Solar Based Rural Electrification in Liberia

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A mio nonno.

”The clear and present danger of climate change means we cannot burn our way to prosperity.

We need to find a new, sustainable path to the future we want. We need a clean industrial revolution.”

Ban Ki-Moon

Secretary-General of the United Nations

Resumo

A população com baixo rendimento que vive nas áreas rurais sofre com a falta de desenvolvimento humano e económico. O acesso à energia é um dos principais impulsionadores para melhorar a saúde, a educação e melhorar a qualidade de vida nos países menos desenvolvidos. À medida que o custo dos sistemas fotovoltaicos de energia e armazenamento continua a diminuir, as mini-redes híbridas baseadas em energias renováveis descentralizadas tornam-se opções cada vez mais atraentes para a eletrificação rural, onde a extensão da rede não é viável. O principal objetivo desta tese é mostrar como as mini-redes híbridas baseadas em energia solar podem ser usadas para resolver o problema do acesso à eletricidade e constituem uma opção de fornecimento de energia sustentável para áreas rurais. Este trabalho foca as vantagens da eletrificação rural e descreve o projeto, instalação e análise de sistemas híbridos baseados em energia solar em cinco aldeias da Libéria. O software HOMER é utilizado como ferramenta para a análise técnico-económica e os modelos matemáticos e as hipóteses assumidas são discutidas. Realiza-se uma otimização usando o software para encontrar a configuração ideal para cada aldeia. Em seguida, realizam-se simulações dos projetos finais para prever os desempenhos dos sistemas. Ilustram-se as configurações finais, com a descrição dos componentes usados nas aldeias. Os dados de produção de energia recolhidos das mini-redes são analisados e comparados com os resultados das simulações do HOMER. Finalmente, os custos do projeto são revisitados e fazem-se várias considerações sobre o projeto, para possíveis melhorias em projetos similares.

Palavras-chave: Eletrificação Rural, Fotovoltaica, HOMER Off-grid, Sistema Híbrido

Abstract

Low income population living in the rural areas suffers from lack of human and economic development. Modern energy access is one of the main drivers to improve health, education, and enhances the quality of life in less developed countries. As the cost of photovoltaic energy and storage systems continues to decrease, decentralized renewable energy base hybrid mini-grids become increasingly attractive options for rural electrification where the grid extension is not feasible. The main goal of this thesis is to show how solar based hybrid mini-grids can be used to solve the problem of electricity access and constitute a sustainable energy supply option for rural areas. This work focuses on the advantages of rural electrification and describes the design, installation and analysis of solar based hybrid systems in 5 villages in Liberia. The software HOMER is used as a tool for the techno-economic analysis and its mathematical models and the assumptions used are illustrated. An optimization with the software is performed to find the optimal configuration and size for each village. Then, simulations of the final designs are accomplished to predict the performances of the systems. The final configurations, with the description of the components used in the villages in Liberia and the installation procedure are illustrated. The energy production data collected from the mini-grid are analyzed and compared with the results from HOMER simulations. Finally, the costs of the project are reviewed and several considerations about the project are discussed, with possible improvements for similar projects.

Keywords: HOMER, Hybrid system, Off-grid, Photovoltaic, Rural electrification

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List of Abbreviations

DoD	Depth of Discharge
EDF	European Development Fun
EDF	European Development Fund
GDP	Gross Domestic Product
GoL	Government of Liberia
HDI	Human Development Index
HDKR	Hay, Davies, Klucher, Reindl solar radiation model
HOMER	Hybrid Optimization Model for Multiple Energy Resources
HRES	Hybrid Renewable Energy System
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IMF	International Monetary Fund
LED	Light Emitting Diode
LPG	Liquefied Petroleum Gas
LRD	Liberia Dollars
MLME	Ministry of Lands, Mines and Energy
MPPT	Maximum Power Point Tracking
NASA	Light Emitting Diode
NEPL	National Energy Policy for Liberia
NORAD	Norwegian Agency for Development Cooperation
NPFL	National Patriotic Front of Liberia
NREL	National Renewable Energy Laboratory

ODA	Official Development Aid
REFUND	Rural Energy Fund
RESMP	Rural Energy Strategy and Master Plan For Liberia
RE	Renewable Energy
RFID	Radio-Frequency IDentification
RREA	Rural and Renewable Energy Agency
SDGs	Sustainable Development Goals
SE4All	Sustainable Energy for All
STC	Standard Test Conditions
TTA	Trama Tecno Ambiental
USAID	United States Agency for International Development
USD	United States Dollar

Chapter 1

Introduction

Modern energy services are crucial for human well-being and for a sustainable development, yet globally over 1.1 billion people are without access to electricity and 2.8 billion people are without clean cooking facilities [1]. As underlined by the Sustainable Development Goals, energy access has a pivotal role for universal development and is central for poverty eradication. On one hand, poor households do not have the financial resources and income security required to switch to more efficient, cleaner fuels and energy technologies. At the same time, the consequences of using traditional fuels, which include impacts on health, women's time and opportunities for income generation, add to the constraints on families attempting to escape from poverty.

Liberia has one of the most underdeveloped energy sectors worldwide with only 13.8% of the population with access to electricity in 2015 [2]. The electricity transmission will grow rapidly in the next years, with the largest cities gaining access through the interconnected grid. However, this would still leave most of Liberia's rural population without access to modern energy services. In rural areas, given the relatively low load requirements of the local population and the significant renewable energy resources, the decentralized off-grid solutions appear to be the best strategy to bring modern energy services. Renewable energy technologies are particularly well suited for off-grid, distributed generation scenario, and may play a significant role in reducing poverty, supporting community institutions and facilitating the generation of basic services such as communication, water access, education and health services.

1.1 Objectives

The main goal of this work is to show how solar based hybrid mini-grids can be used to solve the problem of electricity access and how distributed renewable energy sources can constitute a sustainable energy solution for rural areas. Starting with the explanation of the advantages of modern energy access and then illustrating a case study in Liberia. An objective of this thesis is to exemplify how to proceed in the design and implementation of an actual electrification project in a remote area, as well as to point out some findings that could be useful in other project. Several research questions guided this work in the fulfilment of the main goal:

- What social impact the electricity access has on rural population?
- How does the electrification in rural areas work? How are the actors involved?
- Which is the energy situation in Liberia? Which are the actions required to improve the current situation?
- Which technical solutions for electricity production from renewable energy resources are applicable for the rural electrification?
- Which is the best way to design and simulate an electrification project? Are the results reliable and close to the real situation?
- Which different costs are involved in the electrification project?
- Which of the findings made in this project can be applied to other electrification projects?

1.2 Outlines

In order to answer the research questions stated above, the work is organized in different stages. The chapters of this thesis are summarized in the following lines:

Chapter 1: Introduction of the topic of the thesis, followed by the statement of the goal and the research questions. Further, the description of the thesis structure and its limitations.

Chapter 2: The chapter starts with an overview of the current energy access situation worldwide. Then it is illustrated how access to modern form of energy is a prerequisite to achieve the Millennium Development Goals (MDGs). Finally, the benefits of energy access for universal development and for poverty eradication are described.

Chapter 3: The Liberia profile is delineated in this chapter, with a description of the social, historical and economical situation. Then, the characterization of the country energy situation is provided. Follows the institutional landscape, with the illustration of the main players, the national commitments and the main barriers of rural electrification.

Chapter 4: The case study is described in this chapter, with the definition of the load profile and the information about the different villages.

Chapter 5: This is the central chapter, where the design of the system is implemented. First an optimization with the software HOMER is performed. The mathematical models and the assumptions used in the optimization are illustrated and then the results are shown. Secondly, the final design is described and then simulated with HOMER to predict the performance of the project.

Chapter 6: In this chapter, the final configuration implemented in the real case in Liberia is illustrated, with the description of the different components used.

Chapter 7: The analysis of the systems is performed. First the production analysis, comparing the real data with the results from the software simulations. Follows the economical analysis and several considerations about the project.

Chapter 8: This chapter presents the conclusion of the thesis, followed by some possible improvements for similar projects.

1.3 Limitations

This thesis was accomplished as part of a university internship in the company Sunlabob Renewable Energy. The project described in this work was led by the NGO Plan international that appointed the private company Trama TechnoAmbiental (TTA) for the design of the system and Sunlabob for the installation. My personal contribution in Sunlabob has been the analysis of the post-installation production data of the systems. Given this division of labour in the realization of the project, several information gathered by TTA was not at my disposal. Details about the feasibility study, the decisions regarding the design of the systems and the tariff applied to the villagers were held by TTA as confidential information.

Chapter 2

Electrification of Rural Areas

Access to energy has a critical importance to enhance a sustainable development, strongly influencing all aspects of human life, including access to water, agriculture, health care, education, job creation, climate change and environmental sustainability. In 2017 approximately 1.1 billion people (about 15% of the global population) still lived without electricity and about 2.8 billion people (37% of the global population) without access to clean cooking facilities [1]. The majority of people without access to electricity are in sub-Saharan Africa and in Asia, and most of them live in rural areas. The electrification rate for sub-Saharan countries is 35%, with only 50 GW of installed capacity to supply the electricity of the entire sub-Saharan Africa, excluding South Africa [3]. This value is less than the electricity needs of the entire Republic of Korea. However, significant progresses to promote access to electricity have been made worldwide. Since 2012, more than 100 million people per year have gained electricity access, an increase compared to the rate of 62 million people per year in the previous 12 years (period 2000-2012) [4]. In sub-Saharan Africa for example, the electrification efforts outpaced population growth for the first time in 2014. However, progress remains uneven and the electrification rate is currently only 43%. Most of the people without electricity access live in rural and remote places and, in these conditions, there are only three ways for them to gain access: (1) grid connected electrification; (2) community-level energy grid; (3) household-level power production. Of the 1.1 billion of people that obtained electricity access since 2000, basically all of them gained it through connection to the main grid and of the produced energy, 70% was from fossil fuel, especially from coal (45%) [4]. However, thanks to the declining costs for photovoltaic energy, cheaper and more efficient lighting and new business models, the number of available solutions for renewable access to electricity has increased. Over the last five years, renewable technologies distribution have started to gain ground, especially with off-grid and mini-grid systems, reaching of 30% of new connection's supplying and they are expected to increase in the next years [1].

Distributed energy systems are great solutions for power production in developing countries. Their use can complement or substitute the centralized energy generation systems, providing affordable lighting, communication or education services. Thanks to great improvements in the technologies and the decreases of renewable energies and electronic devices costs, distributed systems can offer an unprecedented opportunity to accelerate the transition to modern energy services in remote and rural areas [1].

As shown by the International Energy Agency (IEA) [4], these off-grid systems offer several advantages:

- Cost saving in many markets
- Modularity, flexibility and rapid construction times
- Fuel availability and stability of its price
- Enhance reliability and resilience
- Improved health through reduction of indoor pollution
- Reductions in deforestation and environmental degradation
- Positive effects on women empowerment

As already illustrated, most of the people that obtained energy access in last years gained it through connection to the main grid. Nevertheless, according to the projection of IEA for the New Policies Scenario, half of those who will gain access in the period 2017-2030, will do it without connection to the main grid and mainly through renewable sources. Moreover, only 37% of the future investments will be dedicated for grid-connected systems. For instance, between 2010 and 2015, off-grid solar energy has been one of the fastest growing industries in providing energy access with 23,5 million solar systems sold worldwide. Furthermore, in 2016 only, 8.2 million of off-grid solar systems were sold, representing a global increase of 41% compared to 2015 [1].

2.1 Sustainable Development Goals

In September 2015 at the United Nation Summit, the 17 Sustainable Development Goals (SDGs) were adopted by the world leaders. These goals universally apply to all over the next fifteen years with the aim of mobilizing the efforts of every country to end all forms of poverty, fight inequalities and tackle climate change, while ensuring that no one is left behind [5]. For the first time, the UN goals include a target focused specifically on ensuring access to affordable, reliable and modern energy for all by 2030 (SDG 7.1). This shows a recognition of the importance of access to modern energy services and its central role in achieving many of the other development goals. In fact, a lack of access to modern energy can make it difficult or impossible for a country to confront the several challenges that it faces, such as poverty (SDG 1), air pollution (SDG 13), low levels of life expectancy and lack of access to essential health-care services (SDG 3), delivering quality education (SDG 4), adaptation and mitigation of climate change (SDG 11), food production and security (SDG 2), economic growth and employment (SDG 8), sustainable industrialization (SDG 9) and gender inequality (SDG 5). Despite an impressive rate of progress in recent years, many difficulties remain in achieving these remarkable goals. For instance, in the energy field only four of the 47 Least Developed Countries could achieve universal access to electricity by 2030 without an acceleration of the rate of increase in access, while only seven more could do so even if they doubled their current rate of progress. On the other hand, in a quarter of the least developed countries achieving this goal by 2030 would require an annually energy access rate 10 times higher in the coming years than over the past decade [6].

2.2 Benefits of Energy Access

As underlined by the Sustainable Development Goals, energy access has a pivotal role for universal development and is central for poverty eradication. The lack of access to energy services in rural communities in developing countries has several effects: limits educational opportunities, leads to negative public health and environmental impacts, and inhibits economic growth. In fact, two thirds of the energy use of the least developed countries is consumed at household level. Households rely primarily on traditional biomass, which therefore remains the main energy source in these countries [6]. However, focusing only on household's energy access is not enough to reach the developing goals. In order to realize these aims, electricity access for public facilities, such as schools and clinics, and for industries is essential. At the same time, it is fundamental to ensure the continuity and reliability of the electricity supplying.

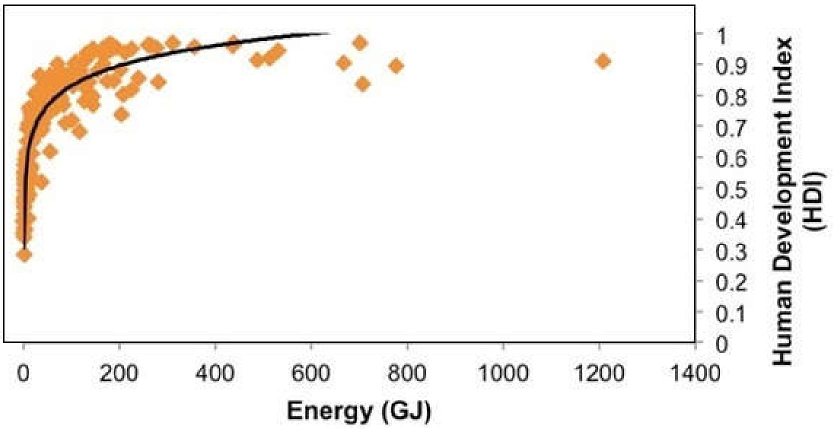


Figure 2.1: Link between HDI and Energy Consumption Per Capita

Energy and Human Development

The HDI is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. In figure 2.1, it can be noticed how the Human Development Index (HDI) is link to the energy consumption per capita [7]. Energy infrastructure is often a prerequisite for income-generating activities and for increasing productivity, education and health-care. As it can be noticed from the graph, when a country starts increasing its energy consumption, there is an exponential increase of the HDI, and vice versa. This ratio then decreases when energy levels approach industrialized country levels.

Energy and Public Health

Health is another area where energy access is particularly important. The use of candles, kerosene and other polluting fuels for lighting has serious implications for health including the release of toxins during combustion, contribution to upper respiratory disease, and safety concerns such as fire hazards and accidental ingestion [8]. Almost half of the global population (3 billion people) rely on traditional fuels like charcoal for household energy and 2.8 million die each year from the high particulate air pollution created by these fuels in poorly ventilated spaces [4]. In fact, according to the data collected by the IEA, shown in figure 2.2, the number of premature deaths from household air pollution is directly correlated to the number of people using traditional fuels for cooking and to the type of fuel [4]. Different alternatives are available, such as improved or advanced biomass cook-stoves and stoves fueled by LPG, natural gas or solar power, which reduce household air pollution. There are other synergies between energy access and health, 60% of health facilities in sub-Saharan Africa have no electricity and 34% of hospital has unreliable electricity access [9]. Access to electricity enabled to store vaccination and medicine in refrigerator. This results in a loss of almost half of vaccines while 70% of electrical medical devices used in developing countries fail. Additionally, a lack of electricity means medical staff often has to work with flash-lights or kerosene lamps [4].

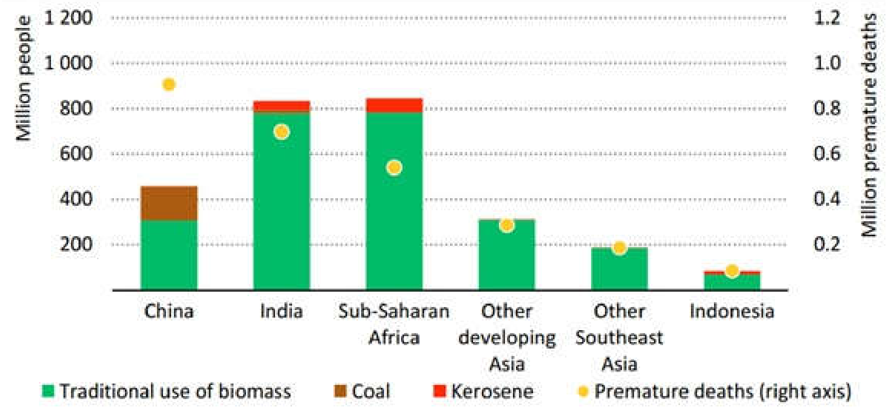


Figure 2.2: Correlation Between Use of Traditional Cooking Fuels and Premature Deaths from Household Air Pollution

Energy and Education

About 90% of children in Sub-Saharan Africa go to primary schools that lack electricity, 27% of village schools in India lack electricity access, and only 50% of Peruvian schools are electrified. Collectively, this corresponds 188 million children in the world that attend schools not connected to any type of electricity supply [10]. Electricity access in fact can play a significant role in improving learning outcomes at schools through several positive benefits. For instance, kerosene lamps are insufficient for the purpose of reading, while electric illumination can extend studying hours and improve school performances. Moreover, electrification facilitates the presence of information and communication technologies in the classroom. In fact, the low-power technologies are transforming the education landscape in many developing countries. Examples are low-cost computers, tablets and e-readers, that are battery driven and require a low power draw [8]. In figure 2.3 is shown the correlation between the electricity access and the primary school completion rate obtained from the World Bank databases [2].

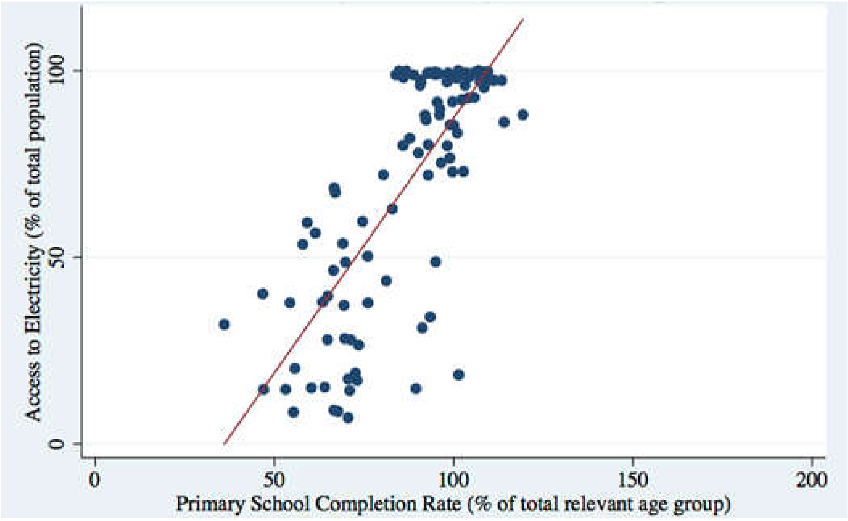


Figure 2.3: Correlation Between Electricity Access and Primary School Completion Rate

Energy and Gender Equality

In developing countries there are many inequalities related with the distribution of energy. In fact, the richest 20% of world's population uses 55% of primary energy, while the poorest 20% uses only 5% of it [8]. This provokes several effects on the life conditions of the poor in developing communities. Moreover, the lack of modern energy access influences more the women over the men. In fact, women in developing countries tend to bear responsibility for collecting and preparing fuel for cooking, as well as the cooking itself. This means impacts on their physical well-being, since in Africa women carry loads that weigh as much as 25-50 kilograms [11]. Households dedicate an average of 1.4 hours a day collecting fuel, so rural electrification can help women reduce this workload, giving them more time for other activities [4]. In the same way, clean cooking facilities strongly improve women's health conditions, since they are the most impacted by household air pollution.

