power factor compensation. [16]

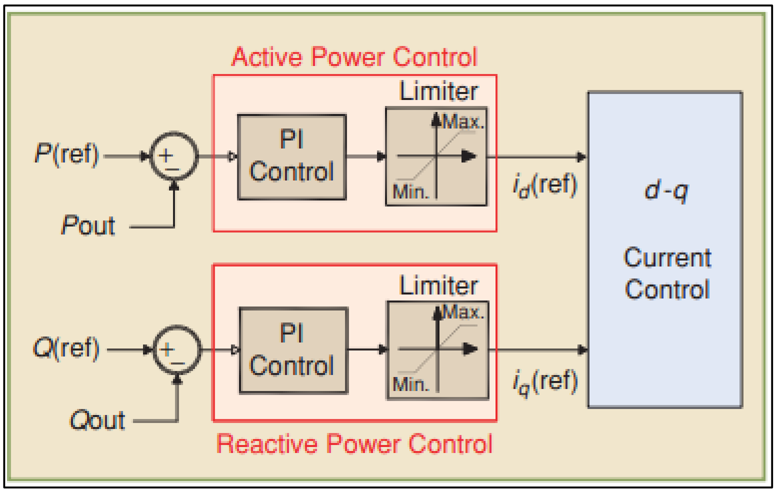


Figure 2.8 : Active and reactive power control [16]

2.2.5 Voltage balancing & control of DC microgrid

Balancing voltage of a DC microgrid is done using a dual bulk half bridge voltage balancer shown in the figure 2.9. It consist of two bridge legs, namely left bridge leg and right bridge leg and a neutral line which usually connected to earth. In this component, complementary driving technology is used between two (Metal Oxide Semiconductor Field Effect Transistor) MOSFET switches as the control strategy shown in figure 2.10 where the expectation is to drive the left bridge leg and the right bridge leg respectively based on the different power quantity of the unbalanced loads. Each bridge consists of MOSFET switches, diode, inductor and capacitor. [12]

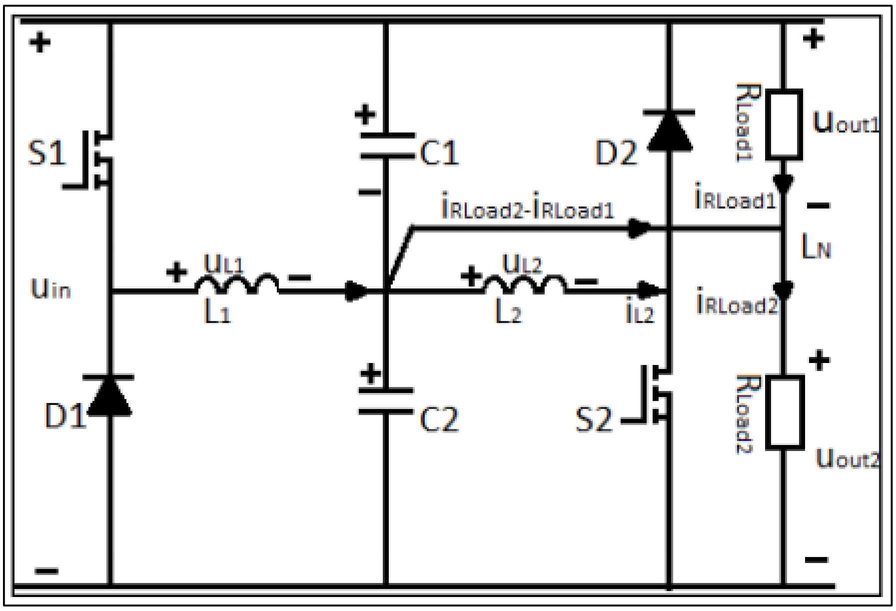


Figure 2.9 : Dual bulk half bridge voltage balancer [12]

Switch S1 is controlled by the output signal (+ue) of the voltage regulator while the negative value (-ue) controls switch S2. The PI algorithm is used as a feedback of current controller. The signal ue is positive when $R_{Load1} > R_{Load2}$, and the left bridge leg is on, where the right bridge leg is not working at that time. As a result of complementary driving technique, only one of the two bridge legs will operate during every switching period. [12]

For simplifications, some assumptions are made such as following.

1) During each switching process output voltages U_{out1} and U_{out2} do not change.
2) All diodes and power switches are the ideal devices do not consider voltage drops and losses.
3) All capacitors and inductors are ideal, and C1 = C2 = C, L1 = L2 = L [12]

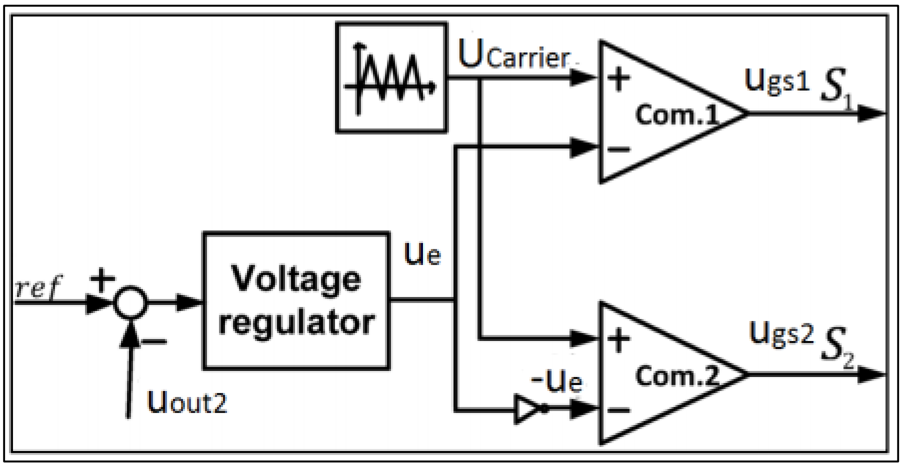


Figure 2.10 : Control Strategy [12]

Each bridge operates in continuous conduction mode (CCM) and discontinuous conduction mode (DCM).

2.3 Grid Interconnection of Microgrids

There is a series of technical standards, namely IEEE Standard 1547 which specifies industrial standard for integration of microgrids and distributed electric power resources to a main utility grid. IEEE Standard 1547™ is published in 2003 and is named as the "IEEE standard for interconnecting distributed sources with electric power systems". Configuration, design specification and operation modes of microgrids are included IEEE 1547 which makes references for formulation, planning, design and integration of microgrids, DERs for grid-connected & islanding schemes. [18]

The typical modular size of variable renewable technologies is well suited to distributed power generation systems in which a number of small power plants are connected to the distribution grid and produce electricity in close proximity to the demand site. [19]

2.3.1 Renewable energy penetration

The penetration is defined in two basic ways. One is in relation to energy and other is in relation with peak power.

Defining penetration by energy, quantifies the energy supplied to the system from renewable sources of interest and it directly relates to displaced power from fossil fuelled sources. It is also a measure of savings in fuel consumption and reduced emissions. The energy based definition is very useful for large systems and it is used in many Renewable Portfolio Standards. Since it depends on the quality of energy resource it inherits a complicated nature. [20]

Peak power based definition provides more of a consistent relationship between penetration and circuits' problems. If any analysis deals primarily with problems in power system, the peak power based definition for penetration is much preferred. [20]

$$\text{Penetration} = \frac{\text{Name plate capacity of intermittent resource in the system/circuit}}{\text{Peak load of the connected system/circuit}}$$

Eqn 2.1: Renewable energy penetration [20]

2.3.2 Generation flexibility

Planning the generation to have flexibility deals with two basic aspects of controlling frequency. Economic re-dispatch of units for every 05 minutes (called load following) is one aspect where the units are re-dispatched for every five minutes as per the economic order or merit order by specifying new load set points from control centre to all generators. Automatic Generation Control (AGC) (called regulation) is the other aspect controlled centrally where every 04 seconds the updated set points are communicated to units participating in AGC. Both aspects should be evaluated relative to the net load of the system. Understanding the load-following and regulation capabilities of a power system is significant in determining the response of the system to load changes and in evaluating its ability to maintain the frequency within the desired control range. [20]

As the penetration of renewable generation increases, obviously the net load variability increases. If the net load variability becomes higher than the available load-following flexibility of the generation units in reserve margin these generation units are forced to absorb the burden of variability and then it might become uneconomical.

Thus other options to manage net load variability should be considered. Options such as load control, load shifting, use of energy storage, and curtailment of renewable generation sources all can be used to reduce net load variability at the time scale of load following. [20]

2.3.3 Methods of increasing renewable penetration

Over the next few decades, carbon free power generating options such as solar PV, wind that will evolve dramatically in power systems. Useful integration of intermittent renewable sources such as solar PV, wind is considered in three general methods. [21]

The amount of usable renewable energy is largely determined by the flexibility of the existing electric power system to vary load. System flexibility is defined as the fraction below annual peak to which a conventional generation fleet may reduce output. [21]

$$\text{System flexibility factor} = \frac{\text{Annual Peak load} - \text{Minimum load from conventional generators}}{\text{Annual peak load}}$$

Eqn 2.2 : System flexibility factor [21]

The flexibility factor of electric power systems will vary by region and by country. Power systems dominated by nuclear power (such as France) will likely to have less flexibility, while systems relying largely on hydroelectric generation (such as Norway) will probably have greater flexibility. A flexibility factor of 60–70% represents a typical flexibility factor for USA based on historical electricity market data. [21]

2.3.3.1 Generation planning approach

2.3.3.1.1 Traditional generation planning process

In traditional approach variable generation is not considered. Hence, the variability is simply excluded from capacity planning. The overall process initialises with forecasting of load demand growth followed by the forecast of the peak demand growth. Capacities of generation and transmission are then planned to match the forecasted peak load. However, renewable generation is considered as “available” during system operation, and the output from committed thermal units is reduced to make the provision for the energy produced by the renewable sources. Eventually, the committed thermal units will operate below the rated power output with lower efficiency, higher emissions, greater operating costs and sub-optimal system operation as the overall result. [20]

2.3.3.1.2 Emerging generation planning process

The emerging generation planning approach incorporate the renewable energy supply at the initial stages of the planning process and consider it during energy growth forecast which allows for more integration of renewable generation for the planning process. The key point is the consideration of variable renewable power generation as a portion of the load. Therefore, the planning process is based on the net load where the variable renewable generation is deducted from the system load to account for incoming from renewable generation. As the renewable generation is varying the applicable load to reduction is estimated analysing the historical renewable resource data which is scaled up to forecast the renewable generation from already existing and newly planned installations. The resulting net load has increased load variability compared with the existing system. When variable renewable penetration is high the scenario of the system must be investigated to make sure system flexibility to match with increased variability. Then, generation and transmission are planned based on the net load and with adequate system flexibility to meet the net load variations. This evaluation of flexibility is significant, since it directly affects system operating costs. As per the load variation, merit order of dispatch might have to be changed to supply the equivalent amount of “pure load” in the most economical way. [20]

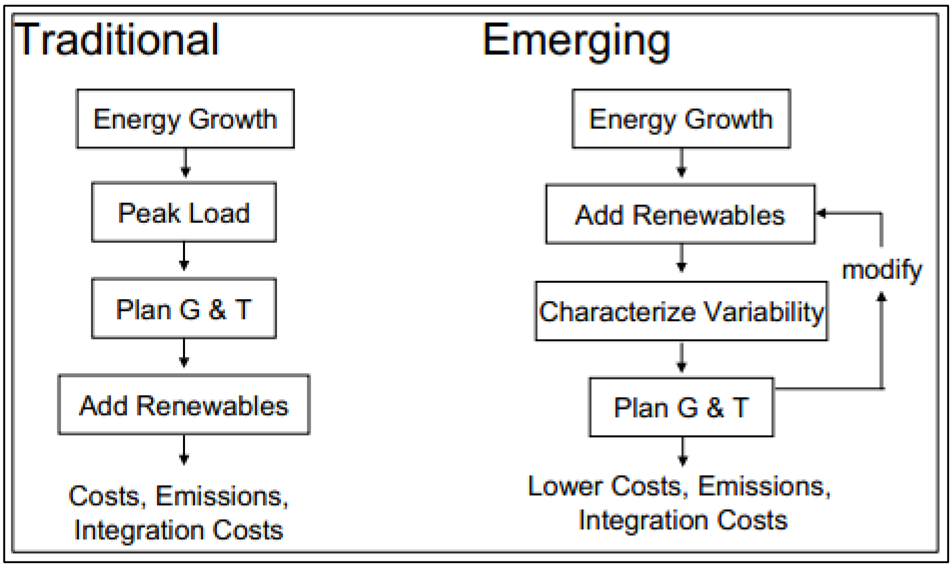


Figure 2.11 : Traditional and Emerging Practice in Generation Planning [20]

Comparison between the traditional and emerging practices is indicated in figure 2.11 above. The attractive option is to reconsider the incorporation of renewable generation. Therefore the evaluation process is iterative, as denoted by the "modify" return step in the flow chart. Evaluating various options in the context of generation planning enables meaningful comparison of the costs versus the benefits they provide. [20]

2.3.3.2 Increasing renewable penetration by improving system flexibility

Increasing overall utility system flexibility is one important alternative to increase the penetration of intermittent renewable such as solar PV, wind etc. economically. This is illustrated graphically in figure 2.12, load duration curve (LDC) for Electric Reliability Council of Texas (ERCOT) for the year 2000. On the curve a minimum loading point at 35 % is placed (equal to a flexibility factor of 65%). In conventional energy systems, all of the energy below this point (equal to about 62% of the total annual energy demand) would be met with inflexible base load plants, limiting renewable variable sources to the upper part of the LDC (which provides about 38% of the total annual demand).

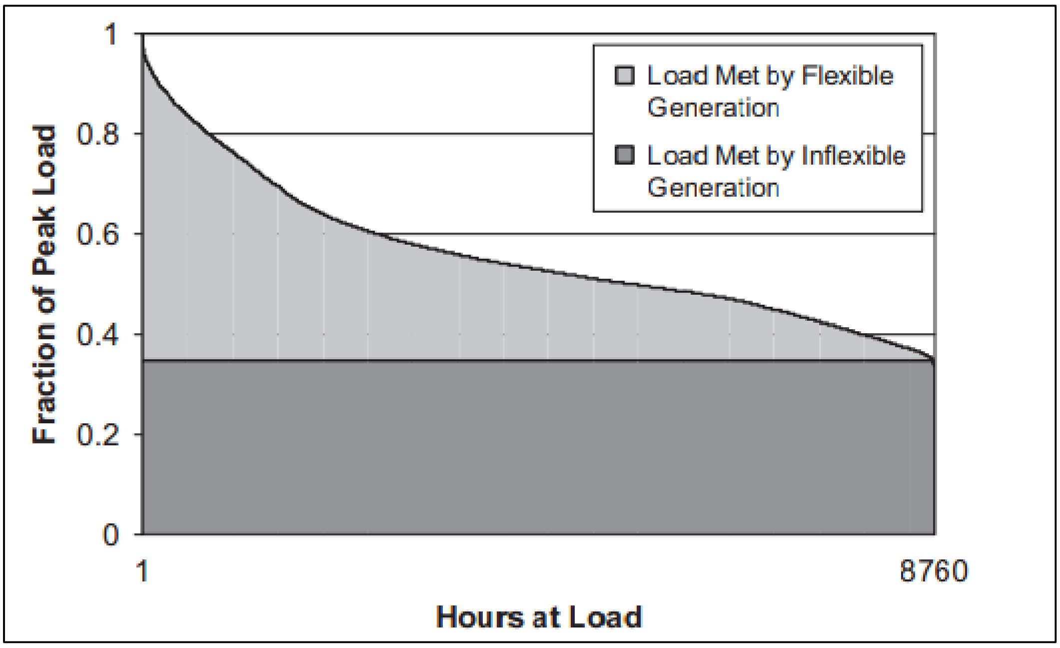


Figure 2.12 : Load Duration Curve for the ERCOT System in 2000 [21]

By varying the minimum loading point in the load duration curve, relationship between flexibility factor and annual energy that may be met by ‘‘variable’’ sources of power can be examined. This relationship is illustrated in figure 2.13. [21]

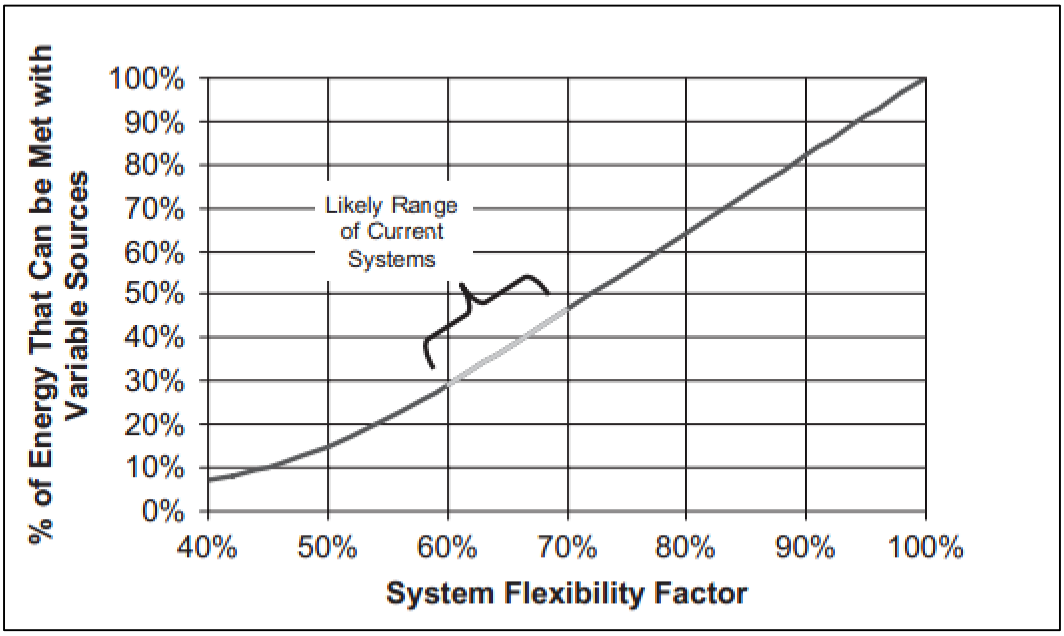


Figure 2.13 : Relationship between flexibility factor and energy produced by variable sources [21]

If a ‘‘typical’’ flexibility factor is assumed to lie 60–70%, the inflexible base load power plants provide from 54% to 71% of the total energy, leaving only 29% – 46% of the available load to the ‘‘variable’’ sources of electric power. As a result, for a traditional electric power system, even if PV could provide all of the energy in the variable part of the demand (through the use of storage for example), it would be unable to provide half of a system’s energy with ‘‘normal’’ flexibility factors.

2.3.4 Transformations in power grids for high penetration of variable sources

The integration of a significant amount of variable renewable energy (e.g. wind, solar etc.) into power grids requires substantial transformations to increase the flexibility of the existing grids. [19]

1) To allow electricity flow, not only from centralised power plants to users, but also from small users/producers to the grid, which is aimed to ensure grid stability when installing distributed generation.
2) To establish intelligent grid and demand management mechanisms aimed at increasing flexibility and responsiveness and reducing peak-loads in order to deal with increased variability.
3) To improve grid interconnection at the regional and international level aimed at increasing balancing capabilities, flexibility, stability and security of supply.
4) To introduce energy storage capacity to store electricity (energy) from variable renewable energy generation when production exceeds demand.

These transformations are nothing but the implementation of smart grid technologies which incorporate grid elements with “smart” functionality to balance supply and demand, together with information and communication technologies to increase flexibility, improve reliability. The experience gathered to date comes mainly from European countries with significant wind and solar installed capacity, such Denmark, Germany, Italy, and Spain. In these countries, associated issues are being solved in the light of further increasing the renewable electricity share. Experience with the integration of a very high (50%) share of variable renewable energy is available from applications on small islands. [19]

2.3.5 Impact of system reliability of integrating microgrids

With the development of the smart grid, more and more DGs are introduced to the distribution networks, which affect the power system reliability obviously. DGs, which are defined as generations with the capacity of less than 10 MW, are widely introduced to the present power distribution systems. Although these distributed energy resources have many advantages such as low investment, environmental friendliness and high flexibility, they have also altered the structure of the traditional distribution system and brought many uncertainties to the present system. In addition to uncertainty of DG's output, the power flow direction in distribution networks with DGs is changed with the operation state of networks, namely, bidirectional power flow, which brings uncertainty for operating condition of distribution networks. Frequency offset and voltage fluctuations are also challenging to the power quality and reliability of distribution system. [18]

Considering the influence of the distributed power supply on the distribution system reliability, the sequential Monte Carlo simulation method is used to evaluate the system reliability based on the minimal path of the DG. The reliability indices defined in IEEE Standard 1366^{TM} are utilised to give a reference to the quantitative assessment of the reliability benefit brought by DG.

