A SUSTAINABLE APPROACH FOR INTEGRATING DISTRIBUTED SOLAR PV GENERATION INTO SRI LANKAN ELECTRICAL GRID

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Degree Master of Science by Research

Department of Electrical Engineering

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DECLARATION OF THE CANDIDATE AND SUPERVISOR

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The above candidate has carried out research for the Masters Dissertation under my supervision.

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Signature of the supervisor Date:

(Prof. K.T.M. Udayanga Hemapala)

Abstract

Sri Lanka is an island with many accessible renewable energy resources. But the poor penetration of these resources to generate electricity, has continued the use of conventional power generation, resulting continuous emissions of greenhouse gases to the atmosphere. Therefore, high penetration of renewable energy could lead to minimizing the greenhouse gas emissions and petroleum dependency of a country. To achieve this, a sustainable approach is required which considers both economic and technical aspects in the long term.

In this research, a sustainable approach for integrating renewable energy into an electrical grid is proposed by using Sri Lankan electrical grid as a case study. First, the renewable energy integration models in the literature is revised and selected a suitable model for this research. Then, an economic analysis is performed by using Hybrid Optimization Model for Electric Renewable (HOMER) legacy version 2.68 to obtain the best system configuration considering cost optimization. After that, the HOMER chosen system configuration is tested for its technical compatibility. To perform the technical analysis, Open Distribution System Simulator (OpenDSS) software is used. However, solar resource is used as the only renewable energy resource in this research, due to the easiness to perform technical analysis. In the technical analysis, a real distribution feeder in Sri Lanka is modelled and tested the feeder for voltage violations while penetrating rooftop solar systems into the feeder. Also, a criterion based Photovoltaic (PV) hosting capacity is defined to the feeder as an important finding by the technical analysis.

The outcome of this research is a sustainable approach for integrating renewable energy into an electrical grid, more precisely to the distribution network of Sri Lankan grid. This approach is sustainable because it is economically and technically sustainable. Such that, this approach could be adopted to plan renewable energy integration models in long run.

Keywords – Economic Evaluation, PV Hosting Capacity, Renewable Energy Integration

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I would like to express my sincere gratitude to those who were behind me in completing this research project.

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List of Abbreviations

Ah	Ampere hour
COE	Cost of Energy
DG	Diesel Generator
DPV	Distributed Photovoltaic
GHG	Green House Gas
GWh	Giga Watt hour
HRES	Hybrid Renewable Energy System
kVA	kilo Volt Ampere
kV	kilo Volt
kW	kilo Watt
kWh	kilo Watt hour
LV	Low Voltage
MG	Micro Grid
NPC	Net Present Cost
PV	Photovoltaic
PVIES	Photovoltaic Integrated Energy System

CHAPTER 1

1. INTRODUCTION

Sri Lanka, a country located near the equator has an abundant solar energy as well as wind energy due to its islanded nature. In the year 2018, total renewable energy generation from major hydro power plants, solar projects, wind power and biomass is 1742GWh [1]. To increase this further, novel approaches need to be considered. This research focus on developing an approach to integrate renewable energy into Sri Lankan grid, more precisely, rooftop solar into the distribution network.

1.1. Background

Today petroleum dependent energy is responsible for 60% of the total carbon footprint of the world and acts as a major cause for the climate change due to the high emission of Green House Gases (GHG) [2]. Greenhouse gases such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) trap heat in the atmosphere and surround the earth as a blanket [3]. As humans burn more coal, natural gas and oil the blanket becomes extremely thick, dense, and less likely to allow heat to escape from the earth. Heat gets trapped inside the blanket of greenhouse gases and the Earth becomes too warm causing many environmental impacts. This significant fact has led many researchers to concentrate their research work on finding an optimized approach to integrate renewable energy sources into power and energy generation.

Renewable energies are the energy resources that are constantly regenerated by nature. There are mainly two types of renewable energies, one is directly generated by the sun such as thermal, photo-electric, and photo-chemical, the other one is indirectly generated by the sun such as wind, hydropower, and photosynthetic, energy which is stored in biomass [4]. Energy generated by other natural activities of the environment such as geothermal and tidal energy are also categorized under renewable energy. Renewable energy does not include energy resources derived from environmentally harmful fossil fuels and waste products of fossil or inorganic sources. Therefore, it is sustainable and will never run out, which ultimately guarantees an energy resource that is non-pollutant and a non-contributor to greenhouse effects and global warming. Figure 1.1 gives an overview of renewable energy resources.

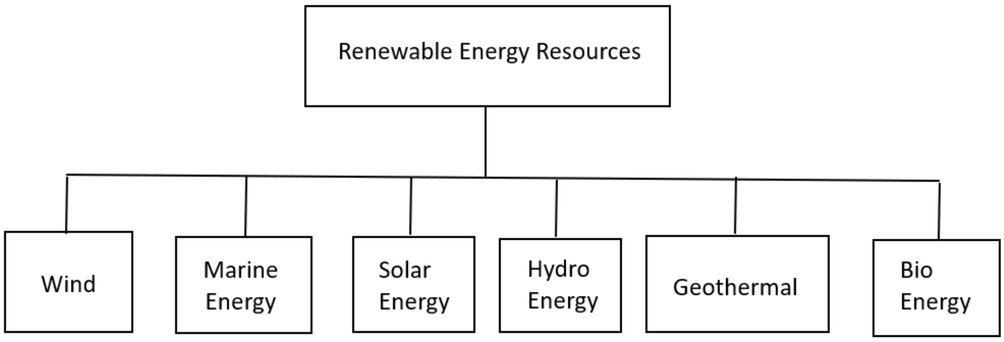


Figure 1.1: Overview of renewable energy resources

These are the widely available renewable energy resources around the world. Some of the above resources such as solar, wind and hydro energy are already used in power and energy generation. But marine energy, geothermal and bio energy are still in the growing stage for the energy generation due to the lack of technical knowledge and research work [5]. Therefore, to convert these natural energy resources into usable forms of energy such as electricity, heat and fuels, advanced technologies are required. It is observed in literature, that most of the research work has been carried out relating to these technologies, without generalizing an overall approach to integrate renewable energy in small scale or large scale [2]. Therefore, the development of such approaches will pave the way for renewable energy adaptation and one day will replace conventional energy by renewable energy generation.

1.2. Motivation

Sri Lanka is an island with many accessible renewable energy resources. But the poor penetration of these resources to generate electricity, has continued the use of conventional power generation, resulting continuous emissions of greenhouse gases to the atmosphere. As of most researchers and governing bodies of the world focusing on reducing climate change caused by harmful greenhouse gases, ultimately reducing the harm to the environment has been the motivation of this research also.

This will not only benefit the environment but also benefit the economy of a country because the less usage of fuel, less the amount of money spends on importing fuel.

1.3. Objectives of study

In Sri Lanka, electricity generation is mainly done by conventional energy resources. From 2012 to 2017, nearly 50% of energy is produced by petroleum dependent energy sources [5]. However, the country has shown an upward trend when it comes to penetrating solar energy to the electrical grid, mainly rooftop solar. By the end of year 2018, the total number of solar rooftops connected to Sri Lankan national grid is 8775 [1]. Therefore, the main objective of this research is to encourage penetration of solar rooftops in Sri Lanka by proposing a sustainable approach while maintain an economic and technical sustainability. This will ultimately reduce the petroleum dependency of the country and the greenhouse gas emissions.

The research is carried out based on following sub objectives.

- To select a renewable energy integration model by studying, how the integration of renewable energy into an electrical grid has been done in literature
- To perform an economic analysis, to find the economic viability of the model
- To perform a technical analysis, to find the technical viability of the model

1.4. Methodology

Methodology of this research can be categorized under three steps.

1. Literature review
2. Economic analysis
3. Technical analysis

Literature review is the most important part of any kind of research. By performing a literature review, the researcher reviewing all the published papers and other materials on the relevant topic. There were many published papers relevant to this research and after a depth literature review, a suitable renewable energy integration model was selected. In this step, the model input and output parameters, the suitable software to conduct an economic analysis etc. were identified.

Economic analysis is performed by using HOMER software. It is a system planning software in the long run. The output of this software is the system configuration, optimized for the lowest net present cost [6]. For an example, if the system has PV panels, battery and a generator as the sources, HOMER selects the capacities of these sources based on a cost optimization. By this analysis, system designer can get a clear idea about how much time it will take to breakeven the total project cost. Likewise, the designer can observe how the system will make profits or losses during its project lifetime.

Technical analysis is conducted to verify the technical viability of the HOMER given system configuration. To do this, a real-life distribution feeder in Sri Lanka is considered. First, the feeder is modelled by using OpenDSS software and then rooftop solar systems were penetrated to that feeder. The total penetrated PV capacity is the HOMER chosen PV size in the economic analysis. After that, the voltage profiles and power flows were taken to observe any violations or abnormality. Then, the technical analysis was continued to find the PV hosting capacity of the modelled feeder.

CHAPTER 2

2. LITERATURE REVIEW

Literature review was conducted by aiming to find a suitable model for the renewable energy integration. There were many renewable energy integration models in literature. Some are Hybrid Renewable Energy Systems (HRES), which had solar-wind or solar-wind-small hydro combinations. However, when reviewing the literature, it was found that most of the literature are related to Distribution Generation (DG) and microgrid concept [7]. Therefore, this chapter first discuss about distribution generation and microgrid concept, then about some renewable energy integration models developed in the literature along with their advantages and limitations.

Mostly, HRES are designed for microgrid concept. Therefore, the models can be categorized as (1) Grid connected microgrids (2) Islanded microgrids.

2.1 Grid connected microgrids

Developing a microgrid for a rural community was carried out in [8]. The objective of their study was to eliminate the load shedding occurs by the utility grid to rural areas. First, researchers have studied the site and identified the problem. Site was Tafelkop community in South Africa which has a grid extension. However, due to the load shedding and frequent failures, the community often suffers from power cuts. Then, they have divided the considered community into two zones and proposed a methodology to integrate existing renewable energy potential to the zones while considering cost aspects and GHG emissions. Load profile of the community was obtained by applying assumptions to their regular using appliances and the renewable resource data was downloaded from Hybrid Optimization Model for Electric Renewable (HOMER) software database. After optimizing the results, researchers have found three suitable configurations and selected the best model due to the lowest Net Present Cost (NPC), operating cost per year and the lowest Cost of Energy (COE).

Reference [8] has implemented a grid connected microgrid (MG) for a rural community whereas [9] has modeled a MG for a seaport with the grid connection. This model was designed to a seaport in Copenhagen, Denmark. The load profile was taken by actual data available and the renewable resource data was downloaded from NASA website. Since this is a seaport, higher potential of wind resource is available. Therefore, the researchers have modeled the MG using solar and wind as renewable energy sources and battery as energy storage with the grid. Simulation and optimization were done by HOMER to find the most optimum system with all the HRES components. One of the significant facts about this research is that they have considered electrical parameters such as unmet electrical load, excess electricity, renewable fraction and capacity shortage while designing the model.

Reference [10] is a case study done for a university in Punjab, India. It says there is an increase of renewable energy promotion in universities. Therefore, authors of [10] has proposed a methodology to implement this concept in a university using smart grid distribution generation. Smart grid is the next step of present micro grid. For the implementation of the smart grid; first, researchers have examined the university. Average load of 185.13kW, peak demand of 2005kW and an average energy demand/day of 4443.1 kWh were found. Other data required by the HOMER software were taken from 11kV substation which was already built at the university premises. Researchers have conducted techno-economic analysis using the HOMER software. Since [10] has used a smart grid infrastructure concept to integrate renewable energy, it consists of energy management, demand response and smart meters to integrate renewable energy with no compromise of the quality of power and reliability. As the result of their research, they have found that the grid dependency and cost of energy of the system was reduced by their proposed design.

2.2 Islanded microgrids

A feasibility study conducted to analyze techno-economic aspects was done for a rural area called Benin, Africa in [11]. Researchers have modeled this study as an islanded microgrid. Therefore, they have used a diesel generator instead of the grid. Load profile was obtained by conducting a survey for 50 selected households and included upcoming systems to the community such as water pumping system, electric flour mill and soldering unit. Other than that, this research has focused on multiple demand criteria and seasonal variations. For sensitivity and optimization analysis, researchers have modeled several HRES systems and found out the combination of PV/Diesel/Battery system as the most optimized one.

Reference [12] has also proposed a HRES for a rural community which already has a mini hydro to supply the electrical demand. Motivation for this research was the incapability of mini hydro to fulfill the emerging electrical demand. There-fore, researchers have suggested to integrate other renewable such as solar to the power generation. Main objective of the research was to provide a cost optimization analysis for the rural area with this proposed system. Site for this research was Malekhu Khola Mahadevsthan in Nepal, India. Load profile was downloaded from a database in HOMER which validated as a similar load profile to the case study area. As for the results, researchers have found 62.7% of electricity was produced by the existing mini hydro, 28.5% by PV and 4.29% by the diesel generator. One of the important facts that can be observed from this research is that, if a HRES has a mini hydro contribution then it will be more economically and environmentally feasible.

Another interesting islanded microgrid design was proposed in [13] for an island which is a tourist destination. Tomia island in Indonesia is a known tourist place with poor electrical supply. This is due to the grid extension difficulties. However, researchers have proposed a method to overcome this issue by penetrating the widely available solar and wind energy resources of the island. For the increased reliability they have suggested to use a diesel generator as a backup supply. Load profile was taken from the actual data available. It was developed precisely considering weekdays and weekend de-mand separately. Multi energy optimization software was used for the simulations and researchers have found the optimal values for HRES components. Furthermore, this research was concerned about the GHG emissions and cost optimization.

Techno-economic energy mix analysis was done by [14] for an off-grid community. Researchers have identified there is a connection between insufficient access to available energy and poverty level of a country. To find an optimum way to integrate available renewable energy as a solution for this problem was the motivation for their research. They have considered multiple demand scenarios such as basic needs, extended needs and normal needs instead of a single load profile. There by, they have calculated peak energy demand for each of them and have designed a HRES for each. Only the Renewable Factor (RF) is changing in these models. HOMER software was used for the simulations and they were done to find the system with the least total NPC. Researchers have calculated COE for the proposed three different energy mixes. They have said that the design engineers seek high reliability at low cost. Therefore, single criteria-based design method is not enough and multi criteria decision approach method is much more suitable.

The focus of [15] was to expand the distribution of microgrids in rural villages where it is believed to be the most suitable solution for the rural electrification. Therefore, it is required to guarantee that microgrid projects are both financially feasible, technically reliable and socially sustainable. To obtain this, the process of evaluating a microgrid design for any other location is followed by a sequential order. (1) Assessment of resources (2) Selecting system parameters (3) Load profile assessment (4) Technical assessment (5) Economic assessment. Assessment of resources is to identify the energy sources such as solar, wind and diesel generator. In this research they have selected a rural area in Sapra in India and solar, wind energy resources have been selected due to their good potential. Solar irradiance and wind data are taken from the NASA Surface Meteorology. The HRES design of [15] was for a single household. For the load, they have mentioned AC loads which are common electrical compliances in rural households. Such as; CFL bulbs, fans, radio, television and mobile chargers. They have calculated 4.08 kWh/d as the load demand with a peak demand of 0.55 kW for a single household. As for the system parameters they have used 1 kW PV module which has a lifetime around for 25 years without any tracking system and SW Whisper 200 wind turbine, manufactured by Southwest Wind Power. The rated output power (DC) of the wind turbine is 1 kW with a hub height of 24m. Trojan L16P battery models were chosen and an inverter of 0.5kW is used. The economic and technical analysis of the HRES model considered for a single household has been carried out in HOMER software. They have obtained PV output power and wind output power approximately 1563kWh/yr and 1194 kWh/yr accounting for 56.69% PV and 43.31% wind power output. As for the wind profile they have obtained, there is a good potential for wind energy in that region resulting 1029.1 kWh/yr excess electricity production. Under economic aspects researchers have considered total NPC of the model and levelized cost of energy. At the end of the research, they have suggested to do a life cycle assessment of the proposed system, measurement of carbon emissions and to study the impact of load growth factors as future studies. Table 2.1 shows the surveyed results of the HRES models.

Table 2.1: Surveyed results of HRES models

Authors	**Evaluation area**	**HRES components**	**Load details**	**Sized approach**	**Results**
Odou and Bhandari (2020)	Benin, Africa	PV, DG, Battery	687.1kWh/d (by survey)	HOMER	150kW (PV) 62.5kVA (DG) 637kWh (Battery)
Dutta and Yue (2018)	Mahadevstha, Nepal	PV DG, Battery, Mini hydro	78.01kW/d (by measurements)	HOMER	63.4kW (PV) 86kW (DG) 186kWh (Battery) 26kW (Hydro)
Adet and Nlabi (2018)	Tafelkop, South Africa	Grid, PV, Battery	250kWh/d (by survey)	HOMER	62.6% RF
Ahm and Othan (2018)	Copenhagen, Denmark	PV, Wind, Battery, Grid	5.2MW peak (by local database)	HOMER	75%
Simaremare and Tambunan (2018)	Tomia, Indonesia	PV, Wind, Batter, DG	1105 kW peak (by assumptions)	HOMER	1695 (PV) 2968kWh (Battery)
Babutude and OM	Abadam, Nigeria	PV, Wind, Batter, DG	95kWh/d (by assumptions)	HOMER	63% RF
Chatterje and Rayudu (2017)	Jharkand, India	PV, Wind, Battery	4.0kWh/d (by assumptions)	HOMER	1kW (PV) 1kW (Wind) 360Ah (Battery)
Shar and Kaur (2016)	Punab, India	PV, Grid, Battery	4443kWh/d (by local database)	HOMER	1kW (PV) 912 Ah (Battery)

After a comprehend analysis of HRES models and reviewing literature, this research is decided to concentrate on small scale distribution generation rather than microgrid concept. Therefore, Figure 2.1 selected as the basic block diagram of a HRES model.

