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Hybrid Off-grid Renewable Power System for Sustainable Rural Electrification in Benin

Case of the village of Fouay, Alibori Division.

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ABSTRACT

Rural areas in Benin, as in many sub-Saharan Africa countries are marginalised, in term of electricity assess due to their remoteness from the grid and challenging to access despite most of the country population lives in those places. Lack of access to electricity is one of the leading reason that still restraint economic development and poverty reduction of rural areas. The scalability and universality of Renewable Energy (RE) offered a unique opportunity to power these communities through decentralised energy system, but RE suffered from their intermittent nature. This study aims to analyse the techno-economic feasibility of off-grid Hybrid renewable energy system (HRES) for sustainable electrification in Fouay village, Alibori Division in Benin as well as analysing the market through two economic value, the Willingness To Pay (WTP) and Ability To Pay (ATP). The load demand is analysed through an onsite survey, solar radiation, wind speed is obtained from the meteorological centre and hydro resource estimated were uploaded in HOMER while setting the projects economics and constraints for optimisation and sensitivity analysis. The survey also included qualitative and quantitative questions related to household's financial status and energy situation, used to compute the ATP and WTP of the community for electricity. The techno-economic analysis showed that Hybrid PV/DG/battery is the least cost optimal system with a Net Present Cost of $555492 and COE of 0.207$/kWh. It provides a reliable power supply with 0% unmet load and reduces battery costs by 30% compared to PV/battery system. In environmental view, it achieves 97% CO_2 emissions reduction compared to standalone Diesel Generator with a high renewable fraction of 96.7%. PV/DG/Battery is found to be economically viable than grid extension with a breakeven even grid extension distance of -1.86km and COE lower than the national grid applied of 0.22$/kWh. The market analysis revealed in overall a great Willingness to Pay of households for the electricity and ability to pay for a cost of electricity of 0.45$/kWh higher than the COE of the design system. This study indicated off-grid HRES as, clean, reliable, and affordable technology to power in a sustainable manner the village of Fouay and need to be replicated in other areas of the country for generalisation.

Keywords: HRES, Sustainability, rural electrification, HOMER, WTP, ATP, BENIN

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List of Abbreviations

ABERME	Agency for Rural Electrification and Energy Control
AC	Alternative Current
ACO	Ant Colony Optimisation
AER	Authority of Electricity Regulation
AI	Artificial Intelligence
ANADER	Benin Agency for the development of Renewable Energy and Energy Efficiency
ARE	Apart from the Regulatory Authority for Electricity
ATP	Ability to Pay
BGED	Breakeven Grid Extension Distance
BoS	Balance of system
CB	Conduction Band
CC	Cycle Charging
CEB	Electrical Community of Benin
COE	Cost Of Energy
CONTROLEC	Agency for the Control of Internal Electrical Installations
CSP	Concentrated Solar Power
DC	Direct Current
DD	Depth of discharge
DG	Diesel Generator
DGE	Directorate General for Energy
ECOWAS	Economic Community of West African States
ELF	Equivalent Loss Factor
GHG	Greenhouse Gases
HAWTS	Horizontal Axis Wind Turbine
HC	Health Center
HOMER	Hybrid Optimisation of Multiple Electric Renewables
HPP	Hydropower Power Plants
HRES	Hybrid Renewable Energy System
IC	Investment Cost
INSAE	National Institute of Statistic and Economy
IRENA	International Renewable Energy Agency
IRR	Interest rate of return
LCC	Life Cycle Cost
LCOE	Levelized cost of energy
LF	Load following
LOEE	Loss of Energy Expected
LOLE	Loss of Load Expected
LPSP	Loss of Power Supply Probability

List of Abbreviations

MCA	Millenium Challenge Account
MV	Medium Voltage
NGO	Non-Governments Organization
NPC	Net Present Cost
NRECA	National Rural Electric Cooperative Association
O&M	Operation and Maintenance
PSO	Particle swarm optimisation
PV	Photovoltaic
RE	Renewable Energy
SBEE	Benin Electric Power Corporation
SHS	Solar Home Systems
VAWTS	Vertical Axis Wind Turbines
VB	Valence Band
VDG	Village Distance to Grid
WMO	World Meteorological Agency
WP	Water Pump
WTP	Willingness To Pay

1. Introduction

1.1.Background

All societies require energy services to meet basic human needs (lighting, cooking, space comfort, mobility, and communication) and to serve productive processes. Lack of access to clean, reliable and affordable energy is a major barrier to poverty reduction, economic development and sustainable environment in poorest countries like Benin [1]. Currently, out of the 1.1 billion people worldwide without access to electricity in 2016, more than 600 million are in Africa [2], and where approximately 730 million of people rely on traditional uses of biomass [3]. The situation is even more critical in sub-Saharan Africa where it is projected by 2030, roughly 600 of the 674 million people will still be without access to electricity, mostly in rural areas[4]. Furthermore, at a regional level, the Economic Community of West African States (ECOWAS) comprised in sub-Saharan Africa average an electrification rate of 34%, the lowest in the world with only 8% in rural areas which account for 60% of the region population[5]. Therefore, to reduce poverty in the region and the whole Africa as a continent, energy access in rural areas should be prioritised.

However, in the past, the energy sector worldwide was majorly dominated by conventional sources of energy (Coal, Oil and Natural gas) which has a strong environmental concern due to the huge amount of greenhouses gases (GHG) emissions and have significantly contributed to the global warming. It is reported that the energy sector represents about two-thirds of all anthropogenic greenhouse-gas emissions[6]. Nowadays, with the wake of climate change, technological progress, development priorities and the sharply decreasing in price has accelerated the world's energy transformation towards Renewable Energy (RE) sources such solar, wind, hydropower, and biomass. In 2016, 62% of added power capacity worldwide was from renewables [7].

Moreover, most of the people without electricity live in rural and remote areas difficult to access and far from the grid which make grid extension projects sometimes unfeasible and costly. So, since renewable energy is available everywhere, decentralised electrification systems based RE is one the suitable solution to power those communities sustainably.

Indeed, the drawback with renewable energy is the sensitivity of the power supply to the weather conditions. To overcome this challenge, combining many sources of energy in a hybrid way comprising both renewable and conventional energy in order to compensate the unavailability of another source. This mix system is one of the emerging technology known as Hybrid Renewable Energy System (HRES) to provide a reliable and cost-effective power supply for community far from the grid [8]. Additionally, HRES reduce battery storage [9], reduce CO_2 emissions [10] and increases the energy output of system [11] which could drive economic development. The configuration of Hybrid systems fitting a locality depend on the available resources.

It is worth noting that not only the technological aspect can help only resolve the problem, but it requires putting in place the right mechanisms to ensure the affordability of the system for the community to make the project sustainable.

In this context, that this study aims to discuss the techno-economic feasibility of HRES as well as the willingness and ability to pay of the community for the electricity.

1.2.Problem Analysis & Motivation

Benin is a small country in sub-Saharan Africa with an area of 116.222 Km^2 and a population of around 10.87 million (World Bank, 2016). It has 12 departments comprising 77 Divisions (see Figure 24). The population growth rate is 6.5% (INSAE,2014) and its economy is mainly based on exportation, regional trade (80% of the traffic with Nigeria) and the production of cotton.
The energy sector is characterized by a low energy consumption with an average of 0.41 toe/capita dominated by traditional uses of biomass (firewood and charcoal). This leads to increasing stress on the forest resource and causes health problems to population due to air pollution. The use of firewood and charcoal represents about half of the overall final energy consumption with 3% and 47% for electricity and petroleum products respectively [12]. Furthermore, 88 % of this energy is consumed by households and transport sector. All the petroleum products consumed in the country is coming from outside.

Concerning the electricity sector, only one-third of Benin population have access to electricity with a very low electricity consumption of 104kWh/inhabitant/year in 2015. With an electrification rate of 27.7%, where only 6.9% have access to electricity in rural areas while 54.5% in urban areas (DGE, 2016). This situation is due to the low electricity production capacity and the strong dependence from importation for its electricity supply (Nigeria, Ghana, and Togo). Over the last decades, the percentage share of the importation ranging from 75% to 95% of the total electricity supply. The local production is mainly from thermal plants, and only 80% of those plants are operational despite the efforts from the government side to upgrade the national capacity. Those plants suffered from frequent maintenance, inconsistency in the availability of the fuel and increase in fuel price since the country is not an oil producer. Consequently, this low energy production is not creating a good environment to attract investors, to develop productive activities which could benefit for the economic development of the country by generating jobs and reduce poverty.

However, the country has abundant renewable energy resources untapped such as solar, wind, hydro and biomass which will be exposed in detail in the energy sector section 2.3 of this document. Conscious about the electricity access challenge, the growing energy demand and regarding its renewable energy potential has led the government to set a minimum target of 25 % of RE in the national energy mix by 2025 put some mechanism in place to facilitate this transition[13].