IEEE Standard 1366™ (2012) is named as "IEEE guide electric power distribution reliability indices". The defined indices in this standard are used to study the reliability impact of DG. Specifically, the following indices are used.

SAIFI: System Average Interruption Frequency Index

SAIDI: System Average Interruption Duration Index

CAIDI: Customer Average Interruption Duration Index

CAIFI: Customer Average Interruption Frequency Index

A simulation test is carried using a sequential Monte Carlo method with minimal path method referring to IEEE Standard 1547 out to evaluate the effectiveness of having DGs for a distribution system.

The figure 2.14 shows a distribution system developed according to minimal path method without DGs.

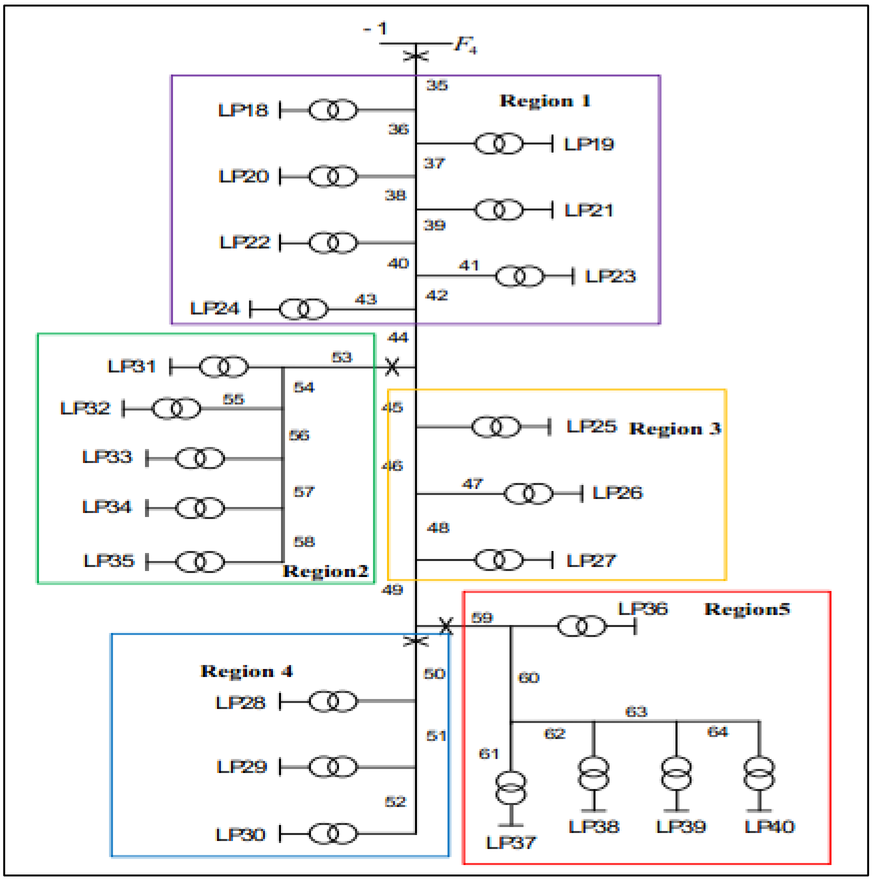


Figure 2.14 : Electricity distribution network without distributed generation [18]

The values of system reliability indices obtained by simulation in sequential Monte Carlo method for the distribution network which draws power only from utility grid without any distributed generators are compared with standard values in the IEEE Standard 1336.in table 2.3.

Table 2.3 : System reliability index comparison - Distribution system without DGs [18]

RBT-BUS6	SAIFI (time/year)	SAIDI (h/year)	CAIDI (h/year)	ASAI
Results of calculation	1.98686	11.14200	5.60783	0.998725
Standard results	1.97781	11.46011	5.79433	0.998692

The percentage error of each system reliable index is between 0.003% and 3.219%, maximum error of which is less than 5%. Thus the simulation results could be considered as appropriate.

Then the system is considered with two DGs with the capacity of 3 MW each connected to the region 2 & region 5 as shown in the following figure 2.15.

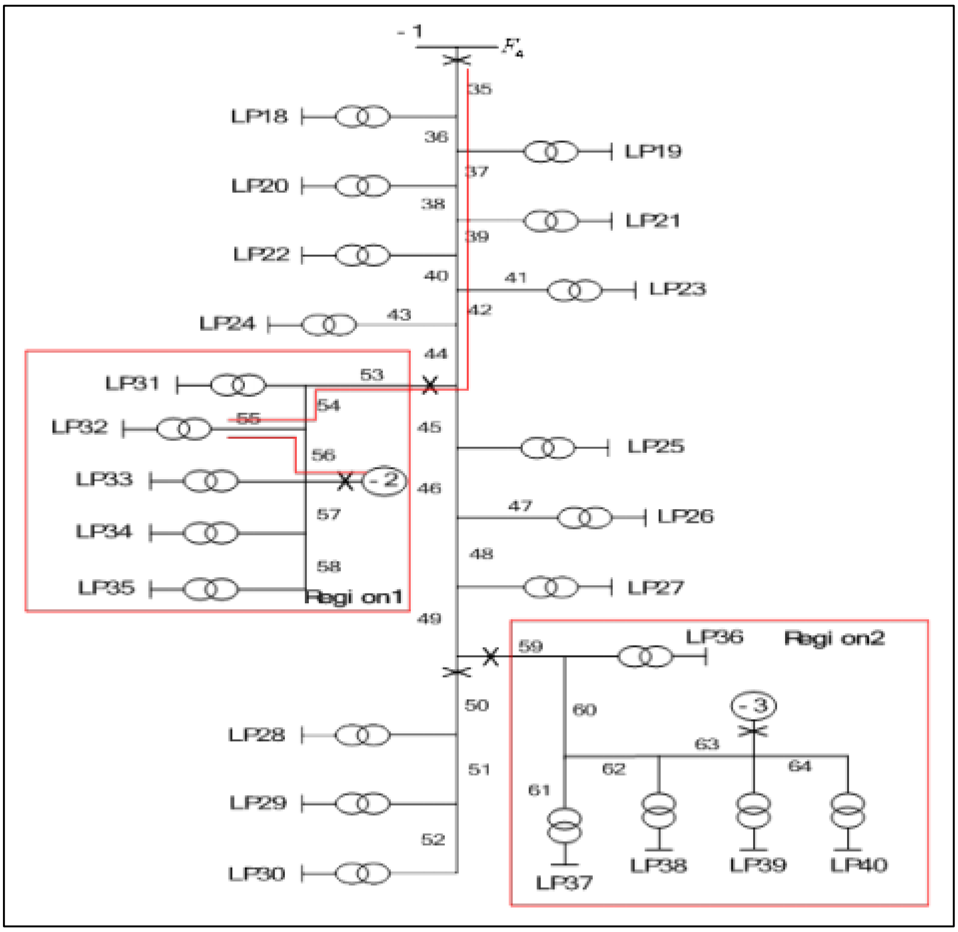


Figure 2.15 : Electricity distribution network with distributed generation [18]

The system with DGs is then simulated again to calculate the system reliability indices using same methodology. Comparison of the system reliability indices in both cases are indicated in the table2.4.

Table 2.4: System reliability index comparison - Distribution system with/without DGs [18]

RBT-BUS6	SAIFI (time/year)	SAIDI (h/year)	CAIDI (h/year)	ASAI	ENS (MWh)
Without DGs	1.98686	11.14200	5.60783	0.998725	95.34200
With DGs	1.70484	8.62515	5.05921	0.998013	68.31667

These results have been obtained assuming that the DGs are sized to supply power during the supply from main feeder F4 is failed. Provided this assumption it can be seen clearly that the introduction of DGs has improved the distribution system reliability indices, which demonstrates the benefits brought by the introduction of DGs and islanding schemes. [18]

2.4 Modelling of a Microgrid

2.4.1 Geographical area

Kalpitiya is a peninsula located in the north western province of Sri Lanka which has about 167 km^2 of land area and nearly 86,405 population as per the department of census and statistics, Sri Lanka. [22] Figure 2.16 shows the topographical map of Kalpitiya area.

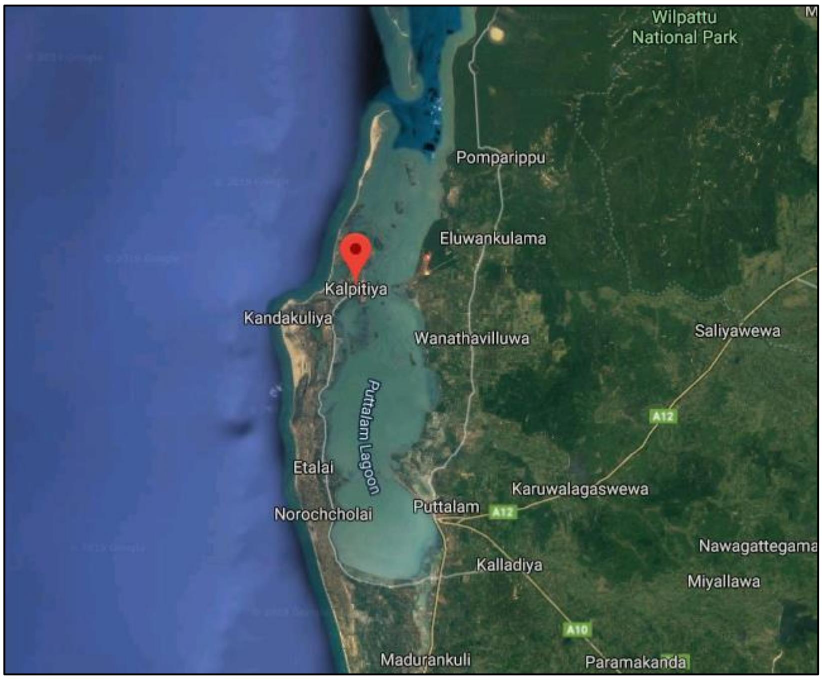


Figure 2.16 : Topographical map of kalpitiya

It is 40 km long land strip bordered by Indian Ocean from west and north, Puttalam lagoon from the east. Coconut plantation and agricultural lands used for onions, chillies, tobacco & vegetables which have 3-6 months crop season account for 60% of total land of Kalpitiya peninsula. It is about 40 km long strip from the starting point of land area to Kalpitiya end point. The area of interest mainly comprises of households and there are no considerable production industries available. However, many independent wind power producers and Lakvijaya Power Plant (LVPP) owned by Ceylon Electricity Board (CEB) had been established and operated in the area.

2.4.2 Availability of renewable energy sources

2.4.2.1 Solar energy

It is important to investigate the availability of solar resource in the particular area. According to the solar resources map developed by NREL & the solar atlas published by SLSEA solar resource potential is much promising compared to other parts of Sri Lanka. Hambantota was selected for the installation of solar energy national park considering the availability of solar resource potential. Table 2.5 shows average solar energy potential assessed and published by NREL.

Table 2.5 : Data from solar resources maps of Sri Lanka developed by NREL [23]

Location	Average solar resource potential($kWh/m^2/day$) as per NREL assessment (tilted at latitude)			
	South west monsoon (May to September)	North east monsoon (December to February)	1st Inter monsoon (March to April)	2nd inter monsoon (October to November)
South east near coastal area (eg : Hambantota)	5.0 – 5.5	5.5 – 6.0	6.0 – 6.5	5.5 – 6.0
Central hills (eg: Ambewela)	4.5 – 5.0	5.0 – 5.5	5.5 – 6.0	5.0 – 5.5
Jaffna peninsula	4.5 – 5.0	5.5 – 6.0	6.0 – 6.5	4.5 – 5.0
North west coast (eg : Kalpitiya)	4.5 – 5.0	5.0 – 5.5	5.5 – 6.0	4.5 – 5.0

It can be clearly seen that west coast of Kalptiya peninsula possesses 4.5 – 6.0 $kWh/m^2/day$ throughout the year which is close to average solar irradiance Hambantota area. This resource could be harnessed much better in Kalpitiya peninsula substantially as this is available throughout the year.

2.4.2.2 Wind Energy

Wind resource is being harnessed in Kalpitiya area by private power producers even now. The wind resource availability and its variations had been studied by NREL in Sri Lanka. It is always important to review the resource availability in Kalpitiya to compare with the resource availability in other parts of the island so as to evaluate the possibility of wind power generation. Table 2.6 shows a comparison of wind resource potential in the best windy areas in Sri Lanka.

Table 2.6 : Data from wind resources atlas developed by NREL [24]

Location	Wind resource potential	Wind power density at 50 m elevation (W/m^2)	Wind speed at 50 m elevation (weibull parameter k=2)
South east coast (Hamabantota to Kirinda)	Good	400 – 500	7.0 – 7.5
West coast (Puttalam, Mannar & islands near Jaffna)	Excellent	500 – 600	7.5 – 8.0
Central hills (Ambewela)	Excellent	500 – 600	7.5 – 8.0

According to the wind potential classification done by NREL, Kalpitiya peninsula possesses a considerable potential to harvest wind power compared to other areas of Sri Lanka with the annual average wind power density values 500 – 600 W/m^2 at 50 metre elevation (Excellent - Class 5).

Along the southeast coast, the 20 m tower near the Hambantota Meteorological Station has recorded 8 m/s winds from June to September period (Classes 5 and 6) and 6.5 to 7.5 m/s winds (Classes 3 and 4) from December through January. The seasonal distribution of wind resource along the west coast is shown clearly by the data from the New Narakkalliya station on the Kalpitya Peninsula. There, Class 6 resource is measured during June, July, and August and Class 5 resource is measured during May and September. In contrast, Class 1 resource prevails from November through April. As far as Kalpitiya wind resource data is concerned there are several data sets published in literature as shown in table 2.7. NREL has published wind data in a wind potential assessment done in 2003 [24]. NASA has published monthly averaged wind speeds for 10 years (1983 – 1993) at 50m elevation in earth terrains similar to airports which was taken from Homer Pro libraries.

Table 2.7: Wind resource data in Puttalam, Kalpitiya area

Month	Monthly average wind speed data (m/s) at 50 m elevation		
	NREL data (From HOMER Pro)	On site measurement (from Pawan dhanavi)	NASA Data (From HOMER Pro)
January	5.60	5.25	4.84
February	3.80	6.04	4.09
March	4.60	4.58	3.56
April	5.20	2.99	3.61
May	9.10	6.17	5.39
June	9.90	12.22	6.65
July	9.30	10.21	5.83
August	9.70	9.32	5.97
September	8.70	7.68	5.17
October	7.00	6.92	4.15
November	5.20	3.75	3.79
December	5.60	4.32	4.59
Annual average	**7.00**	**6.63**	**4.81**

The measured data at 50 m elevation from the ground in Pawan dhanavi wind power plant at Illanthadiya (Kalpitiya peninsula) shows promising annual average wind speed of 6.63 m/s. However, the wind speed values given by NREL is much closer to on site measured values though the wind speed published from NASA showing a considerable under estimation from actual on site measured values. All these data sets can be compared to see the deviation of each data set from one another as shown in the figure 2.17

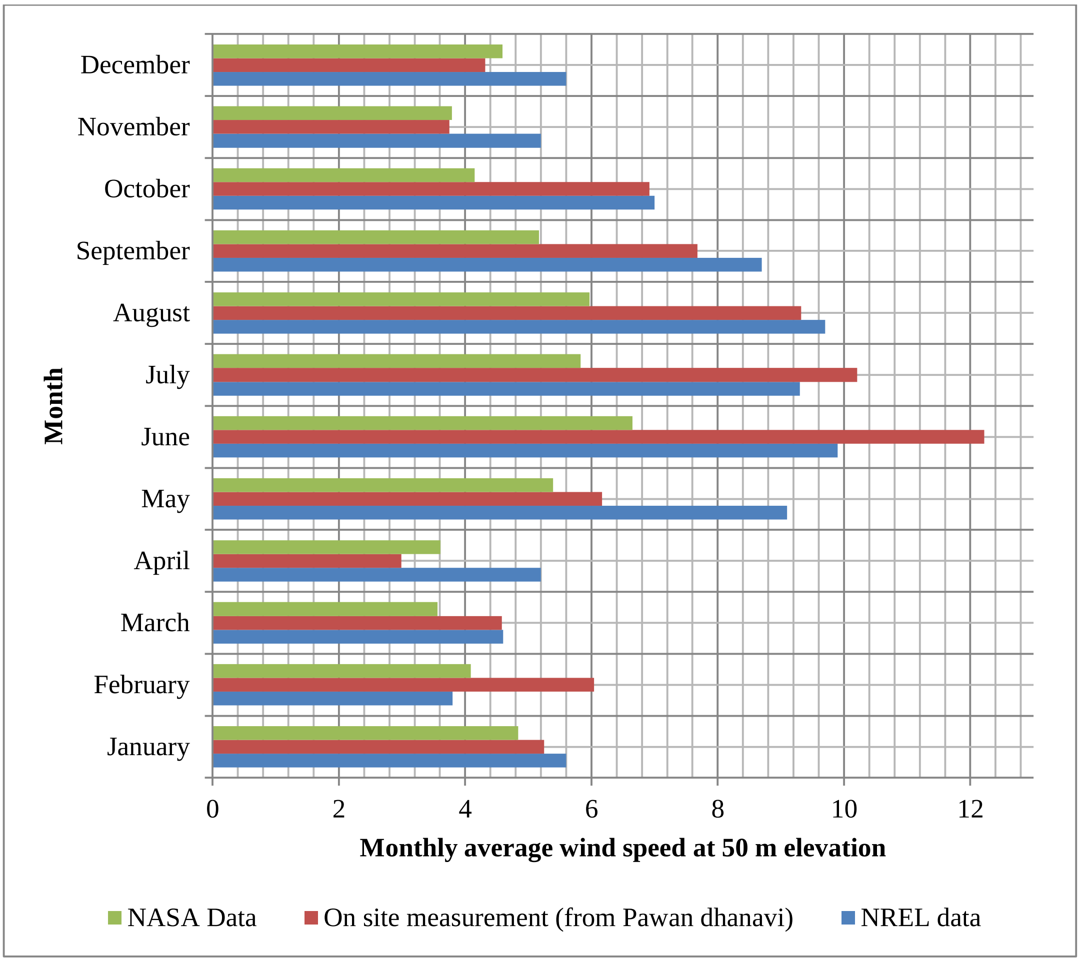


Figure 2.17 : Comparison between wind speed data of NREL, NASA & Onsite measurements

2.4.2.3 Biomass Energy

Government has also recognised biomass as a commercial crop and a third fuel option to generate electricity. Gliricedia, *Gliricedia sepium* by botanical name, was declared as the fourth plantation crop after tea, rubber & coconut.

Biomass can be used as an energy source to generate electricity by different means. It can be burnt directly in a steam boiler to run a steam turbine or gasification can be used to obtain the producer gas to fire in an internal combustion engine.

Staple food of Sri Lanka is rice and it is the crop with highest land area utilisation for cultivation. Rice husk generated in paddy processing was found to have a significant potential for power generation in Ampara, Anuradhapura, Polonnaruwa & Kurunegala districts. As Puttalam is located as a bordering district to Anuradhapura and Kurunegala districts, rice husk is available for power generation. It is found that 30% of excess rice husk could be used for power generation with an annual energy potential of 180 GWh. [25]

The values of average paddy production in Puttalam district in yala & maha seasons from 2006 to 2017 as per the department census and statistics are shown in figure 2.18. and figure 2.19 respectively [26].