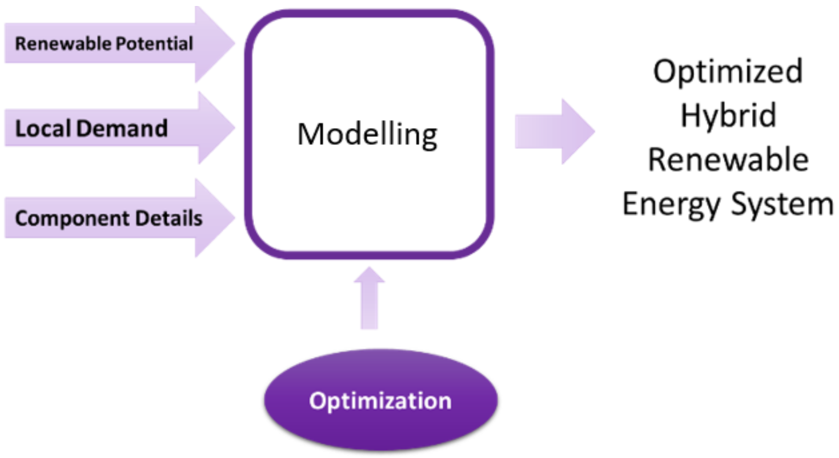


Figure 2.1: Block diagram of a HRES

Here, renewable energy potential, local demand and component details are the inputs to the model. Renewable energy potential means the available solar or wind energy of a concerned geographical location. Local demand refers to the total power consumption of the microgrid or a distribution feeder. However, the load details requirement differs with the software. For a software like HOMER, an hourly time series file of load details is required for a year. Components stands for the model components such as PV module, inverter, grid, diesel generators etc. Then the modelling can be carried out by a suitable software platform. According to the revised literature, HOMER software is found to be the most used software for the modelling to get an optimized HRES for the lowest NPC. Optimization refers to the cost optimization. For that, cost details of the components and economic parameters such as annual real interest rate should be given. Then as the output, an optimized HRES for the lowest NPC can be obtained.

For an example, if the system which is selected is a distribution feeder, then the renewable energy potential; solar energy should be found by its longitude and latitude. Then, as the local demand, total loading of the feeder should be considered. Next, the components such as PV module and inverter cost details should be found.

Likewise, if it is a grid connected system, then the grid buying and selling values should be found. After finding all the inputs, system can be simulated by a software, in this case HOMER, and can get the optimized HRES for the lowest NPC as the output.

2.3 Software platforms

This research focus on conducting an economic and technical analysis for a distribution feeder in Sri Lankan electrical grid. After the literature review, it was found that most of similar studies were carried out by HOMER software. However, the other available software that are used for HRES modelling are reviewed in this chapter. The available software for economic and technical analysis were discussed separately.

2.3.1 Software for economic analysis

HRES development should be able to act as a substitute for conventional energy systems. Therefore, hybrid renewable energy systems should be properly planned without causing an oversized system or an unoptimized design which will ultimately result in high installation costs. For this purpose, there are software that do designs, optimizations, economic planning and analysis of hybrid renewable energy systems. HOMER, RETScreen, TRNSYS and Hybrid 2 are some of the frequently used software for economic analysis [16].

(i) Hybrid Optimization Model for Electric Renewable (HOMER)

Most of the studies have used HOMER for the validation of the proposed HRES model. HOMER is a software designed by National Renewable Energy Laboratory (NREL) in the United States. It performs comparative economic analysis and determines optimal architecture for the Distributed Generation power systems along with control strategies [17]. HOMER performs three main tasks.

1. Simulation: This process determines the technical feasibility and life-cycle cost of a DG power system

2. Optimization: This process simulates many configurations of the DG power system and find out the one at the lowest life-cycle cost with the satisfaction of its technical constraints.

3. Sensitivity analysis: This process determines the impacts on the system configuration of certain parameters. This helps to assess the effects of inputs which the designer has no control such as future fuel prices and average solar radiation [18].

Inputs to HOMER such as electrical loads, renewable resources, constraints, controls, component technical details and type of dispatch strategies, will perform hourly simulations for every possible DG power system combination [19].

HOMER calculates the following four costs for every simulation result:

- COE (Cost of Energy)
- NPC (Net Present Cost)
- O&M (Operations and Maintenance Cost)
- Initial Capital

HOMER defines the NPC as the existing value of all components that are connected in the plant minus the present value of all the revenues that it receives over the lifetime. The total NPC in a year is called the total annualized cost [20]. It is gives as,

$$C_{NPC} = \frac{C_{ann}}{CRF(i, R_{proj})} \text{ ------(1)}$$

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \text{ -------(2)}$$

Here, C_{ann} = Total annualized cost

I = Annual interest rate

CRF = Capacity factor

R_{proj} = Plant lifetime in years

N = Number of years

HOMER defines the levelized cost of energy (COE) as the average cost per kWh of useful electrical energy produced by the system. Equation 3 show how HOMER calculates COE.

$$COE = \frac{C_{ann}}{E_{served}} \text{------(3)}$$

Here,

C_{ann} = Total annualized cost of the system

E_{served} = Total electricity load served

At the end, main HOMER outcomes will be the costs, produced energy, fuel consumption and the emitted pollutants.

One of the good advantages in HOMER is its results simulates in a different type of graphs and tables which enable to compare each model in economic aspects. HOMER can generate synthetic load profiles for residential, commercial, community and industrial environments. On the other hand, there are some disadvantages also. HOMER cannot process multi objective functions because it focusses on solving a single objective function to minimize cost. Moreover, Depth of Discharge (DOD) of a battery is not been considered in the simulations [6]. Likewise, there are many advantages and some disadvantages in HOMER software. But most of the researchers tend to use HOMER for their research despite that.

(ii) RETScreen

RETScreen is also a software tool that is used for feasibility studies of hybrid renewable energy systems. It was developed by Ministry of Natural Resources, Canada for estimating both environmental costs and financial costs along with the benefits of various renewable energy systems for different locations in the world. It uses climate database, project database, product database and hydrology database as the inputs and generates sensitivity and risk analysis, energy efficiency, cogeneration, financial and environmental analysis as the outputs [21]. There are some disadvantages in this software. RETScreen usually neglects the effect of temperature when analyzing performance of solar panels. It has no option to import time series data. Very little options available for search, recovery, picturing features and data sharing problem are some of other disadvantages.

(iii) Transient Energy System Simulation program (TRNSYS)

University of Colorado and University of Wisconsin together developed this software. Thermal systems simulation was the first carried out simulations in the TRNSYS. But with the time passes, this software has updated and changed it features for the simulations of PV, thermal solar and other systems. It uses meteorological data and the models from its own library as inputs and produce dynamic simulation behavior of thermal and electrical energy system as output [16]. One of a major disadvantages of this software is the unavailability of optimization features. However, it carries out simulation with precise accuracy with graphics and some other details.

(iv) HYBRID 2

HYBRID 2 was developed by Renewable Energy Research Laboratory (RERL) of the University of Massachusetts, USA. It can perform thorough long-term performance, cost analysis and forecast the behavior of hybrid renewable energy systems. One of a significant feature of this software is that it can perform time series simulations for 10 min to 1 h time steps [22]. Hybrid systems containing three buses such as wind turbines, battery storage, PV array, diesel generator, power converters and a dump load can be simulated by this software. Disadvantages of this software are its restricted access to parameters and low level of flexibility. Load demand, resources, power system component details and financial data are the inputs to HYBRID 2 and sizing optimization, financial evaluation are the outputs.

After reviewing the above software, it was found that RETScreen does not provide an option to simulate grid connected systems. Likewise, TRNSYS is not user friendly and Hybrid 2 is not compatible with Windows platforms later than Windows XP. Therefore, HOMER software is selected to conduct the economic analysis. When it comes to HOMER, there are two versions. HOMER legacy version and

HOMER pro version. HOMER legacy it a universal access software but HOMER pro is not freely available. Hence, HOMER legacy is selected.

Summary of the software for economic analysis is given in Table 2.2

Table 2.2: Summary of software for economic analysis

	User friendly	**Compatibility with Windows**	**Grid modelling**
HOMER	Yes	Yes	Yes
RETScreen	No	Yes	Yes
TRNSYS	Yes	No	Yes
Hybrid 2	Yes	No	Yes

2.3.2 Software for technical analysis

HOMER software gives a detailed cost analysis without considering the technical aspects of the model. Therefore, it is essential to test the model for its technical viability. There is some software available to conduct a technical analysis such as MATLAB, DigSILENT power factory, and OpenDSS.

(i) MATLAB

MATLAB is a high-performance software mainly used for technical computing. It was developed by University of New Maxico in late 1970s [16]. This is a user-friendly software which is compatible with all Windows platforms. This software is suitable if the research has many algorithms to work with or to develop new models. However, some literature has used this software to model DC microgrids where they have analyzed power electronics of the model. Since this research does not focus on such matter, MATLAB is not suitable for the technical analysis.

(ii) DigSILENT power factory

DigSILENT (Digital Simulator for Electrical Network) power factory is power system analysis software developed in Germany [23]. It combines both reliable and flexible system modelling capabilities with intelligent algorithms and an exclusive database management system. This is a quiet outstanding software to conduct a technical analysis. However, this is not freely available. Also, only a limited number of quality materials were freely available to study this software compared to OpenDSS and MATLAB.

(iii) Open Distribution System Simulator (OpenDSS)

As the name implies, this software is exclusively developed to model distribution networks. This is developed by Electric Power Research Institute (EPRI) [24]. The fact that this software is free and open source has led many researchers to conduct their simulations using this software. Also, anyone who is new to this software, can easily learn this by their own using the large amount of quality learning materials which are available online. An open discussion forum named “SourceForge” runs by the original developers is on internet so that the researchers can directly ask their doubts when modelling. Furthermore, this software can be linked to third party software such as MATLAB or Python, which allow researchers to write user defined algorithms. Therefore, this software was selected to conduct the technical analysis of this research.

Summary of the software for technical analysis is given in Table 2.3.

Table 2.3: Summary of software for technical analysis

	Open source	**Distribution planning and analysis**	**Availability of quality materials**
MATLAB	No	No	Yes
DigSILENT power factory	No	Yes	No
OpenDSS	Yes	Yes	Yes

CHAPTER 3

3. ECONOMIC ANALYSIS

The basic block diagram of HRES which is illustrated in Figure 2.1 is chosen as the model to be followed in this research. As explained earlier, the inputs to the model are renewable energy potential (solar energy), local demand and model component's details. Figure 3.1 shows the model used for case study. In this chapter, step by step method to perform an economic analysis for a HRES is discussed in detail. Since the only renewable energy source used is solar energy, there is no hybrid renewable energy integration. Therefore, HRES is here after referred as the PV Integrated Energy System (PVIES).

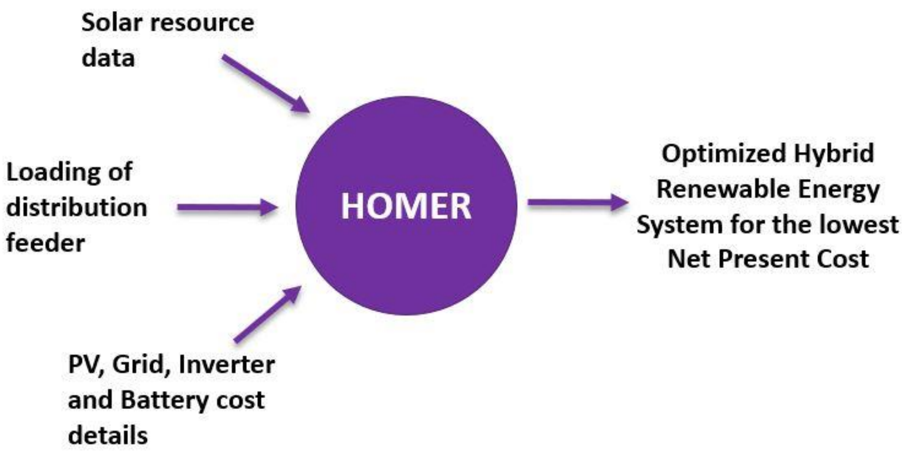


Figure 3.1: Model for the case study

3.1. Estimation of renewable energy potential

Renewable energy potential refers to the available solar and wind energy that can be used to generate electricity. Hydro resource is excluded because it is mostly used in large scale. However, renewable energy potential full depends on its geographical location. Since Sri Lanka is an islanded country and located near the equator, it has significant amount of solar and wind energy [25].

The location of the distribution feeder of case study is Kotte area in Sri Jayawardenepura of Sri Lanka [26]. Longitude and latitude of the location are 6.8868° N, 79.9187° E. Most of the revised literature imported renewable energy data from NASA surface meteorology and solar energy database. Therefore, for this research also the data was imported from the above-mentioned website. Figure 3.2 shows a flow chart which can be followed to import renewable energy data.

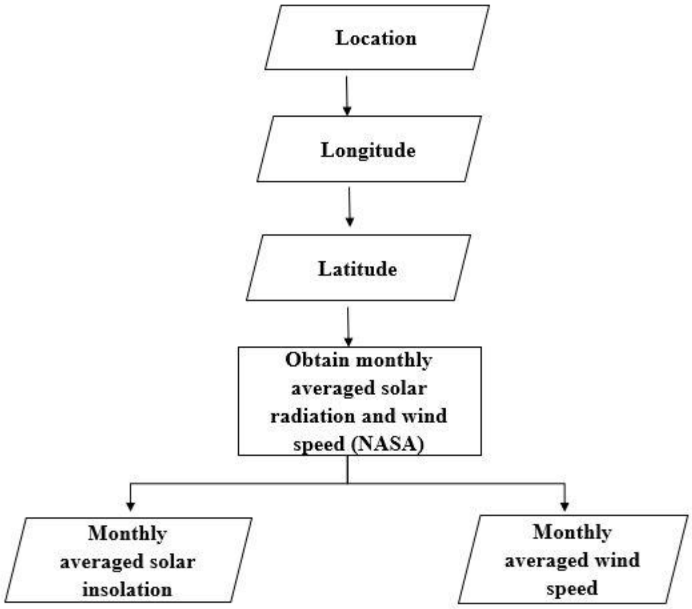


Figure 3.2: Flow chart to estimate renewable energy potential

The main renewable energy that is used in this study is the solar energy. To calculate PV array power for each hour of the year, solar radiation data needs to be inputted to HOMER. After giving the latitude, longitude and time zone of the location, monthly average daily solar radiation was downloaded via internet. In Figure 3.3, bar chart shows the monthly average daily solar radiation and line graph shows the clearness index over the year. It is observed that February to April has a higher solar radiation with a peak value of 6 kWh/m^2/day occurred in February. On the other hand, June to August shows the lowest solar radiation with a minimum value of 4.6 kWh/m^2/day occurred in June. However, due to the abundant solar energy, a scaled annual solar radiation of 5.12 kWh/m^2/day is observed throughout the year.

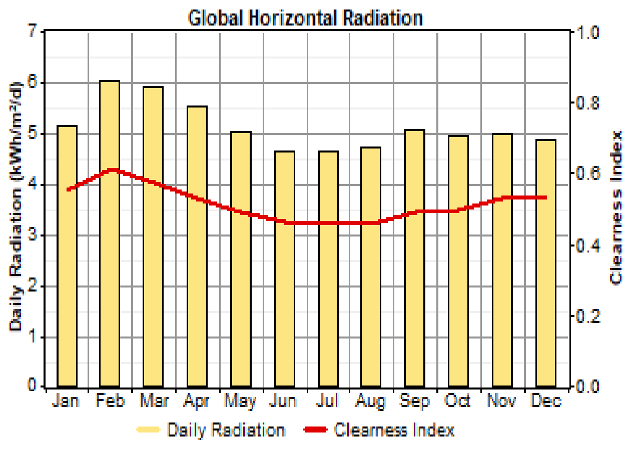


Figure 3.3: Monthly average solar irradiation at 6.8868° N, 79.9187° E

3.2. Estimation of load profile

Development of the load profile is a crucial matter for the success of a PVIES design. Load profile or local demand refers to the total power consumption of the concerned region, in this research, the distribution feeder. First step to get the load profile is to identify the type of region whether it is residential, commercial or industrial etc. Then there are mainly three methods to obtain the load profile. Figure 3.4 shows the proposed flow chart to obtain a load profile.