Energy and Environment

The environmental effects of unsustainable energy use in developing countries are well studied and include several impacts, such as urban and indoor air pollution, acidification, global warming and mass deforestation. In fact, unsustainable energy consumption is the single largest contributing factor to global detrimental environmental impacts [8]. Modern energy access through decentralized renewable energy, particularly to the rural poor, can positively redirect the ecological and social factors that contribute to climate change. Achieving universal energy access is not in conflict with accomplishing climate objectives. In fact, analyzing the Energy for All Case for 2030, the additional demand related with an universal energy access is 37 million tons of oil equivalent (Mtoe), which corresponds to approximately

60 million tons of $CO2_{eq}$ [4]. This value is roughly equivalent to a week's energy demand in the United States. Furthermore, the increase in $CO2_{eq}$ from electricity and clean cooking access is offset by the greenhouse-gas net savings. In fact, the reduction in biomass combustion can save around 165 Mt of $CO2_{eq}$ from methane and nitrous oxide emissions, even without accounting for the reduced $CO2_{eq}$ emissions as these are assumed to be carbon neutral [4].

Chapter 3

Liberia Profile

Liberia is situated in West Africa, neighboring Sierra Leone on the northwest with a 299 km border, Guinea to the north with a total length of land border of 590 km, and Côte d'Ivoire in the east, with a land border of 778 km. On the southwest it is bordered by the North Atlantic Ocean, having 579 km of coastline [12]. Liberia has a tropical climate in the north and an equatorial climate in the south, with a wet season from May to October and a dry season from late October to April. Temperatures have little monthly variation, ranging from 27°C to 32°C during the day and from 21°C to 24°C at night. The main features of Liberia's topography are tropical rain forest, mountainous plateaus, coastal lagoons and mangrove marsh lands. Almost 49 percent of the territory is forest land, and the plateaus (27%) are dedicated to agriculture [13].

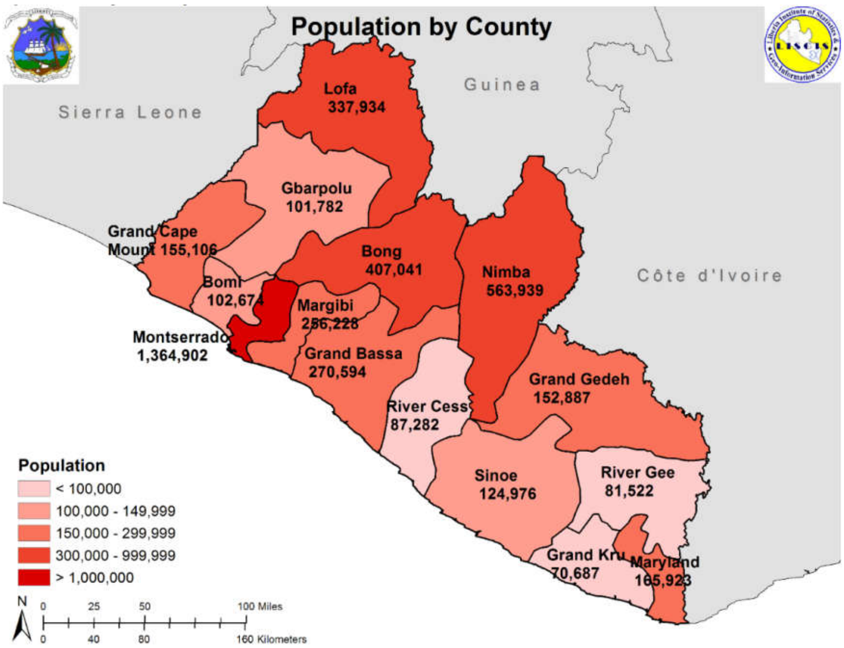


Figure 3.1: Map of Liberia and Population by County

Liberia is divided into fifteen counties (see Figure 3.1 [14]), which are subdivided into a total of 90 districts and further subdivided into clans. The population of Liberia is estimated to be just above 4.2

million with a total of about 990,966 households nationally. Overall, Liberia has a young population, with 44.5% of Liberians being under the age of 15 years [15]. The average household size is estimated to be 4.3 persons per household, however this average is slightly lower (4.2) when it concerns urban centers rather than rural areas [15].

Liberia is one of the most urbanized countries in the region, with roughly half of the population lives in urban areas, with about one-third in the capital city. This is partly the legacy of the civil war when the cities were comparatively safe and attracted internal refugees. The demography further is indicative of a lack of opportunities in the rural economy [16]. Monrovia is the business as well as political capital. Other urban areas of 5,000 or more persons in 2008 accounted 10% of the population while the remaining 61% was the rural population [14]. The education rate in Liberia is low, it is estimated that 64.7% of Liberians are literate, which only means that they are able to read and write [15]. Also regarding the heath system, the situation is still laborious. In the 30 days before a survey accomplished in 2015 by the Government of Liberia, 20.7% Liberians reported visiting a primary health care provider Government facilities, including clinics and hospitals, make up 63.2% of the total visits. Approximately 81.6% of Liberians that visited a health facility, were able to reach within less than 60 minutes and the most common mode of transport is by foot (59.4% of Liberians) [15].

Brief History of Liberia

Liberia was created through a settlement of freed slaves from the United States (US) in 1822 and by 1847 the American-Liberians were able to establish the Africa's oldest republic. In the World War II Liberia supplied rubber for the Allies as they had the world's largest rubber plantation. During this war the USA constructed military bases, airports and roads to the interior. After WWII, the USA government did much to promote foreign investment and to bridge the economic, social, and political gaps between the descendants of the original settlers and the inhabitants of the interior [12].

Between 1989 and 2003 Liberia was upset by two civil wars. During these conflicts, most of Liberia's infrastructures had been destroyed, food insecurity was widespread, poverty rates were high, and many people had been displaced. Indeed, this conflict had grave social, economic and environmental impacts and by the end of 2003, about a third of these people were still living as refugees in neighboring countries [12].

With the restoration of peace, Liberia faced a period of rapid economic growth, experiencing a GDP rate of 7.6% on average in the period of 2004-13, and its nominal GDP more than tripling during this period [12]. However, in 2014 and 2015 Liberia experienced an epidemic of Ebola Virus Disease. It is estimated that Liberia suffered 10,675 Ebola cases, 4,809 of which were fatal [17]. This virus was extremely hard to contain given the country's weak health system resulting from long civil wars. Ebola had a severe impact in the Liberian economy across all sectors of employment, it destroyed the small-scale traders, drove up food prices and led to food insecurity and produced a decrease in exports by 38% [12]. Due to this troubled and difficult past, Liberia is today one of the least developed and poor countries in the world.

Economy

Liberia remains among the five poorest countries worldwide. In 2004 Liberia was the most indebted country in the world. Before the Ebola crisis, Liberia showed robust economic growth of more than 8% but the Ebola entailed a severe economic shock [16]. Liberia relied heavily on foreign assistance, in the period 2003-2014 it was the second country which received the highest Official Development Aid (ODA) grants as percentage of GDP. This ODA grants were given as debt relief with a government debt of 715.2% of GDP [18].

The economy only moderately recovered in 2016. Liberia's nominal GDP was 2.015 billion USD, where 36% came from the agricultural sector, 16% from industry, and the remaining 48% from services [12]. Liberia has had a difficult economic path, nevertheless its projections for the future look prosperous according to the the International Monetary Fund (IMF) [19].

Currently about 2.2 million Liberians or 50.9% of the population is classified as poor. Poverty is higher in rural areas (71.6%) than in urban areas (31.5%) [15]. Nationally only 3.9% of the population is unemployed but , while this value is low, informal and vulnerable employment rates are very high, at 79.9% and 79.5% respectively [15]. The majority of rural population is employed in the agricultural sector. Agriculture, forestry and fishing are the most important activities in Liberia, particularly in rural areas. It is estimated that around 40% of Liberian wage employees receive a monthly salary between 6,000 and 15,000 Liberian Dollars [15]. In table 3.1 is shown the salary structure data collected by the World Bank [20]. It can be noticed that in urban areas, where wage employment is more common, the distribution of wages is more spread out than in rural areas and the amount is lower for female salaries. Nationally 67.5% of total spending is on food and 32.5% is on non-food, including estimated rent for those that own their homes and the estimated use value of household assets [15].

Table 3.1: Percentage distribution of monthly the salary structure in Liberia Dollars (LRD) and US Dollars (USD)

Range						
LRD	USD	National	Male	Female	Urban	Rural
1-1,999	1-12.9	3.0	2.6	4.6	2.1	4.9
2,000-3,499	13-22.6	9.4	8.0	14.5	7.3	13.8
3,500-5,999	22.7-38.8	13.7	11.7	20.7	12.8	15.6
6,000-9,999	38.9-64.7	22.4	23.6	18.3	22.9	21.4
10,000-14,999	64.8-97.0	18.0	18.3	17.0	17.5	19.1
15,000-19,999	97.1-129.4	10.3	11.1	7.4	9.9	11.0
20,000-29,999	129.5-194.1	9.6	10.1	8.1	10.3	8.2
30,000+	194.2+	13.5	14.7	9.4	17.1	6.1

3.1 Energy Situation

Liberia has one of the most underdeveloped energy sectors worldwide. While having one of the lowest rates of access to public electricity (13.8% in 2015), it has one of the highest per-unit costs of electricity (around 0.50 USD/kWh) [12]. Liberia is highly dependent on fuel imports – almost 77 million US gallons of petroleum products were imported in 2012, mostly for transportation, electricity generation and domestic lighting [13]. The absence of electricity access is one of the most considerable obstacles for the development of the Liberian energy sector and for the development of Liberia itself, since basic services such as health care, water and sanitation, education and telecommunications require access to electricity [12].

Before the civil war, more than 7% of the population had access to public electricity with a total installed capacity of 191 MW, of which approximately 98% were in and around Monrovia [13]. Liberian Energy Corporation (LEC), the national electricity utility, was responsible for the generation, transmission and distribution of electricity in Liberia. With the destruction of most of the generation facilities during the war, including the Mount Coffee hydropower plant (63 MW during the wet season), as well as of the transmission and distribution lines, LEC had to temporarily stop the operations [12]. Its recovery started with an emergency program, which supported the construction of a small grid with high-speed diesel generators totaling 9.6 MW of installed capacity, This emergency program was financed by several external institutions – the European Union, United States Agency for International Development (USAID), the Norwegian Agency for Development Cooperation (NORAD) and The World Bank Group [12]. External funding was and is helping the development Liberian energy sector, including LEC's development. The utility had inefficient and poorly engineered distribution, causing high technical losses, inadequate billing and collection systems and was also plagued with power theft. The poor quality of the generation and distribution was translated in frequent and lengthy outages. These factors, along with the high-cost Diesel as the only source of power, the lack of financing for new connections and the consequently high tariffs constrained LEC's ability to increase its customers and fully utilize all generation capacity. The main bottlenecks to an efficient and sustainable development of a national electricity system are the lack of infrastructure for transmission and distribution; and an electricity utility in a precarious financial and technical situation, with an area of service limited to Monrovia.

In 2015 when the project was realized, only about 13.9% of Liberia's total population had access to electricity, of which 79% were in the urban areas and the remaining 21% in rural areas [14]. This value increased to a value of 19.8% in 2016, which still makes Liberia one of the country with the lowest access to electricity [2]. Most households are largely dependent on traditional energy sources such as firewood and charcoal for cooking and heating and candles, battery-powered lights and kerosene for lighting. 82.3% of the households have no access to electricity, the value is even higher in the rural areas (96.9%). The Liberian Electricity Corporation electrifies 15.5% of urban households. In these areas, approximately 14.2% of households obtain electricity from generators (both owned and community sources), while only 1.8% of rural households have access to these options [15]. The percent distribution of main sources of electricity can be noticed in table 3.2 [15].

Table 3.2: Percent distribution of main sources of electricity for the households by location

	Liberia	Urban	Rural
None	82.3	68.8	96.9
Community Generator	5.5	9.9	0.6
Own Generator	2.8	4.3	1.2
Power Supplier (LEC)	8.1	15.5	0.1
Other Sources	1.4	1.5	1.3

3.1.1 Energy Potential

Solar Energy

The humid, tropical climate in Liberia shows relatively constant temperatures throughout the year, around the average of 27°C, hardly ever outside the range of 20°C to 36°C. In Liberia, monthly solar irradiation on horizontal surface ranges from about 4 kWh/m2/day during the rainy season in June, July, August to 6 kWh/m2/day during the height of dry season in February and March. This high and consistent irradiation across the country adds to an average level of 1,712 $kWh/m^2/year$ [21] and gives Liberia a great potential for solar energy. In figure 3.2 is shown the global horizontal irradiation of Liberia from the data collected by Solargis [22] for the World Bank.

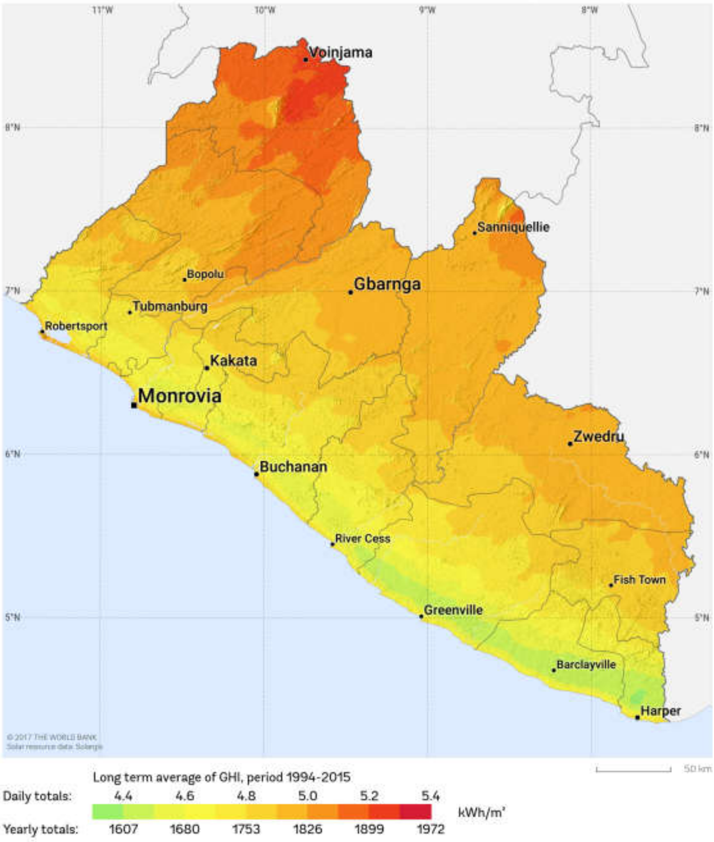


Figure 3.2: Liberia Global Horizontal Irradiation

Hydropower Energy

Liberia has a rainy season between April and November, various rivers and a long sea coast. Yearly rainfall is around 510 cm on the coast, 200 cm inland. Average relative humidity is about 82% in the coastal area during the rainy season, and 78% to 50% in the dry season. According to the Rural Energy Strategy and Masterplan, a hydropower potential of 2,300 MW has been identified in Liberia. This potential is mainly on large rivers with high mean annual flow and low heads. However, the potential varies largely between rainy season and dry season [21].

Biomass Energy

43% of Liberia's territory is covered with forests (41,790 square kilometers) [2], but the Forest Development Authority (FDA) has the exclusive rights to manage forest resources and focuses on large-scale concessions for timber extraction. The US national Renewable Energy Laboratory (NREL) studied biomass resources other than forestry with a view on how these resources could be used for energy purposes. They estimated a potential annual waste stream from logging operations of 20 million m^3 available (162,645 TJ/year) [23]. Moreover, NREL estimates that only 6% of the total cropland in Liberia is currently cultivated, which indicates that in addition to existing resources, there is a large potential for new crops including tree crops that could yield resources suitable for charcoal production [23].

Wind Energy

The potential for wind energy in Liberia is estimated to be relatively low. Although there might be some potential in coastal and mountainous regions, probably not enough for commercial exploitation. According to the 2015 SE4All Action Agenda Report, the wind generation in Liberia is projected to reach 0.47 GWh in 2025 [14]. However, there is no assessment for wind energy or any recommendation to use wind energy in the Liberia Rural Energy Strategy and Master Plan.

3.2 Institutional Landscape

3.2.1 Main Players in Liberia Energy Sector

The **Ministry of Lands, Mines and Energy (MLME)**, especially the **Department of Energy (DoE)**, is responsible to plan, formulate and strengthen energy policies, regulatory frameworks and institutional strategies, to create a conducive environment for delivery of electricity and rural electrification.

The **Liberia Electricity Corporation (LEC)**, a utility financed by various multilateral and bilateral donor agencies, plans to broaden energy transmission and distribution to function through corridors over the country.

The **Rural and Renewable Energy Agency (RREA)**, is an autonomous agency reporting to the president mandated to commercially develop and provide modern energy services to rural Liberia with emphasis on utilizing available local renewable energy resources. The RREA's mandate includes integrating energy into rural development planning, promotion of renewable energy technologies, facilitating delivery of energy products and services and facilitating the funding of rural energy projects including managing a Rural Energy Fund (REFUND) for sustainable energy services financing, coordinating domestic and international financial resources.

3.2.2 National Policies and Commitments

In 2007 the Government of Liberia (GoL) published a Renewable Energy and Energy Efficiency Policy and Action Plan. In this document the government outlines its policy to build and increase the application of renewable energy and energy efficiency technologies in Liberia by promoting investment, technology transfer, market development and local capacity building. The Government, through the Ministry of Lands, Mines and Energy (MLME) adopted its energy strategy and relevant targets in the **National Energy Policy for Liberia (NEPL)** in 2009. The principal objective of the NEPL is to ensure universal access to modern energy services in an affordable, sustainable and environmentally-friendly manner. This is to be achieved by good governance and ensuring financial transparency in all sector transactions, overcoming the significant obstacles to private sector investment in energy supply and creating the requisite institutional, the legal framework and an independent regulatory regime [21].

Liberia is committed to making progress with the United Nations (UN) **Sustainable Energy for all (SE4ALL) Initiative**, and the **Sustainable Development Goals (SDGs)**. SE4All is an initiative which aims to transform the world's energy systems in order to build a more prosperous, healthier, cleaner and safer world. The initiative was launched in 2011, by the UN Secretary-General Ban Ki-Moon, who shared his vision for making sustainable energy for all a reality by 2030 [14]. The commitment of the government of Liberia to SE4ALL Action Agenda has been developed with the backdrop of the country's overall development objectives of the National Energy Policy of Liberia (NEPL) [21].

