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Techno-economic analysis of Hybrid Solar PV and Bioenergy system for use in rural areas of Myanmar

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Renewable Energy

I. Preface

This thesis marks the end of five years as a student, especially the two last years spent at the Norwegian University of Life Science at Ås. While holding an engineering degree within Energy and Environment of buildings, it has been valuable to continue the master program within renewable energy to gain a broader perspective of the Renewable Energy sector. However, I am truly grateful for new friendships and how much I have grown in academics during the time spent at Ås.

The thesis work reflects my interest for both science and culture, by combining them. The analysis in the thesis was made possible thanks to Erik Eid Hohle who introduced me to the Energy Farm's project in Myanmar. I would like to thank him and his colleges Martin Knoop, Rosa Marie Berg and Tord Araldsen at the Energy Farm for their help. They have given me valuable information and support, and introduced me to contacts regarding field work in Myanmar.

Professor Muyiwa Samuel Adaramola has been my supervisor. I would like to thank him for valuable help, guidance and support, and for keeping me focused while I've had too many ideas regarding the thesis work.

Another person who deserves to be thanked is Daud Malik, my dear, for supporting me in numerous ways. Because of his help, it was possible to accomplish the field work in Myanmar. The arrangements required a lot of patients and numerus e-mailing to obtain local contacts in Myanmar. Also, the journey in Myanmar would not have been as adventures and fun without Daud.

In regards of the field work – a lot of friendly and helpful people have been involved in the process. I am grateful for all the help I have received to accomplish the field work in Myanmar and to gain cultural experience. Firstly, I want to thank Mr. Aye Kyaw, uncle James, for his interest and willingness to help. He has supported me throughout the whole field work process. Thank you to Dr. Chaw Chaw (MONREC) that accompanied us to Yedashe where the field work was conducted, and for being a helpful translator.

Additionally, I want to thank my fellow students and flat mates. They are fantastic and truly supportive, and the thesis process has been funnier and easier thanks to you guys. Especially, thank you Tonje Stordalen, Sigrid Toverud, Vegard Bøe and Monika Mannes for constructive discussions and help.

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II. Abstract

Myanmar is situated in the southern part of Asia. This is a country with a high need of increasing their electrification ratio. As much as 70 % of the population are living in rural areas, where the national grid only reaches 7 % of the villagers. Despite limited financing and geographical challenges in rural areas, hybrid renewable energy systems (HRES) may safely generate electricity to rural areas with low energy requirements, and without the need of implementing large facilities or network. An advantage of utilising HRES is the possibility to employ two or more complementary locally available sources of energy.

The objective of this thesis was to find the optimal design and performance of a Hybrid Renewable Energy System (HRES) consisting of Solar PV and bioenergy, which will both meet the energy demand and benefit the local people in Amatgyi Khone, a selected rural village of Myanmar. A field survey research was conducted in the Amatgyi Khone, where quantitative method was used to estimate the village's future load requirements. There are 256 households, schools and public utilities, which altogether, require a daily average primary load of 44,7 kW and a peak load of 107 kW. The region of Amatgyi Khone has abundant availability of solar energy (5,38 kWh/m^2/day) and agricultural crop residues, especially rice husks (2,96 tonnes/day). The selected HRES components comprise Solar PV system, Bio Gasifier Power Plant (BGPP) and battery bank. Several system configurations have been simulated using HOMER software. The total net present cost (NPC) of each system configuration has been calculated for a system lifetime of 25 years, in order to find the lowest energy cost configuration.

The optimal HRES components have the following capacities: Solar PV - 150 kW, bio-gen #1 - 75 kW, bio-gen #2 - 50 kW, inverter - 120 kW and battery bank - 23.966 kWh. The HRES can supply 100 % renewable power with no capacity shortage to the end-users, through mini-grid distribution LV lines. The BGPP accounts for 53,64 % of the total annual generated primary load, and 37 % is generated by the Solar PV system. The estimated value of the NPC and Levelized Cost of Energy (LCOE) is $2.938.238 and $0,719/kWh, respectively. However, by introducing different types of governmental or donor support, the LCOE can be reduced in various amounts. The LCOE can be reduced to $0,266/kWh when the BGPP Operation & maintenance (O&M) costs are completely subsidised. Governmental or donor support is regarded essential for making the electricity supply affordable to the end-users and to ensure development of the energy system.

III. Sammendrag

Myanmar er ett land som er lokalisert i den sørlige delen av Asia. Behovet for å øke elektrifiseringsforholdet i Myanmar er stort. Hele 70% av befolkningen bor i landlige områder, hvor det nasjonale nettverket bare når 7% av landsbyboerne. Til tross for begrenset finansiering og geografiske utfordringer i rurale områder, kan hybridfornybare energisystemer (HFES) stabilt generere elektrisitet til ruralområder med lave energibehov, og uten behov for å implementere store anlegg eller nettverk. En fordel ved å benytte HFES er muligheten til å kunne benytte to eller flere komplementerende, lokalt tilgjengelige energikilder.

Målet med denne oppgaven var å finne det optimale design og ytelse til et hybrid fornybart energisystem (HFES) som består av PV-system og bioenergi. Det HFES skal både møte energibehovet og nytte lokalbefolkningen i Amatgyi Khone, en utvalgt rural landsby Myanmar. En feltundersøkelse ble utført i Amatgyi Khone, hvor kvantitativ metode ble brukt til å estimere landsbyens fremtidige effektbehov. Det er 256 husholdninger, skoler og offentlige forsyninger, som totalt, krever en daglig gjennomsnittlig primær effekt på 44,7 kW og en topp-effekt på 107 kW. Amatgyi Khone-regionen har rikelig med solinnstråling (5,38 kWh / m2 / dag) og jordbruksavlinger, spesielt risskall (2,96 tonn / dag). De utvalgte HFES-komponentene omfatter solcellepanel, biogassifiseringskraftverk (BGPP) og batteribank. BGPP består av en «downdraft» forgasser, kombinert med to biogass-generatorer. Flere systemkonfigurasjoner har blitt simulert ved hjelp av programvaren HOMER. Den totale netto-nåverdi (NPC) for hver systemkonfigurasjon er beregnet for en systemlivstid på 25 år for å finne den billigste system-konfigurasjonen.

De optimale HRES-komponentene har følgende kapasiteter: Sol PV - 150 kW, bio-gen. # 1 - 75 kW, bio-gen. # 2 - 50 kW, inverter - 120 kW og batteribank - 23.966 kWh. Det HFES kan levere 100% fornybar kraft uten kapasitetsmangel til sluttbrukerne, via mini-nettverks distribusjon LV linjer. BGPP står for 53,64% av den totale årlige genererte primærbelastningen, og 37% genereres av Solar PV-systemet. Den estimerte verdien av NPC og LCOE er henholdsvis $ 2 938 248 og $ 0,719 / kWh. Imidlertid kan LCOE reduseres i ulike mengder ved å introdusere ulike typer statlig- eller donorstøtte. LCOE kan reduseres til $ 0,266 / kWh når BGPP O & M kostnadene er fullstendig subsidiert. Statlig støtte eller donorstøtte anses å være avgjørende for å gjøre elforsyningen rimelig for sluttbrukere og for å sikre utvikling av energisystemet.

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TERI:	Innovative Solutions for Sustainable Development (India)
EFIF:	Energy Farm International Foundation. EFIF is established in collaboration of TERI and Energy Farm Norway.
MONREC:	Ministry of Natural Resources and Environmental Conservation (Myanmar)
HRES:	Hybrid Renewable Energy System
BGPP:	Bio gasifier power plant
PV:	Photovotalics
NPC:	Net present cost
LCOE:	Levelized cost of energy
CRF:	Capital recovery factor
O & M:	Operation & Maintenance
LF:	Load following
CC:	Charging cycle

Chapter 1 Introduction

1.1 Background

The Republic of Union of Myanmar are known as the north-western-most country on the mainland of Southeast Asia. The country is located near the shipping lanes through the Indian Ocean, and shares borders with Bangladesh, India, China, Laos and Thailand, as shown in Figure 1.1. Myanmar has a total land area of 676.59 km^2 and a population of about 54,82 million. The population consists of diverse ethnic groups, speaking over 100 languages and dialects (UNDP 2012). About 70 % of the population are living in rural areas, and 25,6 % of the population are living below the poverty line (ADB 2016). The per capita gross domestic product (GDP) of $1308, is regarded as one of the lowest in Southeast Asia (Economics 2016).

Figure 1.1: Map of Myanmar showing the major cities and the neighbouring countries

Myanmar has tropical monsoon weather and three seasons that can be categorised as hot, rainy and cool. The rainfall is influenced by both locality and by monsoons, which usually occurs during the summer time. The land surface varies from an elevation of 5881 in the extreme north at Mount Hkakabo (the country's highest peak) to the Ayeyarwaddy and Sittang river deltas at sea-level in the south. Four mountain ranges running in parallel from north to south, divides the country into three river systems (UNFCCC 2012).

Hence, Myanmar has abundant of hydroelectric resources and also a rich variety of biodiversity, but has ended up as the least economical developed country in South-East Asia (Turnell 2011). The country is facing challenges related to a unique set of energy access and energy security issues. There is a vast need of energy systems that can contribute to productivity and economic development in Myanmar.

The situation of electricity access in Myanmar is problematic, as only 49 % of the population had access to electricity in 2011 (Birol et al. 2013). The national grid can supply electricity to 26 % of the population; 220 of the 396 main towns and only 7000 of the 64.000 villages (Nicholson 2012). Therefore, the power supply is constrained and millions of people do not have access to electricity services to meet their livelihood needs. Figure 1.2 illustrates the electrification situation in Myanmar per January 2015.

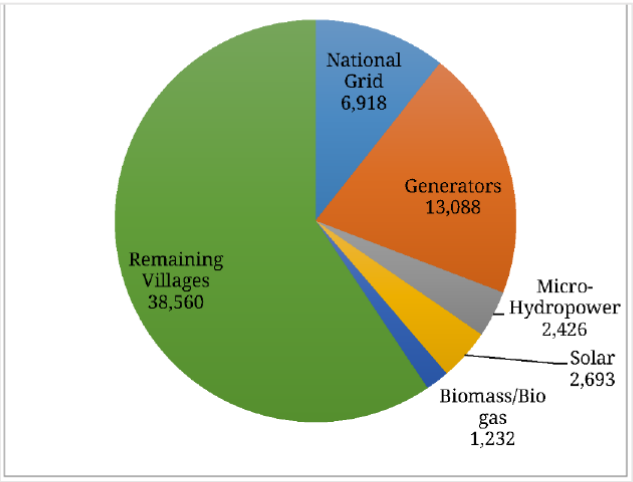


Figure 1.2: Rural Electrification situation in Myanmar per January 2015 (MLFRD 2015).

Myanmar’s average electricity tariff are among the lowest in Asia. Small to medium-size commercial consumers have tariffs level from \$0,03 to \$0,04 per kWh, see Appendix 5 (Bank 2015). The government subsidies the electricity tariffs primarily on the national electricity grid. Hence, the rural poor outside these electricity service areas often pay much higher rates per kWh for privately generated diesel or renewable electricity (Ross 2015).

The national grid is mostly based on Myanmar’s hydroelectric stations which are constrained, operating at partial capacity for only a few hours a day during the dry season (UNDP 2012). Table 1.1 show the installed power capacity in Myanmar by different fuels, whereas two-third of the total installed capacity comes from hydropower. The total capacity reduces from 4422 MW to 1560 MW during dry season, or to about 36 % of the installed capacity. However, the main energy source for 70 % of the population in Myanmar is firewood used for cooking, and about 46 % uses kerosene, candles or batteries as the main energy source for lightning (Nam et al. 2015). This comes as a consequence when regarding that most of Myanmar’s population lives in rural areas.

Table 1.1: Installed Capacity in Myanmar (Nam et al. 2015).

Power Plants	*Installed Capacity*	
	[MW]	*[%]*
Hydro	3005	68
Coal	120	3
Gas	1236	28
Minihydro and solar	5	0
Oil	56	1
Total	*4422*	*100*

The Myanmar government's National Electrification Plan (NEP) aims for universal electricity access by 2030. The first phase of NEP is to extend electricity access to over 1 million households, where 60 % will be connected to the national grid and 40 % will obtain off-grid electricity by 2021 (Nam et al. 2015).

Myanmar has a challenging topography and a low population density in some regions, implying that an extension of the national grid is not the financially most viable solution in rural areas of Myanmar for future development (EUEI-PDF 2013). In rural areas, where 70 % of the population lives and where the national grid only covers 7 % of the population, the off-grid solutions can create vital energy access (UNDP 2012). Hence, a wider range of available solutions needs to be considered to increase Myanmar's electrification ratio (EUEI-PDF 2013). Renewable energy, especially solar, wind and biomass, can play a major role in enhancing electricity access by adopting decentralized energy system options. Due to geographical constraints and limited financing, development of for example stand-alone systems or mini-grid electrical distribution systems in rural areas can firstly be done isolated, and in the future, if the national grid expands into the rural areas, these energy systems can be connected to national gird.

1.2 Renewable energy resources

1.2.1 Biomass potential

The economy in Myanmar is centred around biomass, where wood alone accounts for 70 % of the primary energy supply in 2009. The majority in rural households and many in the urban areas are dependent on biomass, mainly firewood and charcoal, to meet cooking needs. An effective way to secure household energy is through sustainable and efficient harvesting of fuelwood (UNDP 2012). Correspondingly, having an agricultural sector dominated by rice, there is a vast potential of converting rice husks from milling into biomass power plants. Other types of biomass that are abundantly available and could be used in biomass power plants are lumber waste, bagasse, molasses and livestock waste (UNDP 2012).

1.2.2 Wind and hydropower potential

Myanmar has very good potential of wind power and hydroelectricity. It is estimated 365 terrawatt-hours (TWh) of technical potential per year of wind power (Nam et al. 2015). The wind resource potential are vast in specific regions, comprising of Chin and Shan state, the highly elevated parts of the Central Region and especially along the coast (UNDP 2012). The hydropower potential is 34.568 MW of achievable large-scale capacity spread across many potential sites in the country (Nam et al. 2015). However, there are geographical differences, thus limited wind and hydro resources in parts of the central regions of Myanmar.

1.2.3 Solar Energy potential

Myanmar is well suited for solar energy, as it receives good amounts of solar energy due to its near equatorial location. Solar radiation has a vast potential to be converted into power, but due to dependence on weather conditions and seasonal change, solar energy can be unpredictable and unreliable. When considering continuous power supply, stand-alone renewable energy systems (RES) operating 100 % of solar energy may be unrealistic. However, utility of solar PV systems can be supplemented by a storage facility, and/or available resources such as wind, biomass, hydro etc. to distribute uninterrupted power supply (UNDP 2012).

1.3 Hybrid energy system potential

Responding to this vital energy need, RES may safely generate electricity to rural areas with low energy requirements, and without the need of implementing large facilities or network. By using robust energy systems integrated in mini-grid or as stand-alone systems, rural areas can obtain advantage of generally abundant renewable resources. Hybrid renewable energy systems (HRES) are becoming more popular worldwide especially for rural power supply. An advantage of utilising HRES is the possibility to employ two or more complementary sources of energy (Hurtado et al. 2015). Having in mind that the foremost concern for implementation of any renewable energy technology is its economic viability - HRES reveal higher reliability and lower the cost of generation compared to systems based on one primary source of energy (Bhattacharjee & Dey 2014). In this analysis, a project site is selected in a rural area of Myanmar to investigate techno- economic feasibility of a hybrid renewable energy system, comprising of two complementary energy sources that has abundant availability.

1.4 Literature review

In this section, relevant literature is presented in order to put the objective into context. Several research works have been conducted on Hybrid Renewable Energy Systems (HRES) focusing on feasibility, performance and economic viability of decentralized hybrid power systems.

Sharma and Goel's research (2016) used HOMER software to find an optimal HRES to meet the electrical power requirements of an off-grid rural village in India. The research investigates the economic and environmental effects of using local available energy sources such as solar radiation, cow dung and kitchen wastes. It has been estimated that a solar-biogas system compared to biogas generation alone would discharge 83,04 % less CO_2 to the atmosphere. The optimal HRES configuration found to meet the load demand of 50 kW, comprises 20 kW (37 %) solar PV and 30 kW (63 %) biogas generation, 40 tubular gel batteries (each 12 V, 150 Ah) and 20 converters. This system configuration results in COE of $0,476/kW, NPC of $386.971 and CO2 emission of 10.346 kg/year (Sharma & Goel 2016).

Adaramola et al. (2014) conducted a technical and economical assessment of a decentralized hybrid PV solar-diesel power system for applications in Northern part of Nigeria. By using HOMER software, it is found that the combination of PV/Gen/Battery is a viable system type. The cost of generating electricity is cheaper using the hybrid system, compared to three other types of system combinations; Generator only system, Generator/Battery system and PV/Generator system. The total electricity produced, meets the required electrical load with a combination of 43 % by Solar PV and 57 % by generators. A sensitivity analysis is performed to see the effect of variating fuel prices, solar radiation and interest rate. Hence, depending on the interest rate, the systems COE is between $0,348 to $0,378 (Adaramola et al. 2014).

Hurtado et al. (2015) has researched a solar-biomass generation system, aiming to ensure stable electrical supply to a learning centre in the Democratic Republic of Congo. HOMER was used to evaluate the environmental and economic impacts of the energy system, and to test the validation of system operation under different load profiles. Results show that the optimal system configuration comprises 76 % solar PV and 24 % generation from the biomass gasification plant. The system meets generation criteria of 100 % renewable fraction and the demand with 98 %. It was found that the stability criteria cause excess electricity. However, costs are expected to reduce by introducing demand side management strategies. The energy systems COE is $0,8/kWh and its NPC is $169.590. Today, the HRES system has been erected, with a fixed operational strategy that follows the demand to be met and recharging of the battery bank when it is below 30 %. However, surplus of electricity generated can be used, but would require a second energy storage system that could be based on storage of the extra syngas generated by the biomass gasifier (Hurtado et al. 2015).

Pode et al. (2016) research the solution to sustainable electrification in Myanmar. The usage of power plants fuelled by rice husk biomass, due to its abundant availability in rural areas of Myanmar, is found to be a suitable solution to implement self-sustaining power systems for rural electrification. It is argued that the rice husk biomass power systems installed and operated by rice millers is a financially viable business model without the need of grant or subsidy. The electricity tariff from rice husk power plants was estimated to be in the range of $0,12- $0,23 /kWh, depending on capital cost and feedstock cost (Pode et al. 2016).

The studies that are reviewed investigate the possibility of meeting the rural electrification demand – to secure the electricity access and reliability to rural areas. There are conducted several approaches to the HRES including different complementary sources of Renewable Energy, mainly due to abundantly available energy resources. However, there are limited research studies on decentralized hybrid energy systems for usage in rural areas of Myanmar.

In all the research works that are mentioned above, the optimal design of a HRES has been found using HOMER software as an analysing tool. HOMER (Hybrid Optimization of Multiple Energy Resources) are used for optimization and sensitivity analysis, and to evaluate the economic and technical feasibility of many technology options. Factors such as uncertainty of technology costs and energy resources availability are evaluated using HOMER. A product database is incorporated in the software, containing a variety of products from several manufactures. Hence HOMER software is a widely used HRES optimization tool (HOMER 2016).

1.5 Goal and objectives

The objective of this thesis is to find the optimal design and performance of a Hybrid Renewable Energy System (HRES) consisting of Solar PV and Bioenergy, that will both meet the energy demand and benefit the local people in a selected rural village of Myanmar. This thesis is done in correlation to a prefeasibility study executed by Energy Farm International Foundation (EFIF) on Amatgyi Khone village in Myanmar.

1.6 Research questions

Based on the previous studies of literature, research questions that are found interesting to study for the selected project village in Myanmar are the following:

1. What are the required electricity demand for the specific rural village in Myanmar, considering households and community buildings?
2. What local energy resources are available to support power plant in the region?
3. What kind of Hybrid energy system can be proposed based on the available energy resources?
4. What is the optimal system type and configuration of the proposed Hybrid Energy system?
5. Examine the impact of selective variables on optimal energy system (government/donor investment support; interest rate, O&M cost)
6. What is the optimal technical performance of the hybrid Solar PV and Bioenergy system?

1.7 Structure of analysis

The content of the thesis is based on the optimization of a hybrid renewable energy system (HRES), that will meet the demand and benefit the local people in the rural village, Amatgyi Khone, in Myanmar. The thesis consists of 8 chapters, arranged in the following order.

Chapter 1 introduce background information about Myanmar, the countries' electricity access situation, availability of energy resources, and the potential of using a hybrid renewable energy system for rural electrification. Furthermore, relevant literature is presented, followed by goals, objective and research questions.

Chapter 2 presents information about the field survey research that was conducted in Amatgyi Khone village in February 2017. This information supports a prefeasibility study of the Amatgyi Khone project site conducted by The Energy Farm International Foundation (EFIF). The chapter presents background information, field survey research method, energy needs assessment and estimated load duration curves at household level and village level.

Chapter 3 presents an evaluation of the renewable energy resources' availability in the project region to support the HRES. This includes climatic data, solar resources and biomass resources in the village.

Chapter 4 presents the selections of HRES components, including technical characteristics, capital cost, operation and maintenance cost. The estimation of component characteristics is based on requirements related to energy system modelling in HOMER software.

Chapter 5 discuss the modelling of the HRES in the optimization software HOMER. Required data input when modelling in HOMER is presented, comprising technical specifications, resource data and costs. Further is the method of calculating the HRES economic viability presented.

Chapter 6 presents the simulation and optimization results obtained by using HOMER, including selection of optimal HRES configuration, sensitivity analysis, the performance and the economic viability of the proposed HRES.

Chapter 7 contain the discussion.

Chapter 8 present the conclusions and recommendations for further work.

Chapter 2 Field survey research

In this chapter, information about the field survey research is presented. The survey was conducted in Amatgyi Khone village in Yedashe Township February 2017. The information is based on findings from both a field survey research that was conducted in February 2017, and a prefeasibility study of the selected project site conducted by The Energy Farm International Foundation (EFIF) in consultation with MONREC (Ministry of Natural Resources and Energy Conservation, Myanmar). EFIF is a collaboration between The Energy and Resources Institute in India (TERI) and the Energy Farm Norway.

2.1 Energy Farm - Project site Information

In this section, information about the selected project site and general information about the Energy Farm project plans are presented.

TERI in consultation with MONREC, has selected the location of the Energy Farm at Amatgyi Khone Research Station in Yedashe Township, Bago Region in Myanmar (EFIF 2016). The location of Yedashe Township is marked on the map of Myanmar in Figure 2.1.

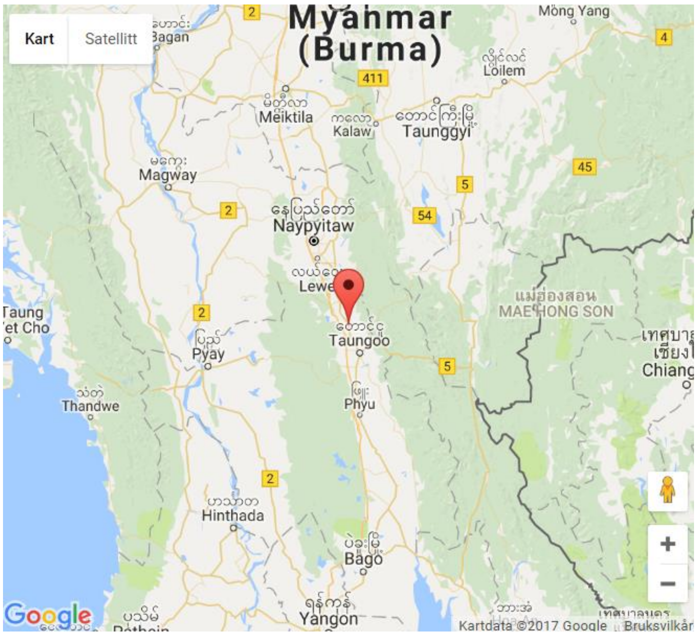


Figure 2.1: Map of Myanmar showing the project site area, Yedashe township (google maps, 2017)

The Amatgyi Khone Research Station has the main purpose of conducting research with Bamboo and other fuelwood species, and in addition demonstrate plantation with agro-forestry methods. The Forest Research Institute that initiated this research station in 1978. Today, MONREC operates the research station with local staff members that are knowledgeable about Yedashe Township. MONREC will play a major role in the operation of activities at the farm by contributing in the form of land, local organization including training station and staff members at the local site (EFIF 2016).

2.1.1 Energy Farm concept

The planning of EFIF's Energy Farm in Amatgyi Khone village are based on the strategies of becoming a market place, meeting place and a knowledge place of production and usage of renewable energy, with emphasis on modern solar- and bioenergy solutions. In addition, make knowledge and solutions within small and medium scale renewable energy accessible to rural communities. Hence, implementation of a Hybrid Renewable Energy System (HRES) as part of the Energy Farm concept may enrich Amatgyi Khone village with possibilities regarding community development.

2.1.2 Socio-economic status of the project site

The Amatgyi Khone village consists of 256 households of different standards. Typical residential homes in this village are shown in Figure 2.2 and 2.3. The village lacks access to the national electricity grid. The closest connecting point to the national grid is approximate 3,2 km from the village. In this matter, no households have access to viable electricity supply. However, over the last few years, some households have invested in small solar PV systems that generates electricity, mainly for lightning purposes (Figure 2.4). The households with the highest income level receives electricity from Solar PV panels connected to batteries (example, see Figure 2.5). These households also rely upon diesel generators when the capacity of the PV is insufficient. Based on information from the village collected during the fieldwork, the number of wealthier households are limited to 4, whereas the number of poor and average standard households are approximate 160 and 92 respectively. Table 2.1 shows the brief information about the selected site.

The predominant occupation in Amatgyi Khone village is agriculture. In this village, the most common crops growing are paddy, sesame, maize, sugar canes, seasonal beans and water melon. The majority of households have a livestock, but it is mainly used for their own consumption. The livestock accounts only for 1 % of the household total average income. Another normal business is processing of charcoal. The wealthiest households receive their income typically from their own business, such as broker, restaurant or a big shop.

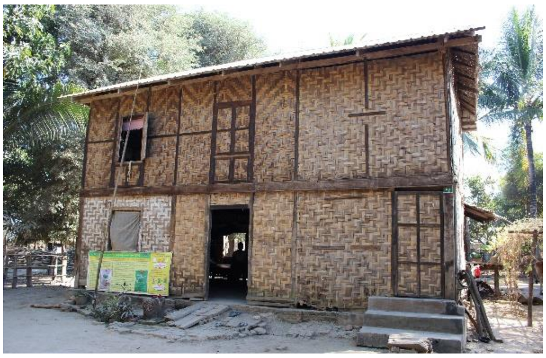


Figure 2.2: Picture of an average household standard in Amatgyi Khone village

Figure 2.3: Picture of an average household standard

Figure 2.4: Solar PV panels used for lightning purposes

Figure 2.5: Solar PV panel in combination with battery

Table 2.1: Information about Amatgyi Khone village (EFIF 2016).

Particulars	*Details*
Name of region & township	Bago region, Yedashe Township
Number of households	256
Total population	1352
Male	672
Female	780
Distance from the local head quarters	3,22 km
Distance from regional head quarters	16,09 km

Residents of Amatgyi Khone village depend on wood collection from the natural forest. They are dependent on wood for cooking, building of houses and homestead. The collection of fuelwood requires sustainable yield, but may consequently cause degradation over time. This is a large concern in Yedashe Township. As a result, degradation may further cause fuelwood scarcity, loss of biodiversity, deterioration of watershed functions, release of carbon dioxide into the atmosphere and soil erosion.

Therefore, substitution of fuelwood with alternative biofuels are desired to reduce the pressure on natural forests. Some of the available biofuel sources are for example crop residues and animal dung.