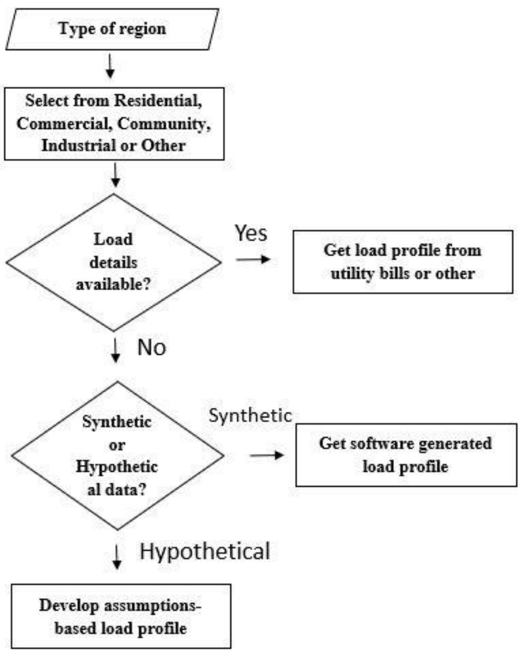


Figure 3.4: Flow chart to obtain a load profile

According to this flow chart, if the load details are available from utility bills or other, then the load profile can be easily generated. If not, there are two other options. (1) To get a software generated load profile, also known as a synthetic load profile (2) To get an assumptions-based load profile, also known as a hypothetical load profile. In most of the past researches, load profile was developed either by using assumptions or by using inbuilt synthetic load profiles of software tools. Rarely there were some studies which used load profile obtained by actual data. However, in this research an assumption-based load profile for one year is developed by using an actual one-day load profile of the feeder.

The only actual data that was available for the feeder was an average weekday load profile obtained in year 2017. Therefore, to develop a load profile for the whole year, following assumptions were used.

- Sri Lanka is a tropical country, hence there is no seasonal variation in the load.
- There is a difference in load profile according to weekday and weekend.

An average daily load profile was available for a weekday in May 2017 for the selected feeder. The data was recorded from the installed smart meters by Lanka Electricity Company Ltd in Sri Lanka [26]. Then, by assuming the daily load profile variation over the year is nearly normally distributed around the average profile, which follows a zero mean normal distribution with a standard deviation of 0.2 (causes deviations in the range of about +/- 50%), load profiles for 255 weekdays were generated by using MATLAB. Since there were no actual data available for a weekend, actual weekday load profile was used as the reference and load was increased and reduced according to time periods as Table 3.1. Likewise, for the weekend, load profiles were obtained using MATLAB for 105 weekend days in 2017.

After merging both weekdays and weekend, a load profile was obtained for 365 days with 8760 steps and fed it to HOMER. For the accuracy of the load profile, HOMER adds 4.48% day to day random variability. Peak demand is 85kW, scaled annual average is 898kWh/d. Since this load profile was obtained in 2017, load scaled annual average was used as a sensitivity variable to make the load profile suitable for year 2020.

Table 3.1: Assumptions for weekend

Time Period	Increment or Decrement	Reason
00.00-04.00	No change	-
04.00-08.00	10% reduce	Less morning routines
08.00-16.00	15% increase	Use of household appliances like washing machines etc.
16.00-20.00	3% increase	Evening activities for weekend
20.00-24.00	No change	-

After that, the load data was imported to the HOMER as an hourly time series file containing 8760 steps. Figure 3.5 and Figure 3.6 show an average daily load profile and the seasonal load profile of the distribution feeder.

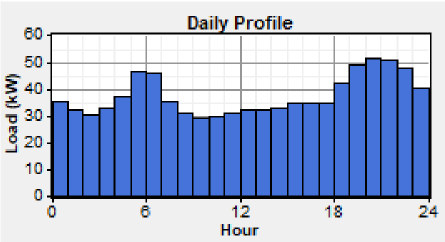


Figure 3.5: Average daily load profile

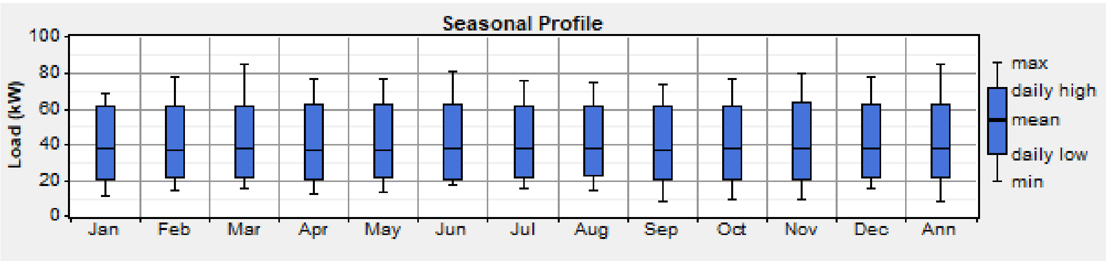


Figure 3.6: Seasonal load profile

3.3 PVIES components modelling

When designing a PVIES, one of the important steps is the identification of PVIES components. The type of the components differs according to the integrated energy system operation modes; grid connected or off-grid. Only difference in the grid connected mode is the presence of the grid with other components. For this research, solar PV module, inverter, battery and the grid are considered as PVIES components. Price details of these were obtained from Sri Lankan hybrid energy system component dealers to input to HOMER software. Table 3.2 shows the price details.

Table 3.2: Price details of components

	PV(335W)	**Inverter(5kW)**	**Battery**
Capital cost ($)	94.84	1040.56	1199
Replacement cost ($)	75	800	950
O&M cost ($/yr)	10	0	0

3.3.1 Solar PV module

HOMER calculates the rated power output under standard test conditions of a PV module using parameters such as; the PV derating factor, solar radiation incident on the PV array in each time step, the incident radiation at standard test conditions. For the maximum harnessing of the solar energy, the collector orientation should follow the movements of the sun so that sun rays always fall perpendicularly on the collector surface. Therefore, to achieve that, single-axis tracking system is used in this research. Because Sri Lanka is located near the equator, so that two-axis tracking is not needed. Lifetime of 20 years and a derating factor of 90% is assumed. HOMER applies derating factor to ensure PV operates under real world conditions considering aging, environmental issues etc.

HOMER use Equation 4 to calculate the power output from PV array [27].

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right) [1 + \alpha_P (T_c - T_{c,STC})] \text{ ------- } (4)$$

where:

Y_{PV} = The rated capacity of the PV array [kW]

f_{PV} = The PV derating factor [%]

G_T = The solar radiation incident on the PV array in the current time step [kW/m^2]

$G_{T,STC}$ = The incident radiation at standard test conditions [1 kW/m^2]

α_P = The temperature coefficient of power [%/°C]

T_c = The PV cell temperature in the current time step [°C]

$T_{c,STC}$ = The PV cell temperature under standard test conditions [25°C]

3.3.2 System inverter

A system inverter is an essential requirement in a HRES because of the presence of both AC and DC buses. In this research, an inverter with 15 years of lifetime, an efficiency of 90% is used.

3.3.3 Battery

The battery used in this research is Surrette 6CS25P. 6V, 1156Ah of 4 batteries per string were used. Therefore, the DC bus voltage is 24V.

3.3.4 Grid

When modelling the grid, grid rates can be selected from scheduled rates or real time prices. For this study, time of day tariffs were used. These rates were obtained from Ceylon Electricity Board and net metering was enabled to calculate net purchases monthly [28]. Table 3.3 shows the grid sell back prices and the time period where rates are applied. Then, yearly rate schedule should be given to HOMER. Another input that needs to be given at the startup is the amount of emissions from the grid. Table 3.4 shows the assumed GHG emissions from the grid.

Table 3.3: Grid rate details

Rate	Price($/kWh)	Sell Back($/kWh)	Applied Time Period
Rate 1	0.08	0.12	23.00-06.00
Rate 2	0.16	0.12	06.00-19.00
Rate 3	0.34	0.12	19.00-23.00

Table 3.4: Assumed GHG emissions from the grid

Greenhouse Gas	Value
CO_2 emissions(g/kWh)	632
Sulfur dioxide(g/kWh)	2.74
Nitrogen oxides(g/kWh)	1.34

3.4 System Constraints and Economic Constraints

When modelling a system using HOMER, there are some constraints to be defined. These can be defined by the user according to the requirement. Given are constraints defined in this study.

3.4.1 System constraints

- Simulation time steps – 60mins
- Dispatch strategy – there are two dispatch strategies in HOMER. (1) load following (2) cycle charging. In load following, generator produces only enough power to supply the load. This strategy is optimal for a system with a lot of renewable energy. The other one is the cycle charging. Here, generator operates at its maximum capacity and the surplus is sent to charge the batteries. A set point should be set for the state of charge of batteries which

indicates the minimum charge level that the batteries will be charged. In this study the dispatch strategy used is the cycle charging.

- Maximum annual capacity shortage – this is the maximum allowable value of the capacity shortage fraction, which is the total capacity shortage divided by the total electric load. Here maximum annual capacity shortage is used as 20%.
- Operating reserve – this is the surplus energy which can be used at a time of an instant load increase or at a sudden decrease of renewable output. User can give four operating reserves by percentages of load and renewable. Namely, (1) hourly load (2) annual peak load (3) solar power output (4) wind power output. In this study, an hourly load of 10% is used.

3.4.2 Economic constraints

Economic constraints used in this study are, annual real interest rate of 8.8% and project lifetime of 25 years.

3.5 Optimization and Sensitivity Variables

In HOMER, there are two types of variables that are important; optimization and sensitivity variables. Optimization variables are used to identify the best HRES component sizes for given constraints. Sensitivity variables indicates the system's sensitivity to the user defined sensitivity variables.

In this study, PV capacity and number of battery units are used as optimization variables. The optimization problem is modelled as follows to give an insight on the optimization happens inside HOMER. Objective function is;

$$\text{Minimize } C_{NPC} = \left(\frac{C_{total}}{Capacity\ Factor}\right) \text{ -------(5)}$$

Where,

$$C_{total} = \sum_{t=1}^{t=T} C(t)$$

$C(t)$ which is given in Equation 5 is the cost function for hour t and T is the total number of hours in the considered evaluation. *Capacity factor* is based on annual interest rate and the evaluated number of years.

$$C(t) = P_{PV}(t).C_{PV} + P_{Bat}(t).C_{Bat} + P_{Grid+}(t).C_{Grid+}(t) - P_{Grid-}(t).C_{Grid-} \text{ ---(6)}$$

Here, C_{PV} and C_{Bat} are the levelized costs for PV and Battery respectively calculated by the given input data. $C_{uti+}(t)$ is the grid rate at hour t and C_{Grid-} is the sell back rate. $P_{PV}(t)$, $P_{Bat}(t)$, $P_{Grid+}(t)$ are the PV power, battery and grid consumption while $P_{Grid-}(t)$ is the sell back power to the grid for hour *t*. Determination of these power values are constrained by the power balance and energy constraints given in [28].

PV capacity (P_{PV-max}) variable is constrained as in Equation 7, where $k(t)$ represents the PV generation availability out of maximum PV generation ratio for hour *t*.

$$P_{PV}(t) \leq k(t).P_{PV-max} \text{ -----(7)}$$

Number of battery units (q) is constrained by Equation 8 and 9 where $P_{Bat-max}$ and $E_{Bat-max}$ are maximum battery power are energy capacities respectively. $E_{Bat}(t)$ is the energy level of the battery at hour *t*.

$$P_{Bat}(t) \leq q.P_{Bat-max} \text{ ------(8)}$$

$$E_{Bat}(t) \leq q.E_{Bat-max} \text{ ------(9)}$$

In the simulations, PV capacities were considered form 0 to 85kW because peak demand is 85kW and it is observed at night. Therefore, 85kW of PV is more than enough to supply load. Number of battery units were considered from 0 to 4. Grid purchase capacity kept constant at 85kW. Sensitivity variables considered in this study are; annual real interest rate (8.8%), solar scaled annual average (5.12kwh/m^2/d), load scaled annual average (898kWh/d) and grid rate 3 power price ($0.34). Grid rate 3 power price was selected as the peak demand was observed when this price was in use. All these sensitivity variables were varied +/- 30% range to study, how a small variation of the sensitivity variables affects the optimum system type.

Economic analysis followed the steps as; (1) Estimation of renewable energy potential (2) Estimation of load profile (3) PVIES components modelling (4) system and economic constraints (5) optimization and sensitivity variables. After completing these steps, HOMER simulation begins. Simulations were done for grid connected (PV-Grid) and grid only modes. Here, grid only mode was used as the reference for comparison. As discussed in this chapter, Figure 3.7 shows the generalized methodology to conduct an economic analysis using HOMER.

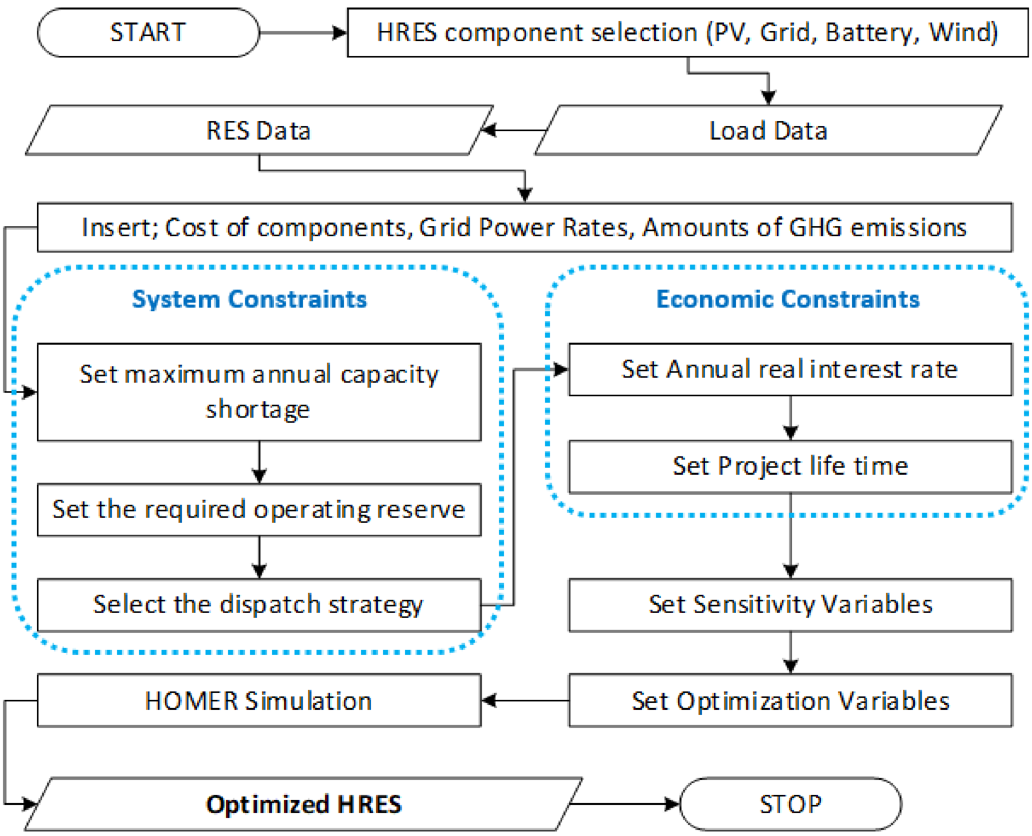


Figure 3.7: Generalized methodology for economic analysis

3.6 HOMER simulation results

There are two types of simulation results. (1) Optimization results. This explains the HOMER chosen PVIES component sizes considering the lowest net present cost. (2) Sensitivity analysis results. This explains the optimized PVIES's sensitivity to the above defined sensitivity variables.

3.6.1 Optimization results

PVIES was simulated by considering some key factors such as, NPC, COE and Renewable Fraction (RF). Table 3.5 shows the HOMER optimized results for PVIES (PV-Grid). Then it is compared with Grid only mode. It is observed that, COE has reduced by 19% and NPC has reduced by nearly a $116000 in PV-Grid system compared to the grid only system. Here, 35% of RF obtained for a PV capacity of 85kW and the number of battery units in the optimal solution was zero.

Table 3.5: HOMER optimized results

Model Name	NPC($)	COE($/kWh)	RF(%)
PV-Grid	477102	0.146	35
Grid only	593847	0.181	0

Figure 3.8 shows the cash flow summary of this PVIES.

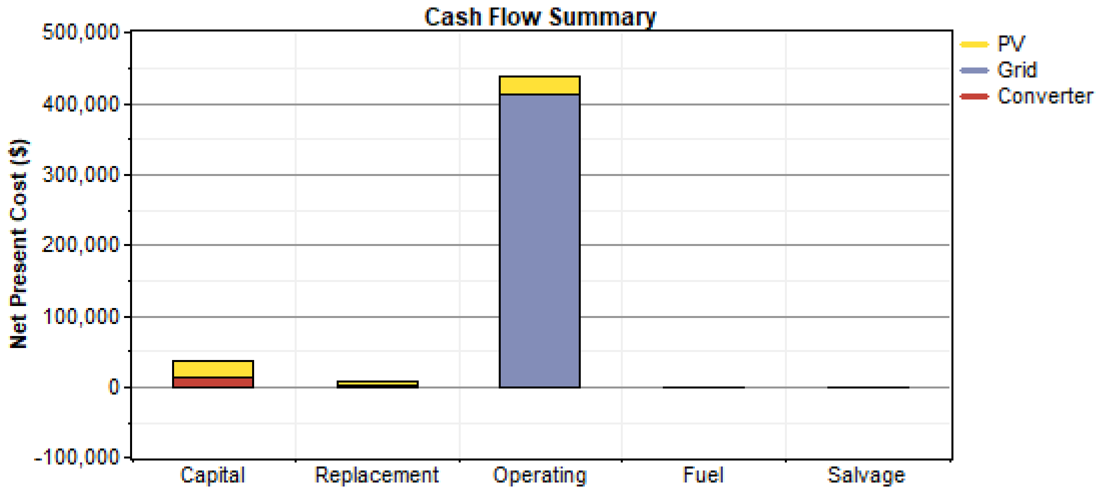


Figure 3.8: Cost flow summary

It is observed that, PV cost and converter cost equally contributing to initial capital cost while the grid dominates in the operating cost category. Since the NPC is positive in this PVIES, investor will make a profit at the end of project lifetime.