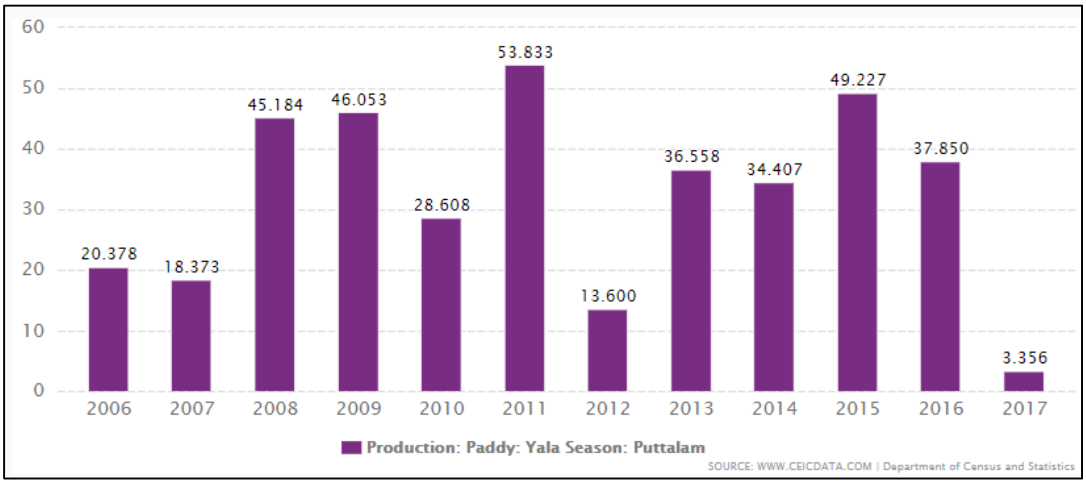


Figure 2.18 : Average paddy production in puttalam in yala season (2006 – 2017) [26]

As shown in figure 2.18, average paddy production in Puttalam district had been varying between a minimum of 13,600 MTwith a maximum of 53,833 MT in yala season until 2016. There had been a drastic reduction of paddy production in 2017 due to the policy changes in the government as well as the adverse weather conditions. However, the paddy production in yala season of 2018 was reported as 46,454 MT in which was quite a high value in comparison to 2016.

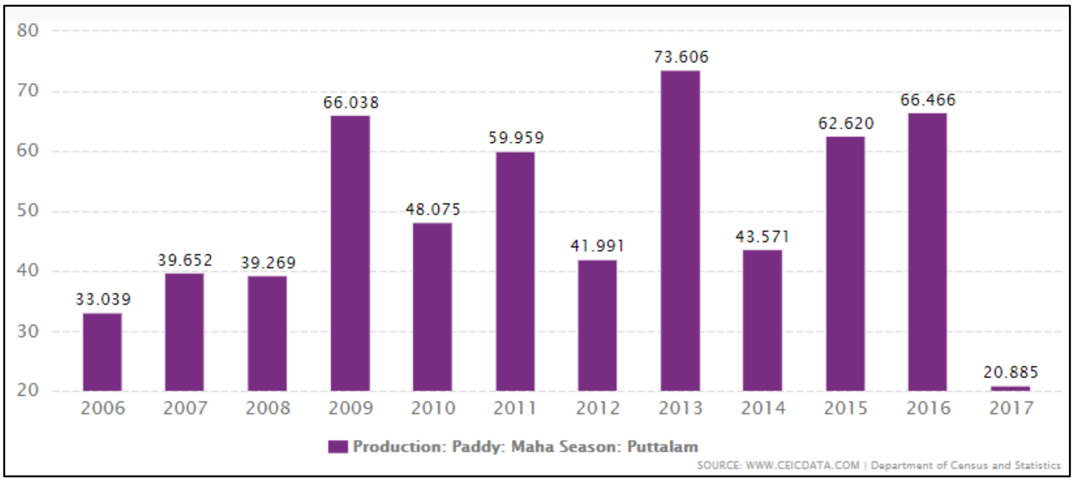


Figure 2.19 : Average paddy production in puttalam in maha season (2006 – 2017) [26]

According to figure 2.19 above, average paddy production in Puttalam district had been varying between a minimum of 33,039 MT and a maximum of 73,606 MT in maha season until 2016. Similar to the yala season in 2017 a drastic reduction of paddy production could be observed in maha season too due to the policy changes in the government as well as the adverse weather conditions. In 2018 also the paddy production in maha season of 2018 was reported as 18,322 MT which less below the average in comparison to the production stats from 2006-2016.

The outer covering of paddy grain is called as rice husk and it accounts for about 20% of its weight. Availability of rice husk is the critical factor to decide whether it is possible to find the sufficient amount of fuel source to operate the power plant. Nearly 40 MT of paddy husk is needed per day for a 1 MW power plant. [25]

On order to run 1 MW power plant with 90% plant factor 13,160 MT of paddy husk is needed. Even if the total paddy husk production in Puttalam district is collected for the power plant, the paddy production should be more than 65,800 MT per year. Looking at the above statistics it seems that the availability of paddy husk in both yala, maha seasons over recent years is marginal to run a 1 MW plant with a 90% capacity throughout a year (329 days). However, there is more paddy production in neighbouring districts such as Anuradhapura and Kurunegala where the paddy husk could be collected easily and transported to Puttalam. As shown in the figures 2.20 &

2.21 there is ample production of paddy in Anuradhapura district as well as in Kurunegala districts. [26]

In order to collect paddy husk there should be a well-organised program unless paddy husk production would be used for other industrial purposes such as biomass boilers, furnaces etc.

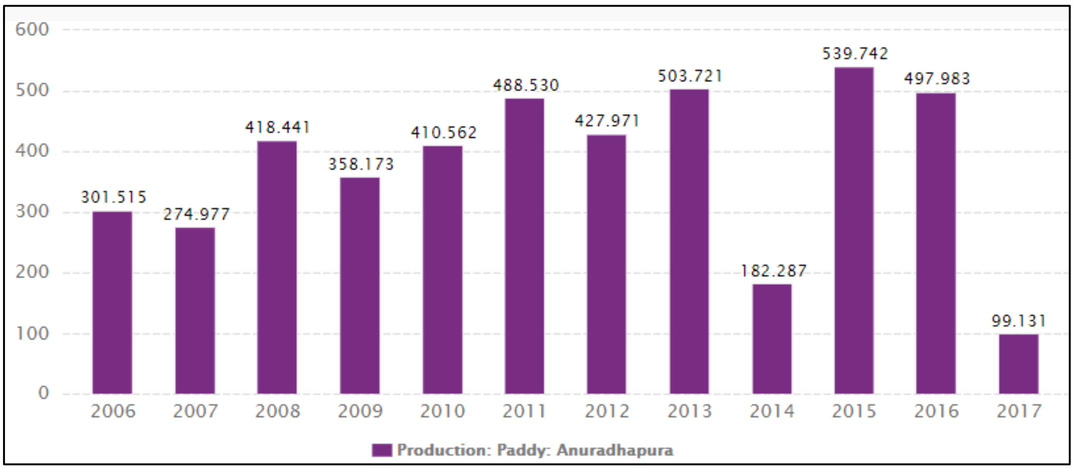


Figure 2.20 : Annual average paddy production in Anuradhapura district [26]

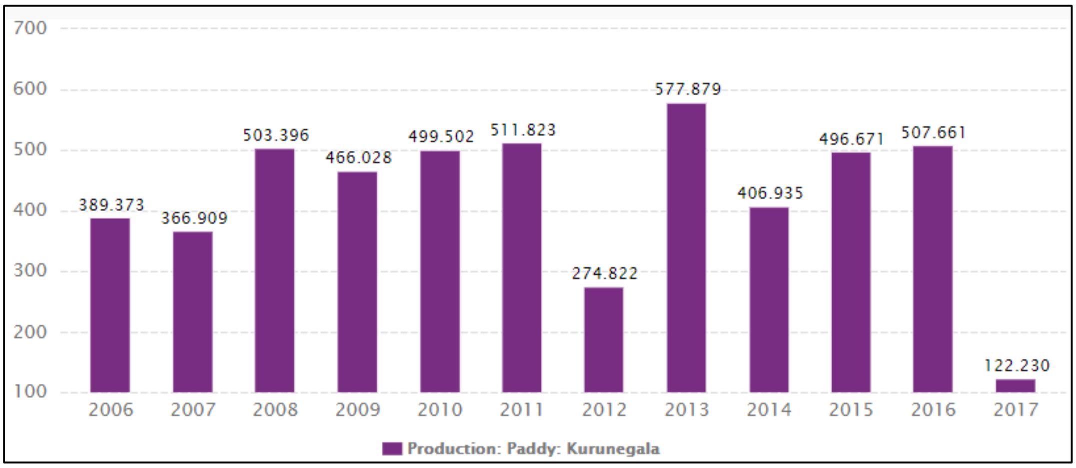


Figure 2.21 – Annual average paddy production in Kurunegala district [26]

2.4.2.4 Municipal Solid Waste (MSW) Energy

In Sri Lanka National Strategy on Solid Waste Management (NSSWM) had been formulated in 2000 and National Policy on Solid Waste Management had been introduced since 2007 with the intention of managing solid waste effectively. The strategy is expected to manage solid waste by prioritising waste avoidance where it could be reduced by reusing unavoidable waste wherever possible, minimising hazardous waste generation and adopting sound residual waste treatment and disposal methods without basic prerequisites for human existence.

National Policies on Solid Waste Management (SWM) were formulated to define the environmentally accountable all institutions integrated solid waste management practices with social responsibility. [27]

Subsequently, several national level plans and policies/strategies were developed as solid waste management was identified as one of the prioritised issues for adopting appropriate infrastructure as mentioned in table 2.8.[27]

Table 2.8 : Solid waste management plans & policies/strategies in Sri Lanka [27]

Year	Policy & Regulation	Description
2000	National Strategy for Solid Waste Management (NSSWM)	■ 3-years action plan, Waste reduction, 3R implementation
2003	Caring for Environment Phase I (2003-2007) Phase II (2008-2012)	■ Funded by United Nations Developing Program; UNDP ■ National Environmental Action Plans
2005	Vision for A New Sri Lanka	■ A Ten Year Horizon Development Framework 2006-2016 formulated by Ministry of Finance and Planning ■ Solid waste and pollution management included in the investment plan
2007	National Policy on Solid Waste Management	■ Waste reduction, 3R implementation, Sanitary landfills ■ Capacity building, Research and development (Best Available Technologies (BAT), Best Environmental Practices (BEP)
2008	Pilisaru Programme Phase I(Jan. 200 –Dec. 2013) Phase II(Jan. 2014–Dec. 2018)	■ National level programme for solid waste management under the chairmanship of Ministry of Environment, CEA, and others. ■ Initial budget amount: 5.675 bil LKR. ■ Target is to introduce small and medium waste treatment system in all local government authorities by year 2018 and to cover 50% by year 2016.
2009	National Action Plan for Haritha Lanka Programme	■ Establishment of National Council for Sustainable Development (NCSD) ■ Sustainable development: Harita (Green) Lanka Programme

Generation of waste amount in Sri Lanka was recorded as 10,786 Tons per day after 2009. According to the table 2.9, most of the waste generation is collected from western province which accounts for 52% & smallest amount is collected from uva.

Table 2.9 : Solid waste generation & disposal sites by provinces [27]

Provinces	Generation amounts (ton/day)		Collection amounts (ton/day)		Collection rates	Number of final disposal sites
1. Northern	566	5%	178	5%	31%	16
2. Eastern	785	7%	347	10%	44%	40
3. North-central	616	6%	91	3%	15%	35
4. North-western	1,134	11%	187	5%	16%	45
5. Central	1,585	15%	304	9%	19%	47
6. Sabaragamuwa	835	8%	178	5%	21%	30
7. Uva	587	6%	116	3%	20%	24
8. Western	3,502	33%	1,793	52%	51%	52
9. Southern	1,158	11%	264	8%	23%	60
Total	10,768	100%	3,458	100%	32%	349

Number of disposal sites in the country was identified as 349 in 2003 even though number of local authorities is 335. As a result of “Pilisaru” project compost facilities were developed to handle 542 tons of solid waste per day which was considered as intermediate treatment.

Ministry of power and energy formulated national energy policies and strategy which encouraged the usage of non-conventional renewable energy technologies into the generation mix. Although several waste to energy projects were launched, they are still ongoing and not completed yet.

World Bank has funded 326 million USD for metro Colombo urban development project where 6% of the budget was allocated for the improvement of solid waste management. It has been planned to transport 1200 MT of solid waste per day to Aruakkalu sanitary landfill site in Puttalam. To generate 1 MW of power for a day requirement of solid waste is about 80 Tons per day. When comparing the amount of solid waste generation to the requirement of solid waste for power generation, it is quite clear there is no shortage of fuel. Since the solid waste would be available in near proximity as well as the continuous supply, there is a possibility of having a waste to energy power plant without dumping all the solid waste for land filing. [27]

Since, there are no waste to energy plants operating in Sri Lanka currently, it would be completely a novel challenging experience for the operation and maintenance. Therefore, it can be clearly seen that considerable amount of renewable energy sources are available to be utilised to generate power for a microgrid in Kalpitiya peninsula.

2.5 Microgrid Simulation in Homer Pro

2.5.1 Solar power output calculation

When the project location is specified by giving the latitude and longitude, it downloads the solar GHI data to internal database. Then either data from NASA surface meteorology and solar energy database or National solar radiation database developed by NREL could be selected for the analysis. Once the solar panel power rating, derating factor are selected, it uses the following equation to calculate the power output of the solar PV.

$$P_{PV} = Y_{PV}\, f_{PV} \left(\frac{\overline{G_r}}{\bar{G}_{r.STC}}\right)\left[1 + \propto_p \left(T_c - T_{c,STC}\right)\right]$$

Eqn 2.3 : Power output of solar PV in HOMER Pro [28]

Where;

P_{PV} Power output from solar PV

Y_{PV} is the rated capacity of the PV array, meaning its power output under standard test conditions [kW]

f_{PV} is the PV derating factor [%]

$\bar{G}_{r.}$ is the solar radiation incident on the PV array in the current time step [kW/m2]

$\bar{G}_{r.STC}$ is the incident radiation at standard test conditions [1 kW/m2]

α_P is the temperature coefficient of power [%/°C]

T_c is the PV cell temperature in the current time step [$T_{c,STC}$ is the PV cell temperature under standard test conditions [25 °C]

If the temperature effects are not taken into account, Homer pro assumes the temperature on the PV array is constant and equation 2.3 simplified to the equation 2.4.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\overline{G_r}}{\bar{G}_{r.STC}}\right)$$

Eqn 2.4 : Solar PV output disregarding temperature effects in HOMER Pro [28]

2.5.2 Wind power output calculation

Similar to solar power output calculation, wind resource data is downloaded to libraries from NASA surface meteorology and solar energy database. Then, HOMER Pro calculates the wind power output of each wind turbine in every time step (60 minutes). The calculation includes a process with three steps. First it estimates the wind speed at the hub height of the wind turbine where hub height is specified. Then power output is calculated for the particular wind speed and hub height at standard air density. After that it is adjusted by a correcting the value for actual air density.

2.5.2.1 Calculating hub height wind speed

HOMER Pro calculates the wind speed at the user specified hub height of the wind turbine. Selection of using the logarithmic law or power law is taken from the user. If logarithmic law is selected, HOMER Pro uses the following equation to calculate the wind speed at the hub height.

$$U_{hub} = U_{anem} \cdot \frac{\ln(Z_{hub}/Z_0)}{\ln(Z_{anem}/Z_0)}$$

Eqn 2.5 : Hub height wind speed calculation using logarithmic law [28]

If user specifies to use the power law, HOMER Pro calculates hub height wind speed using following equation.

$$U_{hub} = U_{anem} \cdot \left(\frac{Z_{hub}}{Z_{anem}}\right)^A$$

Eqn 2.6 : Hub height wind speed calculation using power law [28]

Where:

U_{hub} - the wind speed at the hub height of the wind turbine [m/s]

U_{anem} - the wind speed at anemometer height [m/s]

Z_{hub}	- the hub height of the wind turbine [m]
Z_{anem}	- the anemometer height [m]
A	- the power law exponent

2.5.2.2 Turbine Power Output at Standard Air Density

After the determination of wind speed at hub height, HOMER pro refers to the power characteristic curve of wind turbine to calculate the power output under standard conditions of pressure and temperature.

Coordinates of the power characteristic curve could be specified by the user as appropriate referring to the design manuals of turbine manufacturers. A typical wind turbine characteristic curve is shown in figure 2.22 According to figure 2.22, if hub height wind speed is not within the range between the cut-in wind speed and cut-off wind speed the turbine will be considered to produce no power.

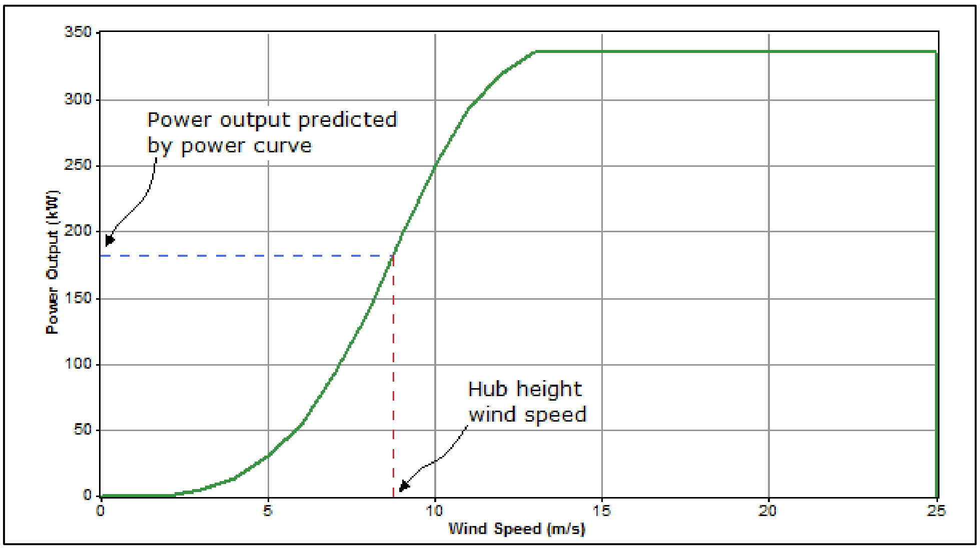


Figure 2.22 Typical Power Curve of wind turbine

2.5.2.3 Applying Density Correction

Basically, characteristic power curve of wind turbine defines the performance under standard temperature and pressure. In order to adjust the calculated value to actual environmental conditions, Homer pro use equation 2.7 to multiply it by the air density ratio.

$$P_{WTG} = \left(\frac{\rho 3}{\rho_0}\right) P_{WTG,STP}$$

Eqn 2.7 : Actual wind power output by applying air density correction [28]

Where:

P_{WTG} - the wind turbine power output [kW]

$P_{WTG,STP}$ - the wind turbine power output at standard temperature and pressure kW]

ρ - the actual air density [kg/m^3]

ρ_0 - the air density at standard temperature and pressure (1.225 kg/m^3)

2.5.3 Customised power resource output

This provides the opportunity to upload a time series data of power output of a renewable power source. To upload the time series data, it should be in .csv format with 8760 rows (i.e.: total number of 1hour time steps per year) of power output data of a particular source in consideration. In order to add biomass power generation and municipal solid waste power generation this option had been used. [28]

2.5.4 Dispatch strategy

When several power generating sources are connected to microgrid, set of rules that govern the operation of those generators with the changing demand is known as dispatch strategy. There are two main strategies Homer pro can adopt to model the microgrid namely load following and cycle charging. In load following strategy, the generation by controllable power sources of the system such as dispatchable generators, grid (if grid connected) and battery bank is sufficient to meet the primary load demand along with the operating reserve requirement. In cycle charging strategy, it serves the primary load where the generators operate at its full output power and excess generation is used for a second priority such as serving a deferrable load, charging a storage bank or serving an electrolyser. Normally, load following strategy becomes optimal when there is more renewable power generation where cycle charging strategy becomes optimal when there is secondary priority of excess generation with low renewable energy generation. [28]

2.5.5 Emission calculation

Homer pro calculates the emission of six pollutants in the system as follows. Namely carbon dioxide (CO_2), carbon monoxide (CO), unburnt hydrocarbons (UHC), particulate matter (PM), Sulphur dioxide (SO_2), Nitrogen dioxide (NO_x). Basically, these emissions are coming from production of electricity by generators & consumption of grid electricity. Homer pro models the emissions of electrical generators by the known fuel properties. When it comes to emission calculation of grid electricity by the defined emission factors (i.e.: g/kWh) for each pollutant stated above. When Homer pro calculates net grid purchases grid emission is calculated by multiplying it from emission factor over the year. This implies if the hybrid system can provide more energy from renewable sources than purchasing from the grid, effective emission can be reduced. [28]

2.5.6 Optimisation of most economical microgrid configuration

In the results Homer pro ranks the system as the best alternative among the all simulated combinations by referring to the net present cost (NPC) or the life cycle cost of the system. Net present cost of a component is calculated by deducting the net present cost of all the revenue that the component earns from the present value of all the costs of installation, operation and maintenance cost over the specified project life time. It is important to note that Homer pro uses the real discount rate for the calculation of time value of money. It calculates the NPC for each component and thereby for the total system as a whole. The combination with the lowest positive NPC becomes best option from the sensitivity analysis. [28]

3 DESIGN OF MICROGRID

3.1 Electrical Load Demand

Electricity distribution for Puttalam area is being done by Puttalam grid substation. According to figure 3.1 it is connected to new Anuradhapura grid substation from one end and other end to New Chilaw from which the Puttalam grid substation could be energised.