2.2 Field survey research

The field research related to this thesis was conducted in the Amatgyi Khone Village at the beginning of February 2017. The purpose of this survey was to assess the energy situation in Amatgyi Khone village. The goals of the assessment are to estimate the village's current energy consumption pattern, to predict their future energy demand, and to carry out an inspection of space requirements for the implementation of a HRES. In addition, this fieldwork helps to assess available energy resources in Yedashe Township, and the general usage of the resources in Amatgyi Khone village.

In this study, field survey method was used. This method is suitable to estimate Amatgyi Khone village's energy situation while considering a certain number of represented households, and in addition consider community buildings and public areas. The method of interview used, were quantitative analysis.

2.2.1 Field research method: Quantitative analysis

For the quantitative analysis, questionnaires were prepared and administered (see Appendix 1). The questionnaire contains questions directed to households, Monastery (High School) and Primary School with location in rural villages. Based on knowledge from EFIF's prefeasibility study, the questionnaire is formatted to suit Amatgyi Khone village. The questions used are both unstructured and structured. The unstructured questions ask the respondent to provide response in their own words, to questions that relate to their daily routines and preferences of electrical appliance usage. While structured questions ask respondents to select an answer from a given set of choices. The outline of the questionnaire is divided into the following parts:

Part 1: Questions about the household/school in general
Part 2: Questions about energy resources and energy consumption
Part 3: Questions about electrical household/school components
Part 4: Daily routines

A total amount of 16 households, a Primary school and a Monastery (High School) were chosen for the interviews. A local staff member of MONREC (Ministry of Natural Resources and Energy Conservation) helped to find a variety of households of different sizes and standards, located throughout the village. The translator during the interviews was represented by MONREC, holding a PhD within forestry.

Because the local people in Amatgyi Khone only speak Burmese, the questionnaire was needed to be held as face-to-face interviews. Both men and women were the respondents in the interviews. It was natural to divide the interviewed households into two types based on income and living standard, described in Table 2.2.

Table 2.2: Description of the two types of households in Amatgyi Khone Village

Household type	*Description of the different household types*	*Number of interviewed households*
I	Households that have no electricity or that receives a small amount of electricity from a Solar PV panel for lightning. They have an average monthly income up to 400 000 MMK per month (converted into USD: $290,67).	**12** **(152 total)**
II	Households that have better living standard and receives power from Solar PV panels w/battery and have a diesel generator. They have an average monthly income from 400.000 MMK to 700.000 MMK per month (converted into $290,67 to $508,68).	**4** **(4 total)**

The number of households chosen for interviews per type I, was 12 households out of 152 households. Initial plan was to interview at least 50 households within this category of household. Due to limited time, this number of interviews was not possible to carry out. All the four households within Type II were interviewed.

2.3 Energy needs assessment of Amatgyi Khone village

In this part, an energy survey with detailed information about the village is presented.

2.3.1 Present electricity supply situation for households

Many households in Type I category do either have no access or to limited access to self-generated electricity. Some of them own a small solar PV panel with installed capacity varying from 25 W to 300 W, combined with batteries with capacity from 20 Ah to 180 Ah. The panels are either personally bought or donated by the government agencies. The solar PV energy cover mainly the need of lightning for a few hours in the evening. Other appliances that Type I typically owns are a small TV or a portable DVD-player and mobile phone chargers.

Households in Type II category have a functional electricity supply solution. They expressed that they in general are pleased with their electricity situation, having a relative high living standard compared to Type I. The energy generation consists of Solar PV panels, battery storage with an average capacity of 300 Ah, combined with a diesel generator used as a buffer. The generator is used both to meet the need of water pumping and for other electrical appliances, especially in the evening. They have electrical appliances such as lightning, fans, stereo, TV, DVD-player, laptop, radio, mobile charger and iron.

Based on findings from the fieldwork, the quality of the PV panels may be considered poor, especially within Type I household. The PV panels have an estimated lifetime that may not be longer than three years. During the fieldwork, it was observed that the panels were poorly placed and covered with dust. Therefore, there is a need for the Energy Farm establishment, to create training centre, where the local population can learn about placement, usage and maintenance of the PV panels.

2.3.2 Fuelwood and cooking needs

The firewood used in Amatgyi Khone village is collected from the natural forests. The interviewed households either collect the firewood by using cattle carts or they buy the firewood from a broker. The average, number of days spent to collect firewood to cover the yearly consumption is 25 days, and they typically use 5 hours per day.

Figure 2.6 and Figure 2.7 illustrate the most common way of cooking in Amatgyi Khone village. As shown in the figures, firewood is normally used to make an open fire for cooking. This type of cooking technique is not very efficient due to high amount of heat loss from the open fire. As a result, the technique requires additional wood compared to more efficient cooking technologies. Another factor that are very important to consider is health problems regarding inhalation of hazardous gaseous from the open fire. Many of the households perform cooking inside in a one-cell house, with inability to ventilate properly (see Figure 2.8). Implementation of more efficient cooking technologies are highly desired. In fact, every single household that were interviewed expressed this desire. Type I prefer a better cooking stove in general, Type II prefer other cooking appliances in addition to a cooking stove, such as a rice cooker and kettle.

Figure 2.6: Common cooking technique in Amatgy Khone

Figure 2.1: Common cooking technique in Amatgy Khone

Figure 2.8: Normal kitchen in a household Type I

2.3.3 Lightning needs of the village

The households that have access to electricity usually use the lighting for a few hours in the evening, between 18:00 to 22:00, or for as long the charged batteries lasts. The households Type I and Type II, on average, have installed 2 to 4 light bulbs respectively. LED lights are mostly used, but fluorescent lights are also used frequently (as shown in Figure 2.9). The power consumption of the light bulbs varies between 3 W to 12 W.

Figure 2: Common types of light bulbs in Amatgyi Khone village

Through interviews with the villagers it became evident that people in general, have a desire to stay up longer in the evenings. Currently, the household Type I customize the day in relation to the hours of sunlight. Their daily routines are usually to wake up early in the morning before sunrise, conduct agricultural field work and go to bed early in the evening because of insufficient lightning possibilities at home. They need light for a longer period of the day. They also desire to have more light bulbs in their households to receive sufficient supply of lightning. In addition, there are no street lights in the village. Installation of street lights in the village would increase the mobility after dark.

2.3.4 Preferences of electrical appliances

The preferences of electrical appliances differ in relation to the household's living standard. Their prior preferences in both household types are, as mentioned earlier, cooking appliances and sufficient lightning. However, additional appliances that are desired within Type I Household category are TV, fan especially for the summer time, and blow torch. Type II household category desire to have TV, refrigerator, air-conditioning (AC) system, fan, washing machine and iron.

2.3.5 Lightning and irrigation needs of the Energy Farm

The Amatgyi Khone research station are using a diesel generator to cover the demand of lightning and water pumping for irrigation (shown in Figure 2.10). They have a need for a reliable and cleaner source of energy to obtain the energy needs. Furthermore, this research station, also have a suitable area for installation of the HRES, shown in Figure 2.11.

Figure 2.10: Amatgyi Khone research station

Figure 2.11: Area available for installation of the HRES

2.3.6 Lightning, cooking needs of the schools

There are two schools in Amatgyi Khone village, a governmental primary school and a monastery school. The Primary school has about 373 students and 15 staff members. The primary school building consists of 10 classrooms and an office (shown in Figure 2.12). The primary school currently lack access to electricity. Due to opening hours from 09:00 am to 04:00 pm, the primary school rely on daylight as the lightning source. However, based on the site survey, increased lightning in the classrooms may provide better study environment for the students. In addition, the Principal of the primary school expressed a desire for implementation of electricity to cover the needs of lightning, cooling, usage of microphone in lectures and a kettle for the office.

The monastery is a residential school, where about 130 students are living and studying. They receive electricity from a diesel generator combined with a solar PV panel and batteries. A more detailed description of the power supply and the electrical appliances used at the monastery can be found in Appendix 2. During the interview, the head of the monastery school mentioned that the monastery need reliable and sufficient power supply. The school needs electricity for cooling during the day, and good lightning, especially in the morning and evening to improve the students' study environment. The students usually do all their study in the classrooms, example shown in Figure 2.13. In addition, the monastery need better cooking facilities than the present solution. Currently, an open fire is used to cook three meals a day for the students and the monks.

Figure 2.12: Primary School in Amatgyi Khone village

Figure 2.13: Ex. of classroom at the Monastery school

2.4 Field survey results: Electrical load duration curves

The propose HRES is designed to meet the whole energy demand of the Amatgyi Khone village. The energy demand can be divided into primary and deferrable loads. The primary loads are loads that must be met at specified times of the day. In this analysis, the primary loads are both at village and household level. Street lights, loads at the primary and monastery schools, and load at the Energy Farm are the loads included at the village level. The household level loads are presented based on two scenarios: Present energy consumption and Future preferred energy consumption.

2.4.1 Present energy consumption in households

By studying the daily habits and energy requirements of the households in the Amatgyi Khone village, the present household energy consumption is estimated. Statistics from the interviews is presented in Appendix 3. able 2.3 shows the list of the most common household appliances used with information about typical wattage rating with time tendencies of use.

The load of each electrical appliances is either found during the site visit or assumed based on a survey of Home Appliances Wattage Consumption Guidelines (Prelec 2016). The hourly duration per day is assumed per electrical appliances, for each of the interviewed households. The average loads of the appliances are found per household Type I and II. The total load demand of the 256 households in the village is estimated by multiplying the average load in each household category with the total number of household per type. Based on this information, the daily primary load profile is generated, as shown in Figure 2.14. The households require a peak load of 45 kW, and the daily average load is 7,28 kW.

Table 2.3: Appliances and loads used in households

Household type	*Electrical application*	*Effect [W]*	*Normally time of use/ Remarks*
Type I & II	2 light bulbs	From 3 to 12 W	04:00-06:00, 18:00-22:00
	TV	75	18:00-22:00
	DVD player	20	19:00-22:00
	Mobile charger	6	05:00-06:00, 19:00-22:00
	Stereo	30	19:00-22:00
	Radio	7	10:00-12:00, 13:00-14:00
Type II	5 light bulbs	From 3 to 12 W	04:00-06:00, 18:00-23:00
	Fan	35	19:00-23:00
	Laptop	50	18:00-20:00

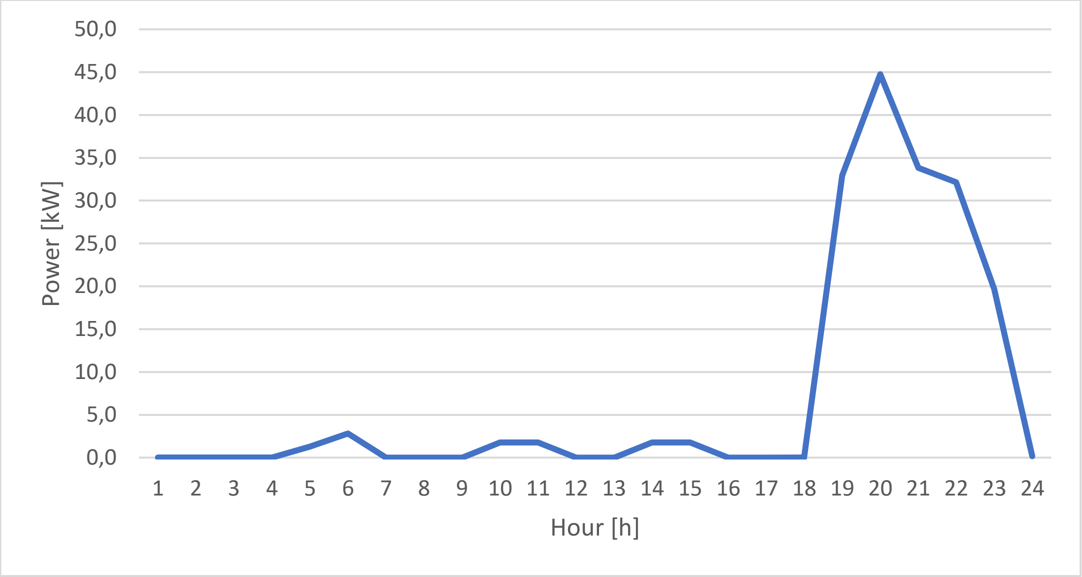


Figure 2.14: Household total daily primary load profile.

2.4.2 Future preferred energy consumption in households

All the households were questioned what kind of electrical appliances they would prefer, if they had unlimited access to electricity. Table 2.4 reflects the appliance preferences by both types of households. The information is valuable in regards of what kind of energy demand the village may get in the future. The time of usage is assumed based on their present daily routines, and the effect of the electrical appliances is assumed based on the survey of Home Appliances Wattage Consumption Guidelines (Prelec 2016). Based on this information, the future daily primary load profile is generated in relation to the HRES lifetime of 25 years, shown in Figure 2.15. The households have a future power requirement, with a peak load of 105 kW, and the daily average load is found to be 42,9 kW.

Furthermore, average daily energy consumption per household type is estimated to be 3,3 kWh and 49,8 kWh, for Type I and Type II respectively.

Table 2.4: Future demand of electrical appliances for households in Amatgyi Khone village

Household type	*Electrical appliances*	*Number of el. appliances per household*	*Effect [W]*	*Time of use/ Remarks*
Type I & II	Lights	4	10	04:00-06:00, 18:00-23:00
	Rice cooker	1/2	630	04:00-07:00, 09:00-11:00, 15:00-17:00
	Mobile charger	2	6	05:00-06:00, 19:00-21:00
	TV	1	75	18:00-23:00
	DVD player	1	20	18:00-22:00
	Stereo	1/2	30	19:00-22:00
	Radio	1/4	7	09:00-11:00, 13:00-15:00
	Fan	1	35	11:00-14:00, 18:00-21:00
Type II	AC	1	3500	11:00-14:00, 18:00-21:00
	Laptop	1	50	18:00-22:00
	Washing machine	1	3000	05:00-06:00
	Iron	1	1100	07:00-09:00
	Fridge	1	900 W during daytime, 450 W during the night	00:00-23:00

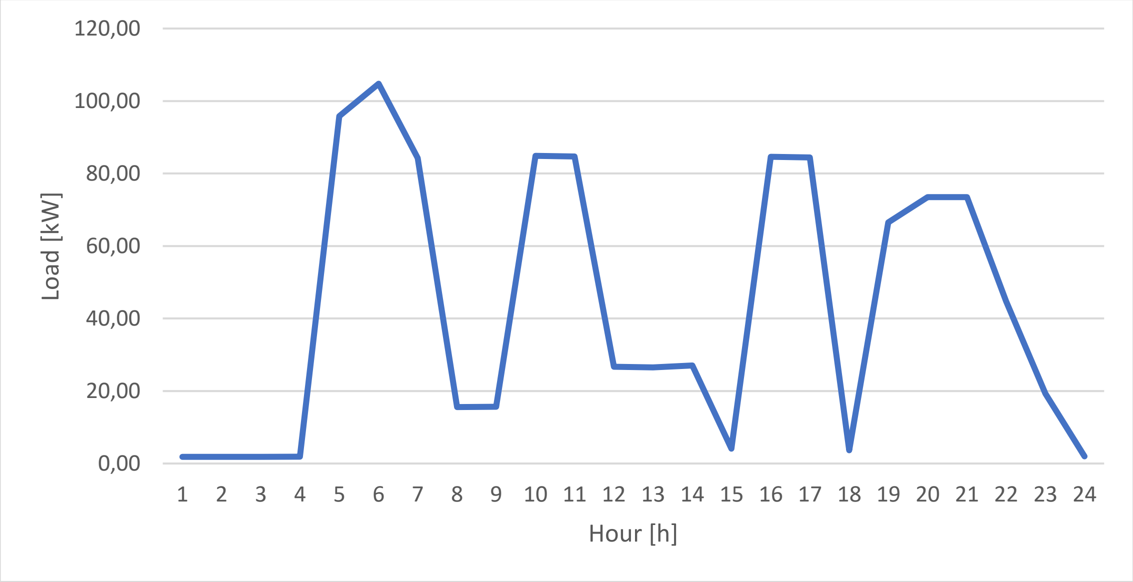


Figure 2.15: Future daily primary load profile for all households.

2.5 Primary load duration curves at Village level

2.5.1 Street lights

TERI have estimated a need of street lights in the village of approximately 20 street lights. In this analysis, it is assumed that each LED lamp requires 70 W, and they are used at 04:00-06:00 and 18:00-00:00. The total street light load is 1,4 kW, and the average daily load is 0,467 kW.

2.5.2 Monastery

Figure 2.16, show the primary load duration curve for the Monastery. The calculations are based on the present power consumption at the Monastery, details shown in Appendix 2. In addition, to account for the demand of cooling during lectures, two fans per class room (33 W) is included in the calculations. The load duration curve in figure 2.16 indicate a peak load of 1,5 kW during the evening, and the daily average load is found to be 0,408 kW.

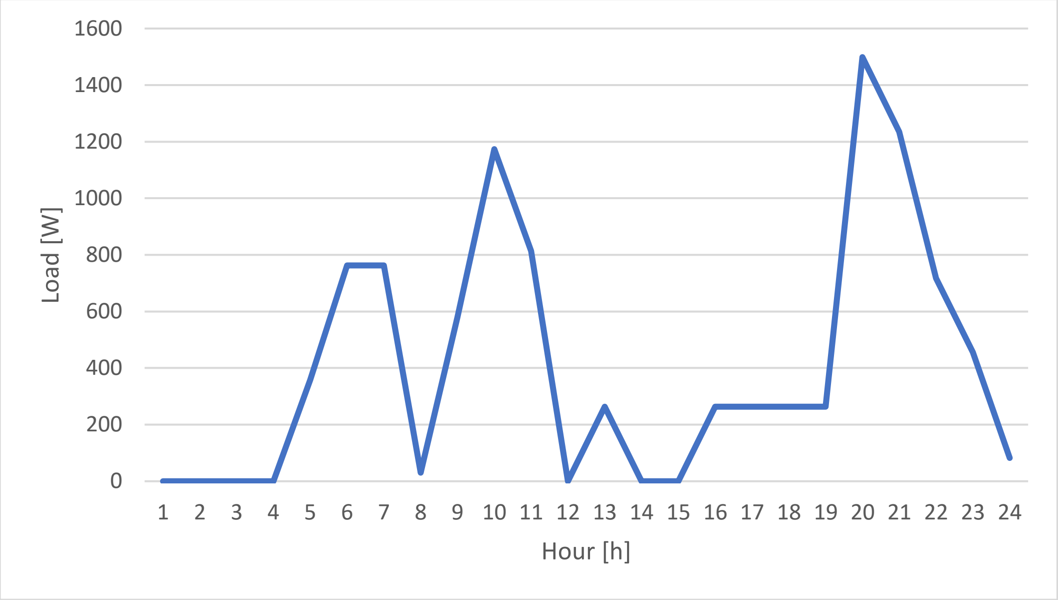


Figure 2.16: Future daily primary load curve at the Monastery.

2.5.3 Primary school

Table 2.5 show the assumed electricity demands at the Primary school. The assumptions are based on an interview conducted with the schools' principal. Figure 2.17 show the primary load duration curve for the Primary school, with a peak load of 1,97 kW, and the daily average load is found to be 0,415 kW.

Table 2.5: Assumed daily electricity demand at the Primary school

Primary school	*Electrical application*	*Number of el. appliances per room*	*Effect [W]*	*Total effect [W]*	*Time of use/ Remarks*
Class rooms	Lights, 10 class rooms	4	11	440	09:00-12:00, 13:00-16:00
	Stereo w/ microphone	4	11	44	09:00-16:00
	Fan	1	35	385	09:00-16:00
Office	Lights, office	1	30	30	09:00-16:00
	Mobile charging	3	10	30	09:00-11:00
	Computer	1	300	300	09:00-12:00, 13:00-16:00
	Printer	1	350	350	09:00-10:00, 15:00-16:00
	Kettle	1	1500	1500	12:00-13:00
	Radio	1	7	7	09:00-10:00, 12:00-13:00

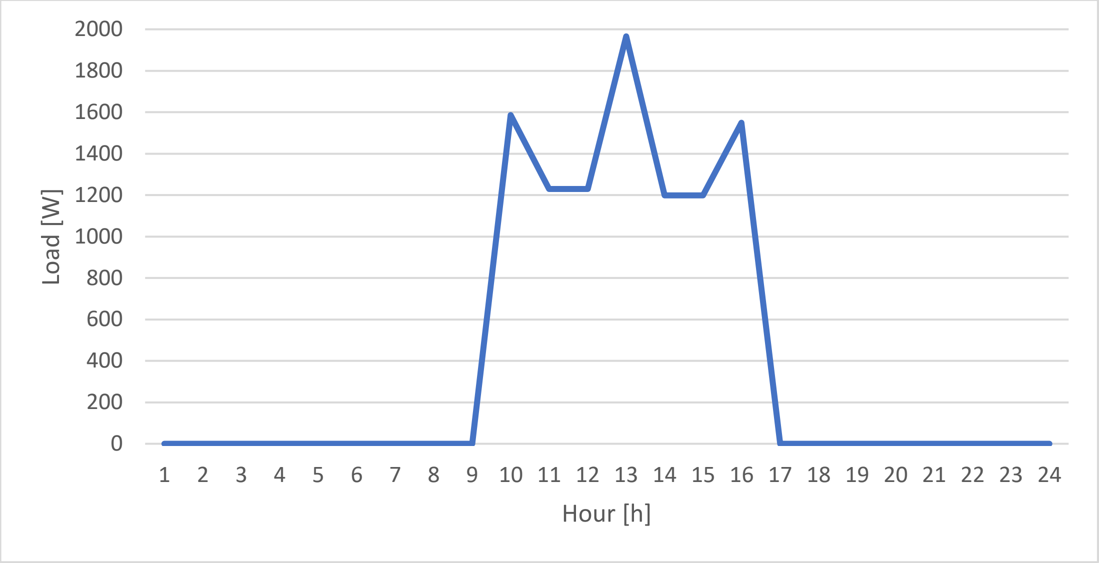


Figure 2.17: Primary school electrical demand daily load profile.

2.5.4 *Energy farm*

Rough estimate of the energy farm's load requirement was carried out. The requirement includes loads for lightning at the research station and to power a water pump for irrigation purposes. Regarding lightning, it is assumed 6 LED lights of 10 W at the research station. The assumed time of use is from 04:00 to 07:00 in the morning and from 18:00 to 22:00 in the evening. Since the research station already have a diesel generator used for water pumping, the deferable loads regarding water pumping is not considered in the analysis.

2.6 Daily deferrable loads (*Water pumping system)*

The deferrable load is a load that must be met within a period, but the exact timing is not important. The water pumps in the village are deferrable loads. Presently, only Type II households own a mechanical water pumping system, driven by a diesel generator. They usually use the water pump three days a week to meet the water requirements of the household. Although, every household need a water pumping system, either a manually/solar/generator or electricity based water pumping system, however, future electrical demand of water pumping system needs further investigation, and is not taken into consideration in this analysis.

2.7 Total Load estimation of Amatgyi Khone village

A combined primary load duration curve for Amatgyi Khone village is presented here, including all the different loads on both household level and village level described in previous sub-sections. This is an estimation of the total future electricity demand of the village, where both the present electricity demand and preferences is taken into consideration, see Appendix 4 for calculations. The load curve, shown in Figure 2.18, consists of electrical loads from the following:

- 252 households type I
- 4 households type II
- Primary School
- Monastery School
- Street lights
- Energy Farm, lightning needs

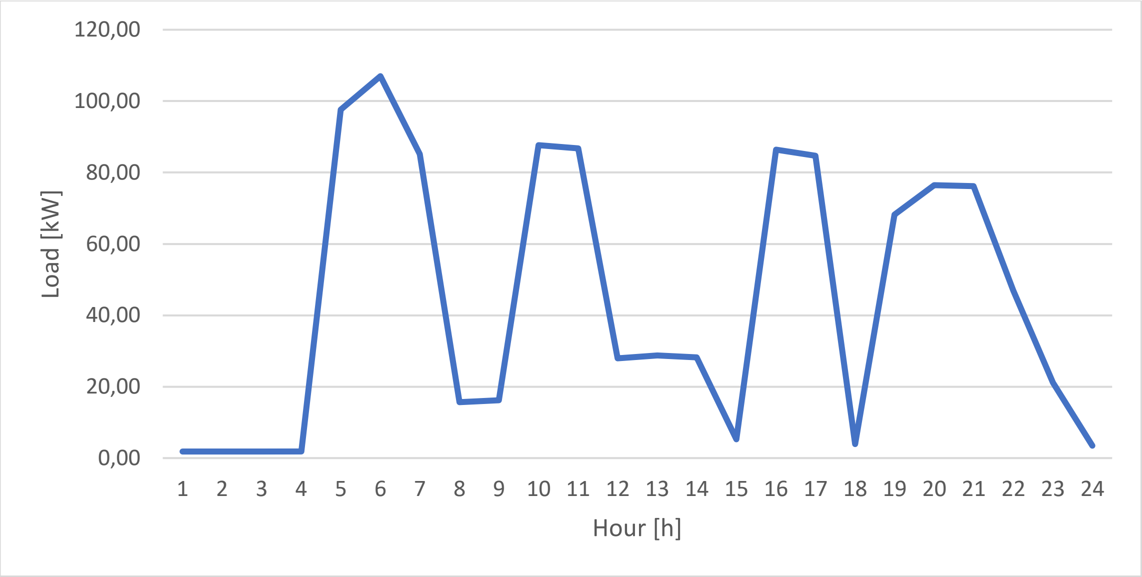


Figure 3: Total future primary load duration curve for Amatgyi Khone village

The proposed HRES will be designed to supply the load requirements, as shown in Figure 2.18. The peak load in the village is 107 kW from 05:00 to 06:00 during the morning, and the daily electrical load demand of the whole village is 1,106 MW, and the daily average load is 46,08 kW. The load factor is equal to the average load divided by the peak load, as a result 0,43 in this situation.

2.8 Household’s cooking requirements

2.8.1 Fuelwood for cooking

As previously mentioned, firewood is the mainly used fuel for cooking in Amtgyi Khone village. Varieties of different wood species are normally used in this area. Table 2.6 shows some of the wood species and their corresponding energy content abundant in the area surrounding the village. During the field work, the moisture content of the fuel wood was measured using the Wood Moisture Meter, REDD ST-123. The calorific values are found based on different research papers. Further, the Specific energy is calculated by using the following relation: 1 kWh = 3,6 MJ.

Table 2.6: Biomass/fuel used for cooking purposes and the power requirements

Biomass/fuel	*Avg. Moist percentage*	*Calorific values (MJ/kg)*	*Specific energy (kWh/kg)*	*Sources*
Rice husk	10 %	15	4,2	(Shen et al. 2012)
Ingyin - *Shorea siamensis*	14 %	18,7	5,2	(Phobdhamjarenjai et al. 2013)
Taukkyan – *Terminalia tomentosa*	14 %	17,93	5,0	(Kataki & Konwer 2002)
In – *Diptencauspus tuberculactus*	19 %	18,83	5,2	(Phobdhamjarenjai et al. 2013)
Thitya - *Shorea oblongifolia*	11 %	18	5	(Krajnc 2015)
Kanyin - *Diptercopus alatus*	17 %	18	5	(Krajnc 2015)
Madame - *Bruguiera cylindica*	13 %	18	5	(Krajnc 2015)
Acacia	-	27,65	7,4	(Pyromex)
Eucalyptus	-	30,1	8,2	(Pyromex)
Charcoal	-	29,6	8,2	(ToolBox)

For cooking, the Type I household collect fuel wood from the natural forest, while the Type II households buy fuel wood and charcoal. Half of type II use a mixture of wood and charcoal, and the other half use only charcoal. The amount of charcoal used is small compared to fuel wood. The major consumption of charcoal is during the summertime (rainy season), when the availability of fuelwood is reduced. While calculating the daily primary load duration for Type II, it is assumed a daily mixture of wood and charcoal.