Moreover, Liberia has the **Vision "Liberia RISING 2030"** aiming for Liberia to become a Middle Income Country by the year 2030. This vision includes and proposes the targets of having 70% of Monrovia be connected to the electricity grid and 35% of the rural areas of Liberia connected to mini-grids, stand-alone units by 2030 [21].

The Sustainable Energy for all (SE4ALL) Initiative foresaw a scenario for the grid connected electric power installed capacity for 2030. The national access to electricity in percent of the population is shown on table 3.3 [14]. Liberia is expected to raise its 2010 access of 1.4% of the population having access to electricity to 34.2% by 2020, and reach the universal access (100%) of the population on or before the target year 2030.

Table 3.3: Electricity access target in % of the population

	2010	2020	2030
Share of Population with Electricity Access	1.4%	34.2%	100%

According to this scenario the RE share is expected to constitute 43% and 23% of the total electricity capacity for the years 2020 and 2030 respectively. (shown in table 3.4 [14]) Total Grid Connected Electric Power Installed Capacity for 2010 was expected to be 22 MW and is targeted to rise to about 178 MW in 2020 and 659 MW in 2030 [14].

3.3 Rural Energy Strategy and Master Plan For Liberia (RESMP)

In 2016, the **Rural Energy Strategy and Master Plan For Liberia (RESMP)** was presented and published by the Rural and Renewable Energy Agency. The RESMP aims to achieve the GoL's rural elec-

Table 3.4: Target for grid connected installed capacity and RE share

Installed Capacity (MW)	2010	2020	2030
Fossil Fuel Generation	17.42	101.86	510.53
Small Hydropower	4.57	4.57	4.57
Large and Medium Scale Hydropower	0	45.63	91.25
Other Renewables (Excluding Hydro)	0	26.35	52.71
Total RE Capacity	**4.57**	**76.55**	**148.53**
Total Installed Capacity	**21.99**	**178.41**	**659.06**
RE Share of the Installed Capacity	*21%*	*43%*	*23%*

trification access rate of 35% by 2030, benefitting about 1.3 million people [21]. The importance of this plan compared to the SE4All is that this document was developed and accepted by the Government of Liberia, while the first one was only the UN development scenario.
The RESM includes ambitious targets for the period until 2030:

- Electrification rate for the population outside of Monrovia of 10% in 2020, 20% in 2025 and 35% in 2030.
- All county capitals, health facilities and secondary schools electrified already before 2025.
- More than 75% of all electricity generated from renewables by 2030 with 19% coming from other than large hydro (small hydro, solar and biomass).
- Universal access to affordable solar lamps, efficient appliances and cook stoves.
- Electrification of at least 2,000 settlements with grid infrastructure connecting at least 50% of those settlement's population by 2030.
- The ten largest settlements in every county electrified with no county having less than 15% electrification rate by 2030.
- A credit/subsidy mechanism for connection of poor and woman-led households through Rural Energy Fund, promoting active participation of women in the jobs that will be created for electrifying the country.

The Rural Energy Strategy and Master Plan For Liberia identifies 92 projects and investments to electrify 265,000 homes outside Monrovia until 2030 [12]. The action plan and rural energy projects are structured under 5 main programs, also shown in figure 3.3 [21]:

1. **(GTG) Growing the Grid Program:** expanding the medium voltage grid from the three planned corridors outside of Monrovia and from new corridors connecting the neighbors countries representing a total investment of USD 308M and the electrification of 164,300 homes. Additionally, GTG includes additional USD 242M investment in on-grid renewable generation to be installed outside Monrovia.
2. **(DG) Decentralized Grids Program:** building large decentralized grids supported by renewable generation, cross border interconnections and Medium Voltage grids guaranteeing the electrification of the 10 largest settlements in each County, if not under GTG program, than through the

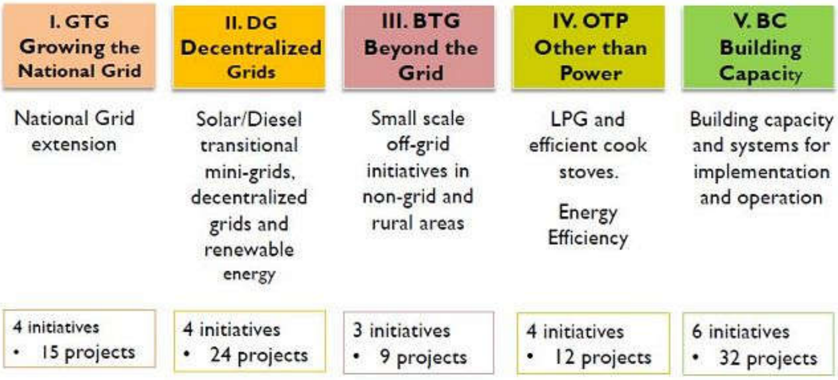


Figure 3.3: Rural Energy Strategy and Master Plan For Liberia (RESMP) Program

development of transitional solar/diesel low voltage mini-grids. Represents a total investment of USD 292M and the electrification of 96,800 homes.

3. **(BTG) Beyond the Grid Program:** electrifying community services, households and public buildings where the grid is not expected before 2025 through 100% solar based off-grid solutions, prioritizing health, education and security. Electrifying 75 future off-grid settlements in an equitable way across counties mainly through Solar Home Systems (SHS) while promoting the sale and rental of solar portable lamps or smaller Solar Home Systems across the country. Represents a total investment of USD 16M and the electrification of 4,000 homes.

4. **(OTP) Other than Power Program:** promoting efficiency in buildings, appliances and cooking. Developing Liquefied Petroleum Gas (LPG) storage and filling infra-structure while promoting availability of cooking gas in all county capitals. Promoting efficient charcoal production and efficient cook stoves requires a total investment of USD 24M.

5. **(BC) Building capacity:** creating the capacity, the institutional framework, the organization, the information and management systems and the infrastructure to implement the Master Plan requires a total investment of USD 52M.

3.3.1 Main Barriers For Development of Rural Energy

An audit was developed in the framework of the Development of the Rural Energy Master Plan for Liberia. Goal of this audit was to enlighten the key representatives of the power sector during the development of the RESMP across all Liberian counties aiming to assess beliefs and expectations regarding rural electrification [12]. Several main barriers to the underdevelopment of the power sector in Liberia were detected:

- **Absence of Funding.** Liberia's power sector is seriously underdeveloped and thus extremely high capital expenses are needed in order to build the necessary infrastructures for transmission and distribution.

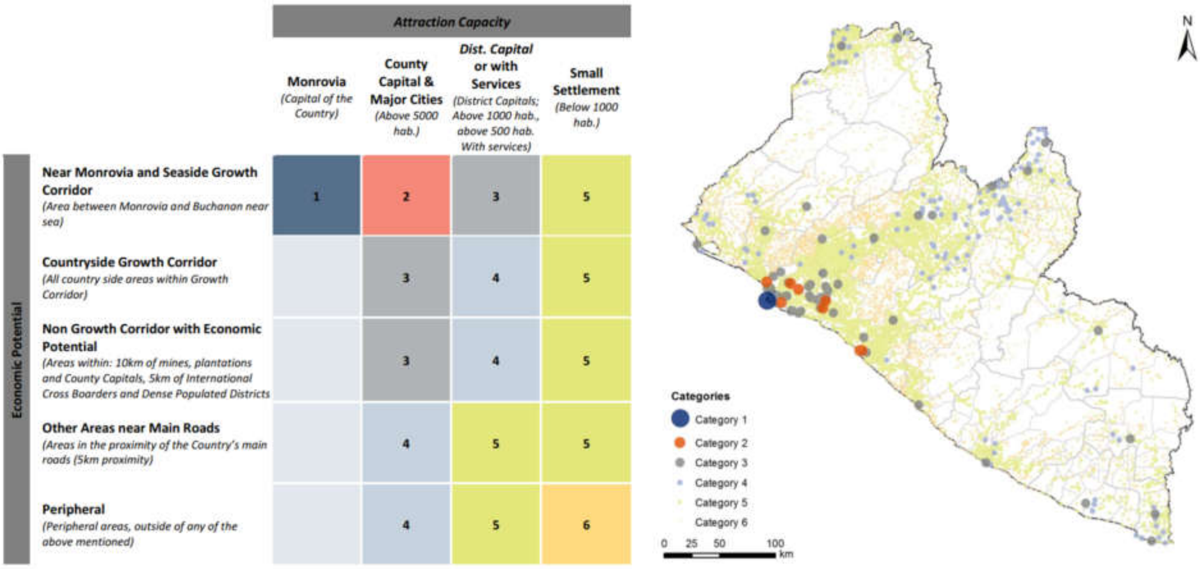
- **Lack of Political Support.** It is the government's responsibility to allocate the funding available to the several sectors. Many respondents appointed that a barrier to electrification was the exclusion of government's priorities, thus indicating that this sector has a lack of political support which challenges its expansion.
- **Lack of Transparency and Accountability.** The monopolistic nature of grid-based electricity, which is the main means of delivery, presents opportunities for rent seeking and can lead to inefficient services, under-investment and poor maintenance of infrastructure.
- **Lack of Human Capital and Technical Capacity.** Having the funds and resources to pay for large-scale projects like electrification is essential, but without the skilled labor and technical capacity it is impossible to develop and maintain them.
- **Limited private sector investment.** The amount of funding needed to invest in the power sector cannot be financed by the public purse alone. Moreover private sector participation can bring a more competitive environment, which can help to boost both the coverage and efficiency of infrastructure services.
- **Need to raise awareness and provide affordable options for electrification thus granting the adoption of the population.** It is extremely important to raise awareness to the benefits of electrification to the population while adapting these options to their customs and life. Furthermore, this utility also needs to be affordable for the population. Addressing issues such as gender sensibility is also necessary in order to ensure that these new options are welcome by everyone and that enable an equitable growth.
- **Electricity theft which undermines the power sector's sustainability.** In order to ensure the sustainability of the sector of for it the keep developing, there is a need to mitigate factors such as electricity theft.

3.3.2 Household Demand Estimation and Willingness to Pay

In the Rural Energy Strategy and Master Plan For Liberia (RESMP) a classification of the different areas of the country was developed in order to differentiate the development and ultimately the electric consumption between different regions. The data used for this task was a GIS database gathered by the Rural and Renewable Energy Agency (RREA), which was accomplished for the 2008 National population and housing census [24].

In order to differentiate the regions of the country, two factors were taken into account to categorize all settlements: the economic potential of the area in which a given settlement is in, and the population and business attraction capacity a settlement may have. The combination of these factors in a class matrix allowed to categorize each one of the country's population communities in six different categories. In figure 3.4 is shown the class matrix and the distribution of the different categories [12].

In order to estimate the household demand and willingness to pay for each one of the six defined



Economic Potential	Attraction Capacity: **Monrovia** *(Capital of the Country)*	**County Capital & Major Cities** *(Above 5000 hab.)*	**Dist. Capital or with Services** *(District Capitals; Above 1000 hab., above 500 hab. With services)*	**Small Settlement** *(Below 1000 hab.)*
Near Monrovia and Seaside Growth Corridor *(Area between Monrovia and Buchanan near sea)*	1	2	3	5
Countryside Growth Corridor *(All country side areas within Growth Corridor)*		3	4	5
Non Growth Corridor with Economic Potential *(Areas within: 10km of mines, plantations and County Capitals, 5km of International Cross Boarders and Dense Populated Districts*		3	4	5
Other Areas near Main Roads *(Areas in the proximity of the Country's main roads (5km proximity)*		4	5	5
Peripheral *(Peripheral areas, outside of any of the above mentioned)*		4	5	6

Figure 3.4: Settlement's demand class matrix (left) and categories distribution (right)

categories, the 2012 Liberia and Energy Access: A Willingness to Pay Analysis report of the World Bank was used in the RESMP [25]. In table 3.5 are shown the monthly household energy expenditures per demand category [12]. The previous tariffs of Liberia were very high (around 50 USD cent/kWh) and they were not considered in the evaluation. This because the tariffs were expected to drop thanks to new, less expensive and more efficient generation technologies(e.g.large hydropower) and because it would had excessively repress electrical consumption [12]. It can be noticed that, a part the category 1 (Monrovia) which was not considered in the study since it is focused on rural areas, the tariffs applied corresponds to a price of electricity of 0.25 USD/kWh, 50% lower that the previous national tariffs.

Table 3.5: Household electricity consumption per demand category

Consumption Category	Monthly Electricity Expenditures (USD/Month)	Monthly Electricity Consumption (kWh/month)
Category 1 (Monrovia)	-	-
Category 2	23.36	93.4
Category 3	18.06	72.2
Category 4	10.02	40.1
Category 5	7.88	31.5
Category 6	5.71	22.8

Chapter 4

Description of the Case Study

The case study described in this work is a project called “Light up Our Futures through Renewable Energy Facility for Rural Isolated Communities in Lofa” in 5 communities. This project was led by the NGO Plan International Liberia and founded by the European Development Fund (EDF). Plan International is an independent development and humanitarian organization which works in 71 countries across the world, in Africa, the Americas and Asia to advance children’s rights and equality for girls. Plan International delegated the feasibility study and the design of the project to the engineering company Trama TechnoAmbiental (TTA). TTA is a global consulting and engineering company with headquarters in Barcelona, fully committed to a sustainable energy development, TTA has been providing specialized services in distributed generation through renewable energies and rural electrification. The installation of the project was then achived by Sunlabob Renewable Energy, a Laos-based company specializing in renewable energy and clean water solutions throughout the developing world.
The overall objective of the project is to contribute to poverty reduction in rural communities in Liberia through the installation of five micro-grid for five small rural communities in Lofa county, Liberia.

Figure 4.1: Location and pictures of the villages

Lofa County lies in the north western corner of the country. It is bounded on the north by the Republic of Guinea, on the west by Sierra Leone and the south by Gbarpolu and Bong Counties and it is the third largest county in Liberia [26]. The capital of Lofa County is Voinjama, which is approximately 12 hours drive from Liberia's capital Monrovia. The five villages, Koyama, Lengbamah, Mamikonedu, Nyengbelahun and Taninahum, are distributed in four different districts of the county: Voinjama, Quandu Gboni, Kolahun and Foya. Their location are shown in figure 4.1. The climate in Lofa is tropical, hot and humid. The temperature normally ranges annually from 24 degrees Celsius to 30 degrees Celsius, with high solar irradiation and an average rainfall of around 290 centimeters [26].

Table 4.1: Daily Demand Classification

User	Tariff Type	Daily Demand (Wh/day)	Max Power (kW)	Material	Units
Residential	T01	275	0.5	Socket	1
				Lamp-holder E27 Strip	1
				Lamp-holder E27	0
				Lamp-holder E27 wall	1
				Switch	1
				LED 14W 800 lumens	1
				LED 5W 300 lumens	1
Residential	T11	550	0.5	Socket	2
				Lamp-holder E27 Strip	1
				Lamp-holder E27	1
				Lamp-holder E27 wall	1
				Switch	2
				LED 14W 800 lumens	2
				LED 5W 300 lumens	1
Residential/ Small Commercial	T21	1100	0.5	Socket	2
				Lamp-holder E27 Strip	1
				Lamp-holder E27	1
				Lamp-holder E27 wall	1
				Switch	2
				LED 14W 800 lumens	2
				LED 5W 300 lumens	1
Small Commercial/ Clinic	T32	1650	1	Socket	2
				Lamp-holder E27 Strip	1
				Lamp-holder E27	1
				Lamp-holder E27 wall	1
				Switch	2
				LED 14W 800 lumens	2
				LED 5W 300 lumens	1
Big Residential	T42	2200	1	Socket	4
				Lamp-holder E27 Strip	0
				Lamp-holder E27	2
				Lamp-holder E27 wall	2
				Switch	3
				LED 14W 800 lumens	4
				LED 5W 300 lumens	1
Schools	T52	2750	1	Socket	2
				Lamp-holder E27 Strip	0
				Lamp-holder E27	2
				Lamp-holder E27 wall	2
				Switch	3
				LED 14W 800 lumens	3
				LED 5W 300 lumens	1
Mills	T62	3300	1	Socket	2
				Lamp-holder E27 Strip	0
				Lamp-holder E27	2
				Lamp-holder E27 wall	0
				Switch	1
				LED 14W 800 lumens	2
				LED 5W 300 lumens	0
Chicken Farm	T82	4400	1	Socket	4
				Lamp-holder E27 Strip	0
				Lamp-holder E27	2
				Lamp-holder E27 wall	0
				Switch	1
				LED 14W 800 lumens	4
				LED 5W 300 lumens	0
Water Pumping	T162	8800	1	Socket	1
				Lamp-holder E27 Strip	0
				Lamp-holder E27	0
				Lamp-holder E27 wall	0
				Switch	0
				LED 14W 800 lumens	1
				LED 5W 300 lumens	0

The villages are in isolated location and connected only through unpaved roads, therefore the connection to the grid is not an available option. 8,412 inhabitants live in the five rural communities and their economy is mainly based on agriculture, with some small scale commercial activities. Five schools, several small health clinics, mills and water pumping systems are present in the villages. Survey and assessment were carried out at each house and community buildings to identify the electricity demand. Different tariff types were then defined in order to classified the daily demand of the facilities. This classification and the daily demand of each village are shown in table 4.1. The facilities are divided in 9 different classes, depending on the energy and power demand. The classes can be gather in three main groups: residential and small commercial (T01, T11 and T21) with the lowest energy demand (lower than 1.1 kWh/day) and a maximum power of 0.5 kW; small commercial, clinic, big residential and schools (T32, T42, T52,) with a middle range consumption of 1.65-2.75 kWh/day; high consumption services and activity, like mills, chicken farms and water pumps (T62, T82, T162) within a range of 3.3-8.8 kWh/day. The scope of the projects is to provide the basic electricity need essential to contribute to poverty reduction. All the buildings are therefore designed to be supplied with the basic electrical needs, such as illumination and sockets for additional electrical devices. Part of the supplied material were two types of LED lights,5 and 14W, that could be mounted in three different setting (regular, strips and on the wall), switches and electric sockets (see table 4.1).

4.1 Koiyama

Koiyama is located in Lofa district and is the closest site to the county's capital, Voinjama. It takes about two hours of driving on a dirt road from Voinjama to the village, which is only accessible by four-wheel-drive pickup truck (e.g. figure 4.1). The main sources of income for the villagers are agriculture and farming, with some small commercial activities. 96 building have to be electrically powered, 77 of these are small households (category T01, T11 and T21) with a consumption lower that 1.1 kWh/day and 12 are small commercial activities. The village has also one church, one school and three mills. The most power consuming facility is the water pump, which requires 8.8 kWh/day. The total energy demand of the village has been estimated from the energy consumption of each building and considering an utilization ratio of the grid of 80% and a future growth of the demand of 15%. In this way a design daily energy demand of 66.79 kWh/day is assumed for the Koiyama village. With its attraction capacity and economical potential Koiyama falls within the category 5 of the settlements' classification (see section 3.3.2 and figure 3.4). In table 4.2 the characteristics of the village and the user demand are illustrated, whereas in figure 4.2 the map of Koiyama is shown.