Table 3.6 and Figure 3.9 shows the electrical production by PVIES components.

Table 3.6: Electrical production by component

Component	**Production** (kWh/yr)	**Fraction**
PV array	128,201	35%
Grid purchases	239,909	65%
Total	368,110	100%

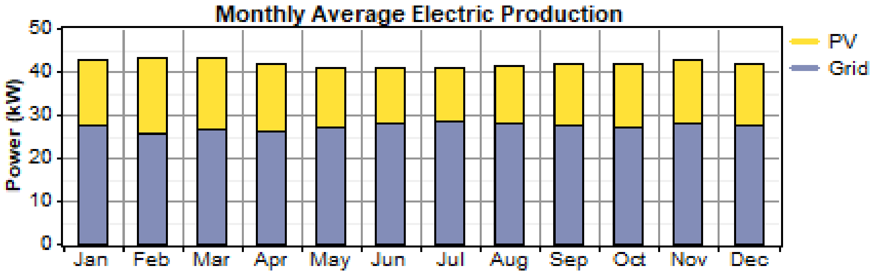


Figure 3.9: Monthly average electrical production

Here, the PV array produce 35% of total energy production. Since the HOMER chosen system does not include the battery, grid must supply all the other energy requirement hence being 65%.

Table 3.7 shows the electrical consumption of PVIES components.

Table 3.7: Electrical consumption

Load	**Consumption** (kWh/yr)	**Fraction**
AC primary load	327,770	93%
Grid sales	26,556	7%
Total	354,327	100%

This PVIES has primary electrical load as the load, no thermal loads. Therefore, 93% of electricity is consumed by primary electrical load and only 7% of excess energy is sold to grid.

Figure 3.10 and Figure 3.11 show the PV output and inverter output.

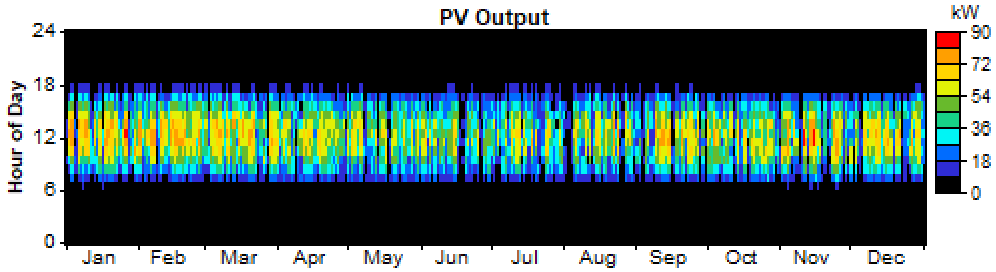


Figure 3.10: PV output

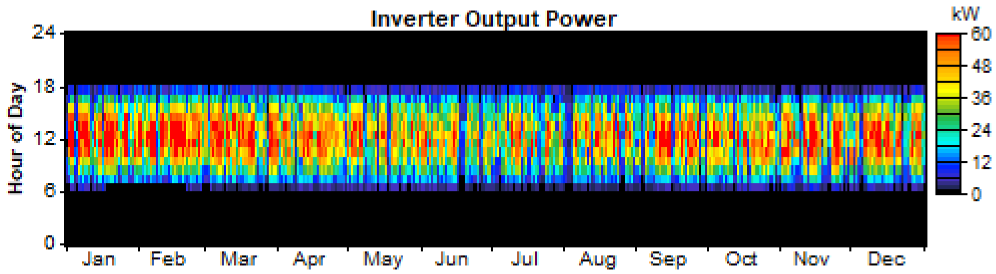


Figure 3.11: Inverter output

As shown in Figure 3.10, PV array (size of 85kW) generates power between 6am and 6pm. Around noon, it generates about 72kW of power in January to April and September to December. However, between May and August it is observed that the power output has been reduced to around 54kW in noon. On the other hand, inverter (size of 60kW) works at its full capacity in noon mostly throughout all the months.

3.6.2 Sensitivity analysis results

Another important analysis can be done using HOMER is the sensitivity analysis according to the user defined sensitivity variables. It gives an optimum system type based on sensitivity variables. Figure 3.12 shows the optimal system type obtained for PVIES.

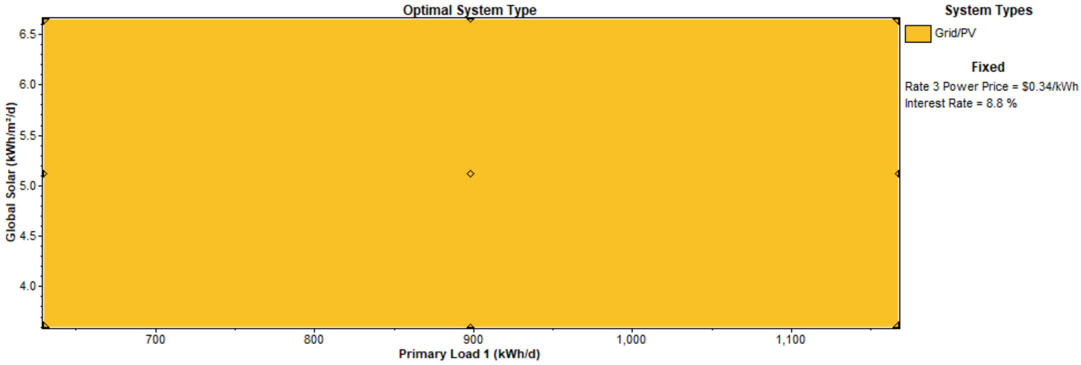


Figure 3.12: Optimal system type

It is observed that, grid is present for every possible combination of sensitivity variables. For lower and higher values of solar radiation, and for lower and higher values of primary load, grid and PV combination stands as the optimal system type. Although this is an acceptable system, to reduce the usage of grid, battery bank should be used as much as possible. This could be accomplished by using low price batteries or by increasing grid peak time power rates. Therefore, to encourage the use of batteries instead of grid, rate 3 grid price which is the grid power price rate used at night peak is increased to get the optimal system type. It is shown that in Figure 3.13, the battery has contributed to all the scenarios. On the other hand, COE has also become a little high to a value of 0.147/kWh which is still less than the COE of currently established grid only system ($0.181/kWh).

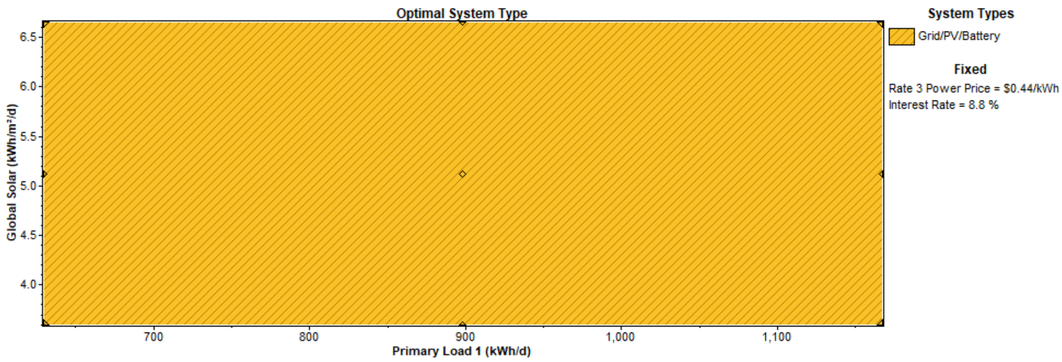


Figure 3.13: Optimal system type after increasing grid power rate

On the other hand, sensitivity analysis can be used to identify, how the optimal system changes across the range of uncertainties. Spider graph in Figure 3.14 shows, how a small variation of the sensitivity variables affects the total NPC.

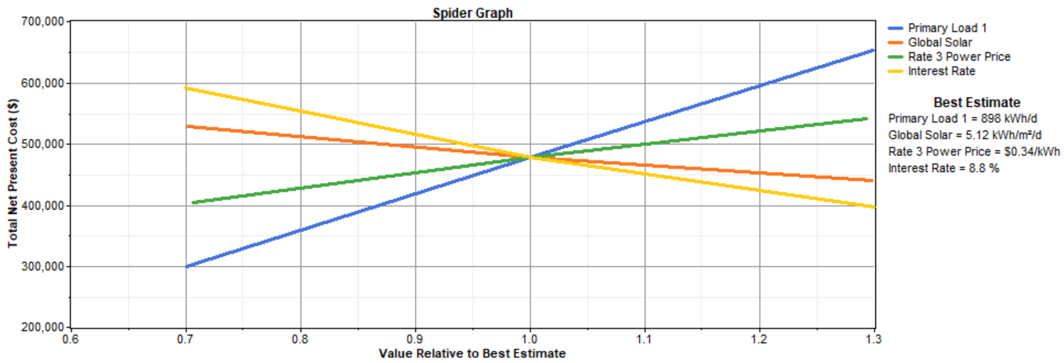


Figure 3.14: Spider graph

It is observed that from the gradients of the graphs, total NPC is more sensitive to primary load because primary load applies throughout the whole day. Global solar and rate 3 power price which are the second most sensitivities show an anti-correlated relationship with each other. Their effect is comparatively lesser as global solar affects the system about 8h/day and rate 3 grid price affects only for 4h/day. Furthermore, interest rate, which is only related to the overall cost analysis, ended up being the least sensitive variable to the NPC.

3.6.3 Environmental and Social Benefits

One of the key factors to integrate renewable energy into electrical grid network is to reduce the emission of GHG [4]. After the simulations, HOMER provides a report of GHG emissions from the optimum system. Table 3.8 gives the GHG emissions from the simulated models. It is seen that, grid only mode emits nearly twice as much as GHGs compared to the PV-Grid mode. According to these results, PV-Grid mode shows a lesser amount of GHG emissions compared to the grid only operation.

Table 3.8: GHG emissions from simulated models

Model Name	**PV-Grid**	**Grid only**
CO2 emissions(g/kWh)	134839	207151
Sulfur dioxide(g/kWh)	585	898
Nitrogen oxides(g/kWh)	286	439

Social benefits of adapting a PVIES directly relates with the environmental benefits. Less emission of GHG means less global warming. Since Sri Lanka is an island, impact of global warming is high. Some of the highlighted effects are, the extinction of rare bird spices, rising of sea level etc. Therefore, the integration of renewables will ultimately reduce these adverse effects. Another related social benefit is the betterment of society. Today, people do not like to have a large petroleum driven power plant near their homes and most of them try to make their electricity bill as much as low. So that, a PVIES will improve people’s life styles and confidently contributes to the reduction of global warming.

With the rise of utilization of renewables in the energy sector, there are lots of researches are carried out in designing PVIES. HOMER is a commonly used software to perform the initial designing of such systems where in depth technical analysis are carried out later. A HOMER based generalized process for designing a PVIES was presented in this chapter while describing the application of the required parameters in the software, using a case study. The presented process could be highly beneficial for new users of HOMER who work on PVIES (or HRES) designing.

CHAPTER 4

4. TECHNICAL ANALYSIS

Technical analysis is conducted to verify the technical viability of the HOMER given system configuration, which is the PVIES with a PV array size of 85kW. To do this, a real-life distribution feeder in Sri Lanka is considered. First, the feeder is modelled by using OpenDSS software and then rooftop solar systems were penetrated to that feeder. The total penetrated PV capacity is the HOMER chosen PV size (85kW) in the economic analysis. After that, the voltage profiles and power flows were taken to observe any violations or abnormality. Then, the technical analysis was continued to find the PV hosting capacity of the modelled feeder.

4.1. Modelling of the distribution feeder

To model the distribution feeder, Distributed PV (DPV) monitoring and feeder analysis project [24] conducted by EPRI (Electric Power Research Institute), who are the developers of OpenDSS, was used. This project contains three large distribution feeders namely; J, K and M. All these feeders are real life feeders that are in USA. EPRI has used real life data to simulate the above feeders. In this research, the DPV test case is used as the reference.

The selected distribution feeder is in Kotte area with 100kVA – AZ0205 Distribution transformer. Figure 4.1 shows a sketch of this feeder.

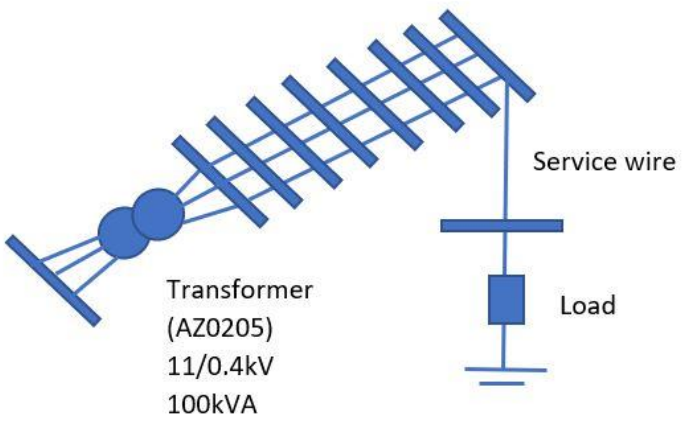


Figure 4.1: Sketch of distribution feeder

The distribution transformer is a 100kVA step-down transformer with voltage levels of 11kV and 400V. Then there are three phase feeders connecting number of poles throughout the feeder with lengths around 60m. Neutral is grounded at the substation. All loads are single phase loads connected via a service wire as shown in Figure 4.1. Lengths of the service wires are within 30-35m. Power factor of 0.95 is assumed and it is taken that the feeder is 85% loaded [26].

When modelling a feeder using OpenDSS, every physical component such as distribution transformer, feeders, loads and service wires needs to be modelled explicitly. Therefore, before start modelling the feeder, following assumptions were used in test case.

- Neutral conductor is not explicitly modeled. It is eliminated by Kron reduction. By employing the Kron reduction, it is defined that the voltage of the neutral = 0.
- All customers are assumed to have equal opportunity to acquire a PV system. Therefore, it is assumed that all customers have a rooftop PV system.

Then, the flow chart in Figure 4.2 was followed to model the feeder.

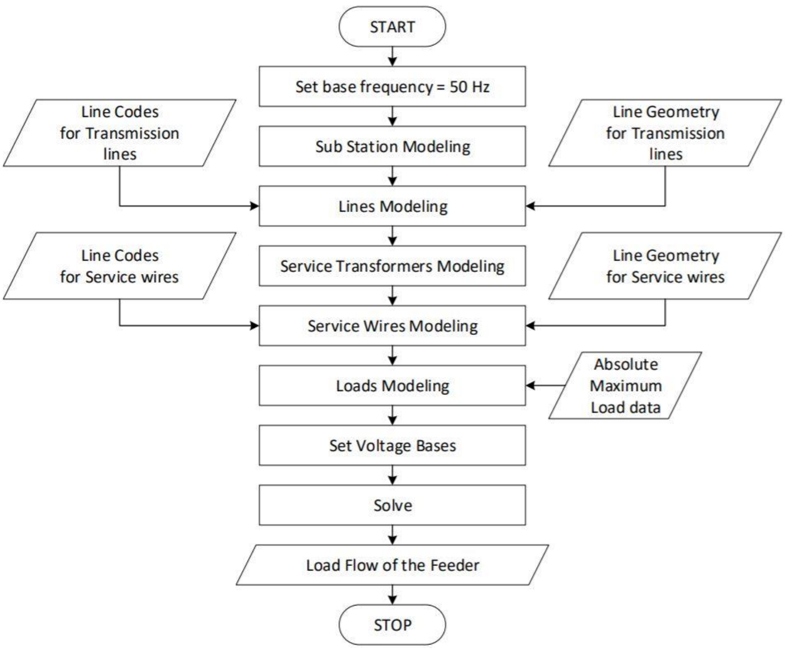


Figure 4.2: Flow chart to model the feeder

In OpenDSS, it is essential to define the base frequency before modelling any component. Then, each component should be modelled separately. Here, the substation means the grid connected bus bar and lines means the three phase feeders. Then, the service transformer or in other words, distribution transformer should be modelled. When modelling the lines, it is required to define line geometry and line codes in OpenDSS. Line geometry refers to the physical spacing of lines. Line codes includes the details of line's impedance matrixes. When modelling the load, flow chart indicates to take absolute maximum load data which is the maximum loading of the feeder, because those are the default load values used throughout this test case. After modelling all the components, voltage bases need to be defined because OpenDSS solves a load flow in per unit values.