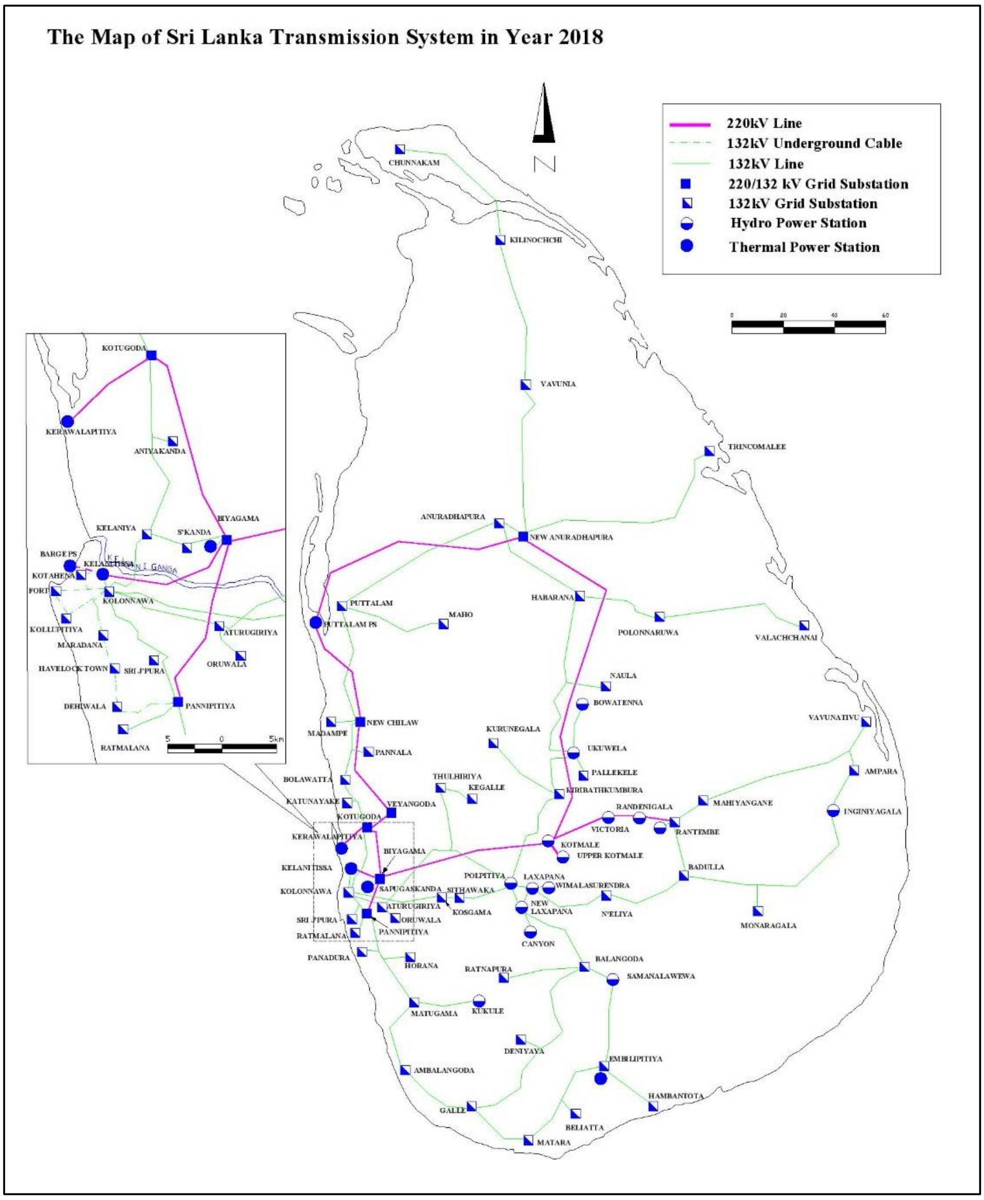


Figure 3.1 : Transmission network of Sri Lanka in 2018

Heladhanavi thermal power plant (the plant was run on fuel oil) was connected to Puttalam grid substation and it was retired in 2015. For a better understanding of power flow in Puttalam area electrical single line diagrams were studied.

It was understood that feeder 03 (33kV feeder) of Puttalam grid substation is feeding the energy to Kalpitiya peninsula after studying the electrical single line diagrams. Therefore, actual load demand data of Kalpitiya peninsula was obtained from Puttalam grid substation for each day in 2018. It is evident that there are several wind power stations which are already in operation as independent power producers in Puttalam, Kalpitiya are. The connections and capacities of wind power stations are given in table 3.1.

Table 3.1 : List of wind power stations in Puttalam [29]

Wind power producer	Rated capacity of one turbine	Number of turbines	Installed capacity	Connection point
Daily life renewable power	1.5 MW	08 nos.	12 MW	Gas insulated switchgear(GIS) of Lakvijaya power plant
Nirmalapura wind power	1.5 MW	07 nos.	10.5 MW	Gas insulated switchgear(GIS) of Lakvijaya power plant
Mampuri-I wind power	1.25 MW	08 nos.	10 MW	Puttalam Grid Substation
Mampuri-II wind power	2.1 MW	05 nos.	10.5 MW	Gas insulated switchgear(GIS) of Lakvijaya power plant
Mampuri-III wind power	2.1 MW	05 nos.	10.5 MW	Gas insulated switchgear(GIS) of Lakvijaya power plant
Naladhanavi wind power	800 kW	06 nos.	4.8 MW	Gas insulated switchgear(GIS) of Lakvijaya power plant

Pawandhanavi wind power	850 kW	12 nos.	10.2 MW	Gas insulated switchgear(GIS) of Lakvijaya power plant
Uppudaluwa wind power	1.5 MW	07 nos.	10.5 MW	Gas insulated switchgear(GIS) of Lakvijaya power plant
Seguwanthiv wind power	800 kW	12 nos.	9.6 MW	Puttalam Grid Substation
Vidatamunai wind power	800 kW	13 nos.	10.4 MW	Puttalam Grid Substation

There are 99 MW of installed capacity of wind power already available at Kalpitiya peninsula. However, 30 MW of wind turbines are connected to Puttalam grid substation while 12 MW is connected to 33 kV power cable (feeder 03) which is coming from Puttalam grid substation to Kalpitiya.

Therefore, power readings in feeder 03 can be considered as the actual electricity demand of Kalpitiya peninsula. The real total electricity demand in Kalpitiya peninsula could have been figured out if the total generation of Kalpitiya wind power plant which is connected to 33 kV line is added to the demand readings in feeder 03.

To model the microgrid in HOMER Pro there is no way to obtain the real load profile in Kalpitiya peninsula due to the unavailability of hourly generation data of Kalpitiya wind power plant. Therefore, the readings in log sheets of feeder 03 at Puttalam grid substation were considered as the existing electricity demand for which the microgrid is to modelled and optimised.

The load demand data were recorded in log sheets for 30 min intervals throughout the day. All the data were entered to microsoft excel and converted it to an hourly load profile for further analysis. Tables and graphs illustrated for the load demand variation throughout a complete year is in Appendix A.

Data in the log sheets were current readings of 33kV feeder. Therefore, to obtain the power consumption at each time step of 30 min interval, equation 3.1 was used

$$P = \sqrt{3}\, V\, I \cos\varphi$$

Eqn 3.1 : Power drawn in a 3-phase line

Where,

V	voltage(33kV)
I	current (log sheet reading)
cos φ	power factor which is assumed to be 0.9.

Average electrical power demand for every 30 min interval starting from 0000h to 2400 h was calculated using the equation 3.1 for an average day in each month, taking monthly average current in each time step. It could be seen that some power demand values at off peak (10.30 p.m to 6.30 a.m) mainly in June, July & August were indicated as negative values as the power generation from Kalpitiya wind power is more than the power demand in Kalpitiya peninsula in that particular time step and excess generation is fed to national grid from feeder 03 at Puttalam grid substation. However, referring to the wind speed data in the months of June, July & August it is best time that wind power is available in the whole year because of south west monsoon.

For the analysis, electrical load profile was derived from the calculated data. Homer Pro software required monthly load profile with 60 minute (01 hour) intervals for both weekdays and weekends separately in the month. Therefore, load demand for weekdays and weekends of each month was calculated separately for every month. Since the data is in 30 minute intervals, average of three (03) 30 minute interval load demand values was taken as the average load of the particular 60 minute interval.

Analysing the monthly average electrical power profile, it could be clearly observed that if the load demand in the month of April could be catered by the microgrid, power demand for almost all the other months of the year could be catered. Therefore, load demand of weekdays and weekends in the month of April is considered as annual load profile for further analysis.

3.2 Grid Connection

Considering the present scenario, the power demand is currently being fulfilled through the national grid. But, in this research it is aim to find out the possibility of catering the power demand with the available resources such as wind, solar, biomass and municipal solid waste with respect to the economics related to it. In that case, Kalpitiya peninsula is intended to become a virtual island as far as the power supply is concerned. Battery storage would be helpful in making Kalpitiya peninsula a virtual island which does not use utility supply. Since the grid connection is already in place battery storage was not considered as a technological option in microgrid. Without battery storage, microgrid could generate power on its own and sell any excess power to the grid as well as draw power from grid if there is any deficit in local power generation.

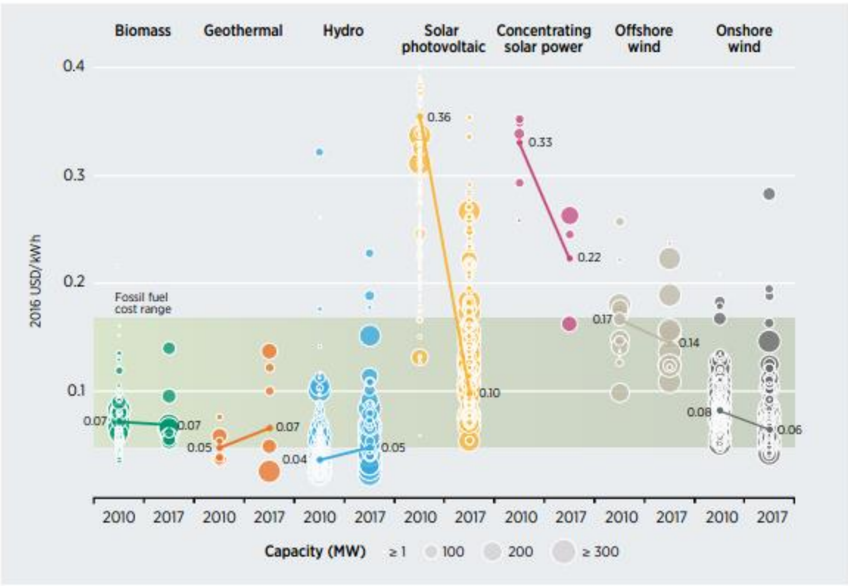
If any excess power is sold to the grid, it was assumed that it replaces the power generated by diesel/fuel oil. Therefore, power purchasing price from grid is considered as Rs.36.00/kWh. Prevailing power purchasing and selling prices utility grid with the power generation cost of each technology related to each power source used in the microgrid has to be studied in order to find out the most economical combination of each source based on their availability as well. Grid sell back price was taken as Rs.25.09 considering the microgrid is in the category of other non-conventional power producer according to the prevailing tariff announcement by Public Utilities Commission of Sri Lanka (PUCSL) with effect from 01.01.2012. Grid power purchasing and sell back rates were assumed to be the same within anytime of the day and throughout the project time period as well.

3.3 Costs of Power Generating Sources

3.3.1 Costs in global power renewable power generation

With the increasing popularity of power generation from renewable sources, a massive continuous improvement had caused to their competitiveness with fossil fuel technologies. Considering the cost values of onshore and offshore wind, solar and biomass projects implemented from 2010 onwards it had been reducing a lot to become more competitive against fossil fuel fired electricity generation in almost every part of the world.

As sown in figure 3.2 levelised cost of energy of mainly solar photovoltaic has the highest reduction of 73% along with the reductions of concentrated solar power as well as onshore and offshore wind, biomass. Global weighted average cost of utility scale onshore wind power technology had been declined from 23% as a result of wind turbine price decreasing 39-58% in 2007-2010 from their peaks and developed turbines such as longer blades with bigger swept area, higher hub heights for higher power ratings per turbine. However, there is no cost reduction of biomass technologies in comparison with solar PV, wind technologies.



Source: IRENA Renewable Cost Database.
Note: Each circle represents an individual project in the IRENA Renewable Cost Database, with the centre of the circle representing the LCOE value on the Y-axis and the diameter of the circle the size of the project. The lines represent the global weighted average LCOE value for a given years newly commissioned projects, where the weighting is based on capacity deployed by country/year.

Figure 3.2 : LCOE of renewable energy technologies from 2010 to 2017 [32]

The main reasons for this cost reduction are technological advancements, global competitive energy markets with supportive policy framework & manufacturing process improvements that reduce material, labour needs. The cost values had been reduced to the cheapest cost range of fossil fuel fired power generating. Therefore, renewable energy technologies could be considered as a competitive alternative to the fossil fuel fired power generating options.

3.3.2 Wind power generation

Wind power is a much abundant resource in Kalpitiya which could be easily connected to the microgrid. The analysis was done to find out how many wind turbines are adequate to run on the most economical, technically feasible microgrid. Wind data from national renewable energy laboratory cannot be used as the homer only permits to use NASA Surface meteorology and solar data base which consist of monthly averaged values over 22 years 1983 July 2005 June. Variation wind resource potential throughout the year taken for the microgrid modelling is shown in figure 3.3 below.

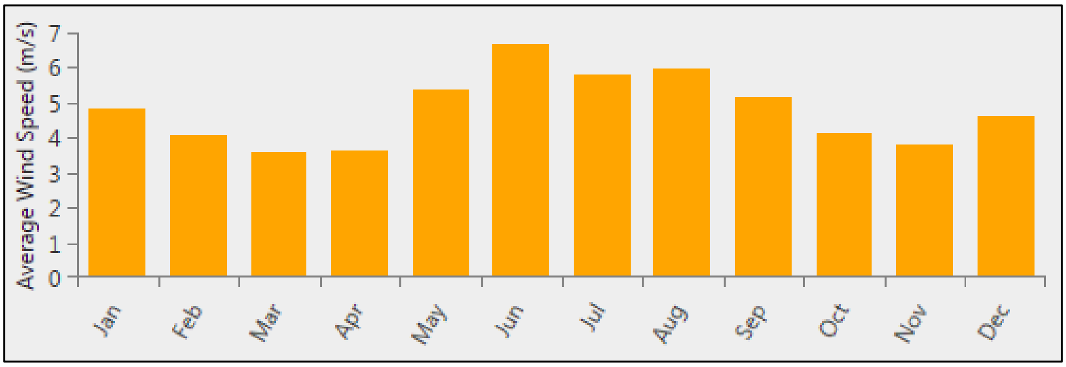


Figure 3.3 : Monthly averaged wind speed in Puttalam (NASA data) from HOMER Pro

Cost values for wind power plants have to be considered referring to the global market prices. Typical global weighted average cost of utility scale onshore wind power projects is around 1,200 USD/kW.

The cost of global weighted average for a utility scale wind power plant has dropped from 5,000 USD/kW in 1983 to 1,500 USD/kW in 2018. So, global weighted average total installation cost had been reduced 73% from 1983 to 2018 period. Decline in total installed costs differs with respect to different countries depending on the amount of deployments in onshore wind power projects. As per the statistics shown in figure 3.4 China, India & United states have been undergoing the largest reduction of total averaged installed costs. Typical country average of total averaged installed cost for wind power plants in India and China had come down to 1,200 USD/kW while the costs in other countries varies in between 1,660 USD/kW & 2,250 USD/kW.

These total installed cost values include several items of the project such as planning work, land acquisition, civil construction work, cost for wind turbines with accessories and the grid connection.

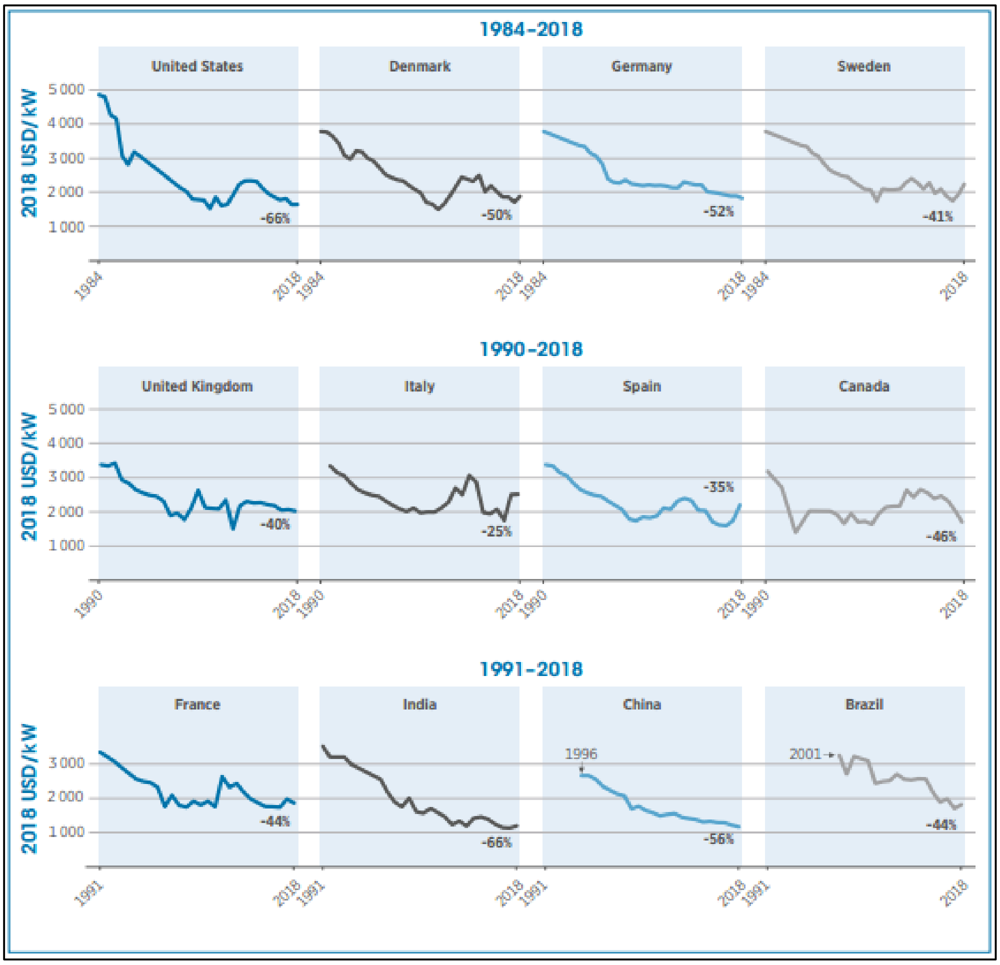


Figure 3.4 : Wind power total installed cost by country [33]

According to figure 3.5 over 60% of the project cost is borne by the cost of wind turbine with related accessories. Therefore, it could be clearly observed that, improvement of wind turbine technology with higher hub heights, large diameter with higher swept area had become one of the main reasons to decline the total average installation cost of wind power projects.

Figure 3.5 : Cost breakdown of a utility scale wind power project [33]

Annual operation and maintenance cost can be taken as 1.5% of total capital cost as recommended by public utilities commission of Sri Lanka (PUCSL) as well as the global energy data.

For the modelling of microgrid, wind turbines similar to Pawandhanavi plant (Gamesa-G58-850 kW) and Nirmalapura plant (Suzlon-S64-1250kW) are considered. Cost values of these two types of turbines are taken referring to the global cost trends as given in table 3.2.