One of them is the establishment in 2014 of the National Agency for the Development of Renewable Energy and Energy Efficiency (ANADER) which plays the role of promoting renewable energy and Energy Efficiency in Benin in alignment with the government vision. Since then, the Republic of Benin has benefited from many regional and national projects in the direction of alleviating the issue of lack of electricity access in rural areas and increase local power production through the support of its technical and financial partners.

So far, most of the project for off-grid rural electrification in Benin are only based standalone solar PV system with battery. Those plants are very limited in capacity and do not allow those beneficiary communities to operate productive businesses which could have generated value and increase their income. Also, due to the stochastic nature of solar energy, the power supply is subject to many fluctuations and population has to adapt themselves to the availability of the power leading to customers dissatisfaction.

Whereas a decentralised energy system with a mix of many sources of energy can reduce their fluctuations, increases the energy output of the system and reduce the energy storage requirements which make the overall system cost-effective [11]. Such kind of system is known as Hybrid Renewable Energy Systems (HRES). It is majorly described in many literatures as an electric energy system, which is made up of one renewable source and one or more sources. These sources could be conventional or renewable or mixed, that works in off-grid or grid-connected mode [9]. This configuration of system could be a viable technology for sustainable rural electrification in Benin. Therefore, there is a need to assess the feasibility of HRES in Benin context which so far to our knowledge, no literature has regarded. The village of Fouay in taken as case study.

Why Fouay village as a case study?

Out of the 12 division of Benin, Alibori and Atacora Division have the lowest connection to the national grid (under 45%), and this percentage reflects the presence of the grid nor explicitly indexing the proportion of people connected or not [14]. The reasons behind this situation are the high connection fee, sometimes-additional expense to extend the network closer to their house and the quality of the service. Furthermore, Alibori Division has the lowest electrification rate in the country of 7.5% (DGE, 2015). Moreover, it has been shown that in the recent report of the National Institute of Statistic and Economy (INSAE) that the Alibori Division is the region where households have the highest monthly energy expense in Diesel Generator [15]. So, regarding the above statistics describing the current state of electricity access in the region, this part of the country should be considered among priority in term of rural electrification.
Against this background, the village of Fouay in the Alibori Division has been selected as case study to find out the best Hybrid Renewable Energy system to sustainable electrify the area and to show the feasibility of such system in Benin environment. The high scenario of electrification through grid extension in the locality is planned in 2018 which is not certain whereas the medium and low are in 2033 and 2032 [16]. In contrast, this Division has enormous renewable energy potential untapped namely solar, wind, biomass and small hydropower potential.

Moreover, most of the paper reviewed on HRES for rural electrification, focus more on the techno-economic analysis, improvement of modelling techniques, comparative analysis of study/configuration system and the reliability of the system. Nevertheless, even though these points are crucial, it is important while designing the system to analyse the socio-economic conditions of the areas to ensure at the same time the affordability which is limited discussed in the literature.

Indeed, the research field of HRES is new, and no project has yet been implemented in Benin so far to our knowledge. Although several studies on hybrid renewable energy system are conducted worldwide, to our knowledge no research for such system in Benin is reported so far.

This study aims to show off-grid HRES as a suitable option for sustainable rural electrification in Benin. So, the village of Fouay is taken as case study to carry the techno-economic feasibility as well as the ability to pay and willingness to pay analysis of the community for electricity.

1.3. Research Questions and Objectives

1.3.1. Research Questions

- What is the current state of energy supply scenario and the renewable energy potential in Benin?
- What are the resources available and electricity demand in the village of Fouay?
- What would be the suitable Hybrid Renewable Energy System (HRES) that meets the load requirements of the village of Fouay which is techno-economic and environmental sound?
- What is the effect of nominal discount rate, fuel price, annual streamflow variation and load growth on the costs and the optimal design HRES?
- Do the design system cost-effective than grid extension considering 15 years of project lifetime?
- Do Fouay inhabitants willing to pay for electricity and able to afford for the optimal design system?

1.3.2. Objectives

The general objective of this work is to design an optimal and affordable HRES for sustainable rural electrification in Benin selecting the village of Fouay as a case study.

1.3.2.1. Specific objectives

- Discuss the energy supply, renewable energy potential and rural electrification scenario in Benin
- Assess the renewable energy potential and the load demand of Fouay village
- Techno-economic analysis and emission reduction of the optimise HRES that meet the demand of Fouay
- Sensitivity analysis on the optimised system with load growth, variable nominal discount rate, variable in fuel price and variable annual streamflow as variables.
- Assess the cost-effective technology between the design off-grid HRES and grid extension if project lifetime is 15 years
- Analyse the Willingness to Pay and Ability to Pay of the community for the optimal design system

1.4. Structure of the thesis

This study is divided into six main chapters and organised as follows. The first chapter is the introduction part which gives an overview of the context in which this thesis takes place, figure out the gaps that the current work seeks to fill and finally expose the objectives and research questions that this study aims to answer to achieve the objectives.

Under the literature review, in chapter 2, the energy sector of Benin Republic is discussed in general, where more insight is given on the current state of the energy supply, the renewable energy potential and rural electrification in the country. In the same framework of literature review, chapter 3 serves as giving the background on Hybrid Energy System. Through basics definition, description of the different components of HRES and modelling. Moreover, software and modellings techniques that have been used so far are discussed.

Basically, the chapter 2 and 3 give the context and the necessary knowledge to understand the concept of Hybrid Energy System and rural electrification in Benin.

Follow up, the methodology (Chapter 4) which highlight the steps trail to achieve the research objectives whereby point out the different methods, sources of data and software used.

Chapter 5 discuss the designing and optimisation of the suitable Hybrid Energy system for sustainable electrification of the study area. It includes the Load assessment, resource assessment, Modeling in HOMER, Optimisation and the willingness and ability to pay analysis. In the end, a short conclusion is drawn for this section.

Finally, in chapter 6 the main conclusions, recommendations, limitations and suggestions for future work are drawn.

2. Energy Sector in Benin

Benin energy sector is characterised by low energy consumption of 0.4toe per inhabitant, with one of the lowest electricity consumption of ECOWAS region of 104 kWh/day/inhabitant. Additionally, it has a low power supply strongly dependent on importation while the demand follows an increasing trend (DGE,2015). The above points mentioned show the high deficit in the power supply and one of the key reason why the economic development of the country is struggling to take off.

2.1. Energy supply

The current energy consumption in Benin is highly dominated by the used of biomass mainly for firewood and charcoal production. For instance, in 2015, biomass-energy accounted for 51 % of the overall energy consumption of the country of 3517 toe. Indeed, a forest land area of 7000000 ha has been estimated in order to provide this service [17]. Which raises the environmental concern and the lack of strong regulation to control the sector. While Climate Change impact is challenging the whole world and effort of each nation is needed to mitigate it. Therefore, Benin country needs to move towards green technologies to reduce pressure on the vegetation which plays key role on Climate Change mitigation by putting in place sustainable policy.
From 2000-2015, the energy consumption in Benin has doubled moving from 1675 to 3517 ktoe (DGE, 2016) while electricity has the lowest share on the final energy consumption (Figure 1) which shows the insufficient power supply.