At the end of this step, feeder is modelled. Figure 4.3 shows a part of the main coding used when modelling the feeder.

```
!service wires
New     Line.B11365A    phases=2        bus1=B11365.1  bus2=XB11365.1         length=0.1       linecode=LVB244        units=kft
New     Line.B11367C1   phases=2        bus1=B11367.3  bus2=XB11367C.3        length=0.115     linecode=LVB244        units=kft
New     Line.B11367C2   phases=2        bus1=XB11367C.3        bus2=XB11367CC.3        length=0.1       linecode=LVB244        units=kft
New     Line.B11368B phases=2  bus1=B11368.2  bus2=XB11368.2        length=0.1       linecode=LVB244        units=kft
New     Line.B11418A    phases=2        bus1=B11418.1  bus2=XB11418.1         length=0.1       linecode=LVB244        units=kft
New     Line.B11418B    phases=2        bus1=B11418.2  bus2=XB11418.2         length=0.1       linecode=LVB244        units=kft
New     Line.B2532B     phases=2        bus1=B2532.2   bus2=XB2532.2  length=0.1       linecode=LVB244        units=kft
New     Line.B56446B    phases=2        bus1=B56446.2  bus2=XB56446.2         length=0.1       linecode=LVB244        units=kft
New     Line.B59351B    phases=2        bus1=B59351.2  bus2=XB59351.2         length=0.1       linecode=LVB244        units=kft
New     Line.B59352A1   phases=2        bus1=B59352.1  bus2=XB59352A.1        length=0.115     linecode=LVB244        units=kft
New     Line.B59352A2   phases=2        bus1=XB59352A.1        bus2=XB59352AA.1        length=0.1       linecode=LVB244        units=kft
New     Line.B59352C    phases=2        bus1=B59352.3  bus2=XB59352.3         length=0.1       linecode=LVB244        units=kft
New     Line.B2630A     phases=2        bus1=B2630.1   bus2=XB2630.1  length=0.1       linecode=LVB244        units=kft
New     Line.B2630C     phases=2        bus1=B2630.3   bus2=XB2630.3  length=0.1       linecode=LVB244        units=kft

!loads
New     Load.XB11365A1          phases=1        bus=XB11365.1  kV=0.23 kW=0.534567483725728        pf=0.95 status=variable  model=4
New     Load.XB11365A2          phases=1        bus=XB11365.1  kV=0.23 kW=0.167103773564667        pf=0.95 status=variable  model=4
New     Load.XB11365A3          phases=1        bus=XB11365.1  kV=0.23 kW=0.0207976432338941       pf=0.95 status=variable  model=4
New     Load.XB11367CC1         phases=1        bus=XB11367CC.3        kV=0.23 kW=0.271701260820394        pf=0.95 status=variable  model=4
New     Load.XB11367CC2         phases=1        bus=XB11367CC.3        kV=0.23 kW=0.107124319630024        pf=0.95 status=variable  model=4
New     Load.XB11367CC3         phases=1        bus=XB11367CC.3        kV=0.23 kW=0.271040484940046        pf=0.95 status=variable  model=4
New     Load.XB11368B1          phases=1        bus=XB11368.2  kV=0.23 kW=0.249076177551489        pf=0.95 status=variable  model=4
New     Load.XB11368B2          phases=1        bus=XB11368.2  kV=0.23 kW=0.245973915866009        pf=0.95 status=variable  model=4
New     Load.XB11368B3          phases=1        bus=XB11368.2  kV=0.23 kW=0.210822894142198        pf=0.95 status=variable  model=4
New     Load.XB11418A1          phases=1        bus=XB11418.1  kV=0.23 kW=0.360036653063228        pf=0.95 status=variable  model=4
New     Load.XB11418A2          phases=1        bus=XB11418.1  kV=0.23 kW=0.261535169101437        pf=0.95 status=variable  model=4
New     Load.XB11418A3          phases=1        bus=XB11418.1  kV=0.23 kW=0.062598317112388        pf=0.95 status=variable  model=4
New     Load.XB11418B1          phases=1        bus=XB11418.2  kV=0.23 kW=0.317989168473335        pf=0.95 status=variable  model=4
New     Load.XB11418B2          phases=1        bus=XB11418.2  kV=0.23 kW=0.0719384859302198       pf=0.95 status=variable  model=4
New     Load.XB11418B3          phases=1        bus=XB11418.2  kV=0.23 kW=0.113582707091835        pf=0.95 status=variable  model=4
New circuit.LV Bus1=Sourcebus basekv=11 pu=1 Mvasc3=783.06 Mvasc1=837.91   !for a balanced three phase source

!Primary Substation Transformer
new transformer.AZ0205 windings=2 buses=(Sourcebus, B11365) conns=(delta, wye) kvs=(11, 0.4) kvas=(100, 100) %Rs=(2.00, 1.56)
%loadloss=2.079 %Noloadloss=0.2540 xhl=3.93 %imag=1.51 rneut=0 xneut=0  wdg=1 maxtap=1.025 mintap=0.925 NumTaps=4

!LV three phase feeders
New Line.OH_B11367 bus1=B11365 bus2=B11367 length=49.352 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B11368 bus1=B11367 bus2=B11368 length=59.377598 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B11418 bus1=B11368 bus2=B11418 length=43.586399 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B2526 bus1=B11418 bus2=B2526 length=35.2728 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B2532 bus1=B2526 bus2=B2532 length=33.268797 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B2547 bus1=B2532 bus2=B2547 length=33.515197 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B2630 bus1=B2547 bus2=B2630 length=47.49759 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B56446 bus1=B2547 bus2=B56446 length=44.383999 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B59351 bus1=B2547 bus2=B59351 length=52.555199 units=m linecode=LVB241 phases=3 enabled=True
New Line.OH_B59352 bus1=B59351 bus2=B59352 length=34.617598 units=m linecode=LVB241 phases=3 enabled=True

Set voltagebases=[11, 0.4]
Calcv
Solve
```

Figure 4.3: Code in OpenDSS

4.2. PV system in OpenDSS

Figure 4.4 shows the block diagram of representing the PV system in OpenDSS.

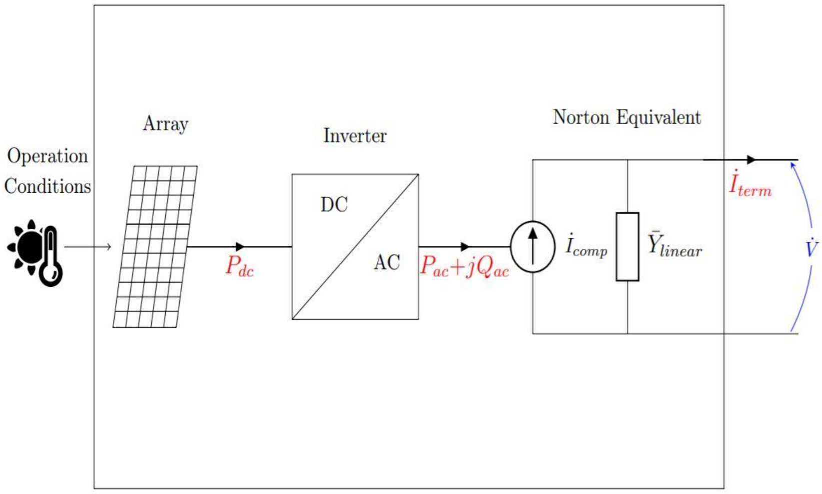


Figure 4.4: PV system in OpenDSS

Source: [24]

This system includes three sub blocks namely; operating conditions, PV array and inverter. Then this connects to the bus as a Norton equivalent as shown in Figure 4.4. Following properties needs to be defined,

- PV array properties
    - Pmpp -power at maximum power point
    - P-T curve
- Inverter properties
    - kVA rating
    - kV
    - Efficiency curve
- Operating conditions
    - Irradiance
    - Temperature

P-T curve is the correction factor curve of the PV array per unit of Pmpp as a function of the PV array temperature. As can be seen in Figure 4.5, the correction factor should be 1.0 for the temperature at which Pmpp is defined, in this case 25 °C. The PV array generates its rated maximum power, Pmpp, when operating at that temperature, 25 °C, and with 1 kW/m^2 irradiance.

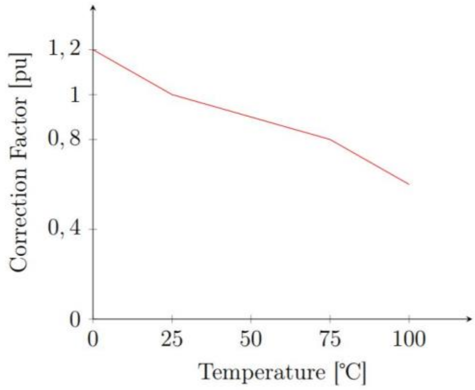


Figure 4.5: P-T curve

Source: [24]

Efficiency curve shown in Figure 4.6 characterizes the variation of the inverter efficiency as a function of the power from PV array, Pdc, in per unit of inverter's kVA rating. However, in OpenDSS present version, model only defines one curve that generally corresponds to the rated voltage of the DC bus.

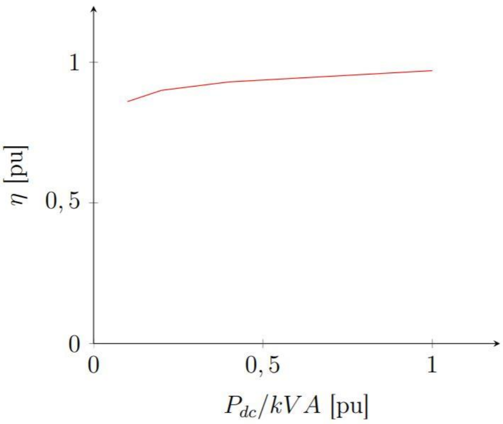


Figure 4.6: Efficiency curve

Source: [24]

After defining these curves, PV system needs to eb define in OpenDSS. Figure 4.7 shows the code used to define a three phase PV system in OpenDSS.

```
!Large, three-phase PV Systems
New xycurve.PT_Curve npts=4 xarray=[0 25 75 100] yarray=[1.2 1 .8 .6]
New xycurve.EFF_Curve npts=4 xarray=[.1 .2 .4 1] yarray=[.86 .9 .93 .97]

New PVSystem.23283PV Phases=3 Bus1=B23283PV kV=0.4 kVA=5.719 Irradiance=1 Pmpp=6.86344 PF=1
~ Effcurve=EFF_Curve P-Tcurve=PT_Curve Temperature=25 %Cutin=0.1 %Cutout=0.1
```

Figure 4.7: Code to define a three phase PV system

In steady state mode, PV output power calculates as Equation 10 and 11,

P_{dc} = Pmpp x irradiance x P-T curve (Temperature) ---(10)

P_{ac} = P_{dc} x Effcurve (P_{dc}) -----(11)

$S = P_{ac} + jQ_{ac}$

Since the power factor is assumed to be 1, reactive component is zero.

4.3 Small scale PV penetration

For a LV feeder, penetrating small scale PV systems (rooftop PV systems) makes sense than penetrating a large-scale PV system. Therefore, in this step, small scale PV systems were distributed among all customers, proportional to their demand by using the "Distribute" command of OpenDSS as follows,

"Distribute kW=85 how=proportional file=distributedgen.DSS"

Now, a file with generators called "distributedgen" is created with the distributed kW values. Then these generator objects were replaced by PV objects to model them as rooftop PV modules.

Here, 85kW of PV was distributed because that is the HOMER selected PV array size. Then the kW values were increased to observe any voltage violation. As mentioned earlier, absolute maximum load of the system is considered. Absolute maximum load is the maximum feeder loading irrespective of the time of the day.

4.3.1 Voltage analysis

When connecting an intermittent source to the grid, it is essential to access the impact on feeder voltage. Over voltage conditions, voltage deviations and voltage imbalances are the main impacts which can be occurred on a feeder. However, in this research, only over voltage condition and voltage deviation are considered. Therefore, voltage results were taken for following criteria,

- Maximum feeder voltage to observe any over voltage condition
- Deviations in voltage from no PV to full PV to observe any voltage deviations

These analyses were conducted to find whether the HOMER chosen PV capacity (85kW) is technically viable. According to [29], over voltage limit can be mentioned based on area type as Table 4.1. Kotte region belongs to urban area category.

Table 4.1: Voltage range according to area type

Area	**Voltage range**
Metropolitan areas	± 6% from the declared voltage
Urban areas	± 6% from the declared voltage
Rural areas	± 6% from the declared voltage

Voltage fluctuation or deviation allowable is 3% for the primary feeders and 5% for the load connected/secondary feeders [24]. Here, the voltage deviation analysis was performed only for the secondary feeders.

Since OpenDSS works with per unit values, the feeder monitoring criteria can be given as Table 4.2. Here, per unit value for over voltage condition is selected as 1.05 by collaborating the conditions given in [29] and [24].

Table 4.2: Feeder monitoring criteria

Criteria	Basis	Flag
Over voltage	Feeder voltage	$\geq$1.05 pu
Voltage deviation	Deviations in voltage from no PV to full PV	$\geq$5% pu

(i) Over voltage analysis

The overvoltage criterion, which is the steady-state voltage appearing throughout the power distribution system, is generally the primary concern of the power system utility. It is viewed as the maximum feeder voltage for each PV deployment scenario and the feeder exposure to those over voltages. The overvoltage caused by PV output can be a key limiting factor to how much PV generation capacity can be supported on a distribution system.

Figure 4.8 shows a simplified feeder model with PV integration. This can be used to obtain over voltage of the feeder as given in Equation 10.

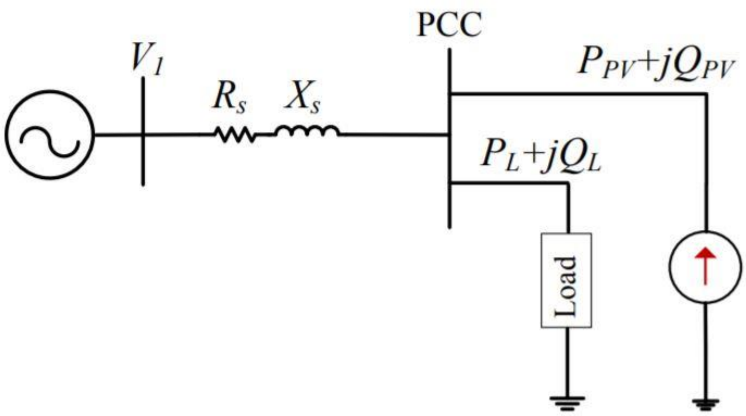


Figure 4.8: Simplified feeder model

Source: [30]

Voltage at PCC can be derived as,

$$V_{PCC} = V_1 + \frac{(P_{PV} - P_L)R_S}{V_{PCC}} + \frac{(Q_{PV} - Q_L)X_S}{V_{PCC}} \text{ -----(10)}$$

Figure 4.9 shows the over voltage analysis results.

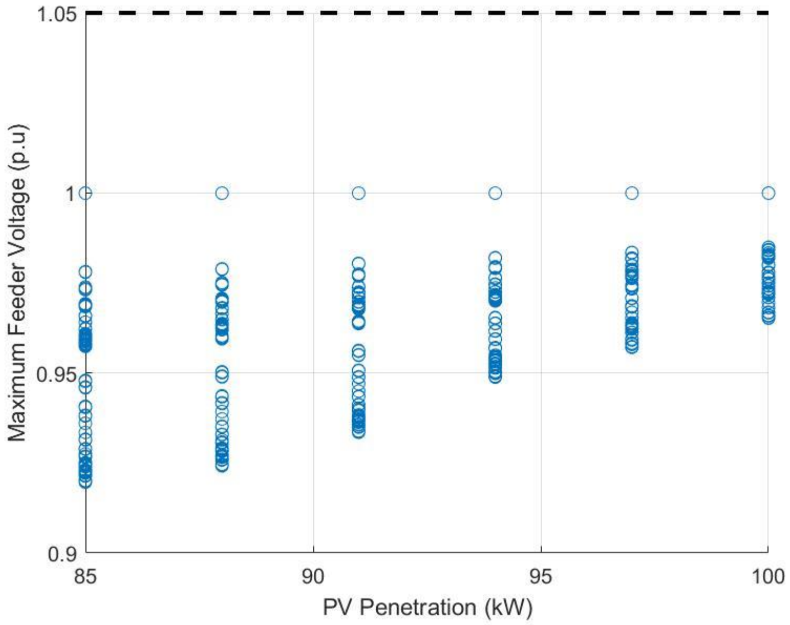


Figure 4.9: Over voltage results

In the modelled distribution feeder, there are 72 buses/poles/connection points. Therefore, in this figure, there are 72 points to each PV deployment. It is observed that, at 85kW PV penetration, there is no over voltage violation. Then, the PV penetration level was increased till 100kW because the penetration level will be limited due to the 100kVA distribution transformer. Furthermore, the source bus or in other words the infinite bus where this feeder is connected to the outer grid, showed no changes in voltage (1 per unit).

(ii) Voltage deviation analysis

The voltage deviation criterion is important due to ramping capability of the PV systems. These systems can change output quickly and unpredictably. The steady-state analysis consists of comparing voltages throughout the system before and after full PV comes online. This quantifies the voltage change that could occur prior to feeder control actions.

Figure 4.10 shows a simplified feeder model with PV integration. This can be used to obtain voltage deviation of the feeder as given in Equation 11.

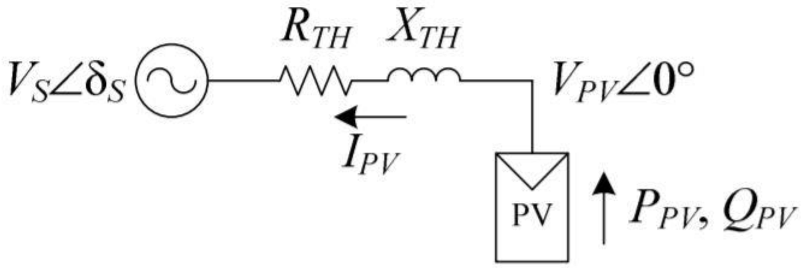


Figure 4.10: Simplified feeder model

$$\Delta V_{PV} = \frac{R_{TH}P_{PV} + X_{TH}Q_{PV}}{V_{PV}} \text{ -------(11)}$$

Source: [31]

Figure 4.11 shows the voltage deviation analysis results.