2.8.2 Calculation of specific energy of daily wood consumption

If the households use more than one type of wood species, the average of the specific energy was found, and further used to calculate the specific energy of the daily wood consumption per household. With information about the daily cooking routines per household, including the average duration of each meal (shown in table 2.7), the daily power duration of cooking could be estimated.

Table 2.7: Average preparation time used per meal in households

Meal	*Preparation time*
Breakfast	25 minutes
Lunch	45 minutes
Dinner	45 minutes

2.8.3 Thermal load demand for cooking

The energy demand of cooking in households are estimated and presented in Figure 2.19, as a daily thermal load demand curve. The thermal load is not considered in the HRES system analysis. However, this information is valuable regarding research that comprises upgrading of the villagers cooking facilities, and to estimate the potential of reducing fuelwood consumption in Amatgyi Khone village. The load presentation is a result of the information received in the interviews in the field survey research. Based on the daily schedule of cooking per household, the average load per hour was calculated, and further multiplied with the total number of households in the village. As most of the villagers use an open fire to cook their food. It is assumed that cooking on open fire is 14,8 % efficient (Mccracken & Smith 1998). The calculated energy requirement of wood is based on the present consumption of wood and the efficiency of open fire. As shown in Figure 2.19, the maximum demand is 633,2 kW of thermal load for cooking. The average daily load required is 107,94 kW.

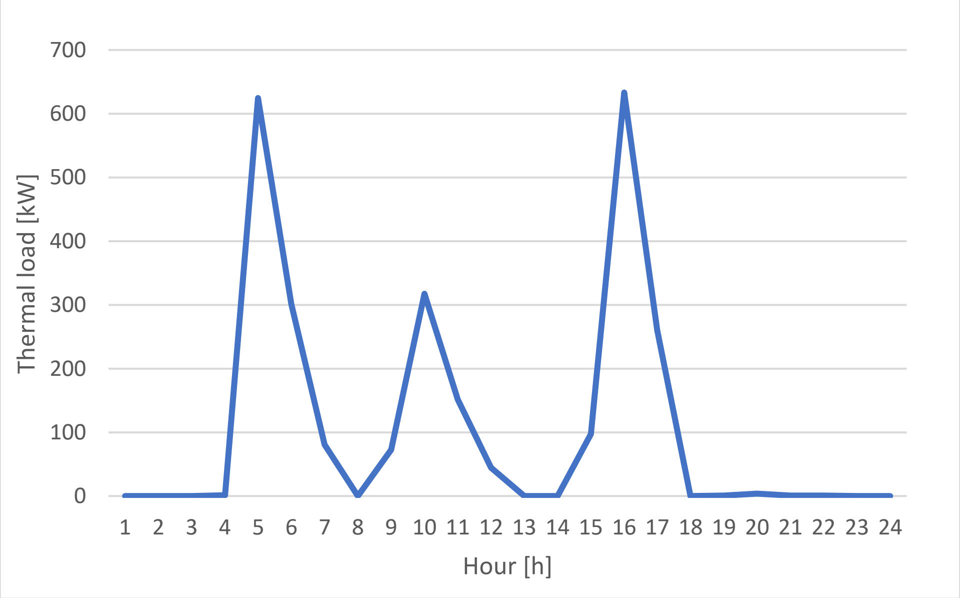


Figure 2.19: Daily thermal load demand curve for household cooking

Chapter 3 Energy Resource Data collection and analysis

The Hybrid renewable energy system requires evaluation of the renewable energy resources in the project region. Solar and biomass resources are assessed more in detail in this chapter, due to good availabilities. First, meteorological data for Amatgyi Khone village are presented, followed by solar resources and optimal placement of PV arrays. Then, availability of biomass in Yedashe Township is estimated, including details of local waste from agriculture. In the last part, the development of rice husks prices is estimated.

3.1 Energy resources

Due to lack of ground measured meteorological data at Amatgyi Khone village, meteorological data from NASA Surface meteorology were collected for use in this study. The geographical coordinates of the selected project site are shown in Table 3.1 and selected meteorological are shown in Table 3.1. The monthly mean temperature ranges in between 19,9 ˚C and 28,3 ˚C throughout the year. The daily temperature variations are highest with an average daily difference of 11,6 ˚C in February. Thus, the seasonal variations are not significant in this area. Also, the day length can be considered similar throughout the year, ranges between 11,0 to 13,2 hours. Based on these climatic data with relatively stable temperature conditions, it is reasonable to assume that the daily load duration profile is constant through the year.

Table 3.1: NASA surface meteorology for Amatgyi Khone Village

	Climate data location
Latitude	19.09 °N
Longitude	96.21 °E
Elevation	510 m
Heating design temperature	14,13 °C
Cooling design temperature	32,26 °C

Table 3.2: Climate data in Amatgyi Khone village from NASA surface meteorology

	Air temp.	*Avg. daily temp. range*	*Relative humidity*	*Atm. pressure*	*Wind speed*	*Heating degree-days*	*Cooling degree-days*
Month	˚C	˚C	%	kPa	m/s	˚C-d	˚C-d
January	20,6	11,1	49,5 %	95,6	2,7	0	334
February	23,3	11,6	41,4 %	95,5	3	0	363
March	26,5	10,9	41,3 %	95,3	2,9	0	491
April	28,3	8,7	48,1 %	95,1	2,5	0	539
May	26,6	6,0	69,4 %	95,0	2,1	0	511
June	24,8	4,5	84,9 %	94,9	2,7	0	442
July	24,4	4,6	85,9 %	94,9	2,6	0	447
August	24,3	4,8	85,5 %	95,0	2,4	0	447
September	24,2	5,3	84,1 %	95,2	2,0	0	432
October	23,6	6,0	79,8 %	95,4	2,1	0	429
November	21,7	7,3	72,2 %	95,6	2,4	0	360
December	19,9	9,2	60,8 %	95,8	2,5	3	318
Annual	24		66,9 %	95,3	2,5	3	5113

It can be observed from the Table 3.2 that the monthly mean wind speed ranges from 2,0 m/s to 3,0 m/s throughout the year. To be able to utilize the wind resources in an energy system, wind speed of more than 3 m/s is required (Lawson 2016). Regarding the poor wind resources in Yedashe Township, wind energy is not considered as an alternative solution in this HRES analysis. Furthermore, due to the small scale of river channel in this area, hydropower system is not considered as a viable solution in the HRES system analysis. It should be noted that these river channels are used to irrigate rice plantation fields.

3.2 Solar energy resources

Myanmar has a good potential of utilizing solar energy, as it receives good amounts of solar energy due to its near equatorial location. With lack of ground-based measured solar resource data for the selected project site, data is obtained by using HOMER's online retrieval system, linked to NASA's website. The data is given as average values per month over a 22-year period (Jul 1983 - Jun 2005). Figure 3.1 shows the annual variations of daily average monthly solar radiation (kWh/m2) and clearness index for the selected site. The values of monthly average daily global solar radiation vary from 7,82 kWh/m^2 in February to 2,62 kWh/m^2 in August. With an annual value of 5,38 kWh/m^2/day. Due to variating monthly global solar radiation, the energy output by a solar energy conversion system would vary from month to month.

The monthly clearness index (CI) is defined as the fraction of solar radiation at the top of the Atmosphere that reaches a particular location on the earth surface (Jiang 2009). Normally the CI varies from around 0,8 in the clearest conditions to near zero in overcast conditions. The CI value at the selected site, varies from 0,39 in July/ August (rainy season) to 0,68 in January/ February (dry season). This implies that the weather conditions in Yedashe Township can be classified as partly overcast. Therefore, according to solar radiation data, the average solar radiation in Amatgyi Khone village is considered to be very good.

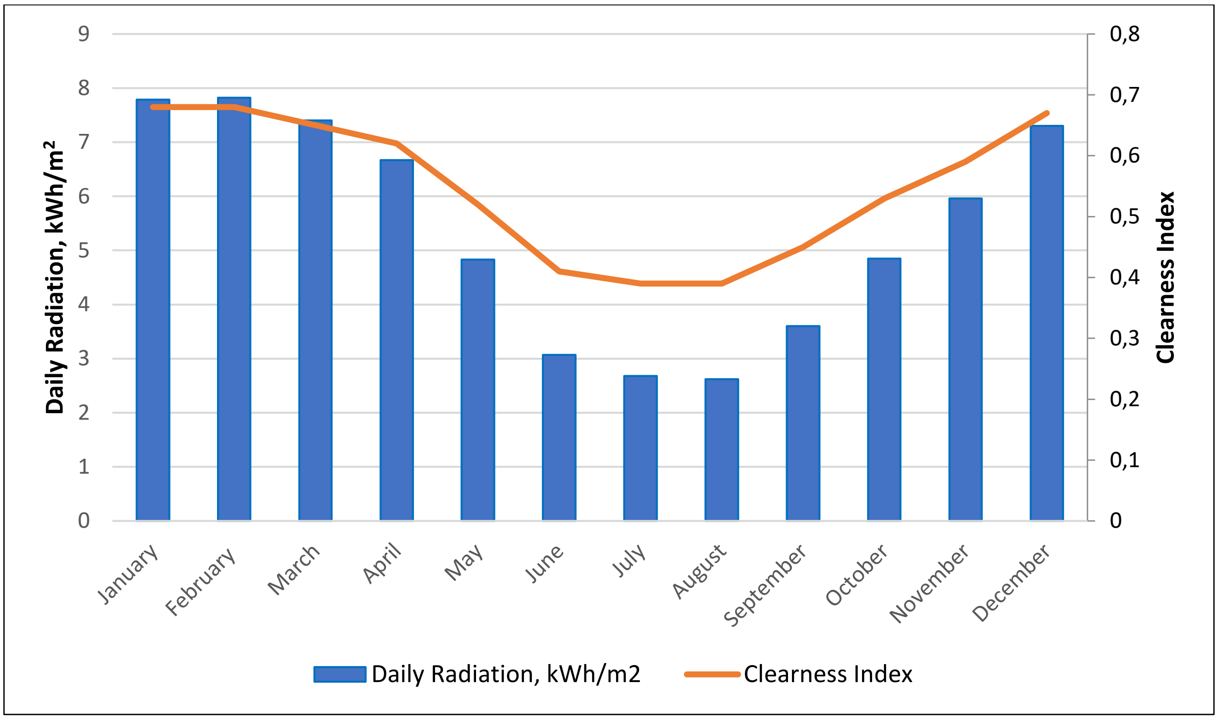


Figure 3.1: Daily average monthly solar radiation (kWh/m2) and clearness index in Amatgyi Khone village

3.2.1 Optimal placement of solar arrays

Aiming to capture the maximum amount of energy from the sun, solar panels should be placed facing towards the sun at an angle of 90°. The position of the sun varies both daily and seasonally. To follow these movements of the sun by the solar panel, a two-axis solar tracker can be used. However, the cost of axis trackers is considered to be relatively high, hence this solution is not widely used in commercial applications. Panels are more commonly mounted with a fixed slope. The fixed slope does normally face towards the equator, and the tilt angle is set to an angle, which is equal to the geographical latitude of the selected location. Generally, this is a good approximation to estimate the optimal angle and to maximize the annual performance of PV panels. However, it is possible to adjust the fixed slope when necessary. The adjustment of the angle depends on both the geographical latitude and the declination angle. The declination angle is an important parameter in order to determine the location of the sun in the sky at any day of the year at any given location (Messenger & Ventre 2005).

The Declination angle (δ) is defined as the angle of deviation of the sun from directly above the equator. The angles vary from 23,45˚ to -23,45˚ within a year, where angles north of the equator are positive and angles south of the equator are negative. The declination angle at any given day of the year, *n*, can be found from the following formula with an accuracy of 0,5˚ (Messenger & Ventre 2005).

$$\delta = 23{,}45 \cdot \sin\left(\frac{360(284+n)}{365}\right) \qquad 3.1$$

3.2.2 Optimal tilt angle

As mentioned earlier, the orientation and the optimum tilt angle of solar panel depends on the latitude (φ) and the declination angle (δ) as well as the time of the day. During solar noon, the radiation is at its highest point. At that time, the path length of the sunrays through the atmosphere is at the shortest. Therefore, it is desirable to tilt the PV modules at an angle where its plane is perpendicular to the sun at solar noon. Thus, optimal tilt angle, $\beta_{optimum}$, of a fixed collector at any given day, should be mounted with its plane at an angle $\phi - \delta$, with respect to the horizontal (Messenger & Ventre 2005). The azimuth, which is the direction that the PV panels face, is towards South (y = 0°) when the $\beta_{optimum}$ is positive and faced North (y = 180°) when $\beta_{optimum}$ is negative (Sunderan et al. 2011).

According to these conditions, the monthly optimal tilt angles for the selected project site of latitude 19.09 °N are estimated as given in Table 3.3. The orientation of the panels should be towards south some months and towards north during other months. Due to higher initiated cost regarding monthly tilt angle adjustments, it is chosen to consider PV system with a fixed angle in this HRES analysis. The optimal tilt angle for fixed south facing PV panel is 19,09° at the selected project location. Figure 3.2 show the effect of the daily Clear-Sky Insolation at variating tilt angles per month. The latitude is 20° N and the azimuth is south (Masters 2013). The highest average yearly clear sky insolation is obtained by a using a tilt angle of 20°, hence using the latitude for the tilt angle is a good selection.

Table 3.3: Monthly variations of optimal tilt angle

Month	*Average declination angle (δ_α)*	*Array tilt ($\varphi - \delta$) (deg)*	*Array orientation*
January	-20,85	40	south
February	-13,33	32	south
March	-2,39	21	south
April	9,49	10	south
May	18,81	0	south
June	23,08	-4	north
July	21,10	-2	north
August	13,30	6	south
September	1,99	17	south
October	-9,85	29	south
November	-19,05	38	south
December	-23,10	42	south

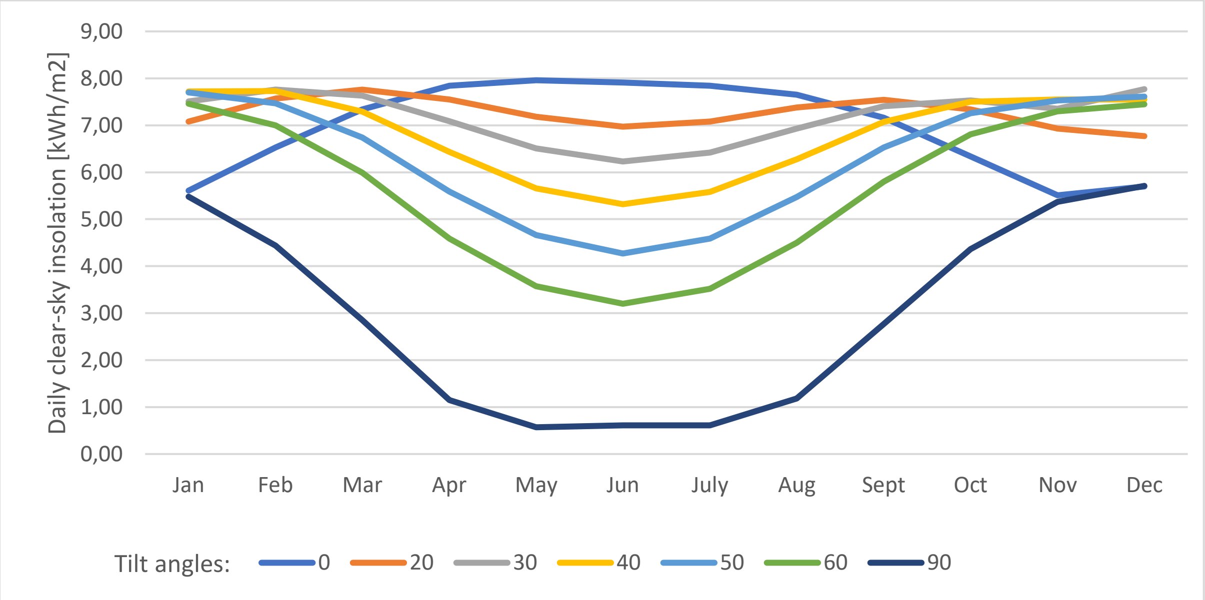


Figure 3.2: The effect of the daily Clear-Sky Insolation at variating tilt angles per month. The latitude is 20° N and the azimuth is south (Masters 2013).

3.2.2 Solar radiation incident on a tilted PV array

The solar radiation data received from NASA’s database are given as global horizontal radiation. To find the power output from tilted PV panels, HOMER calculates the transition of horizontal solar radiation data into radiation on tilted surfaces. The radiation that strikes a horizontal PV surface consists of direct radiation and diffuse radiation. Radiation on tilted surfaces includes an additional parameter, ground reflected radiation (also called albedo effect). This value is selected to be 20 %, which is typical for grass-covered areas.

3.3 Biomass resources

3.3.1 Waste from agriculture

The potential of utilizing crop residues for energy purposes is interesting to explore, having in mind the importance of agriculture in Amatgyi Khone Village. Especially the usage of crop residues that are not in use, such as the paddy that are mainly left in the field. Paddy will by this means be explored in the HRES analysis. Other residues such as cobs from maize and sesame are useful as fuels, but mainly for cooking purposes (EFIF 2016). Table 3.4, show an overview of the seasonal production of the most common types of agricultural crops in Amatgyi Khone Village. The crops comprise paddy, sesame, maize and water melon.

Table 3.4: Calendar showing the seasonal changes for agricultural crops in Amatgyi Khone Village (EFIF 2016).

Crops	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Paddy	🟦	🟦	🟦	🟦					🟦	🟦	🟦	🟦
Sesame					🟦	🟦	🟦	🟦				
Maize				🟦	🟦	🟦						
Water Melon	🟦	🟦	🟦									

EFIF has in addition conducted a study to quantify the animal manure in the Amatgyi Khone village. It is reported that there are about 250 cows and a large amount of pigs used for livestock in the different households. Presently, the animal manure is used as fertilizers on the fields. There may also be a potential of using animal manure for biogas production, by using bio-digesters. Though, the practical aspect of collecting the animal dung from the different household could be challenging. Animal manure are therefore not investigated in this study of HRES. Notwithstanding, the households that have a livestock including cows or pigs, may use the animal dung for cooking purposes in the household. Characteristics of animal manure are shown in Table 3.5.

Table 3.5: Composition of the waste biomass, cattle manure (Basu 2013).

Biomass	*Moisture (wt.%)*	*Organic Matter (dry wt.%)*	*Ash (dry wt.%)*	*HHV (MJ/dry kg)*
Cattle manure	20 - 70	76,5	23,5	13,2

Table 3.6, provides data on the quantity of areas that are under cultivation, and the produced amount of crop residues in Yedashe Township. The total quantity of crop residues available per year comprises 1071 tonnes of paddy and 294 tonnes of maize and sesame. To attain these residues, agreements with farmers needs to be committed. In theory, it is possible to make a marketplace regarding the crop residues, where the farmers can receive an income based on the generated waste.

Table 3.6: Details of crops grown in 2014-2015, Yedashe Township Village (EFIF 2016).

Crop name	*Extent of area under cultivation (acres)*	*Average waste generated per acre (kg)*	*Total quantity of crop residues available (tonnes/annum)*	*Current usage*
Paddy	700	1020	714	Not in use
Paddy (session2)	350	1020	357	Not in use
Maize	175	882	154	Fuel for domestic fodder
Sesame	175	800	140	Not in use

3.3.2 Rice Husks

The by-product, rice husk, from the large rice milling industry in Myanmar, has a major availability in the country. Rice husks are one of the most commonly available lignocellulosic materials that can be converted to different types of fuels and chemical feedstock, through different thermochemical conversion processes (Mansaray & Ghaly 1997). The main characteristics that affect the quality of biomass fuel are moisture content, ash content and particle size and density. Rice husk is flaky and 2-10 mm x 1-3 mm in. As such, it can be fed in a bio gasifier plant as it comes from the source (Basu 2013).

Table 3.7 show the assumed characteristics of rice husk used in the HRES analysis. The parentheses include relevant interval for the given rice husk characteristic. The energy potential of the rice husks fuel for gasification is usually expressed as lower heating value (LHV). The LHV is the amount of heat that is extracted from the combustion of the fuel if water, both from the fuel and generated during combustion, exit in steady flow in a gaseous state. Consequently, the heat of vaporization of the water produced is excluded in the LHV (Mansaray & Ghaly 1997). The LHV selected for the HRES analysis is 14,72 MJ/kg. The *bulk density***,** is defined as the mass portion of a solid fuel divided by the volume of the container which is filled by that portion under specific conditions (Krajnc 2015). The value used in the analysis is 100 kg/m^3. However, densification of rice husk by briquetting and pelletizing can increase its density to a range of 550-700 kg/m^3. Related advantages are high volumetric density and energy, lower transportation and storage costs, and lower emissions during combustion (Mansaray & Ghaly 1997). Due to high investment costs and energy input required for the technique to make rice husk pellets and briquettes, utilization of rice husk pellets and briquettes are not considered in this thesis work.

Table 3.7: Characteristics of rice husks

Rice husk characteristics	***Values***	***Sources***
Particle size	2-10 mm x 1-3 mm	(Basu 2013)
Moisture (% air dry basis)	9,44 (7 - 10)	(Mansaray & Ghaly 1997), (Basu 2013)
C (%)	38,5	Tillman (1978)
H (%)	5,7	Tillman (1978)
N (%)	0,5	Tillman (1978)
S (%)	0	Tillman (1978)
O (%)	39,8	Tillman (1978)
Ashes (% dry basis)	15,14	(Mansaray & Ghaly 1997)
Density (kg/m^3)	100 *(86 – 114)*	(Mansaray & Ghaly 1997)
Higher heating value (HHV), dry (MJ/kg)	15,0 *(14,95 – 15,01)*	(Shen et al. 2012)
Lower heating value (LHV), dry (MJ/kg)	14,72 *(13,24 – 16,2)*	(Mansaray & Ghaly 1997)

3.3.2.1 Rice husk fuel price

The price of rice husk is determined by a supply and demand mechanism. Increasing prices of rice husk may occur in a scenario where rice husk is widely exploited as a feedstock for biomass power. For example, the interest of biomass for power production has increased a lot in Thailand since the 2000s. More than 100 MW of energy is provided by rice husk fired power. The competition for rice husk increased its price from \$28 /tonne in the 2000s to a peak value of \$46 /tonne in 2008. The price was stabilized to \$39 /tonne in 2015. A similar scenario is likely to happen in Myanmar as well (Institute 2015)(p.76). Therefore, regarding the HRES analysis, the chosen price value of rice husk is chosen relative to the phenomenon that happened in Thailand. The price is \$35 /tonne rice husk, and a sensitivity analysis is conducted to understand the scenario of varying fuel prices. The sensitivity interval is the given price situation that happened in Thailand, with prices from \$28 to \$46 /tonne.

Chapter 4 Hybrid renewable energy system components

In this chapter, selections of hybrid renewable energy system (HRES) components are presented. The primary components used in the study are solar PV panel, Bio gasifier power plant (BGPP), battery bank and inverter. The presentation includes technical characteristics, capital cost, operation and maintenance cost of the HRES components. Furthermore, costs related to micro grid are estimated and presented. Figure 4.1 shows the schematic diagram of the proposed energy system.

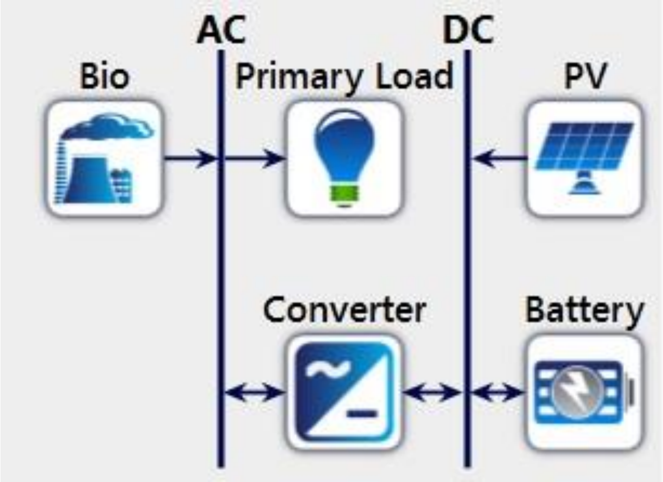


Figure 4.1: Schematic diagram of the hybrid energy system.

The estimation of component characteristics is based on requirements related to energy system modelling in HOMER software, developed by U. S. National Renewable Energy Laboratory (NREL). HOMER software is a tool that simplifies the design evaluation of micropower systems. The systems can be grid-connected or off-grid micropower systems for remote, stand-alone and distributed power generation applications. HOMER facilitates a wide range of renewable and conventional energy technologies, including solar PV, wind turbine, hydro power, storage options, generator (biogas, diesel and gasoline).

4.1 Biomass gasifier plant

The bio-gasifier power plant (BGPP) is important to the HRES to improve the quality and the availability of electricity supply. The BGPP can supply the required load whenever the electricity production from the Solar PV system are low or when the batteries' state of charge does not meet the requirement.

The electricity generation from biomass has three options: gasification based combined cycle, combustion based steam cycle, gasification based gas engine, and gasification of biomass in small gasifiers. Gasification is a process of converting solid biomass fuel into a gaseous combustible gas (called producer gas) through a sequence of thermo-chemical reactions. The gas is, then, cleaned and can be used in a biogas generator. These gas engine plants are generally used in small capacities especially in remote locations, and hence, they are suitable for the HRES.

4.1.1 Biomass gasifier

A gasification plant includes the gasifier reactor as well as support equipment. The design of a gasification plant would involve design of individual units:

- Gasifier reactor
- Biomass-handling system
- Biomass-feeding system
- Gas-cleanup system
- Ash or solid residue-removal system

Gasifiers are classified mainly based on their gas-solid contacting mode and gasifying medium. The gasifiers can either be of a "fixed/moving bed" (< 10 MW_{th}), "fluidised bed" (5 -100 MW_{th}) or "entrained flow" (> 50 MW_{th}). Each type is further subdivided into specific commercial types. According to the load requirement of the village, a fixed or moving bed gasifier reactor is suitable for the HRES analysis.

In entrained-flow and fluidized gasifiers, the gasifying medium carries the fuel particles through the reactor, whereas in a fixed-bed (also known as moving-bed) gasifier, the fuel is supported on a grid. The reason why it is also named a moving bed is because the fuel moves down in the gasifier as a plug. The fixed-bed gasifiers can be built inexpensively in small sizes, which is one of their major attractions.

Throatless Gasifier is within the subgroup of the Downdraft, Fixed-bed Gasifier. Throatless Gasifier is suitable for the HRES, due to applicability to use finer or lighter fuels, such as rice husks. This gasifier type is also called open top or stratified throatless. The reason is that the top is exposed to the atmosphere, and there is no narrowing in the gasifier vessel due to vertical walls. This avoids bridging and channelling of biomass, hence the gasifier is suitable for lighter fuels. The movement of biomass down the gasifier is shown in Figure 4.2, including a description of the temperature gradient during the gasification process (Basu 2013).

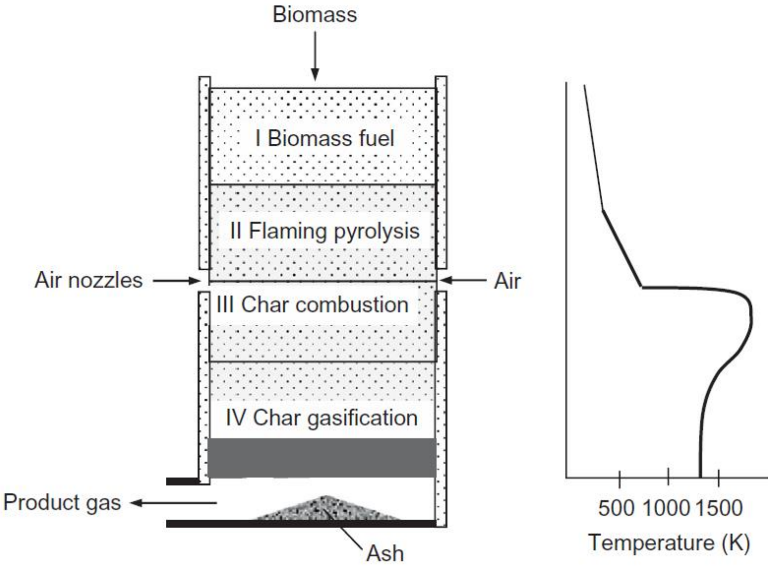


Figure 4.2: Schematic of the operation of a throatless downdraft gasifier (left). Temperature gradient along the height (right) (Basu 2013).

