Ph.D. Dissertation of Engineering

A Study on Suitable Grid Configuration of a Remote Rural Area Using Hybrid PV-Diesel-ESS System

태양광-디젤-ESS 하이브리드 시스템을 이용한 원거리 지방의 전력 계통 구성에 관한 연구

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Abstract

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It is undeniable fact that even though fossil fuels are likely more to fulfill the requirements of energy, the rare of natural resources and their harmful contents for the environment have directed people to search for new energy sources. Renewable resources of energy like hydropower, biomass, wind, solar and other types of clean energy are widely integrated into electric power systems around the world as they can decrease the environmental pollution effectively. However, only using the renewable energy systems cannot be reliable in itself without using the back-up system like engine generators or energy storage devices like batteries. Therefore, hybrid energy system that combines more than one renewable energy technology with back-up system may be obtained by combining various kinds of resources, using diesel-, biomass-, wind-, PV-, or small hydro-generators. Relying on the characteristics of a particular use (that is, willingness to pay and load profile), meteorological facts (wind speed, solar radiation, temperature, and hydro) and

the local provided options, the solution of least cost for a rural off-grid system may contain any combination mentioned above. The decision as to what types of hybrid system that should be utilized must be made on the basic of economic, social, environmental and safety considerations. Therefore, the intent of this dissertation is to show economical for investment in diesel stand-alone or PV-diesel or PV-diesel-ESS hybrid systems in the proposed area for making the investment decision. To reach this objective, the researcher has developed a techno-economic approach described by two models: the reliability model developed beneath the Total Energy Deficit (TED) concept based on the Loss of Power Supply Probability (LPSP) and the economic model based on the calculation of Total Net Present Cost (TNPC) and Cost of Energy (COE) by using Hybrid Optimization Model for Electric Renewable (HOMER) Tool. By combining these two models, it can be decided to the optimal configuration leading to the total system autonomy in the most cost effective manner. The sizing parameters have been used in the screation, i.e. the PV subsystem capacity. Regarding the diesel generator, it is measured to meet the peak electrical demand (due to to the suggested strategy). Applying the developed methodology, all configurations that rate 0% of TED are retained and at the same time, the optimal configuration is predicted on the basis of the less cost by TNPC concept. In addition, the developed model is used to calculate how much fuel is consumed by diesel generator and the amount of CO_2 that can emit. In order to highlight the suggested methodology, three different system configurations have been analyzed, which are diesel standalone, PV-diesel without BESS, and PV-diesel with BESS to supply the Kyit Sone Pwe village which is situated at 20.154N latitude and 94.945E longitude in Magway Township in Myanmar. The yearly average solar radiation of that area is 4.841kWh/m^2/day and it is very important to prepare a proper load data to meet the current situation of the target village. The load determination of that village is 1300 household numbers with average of five family members per household and so, the totally population numbers is around 6500. By calculating the total load demand, the peak demand of that proposed village is 563kW. For the first case, diesel standalone system, although it can meet the power demand, both the fuel cost and CO_2 emission level are too high to be economically feasible. In order to reduce the system operating cost, PV generation was added to the system, creating a PV-diesel hybrid system. However, due to the intermittent output of PV generator, the PV-diesel system was infeasible to maintain the system security for getting the optimal design. In order to address these issues, the system of battery energy shortage (BESS) was added to the PV-diesel hybrid system to store power during the times of excess generation and generate power during the time of power shortages. This system displays the most excellent characteristic by means of net present cost which involves capital cost, replacement cost, fuel cost, operation and maintenance cost that happen during the project lifespan, levelized energy cost, and operating cost. A simulation time step with one hour is provided in this research work, like in the first step, the system reliability model is improved in terms of the concept of LPSP. For this purpose, considering the different combinations of hybrid systems has made several simulations. The algorithm input data set contains hourly solar radiation on the horizontal flat surface, ambient temperature recorded at Magway for 2016, and the energy requirements expressed by the load throughout the year and specifications of the system devices. All of these three systems are simulated by running the developed computer program and the dealings among system configurations, the amount of excess electricity, the amount of CO_2 emitted and system costs are studied. The optimal configurations of the hybrid system are measured in terms of total system reliability (TED = 0%) and system costs. According to the simulation results,

the optimal values of TNPC, COE, and the amount of CO_2 emitted for the proposed PV/diesel/BESS hybrid system are obtained for configuration with $5,212,293 (TNPC), $0.367/kWh (COE) and 947,218 kg/yr, but these values for PV/Diesel systems are significantly increased with $7,984,073 (TNPC), $0.562/kWh (COE) and 1,585,267kg/yr. The fractions of energy production from PV array and generator of the proposed hybrid system are 44% and 56% to meet the demand. This is mainly due to strong solar potential in the Magway region. Therefore, the proposed hybrid system provides the lowest TNPC, COE and carbon emission among these three systems according to the evaluation results. In contrast, the analysis of evaluation results shows that the PV/diesel/battery choice is more economically possible compared to PV/diesel system or diesel generator only.

Keywords: Solar PV, Diesel generator, Hybrid system, HOMER software, BESS

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Chapter 1. Introduction

Although fossil fuels are continually being formed via natural processes for using to produce energy, its harmful impact on the environment such as global warming and rising sea levels, makes people to find new energy sources[1]. In order to conserve and create a sustainable atmosphere, renewable energy sources (RES) have been considered as an alternative energy source due to its environmental friendly attributes. The significant energy security, climate charge mitigation and economic benefits can be made to get by the main application of RES such as hydropower, biomass, and wind, solar and other clean energy types and to decrease the environmental pollution [2]. Furthermore, RES can provide power efficiently at remote areas where construction of generation and transmission system can be costly. However, the composition of power sources within a system has to be determined optimally not only to reduce the overall cost but also to operate the system reliably and stably.

The authors in [3] studied a multi-period mixed-integer linear program for planning and operation management of grid connected PV-battery systems. The program objective which considered the saving in energy cost (electricity bill) was to maximize the net present cost for investment analysis. In [4], Different parameters, namely load profile, have impact on geographical situation, PV/battery installation costs, electricity price, and weather condition on the economic analysis of grid connected PV/battery system, was presented for making the decision to select the right PV/battery system. The authors showed that the choosing of the right PV/battery system is obviously respnsive to these parameters by comparing three different locations. The prior studies have already chosen this PV/battery system for optimal sizing before they write the article, but have not focused on the selection of the optimal configuration before they make the optimal sizing. So, in this dissertation, three possible micro grid systems have been carefully researched to confirm significantly that which one is the most optimal configuration in cost minimization for a chosen rural area among these three configurations by using the actual load data. After that, the research has been continued to choose the optimal sizing of the selected micro grid configuration. Therefore, the main objective of this dissertation is finding of optimal configuration and sizing solution for proposed area.

The problem statement of this research is that the load center of non-electrified villages is located far away from the substation and the national grid. Therefore, these areas cannot access the electricity until now. Most of the people in these villages mainly depend on small petrol engine, batteries and some of people are using candle lamp for lighting, phone charger and other electricity appliances. The need of reasonable and reliable electricity is very much necessary to develop remote rural areas in developing countries [5]. In these regions, electric power is provided by various options. One is for extending the transmission network of existing system, and receiving power from a distant location. However this is not possible t practice because of high price transportation lines, their losses, and stability issue that may occur during long range power transmission [1]. Second is to use the standalone diesel generator to supply, but it is not reasonable due to its great amount of operating price, fuel transportation cost, short operational lifetime and intermittent support [6], and a distinct literature stands on the a lot of fuel-related obstacles of remote societies in the developing world [7]-[9]. Therefore, RE system can be a favorable solution due to its less installation, operation, and maintenance costs. According to the rural electrification organization, one of the most appropriate and environmentally friendly solution to supply electricity to those areas is RESs (Renewable energy

Sources). Out of many RESs, photovoltaic (PV) generation has been one of the most favorable options because of its fewer prices and efficiency measured in other renewable energy solutions [2].

However, a system cannot be solely composed of RES due to its inherent intermittent characteristics, which increases the uncertainty and variability of the power system. Therefore a hybrid system, combination of both renewable and conventional energy sources, has been a promising result for the electrification of remote regions. To get the benefits of above solution, combining in a hybrid system – a diesel generator with renewable energy sources is so often the most optimal option [10]. Specifically, a medium to large scale PV and diesel generator system has been observed for rural electrificated systems in many countries throughout the global [11],[12]. One of the main drawbacks of this system is that there must have at least two diesel generators to use one of them as a standby generator in case of possible outages or maintenances. Although there have been many demonstration projects showing its effectiveness and potential [13], a true market for such system has not yet emerged.

Generally, when a power system is designed, the capacity of the resources within the system should be large enough to maintain the reliability level, and at the same time be cost efficient. Modeling a renewable energy system is quite different from modeling a conventional system. The renewable energy penetration level in hybrid systems around the world is generally in the rate of 11-25% [14].

Therefore, the optimal size of the system components should be determined to guarantee economic feasibility and reliability of the system. The feasibility of a PV-diesel system is affected by some factors mentioned in the following [2]:

1. Solar radiation availability

2. Diesel price
3. PV panel and equipment cost
4. Operation and maintenance cost
5. Lifecycle of system components
6. Value of secondary load
7. Reliability of demand
8. Revenue from sales of electricity

In the past, hybrid power system had been applied to various sites including: (a) extremely remote site, (b) telecommunication site, (c) village power (rural electrification), and (d) environment protection project which will be stated details in Chapter II [15]**.** For an extremely remote site, the priority is on fuel saving, where the priority of telecommunication site has power quality. Furthermore, previous researches that are related to this topic usually evaluate the feasibility of a single micro grid [17]-[20]. As the survey went on the other research papers that have been recently done on this topic, they normally focused only on one system, but in this dissertation, three hybrid systems have been carefully researched to see obviously that the proposed hybrid system is the most optimal design for rural electrification among these three case studies [18]-[20].

A hybrid system composed with PV, diesel generator, and battery energy storage system (BESS) has been suggested to meet the demand reliably and cost efficiently at an islanded rural area [14]. The main objective when designing such system is to minimize reduce the system construction cost by supplying the power reliably. This problem has been solved by applying Hybrid Optimization Model for Electric Renewable (HOMER) software [21] and Microsoft Office Excel. HOMER is a resource capacity optimization program that can be applied to different grid environments, such as standalone or grid connected systems. An excellent ability that HOMER offers is the capability to observe the optimum configuration based on both estimation of cost and performance sensitivity analysis to help understand tradeoffs between disparate technologies and economic considerations. To get the best feasible solution, HOMER is based on three main functions: simulation, optimization and sensitivity analysis.

The simulation environment was constructed by modeling a small village called Kyit Sone Pwe in Myanmar. The demand of 1,300 households has been estimated by calculating the power consumption of a single village in the area. Furthermore, the climatic data for PV energy has been found through NASA's website [22] and the average solar radiation for the region is observed as 4.841kWh/m^2/day. The cost for each system component was obtained from different publications and websites.

Three different system configurations such as diesel standalone, PV-diesel without BESS, and PV-diesel with BESS have been analyzed. A lot of countries have presented a PV-diesel hybrid system with monthly average daily solar radiation, rating 3-6 kWh/m^2 in order to decrease their dependence on fuel consumption [23]-[26].

The organization of the dissertation is as follows. Chapter II reviews the literatures and hybrid system configuration. Photovoltaic-diesel-battery systems can be identified according to their configurations as follows [27]:

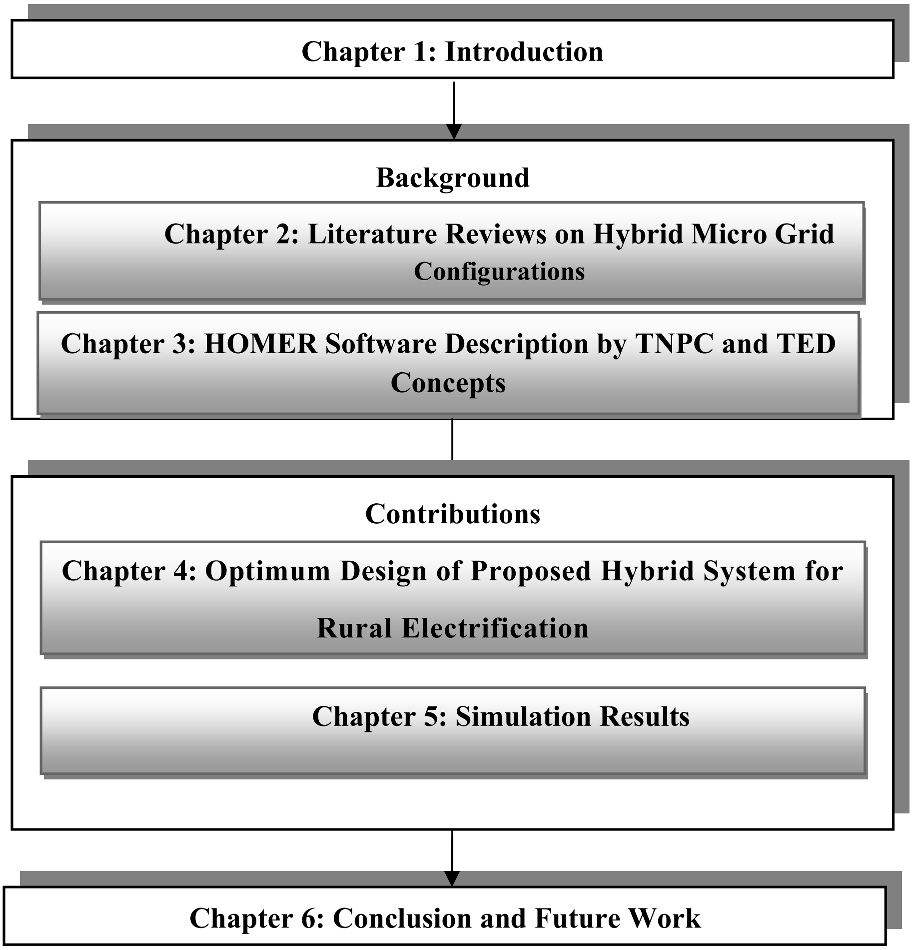
- series hybrid system,
- switched hybrid system, and
- parallel hybrid system. In this dissertation, parallel hybrid energy system will be selected.

Chapter III presents the application of HOMER (Hybrid Optimization Model for Electric Renewable) software with two criteria: economic criteria and reliability criteria. A hybrid system developed HOMER as a tool that is not only enough to predict system performance but also simple and efficient to evaluate numerous design options. Moreover, it ranks the results for getting the optimum configuration [21]. In the simulation system, the performance of singular micro power system configuration was designed by HOMER to decide its technical feasibility and life-cycle cost yearly. In this dissertation, it only highlights on the simulation and optimization tasks.

Chapter IV describes the components of proposed hybrid system. This chapter shows various components of a hybrid system and how they set up their interaction. It aims to inform to understand a hybrid system's complex component interaction. Both hybrid system design and the accuracy of its underlying component and operation features are good. In this chapter, definite characteristics of hybrid components and performances are mentioned, and its performances are discussed in this chapter.

Chapter V supplies the simulation results for the economic operation of stand-alone diesel generator system, PV-diesel hybrid system without BESS, and PV-diesel hybrid system with BESS. The test in a case study is performed to examine the economic operation with very high reliability by using HOMER software with Total Energy Deficit (TED) concept.

Finally, summary of discussions, conclusion and recommendation for further studies are included in chapter VI.


Chapter 1: Introduction
Background
Chapter 2: Literature Reviews on Hybrid Micro Grid Configurations
Chapter 3: HOMER Software Description by TNPC and TED Concepts
Contributions
Chapter 4: Optimum Design of Proposed Hybrid System for Rural Electrification
Chapter 5: Simulation Results
Chapter 6: Conclusion and Future Work

Chapter 2. Literature Reviews on Hybrid Micro Grid Configurations

2.1 Hybrid Power Systems

In order to develop remote rural areas in developing countries, there is a great need of reasonable and reliable electricity [3]. According to the rural electrification organization, one of the most environmentally appropriate solutions to supply electricity to those areas is RESs (Renewable energy Sources). There has been a proof that autonomous redistributed rural electrification based on renewable energy sources is capable of distributing high quality and reliable electricity for irrigation systems, lighting, water supply, communication, etc. by installing stand-alone power system in houses and setting up electricity distribution mini-grids in rural areas [18],[24]. So, there are many benefits of using hybrid power systems over common sources by the improvement in reliability and reduction in the overall size of the power system [28].

2.2 Power Supply Options for Rural Areas

The three power supply options for rural areas are

i. central power plant supply;
ii. fossil fuel-fired supply; and
iii. renewable energy supply.

In figure 2.1 [2], [29], it can clearly see the drawbacks of each power supply options. In the centralized power supplies, there are advantages of economic of scale that reduces the marginal energy costs and the long-run average costs of electricity production. However, they need to contend via long transmission networks for delivering the power [30]. One possible solution to remove the disadvantages of diesel and renewable energy technologies is to make use of combining these two types of technologies with the objectives of utilizing these operating characteristics of costs minimization and availability maximization. Therefore, small scale off-grid hybrid systems make the offer an attractive option to reduce the lower electricity gap in isolated areas of the developed and developing countries in which improving in grid extension is slower than the population growth [31],[32].

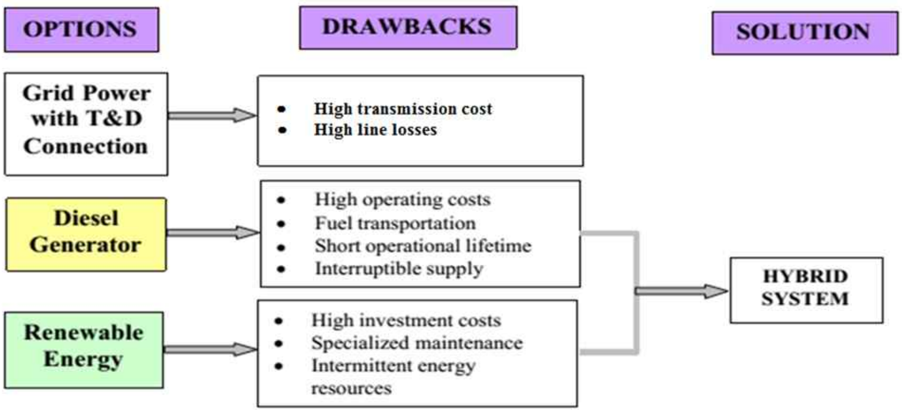
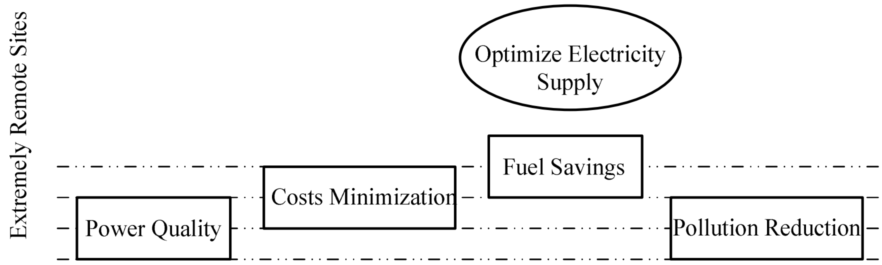


Figure 2.1 Power supply options for rural area [2]

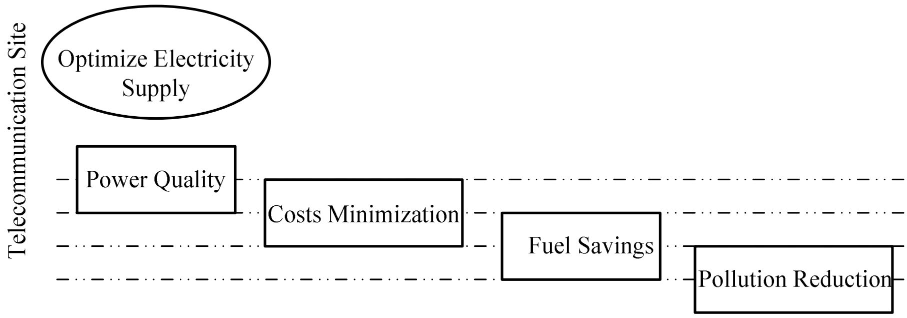
2.3 Goals for Optimal Electricity Supply

The high-level target "Optimize electricity supply" is expressed by a combination of various sub-goals, and the importance of each sub-goal also depends on the application used. The essential sub-goal reaches the higher-level position and raises other goals having a link with it. Figure 2.2(a) presents extremely remote sites in which the high priority situation is fuel saving. Figure 2.2 (b) shows telecommunication sites, where the top priority case is power quality. Village power (rural electrification) is described in figure 2.2(c), and at this stage, the first essential case is to minimize the costs.

For environment protection project shown in figure 2.2(d), the top priority situation is pollution reduction.



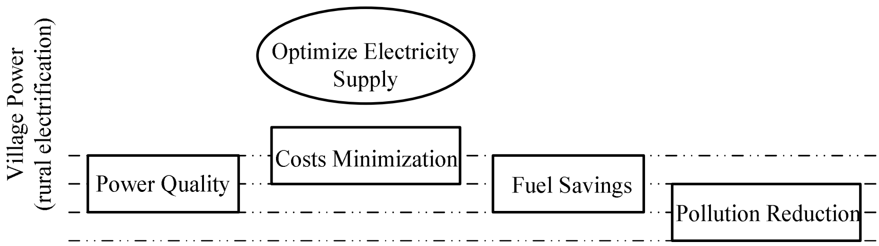
(a) Extremely remote sites



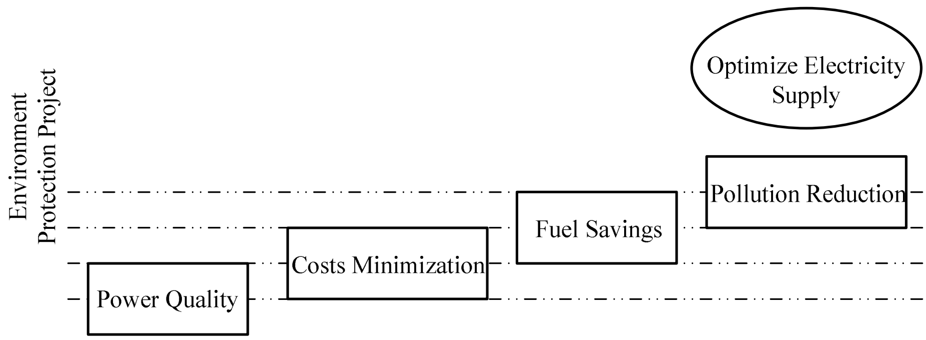
(b) Telecommunication sites

Four different applications are represented as (a) extremely remote sites, (b) telecommunication sites, (c) village power, and (d) environment protection project which are shown by various goals in the highest level of abstraction in Figure 2.2.

To achieve the goal "Power Quality", the system operation must make sure that a disturbed supply meets at least the requirements of minimum power quality for the application. The goal of "Fuel Savings" is to run systems that can bear lower quality electricity supply but this system minimizes fuel consumption. In general, the cost of fuel and conventional electricity generation is lower than the costs associated with loss of load and/or poor quality electricity, so the fuel saving goal can be considered in any case.



(c) Village power (Rural electrification)



(d) Environment protection project

Figure 2.2 Four different applications [33]

"Costs Minimization" associates with the economics of a Hybrid Power System (HPS) application. The electricity generation cost counts on the combination of factors such as type of generators, efficiency, fuel type and cost, maintenance and so on. In some applications, in order to keep overall costs within the specified limits, even a partial shutdown may be acceptable. "Pollution Reduction" is a goal which is designed to minimize pollution and noise levels. In this situation, avoiding conventional power generation is more important than the cost of electricity generation and power quality requirements.