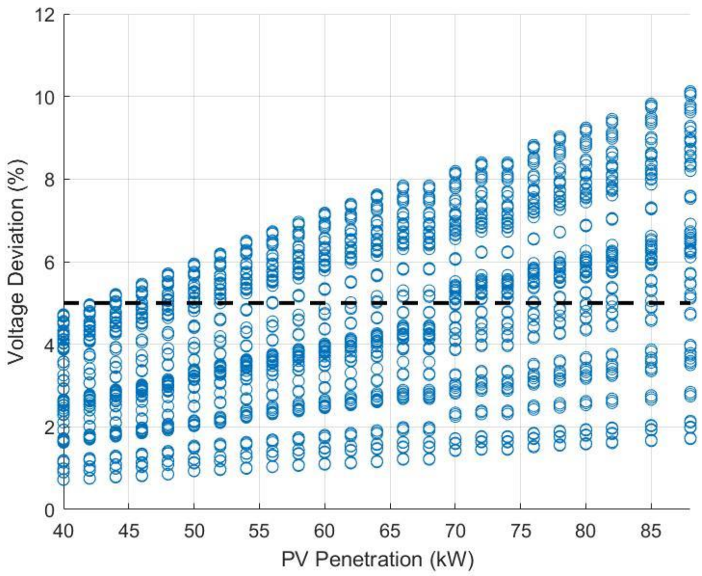


Figure 4.11: Voltage deviation results

Voltage deviation was taken by comparing no PV condition with full PV condition. It is found that, at 44kW PV penetration, the voltage deviation exceeds the threshold. This means, if 44kW of PV comes online to the feeder at once, then there will be a significant voltage deviation. Therefore, the safe margin to penetrate PV is found as 43kW.

Voltage analysis was performed to access the impact on feeder voltage for the PV penetration of HOMER given value (85kW). Based on the over voltage analysis results, it is found that 85kW of PV can be penetrated without violating feeder monitoring criteria. However, based on the voltage deviation analysis, it is found that after 44kW of PV penetration, all the buses show a significant voltage deviation. Therefore, 85kW of PV cannot be penetrated to this feeder without violating voltage deviation threshold.

4.3.2 Power flow analysis

In OpenDSS, power flow through each component can be found as active power, reactive power and apparent power separately. This helps to identify the power generation and power consumption of each component. For an example, Figure 4.12 shows the power flow through distribution transformer at midday prior to PV penetration.

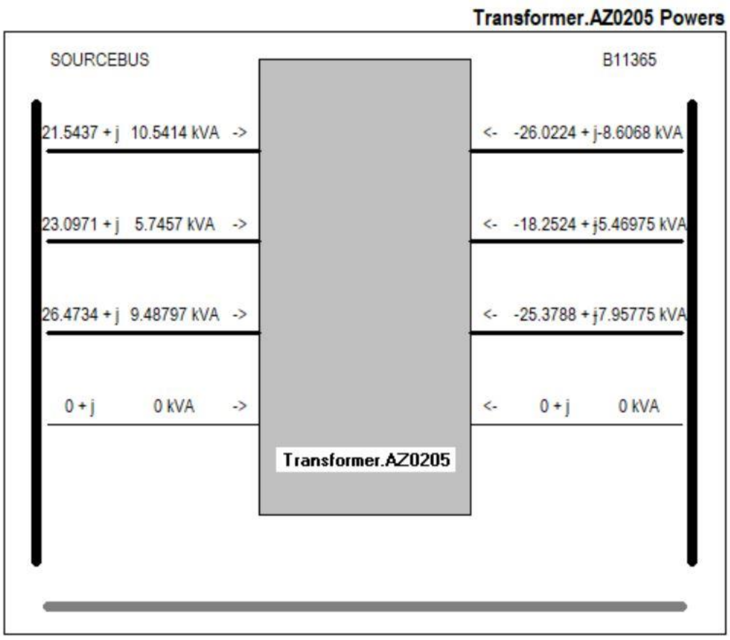


Figure 4.12: Power flow through distribution transformer

Here, the buses connected are source bus and B11365. In OpenDSS, power flow is always shown as an input to the component. As shown in Figure 4.12, totally 75.6kVA of apparent power is transformed by this transformer.

Apart from this element wise power flow analysis, there are two types of plots that can be plotted by OpenDSS namely; circuit plot and daisy plot. Circuit lot shows the power flow along the feeder. Line widths are proportional to the power flow density. This plot is drawn by using XY coordinates. Therefore, this represents the actual geographical view of the feeder. On the other hand, daisy plot shows how PV system is generating power. Yellow circles in this plot show the connected PV systems.

Figure 4.13 shows the circuit plot of the concerned distribution feeder.

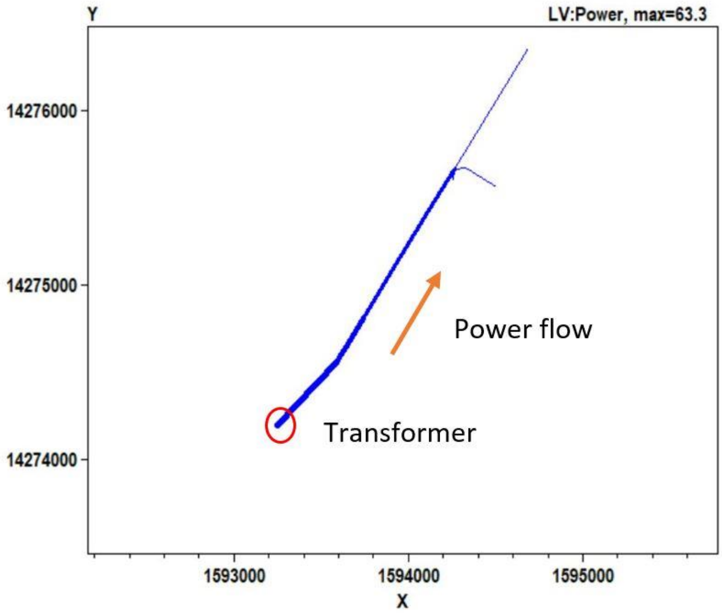


Figure 4.13: Circuit plot

Since line width is proportional to the power capacity flowing, it is clearly shown that high amount of power is flowing from transformer to the rest of the feeder while at consumer end, the power capacity flowing has become less.

Figure 4.14 shows the daisy plot of part of the distribution feeder. Yellow circles represent the PV systems.

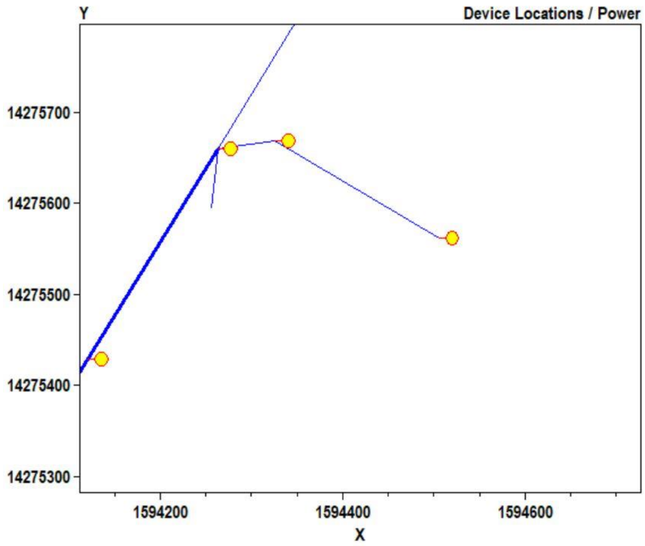


Figure 4.14: Daisy plot

This Figure 4.14 helps to get a visualize idea about the PV system connection points.

From the voltage analysis results, it is found that, at 44kW, feeder violates voltage monitoring criteria. Therefore, 43kW PV penetration is found to be the safe margin for this absolute maximum load level. At this point, based on power analysis it is found that, grid power supply has reduced by 44.5kW.

4.4 Steady state stochastic analysis to find PV hosting capacity

PV hosting capacity is defined as the maximum amount (capacity) of PV that a feeder can accommodate before adverse feeder impact occurs. This value will be dependent on the feeder, PV deployments, and monitoring/evaluation criteria. Feeder monitoring criteria can be used to determine a criteria-based hosting capacity. Ultimately, the lowest of the criteria-based hosting capacities would be the overall PV limit for the feeder. Therefore, to determine the PV hosting capacity for small scale PV integration, a steady state stochastic analysis was performed.

The steady-state analysis determines the 'worst case' feeder response that would occur for the sudden change from zero to full PV output [32]. The steady state analysis is conducted for the four base load levels:

- Absolute maximum – maximum feeder load level derived from 8760 load data; irrespective of time-of-day
- Absolute minimum – minimum feeder load level derived from 8760 load data; irrespective of time-of-day
- Midday maximum – maximum feeder load level derived from 8760 load data; 11am-1pm time considered only
- Midday minimum – derived from 8760 load data; 11am-1pm time considered only

Figure 4.15 and Figure 4.16 show the over voltage analysis for the absolute maximum and absolute minimum loads respectively.

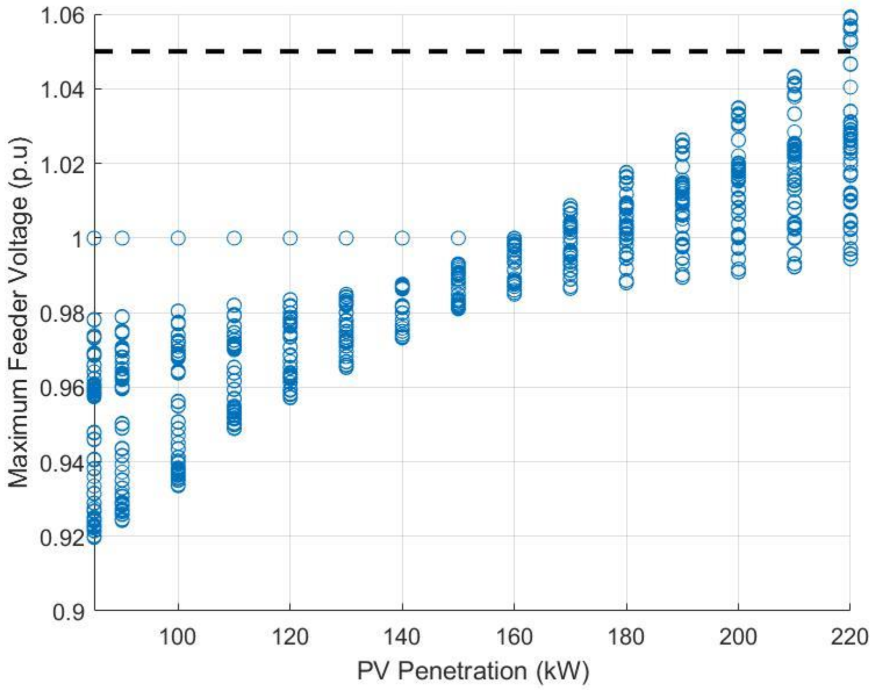


Figure 4.15: Over voltage analysis for absolute maximum load

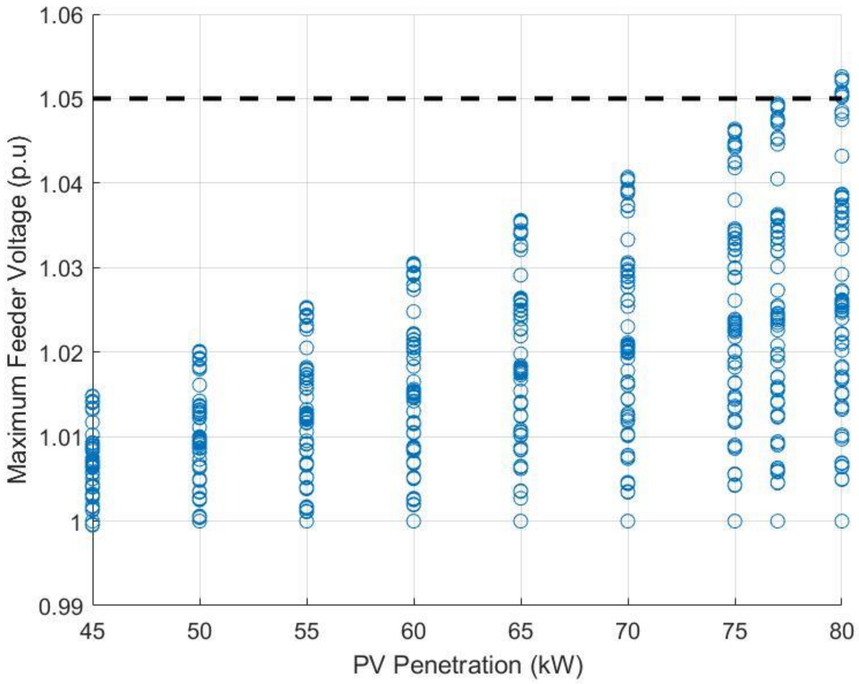


Figure 4.16: Over voltage analysis for absolute minimum load

Overvoltage-based hosting capacity typically increases with increased load [32]. By validating that, it is observed the PV hosting capacity for absolute maximum load is about 210kW while for absolute minimum load is 77kW.

Figure 4.17 and Figure 4.18 show the over voltage analysis for the midday maximum and midday minimum loads respectively.

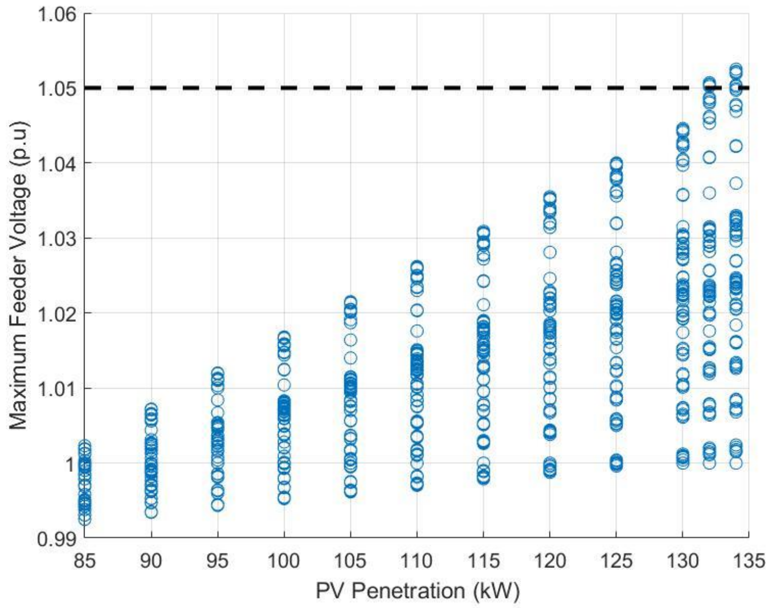


Figure 4.17: Over voltage analysis for midday maximum load

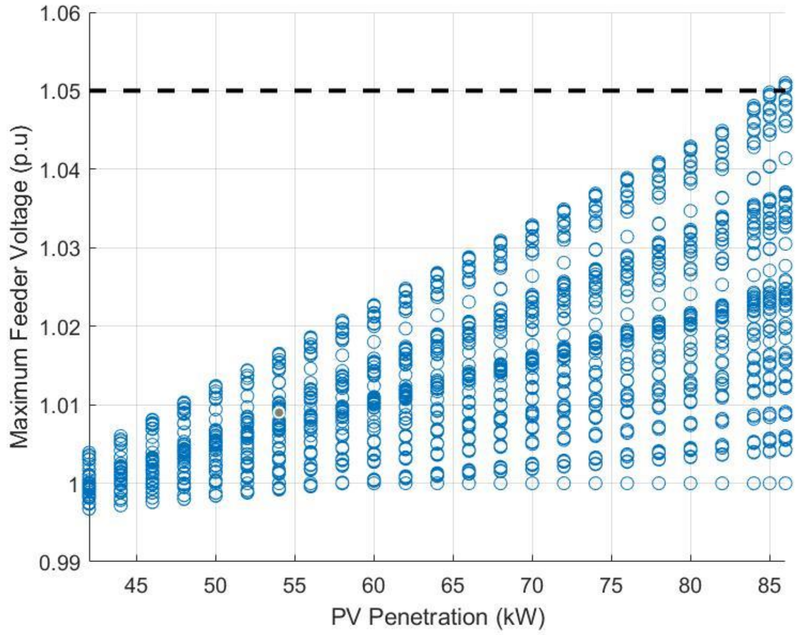


Figure 4.18: Over voltage analysis for midday minimum load

Likewise, it is observed the PV hosting capacity for midday maximum load is 131kW while for midday minimum load is 84kW.

Figure 4.19 and Figure 4.20 show the voltage deviation analysis for the absolute maximum and absolute minimum loads respectively.