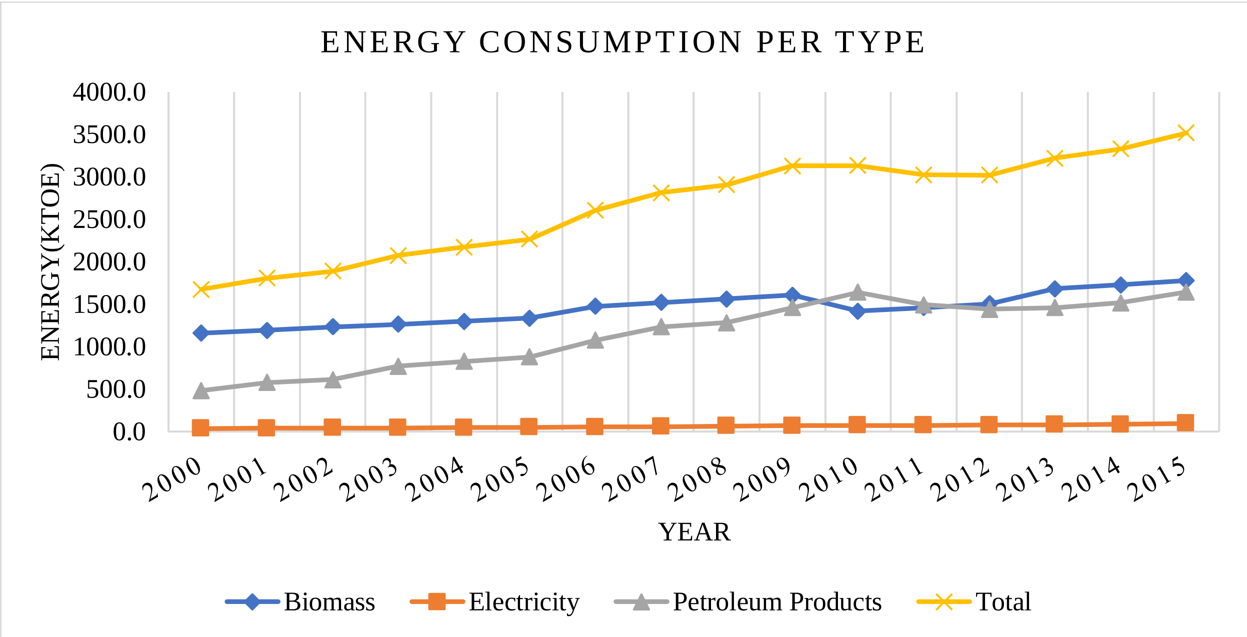


Figure 1: Benin energy consumption per type, 2000-2015, Source: DGE,2016

In addition, by sector, the energy consumption is dominated by household and transport sector where both sectors average yearly of about 87% of the total consumption from 2000 to 2015. It is worth noting the lowest consumption of the industry sector as can be seen in Figure 2. This shows the difficulty faced by the country to provide a good environment to attract industries which have a significant economic impact.

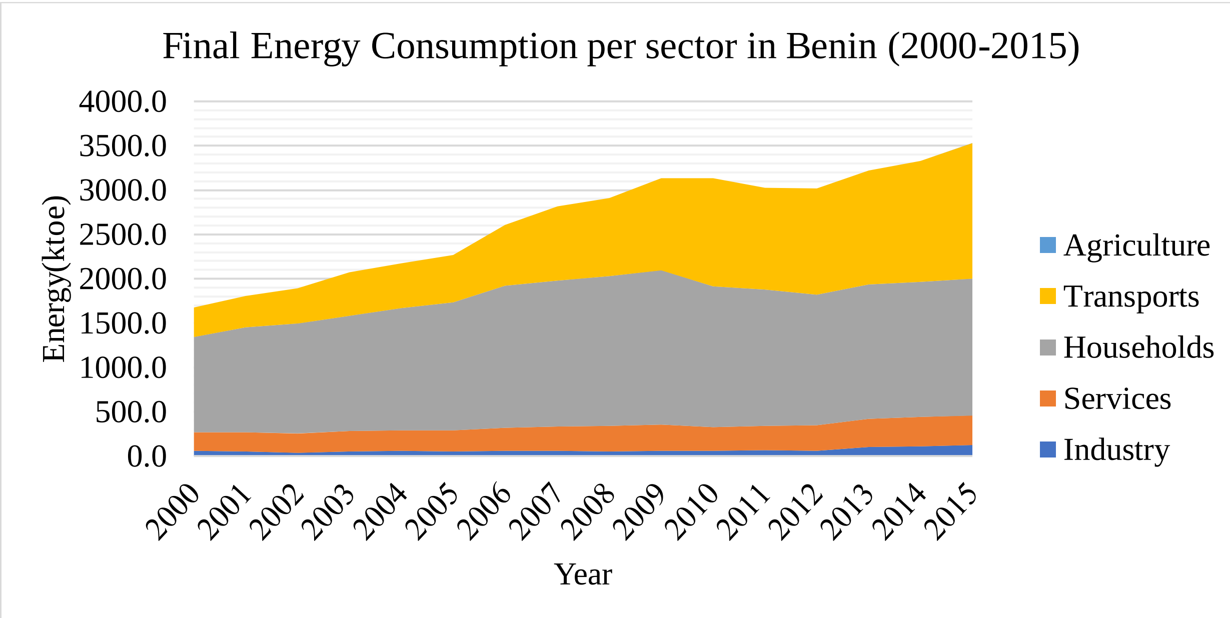


Figure 2: Final Energy Consumption per sector in Benin (2000-2015)

The energy situation of the country is even very critic when looking closely the local production versus the energy imports. Over the last decade, the local production of the country has not exceeded 27% (see trend in Figure 3), and this dependency from outside has resulted in poor power supply quality due to the inconsistency from the providers. In West Africa, Benin Republic has one of the highest rates of power-cut per year (50 days/year) [17]. Also, the renewable energy share on the national production is less than 5 % (Figure 4) while the country has untapped renewable energy potential that can be harnessed. Renewable energy potential of the country is discussed in section 2.3.

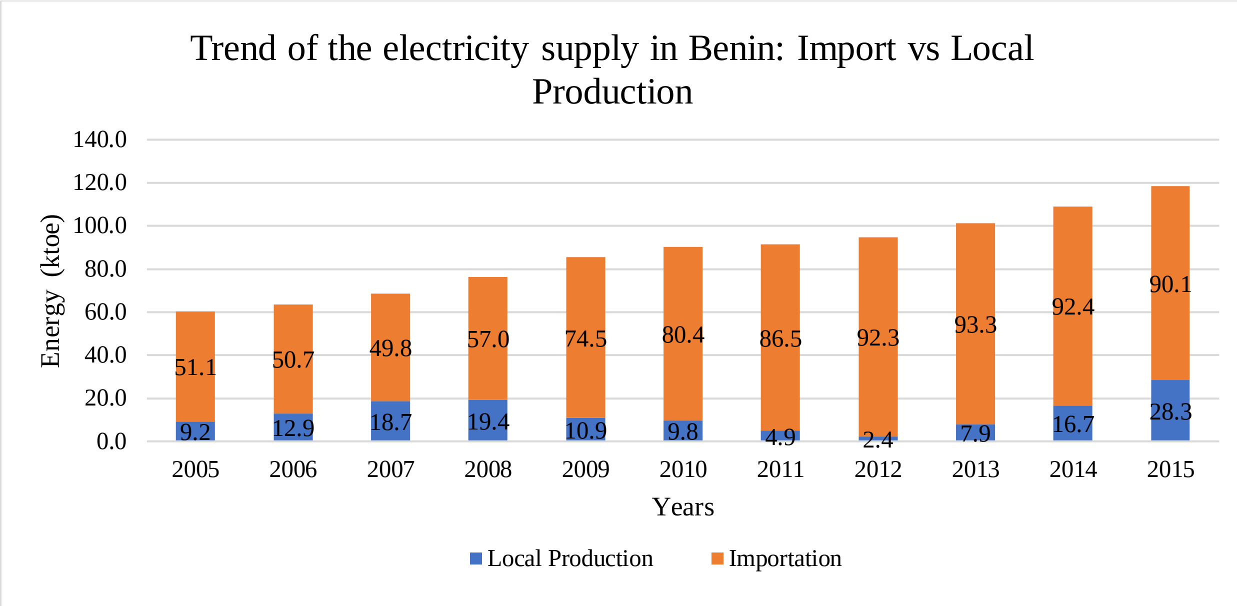


Figure 3: Electricity supply (200-2015): National Production vs Imported Electricity

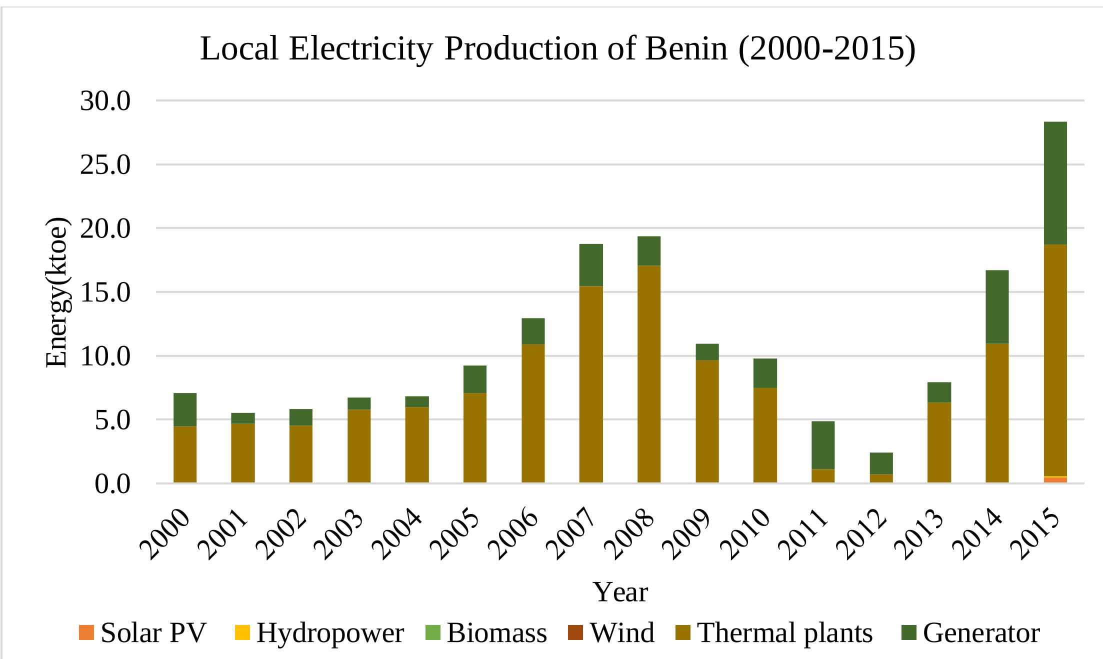


Figure 4: National Electricity Production in Benin (2000-2015), source: DGE, 2017