Each of these goals can be further examined by means of the whole-parts decomposition [33]. The goal of “Power Quality” can be disintegrated into two sub goals: frequency control and voltage control. The goal “Fuel Savings” can be classified into sub-goals: intermittent diesel operation, high renewable energy penetration, and efficient diesel operation. The sub-goals of “Costs Minimization” are to keep the costs of electricity generation, maintenance, and efficient electricity supply to an absolute minimum. And the goal “Pollution Reduction” can be subdivided into minimum conventional power generation and renewable energy optimization.

In this dissertation, the proposed hybrid system has been applied for village power supply (Rural Electrification). So, in rural electrification, the first priority situation is minimization of costs and then second priorities are power quality and fuel saving. For system economic concerns, preventing the choosing of under-sizing of the system can minimize the system costs as well as preventing the choosing of over-sizing of the system can improve the system reliability in power quality concerns.

2.4 Different Types of Hybrid Micro Grid Systems

To build a hybrid system, the different alternative energy sources and storage devices can be combined into many ways. The lists shown in the following are some of the stand-alone or grid-connected hybrid systems that are used at the present time [29], [34].

i. Wind/PV/Fuel Cell(FC)/Electrolyze/Battery system,
ii. Micro-turbine/FC system,
iii. Micro turbine/Wind system,
iv. Gas-turbine/FC system,

v. Diesel/FC system,
vi. PV/Battery
vii. PV/FC/Electrolyze,
viii. PV/FC/Electrolyze/Battery system,
ix. FC/Battery, or Super-capacitor system,
x. Wind/FC system,
xi. Wind/Diesel system,
xii. Wind/PV/Battery system,
xiii. PV/Diesel system,
xiv. PV/Wind/Diesel system and
xv. PV/FC/Super-conducting Magnetic Energy Storage system

2.5 Benefits of Hybrid System

The major benefits or advantages of a hybrid system can be stated as [28], [33]-[35]:

i. The possibility of combination of two or more renewable energy sources is based on the natural local potential of the users.
ii. Environmental issue can be protected especially by the reduction of CO2.
iii. Both wind energy and solar energy, which have low price, can be competitive with nuclear, coal and gas especially considering possible future cost trends for fossil and nuclear energy.
iv. Diversity and security of supply
v. Rapid deployment - modular and quick to install
vi. There is abundant free and inexhaustible fuel.
vii. Costs are predictable and not influenced by fuel price fluctuations although fluctuations in the price of batteries have an influence where these are incorporated.

2.6 PV-diesel-ESS Hybrid Systems

A diesel generator is used with PV or wind by most hybrids because diesel supplies more predictable power on demand. In addition to the diesel generator, a battery is also used in some hybrids. The battery meets with the daily load fluctuation, and the diesel generator takes great care of the long-term fluctuations. For example, the diesel generator is applied in the worst-case weather condition, like an extended period of overcast skies or when there is no wind for many weeks. A diesel generator in a renewable hybrid system often moves out the requirement to build in system autonomy and adds to the system reliability. Moreover, the design capacity of hybrid component can often be minimized as compared to their required sizing in single source systems [34].

Photovoltaic-diesel-battery hybrid energy systems generate AC electricity by combining a photovoltaic array with an inverter, which can operate alternately or in parallel with a conventional engine driven generator.

They can be categorized according to their configuration as follows [28].

i. Series hybrid system
ii. Switched hybrid system
iii. Parallel hybrid system

2.6.1 Series Configuration

Figure 2.3 illustrate a series PV- diesel hybrid energy system. In order to make sure the reliability of hybrid energy systems, both the diesel generator and the inverter are put to be sized to meet peak loads. A typical system operation in which a large fraction of the generated energy is passed through the battery bank results from this process. It is found that there is an increase in cycling of the battery bank and reduced system efficiency. An inverter or motor generator unit converts AC power which sent to the load from DC to regulated AC. The power which is generated by the diesel generator is first amended and subsequently converted back to AC before it is distributed to the load, which leads to considerable conversion losses. The amount of electrical power sent by the photovoltaic array, the battery bank, or the diesel generator can be measured by the actual load demand. The solar controller prevents overcharging of the battery bank from the PV generator when the PV power exceeds the load demand and the batteries are fully charged. Although gaining the energy is marginal for a well sized system, it may contain the highest power point tracking to improve the exploitation of the available photovoltaic energy. The system can be carried out in manual or automatic mode, by combining appropriate battery voltage sensing and start or stop control of the engine-driven generator.

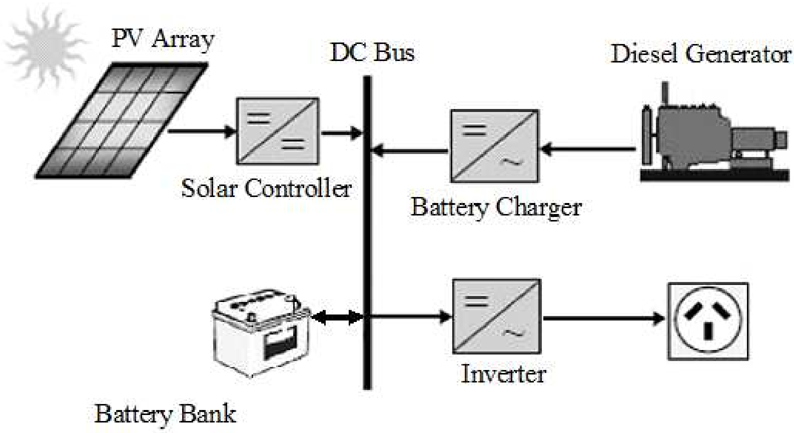


Figure 2.3 Series PV-diesel hybrid energy system [36]

The advantages of such a system are as follow [28], [36]:

i. The engine-driven generator can be sized to be optimally loaded while providing the load and charging the battery bank, until a battery state-of-charge (SOC) is reached up to 70 t0 80%.
ii. No switching of AC power between the different energy sources is needed which simplifies the electrical output interface.

iii. The power provided to the load is not interfered when the diesel generator is started.
iv. The inverter can generate a sine-wave, modified square wave, or square wave, depending on the applications.

The disadvantages of such a system are as follow:

i. The inverter cannot run in parallel with the engine driven generator; therefore, the inverter must be sized to provide the peak load of the system.
ii. The cycling profile needs a large battery bank to limit the depth-of-discharge.
iii. The overall system efficiency is low since the diesel cannot provide power directly to the load.
iv. Inverter failure will result in complete loss of power to the load, unless the load can be provided directly from the diesel generator for emergency purposes.

2.6.2 Switched Configuration

Although the switched configuration of PV-diesel hybrid energy system has operational limitations as shown in figure 2.4, it is one of the most popular installations today. In this system, the operation is carried out either by the engine driven generator or by the inverter as the AC sources, but any parallel operation of the main generation sources is not allowed. The battery bank can be charged form not only the diesel generator but also the renewable energy sources. Compared to the series system, the main benefit of this system is that the engine driven generator can feed the load directly, which results in a higher overall conversion efficiency. Generally, the power in the diesel generator will overstep the load demand, with excess energy which is used to recharge the battery bank. When the electricity demand is low, the diesel generator is turned off and the load is fed from the PV array together with stored energy [36].

Switched PV-diesel hybrid energy systems can be operated in manual mode, although its increased complexity system makes a highly desirable automatic controller include. This automatic controller can be performed with the addition of suitable battery voltage sensing and start/stop control of the engine-driven generator.

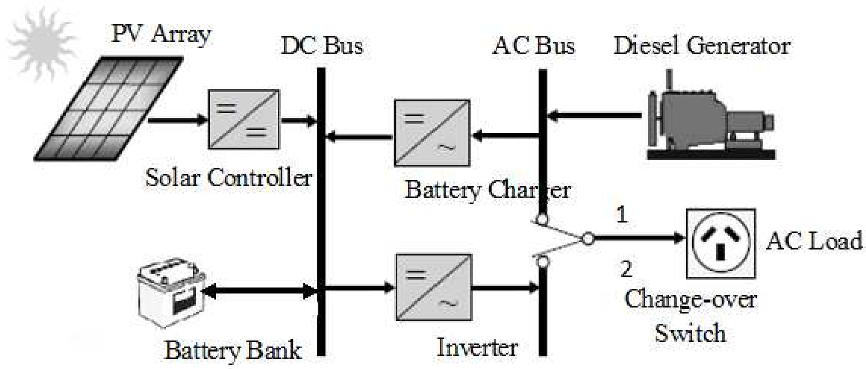


Figure 2.4 Switched PV-diesel hybrid energy system [36]

The advantages of this system are shown as the following [28], [36]:

i. A sine-wave, modified square wave, or square wave can be generated by the inverter depending on the specific application.

ii. The load can be directly provided by the diesel generator, increasing the system efficiency and cutting the fuel consumption.

The disadvantages of this system are as the following:

i. When the AC power sources are transferred, power to the load is briefly disturbed.

ii. Alternator and inverter run by engine are typically designed to supply the peak load, which reduces their efficiency at part-load operation.

2.6.3 Parallel Configuration

In figure 2.5, all energy sources to feed the load separately at low or medium load demand, as well as at peak loads from combined sources by synchronizing the inverter with the alternator output waveform are permitted by the parallel configuration. When overflow energy is obtainable from the engine-driven generator, as well as act as a DC-AC converter (inverter operation, the battery bank, (rectifier operation) can be charged by the bidirectional inverter. Besides, the bidirectional inverter may provide "peak shaving" as part of the control strategy when the engine-driven generator is overloaded [36].

Two notable improvements over the series and switched system configurations distinguish the parallel hybrid energy systems.

i. The maximum load that can be supplied is limited by the inverter plus the diesel generator capacity rather than their individual component rating. Typically, this will lead to the system double. The capability to synchronize the inverter with the diesel generator permits greater adaptability to modify the operation of the system. Future systems should be sized with a reduced peak capacity of the diesel generator, which makes the effect in a higher-level component of directly used energy.
ii. A number of system components can be reached minimum by operating the same power electronic devices not only for an inverter operation but also for a rectifier operation. Moreover, through the incorporation of all power conditioning devices in one central unit, the prices of wiring and system installation can be reduced. This highly integrated system concept has benefits through a more standard approach to system design, but when the load demand expands, it may prevent the appropriate system improvements. A number of potential advantages

over other system configurations are provided by the parallel configuration. If the interactive operation of the individual components is controlled by an intelligent hybrid energy management system, the potential advantages can only be met.

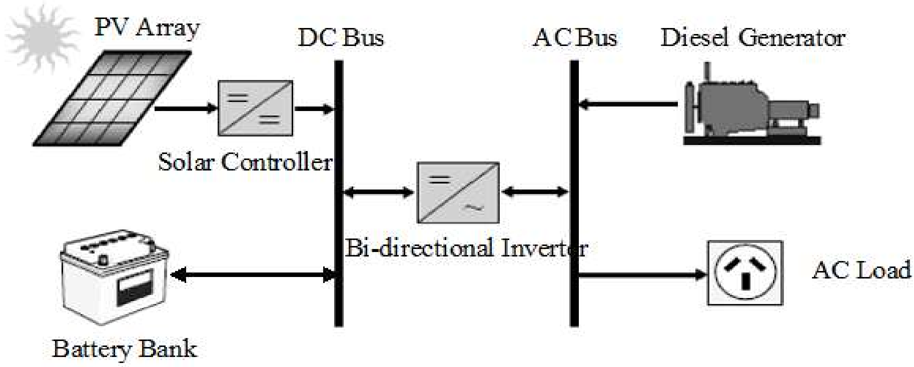


Figure 2.5 Parallel PV- diesel hybrid energy system [36]

Although the production of parallel systems used today contains system controllers of varying complexity and sophistication, they do not modify the performance of the entire system. Generally, not only the diesel generator but also the inverter is sized to provide anticipated peak loads. It is found that most parallel hybrid energy systems do not use their capacity of parallel, synchronized operation of multiple power sources. The advantages of this system are shown in the following [28], [36].

i. The load system can be found in the optimum way.
ii. The efficiency of diesel generator can be increased.
iii. The sustentation of diesel generator can be decreased.
iv. A decrease in the rated capacities of the diesel generator, battery bank, inverter, and renewable energy resources is possible.

The followings are the disadvantages of this system.

i. For a dependable operation of the system, the automatic control is essential.

ii. The inverter has to be a true sine-wave inverter with the ability to synchronize with a secondary AC source.

2.7 Solar Potential in Myanmar

Myanmar is located in the south eastern part of the Asia continent. It has abundance sun shine the whole year, especially in the Central Areas or Dry Zone Areas of the country. The available solar potential of Myanmar is approximately 51973.8TWh per year [Figure 2.6].

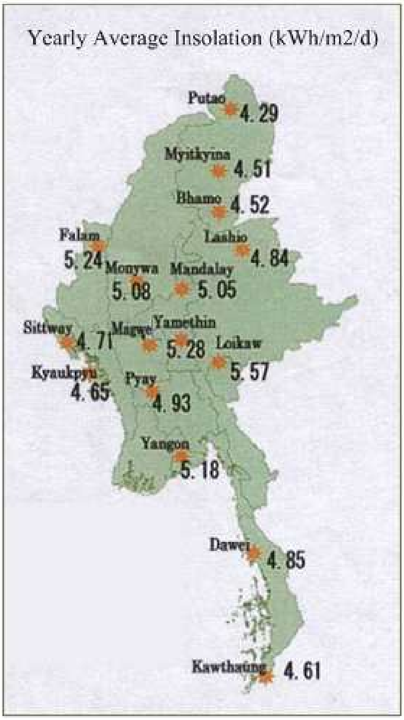


Figure 2.6Yearly average isolation in Myanmar [38]

The experimental measurement of Myanmar Electric Power Enterprise indicated that during droughty seasons [37], the observation of irradiation intensity is more than 5kWh/m^2/ per day. Solar power is found to be a most potential one to hybrid with wind power in Myanmar [38].

2.8 System Operation

The designed system is undertaken to run cycle charging dispatch strategies [40]. It means that the battery bank will be charged by PV array and generator. A generator will likely be required to serve the primary load and produce overflow electricity to charge the battery bank. So when the system begins to charge the battery bank, it continues to do so until it reaches the set point state of charge. If the set point state of charge is generated to the cycle charging strategy, then when the battery state of charge is below the set point and the battery is not discharging in the previous hour, the system should avoid discharging the battery during this hour. The hybrid PV/ diesel configuration system is as figured in Figure 2.8. The PV was used as the base load supply which produced DC power. It was then converted into AC source by using an inverter. Since the PV will charge the battery bank, this take places when there is extra power after meeting the demand of the end user load. If the PV cannot meet the demand, the battery bank will not be charged, but being discharged to cater for the demand. Generator will run if both PV and battery bank cannot meet the demand. During the day, the PV and Generator will run. At night, Generator only will operate. The operating reserve as a percentage of hourly load was 10% meaning that the system must keep enough spare capacity running to serve a sudden 10% increase in the load. Meanwhile, the operating reserve as a percentage of solar power output was 25%. The operating reserve is the safety margin that helps to make sure reliability of the supply in spite of variability in electric load and the solar power supply. As an example, if the load at an hour is 50 kW and the PV output is 30 kW, it means that the operating reserve would be 5 kW + 7.5 kW= 12.5 kW. The diesel generator must therefore supply 20 kW of electricity plus 12.5 kW of operating reserve. So, it can be said that the capacity of the operating generator must be at least 32.5 k.

Chapter 3. Homer Software Description by Total Net Present Cost (TNPC) and Total Energy Deficit (TED) Concepts

3.1 Homer

HOMER, a hybrid system model, was improved at the National Renewable Energy Laboratory NREL in 1993 for both on-grid and off-grid systems. An excellent ability HOMER offered is the capability to find the optimum configuration which is based on the estimation of price as well as performance sensitivity analysis to help understanding tradeoffs between disparate technologies and economic considerations. To get the best feasible solution, HOMER is based on three major tasks: simulation, optimization and sensitivity analysis.

In the simulation process, HOMER forms an exact system configuration by carrying out an hourly time series simulation of its running over one year, deciding the system technical possibility and life-cycle cost. The analysis of the excess renewable energy is made on an hourly basis, comparing the available renewable energy formerly worked out the electric load. HOMER then determines what to do with the surplus energy, changing the system configuration so that little or zero renewable excess exists. After completing one year calculation, HOMER decides whether the system configuration fulfils the restrictions forced by the modeller. If the system is viable, the software makes an estimate of the life-cycle cost taking into consideration of yearly fuel consumption, generator running hours and anticipated battery life. To symbolize the life-cycle cost of a specific system, HOMER uses the total net present cost (NPC) as the measurement. The NPC involves investment costs, operation, the costs of upkeep and substitution that happen during the project lifespan, always reducing future cash flow to the present.

After the simulation process has been carried out to search for viable system configuration, the optimization process decides the best feasible system configuration within the simulation solutions. The best feasible or optimum solutions are the simulation results that meet users' identified restrictions at the lowest possible NPC. To all possible solutions, a level is determined according to the NPC and the one with the lowest NPC is deemed as the optimum system configuration. For a sensitivity analysis, when changes took place in the inputs, the aim of software is to disclose how the outputs of the problem will alter. The HOMER user is capable of entering a variety of values for reactivity variables like the fuel price, the lifespan of a PV array or wind turbine, the grid power price. Its permissible change is also the magnitude of an hourly data set, such as load in renewable energy sources. All this sensitivity analysis is optimized, once again, in order to know the system conduct and permit the user to handle uncertainties to make better designed decision for a better long term. System constituents modeling with HOMER are pretty simple and presume many simplifications. This will not be specified at this point due to its extensiveness but can be better looked in.

The most complicated part of HOMER’s logic system is found in the control dispatch strategies – the so-called energy flow management. In a simplistic way, the modeler has to insert first a margin of power supply (operation reserve) to make sure that system is reliable. In each hour of the simulation year, HOMER works out the renewable source power outputs and decides whether they are able to distribute the electric load plus the pre-defined operation reserve. If not, HOMER decides the best way (minimized cost) to transmit the dispatchable system constituents such as generators, battery bank, grid, so as to offer warranty for the power demand. The dispatchable energy sources are embodied by a set cost in dollars and a marginal cost of energy in dollars per kilowatt hour. Using this constituents transmitter cost, HOMER looks for possible ways to mix all system constituents in such mode that the needed energy can be fulfilled. Of all the dominant solutions discovered, the optimum solution is the one which can provide the load at the lowest cost [41].

For a system composing of not only a battery bank but also a generator, HOMER sets two strategies for battery-charging known as load-following and cycle-charging when the renewable power source cannot supply the load. In load-following strategy, a generator generates the required power to distribute the load, but it does not charge up the batteries. With the cycle-charging strategy, a generator runs at its maximum rated capacity to charge up the battery bank with the excessive power in the system.

To choose an optimal combination of a hybrid system to meet the load demand, assessment can be built on power supply economy by Net Present Cost (NPC) concept and reliability basis by Total Energy Deficit (TED) concept. The suggested methodology for optimal components selection of the studied hybrid system will be discussed in the next sections.

3.2 Economic Criteria

Generally, there are sharply different cost characteristics in renewable and nonrenewable energy sources. Renewable sources seem to have high first principal costs and low running costs, whereas traditional nonrenewable sources are likely to have low capital and high running costs. In its optimization process, HOMER must often compare the economics of a broad variety of system configurations composing of different amounts of renewable and nonrenewable energy sources. To be equal, such comparisons must calculate both capital and running costs. Life-cycle cost analysis also accounts for these costs that occur during the life time of the system. HOMER applies the total net present cost to describe the life-cycle cost of a system. In the literature reviews, the economic analysis of decentralized renewable energy systems has applied several economic criteria. These criteria consider total annualized cost, the life cycle cost, and leveled cost of energy [42-43].

The net present value (NPV) method is used in this research work to explore the economic possibility of the hybrid energy system. The lifetime of this project is 25 years, and the suggested hybrid system has to pay for itself during that period. The analysis will involve the first project cost, or principal cost, including apparatus and installation cost in order to carry out net present value, using one year interval.

The optimal combination of a hybrid solar-wind system can make the best agreement between the two supposed objectives: the system power reliability and system cost. According to the idea of annualized cost of system (ACS), the economy approach is advanced to be the best standard of system cost analysis in this study. The annualized cost of system contains the annualized capital cost C_{acap}, the annualized replacement cost C_{arep} and the annualized maintenance cost C_{amain} due to the studied hybrid solar-diesel system. Four major parts: PV array, battery, diesel generator, and the other devices are considered. The other devices are the apparatus that is not included in the decision variables, including controller, inverter and rectifier. The option between competing technologies for energy services in rural areas can be regarded by a fiscal comparison between various options. The problem of the proper cost of the various types of power projects which have environmental and social benefits limits the scope of this thesis to quantitative outcomes of economic signs.

The model rapidly quantifies the net present value (NPV) of thousands of various alternative systems, the derivative of NPV and cost of energy (COE).

NPV is the best sign of financial value of a project, as it appropriately explains the opportunity costs of principal. Due to the comparison between the NPV and the COE, a ranked order of projects can be acquired and the alternatives can be compared on a like basis, the profit on principal, which is the major limited factor for electricity projects in India. The specifics of the model and the input assumptions for the model are indicated in the next chapter [44].

To make comparison with systems and find the optimum outcome of a village in Magway Region, three types of production constituents, diesel and PV as well as the inclusion of battery power storage are mixed and matched. Although it is feasible to do the projects for many villages at the same time, the first only one for one village can be done actually, and then expanded in phases.

3.2.1 Levelised Cost of Energy (LCOE)

The LCOE of renewable energy technologies differs according to technology, country and project based on the renewable energy sources, principal, running costs and the effectiveness of the technology. The cost of renewable energy technologies can be calculated by the method which is based on discounting financial flows (yearly, quarterly or monthly) to a common basis, taking account of knocking off economic flows.

LCOE is frequently quoted as a suitable summary measure of the whole competition of various producing technologies. Levelized cost embodies the current value of the overall cost of constructing and running a production plant over a presumed economic life and duty cycle, changed into equal yearly payments and described as real currency such as US dollar to get rid of the effect of inflation [44].

A markdown rate is used to reduce future costs and incomes to their current values. LCOE will be worked out by the following equation [45]:

$$LCOE = \frac{TLCC}{\sum_{n=1}^{N}\left[\frac{Q(n)}{(1+r)^n}\right]} \tag{3.1}$$

where

TLCC is the total life cycle cost, [$]

n is the total number of years in project life time , [years]

r is the annual discount rate (based on the value for the specific country of the project), [%]

Q (n) is the energy output of power generation system in the specific year n, [kW].

TLCC is calculated by summing up the expected yearly expenses of the project, returned to the present value of expense [45].

$$TLCC = n = \sum_{n=1}^{N} \frac{C(n)}{(1+r)^n} \tag{3.2}$$

where

C (n) is the cost in year n, [$] .

3.2.2 The Salvage Value

The salvage value is the value remaining in each component of the power system at the end of the project life-time. To calculate that value, HOMER uses the following equation

$$S = C_{rep} \frac{R_{rem}}{R_{comp}} \tag{3.3}$$

where

S is the salvage value, [$]

C_{rep} is the replacement cost of the component, [$]

R_{rem} is the remaining life of the component, [years]

R_{comp} is the lifetime of the component, [years].

For example, if the project lifespan is twenty years and the PV array lifespan is also twenty years, the salvage value of the PV array at the end of the project lifespan will be zero because it has no remaining life. On the other hand, if the PV array lifetime is thirty years, its salvage value will be one-third of its substitute cost at the end of the twenty years project lifespan [46].