Operation principle of the throatless gasification process

The throatless process can be divided into the following four zones:

(i) In the first zone, at the top, piles of raw rice husks are received and dried, and the biomass heats up.

(ii) The second zone receives heat from the third zone principally by thermal conduction. Above 350 °C, it undergoes pyrolysis, breaking down into charcoal, non-condensable gases (CO, H_2, CH_4, CO_2 and H_2O), and tar vapors (condensable gases). The pyrolysis product receives only a limited supply of air from below and burns in a fuel-rich flame, hence the name *Flaming pyrolysis*.

(iii) The third zone burn ash and pyrolyzed char produced in zone II, and generate heat for the pyrolysis. The gases from the hot char undergo steam gasification, producing CO and H_2. The temperature of the downflowing gas reduces relatively, due to the endothermic gasification reactions, but is still above 700 °C.

(iv) The bottom layer consists of hot ash and/or unreacted char, which crack any unconverted tar in this layer.

Figure 4.3 show an illustration of the selected Bio gasifier power plant. Followed by the technical specification of selected downdraft gasifier, given in Table 4.1.

Figure 4.3: Bio Gasifier Power Plant (e-mail correspondence 2017)

Table 4.1: Technical specifications of the selected Biogas gasifier, HT-QHL300B.

Biomass gasifier Model	HT-QHL450S
Biomass gasifier type	Downdraft fixed bed gasifier
Gas output	450 m^3/h
Gas calorific value (LHV)	4,5 - 5,2 MJ/m^3
Efficiency of gasification	> 72 %
Draught fan Power	380 V
Biomass amount	230 kg/h
Biomass dimension	< 20 cm
Biomass humidity <20 %	< 20%
Suitable for generator	150 kW
Price per set	$105 000
Shipping cost from China to Myanmar	$2150

Source: <http://zzhonest.en.made-in-china.com/product/VvSQXYycAGpB/China-China-Supplier-Biomass-Gasifier-for-Sale-Electric-Rice-Husk-Gasifier.html>.

Performance and operating issues

The performance of the gasifier is measured in terms of both quality and quantity of gas produced. The amount of biomass converted into gas is expressed by gasification efficiency. The product quality is measured in terms of heating value as well as amount of desired product gas.

The efficiency of gasification is normally expressed as cold-gas efficiency when considering downdraft gasifiers. Cold-gas efficiency is the potential energy output over the energy input. The total energy input is equal to the LHV of the feed, and the total energy output is equal to the constituents of the product gas (Basu 2013.

Operational issues that are universal to all types of gasifiers are problems related to biomass handling and feeding. While using low-shape-factor (flaky) biomass such as rice husk, it is common that rice husk bonds over the exit of the hopper (Basu 2013). The raw gases from biomass gasifiers usually contain large amount of ash and tar which must be removed to avoid operation problems in the gas engines. The most common methods used of gas cleaning are tar cracking and wastewater treatment for re-circulating. However, this method of water scrubbing, both decreases system efficiency and produces tar-containing wastewater. Gas cleaning is the weakest section of bio-gasifier power plant systems which needs further research (Wu et al. 2002).

4.1.2 Biogas generator

The next step in the bio-gasifier power plant (PGPP) is generation of power by using a generator fuelled by the producer gas. The electricity produced is used to supplement the power production from Solar PV and the battery energy storage. The generator is important during periods when the PV and the storage system does not meet the load requirement.

Two generators are selected for the HRES analysis, whereas one of the generators would act as a backup. The purpose is to obtain a more stable and reliable power supply, due to periods when any of the generators would require maintenance. The generators have rated capacities of 100 kW and 50 kW. The technical specifications of the selected models, Model LHBM100 and Model LHBM50, are given in Table 4.2.

Table 4.2: Technical specifications of the selected biogas generators, LHBM100 & LHBM50

Biomass gas generator	**LHBM100/ LHBM50**
Model LHBM100	
Rated Power/Prime Power	100 kW/ 80 kW
Power range	50 – 150 kW
Model LHBM50	
Rated power/Prime Power	50 kW/ 40 kW
Rated speed	1500 rpm
Overheal Time	>30 000 h
Rated Voltage	400V/230V
Starting system	DC 24 V Electric motor
Rated power factor	0,8
Rated Frequency	50/60 Hz
Output type	AC Three Phase
Cost of Model LHBM100 (incl. shipping)	$11 150
Cost of Model LHBM50 (incl. shipping)	$12 780

Sources: *Generator 100 kW: <http://lvhuanpower.en.made-in-china.com/product/ySDmqvXkXAUJ/China-100kw-Biomass-Gas-Generator-Set-or-Genset-Ce-and-ISO-Approved.html>*
Generator 50 kW: <http://sd-energy.en.alibaba.com/product/60448762277-802971135/50_kw_Small_Biogas_Generator_Price_or_ Electric Generator_Prices.html?spm=a2700.8304367.0.0.2XItJw>

Generators need to operate at nearly 90 % of their output capacity to obtain efficient operation. Hence, by maintaining good efficiency, the fuel consumption can consequently be reduced. Information about the fuel consumption are normally included in the product specification data sheet, given by the manufacturer. HOMER use this information to calculate Equation 4.1, and aggregate a fuel consumption curve for the selected generators. Following, based on the information from the fuel consumption, an efficiency curve is derived.

$$F_c = aP_{rated} + bP_{gen} \tag{4.1}$$

Where

F_c = generator fuel consumption
a = generator fuel curve intercept coefficient [L/h/kW]
b = generator fuel curve slope [L/h/kW]
P_{rated} = generator rated capacity [kW]
P_{gen} = generator power output [kW]

The selected generators have estimated 30.000 hours of lifetime each. However, the actual operating lifetime of a generator can be calculated from Equation 4.2.

$$R_{gen} = \frac{Q_{lifetime}}{Q_{thrpt}} \tag{4.2}$$

Where

R_{gen} = generator operational life [yr]

$Q_{lifetime}$ = running-time of a generator [h]

Q_{thrpt} = actual annual operation time [h/yr]

4.1.3 Bio-gasifier plant costs

Capital cost

The small-scale Bio-gasifier power plant (BGPP) technology is widely used, especially in India. Studies from India show that investment costs are generally low, \$1000 to \$1500 kW^{-1} (IRENA 2012). The Indian companies, HPS and DESI Power, have reported a considerable lower cost (800 \$ kW^{-1}). Though, these companies manufacture its gasifiers locally and by using its own design. Therefore, these low cost advantages may not be available to other projects (Bhattacharyya 2014). In addition, a study from Brazil show a capital cost of approximate 590 \$/kW, where gasifier (500 kW), engine-generator (100 kW) and civil works are included (Fracaro et al. 2011). Hence, the total capital cost of a gasifier power plant is estimated to be \$ 955 kW^{-1} in Fracaro et al.'s analysis.

The costs of biogas-generators are largely dependent on the size. Small sized generators have higher cost per kW installed, and generators with high capacity have lower cost per kW. Hence, the cost curve increases with a gradually reducing gradient. Price variations can also be found among brands and according to features included.

For this thesis work, the costs components for BGPP used are shown in Table 4.3. Also shown in Table xx, are the installation cost and total O&M costs. The economic life of biomass power plant is assumed to be 25 years. A sensitivity analysis is performed to examine the effect of variating cost of BGPP, ranging from \$800/kW to \$1500/kW, on the optimal hybrid energy systems and performance.

Operation and maintenance cost

Operation and maintenance costs (O&M) regarding BGPP are generally divided into fixed and variable costs. The annual fixed O&M costs are normally expressed as a percentage of capital costs with a typically range of 2 - 7 % of installed cost per year (IRENA 2012). The fixed costs consist of labour, scheduled maintenance, routine component/equipment replacement (for gasifiers, feedstock handling equipment, etc.) and insurance. Variable O&M costs depend on the output of the system and are normally around 0,005 $/kWh (IRENA 2012). They include non-biomass fuels costs, ash disposal, unplanned maintenance, equipment replacement and incremental servicing costs. The selected O&M costs in the HRES analysis are given in Table 4.3. In HOMER, the total annual O&M costs are given in *$/h*, which can be found by dividing the yearly O&M costs by the number of hours per year (8760 h).

Table 4.3: Cost estimation of Bio gasifier power plant (PGPP).

Cost Description BGPP	*Unit*	*Value*	*Remarks/Source*
Rated capacity of BGPP	kW	150	
Capital cost Bio gasifier, incl. transport cost	$	107 150	E-mail
Capital cost Biogas engine (100 kW), incl. transport cost	$	11 150	
Capital cost Biogas engine (50 kW), incl. transport cost	$	12 780	
Construction and Installation BGPP 10 % of combined capital cost	$	12 108	Authors assumption
Total capital cost of BGPP	**$/kW**	955	
Annual total O&M Biogas generator #1 Biogas generator #1 (100 kW) Biogas generator #1 (75 kW) Variable: 3,5 % of capital cost, fixed: 0,005 $/kWh	$/h	0,88 0,67	(IRENA 2012)
Annual total O&M Biogas generator #2 Biogas generator #2 (50 kW) Variable: 3,5 % of capital cost, fixed: 0,005 $/kWh	$/h	0,44	(IRENA 2012)

4.2 PV panels

4.2.1 Power output of a PV module

The power output of the PV system is a function of the solar irradiance and the cell temperature, and can be calculated using Equation 4.3:

$$P_{PV} = P_{rated} \cdot f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \left[1 + \propto_p \left(T_c - T_{c,STC} \right) \right], \tag{4.3}$$

where:

P_{rated}	is the rated capacity of the PV array (kW)
f_{PV}	is the PV derating factor
G_T	is the solar radiance incident on the PV array (kW/m^2)
$G_{T,STC}$	is the incident radiation at standard test conditions (1 kW/m^2)
$\propto_p$	is the temperature coefficient of power (%/°C)
T_c	is the PV cell temperature (°C)
$T_{c,STC}$	is the PV cell temperature under standard test conditions (25°C)

In a case where the effect of temperature on the PV array performance is neglected, $\propto_p$ can be assumed to be zero and Equation 4.3 is reduced to:

$$P_{PV} = P_{rated} \cdot f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \tag{4.4}$$

4.2.2 Selection of PV modules

In this thesis, SunVivo PM060MB2 is selected. Table 4.4 shows essential technical specifications of the selected module. The module has a relatively high effect compared to other modules at the market. In addition, Europe-SolarShop could provide shipping and a discount of 8 % while buying several modules, resulting in a reasonable choice of PV modules.

Table 4.4: The Manufacturer BenQs technical specifications of the selected PV module, SunVivo PM060MB2.

Parameter (Units)	***Value***
Module Technology	Monocrystalline solar cells
Normal maximum power, P_{mpp}, (W)	290
Short Circuit Current, I_{SC}, (A)	9,57
Open Circuit Voltage, V_{OC}, (V)	39,7
Current at normal maximum power (P_{MPP}), I_{mpp}, (A)	8,99
Voltage at normal maximum power (P_{MPP}), V_{mpp}, (V)	32,3
Efficiency (Nominal Power) (%)	≥ 17,8
Temperature coefficients:	
P_{max} (%/K)	-0,42
I_{SC} (%/K)	0,05
V_{OC} (%/K)	-0,3
Normal operating cell temperature, NOCT, (°C)	46 ± 2
Dimensions (mm)	1640 x 992 x 40

4.2.2 PV costs

The cost of solar photovoltaic panels (PV) are decreasing due to innovation in the production of solar cells and improvements of manufacturing of solar panels. The overall costs for PV panels ranges between \$1750 and \$2500 per kW of installed capacity. This estimate includes both purchasing of equipment and cost for solar panel installation. However, the price can be assumed to be higher regarding solar home systems, and lower for solar panel installations, e.g. 50 kW-150 kW (Green 2013).

Balance of System (BOS) refers to all components and equipment of the PV system, other than the modules, which includes system electronics and support structure. In addition to inverters, BOS includes equipment such as cables/wires, switches, enclosures, fuses, ground fault and detectors. In this analysis are costs of BOS is set to 40 % of the prices of PV modules and installation costs (Szabó et al. 2011). Table 4.5 show all the estimated prices regarding Solar PV system installations.

Table 4.5: Cost estimation of Solar PV system components

Components of solar PV system	*Prices*	*Sources*
Cost per PV module	$184	(Europe-Solarshop 2017)
Total cost of PV modules 150 kW system requires 518 modules, 10 % cost savings	$87 690	(Europe-Solarshop 2017)
Shipping cost PV modules and other equipment	$2650	E-mail correspondence with Europe-Solarshop (2017)
Total installation cost 2,5 hrs/ kW installed capacity Labour cost per hour: $20	$7500	(Tømmerbakke 2017) Authors assumption
BOS 40 % of PV modules & installation. Cost of Ground mounting structure (*$10 399)* and other equipment.	$38 076	(Szabó et al. 2011)
Total capital cost ($)	$ 135 916	
Total capital cost ($/kW) 150 kW installed capacity	**$906 /kW**	
Replacement cost PV modules and equipment 80 % of total capital cost	$725 /kW	
Annual O&M costs $10/ kWp-yr Based on market assumptions from HOMER's database	$10/yr	HOMER user manual. Labour cost included in system total O&M costs.

4.3 Storage Battery

An off-grid power system require storage for the excess energy that are generated by the variable, renewable energy sources. The storage of energy can be further used during periods when the renewable applications are not producing enough energy. Batteries are the most common storage option used in HRES. Though, by having generators available for backup, it may seem less viable to incorporate batteries into the system. However, for generators to operate efficiently, they need to operate at 90 % of their output capacity. Normally in a battery/generator system, the generator will charge the batteries from 20 – 70 %. Charging the batteries too quickly tends to result in an inefficient charging process. The batteries are also required to have a few days of storage, called Days of Autonomy (DA), to avoid an excessive charging rate. More storage will normally result in somewhat lower use of the generator, since the generator will not necessary need to back up the PV array in the event of cloudy weather for a few days. In general, fewer batteries will be used in a hybrid system, since the generator will supplement the sun. Choice of the number of days of autonomy for the system, however, becomes more dependent on other factors, such as how long it may take to implement emergency repairs on the generator (Messenger & Ventre 2005).

A popular choice in renewable energy systems, are the lead acid batteries, because they are inexpensive on a cost-per-watt base and have a good life capacity (Univeristy 2011). The lead-acid batteries fall into two types: “deep discharge’ and ‘shallow discharge’. Deep discharge is preferred because it can be almost completely drained without too much damage. However, lead-acid batteries are heavy. Other types, such as nickel-metal-hydride, nickel-cadmium and lithium-ion batteries, are sometimes used because they are lighter, require less maintenance and have a longer life and are more flexible in use, but they are very expensive (Thorpe 2013).

The key properties of a battery are the nominal voltage, state of charge (SoC), minimum state of charge, round trip efficiency, maximum discharge current, capacity curve and the lifetime curve. The state of charge is the percentage from the maximum possible charge accessible for the battery. The SoC of the battery depend on the available energy and the load requirements to the HRES, and can be calculated by the equations:

Battery charging:

$$SoC(t) = SoC(t-1)\times(1-\sigma) + \eta_B\left(E(t) - \frac{E_L(t)}{\eta_{inv}}\right) \tag{4.5}$$

Battery discharging:

$$SoC(t) = SoC(t-1)\times(1-\sigma) + \left(\frac{E_L(t)}{\eta_{inv}} - E(t)\right) \tag{4.6}$$

Where:

$SoC(t)$ = the state of charge of the battery bank at time t

$SoC(t-1)$ = the state of charge of the battery bank at time t

σ = the hourly discharge rate

$E(t)$ = the total energy generated by the renewable systems

$E_L(t)$ = the demand of load at time t

η_{inv} = the inverter efficiency

η_B = the battery bank efficiency

The minimum state of charge is the lower limit of battery discharge, thus discharging below the minimum SoC can permanently damage the battery. The round-trip efficiency accounts for thermal losses involved while discharging the batteries. The maximum discharge current of a battery refers to the highest current possible to draw from the battery, to avoid significantly shortening of the battery life.

In this HRES analysis, the battery Surrette 4KS25P is selected, which is a deep cycle lead acid battery (Rolls 2014). The battery characteristics given by the manufacturer is summarised in Table 4.6, for Surrette 4KS25P battery. The cost per Surrette 4KS25P battery is found to be $1300 at the webpage to Solardyne, LLC of Portland, Oregon (SolarDyne 2017).

Table 4.6: Technical specifications for Surrette 4KS25P battery (Rolls 2014).

Parameter (Units)	***Value***
Nominal capacity @100-h rate (Ah)	1904
Nominal voltage (V)	4
Round efficiency (%)	80
Minimum state of charge (%)	40
Float life (years)	12
Lifetime throughput (kWh)	10 569
Maximum discharge current (A)	67,5

The battery life is mainly affected by the operating temperature and the depth of discharge (DoD). DoD are the level of discharge cycle, before the battery is charged again. DoD can be formulated as the inverse of SoC. The manufacturer normally specifies the nominal number of complete charge and discharge cycles as a function of the depth of discharge in the product manual. Based on this information the lifetime curve for Surrette 4KS25P battery are generated by using HOMER, shown in Figure 4.4. This lifetime curve illustrates how the cycles to failure reduces with increasing DoD. The lifetime throughput of a single battery is also illustrated in the figure, and is calculated by HOMER based on the following equation:

$$Q_{lifetime,i} = f_i d_i \left(\frac{q_{max} V_{nom}}{1000}\right) \tag{4.7}$$

Where:

$Q_{lifetime,i}$	is the lifetime throughout of a single battery (kWh)
f_i	is the number of cycles to failure
d_i	is the depth of discharge (%)
q_{max}	is the maximum capacity of the battery (Ah)
V_{nom}	is the nominal voltage of the battery (V)

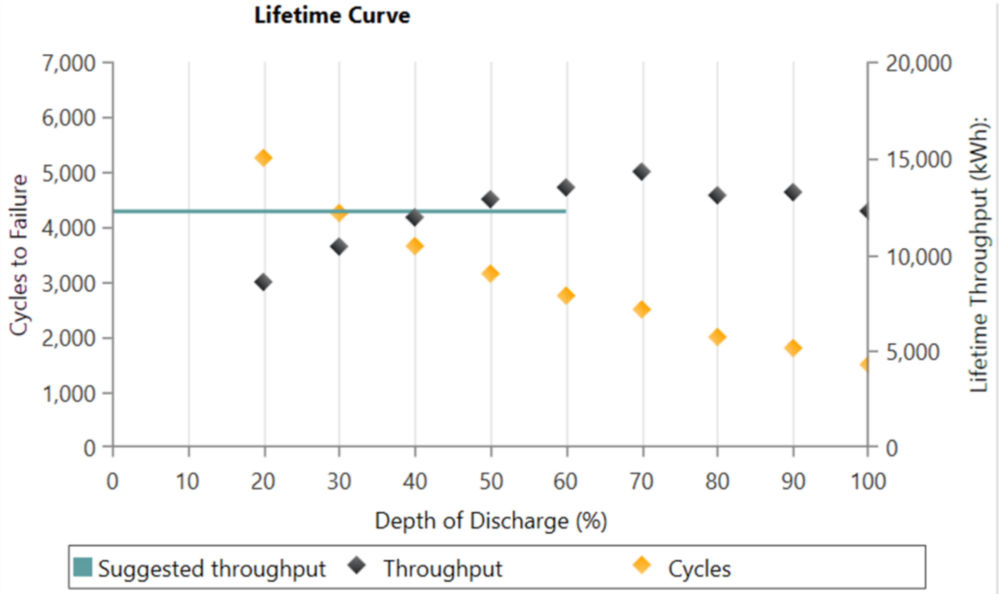


Figure 4.4: Lifetime curve of Surrette 4KS25P, 4V battery

Total battery bank life is determined based on the lifetime throughput of single battery (ref. eq. 4.7), number of batteries, annual battery throughput and the battery float life. The HOMER software calculates the battery life by using the Equation 4.8:

$$R_{batt} = MIN\left(\frac{N_{batt} \cdot Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) \qquad (4.8)$$

Where:

R_{batt}	is the battery life (yr)
N_{batt}	is the number of batteries in the battery bank
$Q_{lifetime}$	is the lifetime throughout of a single battery (kWh) (found in equation 4.7)
Q_{thrpt}	is the annual battery throughput (kWh/yr)
$R_{batt,f}$	is the battery float life (yr)

The capacity of the battery is determined by the amount of energy, withdrawn from start to complete charged state, and is measured in ampere-hours [Ah]. Thus, the capacity depends on the rate of which the energy is withdrawn. A higher discharge current, results in lower capacity. The capacity curve, generated in HOMER for the selected battery, are given in Figure 4.5. The number of nominal capacity that is given by the manufacturer is 1904, and it is shown as the highest data-point in the capacity curve.

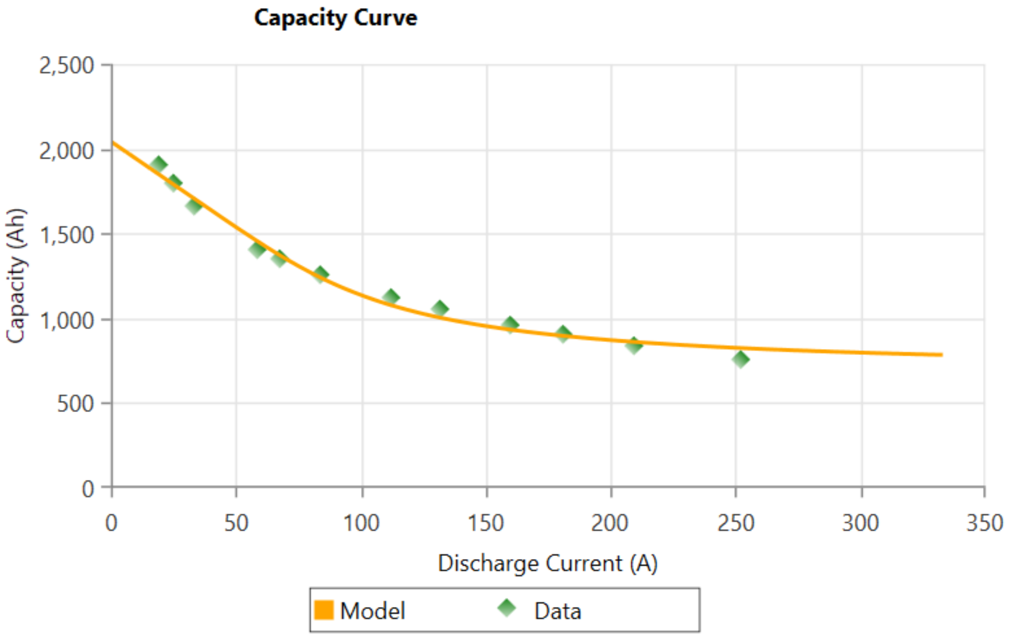


Figure 4.5: Capcity curve of Surrette 4KS25P, 4V battery

Generally, maintenance of batteries involves cleaning of cases, cable and terminals, tightening terminal, addition of distilled water and performance checks (Univeristy 2011). The cost of O&M is selected to be \$10 year^{-1}, based on information from HOMER's database.

4.4 Charge controllers

Charge controllers include a low-voltage disconnect that prevents over-discharging, which can permanently damage the batteries. Hence, the battery life can be extended by using a charge controller, to regulate the flow of electricity to keep the batteries fully charged without overcharging. Charge controllers that include maximum power point tracking (MPPT), optimizes the PV array's output, by increasing the energy it produces. The choice of charge controller must match the size of the PV system and the system voltage (Thorpe 2013). However, the charge controller is normally implemented as a function in the inverter, and therefore it is not further discussed.

4.5 Inverter

A hybrid energy system often need an inverter to convert the DC voltage from the Solar PV panels and the batteries to AC voltage necessary to match the load requirement. The selection of inverter for energy system depends on several factors, such as the waveform requirement of the load and the efficiency of the inverter. In addition, whether the HRES will be part of a grid-connected system or be a stand-alone system. Therefore, the right inverter must be carefully selected for the HRES according to the requirement, and by paying attention to the HRES configurations (Messenger & Ventre 2005).

For optimum performance of a PV system, the rated capacity of the inverter should be higher than the rated capacity of the system in order to prevent operations at overload conditions (Technology 2016). The sizing ratio (R_s) is defined as the ratio of the PV module rate capacity at standard test conditions (STC) to the rated inverter capacity, and can be calculated by using Equation 4.9.

$$R_s = \frac{P_{PV,rated}\,(kW)}{P_{inv,rated}\,(kW)} \tag{4.9}$$

Where, $P_{PV,rated}$ and $P_{inv,rated}$ are the rated PV capacity and rated inverter input power, respectively. The optimal sizing ratio vary between 0,8 and 1,8 depending on location and climatic condition on site, PV-to-inverter cost ratio and orientation of the PV modules (Yohanis & Norton 2006).

Inverters can be categorized according the type of waveform they produce. Whereas, the most common waveforms are square wave, modified square wave and sine wave (Thorpe 2013). Square wave inverters have good surge capacity but high harmonic distortion. They are the least expensive option, but are only suitable for small appliances. Modified square wave inverters can handle higher surge capacities and the output include less harmonic distortion. The Sine inverters have the least distortion, but the lowest efficiency for stand-alone applications, however suitable in a Hybrid energy system (Messenger & Ventre 2005).

Therefore, a pure sine wave inverter is selected in this HRES analysis. It is a combined inverter and battery charger, hence suitable as an off-grid inverter to supply AC load to the micro grid. The selected inverter is a SMA Sunny Tripower 60-10, and the technical specifications of the inverter are given in Table 4.7. The lifetime of the inverter is assumed to be 15 years. The cost of the inverter system is crucial when considering the economy of the Hybrid power system. Inverter price varies among countries and modules, however the average cost range of inverter is found to be 600-1000 per kW (Technology 2016).

Table 4.7: Technical specifications of the inverter, SMA Sunny Tripower 60-10.

Inverter specifications	*Unit*	*Value*
Rated Capacity	kW	60
Maximum Efficiency	%	98,80
DC voltage input	V	565 - 1000
AC voltage output	V	360 - 530
Maximum operating current	A	110
Maximum output current	A	87
Max. efficiency	%	98,8
Nominal output frequency	Hz	50 (44-55)
Ambient temperature range	°C	−40 to +75
Price	$	5938
International Shipping	$	350

4.6 Mini Grid

A mini grid or a distribution grid transmit the electrical power from the hybrid generating station to the end users. Mini grid operates with capacities of 10 kW to few MW. Transmission lines that can be used are either low voltage or medium voltage (LV/MV) transmission lines; single-phase lines or three-phase lines. The LV lines are usually 230 V in single phase or 400 V in three phase systems, and can supply end users at around 1 km, due to voltage drops and cable size. The MV lines can be required if end users are located several tens of km from the hybrid generation station (IED 2013). The required length of the mini-grid network in Amatgyi Khone village is assumed to be 5 km. The households are located at relatively close distances and at a plane topography. Hence, the LV lines are considered suitable for the HRES analysis. In addition, the transmission lines are required to be of 400 V three-phase, 4 wires, due to the power output requirements of the biogas generator.

There are many technologies of various quality and lifetime that can be considered for the mini-grid network, such as bamboo poles with bare iron conductors to concrete or metallic poles with ABC cables

(IRENA 2012). The cost of the LV lines ranges from \$5000 to \$8000/km, and this value can be both lower/higher depending on geographical constraints and technology used (IED 2013). An example from India show that the typical cost of low-voltage distribution line is about \$3000 per km for plane areas and the cost increases by 10–25% for remote, hilly regions (Bhattacharyya 2014). Thus, in this analysis an average cost of \$6000 per km is selected for the mini-grid distribution system. O&M costs are selected to be 2 % of investment cost of the mini-grid distribution system (IED 2013).