Table 3.2 : Costs of wind turbines selected for microgrid modelling

Wind turbine make & model	Capacity of a turbine	Hub height (m)	Capital cost (USD)	Annual O & M cost per turbine (USD)
Gamesa-G58	850 kW	50	1,275,000	18,700.00
Suzlon-S64	1,250 kW	50	1,875,000	27,500.00

Characteristic curve of turbines in Wind01 plant were considered to be similar to Gamesa-G58 turbine given in figure 3.6 and turbines in Wind02 plant were considered to be similar to Suzlon-S64 turbine given in figure 3.7.

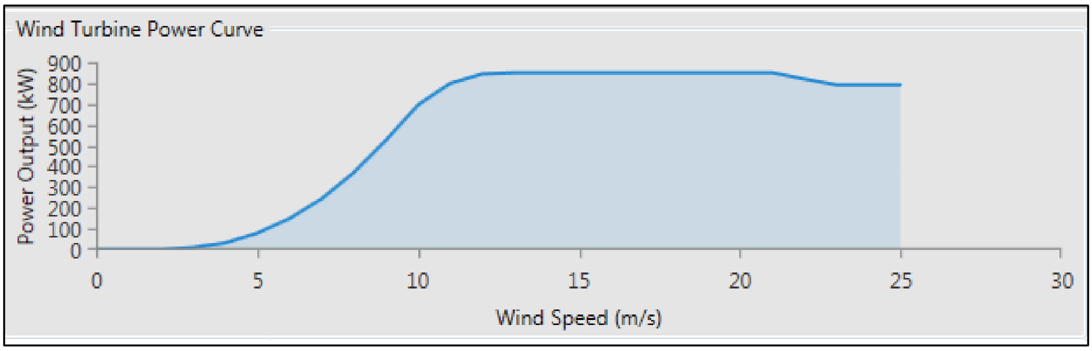


Figure 3.6 – Wind turbine characteristic of Wind01 plant (Gamesa – G58)

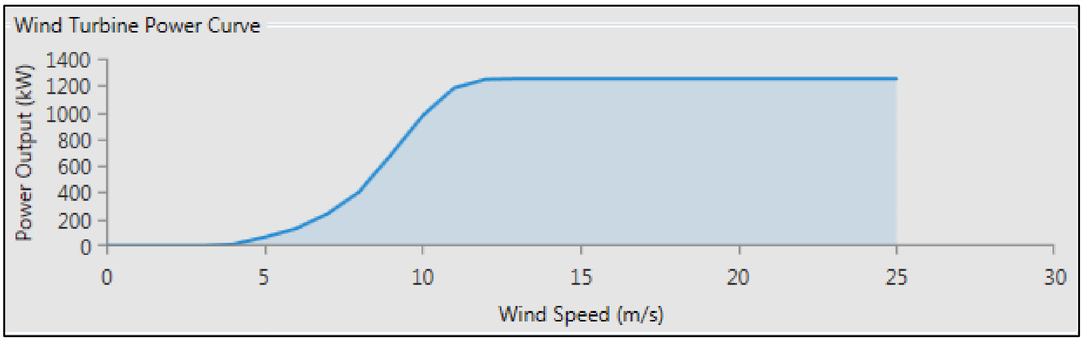


Figure 3.7 - Wind turbine characteristic of Wind02 plant (Suzlon – S64)

3.3.3 Solar power generation

NREL maps of global horizontal irradiation clearly illustrates that a considerable potential is in Kalpitiya area. Solar GHI data considered for HOMER Pro optimisation are the data from NREL as shown in figure 3.8.

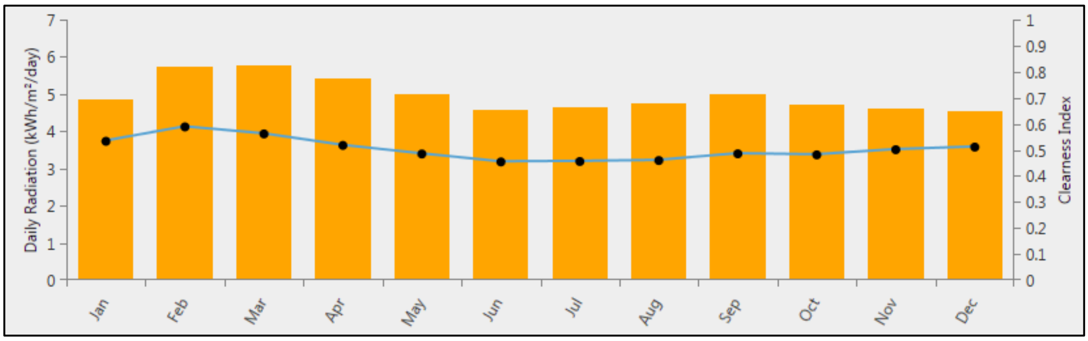


Figure 3.8 : Monthly averaged solar GHI (NREL data) from HOMER Pro

Similar scenarios could be observed as the wind turbine technology when the global market price of solar energy technology is concerned. A rapid cost declination of different solar PV module technologies could be observed from 2010 – 2018 period as per figure 3.9.

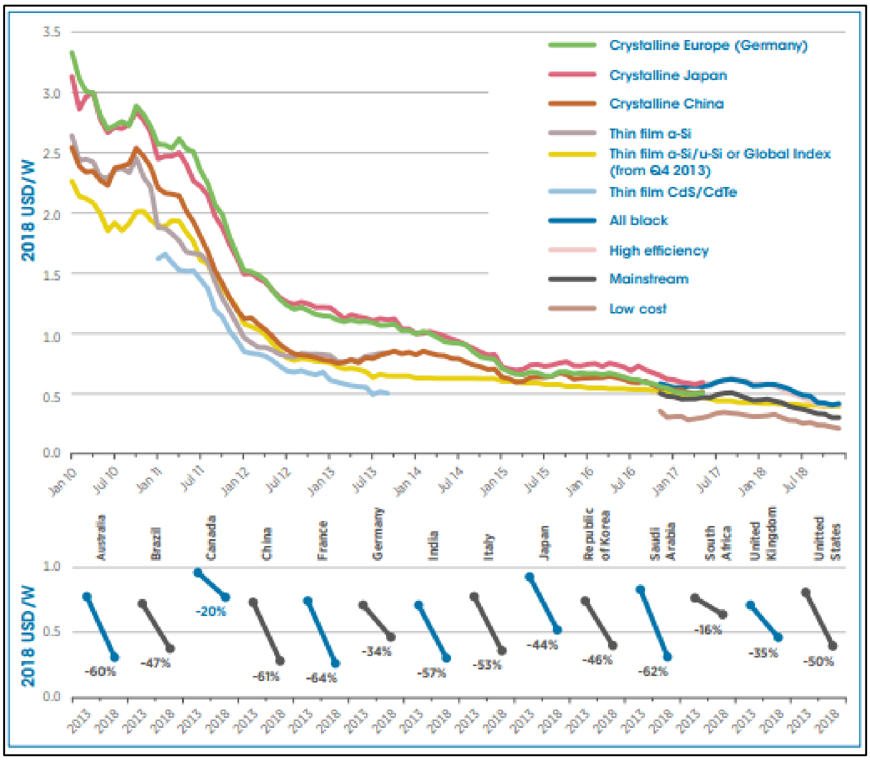


Figure 3.9 – Cost reduction of different solar panel technologies from 2010 - 2018 [33]

According to figure 3.9 there are several solar panel technologies are available. Some technologies such as all black had been introduced in 2017 where the cost of them were also been reduced. Crystalline and thin film technologies are becoming more economical year by year as a result of the technological improvements and market competition.

Cost values for solar power plants have to be considered referring to the global market prices. Typical global weighted average cost of utility scale solar power projects is around 1,210 USD/kW as shown in figure 3.10. The costs of 95th and 5th percentile of global weighted average for a utility scale solar power plant has dropped down from 3,300 – 7,900 USD/kW to 800 USD/kW & 2,700 USD/kW. Global weighted average cost had been reduced 74% from 2010 to 2018 period.

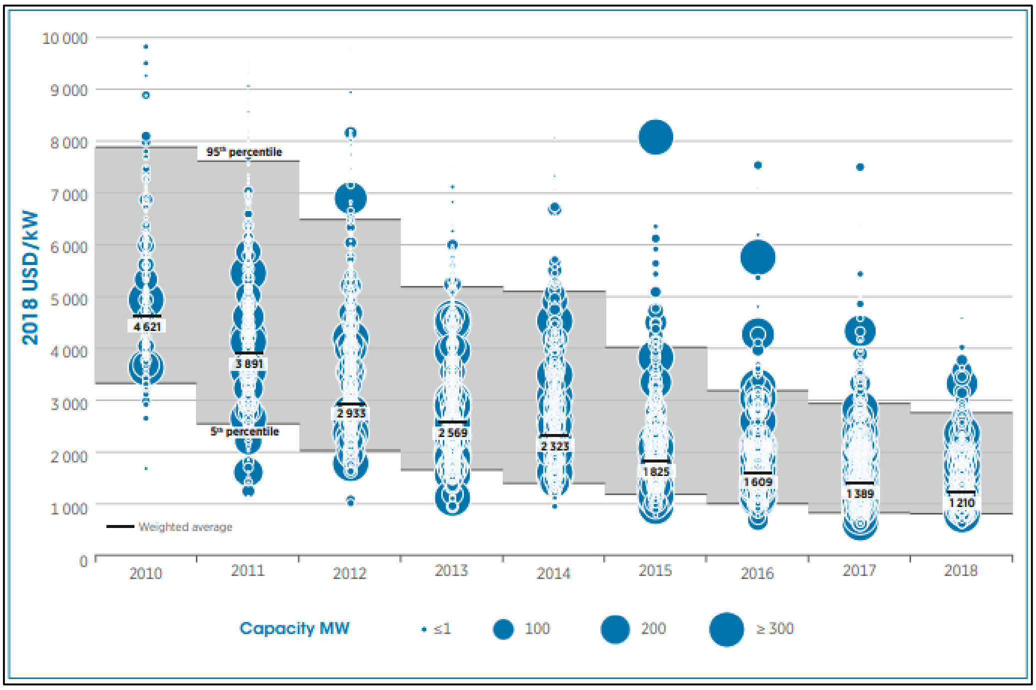


Figure 3.10 - Global weighted average installation costs of utility scale solar PV (2010 – 2018) [33]

Utility scale solar PV costs in different countries of the world had also been reduced by 66% - 84% from 2010 to 2018 period as illustrated in figure 3.11.

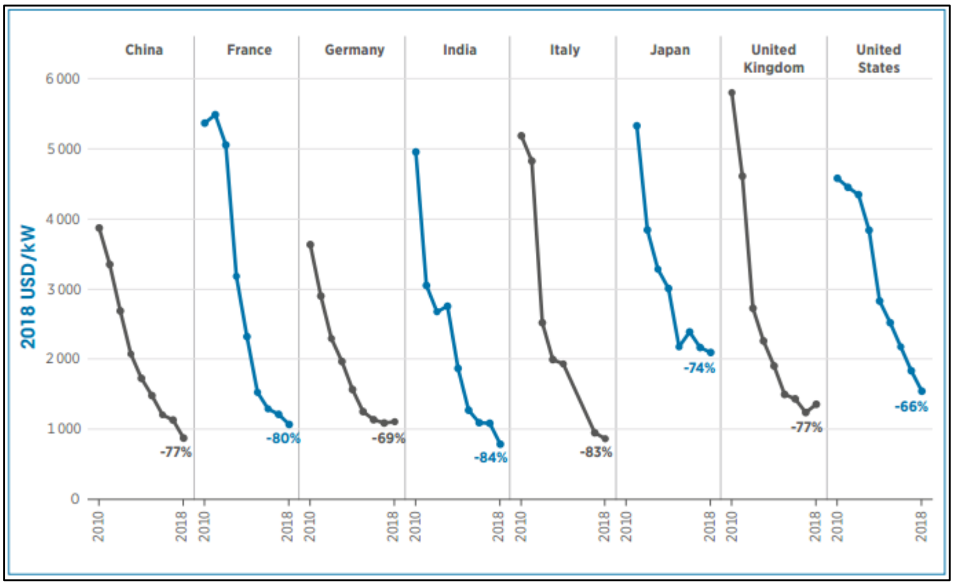


Figure 3.11 - Weighted country average installation costs of utility scale solar PV (2010 – 2018) [33]

It is always important to study on the cost breakdown of a utility scale solar PV project in order to find out the most important and expensive portion. The global averaged cost values include the soft costs such as system designing cost, installation cost as well as the cost for hardware such as modules, inverters, grid connection etc.

As illustrated in the figure 3.12 the major cost component in utility scale solar PV projects could be seen in hardware part of solar PV. The most dramatic change of solar power prices had been there in last few years after 2010. The main reason for this can be identified as the improvements made in solar panel technology to make it cheap than it was in few years ago.

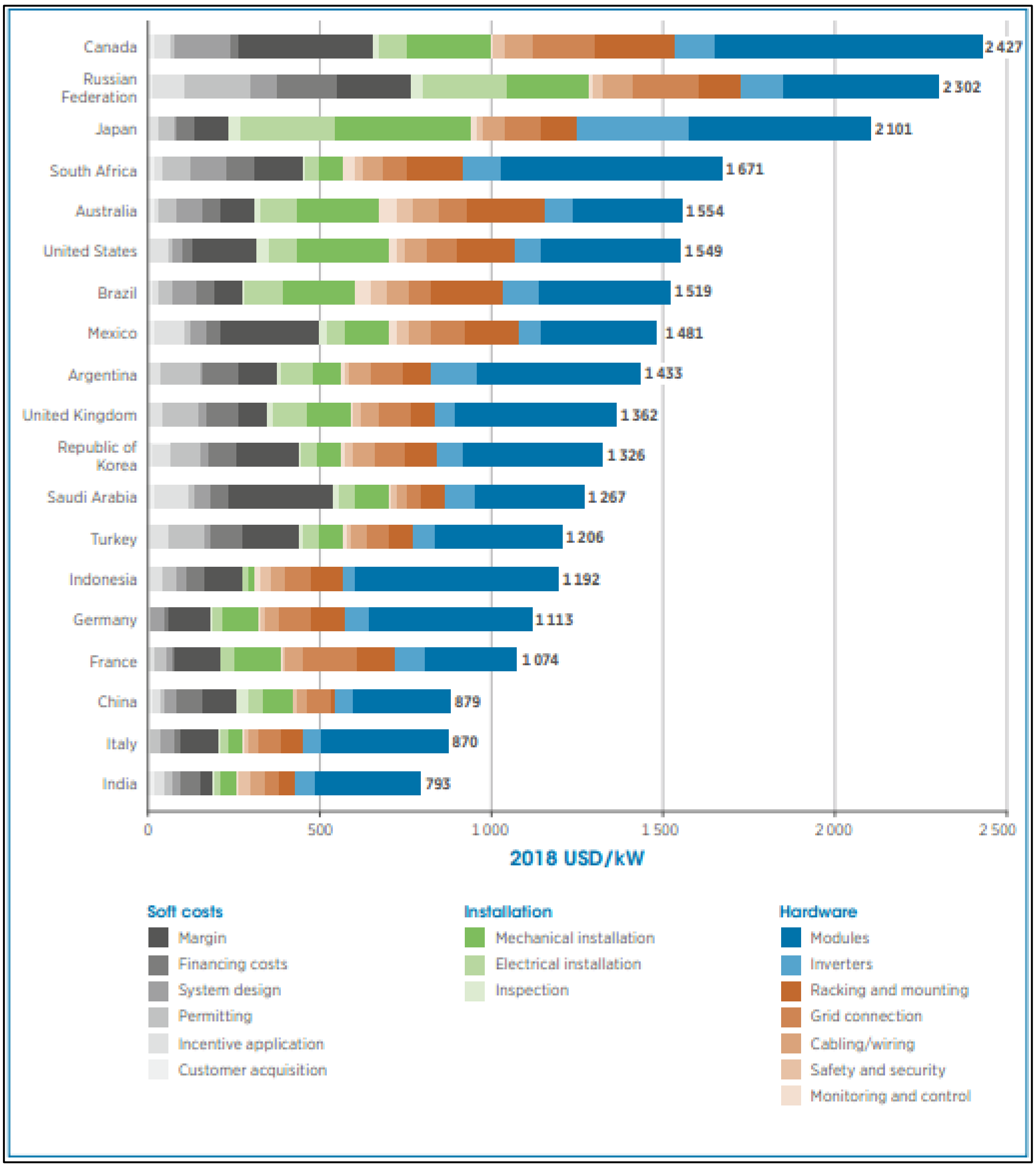


Figure 3.12 - Cost breakdown of utlity scale solar PV projects in G20 countries [33]

However, cost values of solar power has to be referred to these global statistics. Therefore, values shown in table 3.3 were considered for the homer simulation.

Table 3.3 : Costs of solar panels selected for microgrid modelling

Solar panel make & model	Capacity of a panel	Panel efficiency	Capital cost (USD/kW)	Annual O & M cost (USD/kW)
Sharp ND-250QCS	250 W	15.3	400	14

3.3.4 Biomass power generation

Under the biomass power generation, it is considered to use rice husk as the main energy resource. Globally the power generation cost for biomass has become a little downward slide with technology improvements. Hence, it could be expected that the trend may continue to drop more to make biomass power generation less expensive by the time.

There are two widely used biomass conversion technologies that can be adopted. Namely they are direct combustion and gasification. Direct combustion is efficient than gasification technology, it is a hassle free as far as the operation is concerned due to tar, ash content of producer gas in gasification process. Producer gas cleaning is an essential part in plant operation which is would lead plant outages and more maintenance activities. Therefore, direct combustion technology could be adopted where it is possible to run the Rankine cycle with a biomass fired boiler.

Average calorific value of rice husk can be taken as 13.6 MJ/kg the statistics of 1 MW power plant are shown in table 3.4 as follows.

Table 3.4 : Costs of rice husk fired power plant [25]

Plant capacity	Capital cost	Annual O & M cost (5% of capital)	Fuel consumption	Plant life time
1 MW	1,250 USD/kW	62.5 USD/kW	40,000 kg/day	20 years

For a small scale power plant in which the capacity is less than 10 MW that operates on biomass or agricultural waste PUCSL has approved the capital cost should be around LKR 263 Mn/MW and annual operation and maintenance cost to be 5% of total capital cost.

3.3.5 Municipal solid waste power generation

Municipal solid waste management in Sri Lanka had already become an issue with a lot of importance than ever before. With the increasing population and limited land area availability dumping it somewhere won't be a sustainable solution. A survey conducted by Japan International Cooperation Agency (JICA) in 2016 has identified the status of several projects that were proposed in earlier studies. As per the report metro Colombo solid waste management project is underway after the completion of environmental impact assessment of the project. It is estimated to collect 1200 MT waste per day which are generated in metro Colombo region to Meethotamulla and transport them by train to Aruakkalu land filling site which is the quarry operated by Insee cement, Puttalam. In that sense, the source is already in the near proximity with the implementation of this project where a solid waste power generation facility would become feasible to be operated in the microgrid.

There are no such plants in Sri Lanka so far and it would be a new technology introduction as well. For small scale MSW power plants, capacity under 10 MW, PUCSL had approved a capital cost value in Non-conventional Renewable Energy (NCRE) tariff decisions as LKR 399 Mn/MW and about 7% of that capital costs as annual operation and maintenance cost. However, for the homer simulation there are two main technology options considered to be modelled with the microgrid.

3.3.5.1 Producing biogas and refuse-derived fuel (RDF)

Considering a plant to produce biogas from MSW to run a biogas power plant as well as a refuse-derived fuel (RDF) from the remains of biogas power plant to run a power plant from refuse-derived fuel (RDF). Financial terms of this option were taken as per the following table of 4 MW plant statistics found in literature.

Table 3.5 : Costs for a MSW power plant from biogas with RDF plant [30]

Biogas plant capacity	2 MW
Biogas plant factor	70%

RDF plant factor	2 MW
RDF plant factor	80%
Waste to process	700 MT/day
Biogas plant input	500 MT/day
Plant capital cost	LKR 1,436,000
Annual O & M cost	LKR 176,770,000

3.3.5.2 Incineration of MSW

This option was considered to generate electricity from direct incineration MSW without having a biogas or residual derived fuel (RDF) plant. Financial terms of MSW incineration thermal power plant were taken as per the table 3.6 for 9 MW plant.