3.2.3 Net Present Cost (C_{NPC})

The net present cost is the reduced value of all the cash flows which is necessary to run and buy the hybrid system over its lifespan of twenty five years. The following formula was used [47]:

$$C_{NPC} = \frac{C_{anntot}}{CRF(i,N)} \tag{3.4}$$

where

C_{anntot}	is total annualized cost, [$/yr]
CRF	is capital recovery factor
i	is interest rate, [%]

The capital recovery factor is as follow [46]:

$$\mathrm{CRF}(\mathrm{i},\mathrm{N}) = \frac{\mathrm{i}(1+\mathrm{i})^{\mathrm{N}}}{\mathrm{i}(1+\mathrm{i})^{\mathrm{N}} - 1} \tag{3.5}$$

The first variable is the total annualized cost of the system, which is the same as the sum of each constituent's yearly running cost plus its annualized principal expenditure over its helpful lifetime plus the annual fuel cost if it is applicable. By adding the outcomes of all components, the total annualized expenditure can be worked out, $C_{ann,tot}$. The principal recuperation factor is a function of the actual return rate and the project lifespan and is used to reduce the cash flows to time zero [46].

3.2.4 Cost of Energy (COE)

The cost of energy (COE) in \$/kWh is the amount of tax needed to recover the NPC of the hybrid project. However, different tax structures can be used to help poor customers, so the COE figure is only denotative of the average amount of charges that must be provided by the host community [46]:

$$COE = \frac{C_{anntot}}{E_{prim} + E_{def}} \tag{3.6}$$

$$COE = \frac{C_{anntot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{3.7}$$

where

E_{prim} is primary load served, [kWh/yr]

E_{def} is deferrable load served, [kWh/yr]

$E_{grid,sales}$ is the amount of energy sold to the grid per year, [kWh/yr].

The two loads, E_{prim} and E_{def}, are based on village per capital estimate and are tested across a range of values to assess the robustness of the hybrid to grow as demand expands.

The denominator in equation is an expression of the overall amount of useful energy that the system generates per year. The levelized cost of energy is therefore the average cost per kilowatt hour of useful electrical energy generated by the system [46].

3.2.5 Replacement Cost

The cost of replacement means the cost of superseding constituent at the end of the lifespan. This cost is applied to estimate the yearly life replacement cost, and is also different from the first principal cost for a variety of cause.

i. Not all of the constituents require substitute at the end of its life.

ii. The first principal cost is cut or removed by a donor association, but the substitute cost is not.

iii. The set costs are divided by all constituents but at substitute time, they are not.

3.2.6 Annualized Replacement Cost

The annualized replaced cost of a system constitute is the annualized value of all the replacement costs happening throughout the lifespan of the project, minus the salvage value at the end of the project lifespan [46].

HOMER uses the following equation to calculate each component annualized replacement cost:

$$C_{arep} = C_{rep}.f_{rep}.\, SFF\,(\mathrm{i}\,, R_{comp}) - S.SFF\,(\mathrm{i}\,, N) \tag{3.8}$$

where

C_{rep} is replacement cost of the component, [$]

SFF is sinking fund factor

R_{comp} is lifetime of the component, [years]

f_{rep}, is a factor arising because of the constituent lifespan which differs from the project lifespan, R_{rep} the replacement cost duration, is given by [46];

$$R_{rep} = R_{comp}.INT\left(\frac{N}{R_{comp}}\right) \tag{3.9}$$

where

INT is the integer function, returning the integer portion of a real value.

3.2.7 Interest Rate

The interest rate that one enters for HOMER's input is the actual annual interest rate (also known as the real interest rate or just interest rate), the discount rate used to convert between one-time costs and annualized costs, and it is observed in the economic inputs window. The yearly actual interest rate is connected to the minimal interest rate by the equation given below [45]:

$$i = \frac{i' - f}{1 + f} \tag{3.10}$$

where

i'	is nominal interest rate, [%]
f	is annual inflation rate, [%].

By describing the interest rate in this way, inflation is not included in the economic analysis. All costs therefore become actual costs, meaning that they are indicated in terms of constant dollars. It is estimated that the rate inflation rate for all costs is the same [45].

3.2.8 System Constraints

Allowing the less amount of load to go unnerved can yield a significant improvement on the economic performance of the system. As designing the system to get the result during a short period of time in a year or shedding some load helps the battery bank decrease, the capital cost of the hybrid system can be significantly decreased. The maximum annual capacity shortage is the maximum allowable value of the capacity shortage fraction, which is the total capacity shortage divided by the load annual fraction is less than or equal to the maximum annual capacity shortage. Minimum renewable fraction is the minimum allowable value of the annual renewable fraction.

The capacity shortage fraction is

$$f_{es} = \frac{E_{sc}}{E_{tot}} \tag{3.11}$$

where

E_{cs} is total capacity shortage, [kWh/yr]

E_{tot} is total electric load (primary and deferrable load), [kWh/yr].

The total capacity shortage is the total amount of capacity shortage that occurs throughout the year. At the end of the year, this value is applied to calculate the capacity shortage fraction [46].

3.3 Reliability Criteria

Based on the costs of components, fuel, labour, transport and maintenance, it is demanded to evaluate the most cost-effective dimension of all components and their operation strategy. Running the components effectively influences operation costs and, therefore, overall life cycle costs. Management of demand and adjustment to the renewable energy supply and maximization of load factors are very important and there is a significant influence on life cycle costs and sizing. This will also be discussed in this dissertation to evaluate the case scenarios. In this study, reliability of the system is shown in terms of Total Energy Deficit (TED), defined as the ratio of energy not supplied to the consumer when he was asked on the total energy needed. As the energy management strategy, improvement in this study does not allow any energy deficit; therefore, the allowed value of TED is 0%. From the above-described situations, a program is developed in HOMER to size the components for each configuration, for zero load rejection. Using the developed program all configurations which satisfy the rate of 0% of TED is remained. At the same time, the optimal configuration is estimated on the basis of the minimum cost.

3.3.1 Hybrid System Design Procedures

The system design method in this work is shown in Fig. 3.1. Firstly, the amount of load current demand is calculated with managing the load schedule. Next, the regional characteristics of climate weather are considered for at least one year, and determine the available energy. And then, determine the number of PV modules, whose total output is comparatively discrete, as shown in Equation (3.12):

$$\text{Current from solar components} < \text{Current demand load} \tag{3.12}$$

In the process of design, we adopt the concept that the undercurrent demand is complemented by photovoltaic power generators. Based on undercurrent demand, the parallel number of photovoltaic power generators is obtained. And then, since this calculation leads to determine the system predicted in selection criterion as follows:

- Power generation utilization rate is sufficiently high.

$$\text{Generation Power Utilization Rate}\,[\%] = \frac{\text{Loaded current demand [Ah]}}{\text{Gross generation ampacity [Ah]}} \tag{3.13}$$

- There are no extreme deviations in power generation output ratio of various renewable energies.
- From the viewpoint of output stability of the system, it is desirable that multiple numbers of generators should be provided.
- Comparison is made in terms of construction costs of the systems.
- When similar results have been obtained for most items listed, the system having much excess current capacity is selected.

In the below design procedures, the undercurrent demand is not generated. Therefore only the battery capacity for about 5-day-load backup will become necessary, and the battery capacity is determined [49].

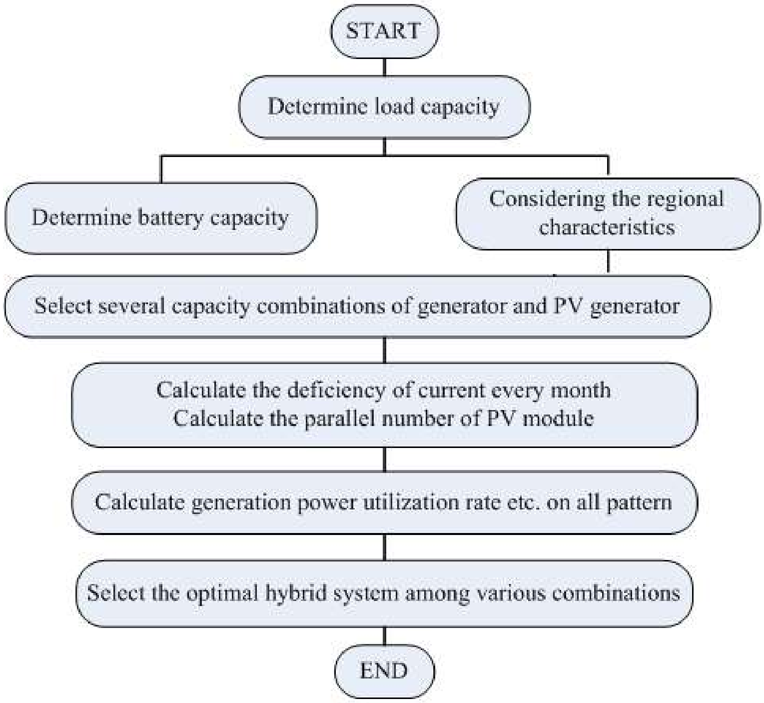


Figure 3.1 Outline procedures for design of hybrid system

3.3.2 Rule of Thumb Method

Rule of thumb method indicated in Table 3.1 and design guidelines which are easily t be used, including a lot f technical details which are hard to be captured in a paper-based design method or even a computer based design optimization. However, they have to limit as they can recommend broadly and intuitively, and it will be opened and improved in other areas.

Table 3.1 Rule of thumb method [50]

Design		Rule of Thumb
Sizing	Renewable energy sizing	40% to 60% of load
	Diesel generator size	Peak load demand in Watt

	Battery size	1 day of battery storage
	Inverter size	Peak (surge) load in Watt
	Battery charger size	Maximum charge current, Diesel capacity rating
Operation	Diesel generator operation	Load factor ≥ 50%
	Battery operation	40% maximum DOD, regular equalization, topping up water
Load Profile	Household load	3 MWh/day (AC)

3.3.3 Ampere Hour (Ah) Method

According to Table 3.2, the main steps are summarized and carried out by the proper-based Ah Method to size PV/diesel system while a hybrid system design by using this method. When the Ah method becomes useful, it is not complex. In spreadsheets, it lends itself to be implemented. In general, Ah methods are advantageous when they fully ignore drops over cables, regulators and so on, and deviations in the operation voltages

With the Ah method, the loads are calculated with their graded power in Watt multiplied by the numbers of hours of each day and the losses occurred through power converting, battery cycling and energy transporting inefficiently.

Then in Ah per day, this value is divided by the voltage of system divides to yield the load. A chosen DC bus voltage is needed to select the number of batteries in series and parallel the highest discharge specification and a battery size which is selected in Ah, and a battery storage requirement in number of days.

The number of peak sun hours per day for different tilt angles to produce values of the DC bus current divides the lad in Ah/day in order to select the number of panels of a chosen PV module. The lowest DC bus current value which is given by the tilt angle is selected. The PV module current divides this bus current to give the number of parallel panels required. By dividing the DC bus voltage through the panel operating voltage, the number of modules in series is calculated. The choice where to go for a hybrid system configuration rather than a single source system can be made based on the available resource.

Table 3.2 Ampere hour design method [51]

Design	Ah Method
Load Profile Estimate [Wh/day] and [Ah/day]	Compile load in Wh/day
	Multiply by loss factors (power conversion, battery cycling, wire inefficiency)
	Divide by system voltage yielding load in Ah/day
Number of batteries in series and in parallel	Select battery type and number of days of storage
	Number of batteries in series obtained though dividing system voltage with battery voltage
	Number in parallel battery strings obtained though matching AH load current

	with the max discharge rate
Number of PV panels in series and in parallel	Divide the load in Ah/day by peak sun hrs per day, yielding so-called ‘DC bus current’ in ampere
	Number of panels in series obtained through dividing system voltage with panel voltage
	Number of panels in parallel obtained through dividing DC bus current with panel output current
Hybridize?	Follow decision guide Yes or No
Redefine storage size	In case smaller battery storage is desired in the hybrid system configuration, redo the calculation on the number of batteries required with new number of days of storage
Choose kW size of Diesel	Choose the generator size to cover peak demand plus maximum charging rate simultaneously
Redefine no of PV panels in series and in parallel	Redo PV calculation taking account of battery and diesel generator sizing
Round off BOS and costing	Choose inverter size, wiring sizes and determine life cycle costs (LCC)

In the decision to hybridize, it is based on whether more than a certain percentage of the given load per day in Watt hours is needed to be covered by the output power of the PV array. Some design-related factors, such as evaluating to the site, environmental factors around diesel generator usage and battery usage, variability of the demand, accessibility of funds, and availability of renewable resources are weighted to originate the hybridization from the Florida Solar Energy Center (FSEC) manual. When a decision is made for a PV/diesel hybrid system or a single source system, it is needed to rely on the weighted sum of these factors.

The storage number of days is not required to define if it is not intended to be larger than in the earliest single- source case. To cover the peak demand and charge the battery at the highest rate simultaneously, the diesel generator size is selected. The number of modules and battery is not generalized. In addition, the life cycles coasts are determined, and an appropriate inverter size and wiring size are chosen.

3.3.4 Loss of Power Supply Probability (LPSP) for System Reliability in Terms of Total Energy Deficit (TED)

In term of technical analysis, several approaches are applied to gain the optimal configurations of hybrid systems. Among these methods, it can be observed that the least square method is applied by the trade-off method, and the technical approach is also known as LPSP. According to the notion of LPSP, to assess the reliability of hybrid system, the technical sizing model for the hybrid power system is improved. The methodology used in the study can be summed up as the following steps.

The total power, P_{tot} (t), generated by the PV generator at hour t is calculated as follows:

$$P_{tot}(t) = P_{PV}(t) \tag{3.14}$$

Then, the inverter input power, P_{inv} (t), is calculated by using the corresponding load power requirements, as follows:

$$P_{inv}(t) = \frac{P_{load}(t)}{\eta_{inv}} \tag{3.15}$$

where

$P_{load}(t)$ is the power consumed by the load at hour t, [kW]

η_{inv} is the inverter efficiency, [%].

During this operation of the hybrid PV/diesel system, different situations may appear.

The wasted energy, defined as the produced energy and not used by the system, for hour t, is calculated as follows [50]:

$$WE(t) = P_{tot}(t)\,\Delta t - \left[\frac{P_{load}(t)}{\eta_{inv}}\,\Delta t + \left[\frac{C_{batmax} - C_{bat}(t-1)}{\eta_{cha}}\right]\right] \qquad 3.16$$

where

$WE(t)$	is the wasted energy, [kWh/yr]
Δt	is the step of time used for the calculations (in this study Δt =1 hour), [hr]
C_{batmax}	is the maximum battery capacity, [kWh/yr]
$C_{bat}(t-1)$	is battery capacity in (t-1) hr, [kWh/yr]
η_{cha}	is the battery charging efficiency, [%].

In case (ii), if the battery capacity reduces to their minimum level, C_{batmin},, the control system disconnects the load and the energy deficit, loss of power supply for hour t can be indicated as follows [50]:

$$LPS(t) = P_{load}(t)\,\Delta t - (\,P_{PV}(t)\,\Delta t + C_{bat}(t-1) - C_{bat\min})\,\eta_{inv} \quad (3.17)$$

where

LPS(t) is loss of power supply in t hr, [kWh/yr].

During that time, the power produced by the PV is assumed constant. So, the power is numerically equal to the energy within this time step.

The LPSP for a considered period T can be defined as the ratio of all the (LPS (t)) values over the total load needed during that period. The LPSP technique is assumed as technical implemented criteria for sizing a hybrid PV/diesel system using a battery bank. The technical model for hybrid system sizing is improved due to the LPSP technique. This can be defined as the following [33]:

$$\mathrm{LPSP} = \frac{\sum_{t=1}^{T} \mathrm{LSP}(t)}{\sum_{t=1}^{T} P_{load}(t)\ \Delta t} \tag{3.18}$$

where

LPSP (t) is loss of power supply probability in t hr, [kWh/yr]

T is the operation time (in this study, T = one year), [years].

The algorithm input data set contains hourly solar irradiation on a tilted plane, hourly mean values of ambient temperature, LPSP, load power requirements during the year and specifications of the system devices. Moreover, it can be introduced for the analysis two more concepts.

The first one is the renewable contribution defined as the ratio of the load supplied by the hybrid PV/diesel system during a given time period over the total load during the same period. According to the LPSP, it can be shown as follows [33]:

$$\mathrm{RC}(T) = 1 - \mathrm{LPSP} \tag{3.19}$$

where

RC(T) is the renewable contribution in T time period, [%].

The second concept is the energy excess percentage which is defined as the wasted energy divided by the total energy produced by the PV generators during the assumed period [33].

$$\mathrm{EXC}(T) = \frac{\mathrm{WE}(T)}{E_{tot}(T)} \tag{3.20}$$

where

EXC (T) is the energy excess percentage, [%].

For a given LPSP value and a defined period, many configurations can technically meet the needed reliability demand of power supply. The optimal configuration can be identified finally from this set of configurations by achieving the lowest LCE. This can be performed by using an economical model developed in the following section.

3.3.4.1 Energy Delivery Factor

The delivered quantity of energy depends on the peak power capacity of the site, and how fully that capacity is utilized. A normalized measure of the power plant performance is the energy delivery factor (EDF). It is defined as the ratio of the electric energy delivered to customers to the energy that could have been distributed if the plants were carried out at full installed capacity during all the 8760 h of the year. It is indicated as follows [33]:

$$\text{Average annual EDF} = \frac{\text{kWh delivered over the year}}{\text{Installed capacity} \times \text{Number of hours in a year}} \tag{3.21}$$

3.3.4.2 RE Penetration

In a hybrid system, design workshop is held at the National Renewable Energy Laboratory, Colorado, U.S., on November 7 in 2007, workshop participants felt that the optimum percentage share of renewable energy sources in terms of system capacity was 70%-85% of load to achieve an optimum reliability versus cost ratio. It was mentioned that the share of renewable sources in a system would mostly be approximately 40%-60%. The proportion of electrical energy or power being provided from renewable sources is generally referred to as the penetration. It is usually indicated as a percentage. When fuel or CO_2 - emission savings are being considered as they have bad environmental impacts, it is useful to consider the average penetration [33]:

$$\text{Average penetration} = \frac{\text{Energy from renewable energy powered generators (kWh)}}{\text{Total energy delivered to loads (kWh)}} \qquad (3.22)$$

Chapter 4. Optimum Design of Proposed Hybrid System for Rural Electrification

4.1 Case Study for Village Power Supply

The case study is considered for supplying electricity to Kyit Sone Pwe Village in Magway Region in Myanmar as a mentioned in introduction. There are about 1300 house-holds with 6500 of local people in this village [53]. To design the solar-diesel-battery hybrid power system for supplying electricity for the whole village, two main portions are divided. They are demand side management and supply side management.

4.2 Demand Side Management

The demand side management has to size the load and calculate the daily energy consumption in kWh. The configuration for managing the total load consumption for the entire site is shown in Fig. 4.1 which describes the total daily load demand for residence, communal facilities, and commercial facilities.

The proposed area in this dissertation is the Kyit Sone Pwe village, which is located at 20.154N latitude and 94.945 E longitude in Magway Township in Myanmar [39]. The problem statement of this research is that the load centre of Kyit Sone Pwe village cannot access the electricity until now. Most of the people in this village mainly depend on small patrol engine, batteries and some of people are using candle lamp for lighting, phone charger and other electricity appliances.

The annual average solar radiation for that area is 4.841kWh/m^2/day and it is very important for preparing a proper load data to meet the current situation of the target village [6]. Load profile is mainly divided into three portions that are residence, communal facilities and commercial facilities. In residence, there are many kinds of non-electrified household level such as a high income level, medium income level and low income level respectively. Electricity demand in low income level is limited to lighting and TV, and the annual growth rate of electricity consumption is small. Some households in the village have only had automobile batteries for watching TV and lighting. A proliferation of mobile phones provides a good indication of income level for the village. In such Medium household level, the annual growth rate of electricity consumption is rapidly increasing.

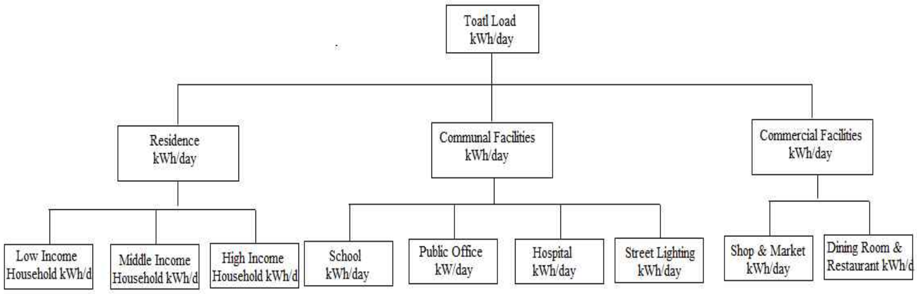


Figure 4.1 Configurations for Managing the Total Load Consumption of the Entire Site

Some households in a high income level own portable generators and vehicles. If such households are electrified, people will purchase electric appliances such as refrigerator, pump motor, fan and karaoke machine, etc. For communal facilities, they include school, public office, hospital and street lighting and the commercial facilities contain shop, market and restaurant. The parallel hybrid energy system is intended to apply for 1300 households residing at the selected site [53]. The equation (Annual Energy consumption (kWh) = ((number of appliance used power rating of each appliance hours of operation number of days)/1000)/7 days) is used for load estimation. The location of the proposed site is as shown in Figure 4.2.

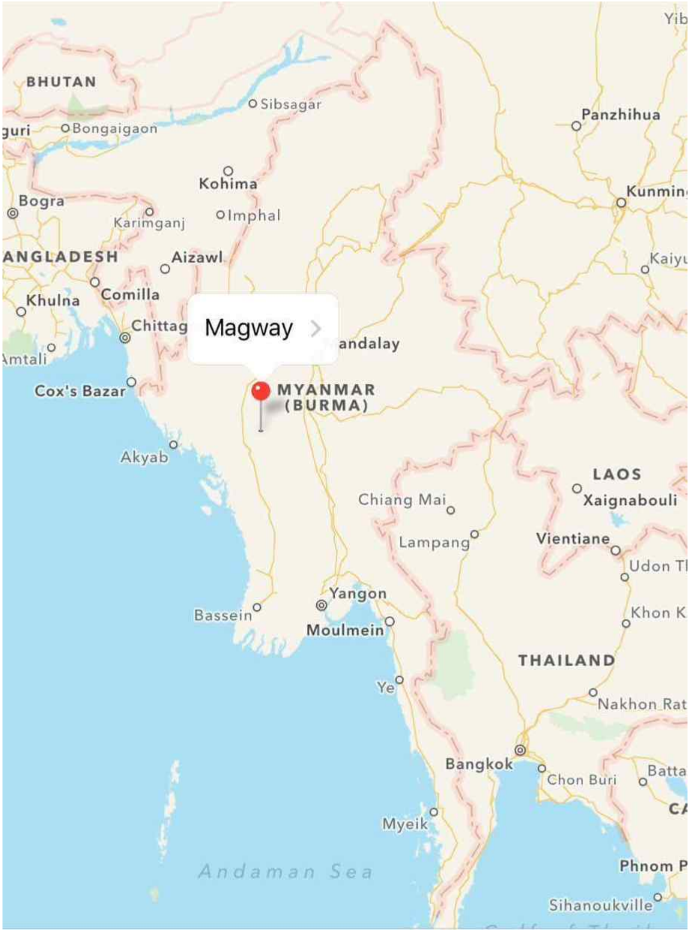


Figure 4.2 Map of Kyit Sone Pwe village [39]

The AC load, a combination of electricity loads, is mainly used for domestics such as lighting, TV and radio sets, refrigeration units, electrical motors which are applied for water pumping and so on. So, their annual electricity consumption rate is also small as shown in Figure 4.3.