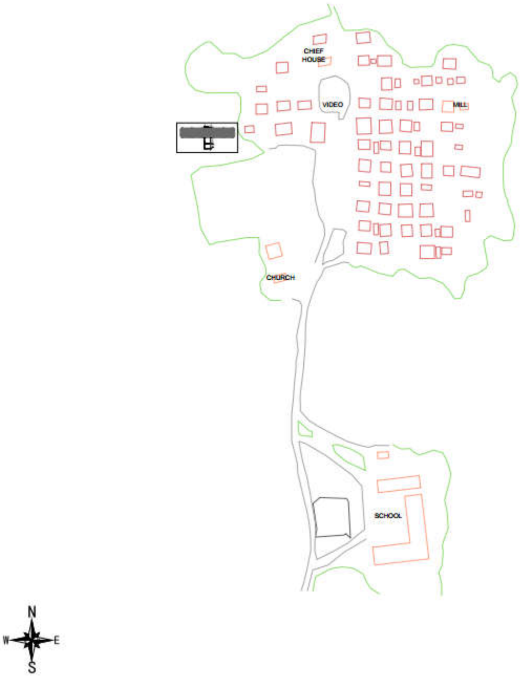
4.2 Lengbamah

Lengbamah is located in Foya District, about 84km far from Voinjama. It takes 10 hours drive on a dirt road from the County's capital to the village, which is only accessible by four-wheel-drive pickup truck (e.g. figure 4.1). Lengbamah is the biggest of the 5 villages to be electrified. The main sources of income are agriculture and farming, but few commercial activities are present. In fact, of the 156 connections needed, 136 are small households (category T01, T11 and T21) with a consumption lower

Table 4.2: Koiyama demand classification

KOIYAMA	
General Characteristics	
Number of Connections	96
Street lighting	LED lamps
Daily Demand	66.79 kWh/day
Future Demand Growth	15%
Utilization Ratio	80%
Design Daily Demand	72.69 kWh/day
Peak Power	7.4 kW
User Demand Survey	
Tariff Type	**No. of Connection**
T01	50
T11	26
T21	1
T32	12
T42	1
T52	1
T62	3
T82	0
T162	1

Figure 4.2: Koiyama map



that 1.1 kWh/day and 15 are commercial activities (T32 and T42). The village has 4 churches, both a clinic and a nurse, several shops and 3 different mills. One common water pumping system supplies the entire village. The total energy demand of the village has been estimated from the energy consumption of each building and considering an utilization ratio of the grid of 80% and a future growth of the demand of 15%. In this way a design daily energy demand of 111.1 kWh/day is assumed for the Lengbamah village. With its attraction capacity and economical potential Lengbamah falls within the category 5 of the settlements' classification (see section 3.3.2 and figure 3.4). In table 4.3 the characteristics of the village and the user demand are illustrated, whereas in figure 4.3 the map of Lengbamah is shown.

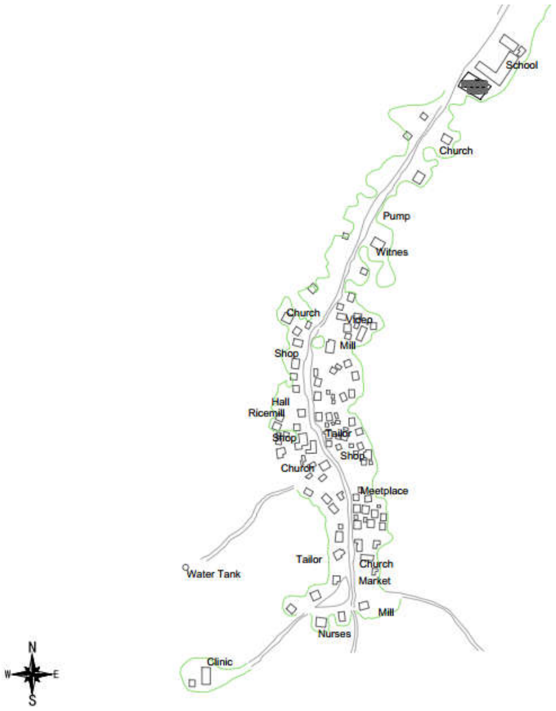
4.3 Mamikonedu

Mamikonedu is located in Quardu-Gboni District, about 20km far from Voinjama. Also in this case, the only available road is unpaved and accessible only by four-wheel-drive pickup truck. Mamikonedu is the second biggest village to be electrified. The main sources of income are agriculture and farming, but few commercial activities are present. 143 connections are needed, 136 are small households (category T01, T11 and T21) with a consumption lower that 1.1 kWh/day and 14 are commercial activities (T32 and T42). The village has several churches and shops, a clinic and a school, one water pump system and one mill. It is also present a chicken farm which is one of the most consuming building of the village. Despite the high number of connection, Mamikonedu's building have a low energy consumption. In fact, the total daily energy demand of the village, considering an utilization ratio of the grid of 80% and a future growth of the demand of 15%, is only 88.2 kWh/day. With its attraction capacity and economical

Table 4.3: Lengbamah demand classification

LENGBAMAH	
General Characteristics	
Number of Connections	156
Street lighting	LED lamps
Daily Demand	111.1 kWh/day
Future Demand Growth	15%
Utilization Ratio	80%
Design Daily Demand	102.2 kWh/day
Peak Power	11.3 kW
User Demand Survey	
Tariff Type	**No. of Connection**
T01	80
T11	46
T21	10
T32	3
T42	12
T52	1
T62	3
T82	0
T162	1

Figure 4.3: Lengbamah map



potential Mamikonedu falls within the category 5 of the settlements' classification (see section 3.3.2 and figure 3.4). In table 4.4 the characteristics of the village and the user demand are illustrated, whereas in figure 4.4 the map of Mamikonedun is shown.

Table 4.4: Mamikonedu demand classification

MAMIKONEDU	
General Characteristics	
Number of Connections	143
Street lighting	LED lamps
Daily Demand	88.2 kWh/day
Future Demand Growth	15%
Utilization Ratio	80%
Design Daily Demand	81.2 kWh/day
Peak Power	9 kW
User Demand Survey	
Tariff Type	**No. of Connection**
T01	81
T11	41
T21	4
T32	14
T42	0
T52	1
T62	0
T82	1
T162	1

Figure 4.4: Mamikonedu map

4.4 Nyengbelahun

Nyengbelahun is located in Kolahun District District District, about 60km far from Voinjama through a dirty road. Nyengbelahun is the smallest village to be electrified. The village economy is mainly based on agriculture and chicken farming. 64 connections are needed, 55 of wich are households (category T01, T11 and T21) and only 5 are commercial activities (T32). The most energy demanding building are the water pumping system and two chicken farms. Therefore, the total daily energy demand of the village is quite low. Considering an utilization ratio of the grid of 80% and a future growth of the demand of 15%, it is equal to 88.2 kWh/day. With its attraction capacity and economical potential Nyengbelahun falls within the category 5 of the settlements' classification (see section 3.3.2 and figure 3.4). In table 4.5 the characteristics of the village and the user demand are illustrated, whereas in figure 4.5 the map of Nyengbelahun is shown.

Table 4.5: Nyengbelahun demand classification

NYENGBELAHUN	
General Characteristics	
Number of Connections	64
Street lighting	LED lamps
Daily Demand	50.3 kWh/day
Future Demand Growth	15%
Utilization Ratio	80%
Design Daily Demand	46.2 kWh/day
Peak Power	5.1 kW
User Demand Survey	
Tariff Type	**No. of Connection**
T01	33
T11	21
T21	1
T32	5
T42	0
T52	1
T62	0
T82	2
T162	1

Figure 4.5: Nyengbelahun map

4.5 Taninahum

Taninahum is also located in Kolahun district, 36km far form the county's capital. Taninahum has realtively high energy demanding buildings. In fact, 101 facilites have to be connected, only 63 of these are small households (category T01, T11 and T21) whereas 33 are commercial activities and big buildings (T32 and T42). Moreover, the village has also a church, one school, three mills and a water pump. The total daily energy demand of the village, estimated from the energy consumption of each building and considering an utilization ratio of the grid of 80% and a future growth of the demand of 15%, is equal to 72.69 kWh/day.

Table 4.6: Taninahum demand classification

TANINAHUM	
General Characteristics	
Number of Connections	101
Street lighting	LED lamps
Daily Demand	102 kWh/day
Future Demand Growth	15%
Utilization Ratio	80%
Design Daily Demand	93.8 kWh/day
Peak Power	10.4 kW
User Demand Survey	
Tariff Type	**No. of Connection**
T01	39
T11	23
T21	1
T32	30
T42	3
T52	1
T62	3
T82	0
T162	1

Figure 4.6: Taninahum map

With its attraction capacity and economical potential Taninahun falls within the category 5 of the settlements' classification (see section 3.3.2 and figure 3.4). In table 4.6 the characteristics of the village and the user demand are illustrated, whereas in figure 4.6 the map of Taninahum is shown.

Finally, the total daily demand for each village is summarized in table 4.7.

Table 4.7: Total Demand Classification

User	**Tariff Type**	**Daily Energy Demand [Wh/day]**	**Koiyama**	**Lengbamah**	**Mamikonedu**	**Nyengbelahun**	**Taninahum**
Residential	T01	275	50	80	81	33	39
Residential	T11	550	26	46	41	21	23
Residential/Small Commercial	T21	1100	1	10	4	1	1
Small Commercial/Clinic	T32	1650	12	3	14	5	30
Big Residential	T42	2200	1	12	0	0	3
Schools	T52	2750	1	1	1	1	1
Mills	T62	3300	3	3	0	0	3
Chicken Farm	T82	4400	0	0	1	2	0
Water Pumping	T162	8800	1	1	1	1	1
Number of Connection			96	156	143	64	101
Total Daily Demand [kWh]			66.79	102.2	81.2	46.2	93.8
Peak Power [kW]			7.4	11.3	9	5.1	10.4

Chapter 5

Design of the Systems

In this chapter the design of the system is illustrated. First an optimization of the 5 systems is performed using the software HOMER, in order to find the optimal size for each village. Then the design commissioned by Plan International to Trama Tecno Ambiental (TTA) [27], is illustrated and finally simulations with HOMER are accomplished to predict the performance of these designs.
Due to the high availability of solar resources, a solar based hybrid renewable energy system (HRES) have been designed for this project. A HRES is a system combing two or more energy sources, operated jointly, including a storage unit and connected to a local AC distribution network (mini-grid). During the day, when the sun is shining, the photovoltaic modules generate electricity that directly powers appliances or can be stored in a battery bank. At night or during days without sunshine the stored energy can be used. The supplementary generator makes the system reliable, offering the possibility of producing power at any time.

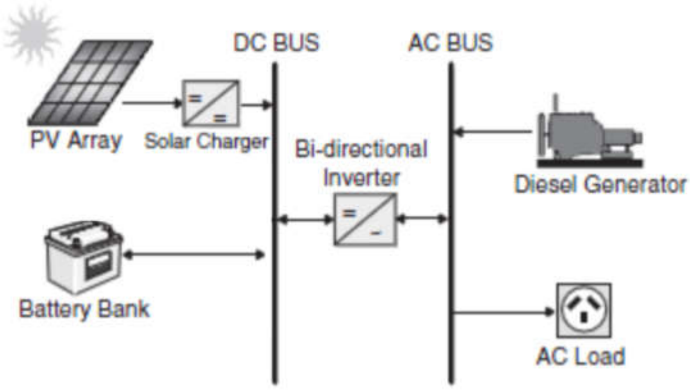


Figure 5.1: System configuration

In figure 5.1 is shown the configuration of the system. The photovoltaic array is connected to the DC bus through a MPPT charge controller. The solar charge controller manages the power going into the battery bank from the solar array. It ensures that the deep cycle batteries are not overcharged during the day and that the power does not run backwards to the solar panels overnight and drain the batteries. Moreover, the solar charger uses a MPPT technology, which stands for “Maximum Power Point Tracking”. This technology constantly monitors the voltage and current output of the PV panels in order to ensure the maximum power output working point. A storage system is a key component in stand-alone renewable energy systems, in fact the intermittence of supply from the solar resource demands the presence of an energy storage in order to improve the reliability of the system. The battery bank in this design is composed by deep cycle lead-acid batteries, which are capable of surviving prolonged, repeated and deep discharges which are typical in renewable energy systems that are off grid. To maintain healthy batteries and prolong battery life, most manufacturers suggest limiting the depth of discharge (DoD) to about 50%. The coupling between the DC and AC bus is achieved by a bidirectional inverter. This device can convert DC power from the modules and the batteries to usable AC power and also convert AC power from the diesel generator to charge the storage system. Finally, a Diesel generator is connected to the AC bus and can supply the load in case of peak demand or solar energy shortage and can assure a correct charging/discharging cycle of the batteries.

5.1 HOMER Optimization

The systems for the 5 villages have been modelled with a software in order to find the optimal sizes of the configurations. The software used for the simulation is HOMER (Hybrid Optimization Model for Multiple Energy Resources), a micro-grid optimization software developed by Homer Energy for the National Renewable Energy Laboratory (NREL) [28].

HOMER simulates the operation of a system by making energy balance calculations in each time step of the year. For each time step, HOMER compares the electric and thermal demand in that time step to the energy that the system can supply in that time step and calculates the flows of energy to and from each component of the system. For systems that include batteries or fuel generators, HOMER also decides in each time step how to operate the generators and whether to charge or discharge the batteries. HOMER performs these energy balance calculations for each system configuration considered. It then determines whether a configuration is feasible, if it can therefore meet the electric demand under the specified conditions and estimates the cost of installing and operating the system over the lifetime of the project. After simulating all of the possible system configurations, Homer displays a list of configurations, sorted by net present cost (NPC), that can be used to compare system design options. In the optimization process, HOMER determines the best possible system configuration by optimizing user defined mix of components that the system should comprise which is, size and quantity of each component and the dispatch strategy the system must use [29].

The total net present cost (NPC) of a system is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, O&M (Operation and Maintenance) costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue. HOMER calculates the total NPC by summing the total discounted cash flows in each year of the project lifetime. The present value of the cash flow that occurs in any year of the project lifetime are calculated through the discount factor. HOMER calculates the discount factor using the following equation:

$$f_d = \frac{1}{(1+i)^N} \tag{5.1}$$

where:

i = Real discount rate [%]

N = Number of years

The real discount rate is used to convert between one-time costs and annualized costs. HOMER calculates the annual real discount rate (also called the real interest rate or interest rate) from the nominal discount rate and expected inflation rate inputs in the following way:

$$i = \frac{i' - f}{1 + f} \tag{5.2}$$

where:

i'= Nominal discount rate = the rate at which the money are borrowed

f= Expected inflation rate

For an HOMER optimization, a micro-power system must comprise at least one source of electrical or thermal energy (such as a wind turbine, a diesel generator, a boiler or the grid) and at least one destination for that energy (an electrical or thermal load, or the ability to sell electricity to the grid). It may also comprise conversion devices like an AC–DC converter or an electrolyzer, and energy storage devices like a battery bank or a hydrogen storage tank. Therefore, to perform the simulations, different inputs must be supply to the software in order to model the villages' systems. The three main categories of inputs that must be provided are the load profile of the village, the local natural resources (solar, wind, temperature) and the designed components.

5.1.1 Load Profile

The load profile is the electrical demand that the power system must meet at a specific time. The electrical load has to be supply to the software in kilowatts for each hour of the year, either by importing a file containing hourly data or by allowing HOMER to synthesize hourly data from average daily load profiles. In this case, the load profiles for each village are the profiles shown in figures 5.2, 5.3, 5.4, 5.5 and 5.6, they were built with the energy daily demand and power peak summarized in table 4.7.

Two parameters were then used to synthesized the load profile data: a daily noise (δ_d) of 10% was assumed and an hourly noise (δ_{ts}) of 20%. These perturbation parameters allow to add randomness to the load data to make it more realistic. In fact, in a real system, the size and shape of the load profile varies from day to day.

The mechanism for adding day-to-day and time-step-to-time-step variability is performed by HOMER,

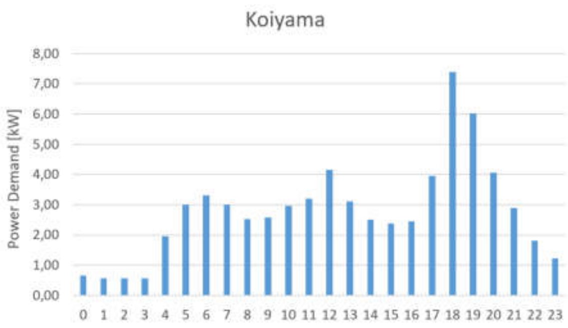


Figure 5.2: Koiyama daily load profile

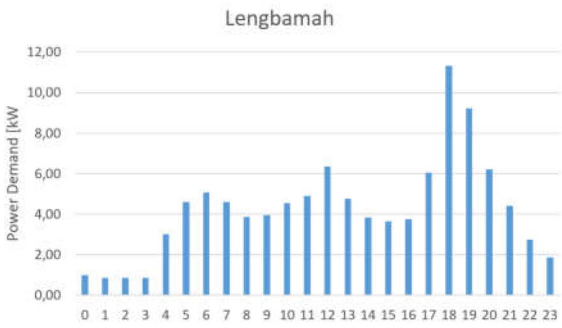


Figure 5.3: Lengbamah daily load profile

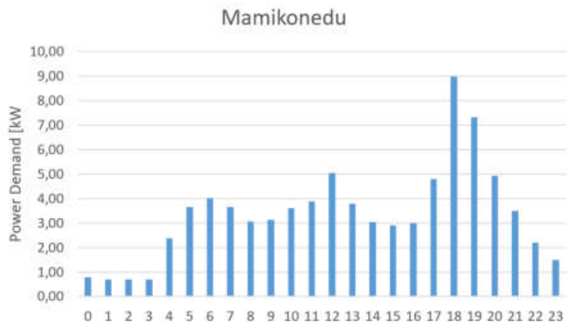


Figure 5.4: Mamikonedu daily load profile

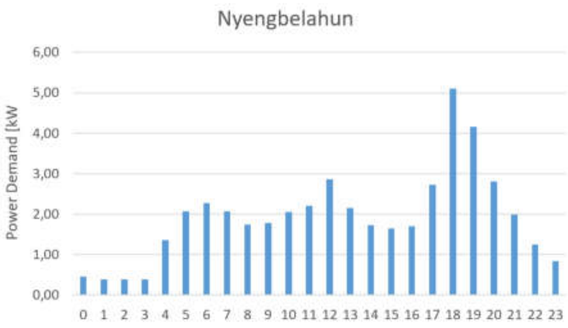


Figure 5.5: Nyengbelahun daily load profile

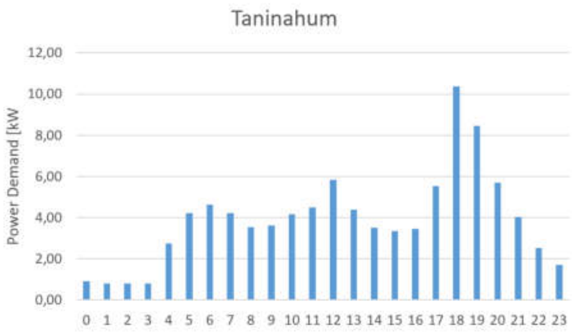


Figure 5.6: Taninahum daily load profile

assembling the year-long array of load data from the specified daily profiles. Then, the software steps through that time series, and, in each time step, it multiplies the value in that time step by the perturbation factor α:

$$\alpha = 1 + \delta_d + \delta_{ts} \tag{5.3}$$

where:

$\delta_d =$ Daily perturbation value

$\delta_{ts} =$ Time step perturbation value

HOMER randomly draws the daily perturbation value once per day from a normal distribution with a mean of zero and a standard deviation equal to the daily variability input (δ_d) and it randomly draws the time step perturbation value every time step from a normal distribution with a mean of zero and a standard deviation equal to the time-step-to-time-step variability (δ_{ts}) input value. The effect of these variability is shown in figure 5.7 with the daily load profiles for Koiyama. It can be notice that the daily profile of figure 5.2 changes in size and shape from day to day.