Table 3.6 : Costs for a MSW power plant with an incinerator [30]

Thermal power plant capacity	9 MW
Biogas plant factor	81%
Waste to process	700 MT/day
Power plant capital cost	LKR 4,855,400,000
Project development cost	LKR 23,000,000
Total capital cost	LKR 4,878,400,000
Total annual O & M cost	LKR 242,770,000

3.4 Economics & Other Constraints

In order to evaluate the financial viability of proposed microgrid configurations financial data such as nominal discount rate, inflation rate and exchange rate. Nominal discount rate is the interest rate where the money could be borrowed from a financial institution or a bank. As per weekly financial indicators published by the central bank of Sri Lanka, the average weighted lending rate (AWLR) specified for licensed commercial banks which had been varying around 14% in 2018, 2019 is taken as nominal discount rate and inflation rate is taken as 6% considering the annual average value of 2018. Exchange rate of 1 USD is taken as LKR 180 for a project life time of 20 years.

HOMER Pro need some constraints which relates to the calculation of required operating reserve of microgrid as well as the capacity shortages. Electrical load was selected as the April load since the load in almost all the other months of the year are low. This would lead to exaggerate the actual required capacity of microgrid. But it will ensure the power supply stability of the system. Therefore, operating reserve as a percentage of renewable power input was considered as 25% and as a percentage in load it was taken as 10% without making too much installed capacity. Minimum renewable fraction of supply was kept as 0% because there can be instances due to technical faults or essential maintenance requirements in each renewable generator. Maximum annual capacity shortage is the fraction of total unmet load to total annual load which should be ideally zero if there are no grid purchases. However, this is expected to as minimal as possible and preferable less than 10%.

4 RESULTS & DISCUSSION

Configurations of microgrid could be simulated in several combinations with the energy sources that are available in Kalpitiya peninsula. As per the available potential of each selected technology, solar PV, wind, biomass (rice husk) & municipal solid waste are taken into consideration for a combination of microgrid. Costs of wind, solar technologies were studied referring to the global cost trends while the cost values of biomass (rice husk), municipal solid waste power generation facilities were referred from other available literature related to Sri Lankan context.

It was assumed that power system would curtail the generation of high cost thermal power (i.e.: oil based power plants) to absorb the NCRE in the microgrid. Optimal combination for utilising energy resources were obtained after HOMER Pro simulation and economics, emissions of each configuration against each other as well in order to figure out a best configuration. Configurations of microgrids were considered as per the table 4.1 and each of them was compared with the base case of power consumption by national grid.

Table 4.1 : Configurations of microgrids

Configuration	Included energy sources
A	Grid + wind 01 + wind 02 + solar
B	Grid + wind 01 + wind 02 + solar + biomass
C	Grid + wind 01 + wind 02 + solar + MSW
D	Grid + wind 01 + wind 02 + solar + biomass + MSW

Simulation results obtained for each configuration mentioned in table 4.1 are discussed in detail in sections 4.1, 4.2, 4.3 and 4.4 respectively and comparison among the configurations is discussed in section 4.5.

4.1 Configuration A (Grid + wind 01 + wind 02 + solar)

Configuration A includes two wind plants, wind01 comprising of 12 nos. 850 kW wind turbines and wind 02 comprising 08 nos. of 1250 kW wind turbines, solar plant with a maximum capacity of 5 MW along with utility grid. Schematic diagram of the system is shown in figure 4.1.

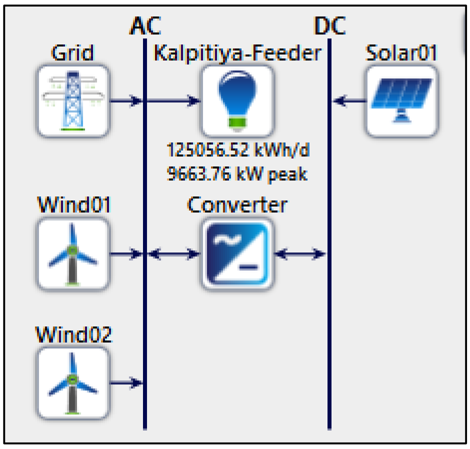


Figure 4.1 : Microgrid configuration A

Results of the HOMER Pro simulation is given in figure 4.2.

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Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture						Cost			
Solar01 (kW)	Wind01	Wind02	Grid (kW)	Converter (kW)	Dispatch	NPC (US$)	COE (US$)	Initial capital (US$)	O&M (US$/yr)
	12	6	99,999		LF	$79.4M	$0.147	$26.6M	$5.20M
500	12	6	99,999	250	LF	$80.3M	$0.148	$28.2M	$5.11M
	12		99,999		LF	$82.4M	$0.168	$15.3M	$6.61M
500	12		99,999	250	LF	$83.2M	$0.170	$16.9M	$6.51M
		8	99,999		LF	$89.7M	$0.185	$15.0M	$7.35M
500		8	99,999	250	LF	$90.5M	$0.187	$16.6M	$7.26M
			99,999		LF	$95.7M	$0.206	$0.00	$9.42M
500			99,999	250	LF	$96.5M	$0.208	$1.61M	$9.32M

Figure 4.2 : Homer optimisation results for microgrid configuration A

Simulation has given all the wind turbines (12 nos.) in wind01, six (06) wind turbines from wind02 along with the utility grid as the most economical combination for configuration A. It was noted that solar power was not included in optimised the system due high availability of wind power plants throughout the year. Capital cost of total system is 26.6 million USD and annual O&M cost is 5.2 million USD which is

19.5% of the initial investment. Levelised cost of energy (LCOE) of the total system is 0.147 USD/kWh which is 26.5% lower than consuming diesel power with a cost of 0.2 USD/kWh. Electrical generation statistics of the simulation for configuration A is given in figure 4.3.

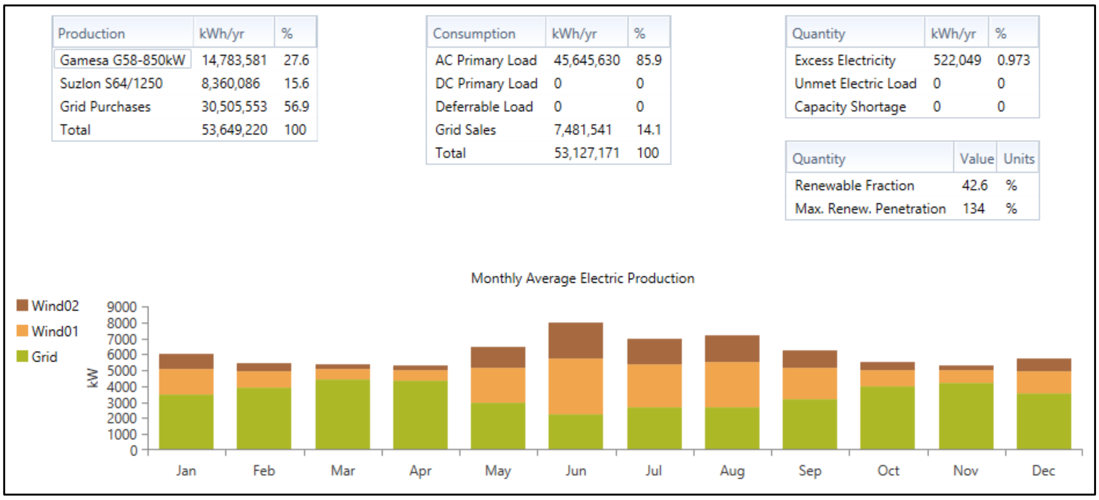


Figure 4.3 : Electricity generation statistics of microgrid configuration A

Referring to the electrical statistics in figure 4.3, the 56.9% of demand could be catered by the utility grid and wind01, wind02 could be able to bear the loads of 27.6% and 15.6% respectively. Since the unmet load is zero, there are no capacity shortages in the system and excess electricity could be counted less than 1% due to the constraint of grid sales given as 10,000 kW in any time step where in real terms excess could also become grid sales as well. Following the constraint, the utility grid sales has been estimated to be 14.1% of total system consumption.

Electrical generation economics of the simulation for configuration A is given in figure 4.4.

You may choose a different base case using the Compare Economics button on the Results Summary Table.

	Architecture										Cost	
							Solar01 (kW)	Wind01	Wind02	Grid (kW)	Converter (kW)	NPC (US$)	Initial capital (US$)
Base system										99,999		$95.7M	$0.00
Current system								12	6	99,999		$79.4M	$26.6M

Metric	Value
Present worth ($)	$16,320,600
Annual worth ($/yr)	$1,606,671
Return on investment (%)	10.9
Internal rate of return (%)	14.9
Simple payback (yr)	6.29
Discounted payback (yr)	8.86

Charts...

Figure 4.4 : Electricity generation statistics of microgrid configuration A

Initial investment of 79.4 million USD could be recovered in 8.86 years which is nearly 1/3 of the project life time. Sensitivity analysis was done with 10,000 kW, 5000 kW, 2500 kW, 1000 kW and 0 kW grid sales and simulation selected 11 turbines from wind01 along with the utility grid as the optimal configuration as depicted in figure 4.5.

Export... Export All... **Sensitivity Cases** Left Click on a sensitivity case to see its Optimization Results. Compare Economics Column

Sensitivity	Architecture											Cost				System
Grid Sale Capacity (kW)							Solar01 (kW)	Wind01	Wind02	Grid (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Initial capital ($)	O&M ($/yr)	Ren Frac (%)
0								11		99,999		LF	$87.5M	$0.189	$14.0M	$7.24M	25.4
1,000								12		99,999		LF	$85.9M	$0.182	$15.3M	$6.95M	28.2
10,000								12	6	99,999		LF	$79.4M	$0.147	$26.6M	$5.20M	42.6
2,500								12		99,999		LF	$84.1M	$0.175	$15.3M	$6.78M	29.5
5,000								12	2	99,999		LF	$82.4M	$0.165	$19.1M	$6.24M	34.4

Figure 4.5 : Sensitivity of grid sales for microgrid configuration A

Renewable penetration is only 25.4% when there is no grid sales and the grid purchasing is 74.6% which is almost 03 times than that. However, the renewable penetration to the system is high (42.6%) when grid sale capacity is 10,000 kW.

Detailed simulation report generated from HOMER Pro is given in Appendix B.

4.2 Configuration B (Grid + wind 01 + wind 02 + solar + biomass)

In Configuration B a biomass power generation plant was added to the microgrid configuration A. Biomass power plant is expected to operate as a base load power plant for the microgrid and rest of the power could be used for catering the demand above the base load as per the availability along with the utility grid. Schematic diagram of configuration B is shown in figure 4.6.

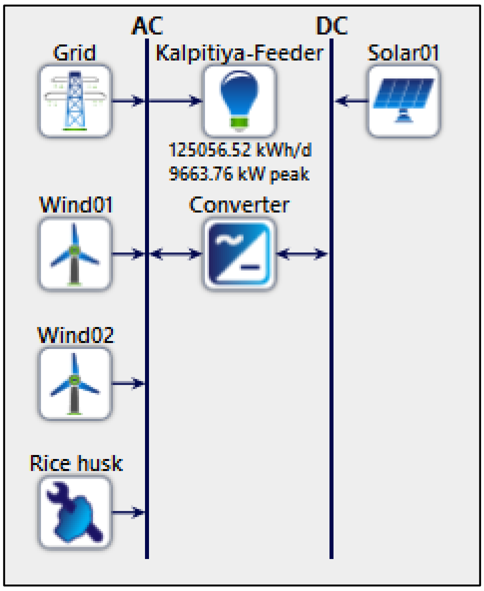
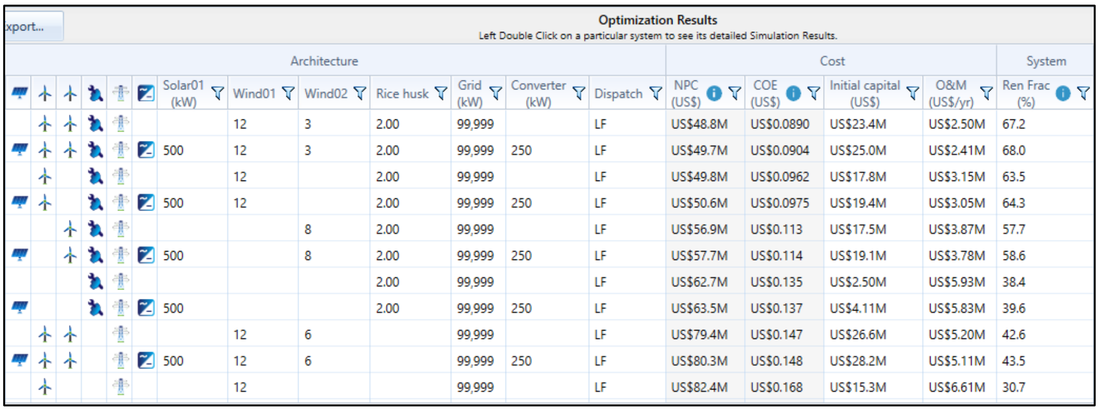


Figure 4.6 : Microgrid configuration B

Homer simulation results in figure 4.7 shows that the best combination of the available energy sources is 12nos. of 850 kW wind turbines, 03 nos. of 1,250 kW wind turbines. 2 MW of biomass power generation along with the utility grid. With the given combination the initial investment is 23.4 million USD with an O&M cost of 2.5 million USD which is slightly less than configuration A. But the LCOE of configuration B has been decreased to 0.0890 USD/kWh.



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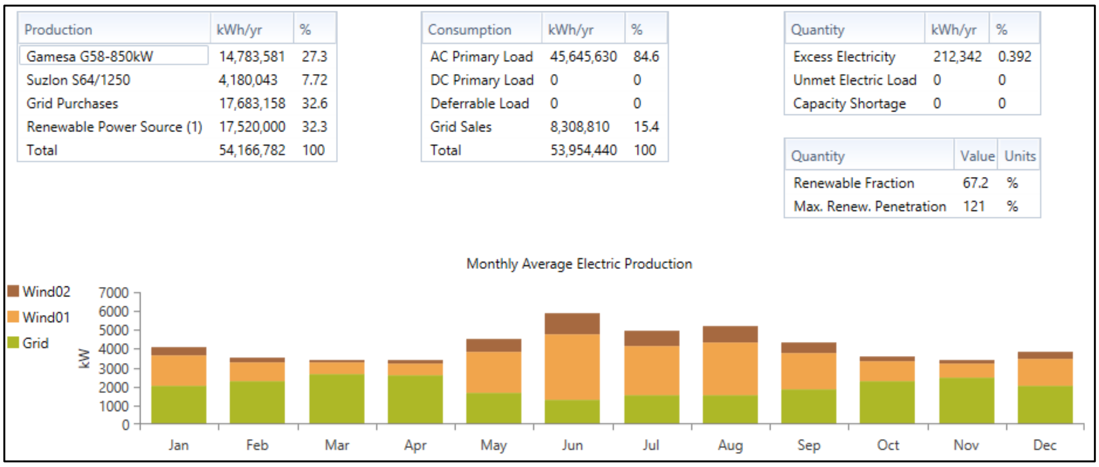
Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Solar01 (kW)	Wind01	Wind02	Rice husk	Grid (kW)	Converter (kW)	Dispatch	NPC (US$)	COE (US$)	Initial capital (US$)	O&M (US$/yr)	Ren Frac (%)
	12	3	2.00	99,999		LF	US$48.8M	US$0.0890	US$23.4M	US$2.50M	67.2
500	12	3	2.00	99,999	250	LF	US$49.7M	US$0.0904	US$25.0M	US$2.41M	68.0
	12		2.00	99,999		LF	US$49.8M	US$0.0962	US$17.8M	US$3.15M	63.5
500	12		2.00	99,999	250	LF	US$50.6M	US$0.0975	US$19.4M	US$3.05M	64.3
		8	2.00	99,999		LF	US$56.9M	US$0.113	US$17.5M	US$3.87M	57.7
500		8	2.00	99,999	250	LF	US$57.7M	US$0.114	US$19.1M	US$3.78M	58.6
			2.00	99,999		LF	US$62.7M	US$0.135	US$2.50M	US$5.93M	38.4
500			2.00	99,999	250	LF	US$63.5M	US$0.137	US$4.11M	US$5.83M	39.6
	12	6		99,999		LF	US$79.4M	US$0.147	US$26.6M	US$5.20M	42.6
500	12	6		99,999	250	LF	US$80.3M	US$0.148	US$28.2M	US$5.11M	43.5
	12			99,999		LF	US$82.4M	US$0.168	US$15.3M	US$6.61M	30.7

Figure 4.8 : Homer simulation results for microgrid configuration B

It is important to examine the electrical statistics illustrated in figure 4.8 in order to find out the contribution of energy sources to cater the demand in microgrid.



Production	kWh/yr	%
Gamesa G58-850kW	14,783,581	27.3
Suzlon S64/1250	4,180,043	7.72
Grid Purchases	17,683,158	32.6
Renewable Power Source (1)	17,520,000	32.3
Total	54,166,782	100

Consumption	kWh/yr	%
AC Primary Load	45,645,630	84.6
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	8,308,810	15.4
Total	53,954,440	100

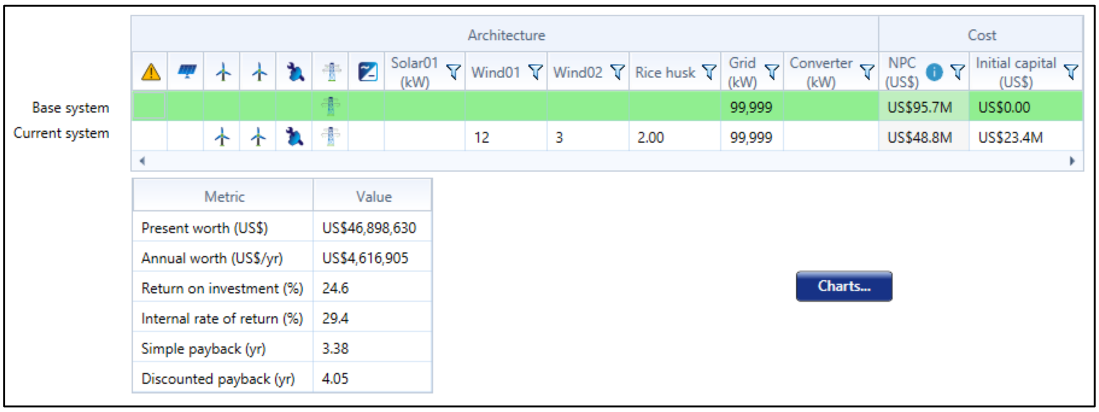
Quantity	kWh/yr	%
Excess Electricity	212,342	0.392
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	67.2	%
Max. Renew. Penetration	121	%

Figure 4.7 : Electricity generation statistics in microgrid configuration B

According to the statistics in figure 4.8, demand could be completely generated with this configuration as the unmet load is zero and no capacity shortage. Excess electricity is also less than 1% which could be grid sales in practical context. Penetration of renewable energy is 67.2% while the grid purchases counts to 32.6% from the energy production and amount of grid sales is estimated to be 15.4% from the energy consumed.

Electricity generation economics of microgrid configuration B is given in figure 4.9.



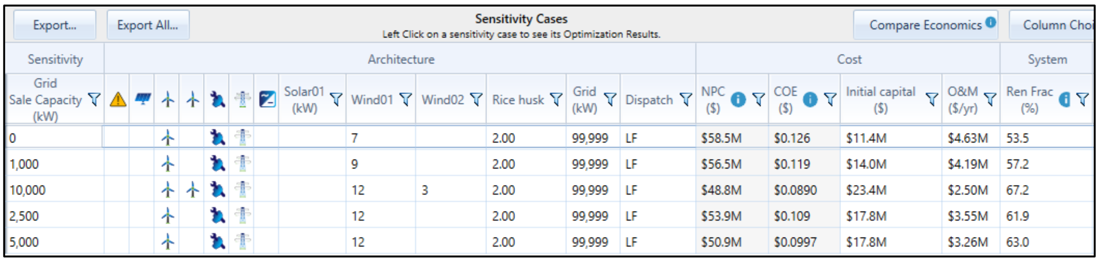
	Solar01 (kW)	Wind01	Wind02	Rice husk	Grid (kW)	Converter (kW)	NPC (US$)	Initial capital (US$)
Base system					99,999		US$95.7M	US$0.00
Current system		12	3	2.00	99,999		US$48.8M	US$23.4M

Metric	Value
Present worth (US$)	US$46,898,630
Annual worth (US$/yr)	US$4,616,905
Return on investment (%)	24.6
Internal rate of return (%)	29.4
Simple payback (yr)	3.38
Discounted payback (yr)	4.05

Figure 4.9 : Electricity generation economics of microgrid configuration B

Economics of configuration B is of much importance which has a direct impact of its practical viability. As mentioned in figure 4.9, discounted payback period of this combination is estimated to be 4.05 years which is promising.