No	Descri-ption	Quan-tity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	Electric light	2	40																									6	480
2	TV	1	70																									4	280
	Total load (Wh/day/family)																												760
	For low income (600), the power consumption of entire site (kWh/day)																												456

Figure 4.3 Load estimation for low income household

NO	Description	Quan-tity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	Electricity light	4	40																									8	1280
2	TV	1	70																									4	280
3	CD/DVD	1	10																									2	20
4	Electric Fan	1	50																									2	100
5	Electric Pot	1	40																									2	80
	Total load (Wh/day/family)																												1.76
	For medium income (400), the power consumption of entire site (kWh/day)																												704.00

Figure 4.4 Load estimation for medium income household

Figure 4.4 shows the rapid increase in the annual growth rate of electricity consumption for medium household level.

Some households which have a high income own portable generators and vehicles as shown in Figure 4.5. Load Estimations for communal loads which contain school, public office, hospital and street lighting are shown in Figures 4.6, 4.7, 4.8, and 4.9.

NO	Description	Quan-tity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	ELectric light	10	40																									8	3200
2	TV	2	70																									6	840
3	CD/DVD	2	10																									5	100
4	Freezer	1	60																									24	1440
5	Electric Fan	1	50																									2	100
6	Electric Pot	1	40																									2	80
	Total load (Wh/day/family)																												5.76
	For high income (300), the power consumption of entire site (kWh/day)																												1728.00

Figure 4.5 Load estimation for high income household

NO	Description	Quan-tity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	Electricity light	2	40																									10	800
2	TV	1	70																									3	210
3	Electric Fan	2	50																									2	400
4	Electric Pot	1	40																									4	160
5	Computer	2	85																									8	1360
	Total load (Wh/day/family)																												2.93
	For one school , the power consumption of entire site (kWh/day)																												2.93

Figure 4.6 Load estimation for school

NO	Description	Quan-tity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	Electricity light	10	40																									6	2400
2	TV	1	70																									8	560
3	Electric Fan	5	50																									4	1000
4	Electric Pot	2	40																									4	320
5	Computer	5	85																									9	3825
	Total load (Wh/day/family)																												8.11
	For one public office , the power consumption of entire site (kWh/day)																												8.11

Figure 4.7 Load estimation for public office

NO	Description	Quan-tity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	ELectric light	8	40																									8	2560
2	TV	1	70																									14	980
3	Microscope	3	10																									10	300
4	Freezer	2	60																									24	2880
5	Electric Fan	20	50																									5	5000
6	Electric Pot	4	40																									8	1280
	Total load (Wh/day/family)																												13.00
	For one hospital, the power consumption of entire site (kWh/day)																												13.00

Figure 4.8 Load estimation for hospital

No	Description	Quantity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	Electric light	1	15																									12	180
	Total load (Wh/day)																												0.18
	For street light (600), the power consumption of entire site (kWh/day)																												108.00

Figure 4.9 Load estimation for street lighting

For commercial load, it is estimated for shop, supermarket, dining room and restaurant shown in figures 4.10 and 4.11.

No	Description	Quantity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	Electric light	4	40																									8	1280
2	TV	1	70																									12	840
3	CD/DVD	1	10																									2	20
4	Electric Fan	1	50																									6	300
5	Electric Pot	1	40																									2	80
6	Freezer	1	60																									24	1440
7	Stereo	1	20																									12	240
8																													
	Total load (Wh/day/family)																												4.20
	For Shop and market (10), the power consumption of entire site (kWh/day)																												42.00

Figure 4.10 Load estimation for shop and market

NO	Description	Quan-tity	Power (W)	Time-zone Operation hours																								Total hours	Electricity (Wh)
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
1	ELectric light	8	40																									7	2240
2	TV	1	70																									5	350
3	CD/DVD	1	10																									4	40
4	Freezer	2	60																									24	2880
5	Electric Fan	2	50																									11	1100
6	Electric Pot	2	40																									6	480
	Total load (Wh/day/family)																												7.09
	For dining room and restaurant (2), the power consumption of entire site (kWh/day)																												14.18

Figure 4.11 Load estimation for dining room and restaurant

The total daily profile for the proposed village is described in Figure 4.12. A load of 28kW and a smaller load of about 21kW occur from midnight to 4am and between 9am and 17pm respectively. The majority of load occurred in the evening, reaching a maximum load of 405.17kW, would likely involve small fluorescent lights, TV, security lights, etc.

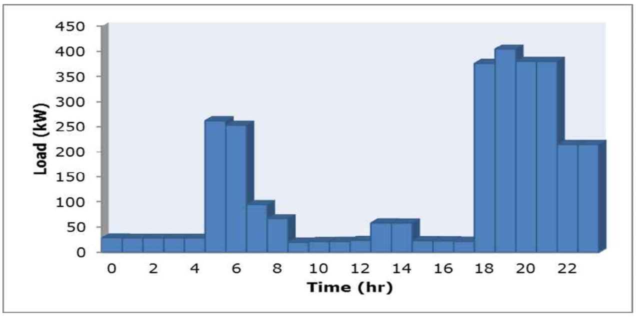


Figure 4.12 Daily load profile for the proposed village

Primary load is electrical load that is satisfied immediately in order to avoid unmet load. The load is provided by alternating current (AC) or direct current (DC) power. Primary load assessment involved baseline data and scaled data for simulation, which are demonstrated with solar resource assessment. To reduce electrical demand, efficiency input, efficiency multiplier, capital cost and lifespan should be examined.

The type of load is also provided on the AC line. The average load is 127kW and the peak load which is the ratio of the average load to the load factor can obtain 563 kW with a load factor of 0.225 to cover the load fluctuation. Figure 4.13 expresses the daily load pattern and the seasonal profile. The load data are collected in 2016 and assumed that these load data will not be changed during project life time-25years. Therefore, it covers the duration, ranging from 2016 to 2040.

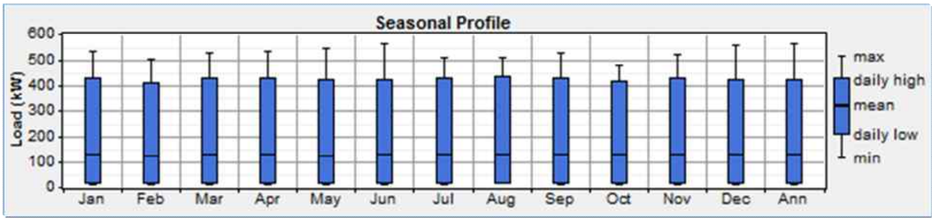


Figure 4.13 Seasonal load profile for the proposed village with HOMER

4.3 Supply Side Management

The supply side management includes finding out the system capacity with sizing the entire system components which are solar PV array, diesel generator-set, battery and converter. For this purpose, the Ampere Hour Method mentioned in section 3.3.3 is applied for the proposed case study. The supply side management will focus on optimal combination of the supply sources for the proposed hybrid system.

4.3.1 Solar Resource of Proposed Site

Table 4.1 shows the solar energy resource for one-year period that was used for the proposed site. The necessary solar radiation data for this region was collected from the NASA Website. The average of annual solar radiation for this area is 4.84kWh/m^2/d.

Table 4.1 Solar resource profile for one-year period

Site location	**Kyit Sone Pwe Village, Magway Region, Myanmar**
Latitude	20.154 N
Longitude	94.945 E
Month	**Daily Solar Radiation- horizontal (kWh/m^2/d)**
January	5.14
February	5.72
March	6.22
April	6.33
May	5.42
June	3.95
July	3.97
August	3.91
September	4.25
October	4.39
November	4.27
December	4.59
Annual	**4.841**

The combination of the optimum system leads to the optimum system design with the lowest cost of energy.

i. Primary Load

ii. Minutes time step = 60

iii. Day to day random variability = 8%

iv. Time to time step random variability = 10%

v. Minimum daily load consumption-scaled annual average =3044 kWh/day

vi. Peak load = 563 kW

vii. Average load = 127 kW

viii. Load factor = 0.225

ix. Solar Resource Inputs

x. Location (latitude 20˚ 9 ′and Longitude 94˚ 56′)

xi. Scale annual average =4.84 kWh/m^2/day

Figure 4.14 shows the global solar and incident solar of the system for the year. For this site, the highest average solar radiation occurs in April and the lowest average in August. For April, the PV array satisfies the whole load during the daytime with enough energy stored in the battery bank to meet the load occurred in the nighttime. The generator needs to operate and charges the batteries to help the PV array in June, July and August.

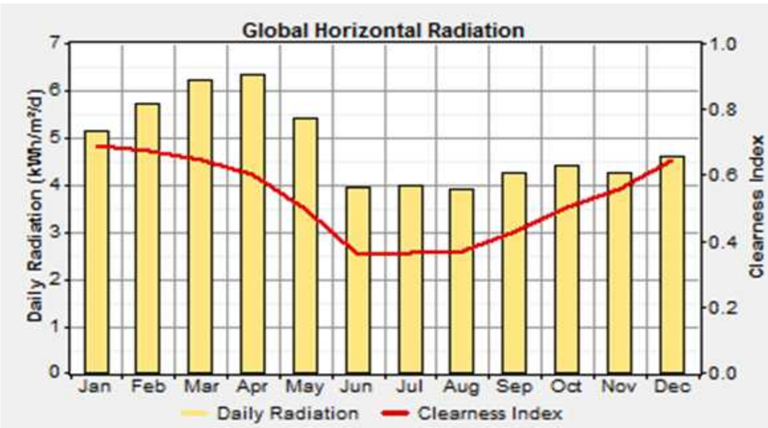


Figure 4.14 Monthly solar radiations and clearness index of the proposed site area

4.3.2 Hybrid System Components

In this research, the proposed hybrid system consists of diesel generator, solar PV-arrays, battery bank (BESS) and converter to achieve the efficient and cost competitive system configuration for improving the life of people especially in rural areas. And then, it needs to find the costs of hybrid system components which include components initial costs, components replacement costs, system maintenance costs, fuel and operation costs, and salvage costs or salvage revenues.

The costs of initial include purchasing the following equipments required by the hybrid system: PV modules, batteries, diesel generator, charge controllers, bidirectional inverter, management unit, cables, and other accessories used in the installation including labors.

4.3.2.1 Selection of Photovoltaic Module

The PV modules used in the proposed system have a capital cost of 420000 dollars without taking other additional constituents of system into consideration. The modules life time is estimated by the manufacturer to be 25 years with an O&M of 100 dollars/year. In the proposed hybrid system, TNP-Trina type of solar modules are chosen to install, and no PV panel replacement costs will occur during the project lifetimes.

i. Lifetime = 25 yrs
ii. Derating factor = 80 %
iii. Slope degree = 20.8
iv. Azimuth angle = 0
v. Ground reflectance = 20 %
vi. No tracking Device
vii. No effect of temperature
viii. Variable size to considered = 600 kW

It is entered at least one size and the value of capital cost in the cost table, as shown in Figure 4.15. Include all costs associated with the PV (photovoltaic) system, including modules, mounting hardware, and installation. In this system, the tracking system and the effect of temperature are neglected.

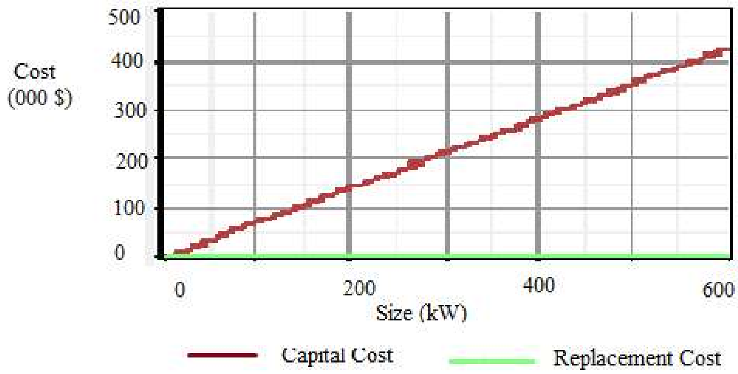


Figure 4.15 Cost curve of PV module

4.3.2.2 Selection of Diesel Generator

The diesel power generator is used as a primary power generation option to increase the reliability of the hybrid system. The sizing of diesel generator must be chosen to cover the peak load demand in kW. So, the AC diesel power generation unit of a size of 600 kW is practically considered to cover the peak load of 563kW of the proposed area. The capital cost of the unit is 61000 dollars and the operation and maintenance (O&M) is 0.01 dollars/h. The replacement cost of the diesel unit is 60000 dollar with 15000 hours of operating lifetimes. The price of fuel at a time of study is taken as 0.8 /L in US dollars with no limit on diesel consumption per year. Quite oppositely, a raise in diesel prices, is expected and something which only strengthens the statement that the system solely supplied by solar power is the economically optimal one. The fuel properties of the diesel power generator were set as: a lower heating value of 43.2 MJ/kg, a density of 820 kg/m^3, a carbon content of 88 percent and sulfur content of 0.33 percent. Figure 4.16 shows the cost curve of diesel generator from 0 to 600kW rating.

i.	Lifetime (operating hours)	= 15000 hrs
ii.	Size to consider	= 600 kW
iii.	Fuel price	= 0.8 $/L
iv.	Lower heating value	= 43.2 MJ/kg (Fuel property)
v.	Density	= 820 kg/m^3 (Fuel property)
vi.	Carbon content	= 88% (Fuel property)
vii.	Sulfur content	= 0.33% (Fuel property)

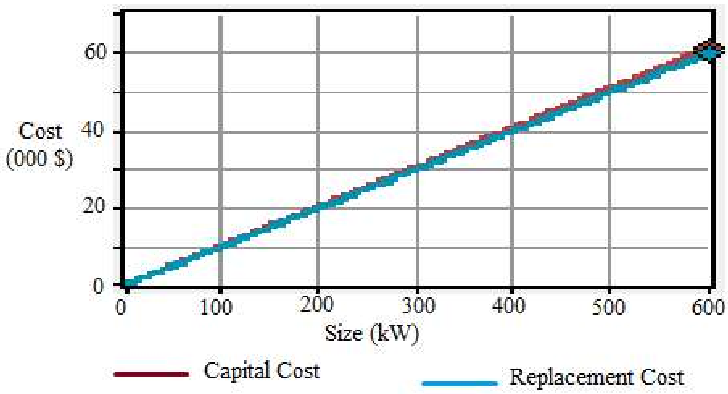


Figure 4.16 Cost curve of diesel generator

4.3.2.3 Selection of BESS

The BESS used in the proposed system is Surrette 6CS25P. So, the Nominal voltage is 6 V and Nominal capacity of 1156 Ah (6.94 kWh) according to the manufacturer's description. The minimum state of charge is 40 percent and maximum charge rate is 1 A/Ah with a maximum charge current of 11A. The lifetime throughput is 9645 kWh. The cost of one battery is taken as 700 dollars and a life time of four years with a replacement price of 600 dollars and O&M cost is 10 dollars/year showed in Figure 4.17. The sizes of battery are variable ranging from 0 to 800 numbers.

i.	Nominal capacity	= 1156 Ah
ii.	Nominal Voltage	= 6 V
iii.	Round trip efficiency	= 80 %
iv.	Min. state of charge	= 40%
v.	Max. charge rate	= 1 A/Ah
vi.	Max. charge current	=41 A
vii.	Lifetime throughput	= 9, 645 kWh

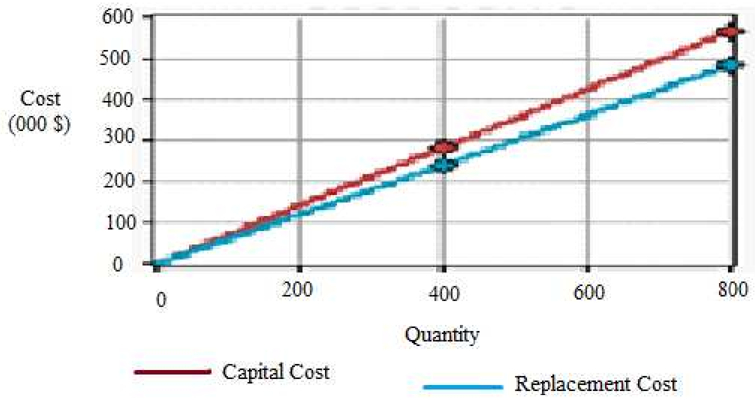


Figure 4.17 Cost curve of BESS

4.3.2.4 Selection of Bidirectional Inverter

Any system that contains both AC and DC elements requires a converter. Bidirectional inverter is used between the DC bus and the AC bus. Its price depends mainly on its rated power and voltage range at both input and output. When specifying the capital and replacement costs, all costs are taken into account with the converter, including installation.

In the case study in this thesis, the capital cost for the bidirectional converter is assumed 500$ per kW, and the inverter efficiency (i.e. 90%) and rectifier efficiency (i.e. 85%) are assumed constant during its lifetime of 20 years. If the converter's cost curve is linearly constant based on the per kW cost when the size is varied, meaning the way its cost varies with size, the cost curve for the capital and replacement cost is shown in Fig. 4.18, the input cost curve for the proposed cased study.

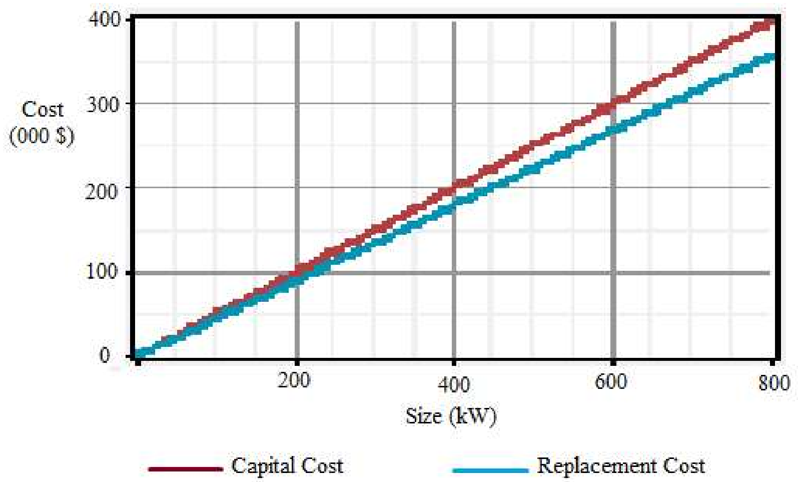


Figure 4.18 Cost curve of bidirectional inverter

4.3.3 System Control Strategy

System control inputs define how HOMER models the operation of battery bank and generators. The dispatch strategy determines how the system charges the battery bank. Dispatch strategy is a set or rule that governs the operation of the generator and the BESS which has two strategies: cycle charging and load following. The optimal system type depends on many factors, including the sizes of the generators and BESS, the price of fuel, the operation and maintenance cost of the generators, the amount of renewable power in the system, and the character of the renewable resources. For the case study in this work, cycle charging strategy is applied so that it will be able to get the high reliability standard.

Chapter 5. Simulation Results

5.1 Case I: Diesel Standalone System

In this problem, we consider the case of diesel standalone system (case study I) to supply the proposed site under optimal condition. Among so many small and remote power systems in the world, diesel generators are the most useful generators. Although a dependable AC output is provided, diesel fuel can often be overpriced because of the extra transport costs for it. Various sizes of diesel generators – ranging from under 1 KW to over a megawatt, are easy to get in the market. Unlike the gasoline generators, diesel generators are dearer, more economical and longer –life ones for maintenance and less fuel consumption. There is a problem with the reduction of system construction costs and also with the reliable power supply. Thus, this problem has been solved by HOMER to be an optimal system.

5.1.1 Mathematical Formulation

This diesel standalone system displays the most excellent characteristic in terms of net present cost which involves investment costs, operation, the costs of upkeep and substitution that happen during the project lifespan, always reducing future cash flow to the present**,** levelized energy cost, and operating cost. Thus, the main function can be formulated by using the mathematical Equations 3.1 to 3.11 described in chapter III with HOMER software.

5.1.2 Simulation Results of Case I

There are lower capital costs for diesel generators, but higher operation cost than renewable energy installation due to the fuel consumption. The disadvantages of generator operation are fuel dependence, transport and storage costs, high maintenance costs, and exposure to fumes and noise.

Diesel generators are the most common generators in a large number of small and remote power systems throughout the world. In this section, the researcher has already described that there is a whole lot demand to supply the 600kW diesel stand-alone system.

5.1.2.1 Generator Operation

Table 5.1 shows the generator operation of Case I in hour per year. As one can be seen from the overview in Table 6.1, the generator is only producing 1,955,878 kWh of energy per year. The numbers of operation hours are 8760 hr/yr with capacity factor 37.2%. Furthermore, the detail results of annual fuel consumption of Case I are displayed in the following Table 5.2.

Table 5.1 Generator production of Case I

Quantity	Value	Units
Hours of operation	8760	hr/yr
Number starts	1	starts/yr
Operational life	1.71	yr
Capacity factor	37.2	%
Fixed generation cost	42.4	$/hr
Marginal generation cost	0.200	$/kWh
Electrical production	1,955,878	kWh/yr
Mean electrical output	223	kW
Min. electrical output	180	kW
Max. electrical output	563	kW

Table 5.2 Annual fuel consumption of Case I

Quantity	Value	Units
Fuel consumption	909,449	L/yr
Specific fuel consumption	0.465	L/kWh
Fuel energy input	8,948,982	kWh/yr
Mean electrical efficiency	21.9	%

5.1.2.2 Annual Emission

The emission of different gases during electricity generation from the Case I (DEG only) and the amount of CO_2 emission is about 2,394,880 kg/yr. Moreover, carbon dioxide is the major source of greenhouse gas for climate change and the detail emission results are shown in Table 5.3.

Table 5.3 Annual emission of Case I

Pollutant	Emission (kg/yr)
Carbon dioxide	2,394,880
Carbon monoxide	5,911
Unburned hydrocarbons	655
Particulate matter	446
Sulfur dioxide	4,809
Nitrogen oxides	52,748

5.1.2.3 Economic Analysis of Simulation Results

Simulation results for case study I to get an optimal system for the proposed site are described by economic analysis. Economics analysis takes a crucial role in HOMER's simulation process due to its operating system to minimize total NPC and its searches for the system configuration with the lowest total NPC in its optimization process. In Figure 5.1 the cash flow summary for the cost of total NPC diesel generator $ 9,787,572 is shown precisely. The portions of total costs for working capital, replacement, and those of O & M and fuel are $61,000, $430,389, $1.120 and $9,300,657 respectively.

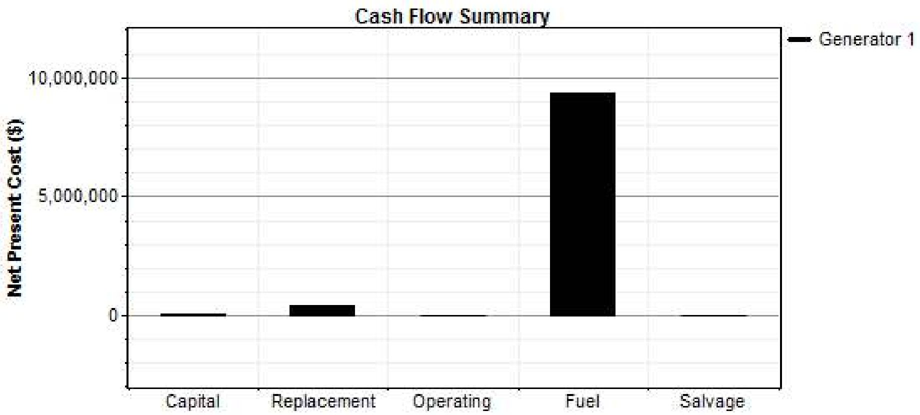


Figure 5.1 Net present cost of Case I

The project life time and annual interest rate are considered 25 years and 8 percent respectively in this dissertation. Table 5.4 shows the economic performance of hybrid system for case study I within the project lifetime.