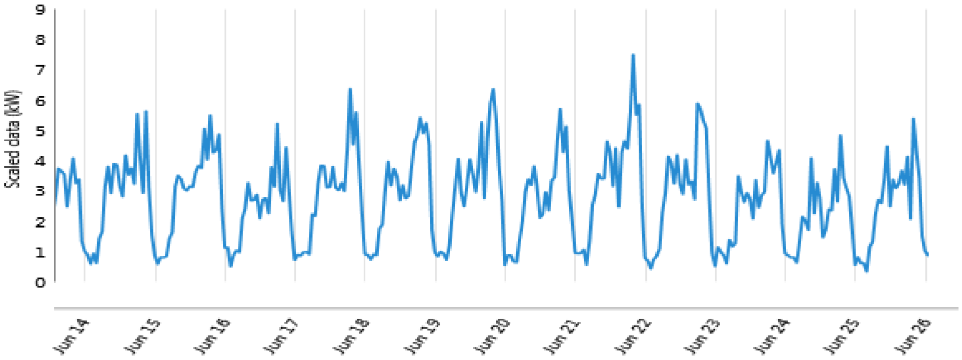


Figure 5.7: Daily Load Perturbation

5.1.2 Resources

The resources that can be included in HOMER simulations are four renewable resources (solar, wind, hydro, and biomass) as well as any fuel used by the components of the system. For this project solar, temperature and wind data were supplied to the software, even if the only renewable resource used is the solar. The data were obtained from the NASA Surface Meteorology and Solar Energy web site [30], specifying the longitude and latitude for each village. In figures 5.8, 5.9 and 5.10 are shown the monthly average solar (irradiation and clearness index), temperature and wind data from NASA for Koiyama village. Then, HOMER synthesizes hourly solar radiation data using an algorithm based on the work of V.A. Graham [31]. This algorithm produces realistic hourly data, requiring only the latitude and the twelve monthly average values. The algorithm creates synthetic solar data with certain statistical properties that reflect global averages. Data generated for a particular location does not perfectly replicate the characteristics of the real solar resource. However, HOMER's tests show that synthetic solar data produce virtually the same simulation results as real data [29]. Differences in key performance output variables like annual PV array production, fuel consumption, generator run time, and storage throughput are typically less than 5%. Differences in key economic output variables like total net present cost and levelized cost of energy are typically less than 2% [29].

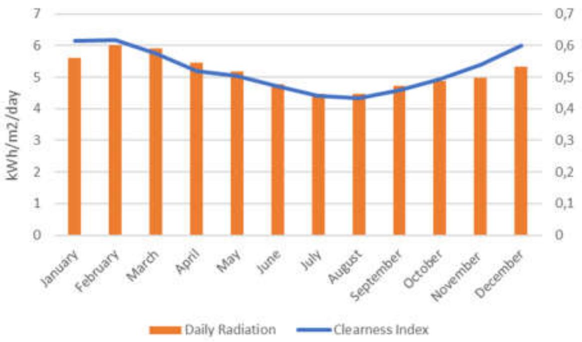


Figure 5.8: Solar irradiation data Koiyama

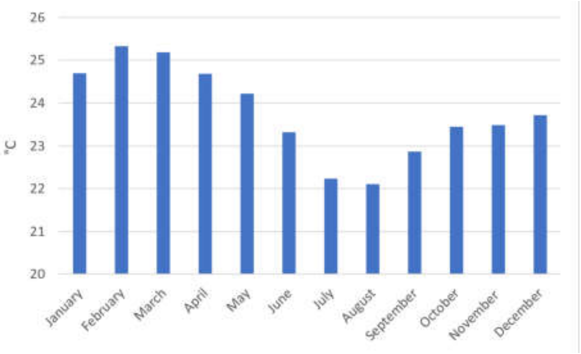


Figure 5.9: Temperature data Koiyama

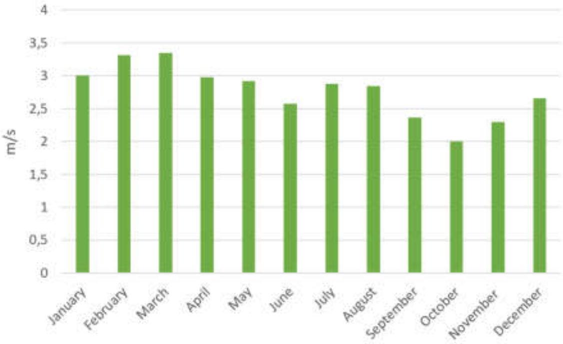


Figure 5.10: Wind speed data Koiyama

HOMER uses these hourly data to calculate the performance of the system. In fact, the photovoltaic power output is affected by the amount of radiation reaching the surface area of the collector. The solar data are expressed with the Global Horizontal Irradiation (GHI), which is the total amount of solar radiation striking the horizontal surface on the earth. However, the power output of the PV array depends on the amount of radiation striking the surface of the PV array, which is tilted with an angle β. So in each time step, HOMER calculates the global solar irradiance incident on the surface of the PV array using the HDKR model [28].

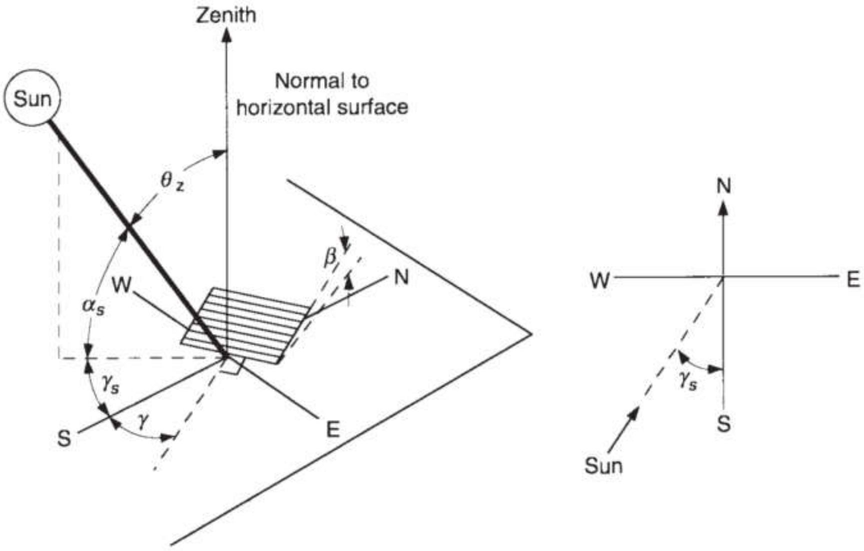


Figure 5.11: Solar Angles

The angles involved in these calculation are described below and are shown in figure 5.11 [32]:

Latitude (Φ) = Angular location north or south of the equator. $-90^{\circ} \leq \Phi \leq 90^{\circ}$ (North positive)

Declination (δ) = Angular position of the sun at solar noon with respect to the plane of the equator. $-23.45^{\circ} \leq \delta \leq 23.45^{\circ}$ (North positive)

Slope (β) = Angle between the plane of the surface in question and the horizontal. $0^{\circ} \leq \beta \leq 180^{\circ}$. ($\beta >$ 90° means that the surface has a downward-facing component)

Surface azimuth angle (γ) = Deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive. $-180^{\circ} \leq \gamma \leq 180^{\circ}$.

Hour angle (ω) = Angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour. Morning negative, afternoon positive.

Angle of incidence (θ) = Angle between the beam radiation on a surface and the normal to that surface.

Zenith angle (θ_z) = Angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.

Solar altitude angle (α_s) = Angle between the horizontal and the line to the sun, that is, the complement of the zenith angle.

Solar azimuth angle (γ_s) = Angular displacement from south of the projection of beam radiation on the horizontal plane. Displacements east of south are negative and west of south are positive.

The HDKR model takes into account the value of the solar resource (GHI), the orientation of the PV array (slope angle β and azimuth σ), the location on Earth's surface (latitude and longitude) and the time. The time of year affects the solar declination, which is the latitude at which the sun's rays are perpendicular to the earth's surface at solar noon. HOMER uses the following equation to calculate the solar declination:

$$\delta = 23.45^{\circ} \sin\left(360^{\circ} \frac{284 + n}{365}\right) \tag{5.4}$$

where:

n = Day of the year (number between 1 and 365)

The time of day affects the location of the sun in the sky, which can be described by the hour angle. HOMER uses the convention whereby the hour angle is zero at solar noon (the time of day at which the sun is at its highest point in the sky), negative before solar noon, and positive after solar noon. HOMER uses the following equation to calculate the hour angle:

$$\omega = (t_s - 12) \cdot 15^{\circ} \tag{5.5}$$

where:

t_s = Solar time [hr]

The value of t_s is 12 hr at solar noon, and 13.5 hr ninety minutes later. The equation above is based on the fact that the sun moves across the sky at 15 degrees per hour.

HOMER assumes that all time-dependent data, such as solar radiation data and electric load data, are specified not in solar time, but in civil time (also called local standard time). HOMER calculates solar time from civil time using the following equation:

$$t_s = t_c + \frac{\lambda}{15^o/hr} - Z_c + E \tag{5.6}$$

where:

t_c = Civil time in hours corresponding to the midpoint of the time step [hr]
λ = Longitude [°]
Z_c = Time zone in hours east of GMT [hr]
E = Equation of time [hr]

The equation of time accounts for the effects of obliquity (the tilt of the earth's axis of rotation relative to the plane of the ecliptic) and the eccentricity of the earth's orbit. HOMER calculates the equation of time as follows:

$$E = 3.82(0.000075 + 0.001868 \cdot \cos B - 0.032077 \cdot \sin B - 0.0141615 \cdot \cos 2B - 0.04089 \cdot 2B) \tag{5.7}$$

where B is given by:

$$B = 360^o \frac{(n-1)}{365} \tag{5.8}$$

For a surface with any orientation, it can defined the angle of incidence, meaning the angle between the sun's beam radiation and the normal to the surface, using the following equation:

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \tag{5.9}$$

where:

θ = Incident angle [°]
β = Slope of the surface [°]
γ = Azimuth angle of the surface [°]
ϕ = Latitude [°]
δ = Solar declination [°]
ω = Hour angle [°]

An incidence angle of particular importance, is the zenith angle, meaning the angle between a vertical line and the line to the sun. The zenith angle is zero when the sun is directly overhead, and 90° when the sun is at the horizon. Because a horizontal surface has a slope equal to zero, the zenith angle can be found setting θ_z = 0° in the equation above, which yields:

$$\cos\theta_z = \cos\Phi\cos\delta\cos\omega + \sin\Phi\sin\delta \tag{5.10}$$

where:

θ_z = Zenith angle [º]

When addressing the amount of solar radiation arriving at the top of the atmosphere over a particular point on the earth's surface, HOMER assumes the output of the sun is constant in time. However, the amount of sunlight striking the top of the earth's atmosphere varies over the year because the distance between the sun and the earth varies over the year due to the eccentricity of earth's orbit. To calculate the extraterrestrial normal radiation, defined as the amount of solar radiation striking a surface normal to the sun's rays at the top of the earth's atmosphere, HOMER uses the following equation:

$$G_{on} = G_{sc}\left(1 + 0.033 \cdot \frac{360n}{365}\right) \tag{5.11}$$

where:

G_{on} = Extraterrestrial normal radiation [kW/m2]

G_{sc} = Solar constant [1.367 kW/m2]

To calculate the extraterrestrial horizontal radiation, defined as the amount of solar radiation striking a horizontal surface at the top of the atmosphere, HOMER uses the following equation:

$$G_o = G_{on}\cos\theta_z \tag{5.12}$$

Because HOMER simulates on a time-step-by-time-step basis, integrating the equation above over one time step allows to find the average extraterrestrial horizontal radiation over the time step:

$$\overline{G_o} = \frac{12}{\pi} G_{on}\left[\cos\phi\cos\delta(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180^{\text{o}}}\sin\phi\sin\delta\right] \tag{5.13}$$

where:

$\overline{G_o}$ = Extraterrestrial horizontal radiation averaged over the time step [kW/m2]

ω_1 = Hour angle at the beginning of the time step [º]

ω_2 = Hour angle at the end of the time step [º]

The equation above gives the average amount of solar radiation striking a horizontal surface at the top of the atmosphere in any time step. The solar resource data give the average amount of solar radiation striking a horizontal surface at the bottom of the atmosphere (the surface of the earth) in every time step. The ratio of the surface radiation to the extraterrestrial radiation is called the clearness index. The following equation defines the clearness index:

$$k_T = \frac{\overline{G}}{\overline{G_o}} \tag{5.14}$$

where:

$\overline{G}$ = = Global horizontal radiation on the earth's surface averaged over the time step [kW/m2]

$\overline{G_o}$ = Extraterrestrial horizontal radiation averaged over the time step [kW/m2]
k_T = Clearness index [-]

As for the solar radiation on the earth's surface, some of the radiation is beam radiation (also called direct radiation), defined as solar radiation that travels from the sun to the earth's surface without any scattering by the atmosphere. The rest of the radiation is diffuse, defined as solar radiation whose direction has been changed by the earth's atmosphere. Diffuse radiation comes from all parts of the sky. The sum of beam and diffuse radiation is called global solar radiation, a relation expressed by the following equation:

$$\overline{G} = \overline{G_b} + \overline{G_d} \tag{5.15}$$

where:
$\overline{G_b}$ = Beam radiation [kW/m2]
$\overline{G_d}$ = Diffuse radiation [kW/m2]

The distinction between beam and diffuse radiation is important when calculating the amount of radiation incident on an inclined surface. The orientation of the surface has a stronger effect on the beam radiation, which comes from only one part of the sky, than it does on the diffuse radiation, which comes from all parts of the sky. However, only the global horizontal radiation must be supplied to HOMER. Then, in every time step, HOMER resolves the global horizontal radiation into its beam and diffuse components to find the radiation incident on the PV array. For this purpose, HOMER uses the Erbs model [33], which gives the diffuse fraction as a function of the clearness index as follows:

$$\frac{\overline{G_d}}{\overline{G}} = \begin{cases} 1.0 - 0.09k_T & for\ k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & for\ k_T \leq 0.22 \\ 0.165 & for\ k_T > 0.80 \end{cases} \tag{5.16}$$

For each time step, HOMER uses the average global horizontal radiation to calculate the clearness index, then the diffuse radiation. It then calculates the beam radiation by subtracting the diffuse radiation from the global horizontal radiation. To calculate the global radiation striking the tilted surface of the PV array, HOMER uses the HDKR model, which assumes that there are three components to the diffuse solar radiation: an isotropic component that comes from all parts of the sky equally, a circumsolar component that emanates from the direction of the sun, and a horizon brightening component that emanates from the horizon. Before applying this model, three more factors must be defined. The first factor is R_b, the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{5.17}$$

Then the anisotropy index, with symbol A_i, which is a measure of the atmospheric transmittance of beam radiation. This factor is used to estimate the amount of circumsolar diffuse radiation, also called forward scattered radiation. The anisotropy index is given by the following equation:

$$A_i = \frac{\overline{G_b}}{\overline{G_o}} \tag{5.18}$$

Finally, the third factor is used to account for the horizon brightening, so the fact that more diffuse radiation comes from the horizon than from the rest of the sky. This term is related to the cloudiness and is given by the following equation:

$$f = \sqrt{\frac{\overline{G_b}}{\overline{G}}} \tag{5.19}$$

Finally, the HDKR model calculates the global radiation incident on the PV array according to the following equation:

$$\frac{\overline{G_T}}{\overline{G}} = \left[1 - \frac{\overline{G_d}}{\overline{G}}(1 - A_i)\right] R_b + \frac{\overline{G_d}}{\overline{G}}(1 - A_i)\left(\frac{1 + \cos\beta}{2}\right)\left[1 + f\sin^3(\frac{\beta}{2})\right] + \rho_g\left(\frac{1 - \cos\beta}{2}\right) \tag{5.20}$$

where:

ρ_g = Ground reflectance (Albedo) [%]

5.1.3 Solar PV Model

HOMER uses a mathematical model described to determine the optimal power generation characteristics of the PV array. Starting from several inputs, like incident solar radiation data, the local area ambient temperature data and the PV module characteristics, the PV power output can be determined by the following equations:

$$P_{Out} = N \cdot P_{PV,stc} \cdot f_{PV}\left(\frac{\overline{G_T}}{\overline{G}_{T,stc}}\right)\left[1 + \alpha_P(T_c - T_{C,stc})\right] \tag{5.21}$$

where:

P_{Out} = Solar PV power output of the array [kW]
P_{PV} = PV power output of a module at STC [kW]
f_{PV} = PV derating factor [%]
$\overline{G_T}$ = Global radiation incident on the PV array [W/m^2]
$\overline{G}_{T,stc}$ = Global radiation incident at STC [W/m^2]
T_c = PV cell temperature [K]
$T_{c,stc}$ = PV cell reference temperature at STC [K]
α_P = Temperature coefficient of peak-power [%/°C]
N = Number of modules

The PV derating factor (f_{PV}) is a scaling factor that HOMER applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated. This factor takes into account for losses like soiling of the panels, wiring losses, shading, snow cover, aging, and so on.

The PV cell temperature is computed with the two following equations:

$$T_c = T_a + G_T \left(\frac{\tau\alpha}{U_l} \right) \tag{5.22}$$

$$\left(\frac{\tau\alpha}{U_l} \right) = \frac{NOCT - 20}{800} \tag{5.23}$$

where:

T_a = Ambient temperature [K]

U_l = Overall heat loss [W/m^2]

τ = PV panel transmittance coefficient [-]

α = PV absorption coefficient [-]

NOCT = Nominal Operating Cell Temperature [K]

Where the Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the following conditions:

$$\begin{cases} Irradiance\ on\ cell\ surface = 800\ W/m^2 \\ Air\ Temperature\ = 20^{o}C \\ Wind\ Velocity = 1\ m/s \\ Mounting = Open\ back\ side \end{cases} \tag{5.24}$$

5.1.4 Diesel Generator Model

The backup generator modelled for this project is a Diesel AC generator. To design the generator two curves must be model: the fuel curve and the efficiency curve.

The fuel curve shows the quantity of fuel the generator consumes to generate electricity. It is assumed in HOMER that the fuel curve is a straight line passing through the two given points, as shown in figure 5.12.