2.2. Electricity demand, access, and Rural electrification

2.2.1. Electricity demand

As can be seen in the previous section, Benin electricity supply is highly dependent on importation (Figure 3) and the electricity consumption is very low (Figure 1) due to the insufficient power supply. Whereas the demand, in contrast, is growing. According to Benin Electric Power

Corporation (SBEE), the electricity demand has increased from 880 GWh in 2006 to 1100 GWh nowadays (SBEE report 2009-2012). It is expected the same trend of increasing by 2025. Table 1 presents a summary of the electricity demand from 2008 to 2015 and projection to 2025.

Table 1: Trend of the electricity demand in Benin, SBEE report 2009-2012

	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2015**	**2025**
Electricity demand (GWh)	779210	802470	872250	896000	940547	1100000	110000	1800000

2.2.2. Electricity access and electrification

The national electrification rate is very low with a strong disparity between rural and urban areas. In 2015, the national electrification rate is about 27.7% with 56.4 % in urban whereas 6.8% in rural areas [17]. Only 3.5 % of increase has been observed in rural areas electrification rate over the last decade (Figure 5) while most of the country population lives in those areas. Therefore, efforts are needed to power this community, to give them, means to drive productive activities which will increase their income and reduce the poverty level in the country.
Furthermore, out of the 12 Division in the country, only the Littoral Division has the highest rate of electricity access and above 50% (Figure 6). This is due to the high concentration of the population in this area and the economic power carried by the fact that all the major governments or organization bodies of the country have them headquarter over there.

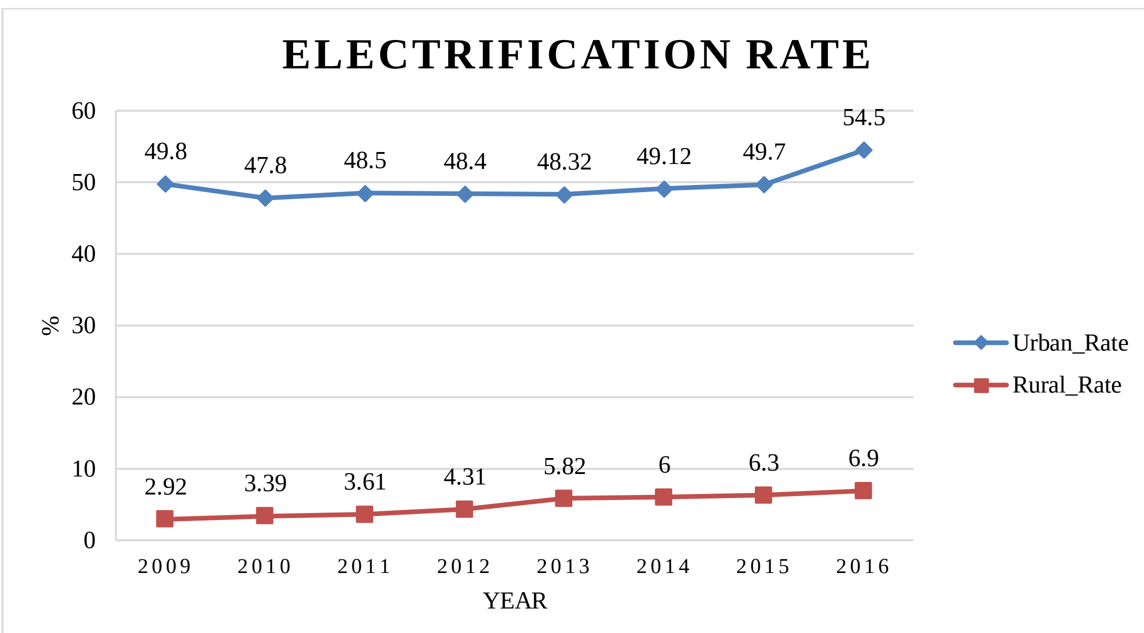


Figure 5: Electrification rate in trend Benin: Urban vs Rural areas [18]

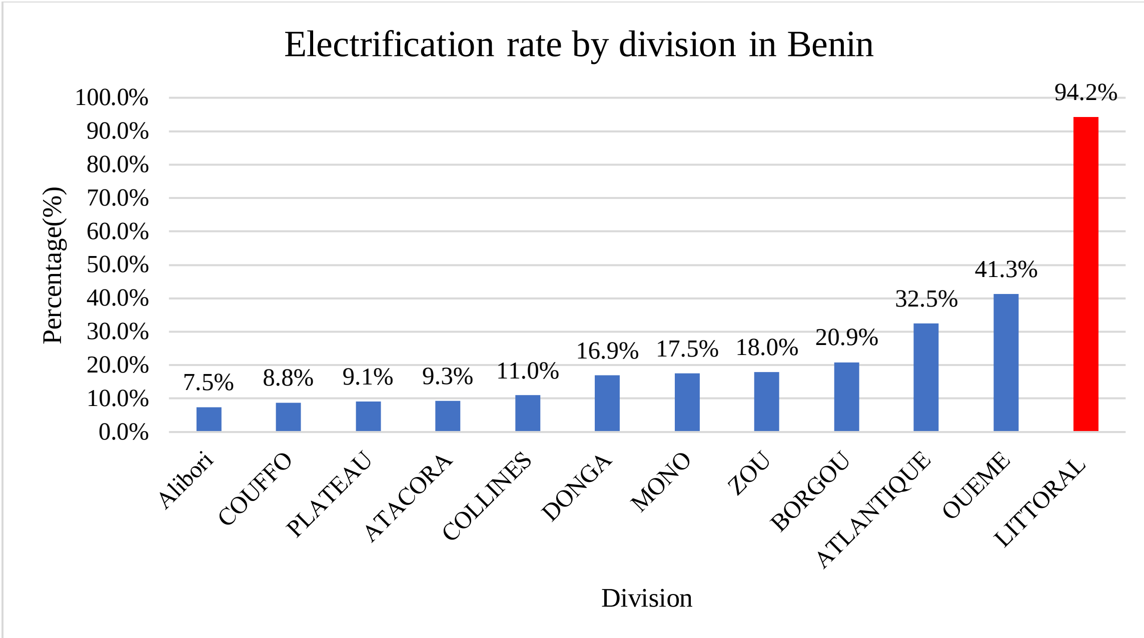


Figure 6: Electrification Rate per Division in Benin

2.3.Energy potential

2.3.1. Energy potential: Solar Energy

The average sunshine in Benin varies from 3.9 to 6.1 kWh/m²/day from the South to the North[19]. The month with high potential are March and December while the lowest is observed from June. The production is around 1560kWh/kWp, 1460kWh/kWp and 1400 kWh/kWp installed per year respectively in the Northern, middle and in humid south part of the country [14].