Figure 5.2 shows the cash flow summary of system component for case study I. Generator has the lowest initial capital cost but it causes the highest fuel cost for the whole project life time.

Table 5.4 Economic analysis of Case I

Description	Value	Units
Capital Cost	61,000	$
Replacement Cost	430,389	$
O & M Cost	1,120	$

Fuel Cost	9,300,657	$
Salvage Value	-5,592	$
Total Net Present Cost	9,787,572	$
Levelized Cost of Energy	0.689	$/kWh
Operating Cost	760,878	$/yr

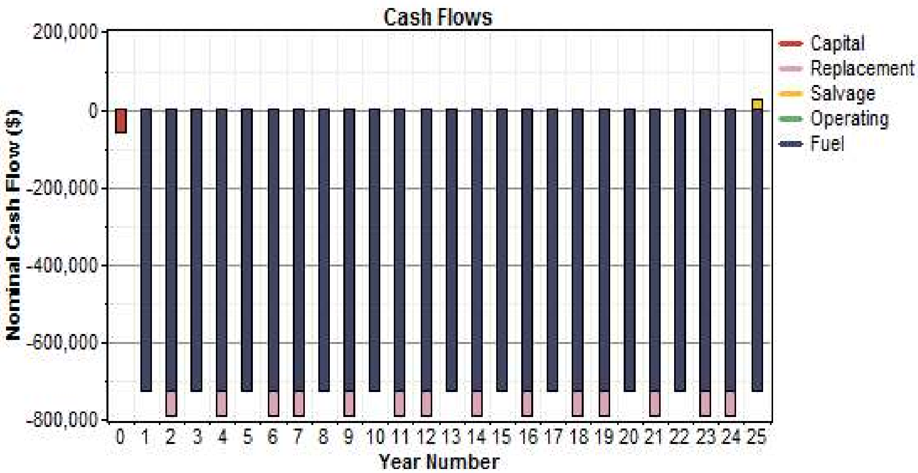


Figure 5.2 Nominal cash flows of Case I

The monthly average electricity production can be seen in Figure 5.3. The power from the generator is only helping to lift the power curve to a higher level and minimizing the unmet load. Therefore, excess electricity is presented 43.2 percent (844,819kWh/yr) in the following Figure 5.4, unmet electric load is zero percentage and also capacity shortage is zero percentage. Moreover, renewable fraction is zero percentage. If the rise of diesel prices is expected, something which only strengthens the statement that the system solely supplied by solar power is the economically optimal one.

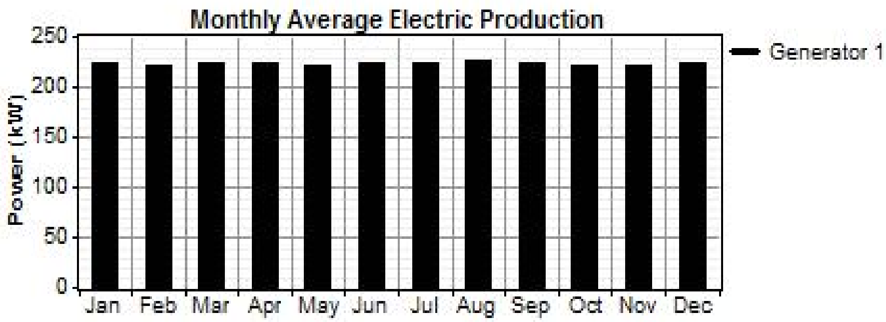


Figure 5.3 Monthly average electric productions for Case I

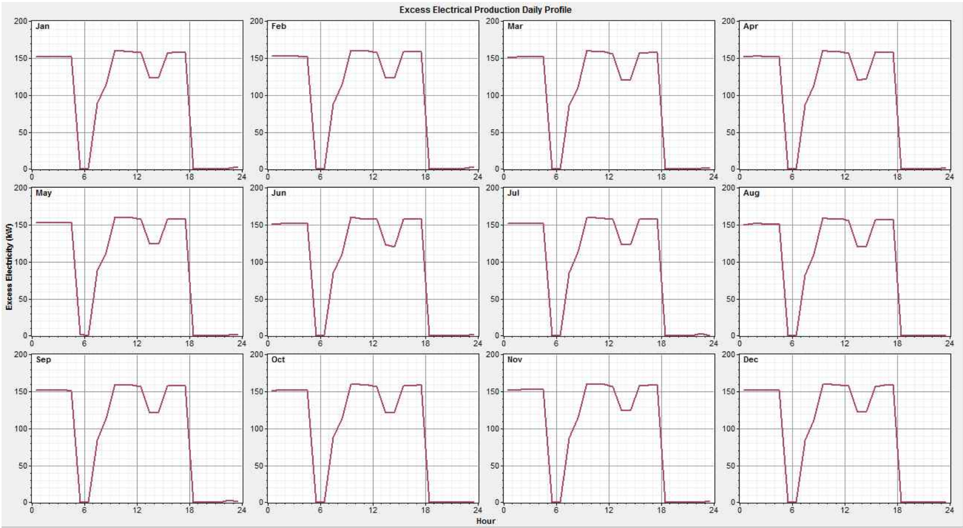


Figure 5.4 Excess electricity production of Case I

5.1.3 Discussion

According to Figure 5.5 and 5.6, although diesel standalone system is able to meet the power demand, fuel dependence, transport and storage cost, high maintenance costs and exposure to fumes and noise can be seen as disadvantages generator operation. In order to overcome these weak points mentioned above, PV generation will be added to the system and a PV-diesel hybrid system will be created. The high value of total net present cost through the 25 years project lifetime of this system is $9,787,572. Therefore, we will present the PV-diesel hybrid system in the next section.

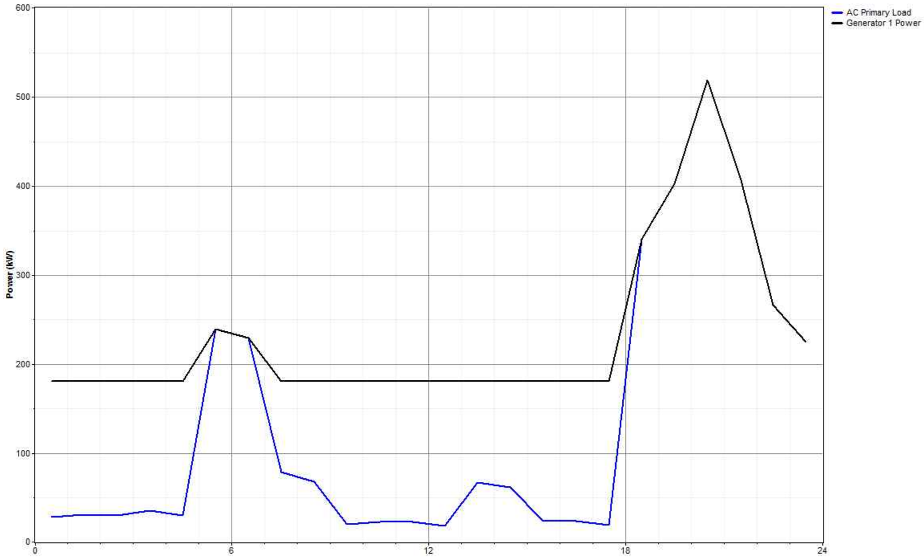


Figure 5.5 The Best performance condition on one of the weekday in summer for Case I

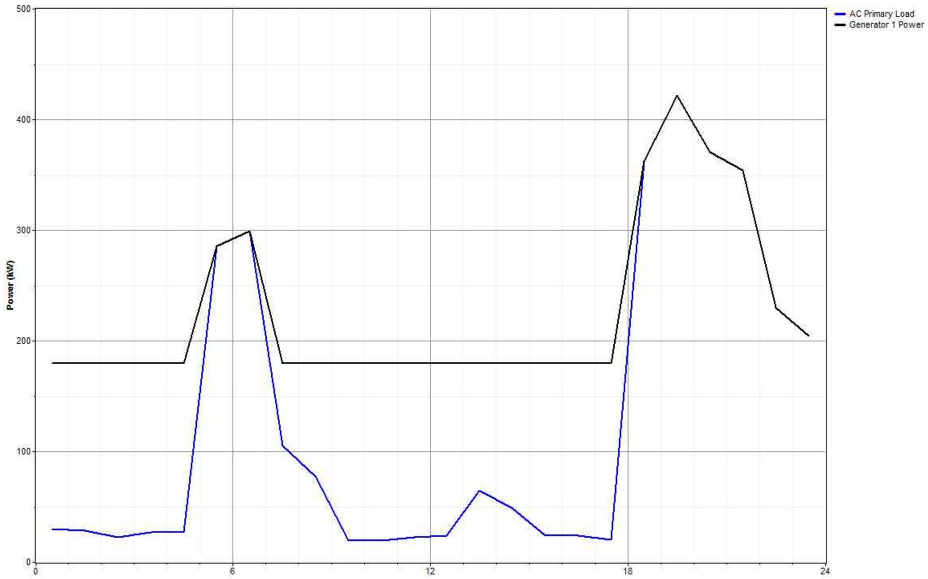


Figure 5.6 The worse performance condition on one of the weekday in rainy season for Case I

5.2 Case II: PV-diesel Hybrid System

In this section, the case of PV-diesel hybrid system (Case II) is used to supply the proposed village to obtain the optimal sizing. The problem is to minimize the CO_2 emission by reducing the using of fuel consumption and to minimize the system operating cost. Thus, HOMER software is applied to solve these problems to get the economic operation of proposed site.

5.2.1 Mathematical Formulation

We can see that this system is economic due to the cost of total current net including initial cost, operation and maintenance cost, and fuel cost during the project. By using the equations 3.1 to 3.22 described in chapter III, we can evaluate the economic costs as total current cost and cost for levelized energy.

5.2.2 Simulation Results of Case II

In this second best option of scaling the system, HOMER found that a large PV-array accompanied with the 600 kW diesel generators as a backup with cycle charging configuration of the generator, was cheaper and thereby optimal alternative. Table 5.5 with the main results for the second best design of the electricity supply states that a system with a 600 kW PV array as well as a backup generator of 600 kW and an inverter capacity of 400 kW is the second best system configuration. This system requires the same amount of modules as the optimal system and however, the biggest different size of inverter. Case II is quite similar to Case III, this case also requires the 600 kW generator as a part of a hybrid system.

Table 5.5 System architecture of Case II

PV array	600 kW
Generator	600 kW
Inverter	400 kW
Rectifier	400 kW

5.2.2.1 PV Data

The PV modules used in the proposed system have a capital cost of 420000 dollars without considering other auxiliary components of system. The module life time is estimated by the manufacturer to be 25 years. The photovoltaic system has no tracking device. Figure 5.7 and Table 5.6 shows the power production from PV.

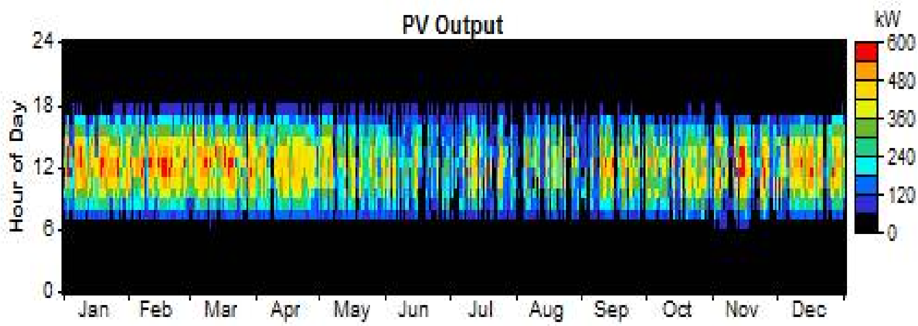


Figure 5.7 PV output curve of Case II

Table 5.6 Power production of PV of Case II

Quantity	Value	Units
Rated Capacity	600	kW
Mean Output	104	kW

Mean Output	2,495	kWh/d
Capacity Factor	17.3	%
Total Production	910,676	kWh/yr
Minimum Output	0	kW
Maximum Output	595	kW
PV Penetration	82	%
Hours of Operation	4,345	hr/yr
Levelized Cost	0.102	$/kWh

5.2.2.2 Generator Operation

In Table 5.7, the generator is producing 1,356,997 kWh of energy per year. The details results of the generator operation are displayed in the following tables. The hours of operation per year range to 5,474 hr/yr, and the generator will have a lifetime of 12 years. The diesel generator is started 428 times and the marginal generation cost is 0.20 $/kWh.

Table 5.7 Generator operation of Case II

Quantity	Value	Units
Hours of operation	5,474	hr/yr
Number starts	428	starts/yr
Operational life	2.74	yr
Capacity factor	25.8	%
Fixed generation cost	42.4	$/hr
Marginal generation cost	0.200	$/kWh

In the Table 5.8, the details around the fuel usage can be seen. The total yearly fuel consumption is 602,001 liters per year and 0.444 liters per kWh of energy are being consumed by the generator.

The generator is operating to fill in the missing power at times when the weather is cloudy and there is not enough energy from the PV array to cover the demand. As one can see the generator is most frequently being used in the early morning or late evening when there is no sunshine. The use of the generator is mostly frequent in June, July, August and September as shown in Figure 5.8.

Table 5.8 Fuel data of Case II

Quantity	Value	Units
Fuel consumption	602,001	L/yr
Specific fuel consumption	0.444	L/kWh
Fuel energy input	5,923,690	kWh/yr
Mean electrical efficiency	22.9	%

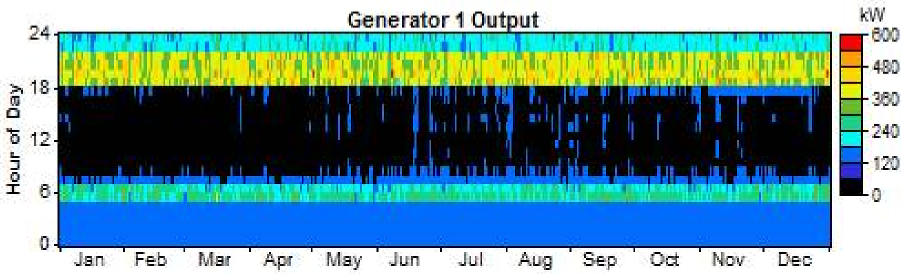


Figure 5.8 Generator output of Case II

5.2.2.3 Converter Data

The converter data is displayed following in Table 5.9. A 400 kW inverter is needed to satisfy the system and transform DC power produced by the PV modules to AC power, which can supply the loads. The mean output of the inverter is 13 kW, however even if this seems to be a low number, one has to keep in mind all the hours in the night which the demand is very poor and this lowers the average. The converter is not in this system working as a rectifier, hence converting AC to DC as no DC loads have to be served as shown in Table 5.10.

Table 5.9 Converter data of Case II

Quantity	Inverter	Rectifier	Units
Capacity	400	400	kW
Mean output	13	0	kW
Minimum output	0	0	kW
Maximum output	114	0	kW
Capacity factor	3.3	0	%

Table 5.10 Converter output power of Case II

Quantity	Inverter	Rectifier	Units
Hours of operation	3,658	0	hrs/yr
Energy in	129,820	0	kWh/yr
Energy out	116,838	0	kWh/yr
losses	12,982	0	kWh/yr

Below the operation and details around the converter/inverter is clarified as shown in Figures 5.9 and 5.10. This is because of the generator activity causing increased energy production and has to pass through the inverter for delivery to the loads. The losses are also slightly higher as the operation of the inverter has increased. The converter is also not in this system working as a rectifier as no DC loads have to be served.

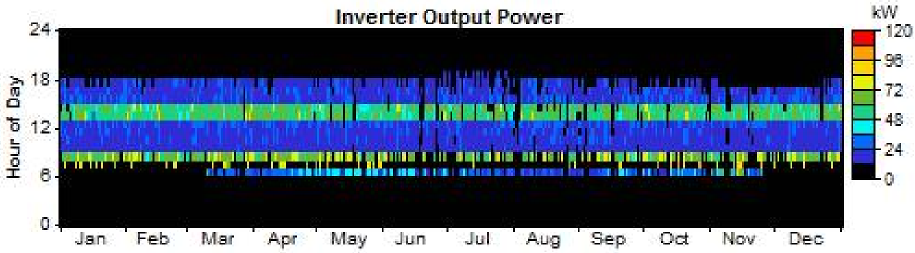


Figure 5.9 Inverter output of Case II

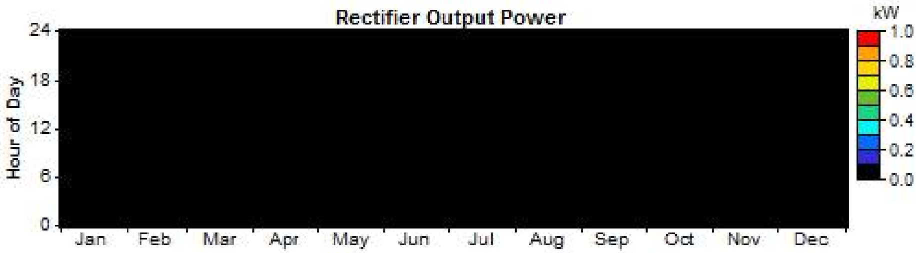


Figure 5.10 Rectifier output of Case II

5.2.2.4 Annual Emission

For the system with a backup generator, another factor to consider is the emissions connected to the operation of the system. For the optimal system of Case II, it will have a little direct emission. One can get a rough overview over the emissions data of the Case II in Table 5.11.

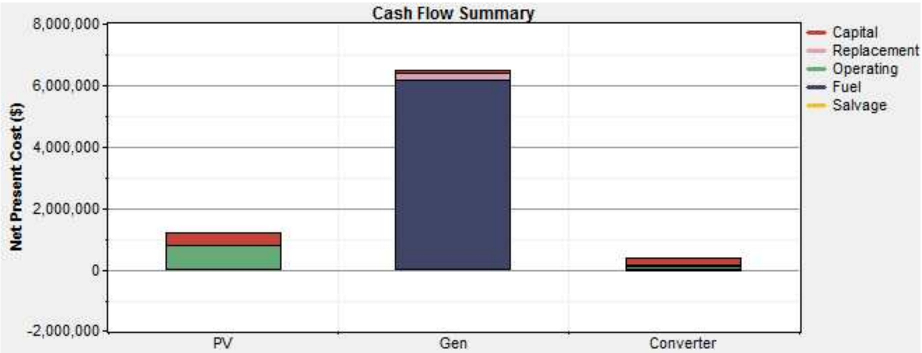
Table 5.11 Emission data of Case II

Pollutant	Emission (kg/yr)
Carbon dioxide	1,585,267
Carbon monoxide	3,913
Unburned hydrocarbons	433
Particulate matter	295
Sulfur dioxide	3,183
Nitrogen oxides	34,916

According to HOMER, among others 1,585,267 kg of carbon dioxide per year will be emitted as well as 34,916 kg of nitrogen oxides are also produced due to the operation of the diesel generator. These are significant magnitudes and they have to be taken into account when determining the optimal system, as not only technical and economical aspects are taken into account but also this pollutant condition must be considered.

5.2.2.5 Economic Analysis of Simulation Results

This system has a NPC of 7,984,073$, a COE of 0.562 $/kWh, and an operating cost of 571,295$ [Table 5.12 and Figure 5.11]. The reason for the higher costs related to this system is likely to be fuel costs, maintenance of the generators as shown in Figure 5.11.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	420,000	0	767,002	0	0	1,187,002
Generator 1	61,000	264,216	700	6,156,477	-12,256	6,470,136
Converter	200,000	56,125	102,267	0	-31,455	326,937
System	681,000	320,341	869,968	6,156,477	-43,711	7,984,077

Figure 5.11 Net present cost of Case II

Following Table 5.13 is displayed the division between power production from the PV array and the generator. The generator produces 60 percent of the total 1,356,997 kWh/yr that is being produced by the system showed in Table 5.12. In this Case II, the amount of unmet load is 0.000671kWh/year and the excess electricity is approximately1, 143,629kWh/year. However this system will have a lower amount of unmet loads as shown in Table 5.14.

Table 5.12 Cost summary of Case II

Description	Value	Units
Capital Cost	681,000	$
Replacement Cost	320,31	$
O & M Cost	869,968	$
Fuel Cost	6,156,477	$
Salvage Value	-43,711	$
Total Net Present Cost	7,984,073	$
Levelized Cost of Energy	0.562	$/kWh
Operating Cost	571,295	$/yr

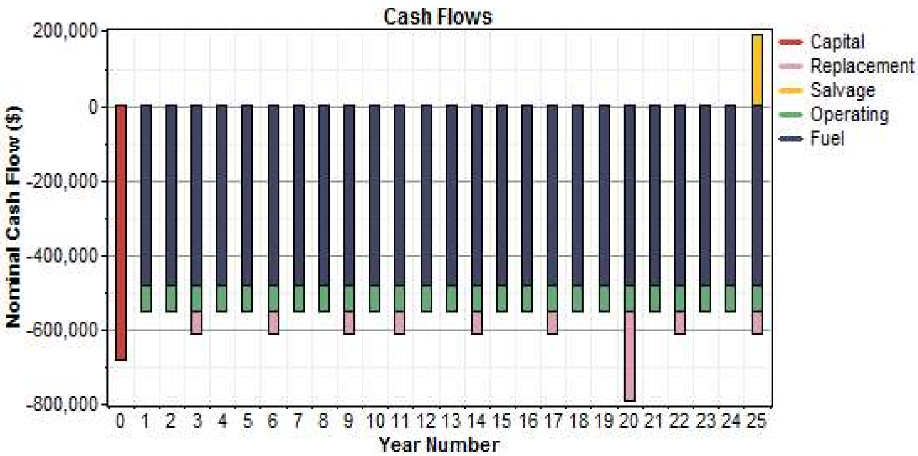


Figure 5.12 Nominal cash flows of Case II

The monthly average electricity production of Case II is displayed in Figure 5.13 and it can be seen from this month that the generator is used and how much power it produces. Between June and July, the generator is being used most frequently. The need for the use of the generator in August and September is the highest. The power from the generator is helping to lift the power curve to a higher level and minimizing the unmet loads. Figure 5.14 shows the excess electricity production for Case II.