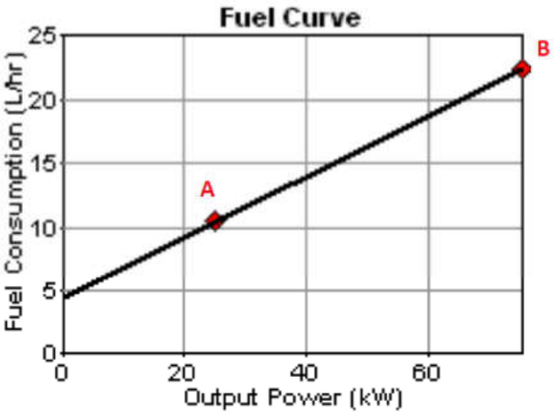


Figure 5.12: Fuel Curve Example

With these two points the intercept and slope of the line can be calculated:

$$Slope = \frac{y_B - y_A}{x_B - x_A} \tag{5.25}$$

$$Intercept = y_A - Slope \cdot x_A \tag{5.26}$$

With slope and intercept, the two following parameters can be computed:

$$F_0 = \frac{Intercept}{RatedOutput} = \frac{Intercept}{Y_{gen}} \tag{5.27}$$

$$F_1 = Intercept \tag{5.28}$$

where:

F_0 = Fuel curve intercept coefficient [units/hr/kW]

Y_{gen} = Rated output [kW]

F_1 = Fuel curve slope [units/hr/kW]

These two parameters compose the fuel curve:

$$F = F_0 Y_{gen} + F_1 P_{gen} \tag{5.29}$$

where:

P_{gen} = Electric output [kW]

The efficiency curve shows how the efficiency of the generator changes with the load:

$$\eta_{gen} = \frac{3.6 \cdot P_{gen}}{\dot{m}_{fuel} \cdot LHV_{fuel}} \tag{5.30}$$

where:

η_{gen} = Generator efficiency [-]

$\dot{m}_{fuel}$ = Mass flow rate of fuel [kg/hr]

LHV_{fuel} = Lower heating value [MJ/kg]

1 kWh = 3.6 MJ

The fuel consumption and the mass flow rate relate as follows:

$$\dot{m}_{fuel} = F = F_0 Y_{gen} + F_1 Pgen \tag{5.31}$$

However, the relation depends on fuel unit. When liter is the unit of the fuel, the mass flow rate and fuel consumption relation depends on density. Thus the equation for mass flow is given as below:

$$\dot{m}_{fuel} = \rho_{fuel}\left(\frac{F}{1000}\right) = \rho_{fuel}\left(\frac{F_0 Y_{gen} + F_1 Pgen}{1000}\right) \tag{5.32}$$

where:

ρ_{fuel} = Fuel density [kg/m^3]

When cubic meter is the unit of fuel flow, the factor 1000 is omitted from the above equation. Therefore, the efficiency equation when the unit of fuel is liters is given by:

$$\eta_{gen} = \frac{3600 \cdot P_{gen}}{\rho_{fuel}(F_0 Y_{gen} + F_1 Pgen) \cdot LHV_{fuel}} \tag{5.33}$$

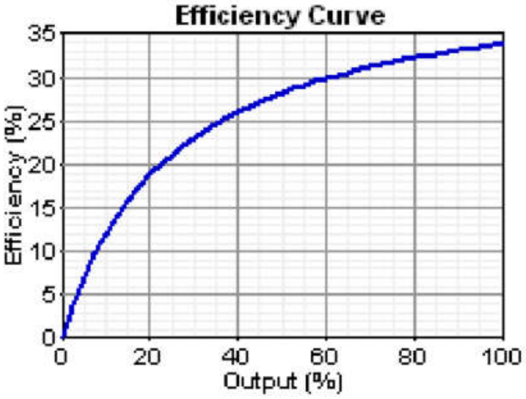


Figure 5.13: Efficiency Curve Example

5.1.5 Inverter Model

In the inverter model, HOMER calculates the energy output from the inverter (E_{PV-inv}) and the energy output from the battery bank ($E_{bat-inv}$) in the following way:

$$E_{PV-inv} = E_{PV} \cdot \eta_{inv} \tag{5.34}$$

$$E_{bat-inv} = \frac{E_{bat(t-1)} - E_{load}}{\eta_{inv} \cdot \eta_B} \tag{5.35}$$

where:

E_{PV-inv} = Energy output from the inverter [kWh]

E_{PV} = Energy output from the PV panels [kWh]

$E_{bat-inv}$ = Energy output from the battery [kWh]

$E_{bat(t-1)}$ = Initial energy stored in the battery [kWh]

E_{load} = Energy consumed by the load [kWh]

η_{inv} = Inverter efficiency [%]

η_B = Battery efficiency [%]

When the inverter works as rectifier, so to convert the excess of AC energy from the backup generator to charge the battery, the equations for the energy are:

$$E_{rec-out} = E_{rec-in} \cdot \eta_{rec} \tag{5.36}$$

$$E_{rec-in} = E_{sur-AC} \tag{5.37}$$

$$E_{sur-AC} = E_{Gen} - E_{load} \tag{5.38}$$

where:

$E_{rec-out}$ = Energy output from the rectifier [kWh]
E_{rec-in} = Energy input to the rectifier [kWh]
η_{rec} = Rectifier efficiency [-]
E_{sur-AC} = Excess energy from AC sources [kWh]
E_{Gen} = Energy generated by the Diesel generator [kWh]
E_{load} = Energy consumed by the load [kWh]

5.1.6 Battery bank Model

The energy generated from PV panels has energy outages in case of absence of the Sun radiation, so to avoid such shortfalls a battery bank should be sized in order to maintain a certain amount of hours of autonomy. The total capacity of the battery can be determined using the following mathematical expression:

$$C_B = \frac{E_L S_D}{V_B (DoD)_{max} \eta_B} \tag{5.39}$$

where:

C_B = Battery capacity [Ah]
E_L = Electrical load [Wh]
S_D = Battery autonomy [days]
V_B = Battery voltage [V]
$(DoD)_{max}$ = Maximum Depth of Discharge
η_B = Battery efficiency [%]

The autonomy of the battery bank is the ratio of battery bank size to the load demand and it is calculated with the following mathematical expression:

$$A_{batt} = \frac{N_{batt} V_{nom} C_{nom} (1 - SoC_{min}) \frac{hr}{day}}{E_{daily} \frac{1000Wh}{kWh}} \tag{5.40}$$

where:

A_{batt} = Battery autonomy [hr]

N_{batt} = Number of batteries

V_{nom} = Single battery nominal voltage [V]

C_{nom} = Single battery nominal capacity [Ah]

SoC_{min} = Minimum battery state of charge [%]

E_{daily} = Average load electrical demand [kWh/day]

5.1.7 Optimization Assumptions

In order to perform the optimization of the systems, the several inputs described in the the previous section 5.1 must be assumed and supplied to HOMER. In table 5.1, the project inputs are shown. First, the information about the locations and the energy and power demands of each site are provided to the software. Then, as already explained in section 5.1.1 a daily noise of 10% and a hourly noise of 20% are used to model the daily profiles. Finally, two constraints are imposed to the optimization process: a system autonomy of 1 day and an unmet load equal to zero. The autonomy is design in order to allow the system to relay only on solar energy in case of a cloudy day, without running the backup generator. The unmet load is zero, so that no electrical load over the year is unserved due to insufficient generation.

Table 5.1: Project Assumptions

	Koiyama	Lengbamah	Mamikonedu	Nyengbelahun	Taninahum
Latitude	8.45	8.24	8.40	8.27	8.39
Longitude	-9.80	-10.27	-9.60	-10.14	-10.06
Daily Demand [kWh]	66.79	102.2	81.2	46.2	93.8
Peak Load [kW]	7.4	11.3	9	5.1	10.4
Daily Noise	10%				
Hourly Noise	20%				
System Autonomy	24 hr				
Unmet Load	0%				

The first component to be modelled is the photovoltaic array. For the optimization, generic flat plate PV modules are selected, with a capital cost of 870 USD/kWp. This modules have an efficiency of 15.51%, a peak-power temperature coefficient of -0.41%/^{o}C, Normal Operating Cell Temperature of 46^{o}C and 25 years of expected lifetime. No tracking system is selected and a derating factor of 80% is assumed to account for the non-ideal conditions. The orientation of the array is set thorough south (azimuth equal to 0^{o}), with a tilt angle of 10^{o}, assumed to be equal to the latitude. The ground reflectance is set to 20%, typical value for dry bare grounds [34]. Finally, the two economical inputs are assumed, a nominal discount rate of 8% and an expected inflation rate of 2%. The assumed inputs are shown in table 5.2.

Also for the Diesel generator, a generic model is used, with a capital cost of 520 USD/kW. Differently from the dimension of PV modules, battery bank and inverter that are optimally sized by the software, the Diesel generator's size must be supplied by the user. Three Diesel generator sizes were chosen in order

Table 5.2: PV Module Assumptions

Type	Generic flat plate
Cost	870 USD/kWp
Efficiency (STC)	15.51%
Power Temperature Coefficient	-0.41%/°C
NOCT	46°C
Lifetime	25 yr
Derating factor	80%
Tracking System	No Tracking
Slope	10°
Azimuth	0°
Ground Reflectance	20%
Nominal discount rate	8%
Expected inflation rate	2%

to supply the electrical demand of the villages, without working at maximum load. For each of these generators, the fuel consumptions at full and half-load are defined. These two parameters are used by the software to compute the fuel curve (see section 5.1.4). The common inputs to all three generators are the minimum load ratio and the heat recovery ratio. The minimum load ratio is 25%, meaning that the generator can not work below 25% of the nominal load. The heat recovery ratio is set to 0, since no fraction of that waste heat that can be captured to serve the thermal load. The price of the Diesel is set to 1 USD/liter (average price in Liberia in the period 2012/14) [2] and for its characteristics, typical average values are assumed (Lower Heating Value 43.2 MJ/kg, density 820 kg/m3, carbon content 88%, sulfur content 0.3%). The inputs parameter are shown in table 5.3

Table 5.3: Generator Assumptions

Type	Generic Genset		
Nominal Power ($\cos\phi = 0.8$)	10 kW	12 kW	24 kW
Fuel Consumption at Full Load [l/h]	3.7	3.7	7.1
Fuel Consumption at Half Load [l/h]	2	2.4	3.9
Cost	520 USD/kW		
Lifetime	15,000 hrs		
Min. Load Ratio	25%		
Heat Recovery Ratio	0%		
Fuel Used	Diesel		
Price	1.00 USD/L		
Lower Heating Value	43.2 MJ/kg		
Density	820.00 kg/m3		
Carbon Content	88.0%		
Sulfur Content	0.3%		

Regarding the battery bank, a generic 1 kWh lead acid model of battery is used, with a capital cost of 130 USD/kWh. 2V batteries are connected in series to form string of 48V, with a nominal capacity of 500Ah (1 kWh) and a lifetime of 25 years. The round-trip efficiency, which means the efficiency of one full charge/discharge cycle, is assumed to be 80%. Moreover, the batteries' state of charge is design to be between 50 and 100%, in order to extend the lifespan of the batteries. The inputs parameters for the battery bank are shown in table 5.4.

The converter is a generic bidirectional model, with capital cost of 700 USD/kW and a lifetime of 15 years. The efficiency when it work as inverter is 90%, while as a rectifier is 85%. The inputs parameters are shown in table 5.5. Finally, also the MPPT charge Controller, shown in table 5.6, is a generic model with a capital cost of 100 USD/kWp, an efficiency of 95% and a lifetime of 15 years.

Table 5.4: Battery Bank Assumptions

Type	Generic 1kWh Lead Acid
Cost	130 USD/kWh
Voltage	2V
Nominal Capacity	500 Ah
Round-trip Efficiency	80%
Initial State of Charge	100%
Minimum State of Charge	50%
Lifetime	10 yr

Table 5.5: Converter Assumptions

Type	Generic Bidirectional Converter
Cost	700 USD/kW
Inverter Efficiency	90%
Rectifier Efficiency	85%
Lifetime	15 yr

Table 5.6: MPPT Charge Controller Assumptions

Type	Generic
Cost	100 USD/kWp
Efficiency	95%
Lifetime	15 yr

5.1.8 Optimization Results

In the optimization process, HOMER simulates each different system configuration in search of the lowest Net Present Cost (NPC) that meet the load demand. The purpose of optimization is to determine the optimal system based on the decision variables imposed by the designer. For this optimization process, the software searched for the lowest NPC but the decision variables to select the best configuration are the autonomy of the system and the unmet load. Moreover, a Load Following (LF) strategy is selected, which means that whenever the generator operates, it produces power to meet the primary load. The charging of the storage bank is left to the renewable power sources. The alternative dispatch strategy would have been the cycle charging (CC) strategy. In the CC strategy, whenever the generator needs to serve the primary load, it operates at full output power. The surplus of electrical production is used to charge the battery bank. The load following strategy has been selected because it produces better performances of the system.

The results of the optimization are shown in table 5.7. It is possible to noticed that for each system has a predicted autonomy about 24 hours and the unmet load is zero, as required by the imposed constrains. The renewable fraction is the fraction of the energy delivered to the load that originated from renewable power sources. The renewable fractions for these optimal configurations is around 87%, which means that most of the demand is supplied by the solar energy. HOMER calculates it according to the following equation:

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{served}} \tag{5.41}$$

where:

f_{ren} = renewable factor

E_{nonren} = Non-renewable electricity production [kWh/yr]

E_{served} = Total electrical load served [kWh/yr]

Table 5.7: System Optimization Results

		Koiyama	Lengbamah	Mamikonedu	Nyengbelahun	Taninahum
PV Modules	[kWp]	22.3	34.3	27.3	15.7	31.3
Generator	[kW]	12	24	12	10	24
Battery Bank	[kW]	134	205	163	93	188
	[Ah]	2792	4271	3396	1938	3917
Inverter	[kW]	12.7	19.3	15.3	8.7	18.0
System Autonomy	[hr]	24.1	23.5	24.1	24.2	23.0
Unmet Load	[%]	0	0	0	0	0
NPC	[USD]	124,228	183,980	143,597	84,247	171,182
Capital Cost	[USD]	52,957	85,033	64,443	38,487	79,280
PV Production	[kWh/yr]	26,805	49,023	39,525	22,655	45,169
Diesel Production	[kWh/yr]	3,567	4,562	3,339	1,979	4,318
Fuel Consumption	[liter/yr]	1,627	1,732	1,472	862	645
Renewable Fraction	[%]	85.4	87.8	88.7	88.3	87.4

5.2 Final Design

A first design of the project was created by Sunlabob according to Plan International's requirements. These systems were optimally sized in order to supply the energy demand of the villages. These first design configurations for the 5 villages are illustrated in table 5.8.

Table 5.8: Description of the first design

	Koiyama	**Lengbamah**	**Mamikonedu**	**Nyengbelahun**	**Taninahum**
No. PV modules	90	126	102	60	114
PV Power	23.4 kW	32.76 kW	26.52 kW	15.6 kW	29.64 kW
Genset Power	12 kW	24 kW	12 kW	10 kW	24 kW
Battery Capacity	2328 Ah	3878 Ah	3108 Ah	1608 Ah	3108 Ah
Charge Controller	5x 5 kW	7x 5 kW	6x 5 kW	4x 5kW	7x 5 kW
Inverter	2x 8 kVA	3x 8 kVA	2x 8 kVA	2x 8 kVA	3x 8 kVA

It is possible to notice that these systems are similar to the optimal configurations design with HOMER and shown in table 5.7. However, due to budget limitation, Plan international decided, after the submission of this initial design, to modified the requirements, decreasing the amount of renewable energy contribution and relying more on the back up generators. Therefore new configurations for the five villages were arranged by Sunlabob and accepted as final designs for the project. The complete description of the final design for each site is shown in table 5.9.

Table 5.9: Description of the final design

	Koiyama	**Lengbamah**	**Mamikonedu**	**Nyengbelahun**	**Taninahum**
No. PV modules	63	90	87	45	87
Total PV Capacity	16.38 kW	23.4 kW	22.62 kW	11.7 kW	22.62 kW
Genset Power	12 kW	24 kW	12 kW	10 kW	24 kW
Battery Capacity	2328 Ah	3108 Ah	3108 Ah	1608 Ah	3108 Ah
Charge Controller	4x 5 kW	5x 5 kW	5x 5 kW	3x 5kW	5x 5 kW
Inverters	2x 8 kVA	3x 8 kVA	2x 8 kVA	1x 8 kVA	2x 8 kVA

In the Koiyama village configuration, the 90 solar modules (260 Wp) initially selected are reduced 63 panels, for a total peak power of 16.38 kWp. The modules are connected in 4 arrays instead of the previous 5. Three arrays comprise 5 strings of 3 modules and 1 array comprises 6 strings of 3 modules. Each array is connected to a charge controller for a total of 4 charge controllers of 5 kW each. The nominal 48V battery bank is unchanged and comprises of 24 2V battery of 2328 Ah capacity. Two inverters of 8 kVA are still used to convert the DC energy produced by the solar arrays and stored in the battery bank. The 12 kW backup generator can feed electricity directly into the village grid or assures a minimum state of charge of the battery bank of 50%.

In the Lengbamah village configuration, the number of solar modules is reduced from 126 to 90 panels (260 Wp), for a total peak power of 23.4 kWp. The modules are now wired in 5 arrays comprising 6 strings of 3 modules. Each array is connected to a charge controller for a total of 5 charge controllers of 5 kW each. The storage system is reduced to a nominal 48V battery bank of 3108 Ah capacity comprising of 24 2V batteries. Three inverters of 8 kVA are still used to convert the DC energy produced by the solar arrays and stored in the battery bank. The 24 kW backup generator can feed electricity directly into the village grid or assures a minimum state of charge of the battery bank of 50%.

In the Mamikonedu village configuration, the number of solar modules is reduced from 102 to 87 panels (260 Wp), for a total peak power of 22.62 kWp. The modules are connected in 4 arrays comprising 6 strings of 3 modules and 1 array comprising 5 strings of 3 modules. Each array is connected to a charge controller for a total of 5 charge controllers of 5 kW each. The nominal 48V battery bank of 24 2V of nominal 3108 Ah capacity is unchanged. Two inverters of 8 kVA are still used to convert the DC energy produced by the solar arrays and stored in the battery bank. The 12 kW backup generator can feed electricity directly into the village grid or assures a minimum state of charge of the battery bank of 50%.

In the Nyengbelahun village configuration, the number of solar modules is reduced from 60 to 45 panels (260 Wp), for a total peak power of 11.7 kWp. The modules are wired in 3 arrays comprising 5 strings of 3 modules. Each array is connected to a charge controller for a total of 3 charge controllers of 5 kW each. The nominal 48V battery bank of of 24 2V nominal 1608 Ah capacity is unchanged. One inverter of 8 kVA is now used to convert the DC energy produced by the solar arrays and stored in the battery bank. The 10 kW backup generator can feed electricity directly into the village grid or assures a minimum state of charge of the battery bank of 50%.

In the Taninahum village configuration, the number of solar modules is reduced from 114 to 87 panels (260 Wp), for a peak power of 22.62 kWp. The modules are connected in 4 arrays comprising 6 strings of 3 modules and 1 array comprising 5 strings of 3 modules. Each array is connected to a charge controller for a total of 5 charge controllers of 5 kW each. The nominal 48V battery bank of 24 2V nominal 3108 Ah (C120) capacity is unchanged. Two inverters of 8 kVA are still used to convert the DC energy produced by the solar arrays and stored in the battery bank. The 24 kW backup generator can feed electricity directly into the village grid or assures a minimum state of charge of the battery bank of 50%.

5.3 HOMER Simulation

In this section, the simulations of the final designs are described. These simulations were accomplished to predict to performance of each of the 5 systems. The long-term operation simulation of a system is the fundamental function of HOMER. The simulation process determines how a particular system configuration, composed by a combination of components of specific sizes, would behave over a long period of time. In this case, a simulation for each village was performed using the configurations defined in the final design (table 5.9). The results of these simulations are summarized in table 5.10. The load consumptions are partially supplied by the PV system and partially by the Diesel generator. The PV systems supply most of the energy demands, in fact the renewable fraction are on average 74%. The total production of the systems, is used to supply the load demand and to charge the battery bank. The excess of electricity is between 2.4% and 5.9% (depending on the system) of the total production. This excess is defined as the surplus electrical energy that must be dumped or curtailed because it cannot be used to serve a load or charge batteries. Excess electricity occurs when surplus power is produced (either by a renewable source or by the generator when its minimum output exceeds the load) and the batteries are unable to absorb it all. If compared with the results from the optimal design of table 5.7, it can be observed that the PV production is slightly lower that the optimal one due to the lower PV sizes. Despite the lower PV power, the predicted unmet load is null, which means that these designs allow the systems to work without any power shortage over the entire year. However, the autonomy of the systems are lower than 1 day, with value around 20 hours.