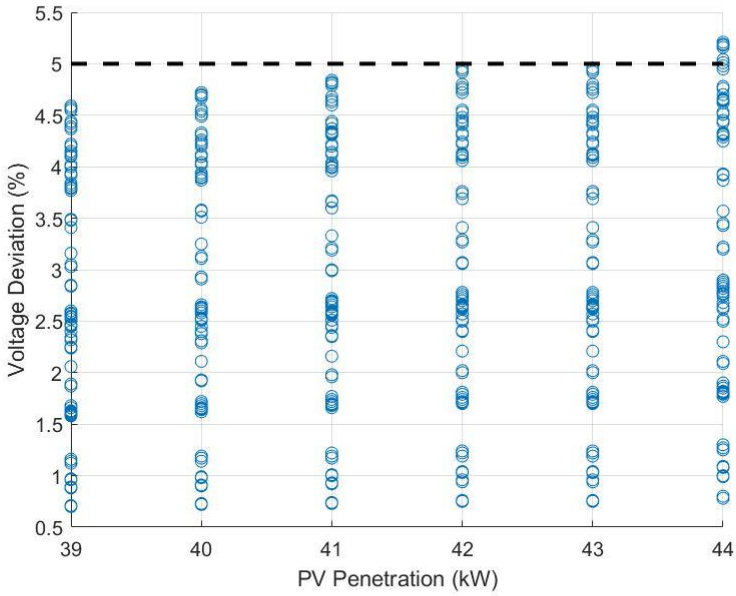


Figure 4.19: Voltage deviation analysis for absolute maximum load

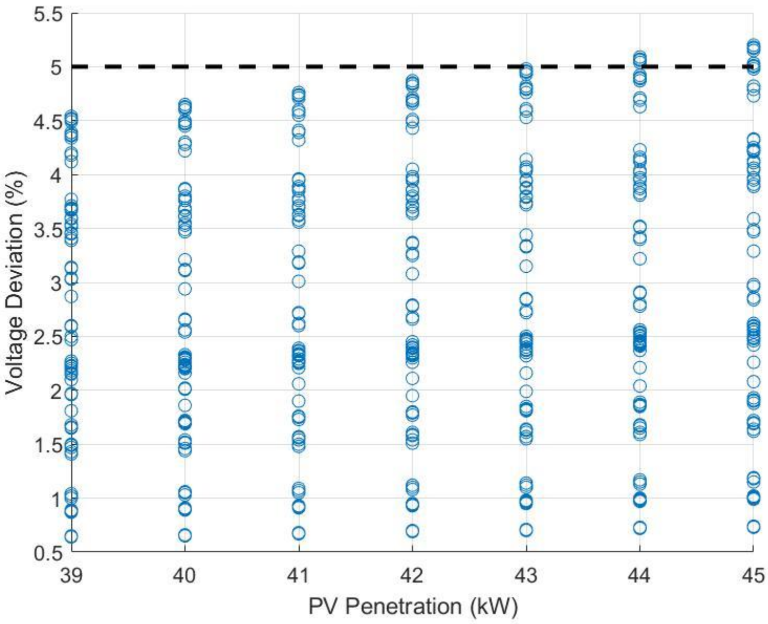


Figure 4.20: Voltage deviation analysis for absolute minimum load

Voltage deviation-based hosting capacity typically decreases with increased load [32]. However, in this feeder, PV hosting capacity based on voltage deviation is almost equal (43kW) for absolute maximum and minimum loads.

Figure 4.21 and Figure 4.22 show the voltage deviation analysis for the midday maximum and midday minimum loads respectively.

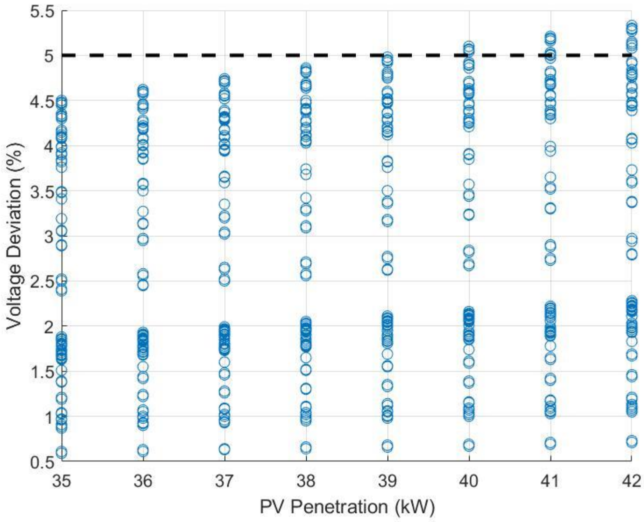


Figure 4.21: Voltage deviation analysis for midday maximum load

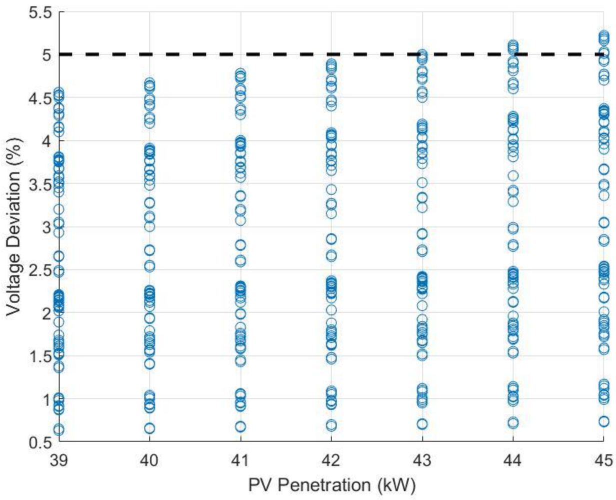


Figure 4.22: Voltage deviation analysis for midday minimum load

PV hosting capacity based on voltage deviation, for midday maximum load is 39kW and for midday minimum load is 42kW.

After this stochastic analysis, PV hosting capacity, based on voltage can be found. Table 4.3 shows the summary of performed stochastic analysis.

Table 4.3: Summary of stochastic analysis

	Absolute Maximum load	**Absolute Minimum load**	**Midday Maximum load**	**Midday Minimum load**
Over voltage	210kW	77kW	131kW	84kW
Voltage deviation	43kW	43kW	39kW	42kW

Therefore, the lowest of the criteria-based hosting capacity that is 39kW would be the overall PV limit for the feeder.

It is observed that the voltage deviation limits the PV hosting capacity rather than over voltage condition. Figure 4.23 shows the minimum PV hosting capacity limit for the feeder.

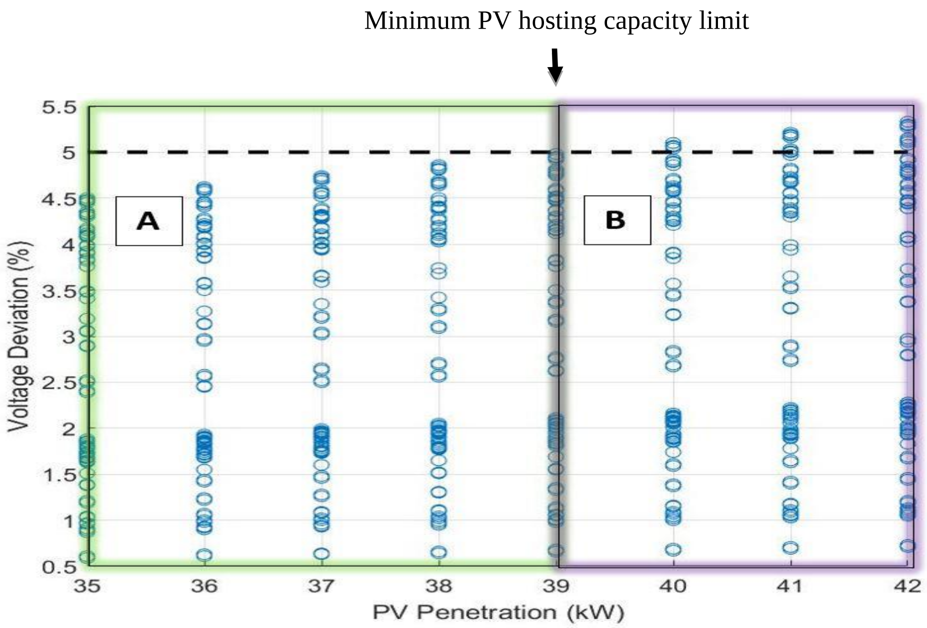


Figure 4.23: Minimum PV hosting capacity limit

Figure 4.23 can be divided into two regions, region A and region B. All penetrations in region A are acceptable because none of the buses show a voltage deviation violation. Some penetrations in region B are acceptable because some buses show a voltage deviation violation in this region. Therefore, 39kW PV penetration is defined as the minimum PV hosting capacity limit for this feeder.

4.5 PV hosting capacity based on feeder section

The previous stochastic analysis was performed by assuming all the PV penetration is distributed among all the consumers proportional to their demand. However, this could be varied due PV distributed location on the feeder. Mainly the feeder can be divided into three sections; front section, middle section and end section.

Figure 4.24 shows how the distributed feeder is divided based on sections to find the PV hosting capacity based on feeder section.

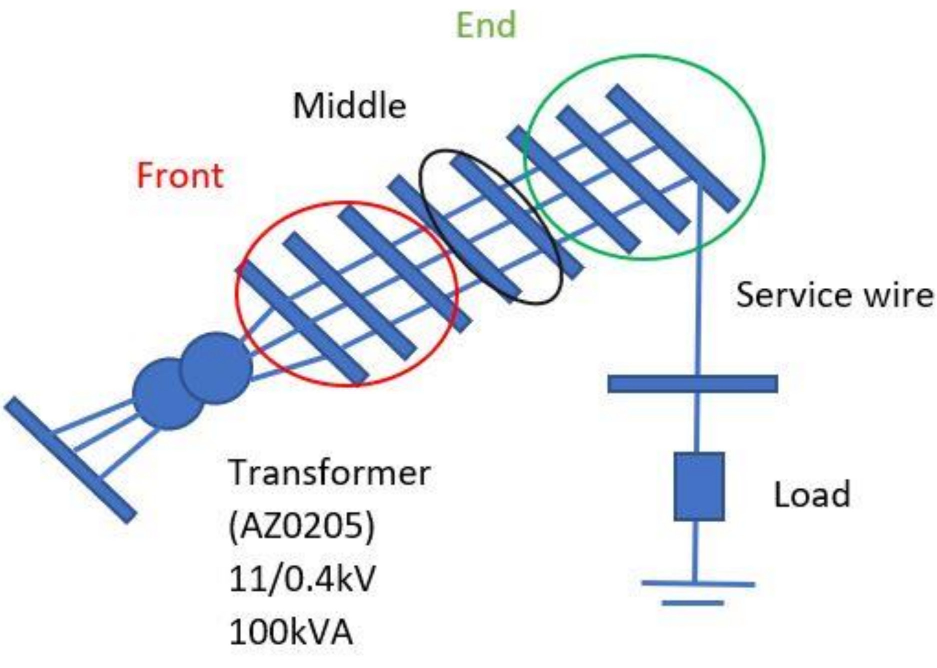


Figure 4.24: Sectioned distributed feeder

First, the total 85kW of PV was distributed to the front section, then to the middle section and finally to the end section to find the PV hosting capacity based on feeder section. Here, for the front section, 30% feeder length from the distribution transformer is considered from the distribution transformer. Likewise, 60% length from the distribution transformer for the middle section and 90% length from the distribution transformer for the end section is considered.

Table 4.4 shows the PV hosting capacity based on feeder section.

Table 4.4: PV hosting capacity based on feeder section

Test Case	**PV distribution**	**PV hosting capacity**
1	To the whole feeder (Base case)	39kW
2	To front section of the feeder (30% of length)	89kW
3	To middle section of the feeder (60% of length)	48kW
4	To end section of the feeder (90% of length)	28kW

It is observed that, more PV can be penetrated to the feeder, if it is distributed on the front section of the feeder (Closer to distribution transformer). Because higher the distance from source means higher the line resistance. Therefore, higher voltage deviation due to PV addition, thus lower PV hosting capacity.

The overall process to find the PV hosting capacity is summarized by this flow chart given in Figure 4.25.

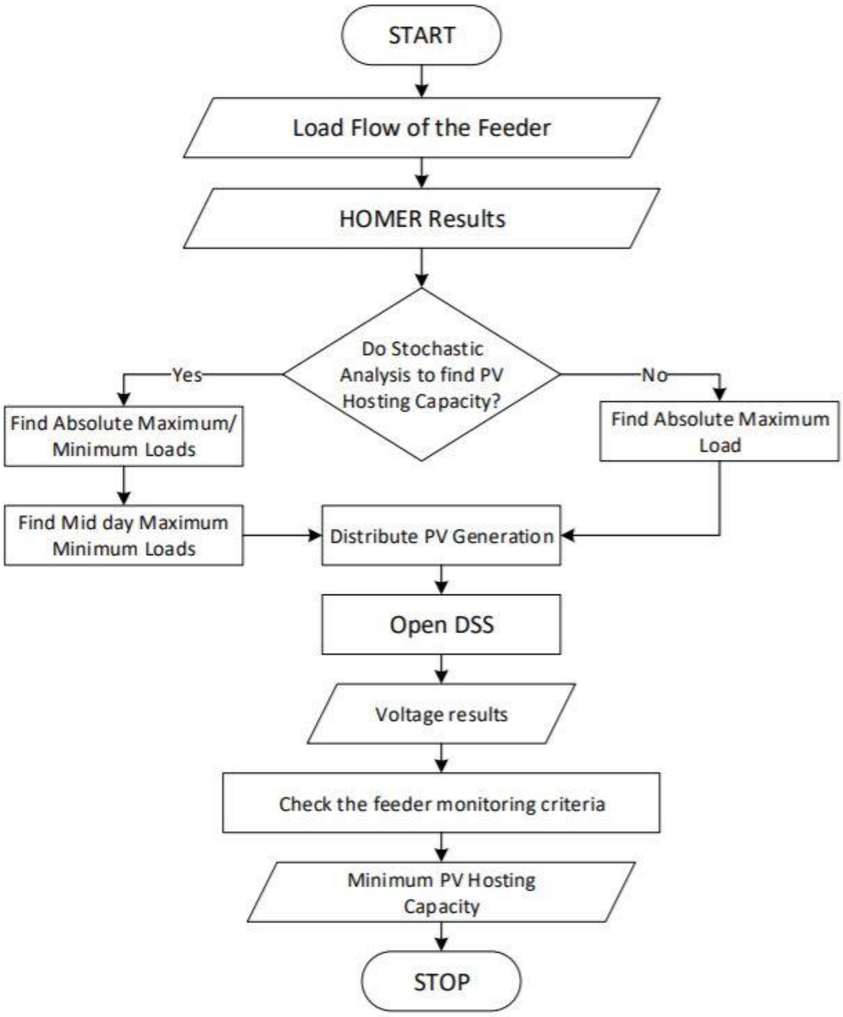


Figure 4.25: Overall process to find the PV hosting capacity

For this, HOMER outcome and modelled distribution feeder are taken as inputs. Then, there are two kinds of analysis which can be performed; (1) To find the PV hosting capacity for a given load (here absolute maximum load is considered) (2) To conduct a stochastic analysis to find the PV hosting capacity by considering various load levels. The main difference between these two analyses is the reliability of the PV hosting capacity limit. If the analysis is performed by considering absolute load levels, the PV hosting capacity limit is found for the worst-case scenario and if it is performed by considering midday values, the PV hosting capacity limit is found for a more realistic scenario.

CHAPTER 5

5. DISCUSSION

High penetration of renewable energy could lead to minimizing the greenhouse gas emissions and petroleum dependency of a country. To achieve this, a suitable renewable energy integration model is required. Hybrid renewable energy system is an integrated model of renewable energy generation and the load. Therefore, this model will depend on the renewable energy resource availability of a concerned geographical area and its local demand. Also, this model varies with the application. As discussed in chapter 2, renewable integration can be done to a microgrid or to a distributed generation system like a feeder. The model also affects by the connection of the grid, whether it is a grid connected system or an islanded system. As most of the literature discussed in chapter 2 relates to islanded microgrids used for the rural electrification, the core concepts were acquired while designing a model to the distribution feeder mentioned in chapter 3. The model used solar energy as the only renewable energy resource and the loading of the feeder was taken as the load profile. Then the components; PV, inverter, grid and battery cost details were suggested to be taken as the other inputs. After identifying the model to be used, the software platforms to conduct an economic analysis and technical analysis were revised in chapter 2. HOMER software for the economic analysis and OpenDSS for the technical analysis were chosen due to their exceptional performance in the previously conducted researches in this caliber.

In chapter 3, an economic analysis was conducted for the proposed model by chapter 2. An assumption-based load profile set for a year was generated using MATLAB. Then, the PV capacity was varied to a maximum of 85kW, which is the peak demand of the feeder. Since HOMER choose a cost optimized configuration, it always looks for the lowest net present cost. Therefore, HOMER includes the maximum given capacity of PV due to its low cost in overall operation. The considered distribution feeder was simulated for two operation modes; grid connected and grid only configuration. It was observed that, grid connected PVIES has an acceptable economic and environmental feature. Optimum PVIES is the PV-Grid configuration with a PV capacity of 85kW, grid and no battery. COE is reduced by 19% and NPC is reduced by nearly a $116,000 with compared to grid only mode. After the analysis of uncertainties in the design, it was found that, total NPC is sensitive most to the load demand. Solar generation and time-based grid power price have found as the second most sensitivities, which shows an anti-correlated relationship with each other. Also, in the view of environmental aspects, optimal PV-Grid system was shown to be the best solution because, it shows nearly 50% reduction of GHG emissions. To summarize the work in chapter 3, a HOMER based generalized process for designing a PVIES was presented while describing the application of the required parameters in the software using a case study. The presented process could be highly beneficial for new users of HOMER who works on PVIES (or HRES) designing.