Table 5.13 Fraction of production

Component	Production (kWh/yr)	Fraction
PV array	910,676	40%
Generator	1,356,997	60%
Total	2,267,672	100%

Table 5.14 Electricity production of Case II

Quantity	Value	Units
Excess Electricity	1,143,629	kWh/yr
Unmet Load	0.000671	kWh/yr
Capacity shortage	0.00	%
Renewable fraction	40	%

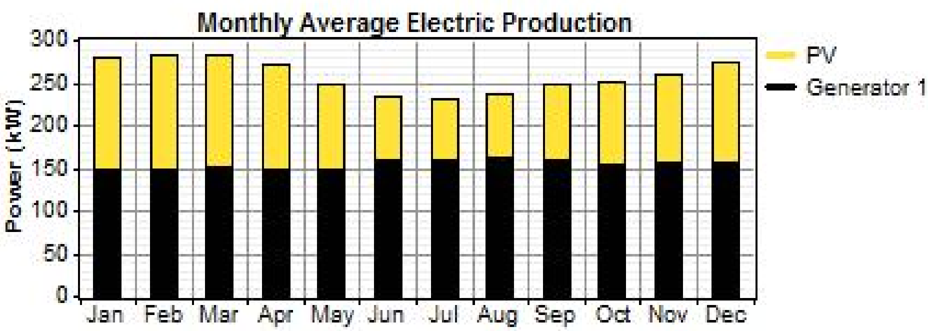


Figure 5.13 Monthly average electric productions for Case II

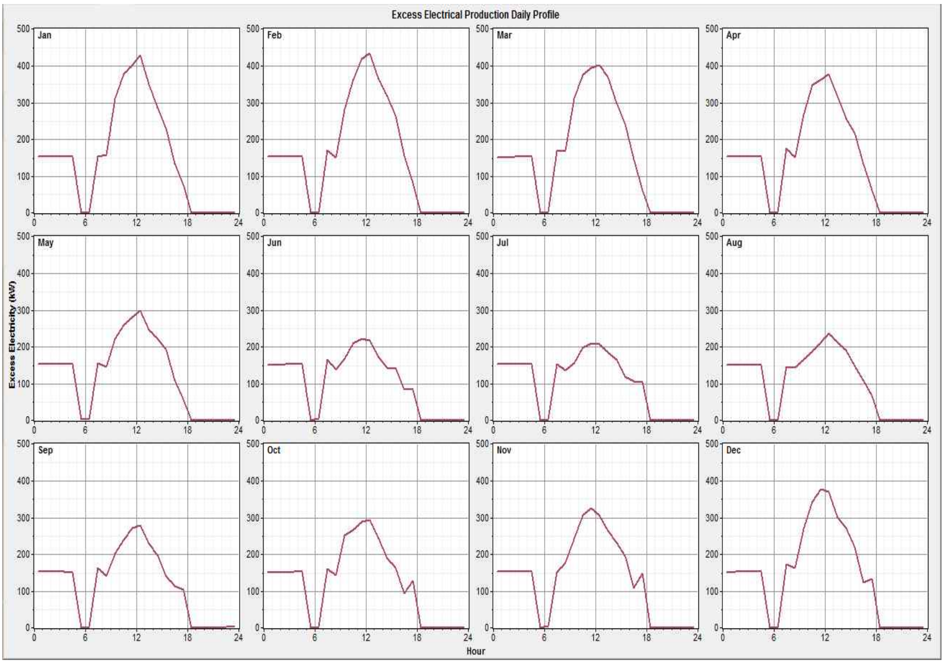


Figure 5.14 Excess electricity production of Case II

5.2.3 Discussion

This chapter proposes the PV-diesel hybrid system for improving the solar power consumption to reduce the CO_2 emission and fuel consumption. Although this system can reduce these above problems with 0% TED, this system was infeasible to maintain the system security and reduce the excess electricity for getting the optimal design due to the intermittent output of PV generator (Figure 5.15 and 5.16). In this problem, a BESS was added to the PV-diesel hybrid system to store power during the times of excess generation and generate power during the time of power shortages. Therefore, the next chapter is described about the PV-Diesel hybrid system with BESS to maximize the reliability of the system.

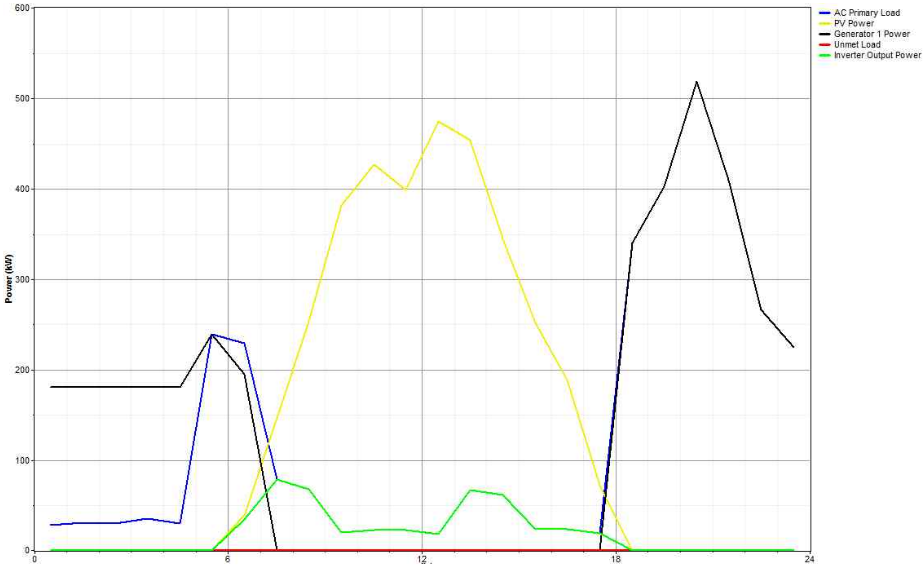


Figure 5.15 The best performance condition of solar Irradiation on one of the weekday in Summer of Case II for 0% TED

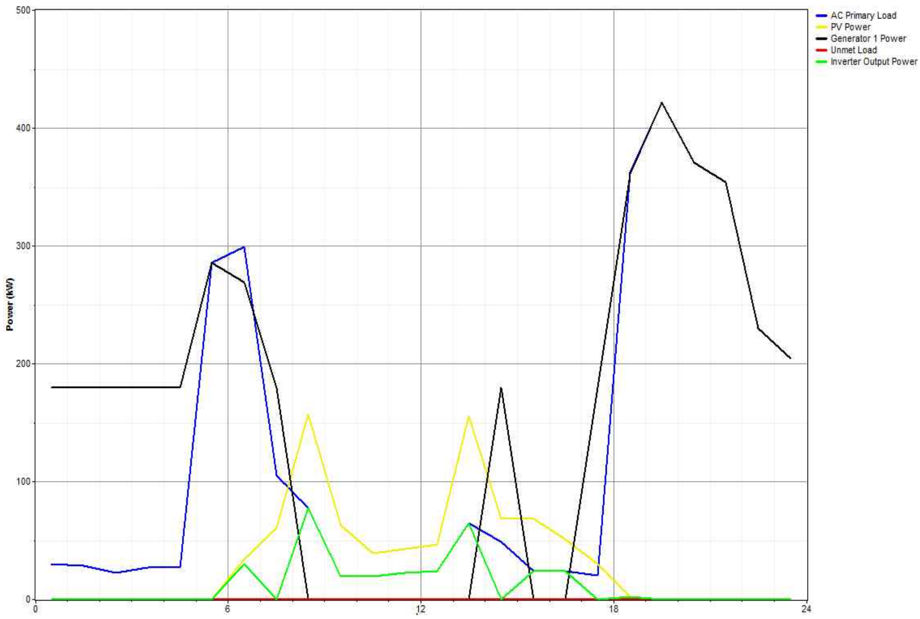


Figure 5.16 The worse performance condition of solar irradiation on one of the weekday in Rainy Season of Case II for 0% TED

5.3 Case III: PV-diesel Hybrid System with BESS

In this problem, the researcher considers the case of PV-diesel hybrid system with BESS (Case III) which is used to supply the proposed village to get the optimal sizing for economic cost evaluation. BESS controls the excess electricity to minimize the system operating cost to make the optimal condition. Thus, the problem is to minimize the excess electricity production which causes the system to be costly to build an optimal system by using of BESS, and then to minimize the system operating cost.

5.3.1 Proposed Hybrid System

In this research, the proposed hybrid system consists of diesel generator, solar PV-arrays, BESS and converter to achieve the efficient and cost competitive system configuration for improving people especially in rural areas. The power ratings for that proposed site are 600kW PV, 600kW generator, 800 surrette 6CS25P BESS and 400kW Convertor which are designed depending on the load profile of the proposed site.

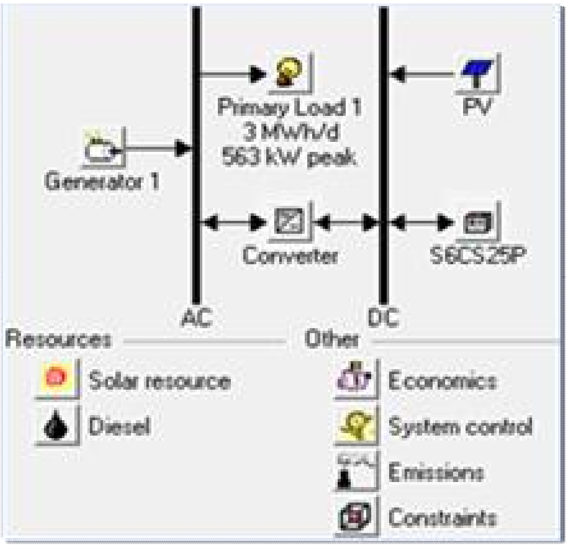


Figure 5.17 Proposed hybrid system with HOMER

Figure 5.17 shows the proposed hybrid system. In this section, the researcher uses the Equations 3.1 to 3.11 to evaluate the system economic cost and use the Equations 3.12 to 3.22 to calculate the system reliability of proposed site by using HOMER tool with 0% TED concept.

5.3.2 Simulation Results of Case III

The Case III is formed by adding 800 Surrette 6CS25P BESS in the original hybrid system (Case II) to analyze the result changing for supplying the whole load demand and the Cash Flow of Case III presents 600 kW Photovoltaic, 600 kW diesel generator and 800 Surrette 6CS25P battery with 400 kW converter are described in Table 5.15.

Table 5.15 System architecture of Case III

PV array	600 kW
Generator	600 kW
Battery	800
Inverter	400 kW
Rectifier	400 kW

5.3.2.1 PV Data

The same overview, only with data for an average year is displayed below Figures 5.18 and 5.19. The hours of the day is represented vertically. The red dots are presented for hours with the highest power production and black gaps represent hours with no power production at all. January, February, March and November are the months where the highest momentarily power production is reached. Months like June, July August, September, and October are characterized by many outages and underproduction of energy. The detail power production of PV is shown in Table 5.16.

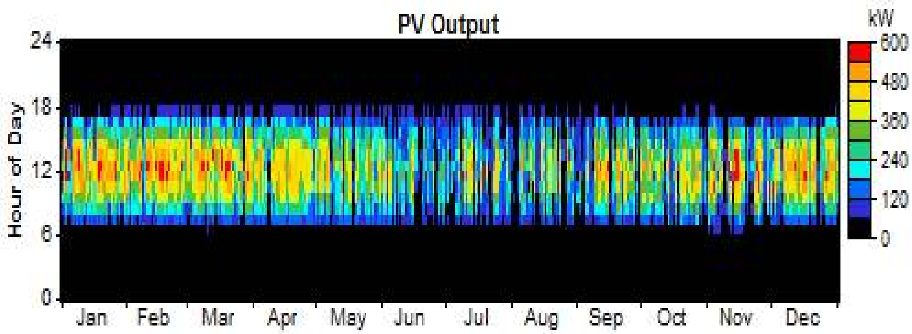


Figure 5.18 PV array output of Case III

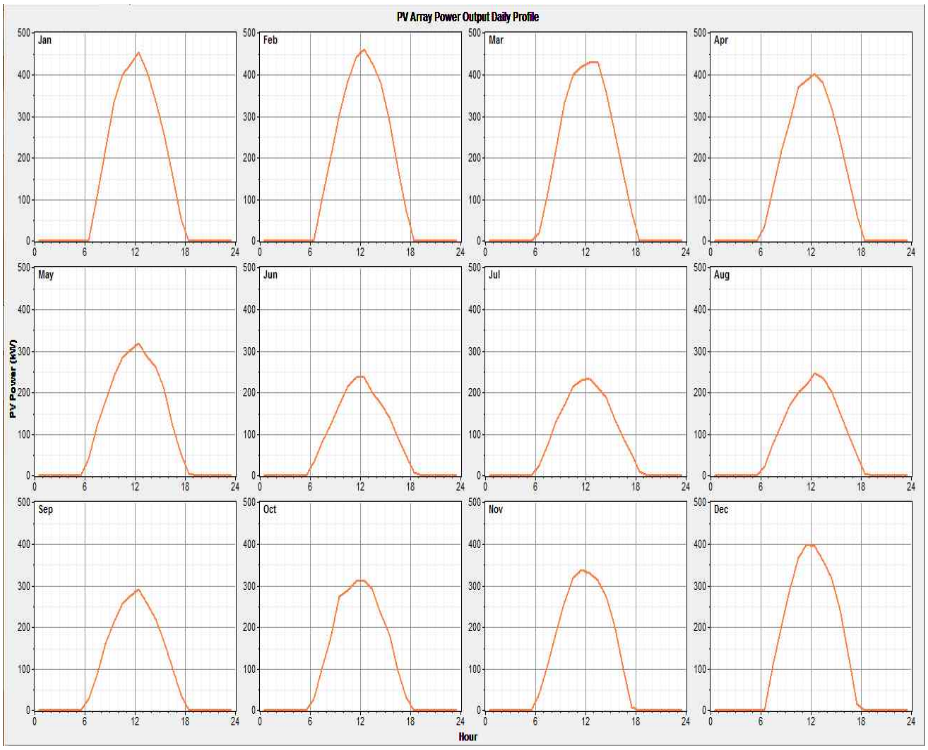


Figure 5.19 PV output curve of Case III

Table 5.16 Power production of PV of Case III

Quantity	Value	Units
Rated Capacity	600	kW
Mean Output	104	kW
Mean Output	2,495	kWh/d
Capacity Factor	17.3	%
Total Production	910,676	kWh/yr
Minimum Output	0	kW
Maximum Output	595	kW
PV Penetration	82	%
Hours of Operation	4,345	hr/yr
Levelized Cost	0.102	$/kWh

5.3.2.2 Generator Operation

As one can see from the overview in Table 5.17, the generator produces 787,246 kWh of energy per year. The details around the operation of the generator are displayed in the following tables. The hours of operation per year amounts to 2,146, and the generator have a lifetime of twelve years. The diesel generator is started 363 times and the marginal generation cost is 0.2 $/kWh.

Table 5.17 Generator operation of Case III

Quantity	Value	Units
Hours of operation	2,146	hr/yr
Number starts	363	starts/yr
Operational life	6.99	yr
Capacity factor	15.0	%
Fixed generation cost	42.4	$/hr

Marginal generation cost	0.200	$/kWh
Electrical Production	787,246	kWh/yr
Mean Electrical Output	367	kW
Minimum Electrical Output	180	kW
Maximum Electrical Output	600	kW

Below Table 5.18 presents that can see the details around the fuel usage. The total yearly consumption is 299,819 liters. Then, 0.381 liters are being used per kWh of produced energy from the generator.

Table 5.18 Fuel data of Case III

Quantity	Value	Units
Fuel consumption	299,819	L/yr
Specific fuel consumption	0.381	L/kWh
Fuel energy input	2,950,224	kWh/yr
Mean electrical efficiency	26.7	%

The generator is operating to fill in the missing power at the time when the weather is cloudy and there is not enough energy from the PV array to cover the demand. As one can see below Figure 5.20, the generator is most frequently being used at dawn or at dusk when the sun is gradually lower in radiations and the sun is in the outage condition. The use of the generator is most frequently in June, July, August, September, November and December.

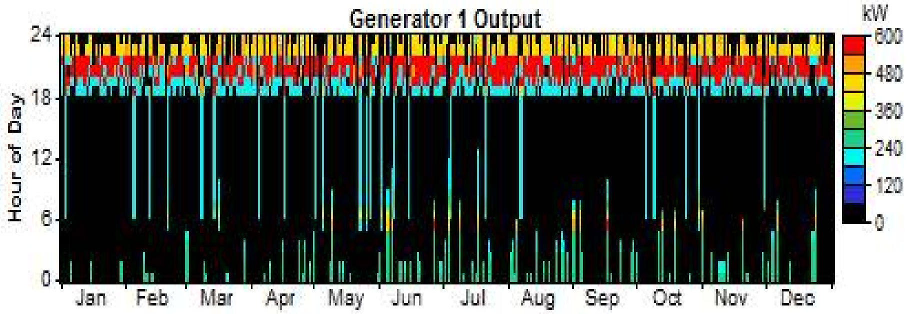


Figure 5.20 Generator output of Case III

5.3.2.3 BESS Data

A BESS of total 800 batteries with a string size of 2 was chosen to be able to have a battery bank operating with a voltage of 6 V. 400 parallel strings each containing 2 batteries were demanded to cover the storage capacity needed to satisfy the system setting and the state of charge in the third case is presented in Figure 5.21.

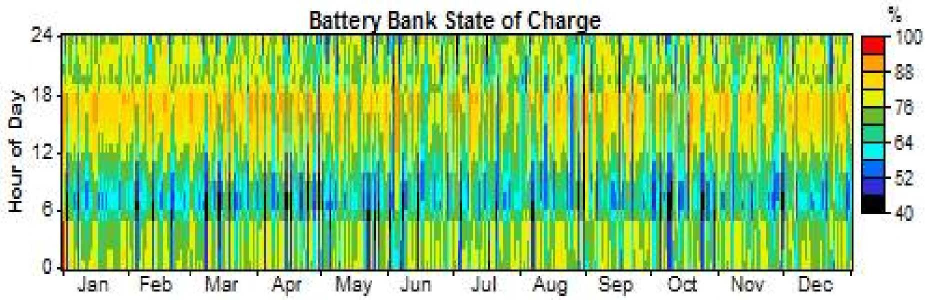


Figure 5.21 State of charge of Case III

The state of charge for an average year is displayed, regarding the hours of the day. One can see that it happens quite frequently so the battery bank is reaching a 90 percent to 100 percent state of charge. This practically means the operation of the batteries as they could cause damaging the BESS and shortening the BESS lifetime at the recent time. Charging full of batteries (marked by red) is characterizing the system. This implies that spillage is a quite frequent problem for the scaled system.

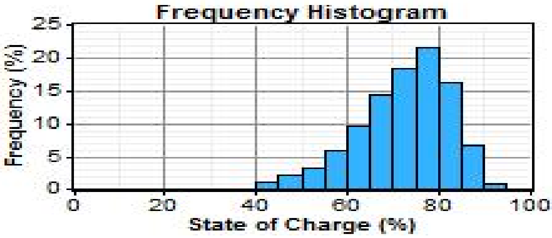


Figure 5.22 Frequency histogram of Case III

On the other hand, at some periods the batteries are reaching the critical level of 30 percent which automatically decouples BESS from the loads to avoid BESS damage, something which is causing shortages and loads not being served. As they face both problems with spillage and un-served loads because of empty BESS, one can conclude with that both a large and a smaller BESS would lead to suboptimal systems as solving a problem that worsens the other issue.

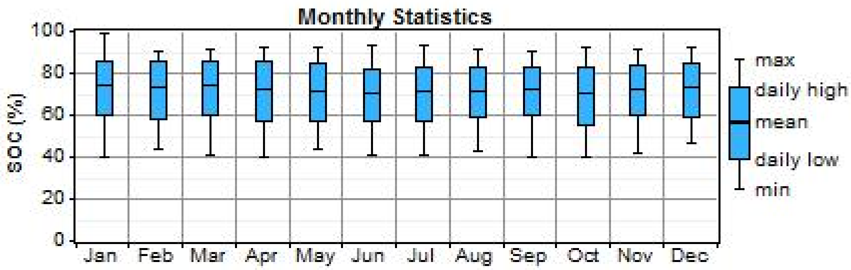


Figure 5.23 State of charge frequency of Case III

The frequency histogram is the other interesting overview provided by HOMER. It basically displays the same as Figure 5.22. However, it shows clearly the occurrences of the different state of charge. The frequency diagram gives important information regarding the healthiness of BESS, and can be used to detect pillage and how frequent the batteries are reaching unhealthy low or high levels. When frequency of batteries closes to 20 percent, SOC of the batteries will reach 70 percent full condition [Figure 5.23]. This is rather high percentage during the batteries is reached at the critical levels. Spillage seems to be a more frequent problem that unmet loads, however one must keep in mind that the two percent loss of load has to be satisfied. It means that no more than two percent of the loads can be unmet. The specified data of battery bank are shown in Table 5.19.

Table 5.19 Specified data of BESS

Quantity	Value	Units
String Size	2	-
Strings in parallel	400	-
Batteries	800	-
Bus Voltage	12	V
Energy in	705,490	kWh/yr
Energy out	565,490	kWh/yr
Storage Depletion	1,234	kWh/yr
Losses	138,765	kWh/yr
Annual Throughput	632,237	kWh/yr
Expected Life	12	yr

5.3.2.4 Converter Data

Below Table 5.20 shows the converter data of Case III. A 400 kW inverter is needed to satisfy the system and transform DC power that is sent by the PV modules to AC power, which can supply the loads.

Table 5.20 Converter data of Case III

Quantity	Inverter	Rectifier	Units
Capacity	400	400	kW
Mean Output	74	29	kW
Minimum Output	0	0	kW
Maximum Output	366	197	kW
Capacity Factor	18.5	7.3	%
Hours of	7,129	1,485	hrs/yr
Energy in	721,784	298,890	kWh/yr
Energy out	649,605	254,054	kWh/yr
Losses	72,179	44,836	kWh/yr

On the below Figure 5.24, the inverter output power over an averaged year is displayed by showing how the output is changing over each hour of the day. As the vertical lines are very varied, it can tell that the loads are changing during a 24 hours period are severe and something that fits with the load profiles that were implemented. The peak occurs at 6 p.m. In this figure, it can also see that the same pattern is mainly repeated over and over again, and implying the same load profile can calculate like the evening.

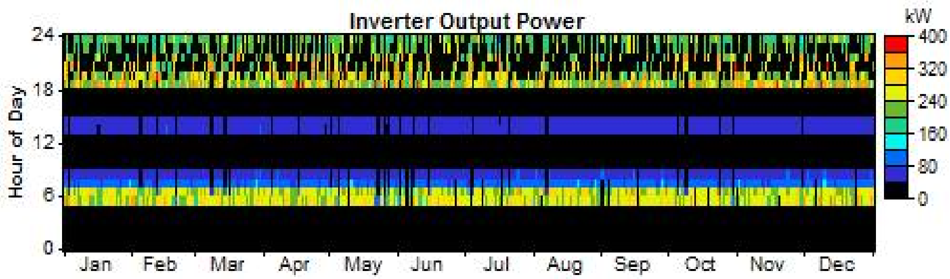


Figure 5.24 Inverter output power of Case III

If the same load profile is specified exactly, there are to be no load changes during the year. However it can detect some dark spaces in between the pattern and the undelivered energy from the PV array has been mentioned. It can see that June, July, August, September as well as December that are the highest delivery deficits.

5.3.2.5 Annual Emission

For the system with a backup generator, another factor to consider is the emissions connected to the operation of the Case III. The optimal Case III will have a little direct emission and from this Table 5.21, it can get a rough overview over the emissions connected to this case.

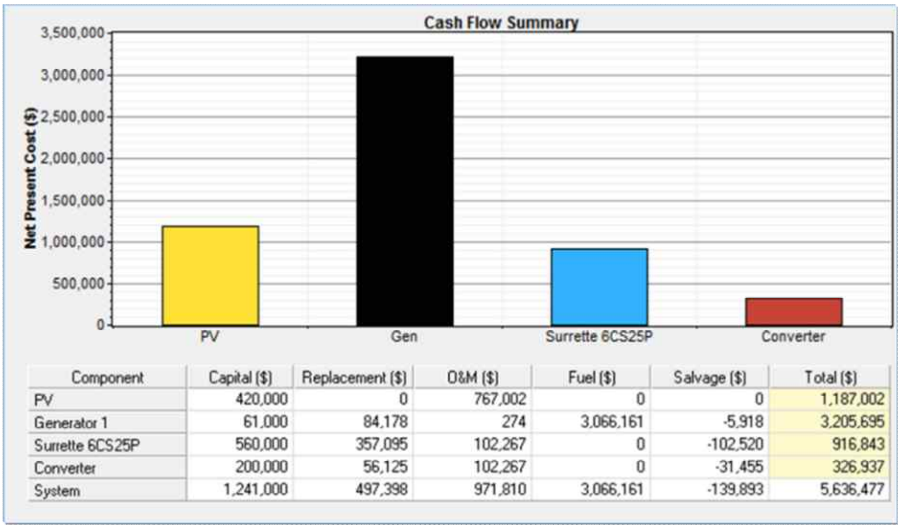
Table 5.21 Emission data of Case III

Pollutant	**Emission (kg/yr)**
Carbon dioxide	789,523
Carbon monoxide	1,949
Unburned hydrocarbons	216
Particulate matter	147
Sulfur dioxide	1,586
Nitrogen oxides	17,390

According to HOMER, among others 789,523 kg of carbon dioxide per year will be emitted as well as 17,390 kg of nitrogen oxides due to the operation of the diesel generator. These are significant magnitudes and they have to be taken into account when determining the optimal system, as not only technical and economical aspects are taken into account but also this pollutions reduction must be considered.