4.7 Alternative cook stove

Due to a vast need of better cooking technologies in Amatgyi Khone village, a cook stove developed by TERI is considered in this thesis work. The cook stove, type SPTL-0610, has higher efficiency compared to the conventional open fire technique. However, the SPTL-0610 is similar to the villager's current cook stove in terms of their habits of cooking with fire wood. EFIF are considering replacing the villagers exciting cook stove with the SPTL-0610 in Amatgyi Khone village, as part of the Energy Farm plans. As shown in section 2.8.3, the require load for cooking is high, hence, covering the cooking demand with electric power, would require a HRES with considerable higher capacity. Though, the price of the cook stove is crucial, considering the villagers willingness and availability to pay. This cook stove is relatively cheap compared to optional solutions such as electrical cook stoves. If financial support could be granted, possibilities to implement this cook stove would be more realistic. In the following section, the cook stove SPTL-0610 is described, followed by estimation of the reduced demand of fire wood if this cook stove is implemented in the Amatgyi Khone village.

4.7.1 Forced draft cook stove, SPTL-0610

The alternative cook stove is a stainless steel forced draft cook stove (SPTL-0610), shown in Figure 4.6. The cook stove has an estimated capacity of serving up to seven family members with their cooking needs. The electricity needed to operate the cook stove is primarily due to operation of a fan. The required fan load is accounted for within the future load estimation of the village in Section 2.7. There are several advantages related to the utilization of an improved cook stove such as, SPTL-0610, compared to traditional mud stove/three stone fires. TERI have listed the following advantages in the prefeasibility study (Mahawar 2015):

- *Less fuel: 60 % less consumption of fuel*
    - *Reduces the time used for fuel collection*
    - *Reduce deforestation due to less consumption of fuelwood*

- *Less smoke: 70 % reduction in smoke*
  - *Beneficial in terms of reduced Indoor Air Pollution (IAP) and healthier environment for women and children*
  - *Controls environmental pollution*
  - *Less problems with soot at cooking pots and kitchen walls*
- *Less Cooking time: Reduces the cooking time by approximately half the time*
- *Local fuel: Chopped locally available solid biomass*
  - *The fuel required does not demand the establishment of a separate fuel supply chain*
  - *Facilitates local and available fuel for cooking*

Figure 4.6: Stainless steel forced draft cook stove developed by TERI (TERI, 2016)

The fan is powered by a battery (12 V and 0,4 Ah). The power charger has a dual charging mode of AC/ grid power supply and solar power supply, rather suitable for households in un-electrified areas. The Ministry of New and Renewable Energy (MNRE), Government of India has approved TERI's stove technology and made it technically qualified for all government funded projects (Mahawar 2015). The technical specifications are listed in Table 4.8.

Table 4.8: Specifications of the cook stove SPTL-0610, developed by TERI.

Specifications	***Values***
Factory price	\$50,4
Stove body	Stainless steel (grade 304)
Battery	12 V, 0,4 Ah Lithium Cobalt Oxide batteries
Efficiency	37 %
Fuel consumption	0,9 – 1,4 kg/h
Fuel type	Fuel wood, crop residue, animal manure
Power supply	12 V DC
Carbon Monoxide emissions	2,25 g/ MJ delivered
Particulate Matter Emissions	147 mg/ MJ delivered
Operational Life	7 years

4.7.2 Reduction of fuelwood consumption

As previously mentioned, scarcity of fuelwood may become a problem in Amatgyi Khone village, in the future. Therefore, a rough estimate is performed to find the reduced usage of fuel wood, with implementation of TERI's cook stove (SPTL-0610). Table 4.9 show the potential energy that can be obtained by using the cooking technologies open fire and SPTL-0610, considering the same amount of fuelwood. It is assumed that a household in average use 15 kg of fuelwood per day, based on information received in the field work interviews.

Table 4.9: Comparison of cooking stove technologies

Cooking stove	*Efficiency (%)*	*Avg. consumption of wood per day, per household (kg)*	*Specific energy (kWh/kg)*	*Brutto daily power of wood (kWh)*	*Energy of wood (kWh)*
Open fire	14,80	15	5,2	78	11,54
SPTL-0610	37	15	5,2	78	28,86

The net daily power of wood per household can be calculated by the following equation.

$$Q = q \cdot m \cdot \eta \tag{4.10}$$

Where:

Q = net daily power of wood
q = power equivalent
m = mass of wood
η = efficiency of cooking stove

Reduced amount of wood consumption per household:

$$\Delta m = \frac{Q_{TERI} - Q_{OF}}{q \cdot \eta_{TERI}} \tag{4.11}$$

Amount of wood required per day using SPTL-0610:

$$m_{TERI} = m - \Delta m \qquad 4.12$$

The reduced amount of fuelwood is found by using Equation 4.11 to be 9 kg/day per household. Further, if 254 households are cooking by using fuelwood at an open fire, but starts to utilize TERI's cooking stove *SPTL-0610* instead. In this case, the total amount of required fuelwood will be reduced with approximately 2286 kg/day, in this village. In addition, other types of fuels can be applied to SPTL-0610, such as crop residues and dried animal manure. Hence, the fuelwood dependency may be reduced.

Chapter 5 HRES Modelling

In this chapter, the modelling of the HRES in the optimization software HOMER are discussed. Required data input when modelling in HOMER is presented, comprising technical specifications, resource data and costs. Further is the method of calculating the HRES economic viability presented.

5.1 Introduction

In the previous chapters, load requirements, the technical details of the selected components and cost estimation are presented. These information's are used in chapter 5 to model an optimal Hybrid Renewable Energy System (HRES) that can meet the electricity demand of Amatgyi Khone village. The optimal HRES is expected to supply electricity at lowest possible price and provide availability to the end-user. The three following system types are considered in the modelling:

- Solar PV and Batteries
- Solar PV and Bio Gasifier Power Plant
- Solar PV, Bio Gasifier Power Plant and Batteries

Several system configurations are used, aiming to find the optimal number and size of the technical components. The modelling is conducted by using HOMER software.

5.2 HOMER software modelling

Modelling in HOMER consists of three principal tasks: simulation, optimization and sensitivity analysis. When simulating, the performance of a system configuration is modelled each hour of the year to determine its technical feasibility and life-cycle cost. In the optimization process, HOMER simulates many different configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost. The technical constraint comprises variating quantity and sizes of components. In the sensitivity analysis process, HOMER performs multiple optimisations under a range of input assumptions to understand the effects of uncertainty or changes in the model inputs. The sensitivity analysis helps the user to understand the effects of uncertainty or changes in variables such as fuel price and availability of resources (Lambert et al. 2006).

5.3 HRES technological configuration

The Hybrid Renewable Energy System (HRES) components generate both DC and AC loads. The PV system and batteries generates DC loads, and by combining these components with an inverter, suitable AC electricity can be provided to the village. The inverter can operate alternatively or in parallel with the bio gasifier power plant. The HRES is modelled in HOMER by using the AC/DC coupled hybrid configuration, shown in Figure 5.1. The system voltage of the DC-bus is set to 48 V, where 12 batteries of 4 volt each are connected in series per string.

However, after selecting the system components of the HRES, several input data are inserted per component in HOMER. The inputs comprise technical specification and constraints, resource data and information about cost. However, most of the inputs are discussed in detail in the previous chapters (2, 3 and 4), and other essential data related to the modelling of the energy system are presented in this section.

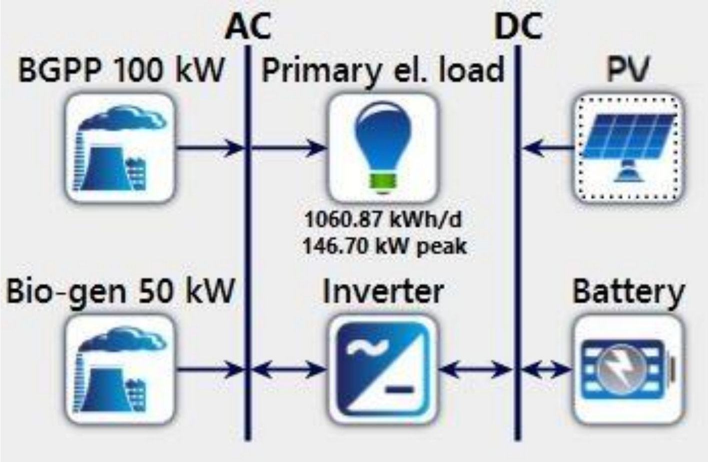


Figure 5.1: Selected HRES AC/DC bus coupling

5.4 Load

The future estimation of village loads, presented in section 2.4.4, is given as a constant load profile. To obtain a more realistic load profile in HOMER, one may adjust it with random variabilities. Values for day-to-day and timestep variabilities are selected to be 10 % and 5 %, respectively. Table 5.1 shows the electric load used in this analysis. The baseline column represents baseline load without random variabilities, while the scaled column values incorporates the random variabilities. The annual peak demand increases to 146,7 kW by including the random variabilities. Furthermore, it can be observed from the table that load factor reduces from 41 % (baseline case) to 30 % in the case of scaled load.

Table 5.1: Electric Load information from HOMER

Metric	*Unit*	*Baseline*	*Scaled*
Annual Average Daily Demand	(kWh/d)	1060,8	1060,8
Annual Average Daily Load	(kW)	44,2	44,2
Peak Load	(kW)	107	146,7
Load Factor		0,41	0,3

5.5 Resources

5.5.1 Solar resources

Figure 5.2 show the annual hourly solar radiation data for the region of Amatgyi Khone village. The time series is calculated by HOMER, based on monthly average solar radiation and clearness index, received by NASA.

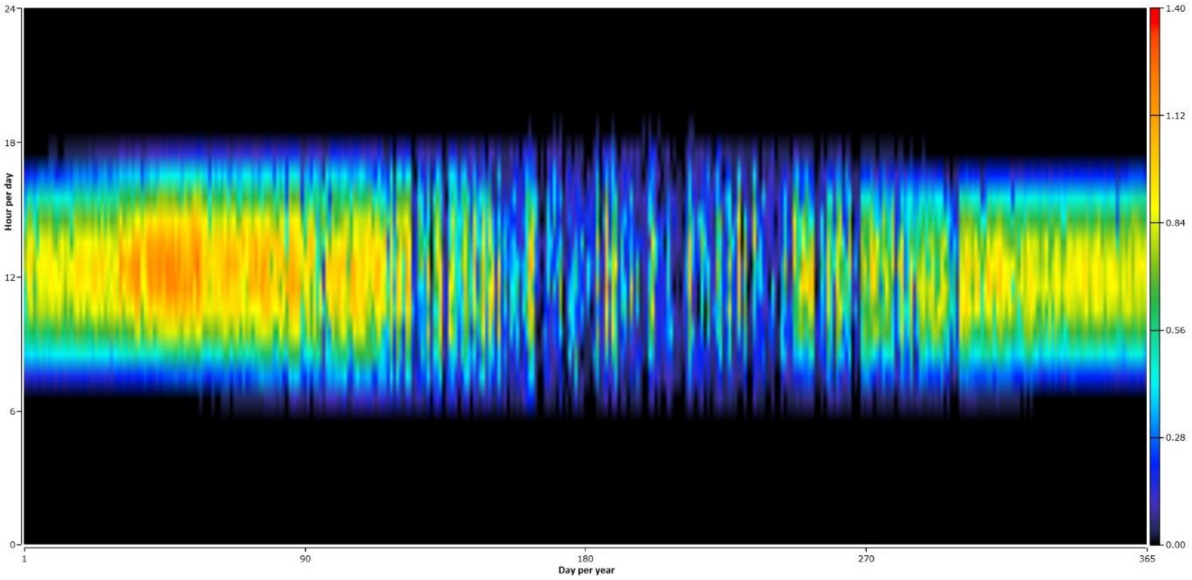


Figure 5.2: Hourly solar radiation data for the region of Amatgyi Khone (kWh/m2).

5.5.2 Biomass resource

Figure 5.3 show the monthly average rice husk available in the selected project region. Amatgyi Khone village has availability to use rice husk for power production throughout the year, if excess of the rice husk produced in January to April can be stored for use during the rainy season, May to August. The scaled annual average rice husk available is further calculated by HOMER to be 2,96 tonnes/day.

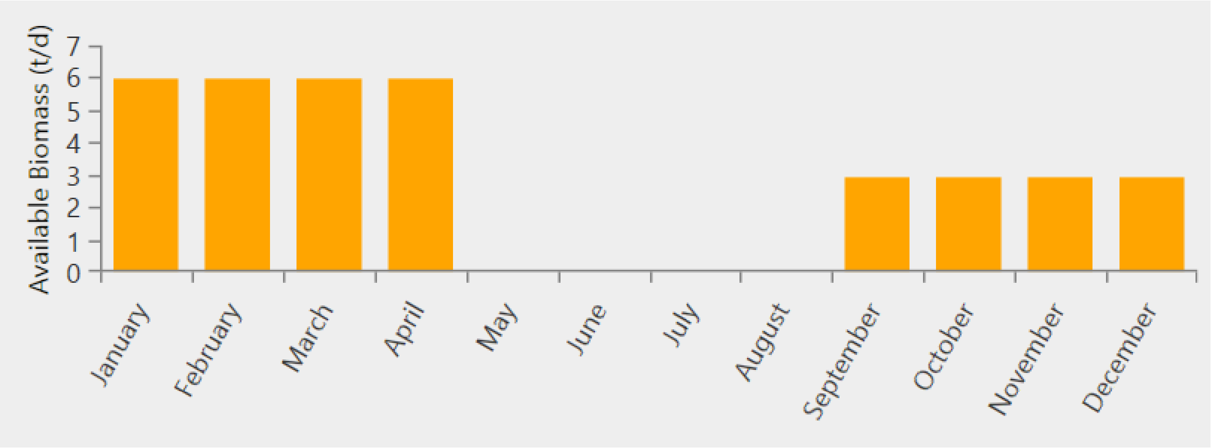


Figure 3: Monthly average available rice husk data.

Selected properties of the biomass resource are given in Table 5.2, previously presented in Section 3.3.2. The gasification ratio, defined as the ratio of biogas generated to biomass feedstock consumed in the gasifier, is assumed to be constant in HOMER. The selected value of gasification ratio is 1 (kg gas/kg biomass).

Table 5.2: Properties of the biomass resource, rice husk.

Properties	*Unit*	*Values*
Average price	$/tonne	28
Gasification Ratio	kg/kg	1
Carbon content	%	38,5
LHV of biogas	MJ/kg	14,72

5.6 Component costs

Table 5.3 shows the size, capital cost, replacement cost as well as O&M cost of the main components of the HRES.

Table 5.3: Summary of HRES component costs

HRES component	*Capacity/Size*	*Capital cost*	*Replacement cost*	*O&M Costs*
Solar PV system	150 kW	906/ kW	725 /kW	$10/yr
Battery	1904 Ah	$1300	$1300	$10/ yr
Inverter	120 kW	$12 226	$9780,8	$0,00
Bio Gasifier & Generator	100 kW	$118 300	$94 640	$0,88/h
Bio Generator	50 kW	$12 780	$10 224	$0,44/h
System costs				
Mini-grid distribution system	5 km	$30 000	$24 000	$600 /yr
Solar PV ground mounting structure	-	$10 399	-	-
Total system cost	-	$50 000	-	$2000/yr

5.6.1 System fixed capital cost

The total system cost includes preparation of the installation site, labour, engineering design cost, costs related to constructing a building for the HRES components, the mini-grid distribution system and other non-component related costs. The total system fixed capital cost is estimated to be $50 000, shown in Table 5.3.

5.6.2 System fixed annual operation and maintenance cost

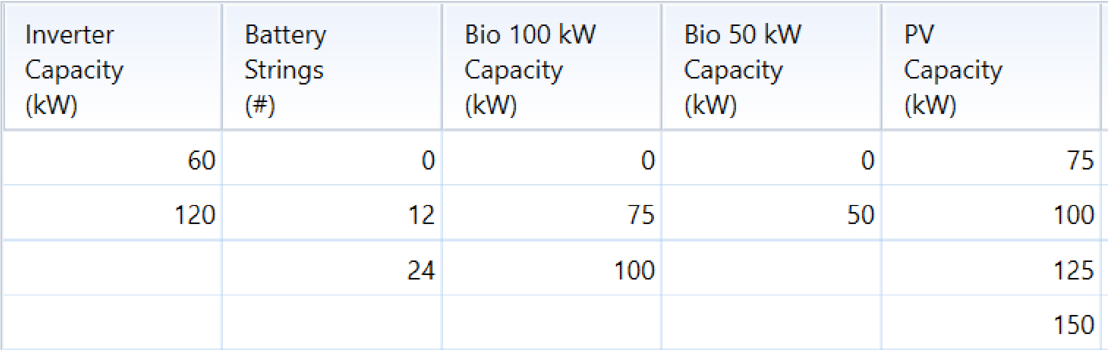
The system fixed O&M costs consists mainly of fixed labour cost, insurance, and O&M of inverter and mini-grid distribution system. It is estimated that the HRES require two full time employees that receive monthly payments. However, O&M costs of PV panels, BGPP and batteries are not included in the system fixed annual O&M costs because they are given individually per component. The system fixed annual O&M costs are estimated to be $2000/yr, shown in Table 5.3.

5.7 Simulation options

5.7.1 Search space

A set of search space consisting of optimization variables can be selected in HOMER. The decision variables are typically size and quantities of the different system components. The search space used in the HRES analysis are given in Table 5.4.

Table 5.4: Search space of optimization variables used for the modelling in HOMER



Inverter Capacity (kW)	Battery Strings (#)	Bio 100 kW Capacity (kW)	Bio 50 kW Capacity (kW)	PV Capacity (kW)
60	0	0	0	75
120	12	75	50	100
	24	100		125
				150

5.7.2 Sensitivity variables

The optimal design of the HRES, should comprise changes of available renewable energy resources, fuel price fluctuation, and interest rate. Multiple optimizations are performed by using different set of input assumptions. A sensitivity analysis reveals how sensitive the optimal design is to changes in function of the most important climatic (and/or) economic assumptions. In this HRES analysis, the main sensitivity variables used in HOMER are given in Table 5.5 and comprise the following:

- Variating interest rate, hence variating input of nominal discount rate from 4 % to 13 %.
- Solar reserve variating from 50 - 100 %.
- Variating capital costs of BGPP from \$800/kW to \$1500/kW
- Subsidies of BGPP O&M costs: Subsidy \$0,5/h (Multiplier: 0,568) and Subsidy \$0,4/h (Multiplier: 0,46).
- Fully subsidy of O&M costs to biogas generator #1 and #2.
- Variating Annual average solar radiation, considered for the range of 4,0 to 6,0 kWh/m^2/day.
- Increasing rice husk fuel prices from \$28 to \$46 per tonne.

Table 5.5: Sensitivity variables used in HOMER.

Nominal discount rate (%)	Solar reserve (%)	BGPP Capital Cost Multiplier (*)	BGPP #1 O&M Cost Multiplier (*)	Generator #2 O&M Cost Multiplier (*)	Solar Scaled Average (kWh/m2/day)	Biomass Price ($/tonne)
13	100	1	1	1	5,3825	28
12	90	0,677	0.76	0	4	35
10	80	1,268	0,568		6	46
8	70		0,46			
6	60		0			
4	50					

5.8 Dispatch strategy

Systems that contain a battery bank and one or more generators require a dispatch strategy, which is a set of rules that determines how the system charges the battery bank. HOMER can follow two dispatch strategies: Load-following (LF) strategy and Cycle-charging (CC) strategy. Under LF the generator produces power to meet the primary load, and the Solar PV or other renewable power sources charge the batteries. HOMER dispatches the controllable power sources such as generator and batteries to serve the primary load at the least total cost. Under CC strategy the generator produces more power than required to serve the primary load with surplus energy used to charge the batteries. In this strategy, HOMER selects the optimal combination of power source to serve the primary load (Lambert et al. 2006).

5.9 Economics

To evaluate economic viability of the HRES, then it is essential to analyse the Levelized Cost of Energy (LCOE) per feasible system and in view of the system lifetime. Generally, renewable energy systems are related to high capital costs and low O&M costs through the system lifetime. In comparison, fuel based energy systems have low capital costs but high O&M costs. Hence, LCOE can be used to compare different energy system configurations, aiming to find the economic viable HRES.

The HOMER optimization algorithm is based on the analysis of Levelized Cost of Energy (LCOE). The optimum system configurations are found by calculating the Net Present Value (NPV) of the system's lifetime cost. All costs that occur within the project lifetime and of different system configurations are included within the search space. Then, different system configurations are ranked according to increasing net present cost, and analysed according to the value of LCOE. The description of the net present cost (NPC) and the LCOE are given in this section.

5.9.1 Net present cost

The total net present cost (NPC) of a system is the present value of all costs that occurs over its lifetime, minus the present value of all the revenue that it earns over its lifetime. Costs involved are capital costs, replacement costs, O&M costs and fuel costs. Equation 5.1 of NPC is used by HOMER software:

$$NPC = \frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)} \tag{5.1}$$

Where:

CRF = Capital Recovery Factor (calculated by eq. 5.2)

i = *real* interest rate [%], also called real discount rate (calculated by eq. 5.3)

R_{proj} = project lifetime [yrs]

The Capital Recovery Factor (CRF) is used to calculate the present value of an annuity, and is calculated by the following equation:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5.2}$$

Where *N* represent the number of years, and *i is the* real interest rate [%], also called real discount rate. The lifetime of the HRES project is chosen to be 25 years, hence *N* equals 25 years. The interest rate is used to convert between one-time costs and annualized costs. In HOMER, the interest rate is calculated by the following equation including nominal discount rate (i') and the expected inflation rate (f) in the Economics input window.

$$i = \frac{i' - f}{1 + f} \tag{5.3}$$

HOMER assumes that the rate of inflation is the same for all types of costs (maintenance cost, labour cost, etc.). Due to a future estimation of inflation by trading economics, the value will be at approximately 4,2 % in 2020. The nominal discount rate is found to be 13 % today by Central Bank of Myanmar. By assuming these values of inflation rate and nominal discount rate, the chosen value of interest rate is found to be 8,45 %, by using Equation 5.3. Figure 5.4 show the development of the interest rate in Myanmar from 1967 to 2017. However, by focusing on the previous ten years, the real interest rate has been variating from about 6 to 12 %. Due to large variations of interest rates in Myanmar, it is interesting to conduct a sensitivity analysis on this variable.

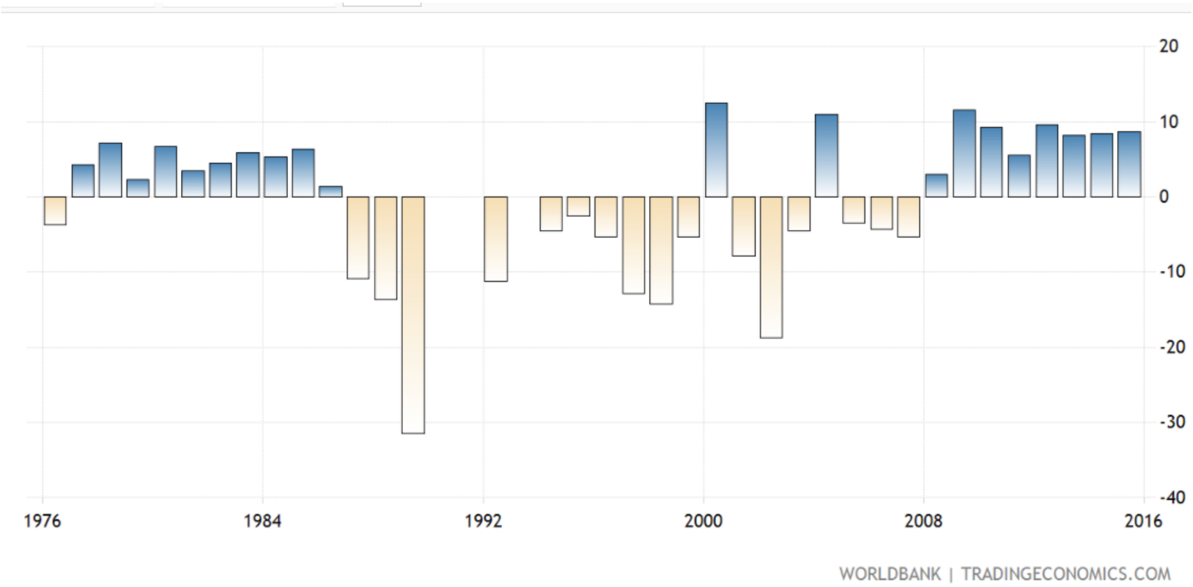


Figure 5.44: Real interest rate (%) in Myanmar, showing the development from 1967 - 2017.

5.9.2 Levelized Cost of Energy

HOMER software computes the Levelized Cost of Energy (LCOE), as the average cost per kWh of useful electrical energy produced by the system. The LCOE can be described as the relation when the total NPC of the useful energy generated throughout the HRES lifetime, is equal to the total net present cost of the project. LCOE of HRES can be calculated by the following equation:

$$LCOE = \frac{Total\ Annualized\ Cost\ \left(\frac{USD}{yr}\right)}{Annual\ load\ served\ \left(\frac{kWh}{yr}\right)} = \frac{C_{ann,tot} - c_{boiler}H_{served}}{E_{prim,AC} + E_{prim,DC} + E_{def}} \tag{5.4}$$

Where:

$C_{ann,tot}$ = total annualized cost of the system [$/kWh]

c_{boiler} = boiler marginal cost [$/kWh]

H_{served} = total thermal load served [kWh/yr]

E_i = electrical load served (*i* refers to the type of load; AC, DC and/or Deferrable)

Because no thermal load is considered and neither electricity sale to the grid or deferrable loads, these variables can be set equal to zero. The resulting Equation 5.5 of LCOE in this analysis are the following:

$$LCOE = \frac{C_{ann,tot}}{E_{prim,AC} + E_{prim,DC}} \tag{5.5}$$

5.9.3 Subsidies

A contribution to the investment cost can impact the feasibility of the HRES significantly. Hence, considering the effect of different levels of Subsidies are relevant. The subsidy values that are selected for this analysis are 25 %, 50 % and 75 %. The new LCOE for the HRES configuration with considering to subsidy levels can be calculated by using Equation 5.6.

$$LCOE_{sub} = \frac{(NPC - NPC \cdot sub) \cdot CRF}{E_{prim,Ac} + E_{prim,DC}} \tag{5.6}$$

Where *sub* refers to the level of subsidy in percentage.

Chapter 6 HOMER Modelling results

The optimal HRES is the option of HRES configurations that has the lowest NPC and COE, that meets Amatgyi Khone village's electricity demand under the specific requirements, discussed in the previous chapters. Furthermore, in this chapter, the results obtained from the HOMER simulations are presented, including selection of optimal HRES, sensitivity analysis, performance of the optimal hybrid system and the economic viability of the proposed HRES.