In order to make configuration B more optimised where the microgrid could be modelled without making overestimated installed capacity a sensitivity analysis was performed by giving 10,000 kW, 5000 kW, 2500 kW, 1000 kW and 0 kW values for grid sales capacity. Sensitivity results are shown in figure 4.10.



Grid Sale Capacity (kW)	Solar01 (kW)	Wind01	Wind02	Rice husk	Grid (kW)	Dispatch	NPC ($)	COE ($)	Initial capital ($)	O&M ($/yr)	Ren Frac (%)
0		7		2.00	99,999	LF	$58.5M	$0.126	$11.4M	$4.63M	53.5
1,000		9		2.00	99,999	LF	$56.5M	$0.119	$14.0M	$4.19M	57.2
10,000		12	3	2.00	99,999	LF	$48.8M	$0.0890	$23.4M	$2.50M	67.2
2,500		12		2.00	99,999	LF	$53.9M	$0.109	$17.8M	$3.55M	61.9
5,000		12		2.00	99,999	LF	$50.9M	$0.0997	$17.8M	$3.26M	63.0

Figure 4.10 : Sensitivity of grid sales for microgrid configuration B

It is evident that renewable penetration is only 53.5% when there are no grid sales which is the lowest and 67.2%, the highest when the sale capacity is 10,000 kW. Levelised cost of energy, annual O&M cost is also 0.089 USD/kWh & 2.5 million USD respectively.

Detailed simulation report generated from HOMER Pro is given in Appendix C.

4.3 Configuration C (Grid + wind 01 + wind 02 + solar + MSW)

In configuration C, MSW taken into consideration instead of biomass. Since the availability of rice husk as the main biomass fuel the plant capacity is limited for a maximum of 2 MW in configuration B whereas capacity of MSW power generation is considered up to a maximum of 4 MW. The schematic diagram of configuration C is shown in the figure 4.11 given below.

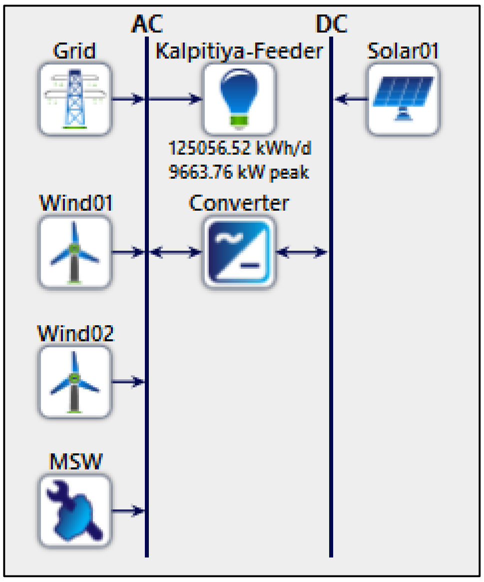


Figure 4.11 : Microgrid configuration C

Simulation results of microgrid configuration C is obtained for grid sale capacity of 10,000 kW as shown in the figure 4.12.

Export...

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture							Cost				System
Solar01 (kW)	Wind01	Wind02	MSW	Grid (kW)	Converter (kW)	Dispatch	NPC (US$)	COE (US$)	Initial capital (US$)	O&M (US$/yr)	Ren Frac (%)
	12		4.00	99,999		LF	US$28.2M	US$0.0489	US$24.2M	US$399,575	87.6
	12	1	4.00	99,999		LF	US$28.5M	US$0.0483	US$26.0M	US$237,215	88.0
500	12		4.00	99,999	250	LF	US$29.3M	US$0.0504	US$25.8M	US$325,188	88.0
500	12	1	4.00	99,999	250	LF	US$29.5M	US$0.0498	US$27.6M	US$164,255	88.5
		8	4.00	99,999		LF	US$33.9M	US$0.0613	US$23.9M	US$985,664	84.8
500		8	4.00	99,999	250	LF	US$34.9M	US$0.0627	US$25.5M	US$907,096	85.3
			4.00	99,999		LF	US$37.5M	US$0.0786	US$8.87M	US$2.82M	74.7
500			4.00	99,999	250	LF	US$38.3M	US$0.0800	US$10.5M	US$2.72M	75.5
	12	6		99,999		LF	US$79.4M	US$0.147	US$26.6M	US$5.20M	42.6
500	12	6		99,999	250	LF	US$80.3M	US$0.148	US$28.2M	US$5.11M	43.5

Figure 4.12 : Homer simulation results for microgrid configuration C

Unlike the previous microgrid configuration C has a renewable penetration of 87.6% which is comparatively high. LCOE has been also further reduced 0.0489 USD while the annual O&M cost is estimated for 399,575 USD. Most economic combination selected by Homer includes all wind turbines in wind01 & full capacity (4 MW) of MSW power generation facility. It is always important to refer to statistics of electrical power generation to identify how power sources and utility grid have been able to balance the demand with the supply. Electrical generation statistics are illustrated in the figure 4.13.

Production	kWh/yr	%
Gamesa G58-850kW	14,783,581	26.0
Grid Purchases	7,071,683	12.4
Renewable Power Source	35,040,000	61.6
Total	56,895,265	100

Consumption	kWh/yr	%
AC Primary Load	45,645,630	80.3
DC Primary Load	0	0
Deferrable Load	0	0
Grid Sales	11,217,508	19.7
Total	56,863,138	100

Quantity	kWh/yr	%
Excess Electricity	32,126	0.0565
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	87.6	%
Max. Renew. Penetration	109	%

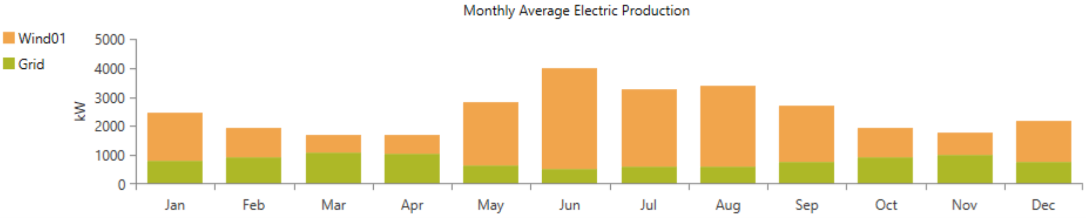


Figure 4.13 : Electricity generation statistics of microgrid configuration C

According to the statistics of figure 4.13, grid purchases is calculated to be 61.6% of total energy production & total grid sales as per the consumption is 19.7%. There is no capacity shortage, unmet loads and amount of excess energy generated is calculated to be 0.0565% which could be negligible in comparison to the demand.

Electricity generation economics of microgrid configuration C is given in figure 4.14.

	Architecture						Cost	
	Solar01 (kW)	Wind01	Wind02	MSW	Grid (kW)	Converter (kW)	NPC (US$)	Initial capital (US$)
Base system					99,999		US$95.7M	US$0.00
Current system		12		4.00	99,999		US$28.2M	US$24.2M

Metric	Value
Present worth (US$)	US$67,457,630
Annual worth (US$/yr)	US$6,640,823
Return on investment (%)	32.3
Internal rate of return (%)	37.3
Simple payback (yr)	2.68
Discounted payback (yr)	3.11

Charts...

Figure 4.14 : Electricity generation economics of microgrid configuration C

When the selected best alternative is compared with the base case (power supply from utility grid only) as shown in figure 4.14 discounted payback period for this microgrid configuration is calculated as 3.11 years. When the sensitivity of grid sales is carried out, highest renewable energy penetration as well as the lowest LCOE is observed at 10,000 kW grid sale value. In figure 4.15 all the best sensitivity cases are listed as given in Homer pro.

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Sensitivity	Architecture						Cost				System
Grid Sale Capacity (kW)	Solar01 (kW)	Wind01	Wind02	MSW	Grid (kW)	Dispatch	NPC (US$)	COE (US$)	Initial capital (US$)	O&M (US$/yr)	Ren Frac (%)
0		1		4.00	99,999	LF	US$39.9M	US$0.0860	US$10.1M	US$2.93M	75.7
1,000		4		4.00	99,999	LF	US$35.8M	US$0.0735	US$14.0M	US$2.15M	80.6
10,000		12		4.00	99,999	LF	US$28.2M	US$0.0489	US$24.2M	US$399,575	87.6
2,500		7		4.00	99,999	LF	US$32.7M	US$0.0636	US$17.8M	US$1.47M	83.8
5,000		10		4.00	99,999	LF	US$30.3M	US$0.0554	US$21.6M	US$859,045	86.2

Figure 4.15 : Sensitivity of grid sales for microgrid configuration C

Detailed simulation report generated from HOMER Pro is given in Appendix D.

4.4 Configuration D (Grid + wind 01 + wind 02 + solar + MSW + biomass)

This microgrid configuration includes all the power sources identified which has a potential in Kalpitiya peninsula. Microgrid integrated with highest diversification of power sources looks like the following schematic diagram shown in figure 4.16 below.

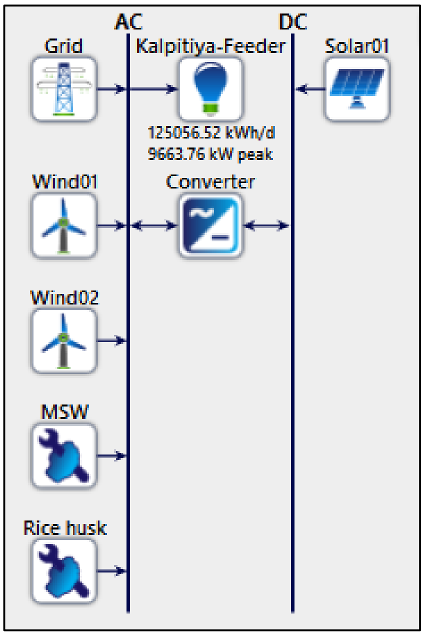


Figure 4.16 : Microgrid configuration D

Microgrid configuration D in figure 4.16 is simulated for a grid sales limit of 10,000 kW in HOMER Pro & it has given the results listed in the figure 4.17.

Export...

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture							Cost				System
Solar01 (kW)	Wind01	Wind02	MSW	Rice husk	Grid (kW)	Dispatch	NPC (US$)	COE (US$)	Initial capital (US$)	O&M (US$/yr)	Ren Frac (%)
	12		4.00	2.00	99,999	LF	US$6.47M	US$0.00926	US$26.7M	-US$1.99M	97.5
	11	1	4.00	2.00	99,999	LF	US$7.05M	US$0.0101	US$27.3M	-US$1.99M	97.5
500	12		4.00	2.00	99,999	LF	US$7.68M	US$0.0109	US$28.3M	-US$2.05M	97.7
500	11	1	4.00	2.00	99,999	LF	US$8.27M	US$0.0118	US$28.9M	-US$2.05M	97.6
			4.00	2.00	99,999	LF	US$9.39M	US$0.0166	US$11.4M	-US$194,632	94.1
		1	4.00	2.00	99,999	LF	US$9.55M	US$0.0165	US$13.2M	-US$363,152	94.9
500			4.00	2.00	99,999	LF	US$10.6M	US$0.0185	US$13.0M	-US$255,747	94.5

Figure 4.17 : Homer simulation results for microgrid configuration D

According to figure 4.17 above, Homer optimisation results has specified 12 nos. 850 kW wind turbines (wind01), 4 MW capacity of MSW plant & 2 MW capacity as the economically beneficial combination for microgrid configuration D. LCOE has become as low as 0.00926 USD/kWh with initial capital cost for the project being 26.7 million USD. Since the O&M cost has become an income it is important to look into the electrical generation statistics shown in the figure 4.18.

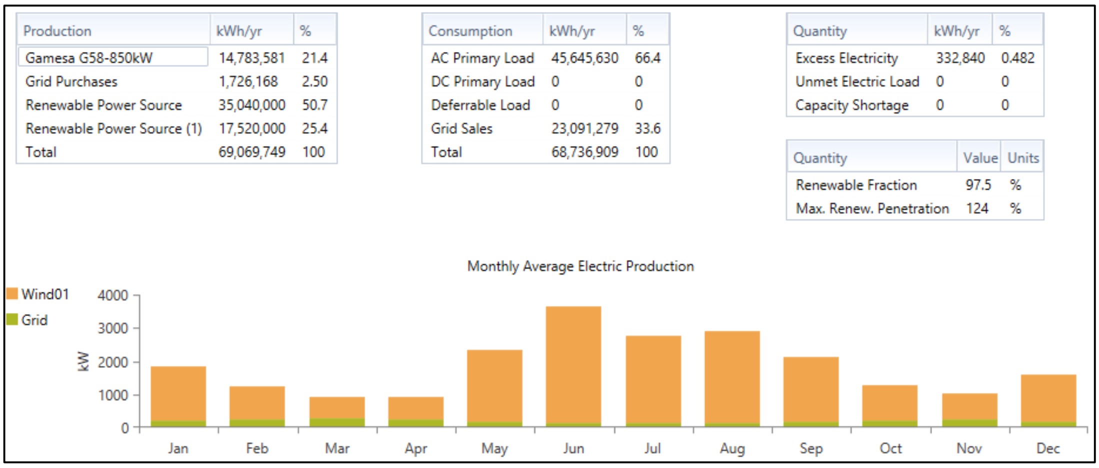


Figure 4.18 : Electricity generation statistics of microgrid configuration D

Similar to the previous cases there is no capacity shortages or unmet loads in microgrid configuration D. In figure 4.18 it evident that renewable penetration is as high as 97.5% where the demand is mainly compensated from DERs making the grid purchasing as low as 2.5% from energy production. However 33.6% of consumed electricity is sold to utility grid so that considerable financial income is obtained in comparison to the cost incurred for grid purchasing. This is the main reason to make annual O&M cost negative which means it is an income for microgrid operator.

Electricity generation economics of microgrid configuration D is given in figure 4.19.

	Architecture						Cost	
	Solar01 (kW)	Wind01	Wind02	MSW	Rice husk	Grid (kW)	NPC (US$)	Initial capital (US$)
Base system						99,999	US$95.7M	US$0.00
Current system		12		4.00	2.00	99,999	US$6.47M	US$26.7M

Metric	Value
Present worth (US$)	US$89,217,820
Annual worth (US$/yr)	US$8,782,990
Return on investment (%)	37.8
Internal rate of return (%)	42.7
Simple payback (yr)	2.34
Discounted payback (yr)	2.68

Charts...

Figure 4.19 : Electricity generation economics of microgrid configuration D

Economic benefit in the particular combination in figure 4.19 shows that discounted payback period of the initial investment is only 2.68 years. If the grid sales are limited, the system architecture could be changed & those are given in a sensitivity analysis done for grid sale capacity as given in figure 4.20 below.

Export... Export All... **Sensitivity Cases** Left Click on a sensitivity case to see its Optimization Results. Compare Economics Column Choices...

Sensitivity	Architecture						Cost				System
Grid Sale Capacity (kW)	Solar01 (kW)	Wind01	Wind02	MSW	Rice husk	Grid (kW)	NPC (US$)	COE (US$)	Initial capital (US$)	O&M (US$/yr)	Ren Frac (%)
0				4.00	2.00	99,999	US$25.8M	US$0.0556	US$11.4M	US$1.42M	92.8
1,000				4.00	2.00	99,999	US$16.3M	US$0.0316	US$11.4M	US$489,568	93.6
10,000		12		4.00	2.00	99,999	US$6.47M	US$0.00926	US$26.7M	-US$1.99M	97.5
2,500				4.00	2.00	99,999	US$10.0M	US$0.0178	US$11.4M	-US$132,270	94.1
5,000		5		4.00	2.00	99,999	US$8.36M	US$0.0136	US$17.7M	-US$923,824	96.4

Figure 4.20 : Sensitivity of grid sales for microgrid configuration D

According to figure 4.20 when there are no grid sales from microgrid, there are no wind turbines in the system and only the MSW, biomass plants are available which still counts 92.8% of renewable fraction. LCOE with no grid sales is 0.0556 USD/kWh & also less than other microgrid configurations A, B, C as well. However, it is clear that grid selling is the reason to reduce the O&M cost with LCOE of microgrid configuration D. Therefore, when the grid sales are increased the dependency of the local demand from the utility grid also reduces as well.

Detailed simulation report generated from HOMER Pro is given in Appendix E.

4.5 Comparison of microgrid configurations

Selected microgrid configurations with 10,000kW grid sales were compared with one another in order to develop more effective, economical and practical microgrid model. Sensitivity analysis for grid sales capacity in each configuration were also carried out in order to make the microgrid autonomous as much as possible. Considering the existing scenario, utility grid supply as the base case each configuration was compared with the existing scenario.

Table 4.2 : Comparison of microgrid configurations

	Microgrid Configuration A	Microgrid Configuration B	Microgrid Configuration C	Microgrid Configuration D
Initial capital (USD)	26.6 Mn	23.4 Mn	24.2 Mn	26.7 Mn
Annual O&M cost (USD)	5.20 Mn	2.50 Mn	399,575	-1.99 Mn
LCOE (USD/kWh)	0.147	0.089	0.0489	0.00926
NPC (USD)	79.4 Mn	48.8 Mn	28.2 Mn	6.47 Mn
Renewable penetration (%)	42.6	67.2	87.6	97.5
Annual grid purchases (kWh/yr)	30,505,553	17,683,158	7,071,683	1,726,168
Annual grid sales (kWh/yr)	7,481,541	8,308,810	11,217,508	23,091,279

Annual CO_2 emissions (kg/yr)	19,279,510	11,175,756	4,469,304	1,090,938
ROI (%)	10.9	24.6	32.3	37.8
IRR (%)	14.9	29.4	37.3	42.7
Simple payback (Years)	6.29	3.38	2.68	2.34
Discounted payback (Years)	8.86	4.05	3.11	2.68

One similarity of all microgrid configurations are that solar power is not included as an energy source for the economically optimised combination. Referring to the table 4.2 above, it is clear that all projects are having a considerable IRR, discounted payback periods varying in between 2.68 to 8.86 years. Economic comparison of microgrid configurations is presented in figure 4.19 below.

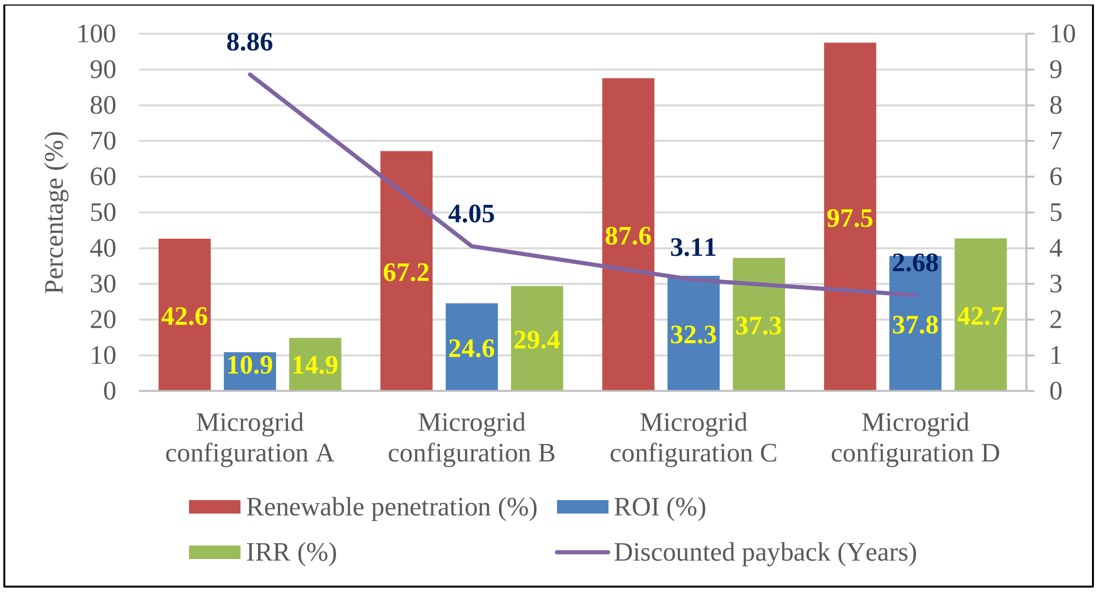


Figure 4.21 : Economic comparison of microgrid configurations

As per the figure 4.19, when the renewable energy penetration is increased the ROI and IRR of the microgrid investment is improving and the discounted payback period has come down to 2.68 years. This implies that an investment of having a microgrid with higher renewable penetration has economic viability. In other words, the total investment could be completely recovered even before the end of first quarter of project life time.