5.3.2.6 Economic Analysis of Simulation Results

The cash flow of the system is also included in \$ 1,187,002 net present cost for PV, \$ 3,205,695 net present cost for Gen 1, \$ 916,843 net present cost for BESS, \$ 326,937 net present cost for converter respectively. The whole system is cost about \$ 5,636,477 in the Case III, as shown in Figure 5.25.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	420,000	0	767,002	0	0	1,187,002
Generator 1	61,000	84,178	274	3,066,161	-5,918	3,205,695
Surrette 6CS25P	560,000	357,095	102,267	0	-102,520	916,843
Converter	200,000	56,125	102,267	0	-31,455	326,937
System	1,241,000	497,398	971,810	3,066,161	-139,893	5,636,477

Figure 5.25 Net present cost of Case III

According to the overview below Table 8.8 provided by HOMER, the total net current cost of the system is \$5,636,475 with the levelized price of energy of \$0.397/kWh in Table 5.22. The fuel cost based on the load profile implemented in HOMER is \$3,066,161. The nominal cash flows of Case III are shown in Figure 5.26.

Table 5.22 Cost summary of Case III

Description	Value	Units
Capital Cost	1,241,000	$
Replacement Cost	497,398	$
O & M Cost	971,810	$
Fuel Cost	3,066,161	$

Salvage Value	-139,893	$
Total Net Present Cost	5,636,475	$
Levelized Cost of Energy	0.397	$/kWh
Operating Cost	343,844	$/yr

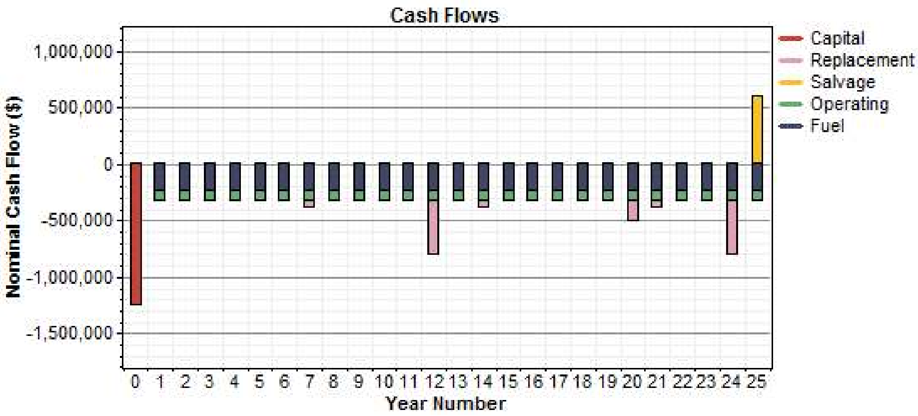


Figure 5.26 Nominal cash flows of Case III

Table 5.23 proposes the fraction of energy production from each component for Case III. The system produces an amount of 329,866 kWh/yr of excess electricity; this represents spilled energy due to fully charged batteries or other losses. The amount of unmet load is 0.000575kWh/year. In the Table 5.24 below, some of those unused kWh are being accounted for as well as shortages are identified. Capacity shortage is almost the same as 'unmet load', meaning electrical demand that remains un-served because electrical production falls short of demand. The difference is that capacity shortage comprises both unmet load and unmet operating reserve. A capacity of 0.00kWh/yr is stated, meaning 0.0 kWh/yr are not satisfying the operating reserves minimum state.

The following Figure 5.27, describes an overview over the monthly average electric production, is displayed. One can see that January, February, March and April are the months with the highest power production.

Table 5.23 Fraction of production of Case III

Component	Production (kWh/yr)	Fraction
PV array	910,676	54%
Generator	787,246	46%
Total	1,697,922	100%

Table 5.24 Electricity production of Case III

Quantity	Value	Units
Excess Electricity	329,866	kWh/yr
Unmet Load	0.000575	kWh/yr
Capacity shortage	0.00	%
Renewable fraction	54	%

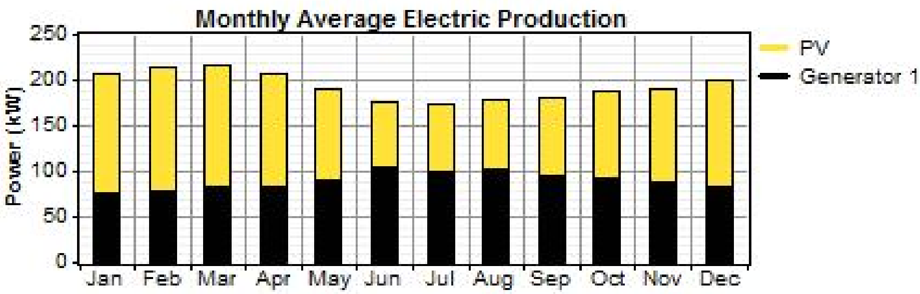


Figure 5.27 Monthly average electric productions for Case III

5.3.3 Comparison Results of Three Case Studies

The simulation results of all three studies are represented in Figure 5.28. And then, the comparison results of the three cases are shown in Table 5.25. According to this Table, total net present cost of Case I is larger than the Case II and Case III. The levelized cost of energy of DEG only is also increased the unit cost, \$0.292, more than PV combination with BESS. On the other hand, the percentage of Excess electricity in DEG only is nearly 7.2 percent less than the case II system but the case III is the least percent of excess electricity in all the systems. Moreover, the PV penetration of Case II and Case III are reasonable amount, about 82 percent (high penetration). In addition, CO_2 Emission of Case III is the very small amount in all cases and the rating is about 789,523 kg per year. Therefore, as the comparison result of these three case studies, the Case III is identified the optimized model from this result data and selected it to implement for this proposed site or village in this dissertation.

PV (kW)	Gen (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost (\$/yr)	Total NPC	COE (\$/kWh)	Ren. Frac.	Diesel (L)	Gen (hrs)
600	600	800	400	\$ 1,241,000	343,844	\$ 5,636,475	0.397	0.54	299,819	2,146
600	600		400	\$ 681,000	571,295	\$ 7,984,073	0.562	0.40	602,001	5,474
	600			\$ 61,000	760,878	\$ 9,787,568	0.689	0.00	909,449	8,760

Figure 5.28 Simulation results of Case III

According to the Figure 5.29 and Figure 5.30, this generation mix (Case III) is the best performance condition on one of the weekday in summer and winter with 0% TED. In this figure, the incident solar radiation increased to maximum point and PV power is very good result at the day time. After day time, the evening and night loads are alternately supplied by diesel generator and inverter output power.

Table 5.25 Comparison results of Case I, II and III

Description	**Case I** **Diesel Standalone System**	**Case II** **PV-diesel Hybrid System**	**Case III** **PV-diesel Hybrid System with BESS**
Total Net Present Cost ($)	9,787,568	7,984,073	5,636,475
Levelized Cost of Energy ($/kWh)	0.689	0.562	0.397
Operation Cost ($/yr)	760,878	571,295	343,844
Excess Electricity (%)	43.2	50.4	19.4
PV Penetration (%)	-	82%	82%
CO_2 Emission (kg/yr)	2,394,880	1,585,267	789,523
Renewable Fraction (%)	0.00	40	54
Fuel Consumption (L/yr)	909,449	602,001	299,819

In the figures 5.31, 5.32 and 5.33, the incident solar irradiance is fluctuated and low performance at the day time therefore the evening and night loads are supplied by only one diesel generator for 0% TED.

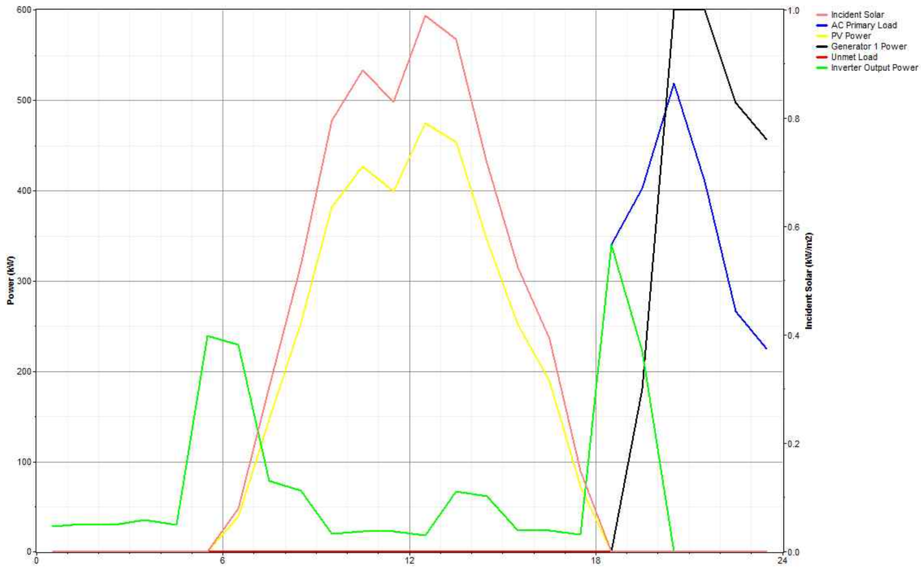


Figure 5.29 The best performance condition of solar irradiation on one of the weekday in Summer of Case III for 0% TED

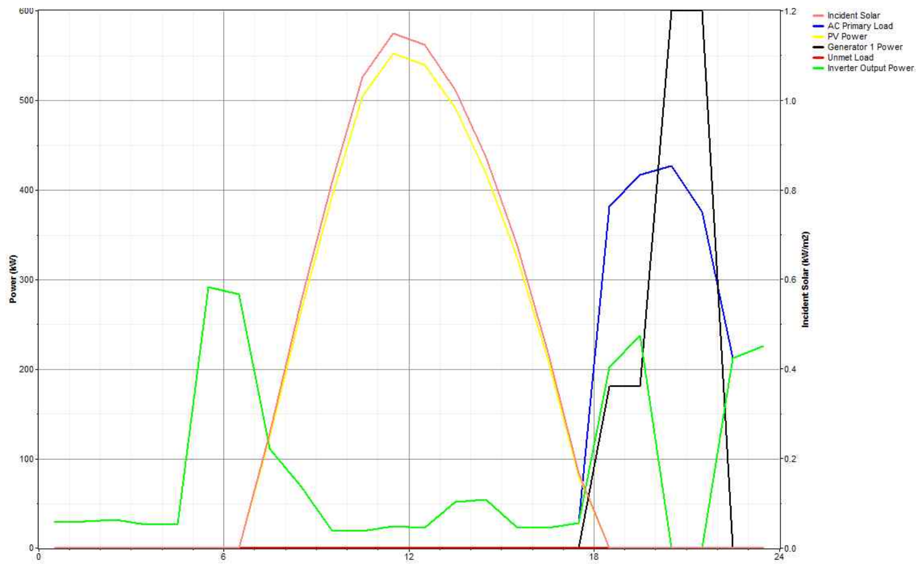


Figure 5.30 The best performance condition of solar irradiation on one of the weekday in Winter of Case III for 0% TED

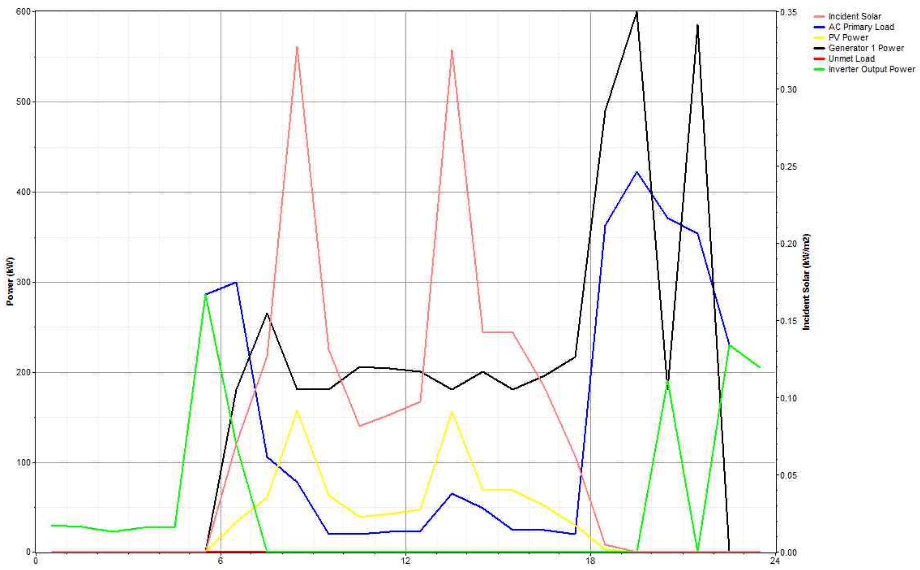


Figure 5.31 The worse performance condition of solar irradiation on one of the weekday in Rainy Season of Case III for 0% TED

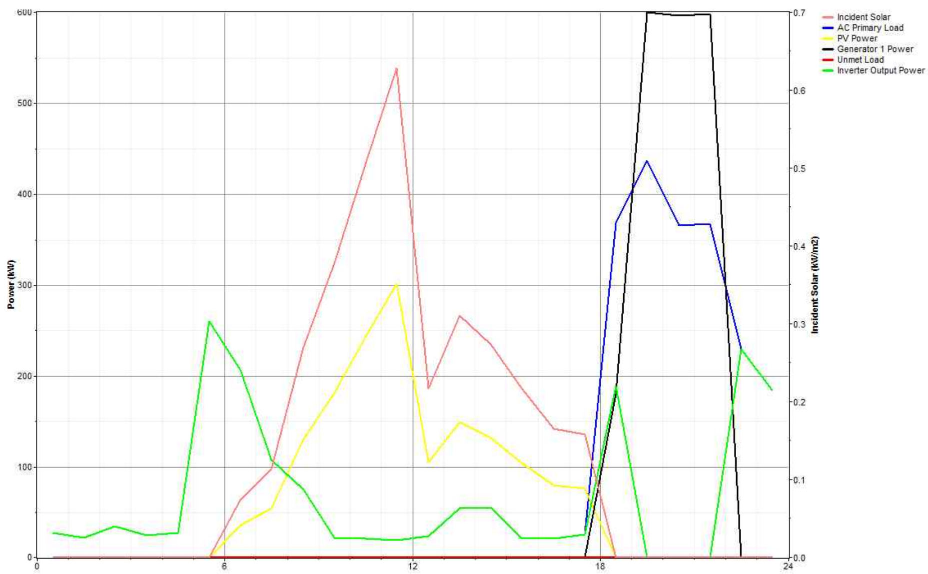


Figure 5.32 The worse performance condition of solar irradiation on one of the weekday in Rainy Season of Case III for 0% TED

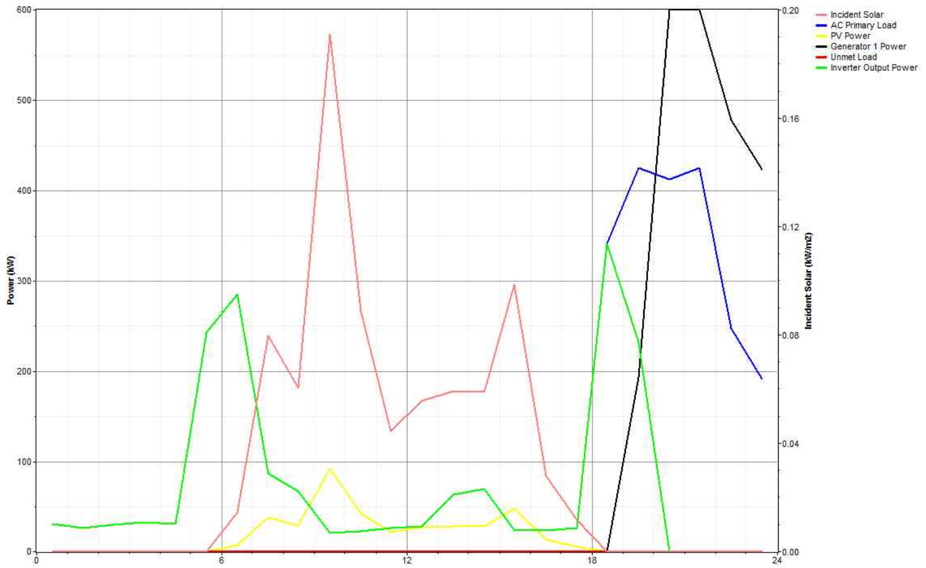


Figure 5.33 The worse performance condition of solar irradiation on one of the weekday in Rainy Season of Case III for 0% TED

5.3.4 Discussion

By comparing these three studies, the Case III becomes the most economic system for the proposed site through the total net current price \$5,636,475, the levelized energy price \$0.397/kWh and the operating cost of \$ 343,844/yr. The fractions of energy production from PV array and generator are 54% and 46% to meet the demand. Therefore, the using of renewable energy fraction is 0.54 and the PV penetration is 82%. Moreover, the excess electricity fraction is only 19.4% and the proposed system just only emits 789,523kg/yr of the carbon emission. It is more effective using the developed PV-diesel hybrid system with BESS to get the most optimal design than using the stand-alone diesel and PV-diesel systems with 0% TED.

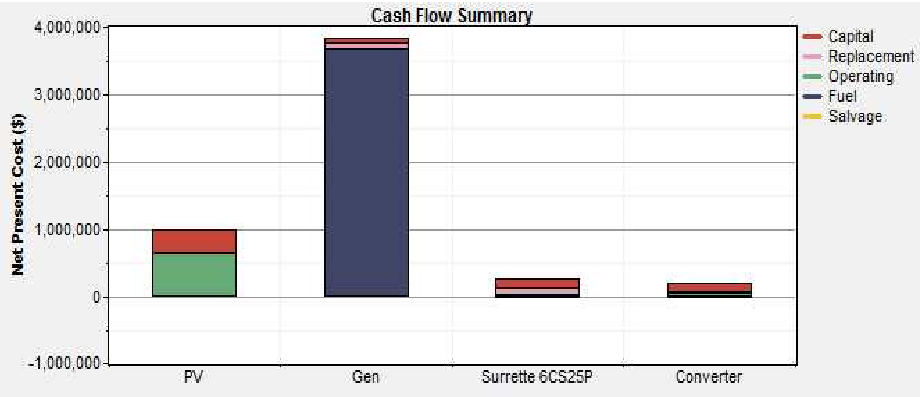
5.3.5 System Sizing of Case III

The results which are changed as Case II are described in the dissertation by adding 600kW PV like 600kW diesel stand-alone system which is the original Case I. In order to overcome a huge energy surplus, the Case III is considered by combining 800 numbers of batteries with Case II.

PV (kW)	Gen (kW)	S6CS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen (hrs)
500	500	200	200	$ 640,833	357,610	$ 5,212,293	0.367	0.44	359,704	2,975
500	500	200	100	$ 590,833	365,332	$ 5,261,007	0.370	0.44	371,708	3,146
400	300	800	300	$ 1,020,500	332,353	$ 5,269,085	0.371	0.41	313,251	3,773
500	400	600	200	$ 910,667	346,676	$ 5,342,349	0.376	0.44	331,030	2,832
500	500	400	200	$ 780,833	358,312	$ 5,361,269	0.377	0.44	352,439	2,832
400	300	800	400	$ 1,070,500	337,446	$ 5,384,194	0.379	0.40	316,442	3,801
400	500	800	400	$ 1,090,833	336,402	$ 5,391,178	0.380	0.41	315,283	2,509
500	500	800	400	$ 1,160,833	333,404	$ 5,422,850	0.382	0.48	299,527	2,400
600	500	200	100	$ 660,833	374,812	$ 5,452,193	0.384	0.48	371,049	3,148
400	400	800	300	$ 1,030,667	346,995	$ 5,466,426	0.385	0.40	330,328	3,351
400	500	600	400	$ 950,833	355,287	$ 5,492,595	0.387	0.40	342,143	2,896
500	600	200	200	$ 651,000	379,283	$ 5,499,506	0.387	0.44	384,799	2,979
500	300	800	300	$ 1,090,500	345,000	$ 5,500,757	0.387	0.46	316,001	3,990
600	500	800	400	$ 1,230,833	334,751	$ 5,510,070	0.388	0.54	288,974	2,333
400	500	800	300	$ 1,040,833	350,429	$ 5,520,498	0.389	0.41	334,384	2,869
600	400	600	200	$ 980,667	355,825	$ 5,529,299	0.389	0.49	329,966	2,832
500	500	600	400	$ 1,020,833	353,021	$ 5,533,631	0.390	0.47	326,863	2,740
500	300	600	300	$ 950,500	360,542	$ 5,559,437	0.391	0.45	341,670	4,495
500	600	200	100	$ 601,000	388,633	$ 5,569,030	0.392	0.43	398,707	3,146
500	400	800	200	$ 1,050,667	353,533	$ 5,570,009	0.392	0.44	330,882	2,831
400	500	800	100	$ 940,833	362,691	$ 5,577,243	0.393	0.42	353,284	3,487
400	600	800	400	$ 1,101,000	350,727	$ 5,584,472	0.393	0.41	332,324	2,373
500	600	800	400	$ 1,171,000	345,686	$ 5,590,022	0.394	0.48	314,129	2,246
400	400	800	400	$ 1,080,667	352,788	$ 5,590,480	0.394	0.40	334,386	3,375
500	500	600	200	$ 920,833	365,915	$ 5,598,450	0.394	0.44	353,227	2,830
500	400	800	300	$ 1,100,667	352,738	$ 5,609,846	0.395	0.47	324,876	3,390
500	500	800	300	$ 1,110,833	352,457	$ 5,616,418	0.395	0.47	324,566	2,833
500	600	400	200	$ 791,000	377,899	$ 5,621,816	0.396	0.44	375,068	2,831
500	400	800	400	$ 1,150,667	350,351	$ 5,629,324	0.396	0.47	319,334	3,230
500	300	800	400	$ 1,140,500	351,167	$ 5,629,590	0.397	0.46	319,763	4,033
600	600	800	400	$ 1,241,000	343,844	$ 5,636,475	0.397	0.54	299,819	2,146
600	500	600	400	$ 1,090,833	355,747	$ 5,638,472	0.397	0.52	317,380	2,664
400	600	600	400	$ 961,000	366,630	$ 5,647,767	0.398	0.40	354,956	2,665
500	500	600	300	$ 970,833	367,308	$ 5,666,267	0.399	0.46	350,638	3,113
600	600	200	200	$ 721,000	387,785	$ 5,678,194	0.400	0.49	382,975	2,969
500	500	800	100	$ 1,010,833	365,529	$ 5,683,521	0.400	0.48	344,618	3,418
500	400	600	300	$ 960,667	369,595	$ 5,685,329	0.400	0.45	350,939	3,779
500	300	600	400	$ 1,000,500	366,484	$ 5,685,400	0.400	0.45	342,770	4,466
600	300	800	300	$ 1,160,500	355,991	$ 5,711,258	0.402	0.51	316,942	4,109
500	500	200	300	$ 690,833	392,853	$ 5,712,813	0.402	0.42	398,026	3,475
600	400	800	300	$ 1,170,667	356,216	$ 5,724,299	0.403	0.52	316,916	3,333
500	500	600	100	$ 870,833	380,144	$ 5,730,353	0.403	0.46	370,581	3,663
600	500	800	300	$ 1,180,833	355,898	$ 5,730,405	0.403	0.53	316,525	2,795
500	400	600	400	$ 1,010,667	369,443	$ 5,733,392	0.404	0.45	343,952	3,599
500	300	600	500	$ 1,050,500	366,400	$ 5,734,322	0.404	0.44	338,822	4,150
600	400	800	400	$ 1,220,667	353,218	$ 5,735,981	0.404	0.52	310,389	3,162
400	600	800	300	$ 1,051,000	367,267	$ 5,745,911	0.405	0.41	354,179	2,741
600	400	800	200	$ 1,120,667	362,674	$ 5,756,863	0.405	0.49	329,808	2,831
500	600	600	400	$ 1,031,000	369,885	$ 5,759,370	0.406	0.46	345,750	2,616
600	600	200	100	$ 671,000	398,143	$ 5,760,598	0.406	0.48	398,083	3,148

Figure 5.34 Simulation results of Optimal Case III

By comparing these three results gained at the same time, Case III, PV-diesel-battery hybrid system is the amazing cheapness. Although it seems that Case III will be costly as it includes many components such PV, battery, diesel and converter, in practice, it is the cheapest one under the same power rating. So, it is undeniable that the Case Study III (PV-Diesel-Battery Hybrid System) is the best configuration of these three configurations under the same condition of power rating. The dissertation is not completed in this stage because the size is also needed to be optimal. It is simulated again by changing the system ratings of each component to select the optimal sizing. So, the fifty combinations of case study III are feasible for proposed area and then the following Figure 5.34 shows the simulation results for system sizing. According to the simulation results, the combination of 500kW PV, 500kW Diesel, 200 numbers of ESS, and 200kW converter which are the least TNPC is chosen as the most optimal size for that proposed area.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	350,000	0	639,168	0	0	989,168
Generator 1	50,833	101,204	317	3,678,579	-485	3,830,448
Surrette 6CS25P	140,000	89,274	25,567	0	-25,630	229,211
Converter	100,000	28,062	51,133	0	-15,727	163,468
System	640,833	218,540	716,185	3,678,579	-41,843	5,212,296

Figure 5.35 Net present cost of Optimal Case III

The cash flow of the system is also included in $ 989,168 net present cost for PV, $ 3,830,448 net present cost for Gen 1, $ 229,211 net present cost for Surrette, $ 163,468 net present cost for converter respectively. The whole system costs about $ 5,212,296 in the Case III, as shown in Figures 5.35 and 5.36.