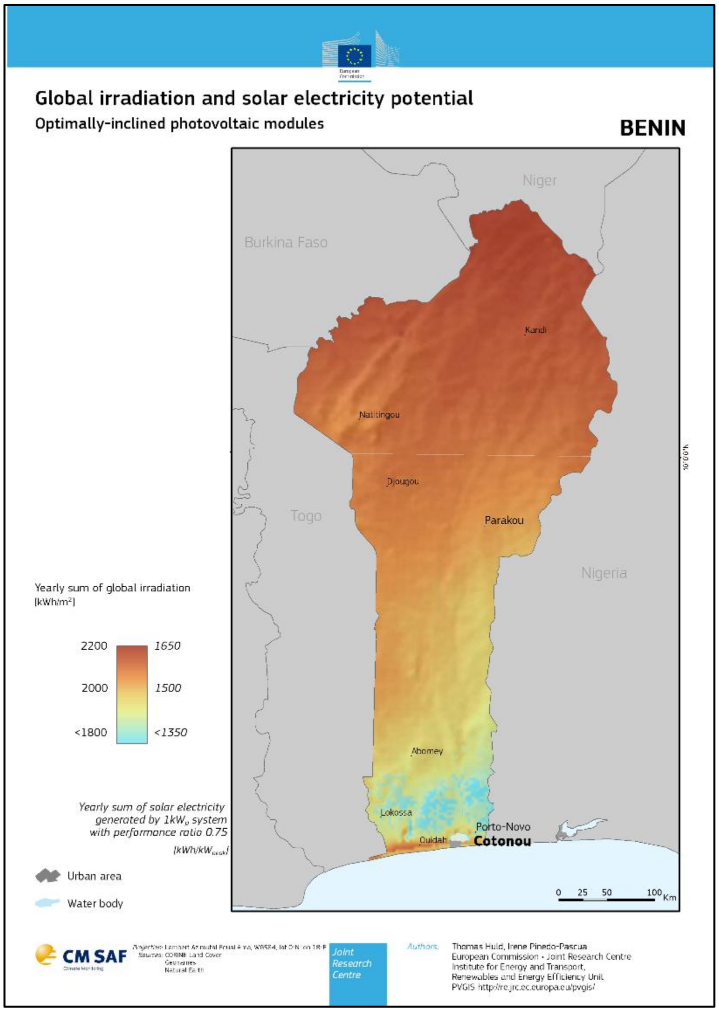


Figure 7: Solar Energy potential of BENIN

2.3.2. Energy potential: Wind Power

The wind speed measured at an altitude of 10 m varies from 3 to 5 m/s[19]. As can be seen from Figure 8, favourable areas are in the West Northern part and Southern region along the coast of the country. The exploitation of wind energy is currently not profitable, apart from some sites not yet identified (micro-climates) and which could accommodate small wind projects[13].

2.3.3. Energy potential: Hydropower

The country hydropower network is concentrated on four major basins, the Niger and Volta Basin for the North, the basin of Ouémé for the middle and the south and finally the Couffo Basin in the West South part. The theoretical hydropower potential for Benin is estimated to be 749 MW (reference period 1998-2014), which is the total of all rivers in the country[20]. Table 2 shows the distribution of theoretical hydropower potential in Benin across different size.

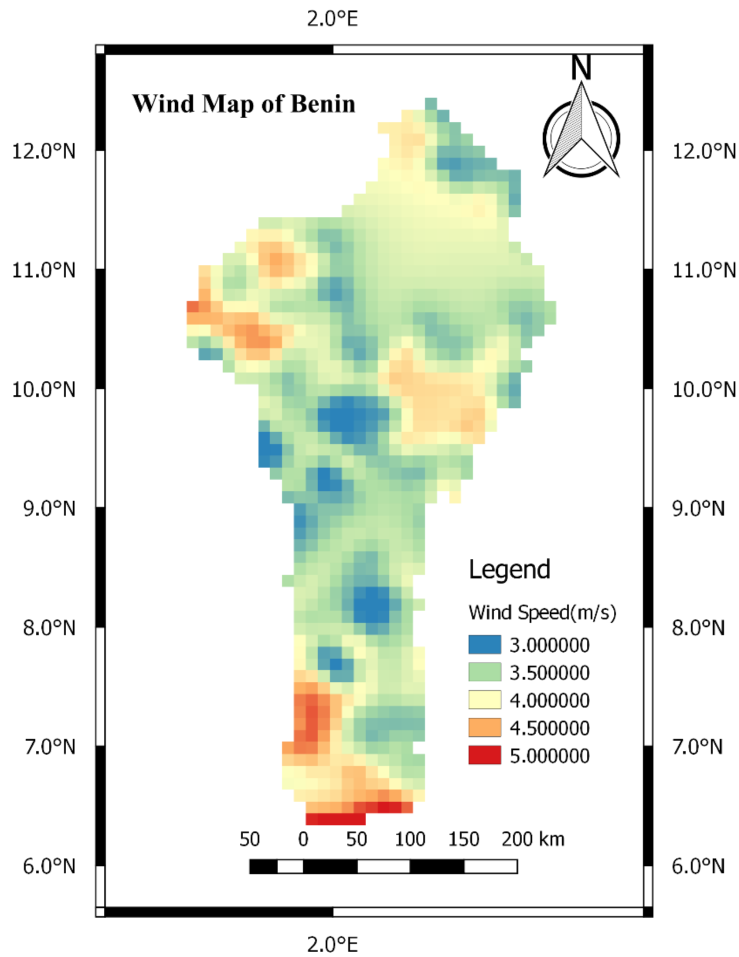


Figure 8: Wind map of Benin derived from [21]

Table 2: Theoretical Hydropower potential of Benin's Republic from [22]

Theoretical Hydropower Potential of Rivers in Benin	
Pico/micro/mini HPP 5 MW	5MW
Small HPP 90 MW	90 MW
Medium/large HPP 239 MW	239MW
No attractive potential 415 MW	415 MW
Total of all rivers in country 749 MW	749 MW
Total of rivers with attractive theoretical potential for pico/micro/mini, small, or medium/large HPP	334 MW

A list of 82 potential sites for mini-hydropower (7kW to 8.7 MW) with a total capacity of 48MW and annual production of 193 GWh / year is available [14] and spread across the country as shown in Figure 9.

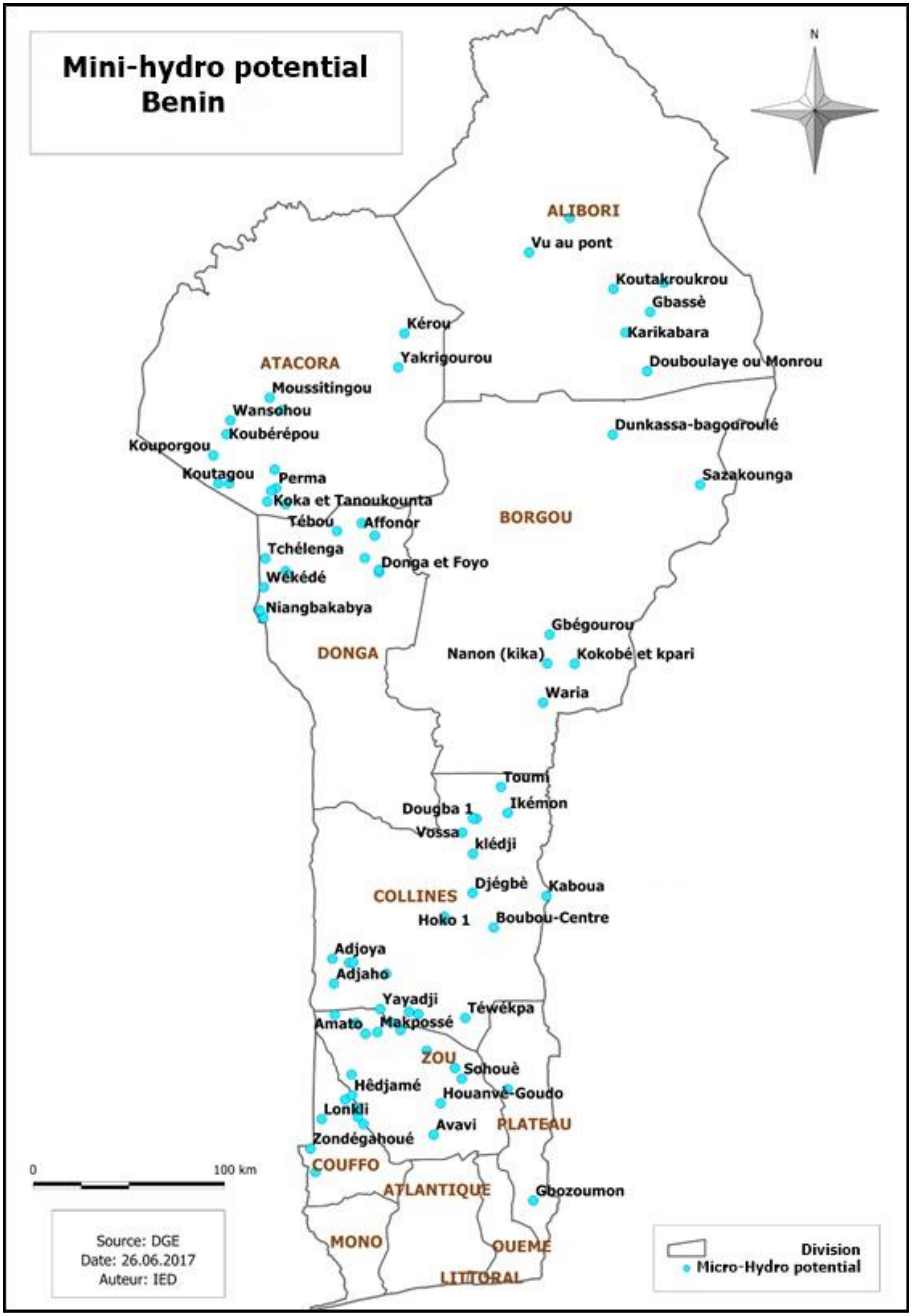


Figure 9: Map of potential mini-hydropower site in Benin from [14]

2.3.4. Energy Potential: Biomass

Benin has a huge potential in bioenergy especially using agriculture residues which at present remains untapped and are majorly burned on the field. The estimated amount of agriculture residues generated by crops type in 2015 and the corresponding energy potential that can be derived are summarized in Table 3.