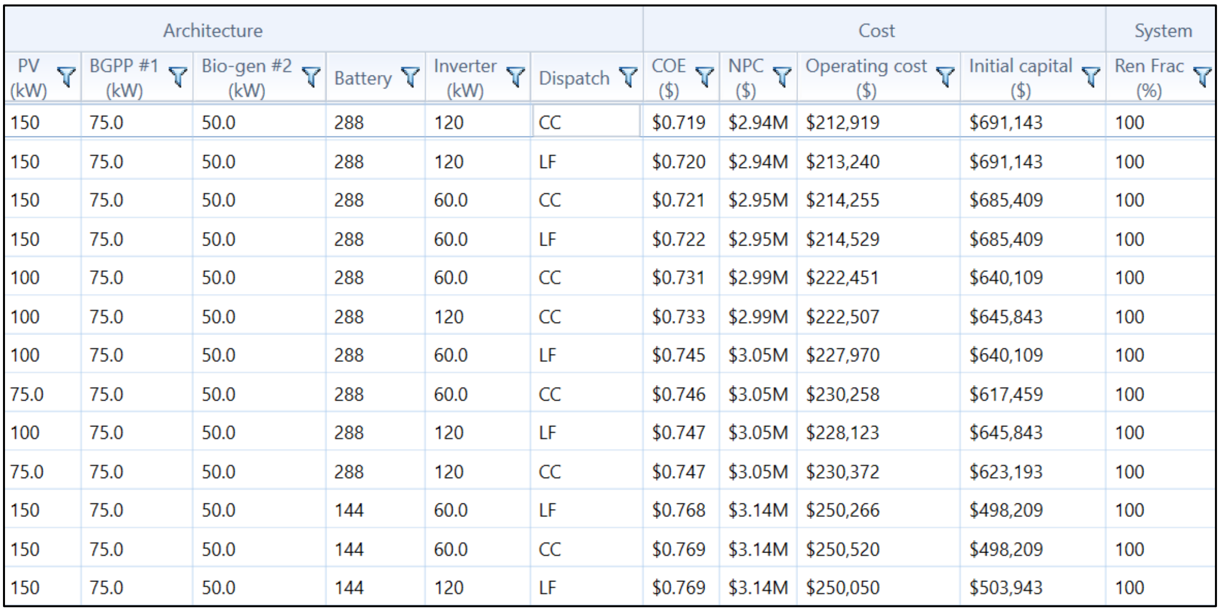
6.1 Optimization results

The optimal HRES configuration from the HOMER simulations is given in Table 6.2 and Table 6.3. Parts of the overall optimization result, shown in Table 6.2, is presented as a list of system configurations in order of increasing NPC. Table 6.3 show the categorized optimization result, which is the option of the most feasible system types. The first configuration shown in both tables is the optimal one. This configuration has the lowest NPC and COE, respectively $2,938 million and $0,719. According to the HOMER simulation result, the optimal HRES-type is a PV/BGPP/Battery system. Information about the optimal system configuration is presented in Table 6.1.

Table 6.1: HRES optimal system architecture

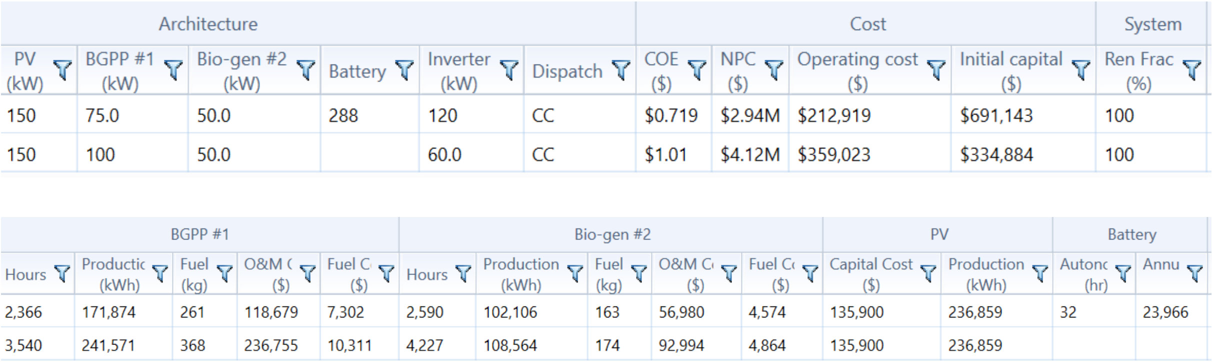
PV system capacity	150 kW
Biogas Generator (#1)	75 kW
Biogas Generator (#2)	50 kW
Battery bank Annual throughput	288 batteries, 24 Strings 23 966 kWh
Converter capacity	120 kW
Dispatch strategy	HOMER Cycle charging
Renewable Fraction	100 %
Capacity shortage	0,0 %

Table 6.2: HOMER overall optimization results, showing optimal system type and configuration in increasing order of NPC.



Architecture						Cost				System
PV (kW)	BGPP #1 (kW)	Bio-gen #2 (kW)	Battery	Inverter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
150	75.0	50.0	288	120	CC	$0.719	$2.94M	$212,919	$691,143	100
150	75.0	50.0	288	120	LF	$0.720	$2.94M	$213,240	$691,143	100
150	75.0	50.0	288	60.0	CC	$0.721	$2.95M	$214,255	$685,409	100
150	75.0	50.0	288	60.0	LF	$0.722	$2.95M	$214,529	$685,409	100
100	75.0	50.0	288	60.0	CC	$0.731	$2.99M	$222,451	$640,109	100
100	75.0	50.0	288	120	CC	$0.733	$2.99M	$222,507	$645,843	100
100	75.0	50.0	288	60.0	LF	$0.745	$3.05M	$227,970	$640,109	100
75.0	75.0	50.0	288	60.0	CC	$0.746	$3.05M	$230,258	$617,459	100
100	75.0	50.0	288	120	LF	$0.747	$3.05M	$228,123	$645,843	100
75.0	75.0	50.0	288	120	CC	$0.747	$3.05M	$230,372	$623,193	100
150	75.0	50.0	144	60.0	LF	$0.768	$3.14M	$250,266	$498,209	100
150	75.0	50.0	144	60.0	CC	$0.769	$3.14M	$250,520	$498,209	100
150	75.0	50.0	144	120	LF	$0.769	$3.14M	$250,050	$503,943	100

Table 6.3: HOMER categorized optimization results, showing the option of the most feasible system types.



Architecture						Cost				System
PV (kW)	BGPP #1 (kW)	Bio-gen #2 (kW)	Battery	Inverter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
150	75.0	50.0	288	120	CC	$0.719	$2.94M	$212,919	$691,143	100
150	100	50.0		60.0	CC	$1.01	$4.12M	$359,023	$334,884	100

BGPP #1					Bio-gen #2					PV		Battery	
Hours	Productic (kWh)	Fuel (kg)	O&M (($)	Fuel C ($)	Hours	Production (kWh)	Fuel (kg)	O&M C ($)	Fuel C ($)	Capital Cost ($)	Production (kWh)	Autonc (hr)	Annu
2,366	171,874	261	118,679	7,302	2,590	102,106	163	56,980	4,574	135,900	236,859	32	23,966
3,540	241,571	368	236,755	10,311	4,227	108,564	174	92,994	4,864	135,900	236,859		

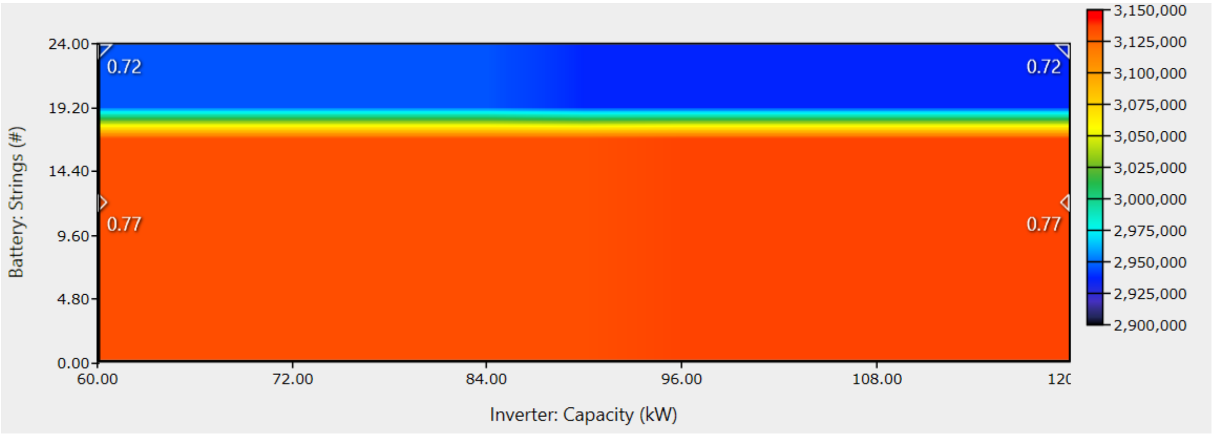


Figure 6.15: Optimal number of battery strings and inverter capacity, represented by the lowest NPC ($) and COE ($/kWh) (Different levels of NPC is represented by colours and COE are the numbers shown at the graph)

As shown in Table 6.3, BGPP is included in each system type, hence excluding BGPP from the HRES is not considered as a feasible solution in the HOMER optimization simulation. The two options of system types comprise PV/BGPP system with and without a battery bank. The HRES system without battery is not viable, due increased usage of BGPP and doubling of O&M costs. Figure 6.1 show that the optimal HRES configuration having 24 battery strings and 120 kW inverter capacity yields the lowest NPC and COE.

The optimal configuration has 100 % renewable fraction and zero capacity shortage. However, emission is not in focus of the HRES modelling. As previous mentioned, the HRES reuse locally available rice husk waste and solar resource as the energy sources. This implies that the emissions related to transport of the energy resource can be disregarded. Hence, emission involved in the proposed energy system are considerable lower than from energy systems including for example conventional diesel generators.

6.2 Sensitivity results

HOMER sensitivity algorithms can be used to evaluate the effect of uncertainties in the input variables of the optimal HRES configuration, as discussed in chapter 5.

6.2.1 Solar reserve and Interest rate

Figure 6.2 shows how variations of solar reserve and nominal discount rate affects the NPC and COE. As shown in the figure, the NPC increases with increasing solar reserve, and it reduces with increasing nominal discount rate. The COE varies from \$0,719 to \$0,876/kWh when the solar reserve varies from 50 % to 100 %. Hence, the optimal HRES configuration is found when the solar reserve is 50 %, thus higher variations will affect to less feasible system configurations. Moreover, considering reduction of the nominal discount rate in the range from 13 % to 4 % affect the COE to vary from \$0,719 to \$0,622/kWh. However, the range of sensitivity does not affect the optimal HRES type. Thus, a reduction of the nominal discount rate is considered preferable, to attain reduced COE of the HRES.

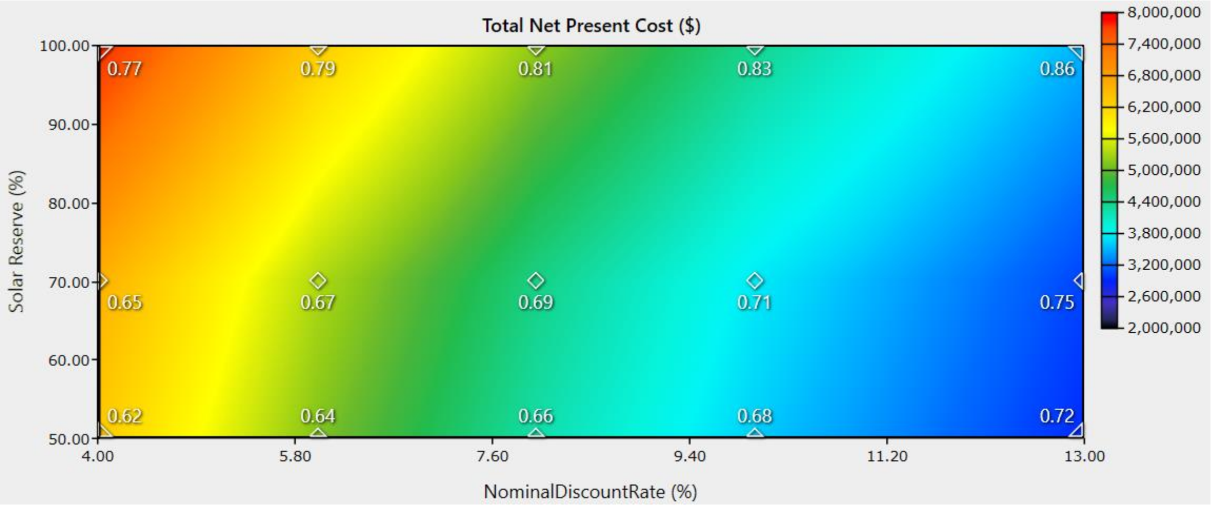


Figure 6.2: Surface plot showing NPC and COE due to variating Solar reserve and Nominal discount rate. The colours represent NPC ($) and the numbers in the graph represent COE ($/kWh).

6.2.2 Capital costs of BGPP

The capital cost of the BGPP is estimated for the range from $800/kW to $1500/kW, shown in Figure 6.3. *Multiplier *1* along the axis represent the selected capital cost of $955/kW. Both NPC and COE increases with increasing capital cost of BGPP. The NPC varies from $2,918 mill to $3,006 mill, and the COE varies from $0,714 to $0,736/kWh. However, when the BGPP capital cost is changed individually as a variable, the optimal HRES configuration is not affected.

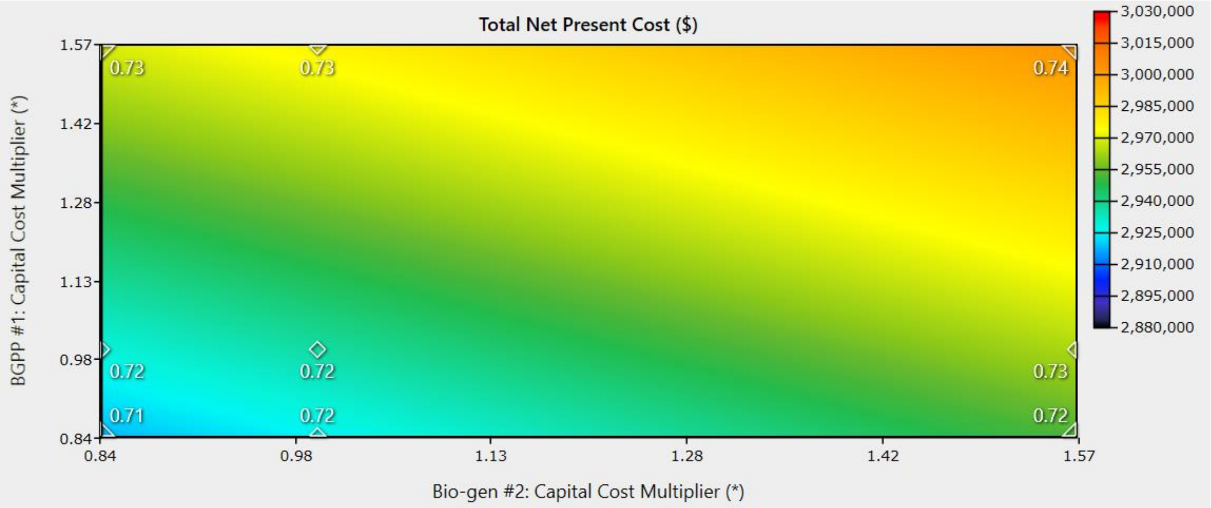


Figure 6.3: Surface plot showing Net Present Cost and Cost of Energy due to variation of BGPP Capital cost.

6.2.3 Subsidies of BGPP O&M costs

In the optimal HRES system solution, O&M costs of the BGPP accounts for 95 % of the total O&M costs of the HRES. The sensitivity analysis is conducted to understand how the HRES optimal system will be affected if the cost of O&M is reduced. If financial support is received as initiatives from the government or from aid organizations, this will mainly affect the O&M costs. Two scenarios of financial support are observed; reduced cost of Generator #1 O&M costs from \$0,67/h to \$0,50/h and \$0,40/h, and complete financial support of O&M costs for the whole BGPP.

In the first scenario, when the O&M cost of generator #1 is reduced to \$0,50/h, the optimal system configuration is not affected. NPC and COE is reduced to \$2,62 mill and \$0,642, respectively. Furthermore, when the O&M cost of generator #1 is reduced to \$0,40/h, the optimal HRES configuration is changed. NPC and COE is further reduced to \$2,43 mill and \$0,594, respectively. The new system architecture, shown in Table 6.4, includes reduced capacities of PV and inverter. The optimization surface plot, in Figure 6.4, illustrates the variations of NPC and COE due to variations of PV capacity and inverter capacity. However, the costs are relatively similar when keeping the optimal system configuration (Section 6.1), resulting in \$2,43 mill and \$0,596, respectively, when reducing the O&M costs of generator #1 to \$0,4/h.

Table 6.4: HRES optimal architecture, when BGPP O&M costs are \$0,40/h due to financial support.

PV system capacity	125 kW
Biogas Generator (#1)	75 kW
Biogas Generator (#2)	50 kW
Battery bank	288 batteries, 12 Strings, 24 748 kWh/yr
Converter capacity	60 kW
Dispatch strategy	HOMER Cycle Charging

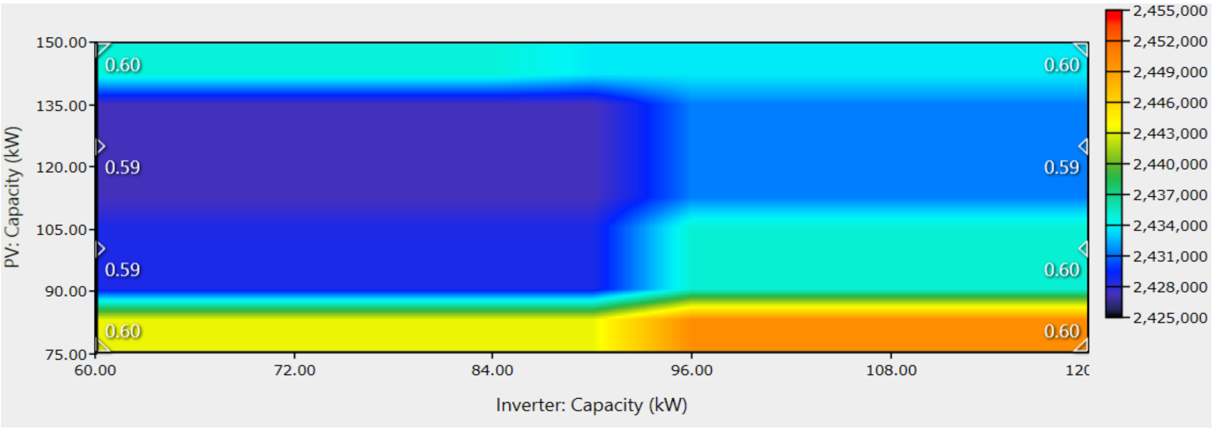


Figure 6.4: Optimization surface plot showing NPC and COE due to variating PV capacity and inverter capacity.

The second scenario comprise complete financial support of the BGPP O&M costs. Figure 6.5 show how the optimal system type is affected by the change in O&M costs, where the values 0 - 1 along the x-axis represent the variating O&M costs of generator #1 from $0,0/h to $0,88/h. The values along the y-axis represent the O&M costs of generator #2 from $0/h to $0,44/h. As shown in Figure 6.5, batteries are excluded from the optimal system type when generator #1 O&M costs are lower than $0,12/h (O&M cost multiplier *0,14). Furthermore, COE is shown for the variating levels of O&M cost support. Hence, if complete financial support of O&M costs is granted, the COE is $0,15 and NPC is $612 447. The new optimal system type is BGPP/Bio-gen/PV, with system configurations given in Table 6.5.

However, by keeping the Optimal System Type, found in Section 6.1, the COE is $0,266 and NPC is $1,086 mill when the O&M costs are completely supported. Figure 6.6 show the relation of the different values of COE to the optimal system type (Section 6.1), due to variating financial support of BGPP O&M costs.

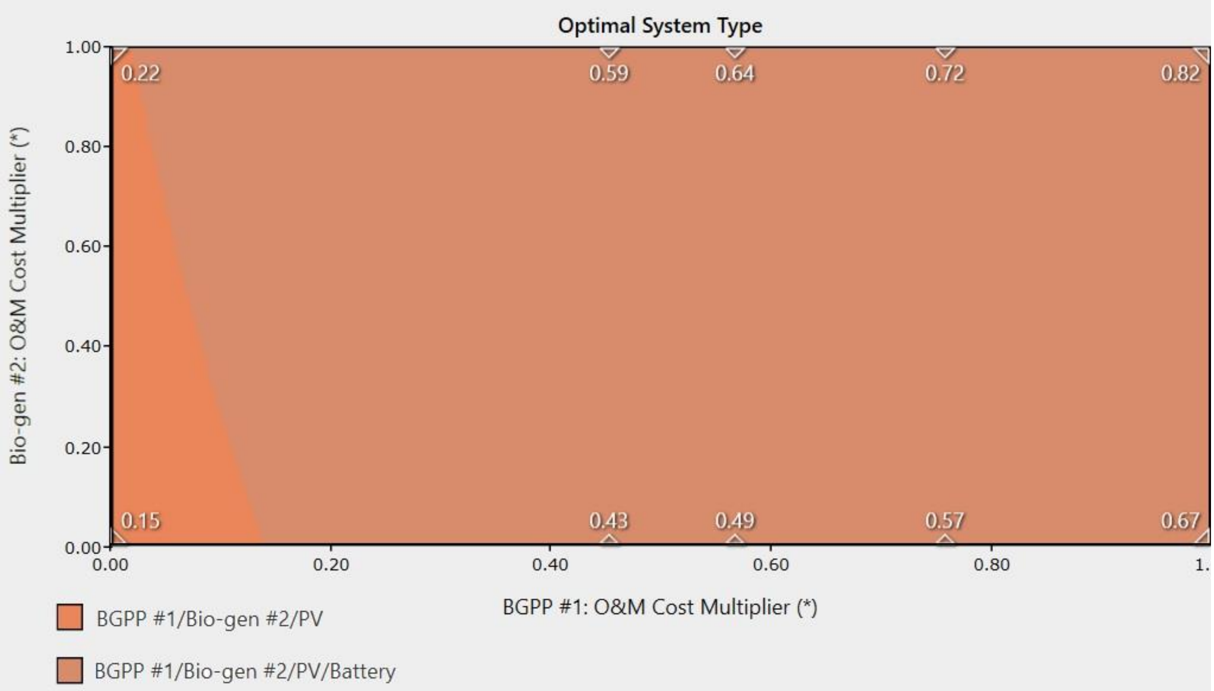


Figure 6.5: Optimal system types and COE due to variations of O&M costs of BGPP and Bio-gen.

Table 6.5: HRES Optimal architecture due to complete BGPP and Bio-gen O&M cost support.

PV system capacity	75 kW
Biogas Generator (#1)	100 kW
Biogas Generator (#2)	50 kW
Converter capacity	60 kW
Dispatch strategy	HOMER Cycle charging

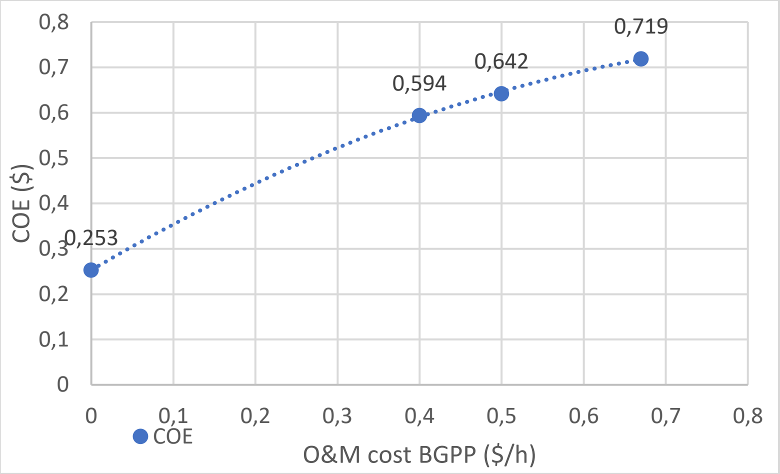


Figure 6.66: COE of HRES optimal system type, due to variating BGPP O&M cost.

6.2.4 Variations of energy resources

The annual average daily solar radiation is estimated to be 5,325 kWh/m^2/day in the selected local region of Myanmar. To understand how the variating amount of solar radiation can affect the optimal HRES type, a sensitivity analysis is performed of variating annual average daily solar radiation from 4,0 to 6,0 kWh/m^2/day. The prices of rice husk, used as a power plant fuel, can be expected to change due to increasing demand of rice husk in the future. The sensitivity analysis is performed for variating rice husk fuel prices from $28 to $46 per tonne.

Figure 6.7 show the sensitivity plot of the selected range of both Solar radiation and rice husk fuel prices. Because the whole area of the sensitivity plot is brown, this implies that the optimal system type is not affected to change for any of the variations considered in this sensitivity analysis. Therefore, the optimal HRES type is BGPP/Bio-gen/PV/Battery. However, both reduced solar radiation and increased biomass price affect to increased COE of the HRES.

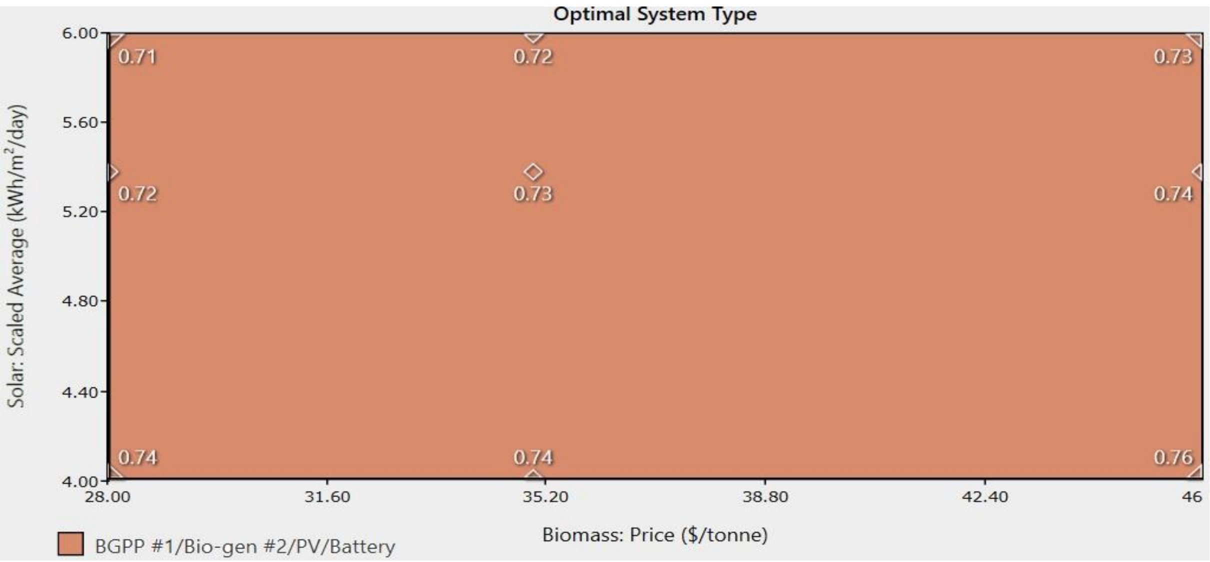
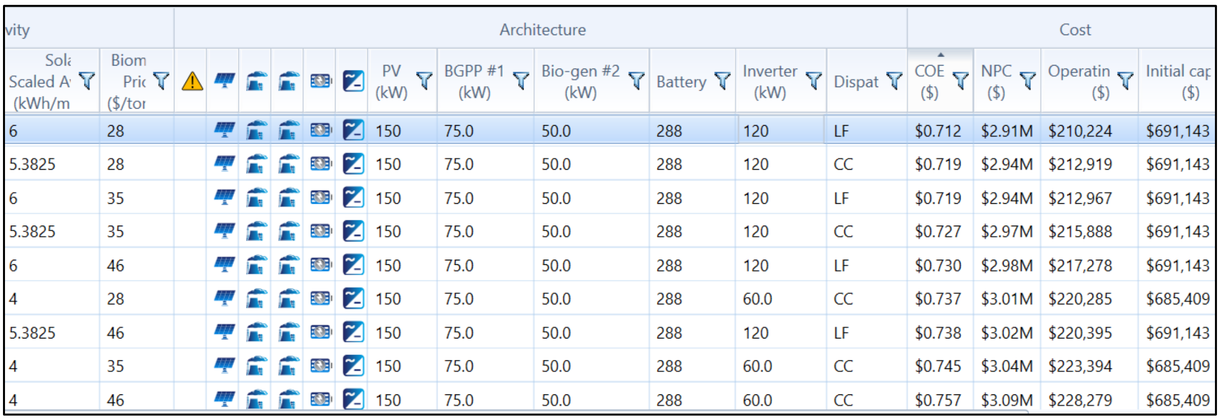


Figure 6.7: Illustration of optimal system type where values of COE are shown due to variations of annual scaled solar radiation (kWh/m²/day.) and rice husk prices ($/tonne).