The above economic analysis is done in the perspective of microgrid operator. If this microgrid is assumed to be a private power producer, then the economic benefits can only be calculated at the end of the year since there are many different energy sources integrated in the microgrid. Assume the revenue for microgrid operator is paid according to flat tariff given in the following table 4.3 announced by PUCSL.

Table 4.3 : Flat tariff for 01-20 years for non-conventional renewable energy technologies announced by PUCSL on 01.01.2012

Technology	All inclusive flat tariff for 1-20 years (LKR/kWh)
Mini hydro	16.70
Mini hydro - local	17.15
Wind	20.62
Wind - local	21.22
Biomass (Dendro)	25.09
Biomass (Agricultural and Industrial Waste)	17.71
Municipal Solid Waste	26.10
Waste heat	9.19

In the perspective of CEB, the cost could be different in each microgrid configuration when it is targeted to reduce the diesel power generation due to the localised power generation in microgrid as well as the net grid sales. As per the calculation in table 4.4, the cost incurred by CEB even if the microgrid is operated as an Independent Power Producer (IPP) with the power purchasing agreement referred to current NCRE tariffs established by PUCSL.

Table 4.4 : Comparison of cost incurred by CEB in utility grid supply & microgrid case

		Microgrid configuration A	Microgrid configuration B	Microgrid configuration C	Microgrid configuration D	Cost for CEB (LKR/kWh)
Base case	Total units consumed from grid (kWh/yr)	45,650,174	45,650,174	45,650,174	45,650,174	36
	Cost of grid power from diesel (LKR)	1,643,406,265.80	1,643,406,265.80	1,643,406,265.80	1,643,406,265.80	
	Total cost for CEB (LKR)	1,643,406,265.80	1,643,406,265.80	1,643,406,265.80	1,643,406,265.80	
Microgrid case	Grid purchases by microgrid (kWh/yr)	30,505,553	17,683,158	7,071,683	1,726,168	36
	Cost of power to feed microgrid from grid (LKR)	1,098,199,908.00	636,593,688.00	254,580,588.00	62,142,048.00	
	Payments for grid sales by microgrid (kWh/yr)					
	Wind01 (kWh/yr)	14,783,581	14,783,581	14,783,581	14,783,581	20.62
	Wind02 (kWh/yr)	8,360,086	4,180,043	-	-	20.62
	Biomass(Rice husk) (kWh/yr)	-	17,520,000	-	17,520,000	17.71
	MSW (kWh/yr)	-	-	35,040,000	35,040,000	26.1
	Total cost incurred grid sales from microgrid (LKR)	477,222,413.54	701,309,126.88	1,219,381,440.22	1,529,660,640.22	
	Total cost for CEB (LKR)	1,575,422,321.54	1,337,902,814.88	1,473,962,028.22	1,591,802,688.22	
Extra cost incurred by CEB for base case (LKR)		67,983,944.26	305,503,450.92	169,444,237.58	51,603,577.58	

In terms of extra cost incurred for base case by CEB, microgrid configuration B is the having the best cost benefit while microgrid configuration D having the least benefit. Since the electricity is generated from diesel power plants in the base case, microgrid is beneficial in curtailing the power generation from diesel. From the benefit that CEB is getting by operating a grid connected microgrid in Kalpitiya peninsula, it is possible to calculate how many hours a particular diesel generator could be stopped in a calendar year as derived in table 4.5.

Table 4.5 : Curtailment of diesel generator operation

	Microgrid configuration A	Microgrid configuration B	Microgrid configuration C	Microgrid configuration D
Extra cost incurred by CEB for base case (LKR)	67,983,944.26	305,503,450.92	169,444,237.58	51,603,577.58
Curtailment of generation by diesel generators (kWh/yr)	1,888,442.90	8,486,206.97	4,706,784.38	1,433,432.71
Curtailment of generation by diesel generators (MWh/yr)	1,888.44	8,486.21	4,706.78	1,433.43
Stoppage time of 1 MW generator (hrs/yr)	1,888.44	8,486.21	4,706.78	1,433.43
Days of 1 MW generator stoppage (Days/yr)	78.69	353.59	196.12	59.73
10 MW Generator stoppage time (hrs/yr)	188.84	848.62	470.68	143.34
Days of 10 MW generator stoppage (Days/yr)	7.87	35.36	19.61	5.97

According to table 4.5 above it is evident that 1 MW diesel generator could be almost left out if microgrid configuration B is implemented. As far as microgrid configuration A, C, D are concerned, the curtailment of generation is about 2.5 months, 6.5 months & 2 months respectively. In the case of 10 MW generator, it can be stopped for a month without operating in the whole year when microgrid configuration B is considered. For instance this is equivalent to stop one diesel engine in Sapugaskanda power station for a month where a capacity of a single generator is 10 MW. The tabulated results are illustrated in figure 4.20 below.

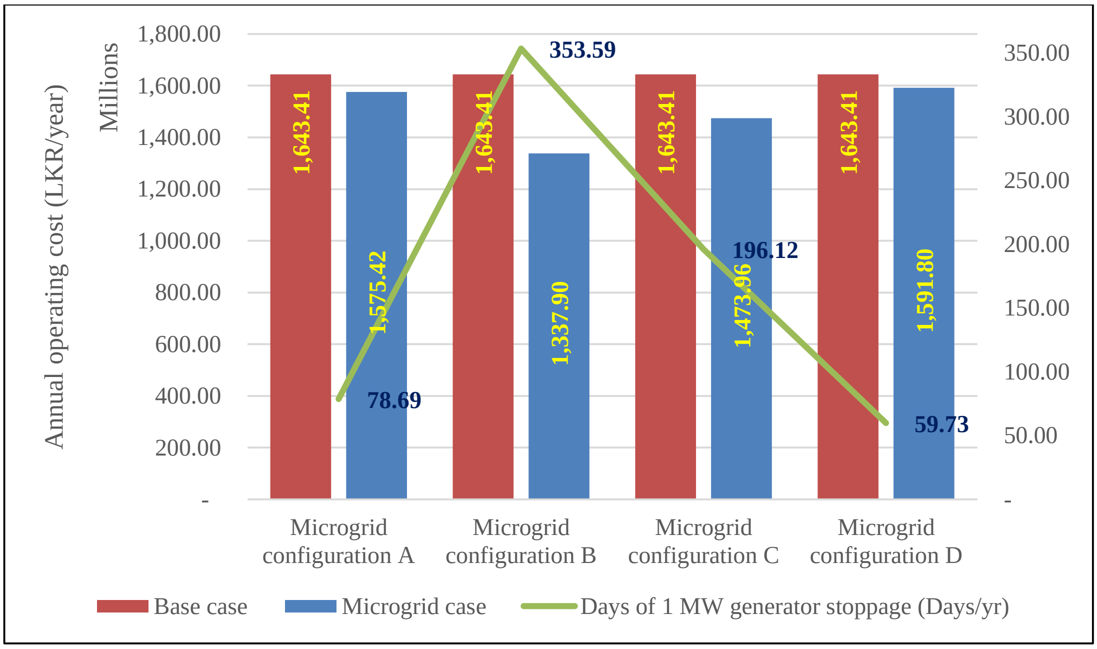


Figure 4.22 : Curtailment of diesel power generation

According to figure 4.20, it is evident that having a microgrid is always economically beneficial than the base case with diesel power generation. Microgrid combination B has become more beneficial in the perspective of curtailing the diesel power generation due to the cost having a biomass (rice husk) power generator is cheaper than using MSW.

5 CONCLUSION AND FUTURE WORK

Hybrid energy system (i.e.: Microgrid) is identified as a promising technical solution to increase renewable energy penetration for an existing system. This is very useful in providing access to electricity for communities in isolated places (i.e.: islands) as well as the curtailment or replacement of fossil fuel usage in existing power systems. There is much more literature available for the modelling, optimising a microgrid design which were carried out for various types of site locations with different combinations of energy sources.

Economic feasibility of a hybrid energy system comprising of selected renewable energy technology options such as wind, solar PV, biomass (rice husk) and MSW for Kalpitiya peninsula was studied in this research. The site location was selected based on the transmission network of Sri Lanka as well as the availability of renewable energy resources. Electrical load demand throughout the year 2018 was obtained from Puttalam grid substation (readings of feeder 03) after studying the electrical single line diagrams of the distribution network. Technical specifications of plant equipment such as wind turbines were selected with reference to the wind power plants operating in Kalpitiya at the moment. Cost of energy for renewable energy technologies were obtained considering both the recent global market cost trends along with the prices in Sri Lankan context.

Four (04) different microgrid configurations were simulated in HOMER Pro for a project life time of 20 years and compared the economics of each case with the base case where Kalpitiya is fed from fossil fuel based (i.e.: diesel) power transmitted through utility grid. Exchange rate was considered as 1 USD = 180 LKR and other financial data needed to calculate the economics such as annual interest rate were referred to the data published by Central Bank of Sri Lanka. For the simulations grid sale capacity was limited to a maximum of 10,000 kW for one hour as the maximum demand of the Kalpitiya is just below 10,000 kW. Looking at the economics of each optimum configuration it was evident that employing a microgrid is feasible in financial terms. Discounted payback period of the simulated microgrids were in the range of 2.68 to 8.86 years for the nearly same initial investments around 24.2 – 26.7 million USD which is promising. If the microgrid is planned to have as an IPP, the NPC of all the configurations are positive which means it is profitable.

To avoid overestimation of component capacities a sensitivity analysis was carried out for each microgrid configuration. Microgrid grid sales were assigned as 10000 kW, 5000 kW, 2500 kW, 1000 kW & 0 kW for the sensitivity analysis. Results showed that combination with 10,000 kW grid sales provided the best figures in all cases because fraction of grid sales while off grid systems are having the best net present cost. In CEB perspective it is a matter of which alternative saves the most for CEB which in return reduce the public money spent on fossil fuel. Financial benefits were calculated by assuming that microgrid owner is an independent (i.e.: private) power producer who install, operate, maintain it & the payments for grid purchased energy is paid at the end of the year for the prevailing NCRE 1- 20 year flat tariff. It was clear that 1 MW generator could have been stopped for almost one year as far as the incurred extra cost is considered in using utility grid for Kalpitiya.

During the HOMER Pro simulation, the availability of power generation from MSW and rice husk power was assumed to be 100% due to the unavailability of data regarding the realistic maintenance schedules. Therefore, modelling of microgrid with realistic maintenance schedules shall be a future work. Reliability improvement of electricity supply of Kalpitiya peninsula of each microgrid configuration could also be analysed. Further financial benefits on energy savings by reduction transmission energy loss could also be investigated as a future study.

It could be seen clearly that the contribution of renewable energy sources for distributed generation could be increased to achieve a considerable percentage from system’s energy with efficient, cost effective electricity generation and reduce the fossil fuel imports drastically. Reduction of the import of fossil fuel can save lots money becoming such a relief on the country’s balance of trade. This study is an initial step towards the investigation of a most suitable strategy specially to integrate more solar power, other renewable energy sources to Sri Lankan power system so as to providing quality, reliable, sustainable and affordable energy while achieving economic prosperity of the nation.

REFERENCE LIST

[1] K. Ratneswaran , "Hybrid Power System for Eluvaithivu Island Sri Lanka," *Master of Science Thesis,* pp. 1 - 61, 2011.

[2] M. G. Udayakanthi, "Design of a Wind-Solar Hybrid Power Generation System in Sri Lanka," *KTH Industrial Engineering and Management,* pp. 1 - 61, 2015.

[3] S. Rehman, A. M. Mahbub, . J. Meyer and . L. M. Al-Hadhrami, "Feasibility study of a wind-pv-diesel hybrid power system for a village".

[4] S. A. Shezan, R. Saidur, K. R. Ullah, W. T. Chong and S. Julai, "Feasibility analysis of a hybrid off-grid wind–DG-battery energy system for the eco-tourism remote areas," vol. 17, December 2015.

[5] M. Hasan and O. B. Momin, "Performance Analysis and Feasibility Study of Solar-Wind-Diesel Hybrid Power system in Rural Areas of Bangaladesh," *International Journal of Engineering Research and General Science,* pp. 410 - 420, September 2015.

[6] A. V. Anayochukwu, "Feasibility Assessment of PV Diesel Hybrid Power system for an Isolated off Grid Catholic Church," *Renewable Energies Reaseach Nucleus,* pp. 49 - 63, 2013.

[7] M. Laidi, S. Hanini, B. Abbad, N. K. Merzouk and M. Abbas, "Study of a Solar PV-Wind-Battery Hybrid Power System for a Remotely Located Region in the Southern Algerian Sahara: Case of Refrigeration," pp. 30-38, 2012.

[8] J. G. FANTIDIS, D. V. BANDEKAS and . N. VORDOS, "Techno-economical study of hybrid power system for a remote village in Greece," *Recent Researches in Energy, Environment and Sustainable Development,* pp. 30 - 35.

[9] V. O. Okinda and N. A. Odero, "A REVIEW OF TECHNIQUES IN OPTIMAL SIZING OF HYBRID," *International Journal of Research in Engineering,* pp. 153 -161, November 2015.

[10] S. :. R. P.-B. IEEE-PES Task Force on Microgrid Control - Chairman:Claudio A. Cañizares, "Trends in Microgrid Control," *IEEE Transactions on smart grid,* vol. V, no. 4, pp. 1905-1919, July 2014.

[11] S. m. I. E. S. M. I. M. R. a. F. M. F. I. P.Ferraro, *On the impact of Microgrid Energy Management Systems on Power System Dynamics,* 2016-2017.

[12] R. R. T.-L. E. D. L.-I. G. G. I. Darshana Baghel-PG Scholar, "Voltage balancing in solar based DC Micro-grid system," *International Research Journal of Engineering & Technology(IRJET),* vol. 04, no. 01, pp. 964-968, January 2017.

[13] S. AG, Microgrids, 2011.

[14] V. V. V. R. S. Matthew T. Lawder, "Balanci ng autonomy and utilizat ion of solar power and battery storage for demand based microgrids," *Journal of Power Sources,* vol. 279, pp. 645-655, 6 January 2015.

[15] T. Z. S. D. a. Y. Z. Jingwei Hu, "An Overview on analysis and Control of Micro-grid System," *International Journal of Control and Automation,* vol. 8, no. 6, pp. 65-76, 2015.

[16] R. I. H. a. A. D. Farid Katiraei, "Microgrids Management - Controls and operation aspects of microgrids," *IEEE power & energy magazine,* pp. 54-65, May/June 2008.

[17] M. M. Rahman, "Microgrid frequency control using multiple battery energy storage systems (BESSs)," Brisbane, Australia, 2015.

[18] Y. Y. Shiyu Liu, *Impact of Distributed Generation on Electric Power Distribution System Reliability,* Nanjing.

[19] J. N. &. S. T. (CRES), "Renewable Energy Integration in Power Grids," April 2015.

[20] J. Bebic, "Power System Planning:Emerging practices Suitable for Evaluating the Impact of High-Penetration Photovoltaics," Niskayuna, New York, February 2008.

[21] R. M. M. Paul Denholm, "Evaluating the limits of solar photovoltaics (PV) in electrical power systems utilizing energy storage and other enabling technologies," *Energy Policy,* no. 35, pp. 4424-4433, April 2007.

[22] D. o. C. a. Statistics, "Department of Census & Statistics, Sri Lanka," 01 November 2019. [Online]. Available: http://www.statistics.gov.lk/. [Accessed December 2019].

[23] R. G. B. M. &. D. H. Dave Renne, "Solar resource assessment for Sri Lanka & Maldives," National Renewable Energy Labortory, US Deapartment of Energy, Colarado 80401-3393, 2003.

[24] M. G. S. S. H. D. H. R. D. Elliot, "Wind Energy Resource Atlas of Sri Lanka & the Maldives," National Renewable Energy Labortory, Colarado - 804101 - 3393, 2003.

[25] A. S. R. &. S. Perera, "Potential & viability of rice husk based power generation in sri lanka," *Engineer,* vol. XXXXVI, no. 04, pp. 9-17, 2013.

[26] "www.ceicdata.com," CEIC, 2020. [Online]. Available: https://www.ceicdata.com/en.

[27] J. I. C. Agency, "Data Collection Survey on Solid Waste Management in Democratic Socialist Republic of Sri Lanka," Kokusai Kyogo Co. Ltd, 2016.

[28] H. E. LLC, "Homer Pro 3.12," 13 August 2018. [Online]. Available: https://www.homerenergy.com/products/pro/docs/3.12/index.html.

[29] M. Pierrot, "The Wind Power - Wind Energy Market Intelligence," 2005. [Online]. Available: https://www.thewindpower.net.

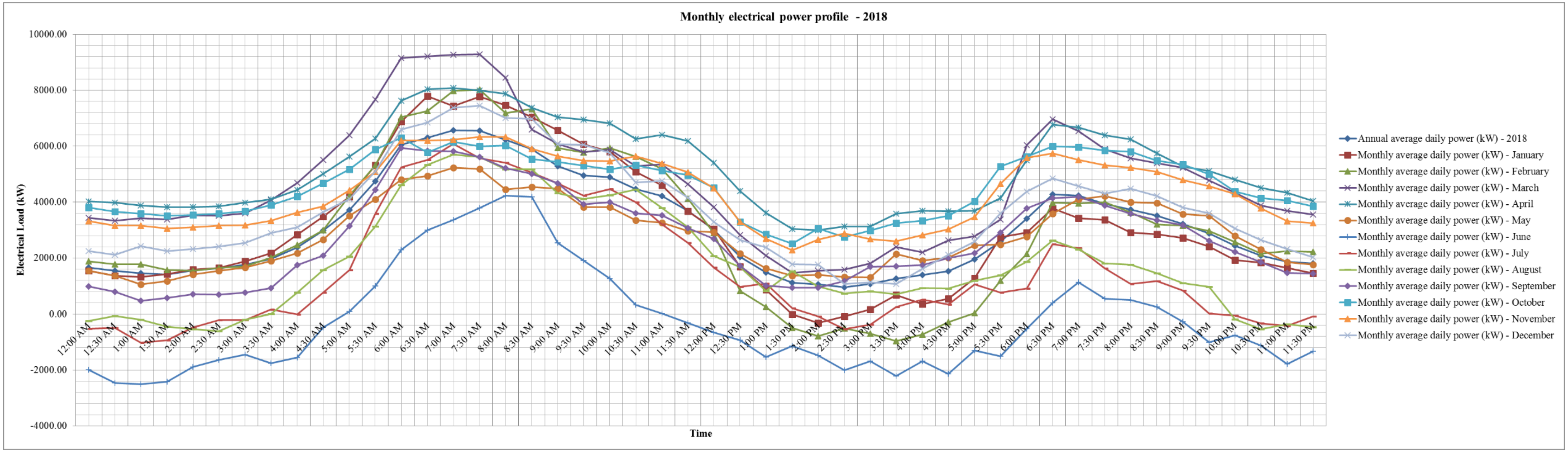
[30] J. Senanayake, "Economic & Financial Feasibility of Power Generation from Municipal Solid Waste : A case study based in western province of Sri Lanka," University of Moratuwa, Katubedda, 2014.

[31] T.Kaur, "Solar PV Integration in Smart Grid - Issues and Challenges," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. IV, no. 07, pp. 5861-5865, July 2015.

[32] IRENA, "Renewable power generation costs in 2017," International Renewable Energy Agency, Abu Dhabi, 2018.

[33] IRENA, "Renewable power generation costs in 2018," International Renewable Energy Agency, Abu Dhabi, 2019.

APPENDIX A : ELECTRICAL LOAD DEMAND OF KALPITIYA



APPENDIX B : SIMULATION REPORT OF MICROGRID CONFIGURATION A

APPENDIX C : SIMULATION REPORT OF MICROGRID CONFIGURATION B

APPENDIX D : SIMULATION REPORT OF MICROGRID CONFIGURATION C

APPENDIX E : SIMULATION REPORT OF MICROGRID CONFIGURATION D