Table 3: Agriculture residues and producible estimation in 2015 [13]

Crops Type	Average Production (ton)	Residues or other sub-Product	Ratio residue/product	Quantity of residues available (tons)	Calorific Value (kcal/kg)	Available Energy (ktoe)	Potential electricity Production (MWh)
Maize (local)	23772807	Raffles	1.00	23 772 806.80	3 500	83204.8	96725607
		Stems and leaf	3.00	71 318 420.40	2 500	178296.1	207269159
Rice	115780685	balls	1.00	115 780 685.00	3 000	347342.1	403785139
		Straw	0.25	28 945171.25	2 500	72362.9	84121904
Small Millet	12346	rods	2.00	24 692.00	2 500	61.7	71761
		spikes	0.50	6173.00	3 500	21.6	25116
Sorghum	152893	rods	2.00	305 786.00	2 500	764.5	888690
		spikes	0.50	76 446.50	3 500	267.6	3110417
Cotton	266497	Stalks and stalks	2.70	719 540.82	4 100	2950.1	3429511
		hulls	0.30	79 948.98	3 900	311.8	362468
		Inter	1.00	266 496.60	3 500.00	932.7	1084308
TOTAL							100811813

It has been shown that the use of agriculture residues for electricity production can generate up to 2700 GWh by 2020.
Regarding household garbage, for only the economic city of Cotonou in 2010, 700tons of garbage is produced per day which can be used to power a plant size capacity of 5MW. Furthermore, only 6% of the actual cultivated land is needed to cover the country need in biofuel by 2020, based on a production of 11150 million litres of ethanol and 207 million litres of biodiesel by 2020[17].

2.4. Institutional Framework of the Energy Sector

The institutional framework of Benin energy sector is organized as described in the diagram below:

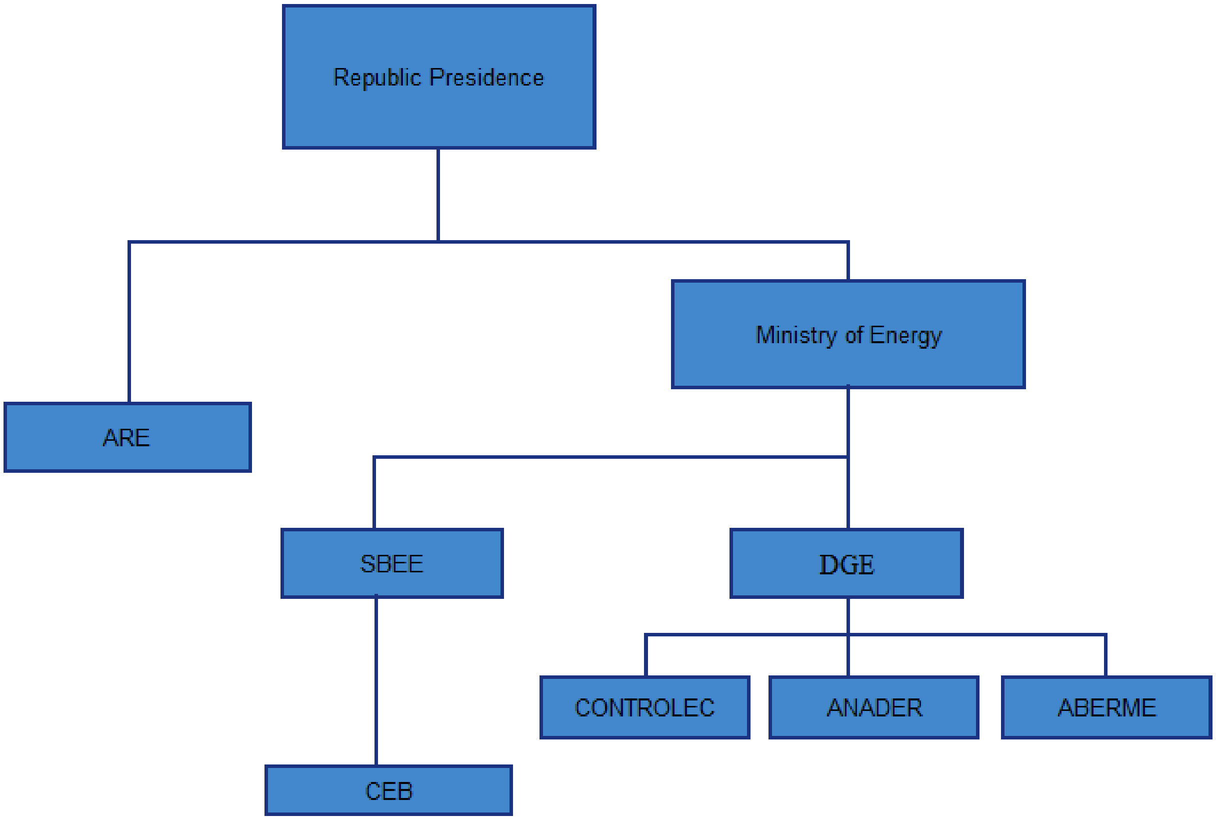


Figure 10: Benin Electricity Sector Organization Chart

The Ministry of energy is responsible for the management of the energy sector and in particular the subsector of renewable energy. It guides the national policy on energy and supervises all the structures/agency directly involved in the energy sector apart from the **Regulatory Authority for Electricity** (**ARE**).

The Directorate General for Energy (DGE), liaising with other relevant national bodies, proposes the state policy in the energy sector, ensuring its implementation, monitoring, and evaluation.

The **National Agency for Rural Electrification and Energy Contro**l (**ABERME**) implements the state policy in the field of rural electrification and energy control.

The **Electrical Community of Benin (CEB)** oversees the importation, production, and distribution of electrical energy of Benin and Togo.

The **Benin Electric Power Corporation (SBEE)** provides distribution and marketing of electricity in Benin.

The **Agency for the Control of Internal Electrical Installations** (**CONTRELEC**) whose mission is to control the indoor electrical installations of residential buildings of new subscribers of the **SBEE**, before connection to the grid[23].

The Authority of Electricity Regulation (AER) ensures compliance with laws and regulations governing the subsector of electricity, protect the public interest and ensure continuity of service, quality services, the financial balance of the subsector and its harmonious development.

Benin Agency for the Development of Renewable Energy and Energy Efficiency (ANADER), promote the development of renewable energy and energy efficiency in alignment with the government vision.

In general, the energy sector is characterized by:

- Low energy consumption mainly dominated by households in form of biomass-energy for firewood and charcoal production
- Low energy supply with a lowest consumption for the industry sector
- 100% of petroleum products are imported and more than 80% in term of electricity supply
- Low electricity consumption per capita due to the insufficient power supply and continuous increase electricity demand
- Low electricity access with a huge gap between rural and urban areas
- Renewable energy share is very low while the country has untapped potential

3. Modelling and Simulation of Hybrid Renewable Power system

3.1. Introduction

Hybrid Renewable Energy Systems (HRES) are defined as an electric energy system, which is made up of one renewable source and one or more sources. These sources could be conventional or renewable or mixed, that works in off-grid (standalone) or grid-connected mode [9]. HRES working in standalone mode is one of the most promising applications of renewable energy technology in remote areas, where the grid extension is costly, and the cost of fuel increases drastically with the remoteness of the location [24].

Different hybrid configuration is adopted depending on the resources available at the location such as solar, wind, Biomass or micro-hydro power and its potential. Also, most HRES incorporate backup power through batteries, fuel cell or/and diesel engine generator. For instance, S. Rehman et al., 2016 found that Hybrid PV/Wind/DG/battery is an attractive option for off-grid rural electrification in Pakistan. Londe et al.,2017 study results showed that a Wind/Diesel Generator/Battery-powered microgrid has the lowest cost for with a breakeven grid extension distance of -45.38 km and is a viable option for electrifying far from the grid unelectrified areas of the Eastern Cape of South Africa. While Basir Khan MR et al.2015 found integrating the PV, micro-hydro and battery system to the existing diesel generator systems is the most favourable option based on current energy situations in Tioman Island in the South China Sea.