Table 5.10: Simulation Results

		Koiyama	**Lengbamah**	**Mamikonedu**	**Nyengbelahun**	**Taninahum**
NPC	[USD]	139,424	217,445	151,904	93,210	192,198
Capital Cost	[USD]	48,250	71,638	59,119	32,489	65,359
Load Consumption	[kWh/yr]	24,378	37,303	37,303	16,863	34,712
PV Production	[kWh/yr]	23,686	33,838	32,710	16,919	32,710
Genset Production	[kWh/yr]	6,313	11,986	5,460	4,203	9,883
Excess of Electr.	[kWh/yr]	758	1,089	2,272	750	1,135
	%	2.5	2.4	5.9	3.6	2.7
Renewable Fraction	[%]	74.1	67.8	81.6	75.1	71.1
Autonomy	[hours]	20.1	17.6	22.2	20.0	19.2
Unmet Load	[%]	0	0	0	0	0
Diesel Consumption	[liters/yr]	2,868	4,545	2,401	1,831	3,763

In figures 5.14 and 5.15 are shown the monthly average values and the daily profiles of the renewable power output for the Koiyama village predicted by HOMER. It is possible to notice that the PV production is lower during the rainy season (from May to September) as predictable from the solar data shown in figure 5.8. The results of the simulations and the PV daily productions are analyzed and further discussed in comparison with the data from the real project in chapter 7.

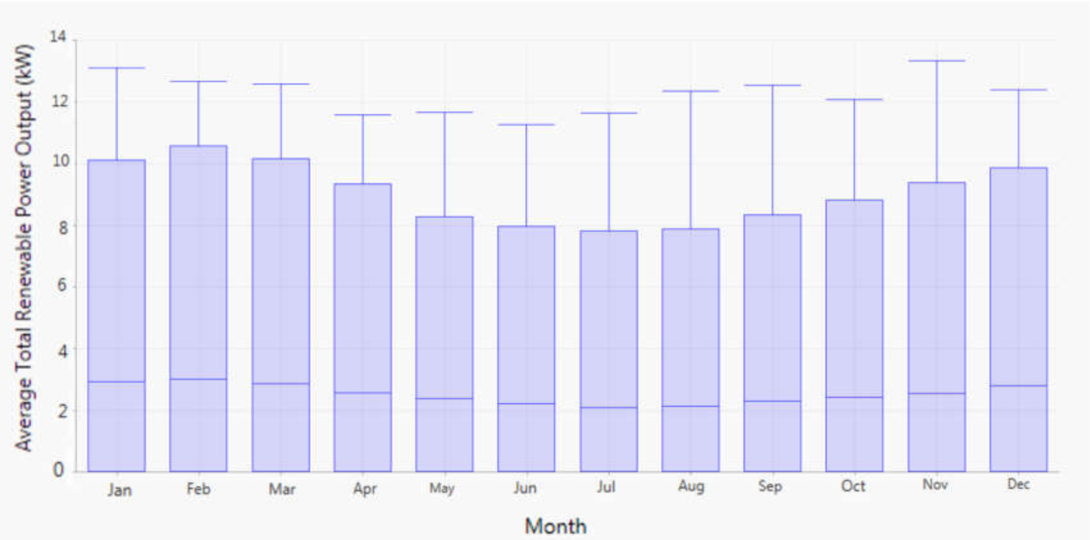


Figure 5.14: Koiyama monthly average PV output

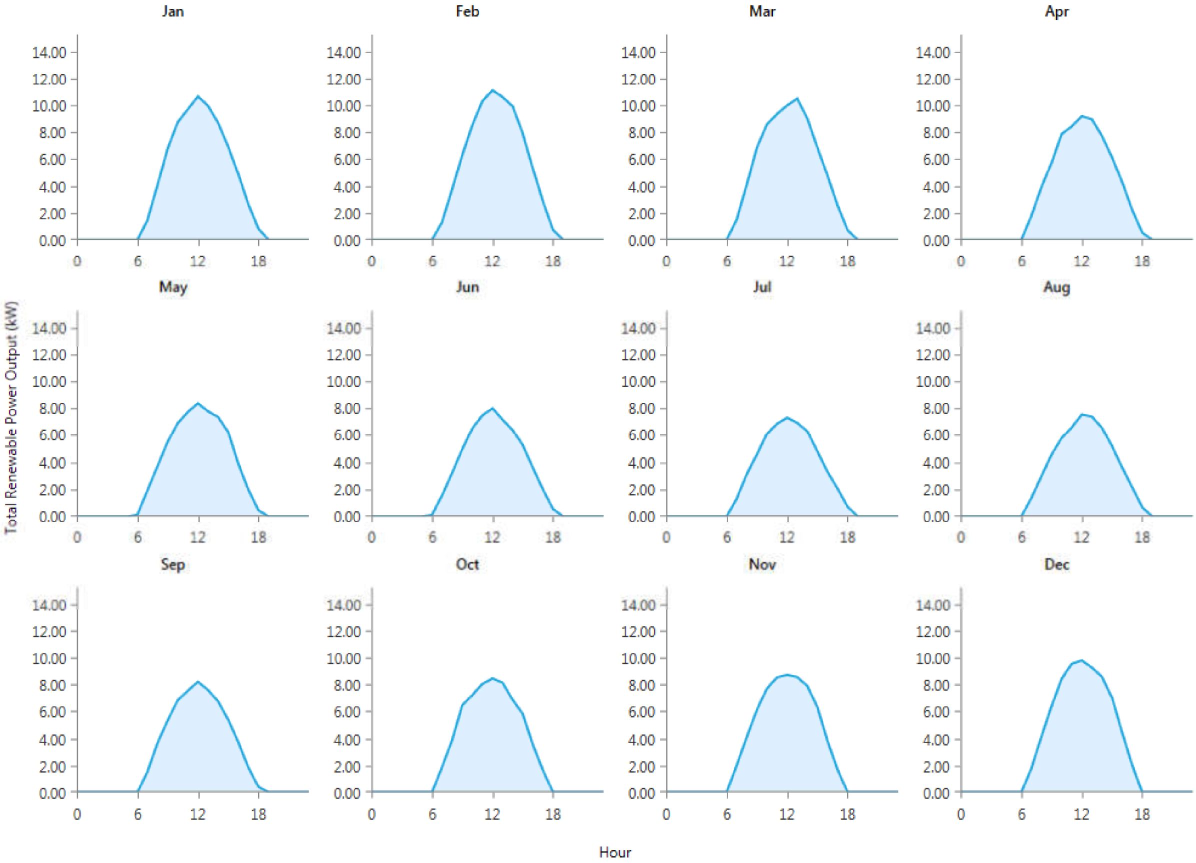


Figure 5.15: Koiyama daily profile PV output

Chapter 6

System Implementation

The system was implemented in 2017 by Sunlabob Renewable Energy. The installation started on 13th of April and was concluded after two month at the beginning of June. The installations were constructed in all the villages with the same procedure and simultaneously. First the powerhouse was built, renovating a preexisting building. On top of the powerhouse a pergola structure was mounted (see further in section 6.1 for the description of the structure) to harbor the PV modules. Later, all the equipment (inverters, charge controllers, batteries, genset) were installed inside the powerhouse and the energy supplying board in each household. After the electrical earthing of each component and each building, the wiring of all the systems was carried on.

When the installation was completed, three final procedures were performed to check the fulfilment of the systems:

- **Inspection of Equipment, Cabling and Connections:** All electrical equipment were inspected for damage or non-functioning, such as circuit breakers, fuses, meters, etc. and all the exposed cables examined for any damage to the insulation.
- **Commissioning:** The commissioning of the system included electrical testing of all equipment and functional checks to verify the equipment functions correctly according to the design specification.
- **Testing:** Once the commissioning of all equipment was finished, the functioning of the entire solar generation plant has been tested and output power was measured.

In figure 6.1 is shown the power line diagram for the Koiyama system. In all the villages is implemented the same scheme, adapted according to the local size and requirements. It can be noticed that each PV array is connected to a protection box, in which is installed a over-voltage protection device and a circuit breaker. Moreover, each photovoltaic string is protected on the negative pole with an electrical fuse. These three devices safeguard the arrays from potential over-currents, overloads and short circuits. After the protection boxes, each PV array is connected to a charge controller and then to the DC protection box. In this box the charge controllers MPPT, the inverter and the battery bank are wired together. The electric energy can flow only in one direction from the charge controller and in both direction through the battery bank and inverters connection. This allows the storage to be charge alter-

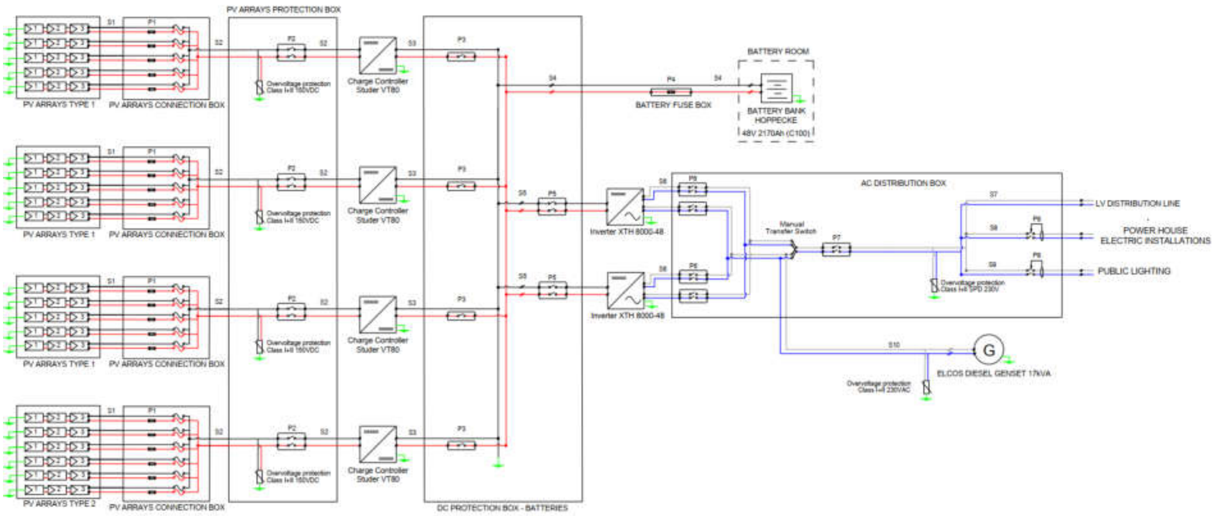


Figure 6.1: Power Line Diagram for Koiyama

natively by the solar energy or from the inverter and to be discharged when the energy is required. The bidirectional inverters can converter the DC in AC and viceversa. In blue on the right side of the scheme are represented the AC connections. On the AC bus are combined the inverters, the Diesel generator and the connections to the Low Voltage distribution line, to the local electrical system in the powerhouse and to the public lighting system of the village. All the power line of the system are safeguarded from electrical failure by several protection devices, placed before and after each component.

6.1 Components

In this section the components of the project are described, explaining their brands, models and characteristics. All the components were selected according to the requirements imposed by Plan International. The proposed materials are high quality and tested for harsh environmental conditions.

Powerhouse

All the system components, except the PV array and the PV combiner boxes, are located inside a power house. The powerhouse is divided in three different rooms. In one room are located the charge controllers, inverters, and the combiner boxes. These components are mounted on galvanized steel rails and the cables lay neatly on cable trays. The batteries are installed in a separate room on racks and the back-up generator are installed in the dedicated gen-set room.

Photovoltaic Panels

The selected photovoltaic panels consist of 260Wp poly-crystalline Sunmodule Plus from SolarWorld. These modules are formed of 60 cells and framed in anodized aluminum. Each module is equipped with an UV resistant IP65 junction box with three bypass diodes. The PV modules have efficiency greater than 15.5% and high yields are ensured due to the integrated water drainage concept, which improves the self-cleaning effect. Moreover, the positive power tolerance of 0/+5 Wp guarantees utmost system efficiency. Regular tests by TÜV Rheinland were performed on the modules to guarantee the rated outputs. SolarWorld PV modules are also tested for harsh environmental conditions and certified according to the international standards, like: Salt Mist Corrosion (IEC 61701), Ammonia Corrosion (IEC 62716) and Potential-induced degradation (PID) Safe.

Figure 6.2: Powerhouse and PV Structure

PV Array Support Structure

The solar modules are installed on a Pergola type mounting structure above the powerhouse (see figure 6.2). This structure is made out corrosion resistant galvanized steel with a tilt angle of 10○ facing south. Due to the irregularity of the ground special attention has been paid to assure that all modules have the same tilt angle. The pillars of the structure are anchored to the ground in a concrete foundation and they are designed to withstand wind loads of 120 km/h. The modules are easily accessible for periodical cleaning and inspection and the mounting structure complies with applicable building codes, regulations and standards.

Battery Bank

The battery bank consists of 24 2V Hoppecke OPzS Solar. These are lead-acid, deep discharge, flooded batteries and offer a cycle life of up to 1500 cycles at DoD 80%. The batteries are connected in series and installed on a rack inside the powerhouse. Battery types for each system and their capacities can be found in table 6.1. The Hoppecke OPzS Solar Power has been well proven for decades, have a very high reliability under rough equatorial, coastal operating conditions and require low maintenance due to optimized alloy and large electrolyte reserve. The robust design features tubular plates which are placed inside a container made from high quality transparent plastics. Diluted sulphuric acid with a density of 1.24 kg/l is used as the electrolyte. The batteries conform to IEC 60896 and DIN 40736 and are manufactured in Europe. The battery bank is shown in figure 6.3 on the right.

Table 6.1: Batteries specifications for each location

	Koiyama	Lengbamah	Mamikonedu	Nyengbelahun	Taninahum
Model	2V Hoppecke OPzS Solar				
Battery Capacity	2328 Ah	3108 Ah	3878 Ah	1608 Ah	3108 Ah
Bank Voltage	48V				
Total Capacity	111.7 kWh	149.2 kWh Ah	186.1 kWh	77.2 kWh	149.2 kWh

Charge Controller

The selected solar charge controllers are Studer Innotec VT-80 MPPT (IP54). They provide maximized battery life due to an optimal 4 step charge process: bulk (at constant current), absorption, floating and equalization. The VarioTrack charge controller utilizes a sophisticated algorithm that ensures that the maximum available power from the solar PV modules is delivered to the batteries. The battery management parameters can be adjusted and an LED display indicates the battery charge current and state of the VT-80. Both tracking efficiency and conversion efficiency are greater than 99% and self-consumption is under 1W in night mode. In addition, it is fully protected against reversed polarity, incorrect wiring, over temperature, battery over-voltage and reverse current by night. The combination of the VT-80 with Studer XTH 8000-48 inverter ensures that the components can and can operate together seamlessly. Beyond that these devices are designed to form one system, ensuring that there are no interferences affecting their efficiency or technical capability. In figure 6.3 in the left picture are visible the 4 charge controller mounted on the wall in Koiyama powerhouse.

Figure 6.3: Equipment Room (Left) and Battery Bank (Right)

Bidirectional Inverter

Studer's XTH 8000-48 is the bidirectional sinusoidal inverter. It is a robust and highly efficient device capable of converting DC power from the battery bank to AC power to feed the loads as well as charging the battery bank from an external AC source (such as a genset). The transfer system is active when the AC genset is available at the AC input of the XTH 8000-48. The transition between inverter and transfer mode is achieved without any power cut. The Smart-Boost function allows the XTH to assist the genset via the inverter function. In this way, the currents from both sources (AC-in and inverter) are combined to deliver the energy required by big loads if the loads are more than the AC source (Genset) can supply. Monitoring, control, programming and data logging on-site or remotely is possible with the RCC-02 remote control and detailed information on the accessories can be found in the subsection 6.1. Two inverter Studer's XTH 8000-48 can be seen in figure 6.3 in the left picture mounted on the wall in Koiyama powerhouse.

Remote Control

The Studer RCC-02 remote control and programming center is connected via a communication bus to all Studer VT-80 MPPT charge controllers, Studer XTH inverters and the Studer BSP in the system. The RCC-02 enables the user to supervise the system and to completely adapt it allowing for fully optimized operation of the system. The RCC-02 continually collects all required data from the devices within the system, and this data can be viewed on site via the RCC-02 digital display or downloaded from the SD card within the device. The Studer evaluation software can be set to issue daily, weekly, monthly and yearly performance reports automatically including values such as, but not limited to, the consumed and produced energy, the battery current and voltage, the output power and the relay status. The data can then be analyzed graphically with a dedicated Microsoft Excel document.

Communication Set

The charge controller and inverter systems can be constantly controlled from any remote terminal, computer, tablet or smart-phone via the communication set Xcom-GSM which connects to sites with GSM mobile coverage. Studer Innotec provides this plug-and-play solution using a secure server and a simple and user-friendly interface, including access to all parameters, real-time display of measured data of all devices included in the system and access to the last 30 days of log files. Furthermore it allows the users to configure alarm messages to be sent to one or more persons by e-mail or SMS.

System monitoring

Additionally to the Studer RCC-02 remote control that collects data from the charge controllers, inverters and battery monitor, a Solar Monitor unit is also installed. The Solar Monitor unit reads data from various sensors and measurement devices, such as ambient and solar module temperature, irradiance sensor and AC meters. Furthermore, the Solar Monitor unit communicates with the RCC-02 via the Studer XCOM and thus collects all required data from the Studer equipment. The Solar monitor unit works as a data logger with a web based evaluation software where reports on plant efficiency and production data can be issued. Alarms and failures are shown on the web portal and can be sent via email as well. The unit is protected against over-voltage according to IEC 61643-21 and can withstand up to 150 discharges. The monitoring system can be accessed from any personal computer or android device.

Diesel Generator

The Elcos open-frame version Diesel Generators were used for this project. They work in conjunction with the bidirectional inverter and thus ensure that the battery bank is sufficiently charged to prevent prolonged low state-of-charge and accelerated battery damage. The Elcos Genset includes a fuel tank of 85 liters with inspection hatch to allow cleaning and a low fuel level shutdown automatic system. The 3-cylinder diesel engine features a tropicalized radiator and rotating components protection guards. The generator set specification used for each village can be seen in the table below.

Table 6.2: Diesel generator specifications for each location

	Koiyama	Lengbamah	Mamikonedu	Nyengbelahun	Taninahum
Type	GE.PK.017/015.BF	GE.PK.034/031.BF	GE.PK.017/015.BF	GE.PK.016/013.BF	GE.PK.034/031.BF
Diesel Motor	Perkins 403A-15G2	Perkins 1103A-33G	Perkins 403A-15G2	PERKINS 403A-15G1	Perkins 1103A-33G
Power	15 kVA/12 kW	31 kVA/24 kW	15 kVA/12 kW	13 kVA/10 kW	31 kVA/24 kW

Metering System

The selected meter is the IP53 protected Circutor Electricity Dispenser BII, a single-phase meter with an electric energy dispensing function to control the demand. The energy dispenser function is based on the patented concept of the daily energy allowance, providing smart management of the available electricity to the user. It includes a main switch that works as a maximum power and maximum demand control as well as an auxiliary switch that can be used for connection or disconnection of nonessential consumptions. The meter has a standard optical port and a communications port for network connection used for the writing/reading of parameters and for data logging.

Moreover, the meter is equipped with a RFID card reader/writer (see figure 6.5), which reads, writes, formats and modifies user cards. The RFID cards are used to program the dispenser meter with the tariff, a combination of current limit and energy daily allowance, for each user. For each user three tariff rates can be programmed with wireless RFID card reader. Through the LCD screen and LEDs is then possible for the user to check the energy availability.

Figure 6.4: Household Electric Board

Figure 6.5: RFID card reader/writer and RFID Card

The dispenser is mounted on a board with an electric system composed by light bulbs, sockets, switches and breakers. The number of each components is sized according to amount established in the tariff classification shown in table 4.1. An example of one board for the tariff T01 can be seen in figure 6.4. One of this board is installed in each household or facility of the villages. The user can go to a central station where they can charge their RFID cards thought the RFID reader. Afterward they can active the dispenser in their house and consume the amount of energy that they bought.