Furthermore, it is required to investigate whether the optimal HRES configuration, found in section 6.1, is affected by variation of solar radiation and increasing prices of rice husk fuel. Table 6.6 show the different optimized system configurations at variating range of annual solar radiation and variating rice husk fuel prices. As shown, the optimal capacity for all components are equal to the optimal HRES configuration found in section 6.1, except the inverter capacity. As shown in Figure 6.8, the inverter size can be reduced, if the annual average solar radiation is lower than expected.

Table 6.6: HRES optimized system configurations at various range of Annual average solar radiation and rice husk fuel prices.



vity		Architecture							Cost			
Sola Scaled A (kWh/m	Biom Pric ($/tor	⚠	PV (kW)	BGPP #1 (kW)	Bio-gen #2 (kW)	Battery	Inverter (kW)	Dispat	COE ($)	NPC ($)	Operatin ($)	Initial cap ($)
6	28		150	75.0	50.0	288	120	LF	$0.712	$2.91M	$210,224	$691,143
5.3825	28		150	75.0	50.0	288	120	CC	$0.719	$2.94M	$212,919	$691,143
6	35		150	75.0	50.0	288	120	LF	$0.719	$2.94M	$212,967	$691,143
5.3825	35		150	75.0	50.0	288	120	CC	$0.727	$2.97M	$215,888	$691,143
6	46		150	75.0	50.0	288	120	LF	$0.730	$2.98M	$217,278	$691,143
4	28		150	75.0	50.0	288	60.0	CC	$0.737	$3.01M	$220,285	$685,409
5.3825	46		150	75.0	50.0	288	120	LF	$0.738	$3.02M	$220,395	$691,143
4	35		150	75.0	50.0	288	60.0	CC	$0.745	$3.04M	$223,394	$685,409
4	46		150	75.0	50.0	288	60.0	CC	$0.757	$3.09M	$228,279	$685,409

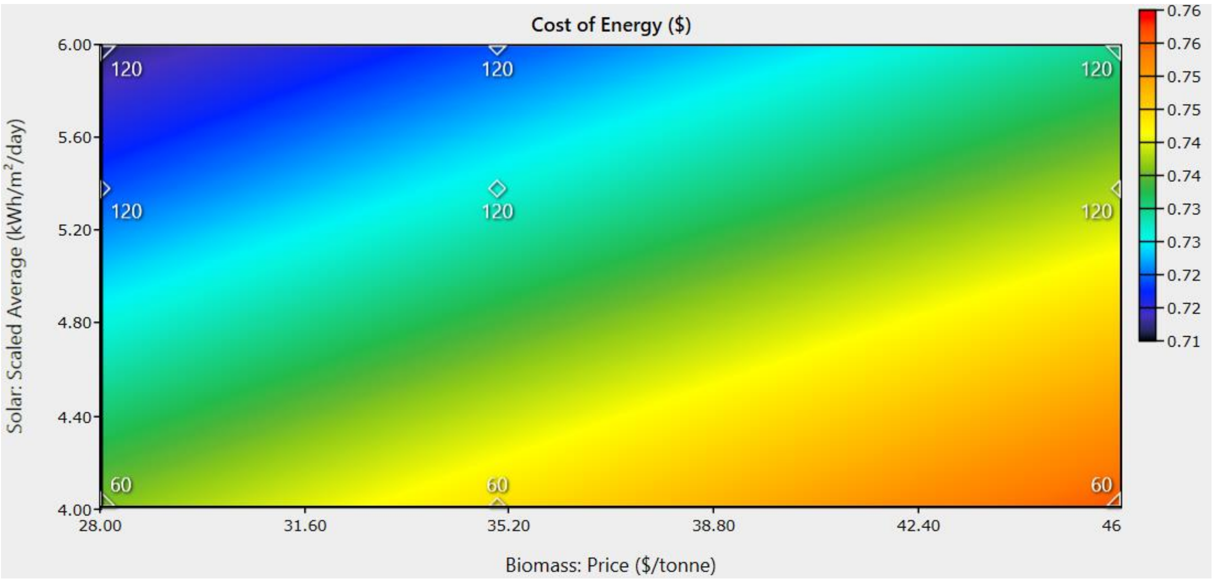


Figure 6.87: Surface plot showing optimal inverter capacity and COE due to variating annual solar radiation and biomass prices.

6.2.5 Key findings Sensitivity and Optimization analysis

By studying the results of the optimization and sensitivity analysis obtained from HOMER simulations, it can be concluded that the optimal Hybrid Renewable Energy System is a PV/BGPP/Bio-gen/Battery system with configurations given in Table 6.7. The key findings are summarized in Table 6.8, where all costs are related to the optimal HRES type and configuration found in Section 6.1.

Table 6.7: Optimal Hybrid Renewable Energy System configuration.

PV system capacity	150 kW
Biogas Generator (#1)	75 kW
Biogas Generator (#2)	50 kW
Battery bank	288 batteries, 24 Strings, 11 105 kWh
Converter capacity	120 kW
Dispatch strategy	HOMER Load Following
Renewable Fraction	100 %
Capacity shortage	0,0 %

Table 6.8: Key findings from the sensitivity and optimization analysis from HOMER.

Sensitivity variables	*COE* *$*	*NPC* *$ million*	*Effect of HRES system type/configuration*
Base case optimal HRES	**0,719**	**2,938**	
Interest rate (variations of nominal discount rate from 4 % to 13 %)	0,622 - 0,719	6,409 - 2,938	
Solar reserve variating from 50 % to 100%	0,719 - 0,876	2,938 – 3,580	
Capital cost of BGPP variating $800/kW to $1500/kW	0,714 - 0,736	2,918 - 3,006	
Support of BGPP O&M cost from $0,67/h to $0,5/h.	0,642	2,620	
Support of BGPP O&M cost from $0,67/h to $0,4.	0,596	2,430	Could change inverter capacity to 60 kW
Complete support of BGPP O&M costs	0,266	1,086	Could change to BGPP/bio-gen/PV
Variating annual average solar radiation from 4 – 6 kWh/m^2/day	0,712 - 0,738	2,909 - 3,010	
Increasing rice husk fuel prices from $28 to $46	0,719 - 0,738	2,938 – 3,017	

6.3 Analysis of the Optimal Hybrid Renewable Energy System costs

According to the simulation results from HOMER, the techno economic optimal HRES requires an initial investment cost of $691.143 and it has a total NPC of $2.938.238. The HRES can supply the required load to Amatgyi Khone village with a COE of $0,719/kWh.

Figure 6.9 shows the net present value of the different costs involved in the HRES project, throughout its lifetime of 25 years. Operational costs are considerable higher than other system costs involved in the project. As revealed in the sensitivity analysis, subsidies on BGPP O&M costs, can lead to reduced NPC and COE of the optimal hybrid system. Complete subsidy of the BGPP O&M costs results in COE and NPC of $0,266/kWh and $1,086 million, respectively.

Furthermore, are the project costs illustrated in Figure 6.10 as a discounted cash flow graph for the project lifetime. As shown, the battery replacement costs occur after 12 years and 24 years, and the inverter after 15 years. Biogas generator #1 and #2 must be replaced after estimated operational lives of 12,7 years and 11,6 years, respectively.

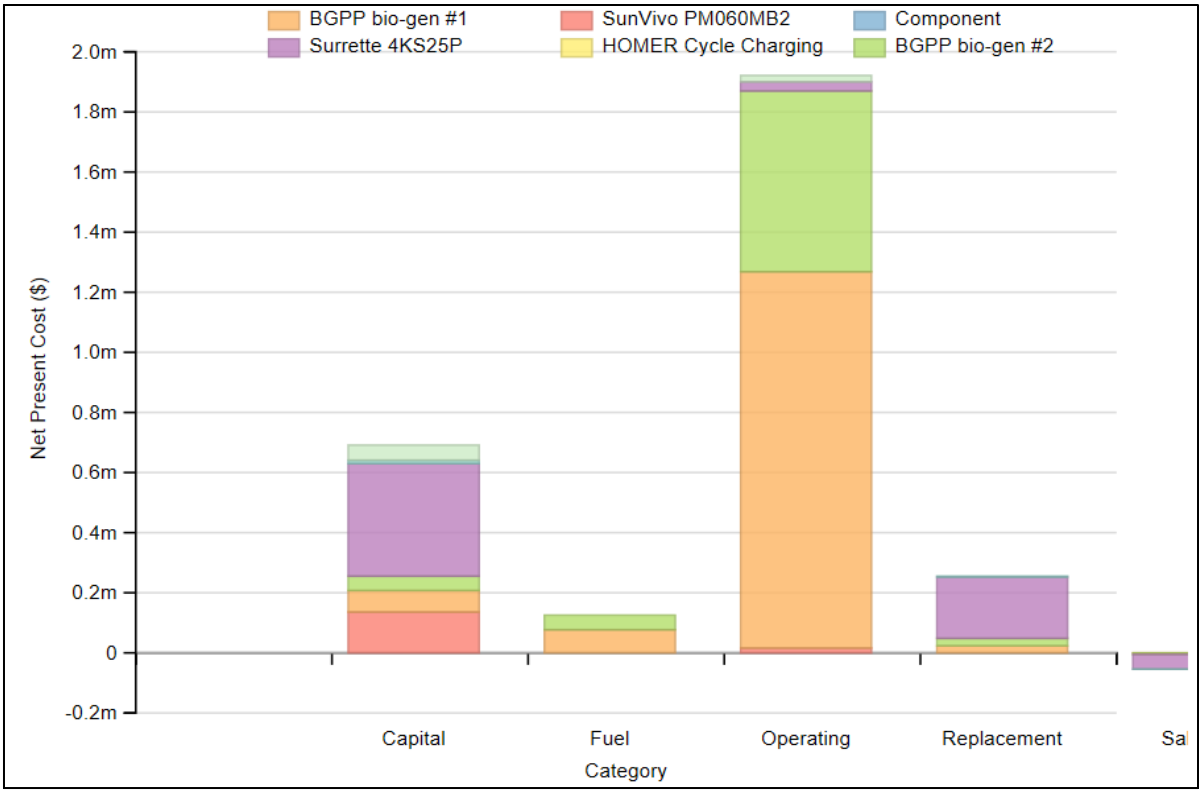


Figure 6.9: HOMER simulation result showing Net present costs of optimal HRES, categorized per cost type.

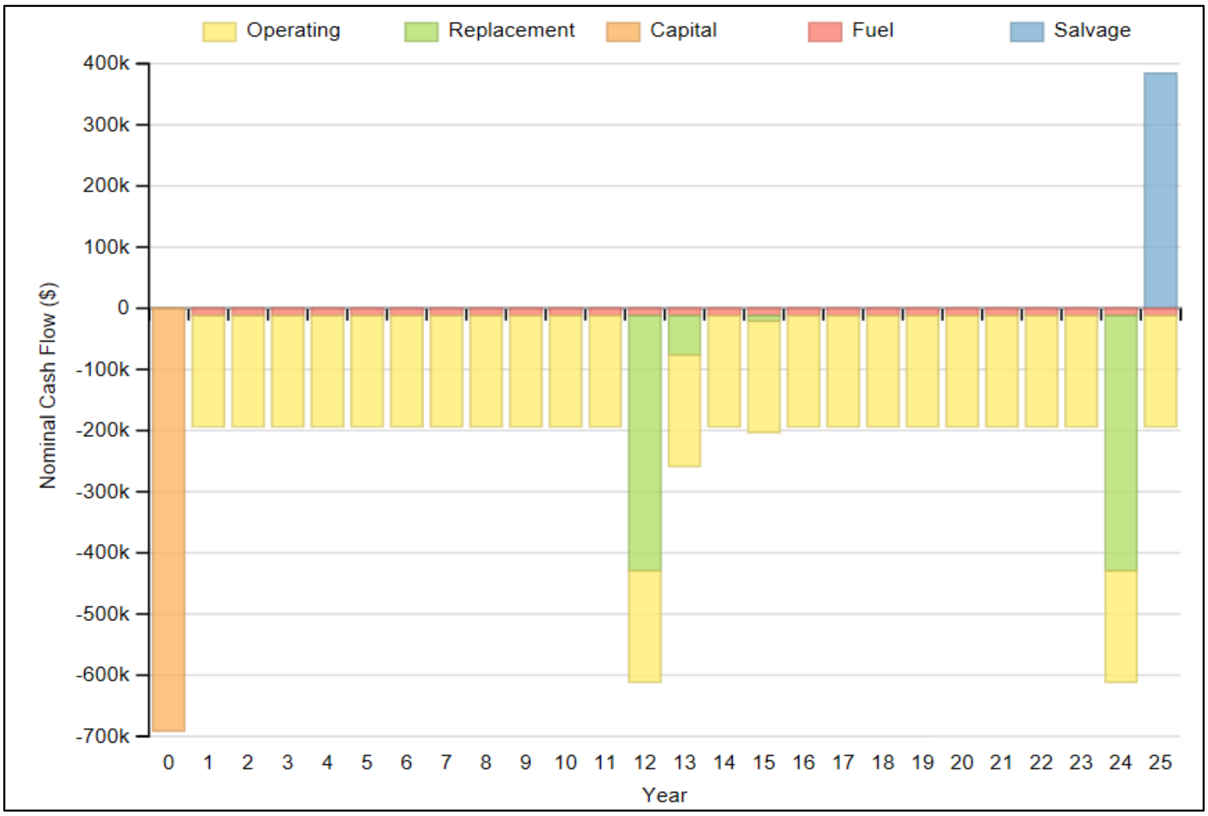


Figure 6.10: Discounted cash flow of the project throughout the lifetime.

6.4 Performance of the HRES

The monthly average electric production is shown in Figure 6.11. The HRES follow the dispatch strategy, cycle charging. The optimal combination of Solar PV and biogas generation to serve the village primary AC load demand, variates throughout the year due to availability of solar radiation. The BGPP has a relatively stable electric production throughout the year, thus it increases slightly during the summer time (rainy season). Hence, the excess production from the biogas generators, after meeting the village primary AC load demand, is used to charge the batteries.

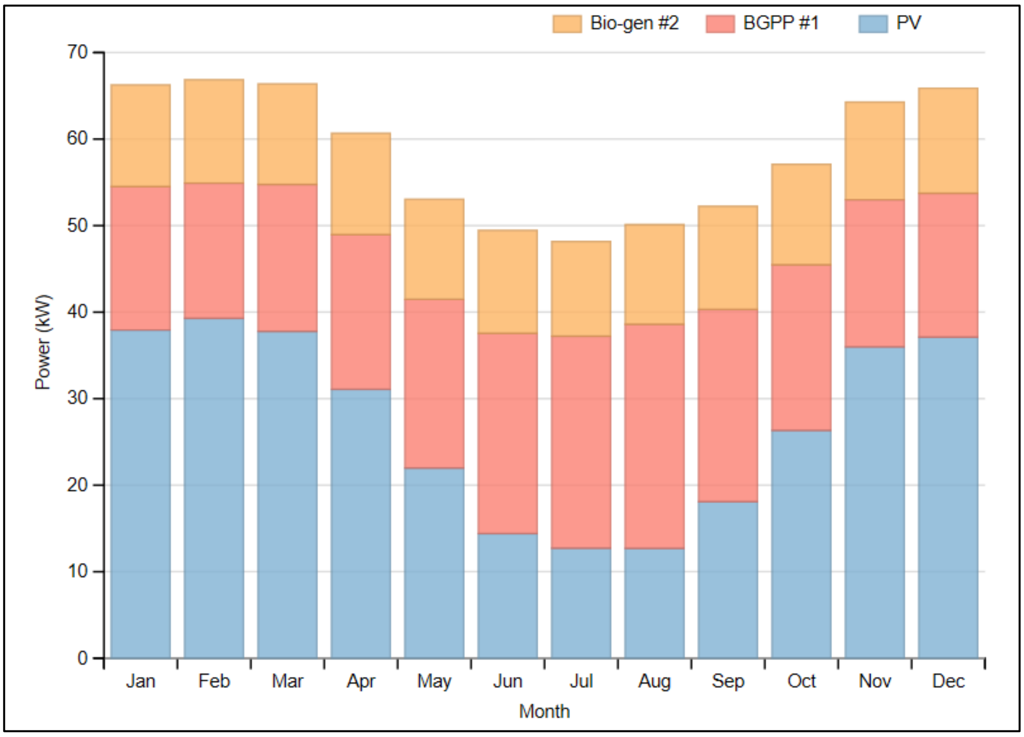


Figure 6.11: Monthly average electric production per system component.

The annual electricity generation from the different HRES components and other relevant performance information is presented in Table 6.9. The complete HRES report can be seen in Appendix 6. The yearly electricity produced from the solar PV system accounts for 46,7 %, while the BGPP accounts for 53,64 %. The renewable fraction of the HRES is 100 %, and its capacity shortage is non-existent. Further, the capacity factor of the solar PV system is 18,03 %, which is relatively low and can be explained by variating availability of solar radiation. While generator #1 and generator #2 have capacity factors of 26,2 % and 23,3 %, respectively.

Table 6.9: Electrical performance of the optimal HRES

		kWh/yr	*%*
Production	Solar PV system	236 859	46,37
	Biogas generator #1	171 874	33,65
	Biogas generator #2	102 105	19,99
Consumption	AC Primary load	387 218	
Quantity	Excess electricity	115 829,5	22,7
	Capacity shortage	22,7	0,0
Quantity	Renewable fraction	100 %	
	Hours of operation gen #1	2366 hrs/yr	
	Hours of operation gen #2	2590 hrs/yr	

6.5 Economic Viability

The implementation of the HRES to the rural village Amatgyi Khone would require development of an electrification scheme. This type of rural electrification scheme can be implemented either private based, for example as an initiative from EFIF, or as a combination of private sector and utility based. However, government or donor support will be essential to make the proposed HRES electricity supply affordable to the end-users and to ensure development of the energy system. The optimal HRES entails a LCOE which is significantly higher than national grid electricity tariffs in Myanmar. However, the rural electrification scheme cannot be compared to the national grid tariff which already incorporates high levels of governmental subsidy.

The HRES's LCOE are used as the main indicator of the systems economic viability. It represents the electricity tariff that can cover the HRES's capital and O&M costs during the project lifetime. Table 6.10 show how the various levels of government/donor support scenarios can contribute to reduce the HRES's LCOE. Equation 5.6 is used to calculate the LCOE while incorporating different support scenarios. As shown in Table 6.10, the LCOE can be reduced to for example \$0,288/kWh with 60 % capital support.

Table 6.10: Effect of subsidies on the electricity price.

Subsidy as a percentage of total HRES capital cost (%)	0 %	20 %	40 %	60 %	70 %	80 %
LCOE (\$/kWh)	0,719	0,575	0,431	0,288	0,216	0,144

Chapter 7 Discussion

The objective of this thesis was to find the optimal design and performance of a Hybrid Renewable Energy System (HRES) that will both meet the energy demand and benefit the local people in a selected rural village of Myanmar. The thesis work is a contribution to the Energy Farm International Foundation's (EFIF) plan of implementing an Energy Farm in Myanmar. The village regarded, Amatgyi Khone, is located in Yedashe Township, Bago region. There are 256 households, a residential school, a primary school, an Energy Farm research station and public utilities, which are all comprised in this analysis. The daily average primary village load, required, is 44,2 kW and the peak load of 107 kW that occurs in the morning time. A future load profile, given in Section 2.7, is assumed to be constant throughout the year, because the project region is neither affected by seasonal changes or day length variations.

The future village load is based on information from field survey research, where quantitative research method was used. The future loads are estimated based on respondent's preferences of electrical components at household level and village level, assumed wattage ratings of components and their daily routines. A higher number of respondents would have been preferable to reduce biases in the survey research. However, a variety of household standards were interviewed and all of households Type II were represented, which yields the highest and lowest power consumers of Amatgyi Khone village. Considering a future load, is assumed to be necessary as village development may occur when the village receive power supply. Opportunities rises for growth in the living standard and the start-up of small businesses and restaurants.

The village is mainly depended on fuelwood for cooking, and the wealthiest households (Type II) use a mixture of wood and charcoal. All the household desire better cooking facilities, as the present cooking technique, open fire, involves large quantities of wood consumption and indoor air pollution. The average daily thermal load for cooking in the village is 107,94 kW, with a peak demand of 633,2 kW. However, the assumed efficiency used in the calculations is related to the present cooking technique, which is not very efficient. Consequently, implementation of new cooking technologies with higher efficiency, would require a lower thermal load demand. However, the thermal load estimated for cooking is high, and would require a HRES with considerably high capacity, therefore, covering the cooking demand with electric power is not regarded as a feasible solution.

The solar radiation in Amatgyi Khone village is considered very good, with an annual average daily global solar radiation of 5,38 kWh/m^2/day. In addition, the amount of crop residues in Yedashe Township are vast, with a rice husk availability of 2,96 tonnes/day. Wind and hydro resources was investigated, but was not adequate in this region of Myanmar. Therefore, locally available solar and rice husk biomass resources are selected to support electricity generation in the HRES.

According to the load requirement of the village and due to applicability to use rice husks, a throatless gasifier, within the subgroup of the downdraft, fixed-bed gasifier, was selected combined with two biogas generators. Two generators were selected to increase the power systems reliability, due to periods of scheduled maintenance and operational problems. Combining such a bio gasifier power plant (BGPP) with solar PV systems is beneficial, because solar PV system can help to reduce the BGPP plant O&M costs and extend the operational lifetime of the generator. Additionally, a PV/BGPP system can supply more reliable electricity whenever the electricity production from the solar PV system are not sufficient. According to Sharma and Goel's research (2016) the solar-biogas system compared to biogas generation alone have a potential to discharge much less CO_2 to the atmosphere. The selection of HRES also included batteries, because more storage will normally result in somewhat lower use of the generator, since the generator will not necessary need to back up the PV system in the event of cloudy weather for a few days.

Due to a vast need of better cooking technologies in Amatgyi Khone village, the forced draft cook stove, model SPTL-0610, was selected. It has higher efficiency compared to the traditional open fire technique. The cooking technique is comparable to the villager's current solution in terms cooking with fire wood. However, the consumption of fuel wood would be considerable reduced due to implementation of this type of cook stove in the households. Consequently, this could benefit the villagers in terms of spared time for collecting the fuelwood, secure the villagers from fuelwood scarcity in the future, and reduce the hazardous indoor-air pollution in the households.

The selected HRES components have been simulated in HOMER software, using many different system configurations. To find the optimal HRES type and configuration, the NPC and the LCOE of each system configuration have been calculated for a technical lifetime of 25 years. The optimal HRES is the least costly HRES option, that meets Amatgyi Khone village's electricity demand under the specific requirements. The optimal HRES configuration is based on the selected village's load requirements and availability of renewable energy resources, hence the results should not be extrapolated to other villages. According to the simulation and optimization results, the optimal HRES type is a solar PV/ BGPP/Battery system, which was found more feasible than two other options considered; Solar PV/BGPP and Solar PV/Battery. The optimal HRES configurations is given in Table 7.1.

Table 7.1: Optimal HRES configuration

PV system capacity	150 kW
Biogas Generator (#1)	75 kW
Biogas Generator (#2)	50 kW
Battery bank, Annual throughput	288 batteries, 24 Strings, 23 966 kWh
Converter capacity	120 kW
Dispatch strategy	HOMER Cycle charging

The HRES type without battery is not considered as a feasible system option, mainly due to increased usage of BGPP and a doubling of the systems O&M costs. This can be explained by high O&M costs regarding the BGPP, which accounted for 95 % of the total HRES operational costs. Furthermore, the optimal HRES configuration contains a relatively high amount of batteries. Hence, disposal of batteries at the end of the lifetime must be taken into consideration.

The optimal HRES can meet the village primary load requirements without any capacity shortage and at a renewable fraction of 100 %. The BGPP accounts for 53,64 % of the total annual generated load where generator #1 supply 171.874 kWh and generator #2 supply 102.104 kWh. The remaining primary annual load supply of 46,37 % is generated by the Solar PV system, which equals 236.859 kWh. The HRES follow the dispatch strategy, cycle charging. The optimal combination of Solar PV and biogas generation to serve the village primary AC load demand, variates throughout the year due to availability of solar radiation. The BGPP's electric production increases slightly during the summer time (rainy season). The excess production from the biogas generators, after meeting the village primary AC load demand, is used to charge the batteries.

The optimal HRES requires an initial investment cost of $691.143 and it has a total NPC of $2.938.238, and the HRES can supply the required load to Amatgyi Khone village at a COE of $0,719/kWh. Moreover, to evaluate for the effect of uncertainties in the input variables of the optimal HRES configuration, a sensitivity analysis has been conducted in HOMER. As a result, the range of sensitivity does not affect to change of the optimal HRES configuration, but the HRES costs will be affected in various amounts. The selected nominal discount rate is relatively high, but if special agreements with the bank could be arranged, this would be preferably to obtain a reduced COE to the end-user. Similarly, as mentioned earlier, the BGPP's O&M costs are considerably high. If governmental/donor support could be granted to subsidise all the BGPP's O&M costs, the COE and NPC can be reduced to $0,266/kWh and $1,068 million, respectively. Furthermore, the price of the rice husk used as fuel in the power plant, may be affected to increase in the future in a scenario where rice husk is widely exploited as a feedstock for biomass power. In a scenario if the rice husk fuel prices increase from $28 to $46/tonne, the COE and NPC of the HRES will increase from $0,712 to $0,738/ kWh and $2,909 to $3,010 million, respectively.

Furthermore, implementation of a rural electrification scheme is essential to make the proposed HRES electricity supply affordable to the end-users and to ensure development of the energy system. To realize this type of rural electrification scheme, government or donor support is required. Table 7.2 show how the various levels of government/donor support scenarios can contribute to reduce the HRES's LCOE, and the household types availability to pay per support scenario. Type I and Type II households have average monthly income of about $145 and $500, respectively. Furthermore, average daily energy consumption per household type is estimated to be 3,3 kWh and 49,8 kWh, for Type I and Type II, respectively. However, this is considered to be a future load scenario in which the Type II households possess highly power consuming electrical household components as air condition and washing machines.

As shown in the table, in the scenario without any support, Household type I need to pay 49 % of their average monthly income for electricity. Moreover, Household Type I may have availability to pay due to support scenario of at least 40 %. Contrary, household Type II would need the support scenarios of at least 80 % or 90 %, to be able to pay for the monthly electricity prices. This is considering that the household incomes stay the same for the future scenario. With this said, economic stability to buy appliances in a future scenario is necessary, hence, the model expects economic growth in the village.

Table 7.2: Effect of subsidies on the electricity price and availability to pay per household type.

Subsidy as a percentage of total HRES capital cost (%)	0 %	20 %	40 %	60 %	70 %	80 %	90 %
LCOE ($/kWh)	0,719	0,575	0,431	0,288	0,216	0,144	0,072
Monthly COE as % of avg. income Household Type I	49 %	39 %	29 %	20 %	15 %	10 %	5 %
Monthly COE as % of avg. income Household Type II	239 %	191 %	143 %	95 %	72 %	48 %	24 %

Additionally, development of an O&M scheme is important to ensure sustainable operation of the HRES in the rural village. Local people can be trained for basic maintenance, such as monitoring the HRES operation and routine maintenance, and for example to collect monthly fees from the end-users.

The method using LCOE as value of economic viability, does not reveal the true extent of the benefits of implementing electricity supply in rural villages. In reality, the HRES replace low-quality and often polluting options such as kerosene, flashlights and diesel generators. Investment of such power systems may also be viewed as investment in health, productivity and jobs (Adamarola et al. 2017).