The technical analysis for the distribution feeder was conducted in chapter 4 with the output from HOMER software in chapter 3. OpenDSS software, which is a challenging software involves lots of coding, was studied from the scratch. Then, the chosen distribution feeder (AZ0205) was modelled to penetrate small scale PV as rooftop solar systems to the feeder. PV integration was done for the HOMER chosen system (85kW) and found that the HOMER chosen values are not technically viable. Here, over voltage analysis and voltage deviation analysis were performed. It was observed that, voltage deviation has more effect on feeder voltage than the over voltage condition. After that, a steady state stochastic analysis was performed to find the minimum PV hosting capacity limit, which was found as 39kW. Finally, an analysis was performed to get the PV hosting capacity based on feeder section. It is observed that, more PV can be penetrated to the feeder, if it is distributed on the front section of the feeder (Closer to distribution transformer). Because higher the distance from source means higher the line resistance. Therefore, higher voltage deviation due to PV addition, thus lower PV hosting capacity. At the end of technical analysis, overall process was generalized and presented to obtain the PV hosting capacity of a given feeder.

CHAPTER 6

6. CONCLUSION

6.1 Achievement of objectives and research outcome

The main objective of this research was, "To encourage penetration of solar rooftops in Sri Lanka by proposing a sustainable approach while maintain an economic and technical sustainability". Then, this was sub categorized into three as, (1) To select a renewable energy integration model by studying, how the integration of renewable energy into an electrical grid has been done in literature. (2) To perform an economic analysis, to find the economic viability of the model. (3) To perform a technical analysis, to find the technical viability of the model. The methodologies to achieve those objectives were proposed in chapter 2, chapter 3 and chapter 4.

Research outcomes can be pointed out as follows.

- Location and load demand are dominant factors. Therefore, it is necessary to choose the location correctly and calculate the load demand perfectly. Likewise, other system components' size and cost details should be acquired correctly. The outcome is illustrated by Figure 3.1, Figure 3.2 and Figure 3.4.
- Next step is to conduct an economic analysis, to observe how the selected model gives profits in future years. Because at the end, all that matters is the impact on the economy. However, in this step, environment impact also considered. The outcome is illustrated by Figure 3.7.
- Final step is to analyze whether the above model is technically viable. The impact from small scale PV penetration is analyzed in this approach. Furthermore, PV hosting capacity is also calculated to ensure a safe renewable integration. The outcome is illustrated by Figure 4.2 and Figure 4.25.

6.2 Limitations

This research focus on proposing a sustainable approach to integrate renewable energy to Sri Lankan electrical distribution network. Therefore, this approach cannot be applied to transmission network or in other words to the whole Sri Lankan grid directly. This approach only considers about the feeder based renewable integration. If this approach is to be used in transmission network, it is suggested to consider flexibility of the grid first [33].

Another limitation of this research is the PV sizing in HOMER. Since PV cost always low compared to the other sources and the excess PV generation brings an income to the system via grid sales, HOMER always selects the system configuration including the maximum given PV capacity. Therefore, PV capacity always limited to the peak demand of the feeder.

Other than that, the data unavailability of the overall distribution network has limited the application of this approach on one feeder, since OpenDSS requires full details about the included distribution lines, transformers and loads.

6.3 Future work

Future work relates to this study will mostly about PV hosting capacity. In this research PV hosting capacity limit was calculated without conducting any operational or locational flexibility study. Therefore, if a flexibility analysis which accounts the generation and transmission constraints of the overall system was performed before finding the PV hosting capacity, the results may be more accurate.

Also, this research has only found the minimum hosting capacity limit of the distribution feeder. As a further analysis, this research could be continued for finding the maximum PV hosting capacity limit.

Furthermore, the proposed methodology could be applied on feeders of different areas with contrasting geographical and social conditions, and the variation in the results could be analyzed.

Reference List

[1] W. Fernando, N. Gupta, and C. S. Özveren, “The electricity infrastructure in Sri Lanka then, now and hereafter,” in *2017 52nd International Universities Power Engineering Conference (UPEC)*, Aug. 2017, pp. 1–6, doi: 10.1109/UPEC.2017.8231986.

[2] A. Bandara, K. Hemapala, and N. C. Ekanayake, “A Survey on Hybrid Renewable Energy Systems for Microgrid Application,” in *2020 IEEE 9th Power India International Conference (PIICON)*, Feb. 2020, pp. 1–6, doi: 10.1109/PIICON49524.2020.9113033.

[3] I. A. Nassar and M. M. Abdella, “Impact of replacing thermal power plants by renewable energy on the power system,” *Therm. Sci. Eng. Prog.*, vol. 5, pp. 506–515, Mar. 2018, doi: 10.1016/j.tsep.2018.02.002.

[4] M. H. T. T. Thilekha *et al.*, “Impact of Large-Scale Wind and Solar Power Integration on Operating Reserve Requirements of an Islanded Power System,” in *2018 Moratuwa Engineering Research Conference (MERCon)*, May 2018, pp. 589–594, doi: 10.1109/MERCon.2018.8421919.

[5] A. A. C. Priyangika, W. D. A. S. Wijayapala, and H. M. W. Banda, “The impact of distributed generation on transmission and distribution losses in Sri Lankan power system,” in *2016 Electrical Engineering Conference (EECon)*, Dec. 2016, pp. 54–58, doi: 10.1109/EECon.2016.7830935.

[6] A. Etxeberria, I. Vechiu, H. Camblong, J. M. Vinassa, and H. Camblong, “Hybrid Energy Storage Systems for renewable Energy Sources Integration in microgrids: A review,” in *2010 Conference Proceedings IPEC*, Oct. 2010, pp. 532–537, doi: 10.1109/IPECON.2010.5697053.

[7] N. Rajaković and I. B. Bjelić, “Planning of the optimal energy mix for smart cities,” in *2017 IEEE Manchester PowerTech*, Jun. 2017, pp. 1–6, doi: 10.1109/PTC.2017.7981182.

[8] K. E. Adetunji, O. A. Akinlabi, and M. K. Joseph, “Developing a Microgrid for Tafelkop Using HOMER,” in *2018 International Conference on Advances in*

Big Data, Computing and Data Communication Systems (icABCD), Aug. 2018, pp. 1–6, doi: 10.1109/ICABCD.2018.8465442.

[9] N. B. Ahamad, M. Othman, J. C. Vasquez, J. M. Guerrero, and C. Su, “Optimal sizing and performance evaluation of a renewable energy based microgrid in future seaports,” in *2018 IEEE International Conference on Industrial Technology (ICIT)*, Feb. 2018, pp. 1043–1048, doi: 10.1109/ICIT.2018.8352322.

[10] H. Sharma and G. Kaur, “Optimization and simulation of smart grid distributed generation: A case study of university campus,” in *2016 IEEE Smart Energy Grid Engineering (SEGE)*, Aug. 2016, pp. 153–157, doi: 10.1109/SEGE.2016.7589517.

[11] O. D. T. Odou, R. Bhandari, and R. Adamou, “Hybrid off-grid renewable power system for sustainable rural electrification in Benin,” *Renew. Energy*, vol. 145, pp. 1266–1279, Jan. 2020, doi: 10.1016/j.renene.2019.06.032.

[12] S. Dutta, A. Qian, A. Adhikari, W. Yue, Z. Yufan, and L. Zhaoyu, “Modelling and Cost Optimization of an Islanded Microgrid with an Existing Microhydro using HOMER Software,” in *2019 2nd Asia Conference on Energy and Environment Engineering (ACEEE)*, Jun. 2019, pp. 74–78, doi: 10.1109/ACEEE.2019.8816972.

[13] A. A. Simaremare, H. B. Tambunan, P. A. A. Pramana, and B. S. Munir, “Optimization of Renewable Energy Penetration for Microgrid System – Case Study of Tomia Island,” in *2018 3rd International Conference on Information Technology, Information System and Electrical Engineering (ICITISEE)*, Nov. 2018, pp. 180–183, doi: 10.1109/ICITISEE.2018.8720965.

[14] O. M. Babatunde, M. U. Emezirinwune, H. Denwigwel, and J. T. Akin-Adeniyi, “Hybrid power system for off-grid communities: Techno-economic and energy mix analysis,” in *2017 IEEE 3rd International Conference on Electro-Technology for National Development (NIGERCON)*, Nov. 2017, pp. 946–952, doi: 10.1109/NIGERCON.2017.8281960.

[15] A. Chatterjee and R. Rayudu, “Techno-economic analysis of hybrid renewable energy system for rural electrification in India,” in *2017 IEEE Innovative Smart*

Grid Technologies - Asia (ISGT-Asia), Dec. 2017, pp. 1–5, doi: 10.1109/ISGT-Asia.2017.8378470.

[16] S. Sinha and S. S. Chandel, “Review of software tools for hybrid renewable energy systems,” *Renew. Sustain. Energy Rev.*, vol. 32, pp. 192–205, Apr. 2014, doi: 10.1016/j.rser.2014.01.035.

[17] J. Gautam, M. I. Ahmed, and P. Kumar, “Optimization and Comparative Analysis of Solar-Biomass Hybrid Power Generation System Using Homer,” in *2018 International Conference on Intelligent Circuits and Systems (ICICS)*, Apr. 2018, pp. 397–400, doi: 10.1109/ICICS.2018.00087.

[18] H. G. Svendsen, A. A. Shetaya, and K. Loudiyi, “Integration of renewable energy and the benefit of storage from a grid and market perspective - results from Morocco and Egypt case studies,” in *2016 International Renewable and Sustainable Energy Conference (IRSEC)*, Nov. 2016, pp. 1164–1168, doi: 10.1109/IRSEC.2016.7984007.

[19] P. Sharma, M. Kolhe, and A. Sharma, “Economic performance assessment of building integrated photovoltaic system with battery energy storage under grid constraints,” *Renew. Energy*, vol. 145, pp. 1901–1909, Jan. 2020, doi: 10.1016/j.renene.2019.07.099.

[20] F. Foroutan and S. M. M. Gazafrudi, “Techno-economic evaluation of a hybrid PV/wind system with grid/DG/Battery backups for an educational department in Tehran,” in *2019 27th Iranian Conference on Electrical Engineering (ICEE)*, Apr. 2019, pp. 2083–2089, doi: 10.1109/IranianCEE.2019.8786416.

[21] B. Dekeda and M. Adonis, “The Case for Integration of Renewables in Rail Freight Yards in South Africa,” in *2019 International Conference on the Domestic Use of Energy (DUE)*, Mar. 2019, pp. 156–162.

[22] H. Gözde and M. C. Taplamacioğlu, “Integration of renewable energy sources into turkey electric energy network general problems and solution proposals,” in *2018 5th International Conference on Electrical and Electronic Engineering (ICEEE)*, May 2018, pp. 289–292, doi: 10.1109/ICEEE2.2018.8391348.

[23] J. Bing, O. Bartholomy, and P. Krishnani, “Validation of solar PV power forecasting methods for high penetration grid integration,” in *2012 IEEE Power*

and Energy Society General Meeting, Jul. 2012, pp. 1–6, doi: 10.1109/PESGM.2012.6345562.

[24] M. Rylander, J. Smith, D. Lewis, and S. Steffel, "Voltage impacts from distributed photovoltaics on two distribution feeders," in *2013 IEEE Power Energy Society General Meeting*, Jul. 2013, pp. 1–5, doi: 10.1109/PESMG.2013.6672320.

[25] M. L. Kolhe, K. M. I. U. Ranaweera, and A. G. B. S. Gunawardana, "Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka," *Sustain. Energy Technol. Assess.*, vol. 11, pp. 53–64, Sep. 2015, doi: 10.1016/j.seta.2015.03.008.

[26] H. Jayawardhana, K. Hemapala, A. Bandara, and P. D. Silva, "Defining of Normalized Load Profile Curves for Domestic Customer Groups to Estimate Feeder Power Loss," in *2018 3rd International Conference on Information Technology Research (ICITR)*, Dec. 2018, pp. 1–6, doi: 10.1109/ICITR.2018.8736138.

[27] "HOMER - Hybrid Renewable and Distributed Generation System Design Software." https://www.homerenergy.com/ (accessed Oct. 30, 2020).

[28] A. Herath, S. Kodituwakku, D. Dasanayake, P. Binduhewa, J. Ekanayake, and K. Samarakoon, "Comparison of Optimization- and Rule-Based EMS for Domestic PV-Battery Installation with Time-Varying Local SoC Limits," *J. Electr. Comput. Eng.*, vol. 2019, p. 8162475, Feb. 2019, doi: 10.1155/2019/8162475.

[29] "Codes & Statements | PUCSL." https://www.pucsl.gov.lk/legal_documents_types/codes/ (accessed Oct. 30, 2020).

[30] A. Dubey, S. Santoso, and A. Maitra, "Understanding photovoltaic hosting capacity of distribution circuits," in *2015 IEEE Power Energy Society General Meeting*, Jul. 2015, pp. 1–5, doi: 10.1109/PESGM.2015.7286510.

[31] P. Chirapongsananurak and N. Hoonchareon, "Grid code for PV integration in distribution circuits considering overvoltage and voltage variation," in *TENCON 2017 - 2017 IEEE Region 10 Conference*, Nov. 2017, pp. 1936–1941, doi: 10.1109/TENCON.2017.8228175.

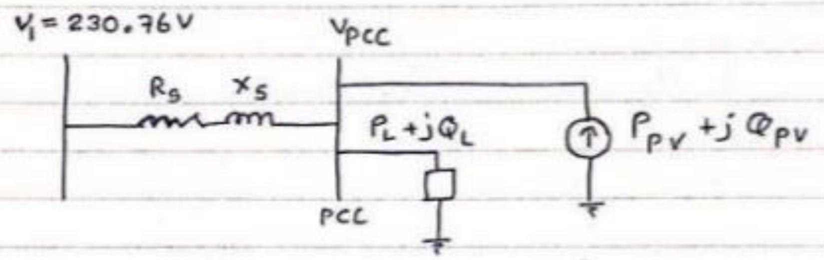
[32] J. W. Smith, R. Dugan, M. Rylander, and T. Key, “Advanced distribution planning tools for high penetration PV deployment,” in *2012 IEEE Power and Energy Society General Meeting*, Jul. 2012, pp. 1–7, doi: 10.1109/PESGM.2012.6345628.

[33] M. A. Bucher, S. Delikaraoglou, K. Heussen, P. Pinson, and G. Andersson, “On quantification of flexibility in power systems,” in *2015 IEEE Eindhoven PowerTech*, Jun. 2015, pp. 1–6, doi: 10.1109/PTC.2015.7232514.

Appendix A: Over voltage result verification

Voltage results varification

Loads connected to B11365 bus is selected.



Line parameters,

$$R_s = 0.058\ \Omega/kft \times 0.1kft = 0.0058\ \Omega$$

$$X_s = 0.12060\ \Omega/kft \times 0.1kft = 0.01206\ \Omega$$

Total load connected to the bus,

$$P_L = 0.534 + 0.295 + 0.047 = 0.876\ kW$$

$$pf = 0.85$$

$$\therefore\ Q_L = 0.542\ kvar$$

Total PV connected to the bus,

$$P_{PV} = 0.641 + 0.355 + 0.056 = 1.052\ kW$$

$$pf = 1$$

$$\therefore\ Q_{PV} = 0$$

Voltage at PCC can be derived as,

$$V_{pcc} \simeq V_1 + \frac{(P_{PV} - P_L)R_s}{V_{pcc}} + \frac{(Q_{PV} - Q_L)X_s}{V_{pcc}}$$

$$V_{pcc}^2 - V_1 . V_{pcc} - \left[(P_{PV} - P_L)R_s + (Q_{PV} - Q_L)X_s\right] = 0$$

$$V_{PCC} = \frac{V_1 \pm \sqrt{V_1^2 - 4[(P_{PV} - P_L)R_S + (Q_{PV} - Q_L)X_S]}}{2}$$

Calculation,

$$4[(P_{PV} - P_L)R_S + (Q_{PV} - Q_L)X_S]$$

$$= 4[1.0208 - 6.53652]$$

$$= -22.14608$$

$$\sqrt{V_1^2 - 4[(P_{PV} - P_L)R_S + (Q_{PV} - Q_L)X_S}$$

$$= \sqrt{230.76^2 - (-22.14608)}$$

$$= 230.807$$

$$\therefore V_{PCC} = \frac{230.76 + 230.807}{2}$$

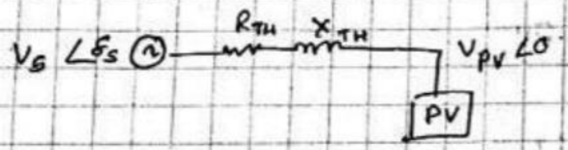
$$= 230.783 \text{ V}$$

Open DSS given $V_{PCC} = 230.74$ V

Appendix B: Voltage deviation result verification

Voltage deviation result verification

PVs connected to B11365 bus are selected.



$R_{TH} = 0.0058\ \Omega$

$P_{PV} = 0.876\ kW$

$V_{PV} = 230.74\ V$

$$\Delta V_{PV} \approx \frac{R_{TH} P_{PV} + X_{TH} Q_{PV}}{V_{PV}}$$

$$\simeq \frac{0.0058 \times 876}{230.74} \quad (Q_{PV} = 0)$$

$$= 2.2\%$$

OpenDSS given voltage deviation = 2.36%