In this study, Solar, Wind, and Hydropower are the main sources assessed while for energy storage Battery and Diesel Generator are considered. Since some PV panels power output is in DC and Hydro, Wind in AC, Converter comes into play to serve as an interface between the two systems.

3.2. Description and modelling of Hybrid Energy component

3.2.1. Photovoltaic System

Two main type of technologies are used nowadays to harness solar energy for electricity production namely solar photovoltaics (PV) and Concentrated Solar Power (CSP). For decentralised energy systems, the solar photovoltaic system is mostly used compared to CSP. Most of CSPs are for on-grid electricity generation, and they are medium or large plants (in the order of MWs) which can benefit from the economies of scale [25].

Basically, solar PV modules are composed of solar cells which are made of semiconductor converting the sunlight into electricity. Most commercial solar cells consist of silicon doped with small levels of controlled impurity elements, which increase the conductivity because either the conduction Band (CB) is partly filled with electrons (**n-type** doping) or the Valence Band (VB) is partly filled with holes (**p-type** doping) [26]. Current flowing in the semiconductor is generated by the movement of light when p doped, and n doped are brought together. So, when photons with enough energy strike on PN-junction, it allows electrons to move from the VB to the CB creating an electron-hole pair. Then, the PN-junction separates the electrons and holes to generate external electric current. The n-type and p-type silicon become the negative pole and the positive pole respectively of the solar cell (Figure 11).

However, the properties of the PV modules depend intrinsically on the type of solar cell they are composed of and the interconnection among modules. Solar cells can be classified into three main generation. The first-generation of solar cells are based on silicon wafers while the second are on amorphous silicon, CIGS, and CdTe. The new promising technologies are classified in the 3rd generation such as Nanocrystal-based solar cells, Polymer-based solar cells, Dye-sensitized solar cells and Concentrated solar cells. In the interconnection side, solar cell put together in series increase the voltage while increasing the current in parallel.

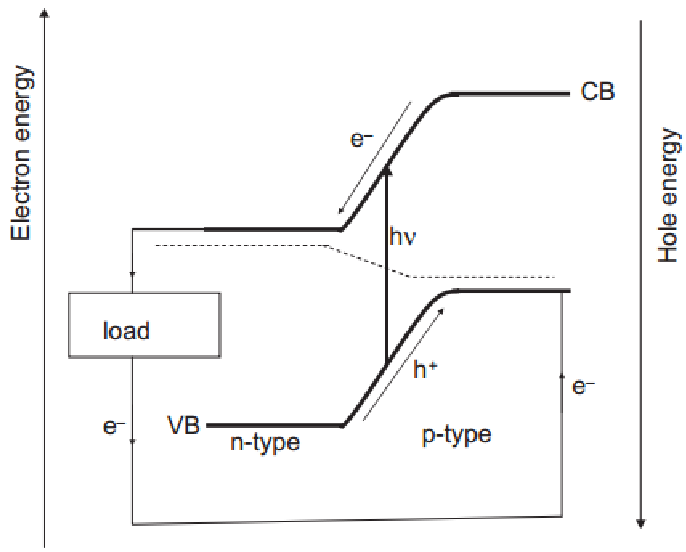


Figure 11: The working mechanism of a silicon p– n -junction solar cell [26]

The standard model representing real solar cells (or called one-single model) is shown in Figure 12 which goes deeper into electrical losses in the solar cell. These imperfections are clumped into Series Resistance (Rs) and Parallel resistance (Rsh) [27].

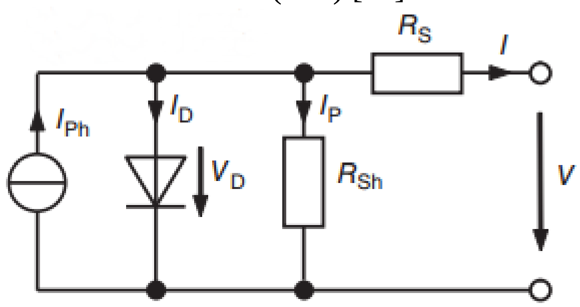


Figure 12: Standard equivalent circuit for real solar cells

The characteristic curve equation of the standard model:

$$I = I_{Ph} - I_S \cdot \left(e^{\frac{V + I \cdot R_S}{m \cdot V_T}} - 1 \right) - \frac{V + I \cdot R_S}{R_{Sh}} \quad (1)$$

where I is the output current (A), Is is the inverse saturation current which depends on temperature, Iph is the photocurrent (A) which depends on solar radiation and cell temperature, V is output voltage, Rs is series resistance.

Hourly power output from PV system Psj (kW) with an area Apv (m^2) on an average day of the j^{th} month is given by equation 2 when total solar radiation of Itj (kW/m^2) is incident on the PV surface[28].

$$P = I_{tj}.\eta.A_{PV} \tag{2}$$

Where system efficiency η is given by equation 3

$$\eta = \eta_{pc}.\eta_m.P_f \tag{3}$$

η_m , PV system efficiency is defined as follows [29]:

$$\eta_m = \eta_r[1 - P_f.\beta(T_c - T_r)] \tag{4}$$

$$T_c = T_a + \frac{\alpha\tau}{U_l} I_T \tag{5}$$

$$\frac{U_l}{\alpha\tau} = \frac{I_{t,NOCT}}{(NOCT - T_{A\,NOCT})} \tag{6}$$

The efficiency η is given by equation, η_r is module reference efficiency, η_{pc} is power conditioning efficiency, P_f is power factor, β is array efficiency, Tr is reference temperature, Tc is monthly average cell temperature is calculated using the equation 5. Ta is instantaneous ambient temperature, $NOCT$ is normal operating cell temperature, $I_{t,NOCT}$ = 800W/m2 for a wind speed of 1m/s (B. Bhandari et al.,2015, Sawle et al.,2016).

3.2.2. Wind Energy modelling

Historically, wind energy was used to pump water, mill grain and other mechanical power applications. Nowadays, with the wake of climate change, wind energy is widely used for electricity production since it is free and do not pollute the environment. Furthermore, on-shore wind is now one of the lowest cost sources of electricity available, and in Africa, the LCOE range is between USD 0.046 to USD 0.145/kWh[3].
However, the working principle of wind turbines is basically, the conversion of kinetic energy of the wind into mechanical energy and then in electrical energy through a generator. The wind turbines are classified based on the orientation of the blades. The Horizontal Axis Wind Turbine, or HAWTS, and Vertical Axis Wind Turbines, or VAWTS [27].
To estimate the economic feasibility of wind projects and to design turbines, wind speed estimates are required at elevations from 60 to 100 m above the ground level (Ray *et al.*, 2006). Measurement is usually taken at 10 m height; therefore, extrapolation methods are used to determine wind speed at different. One of them is the power law profile equation where the wind velocity increases with height above the ground and is represented by the formula below [30]:

$$\frac{V_1}{V_2} = \left(\frac{Z_1}{Z_2}\right)^{\alpha} \tag{7}$$

Where:

Z_1: wind velocity at some reference height Z_1;

Z_2: wind velocity at height Z_2 *and*
α: Hellman exponent.

The constant Hellman exponent (α) depends on the nature of the surface, the stability of the air, temperature, time of the day, season, and surface roughness (Ozgonenel and Thomas, 2012). For instance, the smooth terrain has 0.10; grass ground has 0.15, land with shrubs and hedges has 0.2 and coefficient will as per the ground roughness[31].

Another way, the wind speed can be adjusted to hub height according to a logarithmic profile by equation used by [32]:

$$v(Z_0).ln\left(\frac{Z_r}{Z_O}\right) = v(Z_r).ln\left(\frac{Z}{Z_2}\right) \quad (8)$$

Where:
Zr: is the reference height (m);
Z : the height where wind speed is to be determined (m);
Z_0: the measure of surface roughness (0.1– 0.25 for cropland);
$v(Z_0)$: the wind speed at the height of Z m (m/s) and
$v(Z_r)$: the Wind speed at the reference height (m/s).

The theoretical power available from the wind turbine is given by the equation following [28], [30]:

$$P = \frac{1}{2}\left(\rho C_p . A . V^3\right) \quad (9)$$

Where ρ is the air density (kg/m^3), is the swept area of the rotor blades (m2), V is the velocity of wind (m/s) and Cp is the power coefficient of the wind turbine known as Betz limit. The theoretical maximum power of the turbine can be extracted for a cp value of 0.593. Which means that, only 59% of the wind power can be used by the wind turbine (J. Sawadogo et al., 2015).

The power curve of a wind turbine is a graph that represents the turbine power output at different wind speeds values.