Chapter 8 Conclusion and Further Work

8.1 Conclusion

The need to increase the electrification ratio in Myanmar is vast. 70 % of the population are living in rural areas, where the national grid only reaches 7 % of the villagers. Due to limited financing and geographical challenges and limited power supply, expanding the national-grid into the rural areas is not considered as a viable solution. Responding to this vital energy need, hybrid renewable energy systems (HRES) may safely generate sufficient power to rural areas with low energy requirements, and without the need of implementing large facilities or network. Furthermore, in the future, if the national grid expands into the rural areas, the mini-grid systems can be connected to the national grid.

The objective of this thesis was to find the optimal design and performance of a Hybrid Renewable Energy System (HRES) that will both meet the energy demand and benefit the local people in a selected rural village of Myanmar. Information about the village load requirement is based on field survey research conducted in the village, Amatgyi Khone. The daily average primary village loads are 44,2 kW, with a peak demand of 107 kW, comprising loads on both household and community level. This is a load scenario where the villager's future desire and preferences of electrical equipment is taken into consideration. Moreover, due to a considerably high estimated thermal load required for cooking, it is not considered feasible to cover this load with electric power from the HRES.

Due to abundant availability of solar energy and agricultural crop residues, especially rice husks, in Amatgyi Khone village, hence, solar and biomass technologies are selected to support the HRES. The selection of HRES components resulted in bio gasifier power plant (BGPP), solar PV system and battery bank. The BGPP consists of a throatless gasifier, within the subgroup of the downdraft and fixed-bed gasifier, combined with two biogas-generators.

Additionally, responding to the villager's needs of a more efficient and less polluting cook stove, a forced draft cook stove was regarded. Consequently, implementing such a cook stove, could benefit the villagers in terms of spared time for collecting the fuelwood, secure the villagers from fuelwood scarcity in the future, and reduce hazardous indoor-air pollution.

According to the simulation and optimization results from HOMER software, the optimal HRES type is a solar PV/ BGPP/Battery system. This system type was found more feasible than two other options considered; Solar PV/BGPP and Solar PV/Battery. The optimal HRES components have the following capacities: Solar PV - 150 kW, bio-gen #1 - 75 kW, bio-gen #2 - 50 kW, inverter - 120 kW and battery bank - 23.966 kWh. The battery bank consists of 288 batteries attached by 24 strings, and is charged according to cycle charging. The HRES can supply 100 % renewable power with no capacity shortage to the end-users, through mini-grid distribution LV lines. The BGPP accounts for 53,64 % of the total annual generated load, and the remaining primary annual load supply of 46,37 % is generated by the Solar PV system.

The estimated value of the NPC and LCOE is $2.938.238 and $0,719/kWh, respectively. However, by introducing different types of governmental or donor support, the LCOE can be reduced in various amounts. It is found that the LCOE can be reduced to $0,266/kWh when the BGPP O&M costs are completely subsidised. Another type of governmental or donor support can be introduced to reduce the HRES investment cost. Hence, a 40 % support scenario would be recommended to meet household Type I's availability to pay for monthly COE. Contrary, household Type II would require support scenarios of at least 80 % or 90 %, to be able to pay for the monthly COE. Hence, governmental or donor support is regarded essential for making the electricity supply affordable to the end-users and to ensure development of the energy system. However, this is considering that the household incomes stay the same for the future scenario. With this said, economic stability to buy appliances in a future scenario is necessary, hence, the model expects economic growth in the village.

Additionally, measuring the viability of HRES in terms of LCOE, does not reveal the true scope of the benefits occurring when implementing electricity supply in rural villages, such as Amatgyi Khone. In reality, the HRES replace low-quality and often polluting options such as kerosene, flashlights and diesel generators. It creates numerus advantages for the local villagers, such as better study environment in the schools, increased mobility after dark and indoor environment in general. Investment of such hybrid renewable energy systems may also be viewed as investment in health, productivity and jobs.

8.2 Further work

Based on limitations in the scope of this thesis, it is conducted a list of themes that are interesting and recommended to study further in relation to this thesis work:

- Consider an operation and maintenance schedule of the HRES power plant.
- Research opportunities for sustainable disposal of batteries.
- Conduct a detailed analysis of the mini-grid's technical design and the economics involved. It is recommended to develop a management system for the mini-grid distribution system.
- Propose a new cooking solution for the monastery residential high school.
- In Amatgyi Khone village, there are about 70 wells in total. Most of the wells have a manually water pumping system, and there are three generator based water pumping system. Hence, there is a need to investigate possibilities regarding water pumping systems in the village. Especially the potential regarding implementation of solar based water pumping systems.

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Appendix

Appendix 1: Questionnaire

The questions in the analysis are related to the energy consumption in households.

Questions about the household in general:

1) Information about the number of people living in the household can be used to predict the energy consumption in the household.

   a. How many adults are living in the household? (please write the number in the box)

      ☐ Adults

   b. How many children are living in the household?

      ☐ Children

2) May I ask, what are the average monthly income to this household?

   Answer:

   ____

   ____

3) Does the household have any livestock?

☐ Yes

☐ No

If yes, please answer what kind of livestock do the household have, and how many?

Please write the number of livestock in the box:

☐ Cow

☐ Buffalo

☐ Pig

☐ Chickens

☐ Goat

☐ Other: _______________

4) This question is related to what the people in the household do for a living. If the people living in the household have work connected to the household this will affect the energy consumption.

a. Is the work connected to the household or is it external? (tick the correct box)

☐ Household
☐ External
☐ Other: ____

If the work is connected to the **household**, please answer question b.

b. What do the people in the household do for a living?

☐ Farming
☐ Store
☐ Livestock
☐ Agriculture
☐ Other: ____

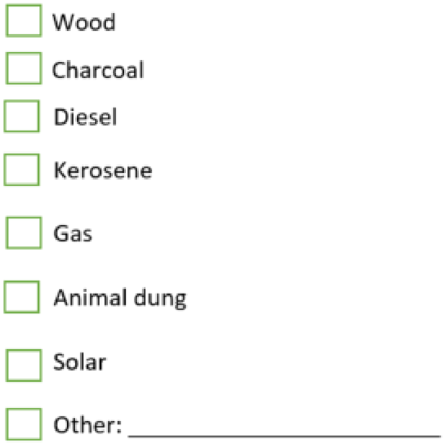
Questions about energy resources and energy consumption:

5) Which of the following energy resource does your household use for cooking and/or electrical purposes in the household?

For cooking purposes:

☐ Wood
☐ Charcoal
☐ Diesel
☐ Kerosene
☐ Gas
☐ Animal dung
☐ Solar
☐ Other: ______________________

For electrical purposes:



☐ Wood
☐ Charcoal
☐ Diesel
☐ Kerosene
☐ Gas
☐ Animal dung
☐ Solar
☐ Other: ______________________

6) What is the quantity of the resource used?

a. Amount of the resource used per day for cooking?
Answer:

b. Amount of the resource used per day for electrical consumption?
Answer:
____
____

7) If the energy resource used is **wood,** please answer the following questions:

a. Where do the household collect the wood?

☐ Natural forest

☐ Fuel wood plantation

☐ Community forests

☐ Tops and lops from timber extracted areas

☐ Do not know

☐ Other: ____

b. What type of wood is used?
Answer:
____
____

c. How much time is spent for collecting the wood?
Circling the right option:

Days per week:	0	1	2	3	4	5	6	7
Hours per day:	0	1	2	3	4	5	6	7

d. If wood is used for cooking and/or electrical, how much wood is used per day for the different purposes:

☐ Cooking Amount of wood (per day): ____

☐ Electrical Amount of wood (per day): ____

☐ Other: ____

Questions about electrical household components

8) What kind of electrical equipment are used?
Answer:

☐ Light bulb

☐ Radio

☐ Fans

☐ Mobile phone charger

☐ Other:____
____

10) How many light bulbs does the household have?
Circling the right option:

0 1 2 3 4 5 6 7 8 9 10

Other: ______

11) What is the effect of each light bulb?
Answer:
____

12) The following questions are related to usage of lights:

a. At what times would you prefer to use lights during the day?
Answer:
____
____

b. At what times do the household use lights during the day?
Answer:
____

13) Does the household contain a water pumping system?
Answer:

☐ Yes

☐ No

If yes, please answer the following questions:

a. How is the water pumping system powered?
Answer:
____
____

b. At what times during the week is the water pumping system normally used?
Answer:
____
____

c. If a diesel generator is used, how much fuel is used per week?
Answer:
____
____

d. What is the fuel price?
Answer:
____
____

14) Can you please tell me about the families’ daily routine?

a. At which times are cooking normally performed during the day?
Answer:

Breakfast: ____

Lunch: ____

Dinner: ____

b. At what time do the family wake up in the morning, and when do they go to sleep?
Answer:

Wake up: ____

Go to sleep: ____

15) If the village had access to electricity, what kind of electrical appliances would the household prefer?
Answer:
____
____

Appendix 2: Electrical applications and power supply at the Monastery

Electrical applications used at the Monastery

Room	**Electrical application**	**Number of el. application**	**Effect**	**Usage**
Class room 1	Spiral light bulb	2	28 W	04:30 – 07:00 am 07:00 – 11:30 pm
Class room 2	Fluorescent light	2	20 W	
Class room 3	Spiral light bulb	1	28 W	
	Fluorescent light	2	20 W	
5 Apartments/ sleeping room	Spiral light bulb	1 (5)	28 W	
4 Buildings for Monks	Fluorescent light	2 (8)	20 W	
	Spiral light bulb	2 (8)	28 W	
Library	LED light bulb	1	5 W	Used on Sundays
	Fluorescent light	2	20 W	
Religious speech room	Spiral light bulb	4	28 W	
	Fluorescent light	8	20 W	
Head building (one of the Monk's building)	Fan	2	33 W	From April to September
	Computer	2	275 W	
	Printer	3	120 W	
	Cell phone charger	3	10 W	*Source: http://www.erakiprelec.co.za/wattage-consumption.html*

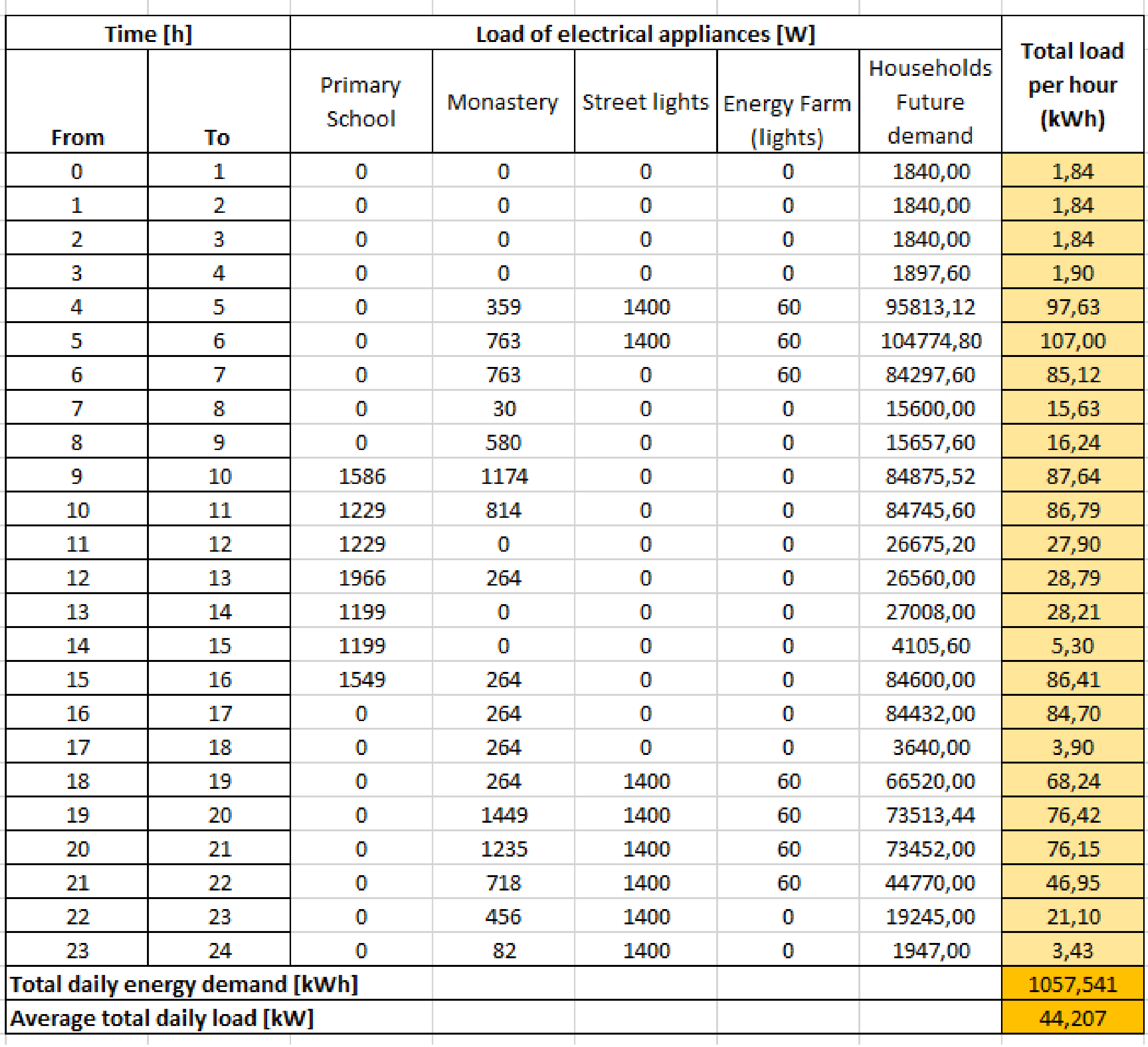
Electrical power supply at the Monastery

Application	**Number**	**Power**	**Usage**
Solar PV panel	1	100 W	
	1	300 W	
Battery	1	100 Ah	
	1	150 Ah	
Diesel generator			Every day 07:00 pm to 11:30 pm (sometimes daytime)
Diesel		0,5 gallon/day	

Appendix 3: Calculations of Households load demand

Time [h]		Total future load duration curve - Load of electrical appliances [W]															
		Type I & II										Type II					
From	To	Lights	Cooking (fan load, SPTL-	Rice cooker	Mobile Charging	TV	DVD-player	Stereo	Radio	Laptop	Fans	AC	Iron	Washing machine	Combined Fridge	Total load per hour	Total load per hour
		10	W	630	6	75	20	30	7	50	35	3500	1100	3000	900	Wh	kWh
0	1	40	0	0	0	0	0	0	0	0	0	0	0	0	1800	1840	1,84
1	2	40	0	0	0	0	0	0	0	0	0	0	0	0	1800	1840	1,84
2	3	40	0	0	0	0	0	0	0	0	0	0	0	0	1800	1840	1,84
3	4	40	57,6	0	0	0	0	0	0	0	0	0	0	0	1800	1897,6	1,90
4	5	12840	533,12	80640	0	0	0	0	0	0	0	0	0	0	1800	95813,12	95,81
5	6	12840	172,8	80640	3072	0	0	0	0	50	0	0	4400	0	3600	104774,8	104,77
6	7	0	57,6	80640	0	0	0	0	0	0	0	0	0	0	3600	84297,6	84,30
7	8	0	0	0	0	0	0	0	0	0	0	0	0	12000	3600	15600	15,60
8	9	0	57,6	0	0	0	0	0	0	0	0	0	0	12000	3600	15657,6	15,66
9	10	0	187,52	80640	0	0	0	0	448	0	0	0	0	0	3600	84875,52	84,88
10	11	0	57,6	80640	0	0	0	0	448	0	0	0	0	0	3600	84745,6	84,75
11	12	0	115,2	0	0	0	0	0	0	0	8960	14000	0	0	3600	26675,2	26,68
12	13	0	0	0	0	0	0	0	0	0	8960	14000	0	0	3600	26560	26,56
13	14	0	0	0	0	0	0	0	448	0	8960	14000	0	0	3600	27008	27,01
14	15	0	57,6	0	0	0	0	0	448	0	0	0	0	0	3600	4105,6	4,11
15	16	0	360	80640	0	0	0	0	0	0	0	0	0	0	3600	84600	84,60
16	17	0	192	80640	0	0	0	0	0	0	0	0	0	0	3600	84432	84,43
17	18	40	0	0	0	0	0	0	0	0	0	0	0	0	3600	3640	3,64
18	19	12840	0	0	0	19200	6320	0	0	1600	8960	14000	0	0	3600	66520	66,52
19	20	12840	61,44	0	3072	19200	6340	3840	0	1600	8960	14000	0	0	3600	73513,44	73,51
20	21	12840	0	0	3072	19200	6340	3840	0	1600	8960	14000	0	0	3600	73452	73,45
21	22	12840	0	0	0	19200	5290	3840	0	0	0	0	0	0	3600	44770	44,77
22	23	7680	0	0	0	9600	40	0	0	0	125	0	0	0	1800	19245	19,25
23	24	147	0	0	0	0	0	0	0	0	0	0	0	0	1800	1947	1,95
Total avg. load [kW]																	42,902
Total daily load (MWh)																	1,030

Appendix 4: Calculations of Total load demand



Time [h]		Load of electrical appliances [W]					Total load per hour (kWh)
From	To	Primary School	Monastery	Street lights	Energy Farm (lights)	Households Future demand	
0	1	0	0	0	0	1840,00	1,84
1	2	0	0	0	0	1840,00	1,84
2	3	0	0	0	0	1840,00	1,84
3	4	0	0	0	0	1897,60	1,90
4	5	0	359	1400	60	95813,12	97,63
5	6	0	763	1400	60	104774,80	107,00
6	7	0	763	0	60	84297,60	85,12
7	8	0	30	0	0	15600,00	15,63
8	9	0	580	0	0	15657,60	16,24
9	10	1586	1174	0	0	84875,52	87,64
10	11	1229	814	0	0	84745,60	86,79
11	12	1229	0	0	0	26675,20	27,90
12	13	1966	264	0	0	26560,00	28,79
13	14	1199	0	0	0	27008,00	28,21
14	15	1199	0	0	0	4105,60	5,30
15	16	1549	264	0	0	84600,00	86,41
16	17	0	264	0	0	84432,00	84,70
17	18	0	264	0	0	3640,00	3,90
18	19	0	264	1400	60	66520,00	68,24
19	20	0	1449	1400	60	73513,44	76,42
20	21	0	1235	1400	60	73452,00	76,15
21	22	0	718	1400	60	44770,00	46,95
22	23	0	456	1400	0	19245,00	21,10
23	24	0	82	1400	0	1947,00	3,43
Total daily energy demand [kWh]							1057,541
Average total daily load [kW]							44,207

Appendix 5: Electricity tariffs Myanmar

Table 6: Electricity tariffs for residential and small to medium-size commercial consumers, public buildings, and street lights in Myanmar (as of April 2015) (Bank 2015).

Electricity Tariffs for Residential and Small to Medium-size Commercial Consumers, Public Buildings, and Street Lights (as of April 2015) (Bank 2015)		
Consumption (kWh/Month)	Kyats/kWh	$/kWh equivalent
0-100	35	0,03
101-200	40	0,03
201+	50	0,04

Source: Adapted from World Bank NEP Project Appraisal Document, August 2015.

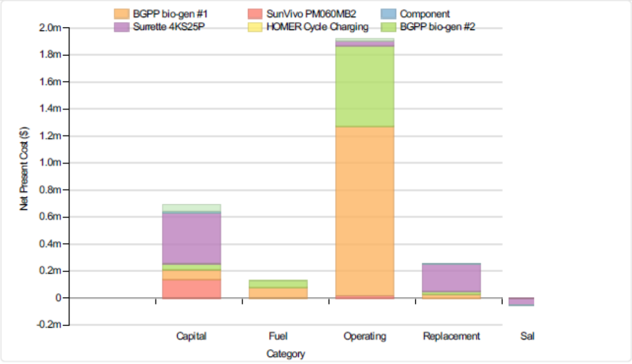
Appendix 6: HOMER System Report

System Report

System architecture

PV	SunVivo PM060MB2	150	kW
Generator	BGPP bio-gen #1	75	kW
Generator #2	BGPP bio-gen #2	50	kW
Storage	Surrette 4KS25P	24	strings
Converter	Sunny Tripower	120	kW
Dispatch Strategy	HOMER Cycle Charging		

Cost summary



Cost Summary

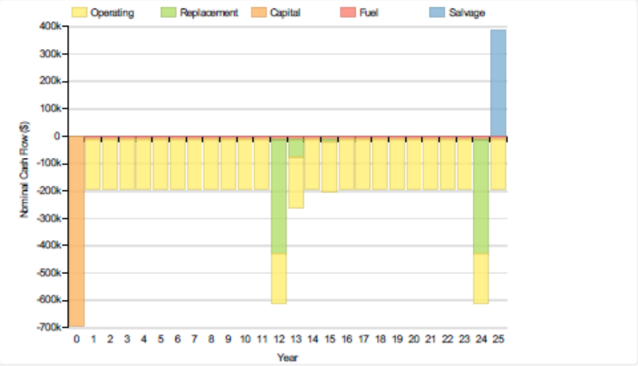
Total net present cost	2938238	$
Levelized cost of energy	0.719	$/kWh

Net Present Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
SunVivo PM060MB2	135,900	0	15,831	0	0	151,731
BGPP bio-gen #1	71,625	23,929	1,252,503	77,058	-259	1,424,857
BGPP bio-gen #2	47,750	24,407	601,352	48,276	-5,123	716,662
HOMER Cycle Charging	0	0	0	0	0	0
Surrette 4KS25P	374,400	203,796	30,395	0	-48,584	560,007
Sunny Tripower	11,468	2,839	0	0	-433	13,874
Other	50,000	0	21,107	0	0	71,107
System	691,143	254,971	1,921,188	125,335	-54,399	2,938,238

Annualized Costs

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
SunVivo PM060MB2	12,877	0	1,500	0	0	14,377
BGPP bio-gen #1	6,787	2,267	118,679	7,302	-25	135,010
BGPP bio-gen #2	4,524	2,313	56,980	4,574	-485	67,906
HOMER Cycle Charging	0	0	0	0	0	0
Surrette 4KS25P	35,476	19,310	2,880	0	-4,603	53,062
Sunny Tripower	1,087	269	0	0	-41	1,315
Other	4,738	0	2,000	0	0	6,738
System	65,488	24,159	182,039	11,876	-5,154	278,407

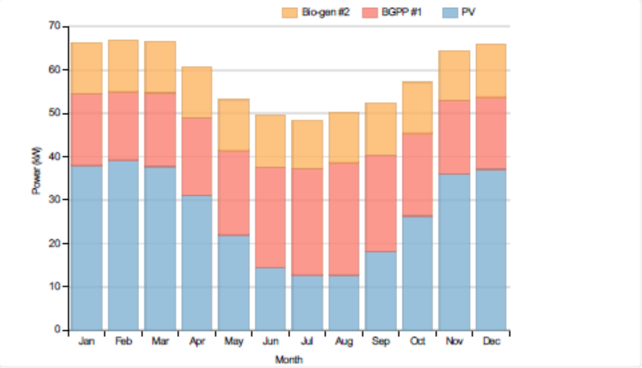


Electrical

Quantity	Value	Units
Excess electricity	115829	kWh/yr
Unmet load	0	kWh/yr
Capacity shortage	23	kWh/yr
Renewable fraction	1	

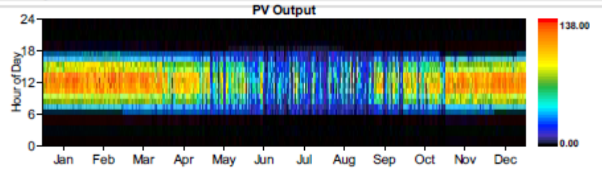
Component	Production(kWh/yr)	Fraction (%)
PV	236,859	46
Generator	171,874	34
Generator	102,105	20
Total	510,838	100

Load	Consumption(kWh/yr)	Fraction (%)
AC primary load	387,218	100
DC primary load	0	0
Total	387,218	100



PV:SunVivo PM060MB2

Quantity	Value	Units
Rated capacity	150	kW
Mean output	27	kW
Mean output	648.93	kWh/d
Capacity factor	18.03	%
Total production	236859	kWh/yr
Minimum output	0.00	kW
Maximum output	137.99	kW
PV penetration	61.17	%
Hours of operation	4325	hrs/yr
Levelized cost	0.061	$/kWh

Quantity	Value	Units
		

Generator:BGPP bio-gen #1

Quantity	Value	Units
Hours of operation	2366	hrs/yr
Number of starts	1007	starts/yr
Operational life	13	yr
Fixed generation cost	52.35	$/hr
Marginal generation cost	0.04	$/kWh
Electrical production	171874	kWh/yr
Mean electrical output	73	kW
Min. electrical output	38	kW
Max. electrical output	75	kW
Fuel consumption	261	L/yr
Specific fuel consumption	1.52	L/kWh
Fuel energy input	1066255	kWh/yr
Mean electrical efficiency	16	%

Generator:BGPP bio-gen #2

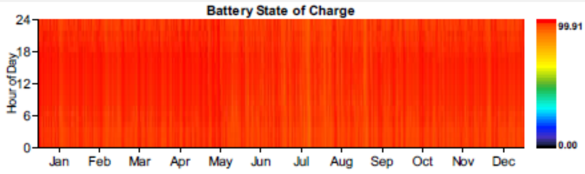
Quantity	Value	Units
Hours of operation	2590	hrs/yr
Number of starts	1492	starts/yr
Operational life	12	yr
Fixed generation cost	23.43	$/hr
Marginal generation cost	0.04	$/kWh
Electrical production	102105	kWh/yr
Mean electrical output	39	kW
Min. electrical output	25	kW
Max. electrical output	50	kW
Fuel consumption	163	L/yr
Specific fuel consumption	1.60	L/kWh
Fuel energy input	667997	kWh/yr
Mean electrical efficiency	15	%

Battery:Surrette 4KS25P

Quantity	Value
String size	12
Strings in parallel	24
Batteries	288
Bus voltage	48

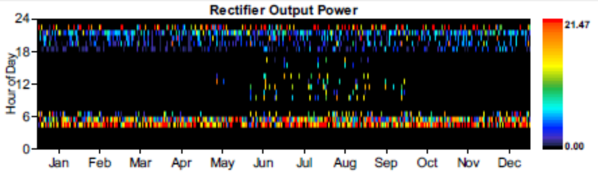
Quantity	Value	Units
Nominal capacity	2352	kWh
Usable nominal capacity	1411	kWh
Autonomy	32	hr

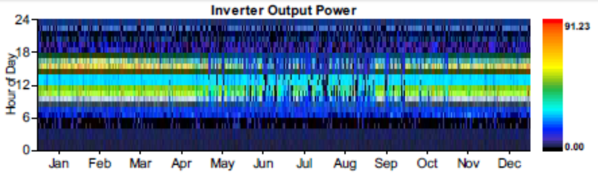
Quantity	Value	Units
Battery wear cost	0.138	$/kWh
Average energy cost	0.035	$/kWh
Energy in	26780	kWh/yr
Energy out	21436	kWh/yr
Storage depletion	13	kWh/yr
Losses	5331	kWh/yr
Annual throughput	23966	kWh/yr



Converter

Quantity	Inverter	Rectifier	Units
Capacity	120	119	kW
Mean output	15	2	kW
Minimum output	0	0	kW
Maximum output	91	21	kW
Capacity factor	12	2	%
Hours of operation	7,305	1,455	hrs/yr
Energy in	129,654	14,860	kWh/yr
Energy out	128,098	13,968	kWh/yr
Losses	1,556	892	kWh/yr





Emissions

Pollutant	Emissions	Units
Carbon dioxide	581	kg/yr
Carbon monoxide	6	kg/yr
Unburned hydrocarbons	6	kg/yr
Particulate matter	0	kg/yr
Sulfur dioxide	0	kg/yr
Nitrogen oxides	1	kg/yr

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