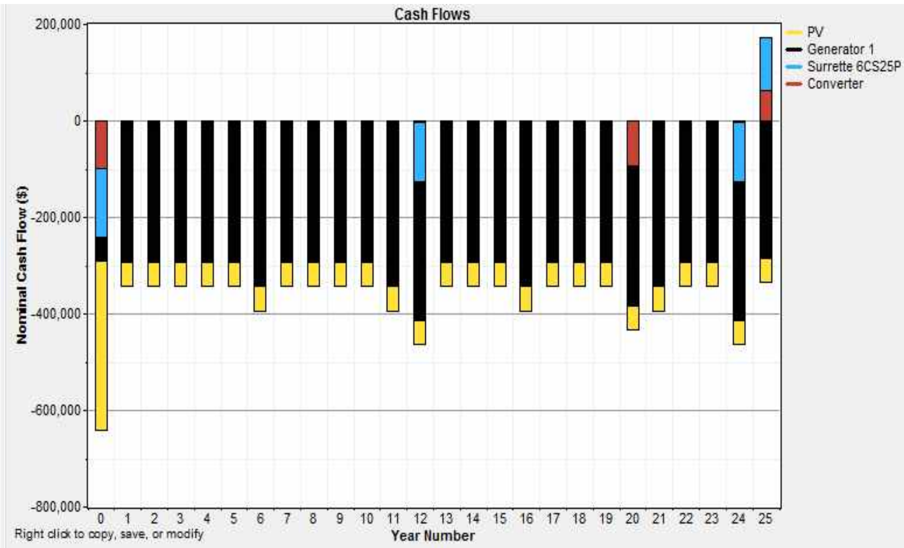


Figure 5.36 Nominal cash flows of Optimal Case III

Table 5.26 Fraction of production of Optimal Case III

Component	Production (kWh/yr)	Fraction
PV array	758,897	44%
Generator	962,814	56%
Total	1,721,711	100%

The fraction of energy production from each component for Case III is described in Table 5.26. The system produces an amount of 557,234 kWh/yr of excess electricity; this represents spilled energy due to fully charged BESS or other losses. The amount of unmet load is 0.000219kWh/year.

An overview over the monthly average electric production is displayed in the following Figure 5.37.

Table 5.27 Electricity production of Optimal Case III

Quantity	Value	Units
Excess Electricity	557,234	kWh/yr
Unmet Load	0.000219	kWh/yr
Capacity shortage	0.00	%
Renewable fraction	44.1	%

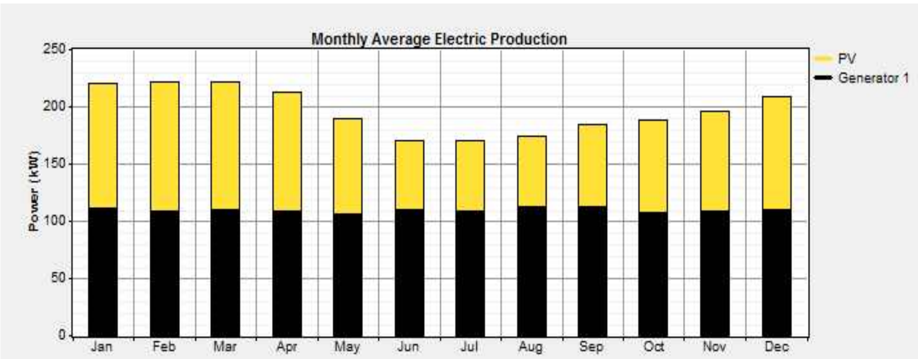


Figure 5.37 Monthly average electric productions for Optimal Case III

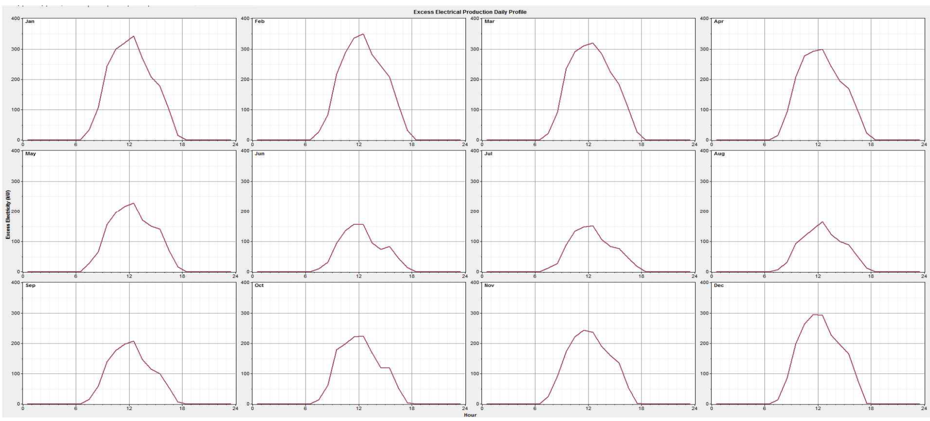


Figure 5.38 Excess electricity production of Optimal Case III

5.3.6 Overall Comparison Results

According to this Table, total net present cost of Case III is the minimum among these systems. The percentage of Excess electricity in DEG only is nearly 7.2 percent less than the case II system but the case III is the least percent of excess electricity in all the systems.

Table 5.28 Overall comparison results

Description	Case I	Case II	Case III
Total Net Present Cost ($)	9,787,568	7,984,073	5,212,293
Levelized Cost of Energy ($/kWh)	0.689	0.562	0.367
Operation Cost ($/yr)	760,878	571,295	357,610
Excess Electricity (%)	43.2	50.4	32.4
PV Penetration (%)	-	82%	68.3
CO2 Emission (kg/yr)	2,394,880	1,585,267	947,218
Renewable Fraction (%)	0.00	40	44.1
Fuel Consumption (L/yr)	909,449	602,001	359,704

Moreover, the PV penetration of Case II and Case III are reasonable amount, about 82 and 68.3 percent (high penetration). In addition, CO_2 Emission of Case III is the very small amount in all cases and the rating is about 947,218 kg per year. So, the Case III with new system rating is selected as the most optimal model due to the comparison result of these three case studies to supply that certain area.

Chapter 6. Conclusion and Future Work

6.1 Conclusion

The proposed area of this research is Kyit Sone Pwe Village, Magwe Region in Myanmar in which the electricity is not accessed from national grid and extension of the grid is also very expensive, or it is the place where the grid cannot work out without much losses is se and the renewable energy potential for this region is evaluated to make the analysis of cost of energy. The technical factors and some nontechnical factors affect the high capital price of hybrid systems, so it is needed to consider the effect of each factor to perform the study of the hybrid system. Correct system-sizing mechanism of the system's components is one of the crucial factors, which directly affect the price of electricity. Components' over-sizing in hybrid system makes the system dearer, while under-sizing makes the system unreliable. Thus, economical and reliable benefits are given to the system by optimum sizing for different components. Therefore, this thesis will highlight the optimum system design with minimizing the electricity cost.

This analysis investigates the options for providing electricity to the village using solar and diesel power sources. The results show the impact of different assumptions about the solar resource, and fuel price applying a hybrid software tools HOMER with TED concept. the components system's technical and economical parameters are applied to perform the simulation results which are presented in the previous chapter.

For supplying electricity to the proposed village, it is needed to manage the total load demand. In this research work, the load profile for rainy season is assumed lower than that of other seasons. When the load schedule is managed firstly, the possible minimum demand load is encountered but the simulation will perform to cover the load demand which is becoming to increase in future. This research work provides a simulation time step with one hour as in the first step, the reliability model of the system is developed in terms of the concept of TED concept. For this purpose, considering different combinations taken into account: the PV generator, diesel, and the storage of capacity (BESS), has made several simulations.

This dissertation highlights to improve the optimal sizing model based on zero load energy deficit approach to optimize the capacity sizes of various stand-alone PV/diesel/BESS hybrid system components. The suggested model considers the hybrid system submodels, TED for the reliability of system, and TNPC and COE for system optimization. The flow diagram of the hybrid optimal sizing model is also illustrated. Exploiting the developed model, all configurations giving the rate of 0% of TED are remained. At the same time, the optimal configuration is predicted on the basis of the minimum price. By using solar radiation and ambient temperature data collected on the site of Magway (Myanmar), the optimized system is compared to the choices of other energy source.

The optimal system type for this option is PV-diesel hybrid system with BESS as mentioned in the previous chapter. The system operation needs to provide better reliability with matching the balance of the system. The optimal design of this system was found by comparing three different hybrid configuration topologies which are diesel stand alone system, solar-diesel hybrid system with BESS and solar-diesel hybrid system without BESS. And then HOMER algorithm with TED concept and Microsoft office excel tool have been used to design the off-grid power system for that village. HOMER, the model of micropower optimization, simplifies the task to evaluate designs of both off-grid and grid-connected power systems for a variety of applications. HOMER's three main functions are simulation, optimization, and sensitivity analysis. In case study I, 600kW diesel stand-alone system is considered to supply the whole load demand. In case study II, the hybrid system contains 600kW PV, 600kW generator, and 400kW converter and the case study III considers 500kW PV, 500kW Generator, 200 Surrette 6CS25P batteries, and 200kW Converter to meet the demand. The climatic data for solar energy source has been obtained by NASA website. By comparing these three studies, the PV-diesel hybrid system with BESS becomes the most economic system for the proposed site by computing the TNPC of $5,212,293, the levelized energy cost of $0.367/kWh and the operating cost of $ 357,610/yr. The fractions of energy production from PV array and generator are 44% and 56% to meet the demand. Moreoever, the excess electricity fraction is only 32.4% and the proposed system just only emits 947,218/yr of the carbon emission. In contrast, the results show that the significant fuel saving can be achieved by using the developed PV-diesel hybrid system with BESS by comparing with diesel stand alone and PV-diesel systems.

The major point to conclude this paper is that the choosing system devices represent an important step in the optimal sizing of the hybrid PV/diesel system with BESS so that the system operation will need the load with improving reliability of the system.

The second conclusion that can be withdrawn from this work is the possibility to create a typical design for hybrid energy systems to supply energy in remote area wherever the site or location has a favorable solar radiation. The design optimization of hybrid energy systems is dependent of countless variables. To be certain, the more important parameters that influence the capital costs of the system are associated with the technologies and the investment costs of the components. According to the current cost of PV module, Diesel and BESS, the COE ($/kWh) is 0.367$/kWh, the initial cost is expected to decrease in the near future to reduce that energy cost. Even though, using RE sources is far more popular than the past while the cost of the components are decreasing.

Finally, the proposed system is aimed to not only optimize the energy cost but also increase the system reliability by using HOMER Tool with 0% of TED concept. According to simulation results which have been obtained by using HOMER tool, TNPC \$5,209,654 in the proposed PV-diesel-BESS hybrid system (case study III) is obviously less than the other two systems (case studies I and II) and LCOE is also much lower than the others. Even then, the excess electricity of the proposed system is only 32.4% which is making the proposed hybrid system more economic than the other two systems. Furthermore, the 68.3% of PV penetration of that proposed hybrid system can be profitable for that concentrated area. By applying the proposed hybrid system (case study III), the environmental affects which can cause several problems for indigenous people due to the release of carbon dioxide will be reduced because that proposed system can decrease the CO_2 emission up to 947,218 kg per year. As the renewable energy fraction of that proposed system can be used up to 44%, the fuel consumption can be reduced up to 359,704 L per year. Therefore, the proposed hybrid system (case III) is selected and identified as the optimized model to implement for certain chosen rural area in this research work. As the survey went on the other research papers that have been recently done on this topic, they normally focused only on one system, but in this research, three hybrid systems have been carefully researched to see obviously that the case study III is the most optimal design for rural electrification among these three case studies [11-12]. Therefore, it is undeniable that this dissertation gives the best solution for economic cost evaluation of rural electrification with very high reliability.

In this dissertation, however, the following assumptions are restricted:

1. The unstable prices of all of hybrid system components are used in this hybrid system that can change the system optimization.

2. The capacity penalties of each component are not considered in this thesis.
3. No tracking device for collection of solar radiation is employed so the prediction error of solar power can be obtained. It presents no additional cost but provides a lower energy.
4. Only cycle charging strategy is employed to manage the system control unit closely to operate the standard condition. Only the impact of SOC, current and time between full charges is considered in the economic operation of BESS.
5. Consideration of temperature effect is out of concerns; only the monthly solar radiation is used in this study.

6.2 Future Work

The research conducted in this dissertation can be extended with various directions as follows.

Much favors should be contributed to controllers, determined the operational stages and integration with the conventional diesel generator. Trying the controllers near system limits of stability to extend the periods of time is imperative. System control inputs define how HOMER models the operation of BESS and generators. The dispatch strategy determines how the system charges BESS. Dispatch strategy is a rule that governs the generator operation and the battery bank having two strategies: cycle charging and load following. The optimal system type relies on many factors, covering the sizes of the generators and BESS, the fuel cost, the operation and maintenance price of the generators, the amount of renewable power in the system, and the character of the renewable resources. In this dissertation, the researcher only uses the cycle charging strategy as the system control unit. This research has not covered the control unit of load following strategy for overall hybrid system. So, the researcher would like to recommend that the future work should highlight on well implementation of the algorithm covering the load following strategy or advanced strategy for control unit. It should be concentrated on how the operating decisions, sizing choices and cost are elated to different higher demand load profiles of hybrid system studied in this research.

Furthermore, in this dissertation, the formulation of operating conditions including SOC, current and time between full charges is mainly for Surrette 6CS25P BESS type. This is because, among all types of batteries, Surrette 6CS25P BESS takes advantages of a low-cost, high efficiency and particularly, a high degree of maturity. However, battery technologies are developing quickly today with lower cost while the technical performance is much improved - such as Surrette S460, Trojan L16P, Trojan T-105, and USB US-250 BESS types.

Finally, in this dissertation, the researcher has only discussed the simulation and optimization analysis by HOMER tool. In such hybrid system, the right, role and responsibility of sensitivity analysis need to be clear and the proposed hybrid system considers the cause and effect of it with respect to a very important issue of power systems. In future work, the researcher will extend the studying about the sensitivity analysis of the proposed hybrid system.

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논 문 초록

화석 연로로 에너지를공급하는 것은유용하지만, 그 자원이 유한하며 환경 문제를 발생 시키기 때문에 사람들은 새로운에너지 자원을 찾게 되었다.수력, 바이오 매스, 풍력, 태양열 및 기타 청정 에너지와 같은 신재생 에너지 자원은 환경 오염을 효과적으로 감소시킬 수 있기 때문에 전 세계의 전력 시스템에 광범위하게 적용되고 있다.그러나 엔진 발전기나 에너지 저장 장치와 같은 백업 시스템을 사용하지 않고, 신재생 에너지만 사용하는 시스템은 신뢰하기가 어렵다. 따라서백업 시스템과하나 이상의 신재생 에너지 기술을 결합한 하이브리드 에너지 시스템은 디젤, 바이오 매스, 풍력, 태양광 또는 소형 수력 발전기와 같은 다양한 자원을 결합하여 얻을 수 있다.독립된 교외 지역은특정한 이용 특성(예를 들어,지불 의향 혹은 부하 곡선), 기상학적 상황(예를 들어,풍속,태양 복사,온도 및 수력), 그리고 지역 공급 옵션에 따라서 위의 자원들을 다양하게 조합하여 최소 비용으로 시스템을 구성할 수 있다.하이브리드 시스템을 어떤 유형으로 구성할지는 경제, 사회, 환경 및 안전을 고려하여 결정해야만 한다.이에 따라,본 논문의 목적은 투자 결정을 하기 위해서 제안 된 지역에 단독디젤,태양광-디젤그리고태양광-디젤-배터리 하이브리드 시스템 중에서 어떤 시스템에 투자하는 것이 경제적인지 확인하고자 한다. 이 목표를 달성하기 위해전원 공급 장치 손실 확률(LPSP: Loss of Power Supply Probability)을 기반으로 하는 총 에너지 부족분(TED: Total Energy Deficit)개념을 이용하여 개발한 신뢰도 모델과총 현재 순 비용(TNPC: Total Net Present Cost)과 에너지 비용(COE: Cost of Energy)계산을 기반으로 하는 경제적 모델, 두 모델을 이용하여 기술-경제적 접근법을 HOMER Tool 로 개발하였다. 이 두 모델을결합하여비용측면에서 가장 경제적이면서 시스템이 독립적으로 운영될수있도록 하는 최적구성을결정할 수있게 되었다. 시뮬레이션에서

태양광 용량과 같은 크기 조정 매개변수들이 사용된다.디젤 발전기는 최대 전기 수요를 충족하는 크기로 정해진다 (제안 된 전략에 따름). 개발된 방법론을 적용하면, 모든 케이스들의 시스템이 TED0%를 유지하도록 운영될 때, TNPC 개념에 기반한 최소 비용 기준에 따라 최적 시스템을 예측할 수 있다. 또한, 개발 된 모델은 디젤 발전기가 소비하는 연료 및 방출하는 CO_2의 양을 계산하는 데 사용된다.제안 된 방법론을 강조하기 위해서 20.154N 위도 및 94.945E 경도에 위치한 미얀마 Magway의 Kyit Sone Pwe 마을에공급하기 위한 세가지 시스템,즉 단독 디젤, BESS 가없는태양광-디젤, BESS 가있는태양광-디젤 구성을 분석하였다.해당 지역의 연 평균 일사량은 4.841kWh/m^2/day 이며,대상이 되는 마을의 현재 상황을 충족하는 적절한 부하 데이터를 준비하는 것이 매우 중요하다. 이 마을의 부하는 가구 당 평균다섯 명의 구성원이있는 1300 개의 가구로 총 인구수는 약 6500 으로 결정하였다. 총 부하의 수요를 계산하면,제시 된 마을의 피크 수요는 563kW 이다. 첫 번째 케이스인 단독 디젤 시스템의 경우, 전력 수요를 충족시킬 수 있지만 연료 비용이 높고 CO_2 배출량이 많기 때문에 경제적으로 시스템을 구현하기가 어렵다. 그래서 시스템 운영 비용을 줄이기 위해태양광발전을 시스템에 추가하여태양광-디젤 하이브리드 시스템을 생성하였다.그러나태양광-디젤 시스템은태양광 발전기의 간헐적인 출력으로 인해 최적설계를 위한 시스템 안전을 유지하는 것이 불가능하였다.이러한 문제를 해결하기 위해태양광-디젤 하이브리드 시스템에 BESS 를추가하여 과잉 발전시 전력을 저장하고 전력 부족시 전력을 출력하였다. 이 시스템은프로젝트 기간 동안 발생하는 자본 비용, 교체 비용, 연료비및 유지 보수 비용과 관련된 현재 순비용과 전기 가격그리고운영 비용 측면에서 가장 우수한 특성을 나타냈다.이 연구에서 시뮬레이션 시간 단위는 한 시간이며,첫 번째 단계에서 LPSP 개념 기반으로 시스템 신뢰도 모델을 개발한다.이런 목적으로

하이브리드 시스템의 여러 조합을 고려하여 몇 개의 시뮬레이션을 수행하였다. 알고리즘의 입력 데이터는 2016 년 Magway 의 온도 데이터로 나타낸 지표면에서의 시간별 태양 복사와 1 년 동안의 수요로 나타낸 에너지 요구량 그리고 시스템 장치의 사양으로 구성된다.세 시스템 모두 개발 된 프로그램으로 시뮬레이션 되고,시스템 구성,과잉 발전량, CO_2 량, 그리고 시스템 비용의 관계를 연구한다.하이브리드 시스템의 최적 구성은 전체 시스템 신뢰도(TED = 0 %) 와 시스템 비용 측면에서 결정된다.시뮬레이션 결과에 따르면,제안된 태양광/디젤/배터리 하이브리드 시스템의 TNPC, COE, 그리고 CO_2 배출량의 최적 값이 각각 $5,212,293 (TNPC), $0.367/kWh (COE) 그리고 947,218 kg/yr 으로 얻어진다. 그러나 태양광/디젤 시스템의 경우 이 값들이 $7,984,073 (TNPC), $0.562/kWh (COE) 그리고 1,585,267kg/yr 으로 매우 증가한다.제안된 하이브리드 시스템이 수요를 충족시키기 위한 태양광 발전기와 디젤 발전기의 에너지 생산 비율은 44% 및 56%이다. 이것은 Magway 지역의 강력한 태양 에너지때문이다.평가 결과에 따라 제안 된 하이브리드 시스템의 TNPC, COE 및탄소 배출량이세 시스템 중에서 가장 낮다. 그리고평가결과는태양광/디젤/배터리 시스템이태양광/디젤 시스템 또는 디젤 발전기만 사용하는 시스템에 비해 경제적으로 실현 가능함을 보여준다.

주요어: 태양광, 디젤발전기, 하이브리드 시스템, HOMER 프로그램, 배터리 에너지 저장장치

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