Street Connections and Lights

Finally, in each village the connection between the different buildings were realized. Electrical cables connected the powerhouse to each user through overhead electrical lines. Several wooden poles support the cables and the electrical connection points for the different buildings. Moreover, five outdoor lights were installed in strategic positions in each village in order to provide street illumination. In figure 6.6 is shown the electrical connection of Koiyama village and in figure 6.7 a street light.

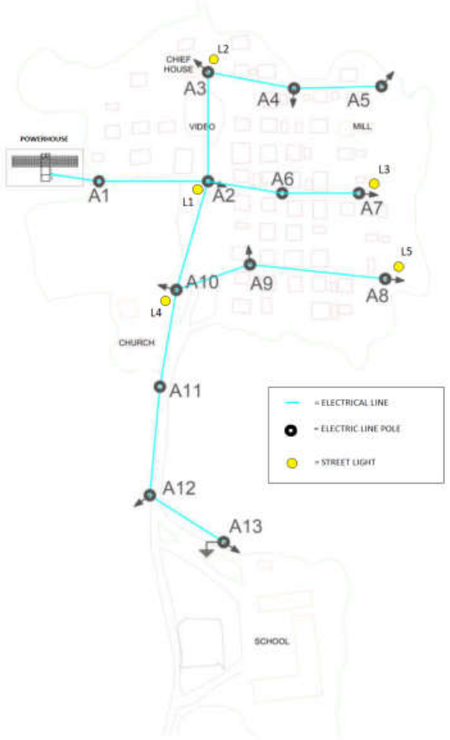


Figure 6.6: Electrical Connection in Koiyama

Figure 6.7: Outdoor Street Light

Chapter 7

System Analysis

In this chapter the analysis of the project is performed. First, the data collected by the grid analyzer installed in each village are illustrated and compared the results of the simulation accomplished in section 5.3. Then, in section 7.2 the economical analysis is illustrated and finally some considerations about the project are discussed in section 7.3.

7.1 Production Analysis

After the implementation of the micro-grids, the data from the monitoring system Studer RCC-02 (see section 6.1) have been collected and graphically analyzed with the Xtender Analysis Tool in order to evaluate the performance of the systems. The monitoring devices collected data for nine months, from July 2017 to April 2018.

		Koiyama	**Mamikonedu**	**Nyengbelahun**
Load Consumption	Measured [kWh]	10,671	5,048	2,844
	Expected [kWh]	18,284	27,977	12,647
	Difference [%]	42%	82%	78%
PV Production	Measured [kWh]	13,336	9,633	5,189
	Expected [kWh]	17,765	24,533	12,689
	Difference [%]	25%	61%	59%
Genset Production	Measured [kWh]	851	0	0
	Expected [kWh]	4,735	4,095	3,152
	Difference [%]	82%	100%	100%
Renewable Fraction	Measured [kWh]	92%	100%	100%
	Expected [kWh]	74%	85%	75%

Table 7.1: Production analysis results and comparison with simulations

These data have then been compared with the theoretical production simulated with HOMER in section 5.3. These results are summarized in table 7.1. The measured are the data collected by the grid analyzer (Xtender), while the expected are the production data from the simulations over the same period (from July 2017 to April 2018). In the table are shown the data for only 3 villages, while for Lengbamah and Taninahum the production analysis are not available. For Lengbamah the absence of data is due to failure of the system caused by lighting strikes. For Taninahum, the lack is due to delays in collecting of the data. More consideration about these two systems are explained in section 7.3. It is easy to see as the real value are way lower than the expected ones. Both the PV production and the load consumption are lower, with different ranges depending on the village, while the backup generators is almost never used. For Koiyama the data are closer to the expected values. In figures 7.1, 7.2 and 7.3 are shown the monthly averaged daily PV productions from the HOMER simulation (in red) and from the Xtender analyzer (in blue).

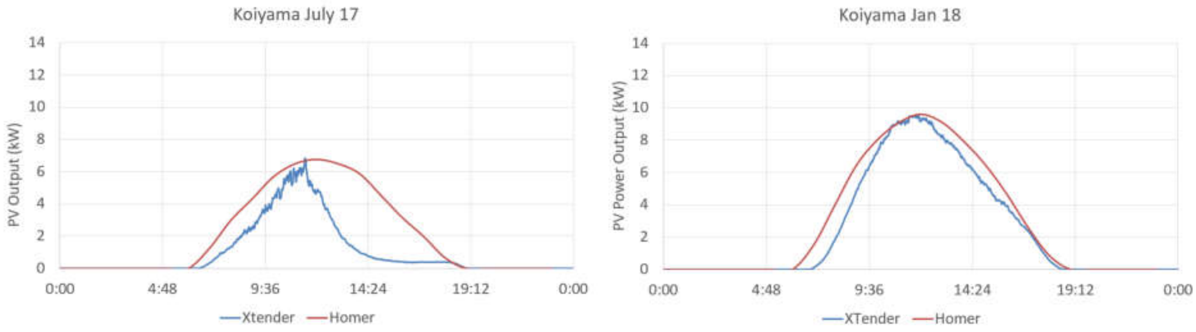


Figure 7.1: Production comparison for Koiyama

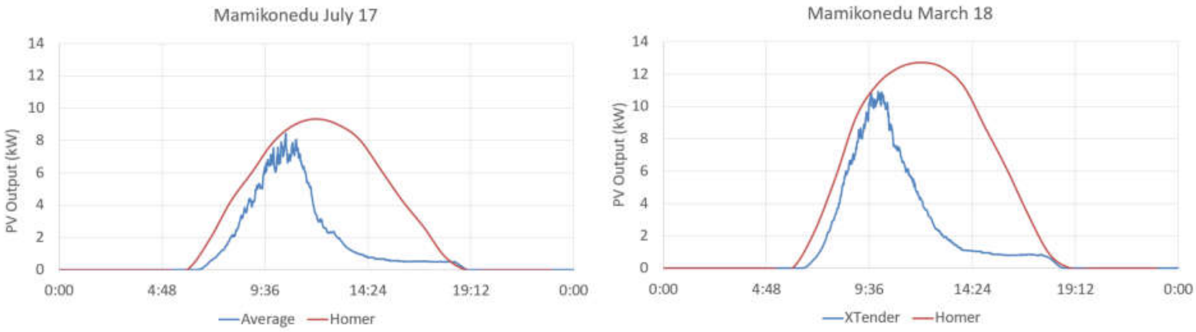


Figure 7.2: Production comparison for Mamikonedu

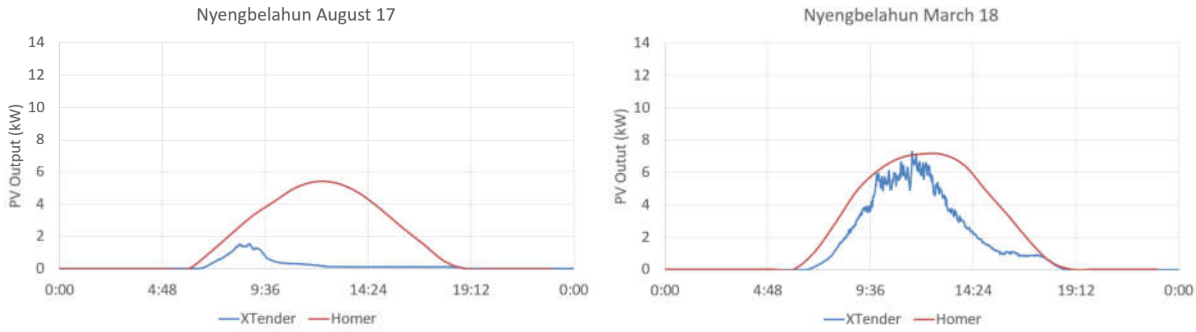


Figure 7.3: Production comparison for Nyengbelahun

For each village, the production in the first months of use (July, August) are compared with the production in the final period of analysis (January, March). First, it is possible to notice that both the Xtender and the HOMER data have a tendency to growth in peak value and shape over this period. As expected from the GHI resources (figure 5.8), this increases in peak values of the PV production in the winter period is due to the end of the rainy season, therefore to higher solar irradiance. The real PV productions (Xtender) tend to increase over that period, assuming the same shape and size of the predicted production. These increases are easy to notice for Koiyama and Nyengbelahun but they are also true for Mamikonedu, where the shape remain basically the same but the production is higher (higher peak). This trend is due to a growth in the energy demand of the villages. In fact, in the first period the electricity consumptions were still low and after some months the use of the mini-grids increased, thanks to the familiarization of the villagers with the systems and their higher electricity needs (e.g. new electric devices). Due to this low energy consumption, the solar energy is enough to maintain the state of charge of the batteries in the optimal range and to supply the demand. Therefore, as observable also in table 7.1 the backup generators are rarely or never run and the renewable fractions are close or equal to 100%.

This behaviour is easier to noticed in figures 7.4 and 7.5, where the PV productions are compared with the AC power outputs (load demand), AC power inputs (Backup generation) and the State of Chargse (SoC) of the battery banks. In the case of Nyengbelahun in August 2017, the PV production reaches its peak around 9 a.m.. This happen because the battery bank is fully charged (SoC=100%). Therefore, the PV production is stopped and then it stabilized on low generation values, used only to keep the battery charged. The AC power demand is in fact really low, around 200W, and the energy is consumed only during the nighttime, caused only by the street lights.

On the other side, the Koiyama case in January shows the perfect PV production of the system. The AC load is low during the night, increases in the daily hours and has a peak demand in the evening around 8 p.m.. It is possible to noticed what already underlined before: the PV array produces enough energy to supply the load and to charge the battery bank, and the backup generator is not needed, in fact the AC Power Input is always equal to zero.

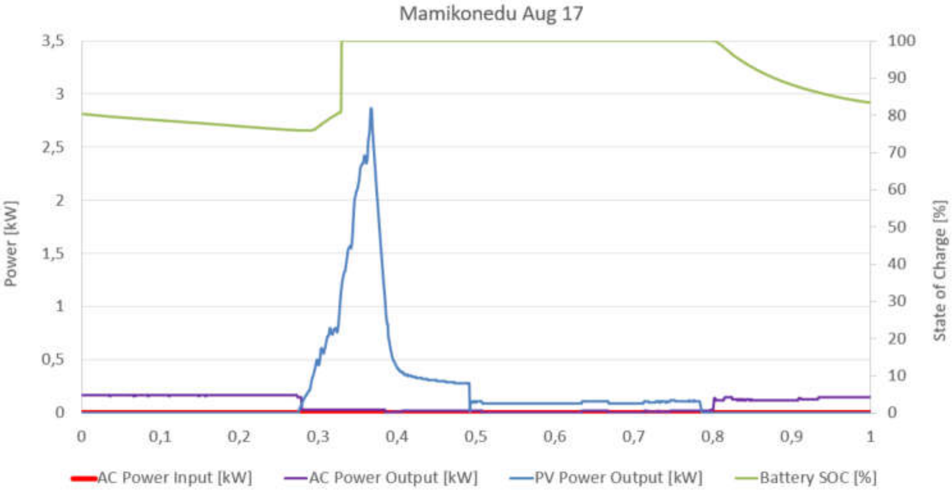


Figure 7.4: Production analysis for Nyengbelahun in August 2017

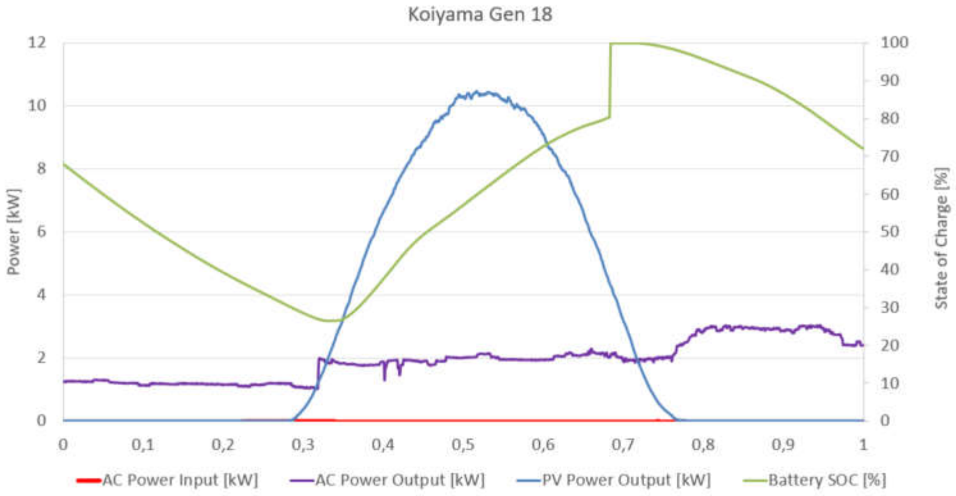


Figure 7.5: Production analysis for Koiyama in January 2018

7.2 Economical Analysis

In this section the costs of the project are discussed. First, the cost of the different components have been analyzed and summarized in table 7.2. These costs are related to the final design described in section 5.2, which is the implemented design. The total cost of the components account for 691,761.3 USD. A total of 373 PV panels were installed, with an unitary price of 225 USD. The all solar modules account for 12% of the total cost, without considering an additional 6% for the mounting structure. The battery banks, traditionally the most expensive component of an off-grid system, constitute 13% of the total cost. This fraction is not the highest, thanks to the low price of the lead acid batteries of 130 USD/kWh. The dispenser systems are the most expensive component of the project (14%). This because one dispenser has been installed in every household (590 dispensers), each with a unitary price of 150 USD. The last big share (12%) is the cost of the accessories, which includes lights, street lamps, poles, tools, screws, clamps, etc.. With the change from the initial to the final design, several components have been avoid, for a total saving that account to 100,622 USD. This change allowed to save almost 15% of the total components cost.

In table 7.3, the total cost of the system is shown. The components cost described in the previous table account for 69% of the total system cost, while the civil work and installation costs are 20%. The cost of the shipping and transportation of the components to the sites are 3% of the total. Finally, the engineering cost is 8% of the total and the last 1% are import taxes. The total cost of the system is 1,007,953.9 USD, for a PV peak power of 96.72 kWp, which means a cost of 10,421 USD/kWp.

According to the simulation (table 5.10), the total investment cost of the project, sum of the capital costs of each system, account for 276,855 USD. This result is consistent with the final cost of the system. In fact, HOMER considers only the cost of PV modules, Diesel generators, inverters and MPPT charge controller, and the sum of these components' costs in the final systems are equal to a total of 318,898 USD, 10% higher than the predicted amount.

Table 7.2: Distribution of the Components Cost

	Costs	
	USD	Percentage
PV Modules	83,995.9	12%
Mounting Structure	43,414.8	6%
Diesel Generators	44,404.6	6%
Battery Banks	88,058.2	13%
Inverters	59,025.4	9%
Charge Controllers	23,062.6	3%
Dispenser Systems	99,256.5	14%
Cables	71,536.4	10%
Distribution Boxes & Rails	37,515.7	5%
Grounding	31,691.8	5%
Electrical Protections	25,899.2	4%
Accessories	83,900.0	12%
Total Components Cost	691,761.1	

Table 7.3: Distribution of the Project Total Cost

	Costs	
	USD	Percentage
Total Equipment Cost	691,761.1	69%
Civil Work & Installation	196,620.9	20%
Design Cost	82,938.3	8%
Shipping Cost	27,543.4	3%
Administrative Charge	9,090.2	1%
Total Cost	1,007,953.9	

7.3 Considerations on the Project

During the realization of this project, several difficulties have been observed. One of the first barrier is the remote location of the sites. In fact, as illustrated in chapter 4, the villages are located at several hours from the main cities and accessible only through by four-wheel-drive pickup truck. This situation influences all the aspects in the installation and maintenance of a min-grid. First of all, the delivery of the equipment to the sites, that can involve complex logistic, delays and, therefore, additional costs. Moreover, the systems were designed to be controlled remotely through the control and communication components (see section 6.1). However, the in the villages no internet connections are available, which creates several disadvantages. For the collection of the production data, for example, the remote control system has to save the data on a SD card, since the communication set can not work. The SD cards must be periodically collected by a technician, before being elaborated and analyzed. This problematic is the cause of the absence of the production data for Taninahum. In fact, due to delays in the collection and delivery of the SD cards, the data are not available yet, despite the system is producing.

The absence of internet connection with the system created also difficulties in the security of the systems. In fact, the remote location of the grid together with the lack of control, make room for improper use of the systems. For example, in some villages have been reported illegal electrical connections to the mini-grid or bypassing of the dispenser. This problematic, not only generate an economic loss, but also a safety issue due to eventual electric shocks or damages to the mini-grid.

An additional problematic faced in this project was due to some lighting failures in Lengbamah village. Despite the electrical protection devices and grounding of all the components, several lighting strikes damaged the system, breaking various components. The Lengbamah village is located on top of a high hill, which causes more lightning issues. The grounding protection in Lengbamah must therefore be improved.

Chapter 8

Conclusions

In this thesis, the design and installation of hybrid mini-grids were presented, illustrating how they can constitute a significant and sustainable option for rural electrification. In chapter 2, the central role of access to modern energy in achieving many of the development goals is underlined. The lack of electricity in fact can make it difficult or impossible for a country to confront the social, economic and ecological challenges that it faces. Especially in Liberia, where its heavily underdeveloped energy sector is one of the most considerable obstacles for the development of the country. In last years, the public authorities, with the support of international funds, made many efforts to improve the situation. This vision for the future proposes the targets of reaching 70% of the capital to be connected to the national grid and 35% of the rural population to gain access to electricity. Given the relatively low load requirements of the villages and the significant solar energy resources, the solar based hybrid off-grid solutions appear to be the best strategy to bring modern energy services to the rural areas.

In this institutional framework, the electrification project of 5 villages in Liberia has been illustrated. First, the energy needs of the different villages have been analyzed in order to define the load profiles of the systems. For the optimal design of the systems the software HOMER was used. The purpose of optimization is to determine the best combination of components, based on the decision variables imposed by in the design.The results obtained by the optimization where then used as comparison for the design implemented by TTA. The outcomes of this comparison highlighted how the first version of the final design was consistent with the theoretical optimal configuration. The final design has then been modified due to budget limitation and renewable energy contribution was decreased, from an average value of 87% to 74%.

Afterwards, the final design has been simulated with HOMER in order to predict to performance of each of the 5 systems. The simulation results were discussed in section 7.1, where they have been compared with the production data of the implemented systems. This comparison underlined as in the first months the electricity consumptions of the villagers were still low and the systems were not used to their full capacity. After some months the use of the mini-grids increased, thanks to the familiarization of the villagers with the systems and their higher electricity demands, reaching in some cases the full potential.

An economic analysis of the project has been discussed, explaining the distribution of the different costs.

The final cost for the electrification was discovered to be 10,465 USD/kWp. The budget cut allowed to saved 100,622 USD of capital investment, correspondent to 12.7% of the total components costs.

In chapter 6, the process in the realization of the systems was elucidated, with the description of the different components used. Finally, in section 7.3 some of the problematic factors encountered in the realization of the systems have been illustrated. Most of these issues, like the difficulties in the delivery of materials to the sites, the absence of internet connection and therefore the lack of remote control of the system are due to the remote location of the installations.

After the economical and implementation analysis of this work, it is certainly that grid centralized grid systems are easier to install, more efficient and cost-effective systems compared to decentralized electricity provision. Especially due to the high cost of investment of the mini-grid, which the rural communities cannot afford. However, hybrid mini-grid systems, when properly designed and supported by international funds, can be a powerful technology for achieving rapid rural electrification, improving at the same time the living conditions of the local population and supporting the socioeconomic development of rural communities.

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