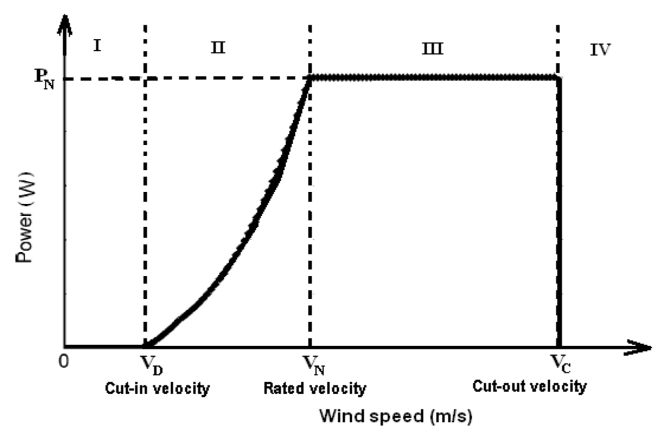


Figure 13: Power and efficiency curves characteristics of wind turbine

The cut-in speed is the speed of wind required to set the turbine in motion whereas the cut-out speed is the wind speed at which the turbine stops for safety reasons. When the wind turbine is defined by its cut-in speed (*Vi*), rated wind speed (*Vr*) and cut-out speed (*Vc*), the wind power output from the wind turbine, P_T can be determined from its wind turbine performance curve by summing the following terms[33]:

$$P_T = \begin{cases} 0 & , \quad \text{for } V < V_I \\ \frac{1}{2}\rho A \int_{V_i}^{V_r} V^3 & , \quad \text{for } V_i < V \geq V_r \\ P_r A \int_{V_r}^{V_c} f(v)dV & , \quad \text{for } V_r < V \geq V_c \\ 0 & , \quad \text{for } V > V_c \end{cases} \qquad (10)$$

where P_r is the rated wind power expressed by:

$$P_r = \frac{1}{2}\rho A V_R^3 \qquad (11)$$

3.2.3. Hydropower modelling

Hydropower is the largest renewable energy source, and it produces around 16 % of the world's electricity and over four-fifths of the world's renewable electricity[34]. Hydro-turbines convert water pressure into mechanical shaft power, which can be used to drive an electricity generator [35]. Hydropower plants can be classified according to the size of installed capacity, head availability, operation regime, and purpose of plants structures[36].

Regarding the operation scheme or hydraulic characteristic can be divided into:

1. *Run of the river*: schemes generate electricity by immediate use of the inflow.
2. *Storage* schemes: a scheme which has water storage in upstream of a dam structure to create a reservoir that helps to operate for the whole year especially dry time.
3. *Pump storage* schemes: store water by pumping it from a lower reservoir or a river to a higher reservoir.

Depending on the head being exploited for electricity production, Hydropower plants scheme are divided into the following categories:

1. High head: H > 100 m
2. Medium head: 30 m < H < 100 m
3. Low head: H < 30 m

Concerning the installed capacity, hydropower plants can be classified as shown in Table 4 and this classification varies from one country to another.

Table 4: Classification of Hydropower Plants based on Power Output

Type of plant	Unit size	Total installed capacity
Micro	1 to 100kW	Up to 1000kW
Mini	101 to 1000kW	Up to 2000kW
Small	1001kW to 5 MW	Up to 25MW
Medium	15 to 50 MW	Up to 250 MW
High	Above 50 MW	Above 250 MW

However, apart from its main purpose of generating electricity, hydropower plants can be used for flood prevention, drought mitigation, irrigation, water supply and improving conditions whereby raising the water level in a reservoir improves conditions for navigation, fishing, tourism and recreation [36].
Turbine is the main piece of equipment in the hydropower scheme that converts the energy of the falling water into the rotating shaft power [37]. Hydro-turbines can be grouped according to the head as presented in Table 5.

Table 5: Groups of water Turbines [37]

Turbine Runner	***High Head***	***Medium***	***Head Low***	***Head Ultra- Low Head***
Impulse Pelton	Turgo	Crossflow Turgo Multi-jet Pelton	Crossflow Multi-jet – Turgo	Waterwheel
Reaction		Francis Pump- as – turbine	Propeller Kaplan	Propeller Kaplan

The selection of the most suitable turbine for any particular hydro site depends mainly on two of the site characteristics – head and flow available and is presented in the chart Figure 14.

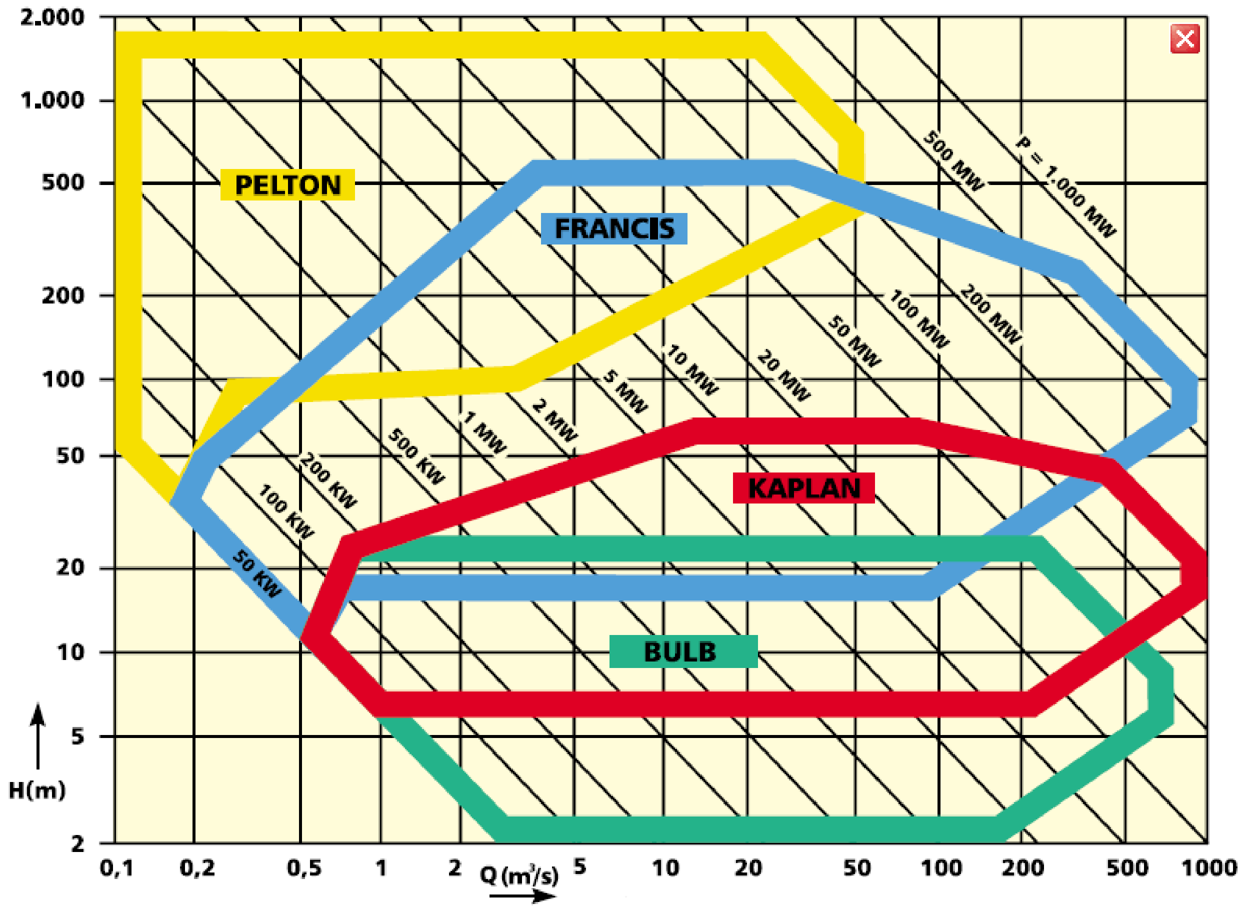


Figure 14: Turbine Application Chart based on Head and Discharge (S. A. Pereira et al.,2015)

Hydropower power theoretical power output at a specified head and discharge is expressed by the equation[35], [36]:

$$P=\rho \times g \times Q \times \eta \times H \tag{12}$$

where:

P	Power at the generator terminal, in kilowatts (kW)
ŋ	is the overall efficiency of the power plant
ρ	is the density of water [1000 kg/m³]
g	is the acceleration due to gravity [9.81 m/s²]
H	is the net head [m]
Q	is the volume flow rate passing through the turbine [m³/s]

The river discharge is not constant in time and is influenced by seasonal variation and weather parameters. Accurate information on the river streamflow over a certain period is important to estimate precisely the potential power generation through gauges stations. However, the discharge data are sometimes unavailable on sites where hydropower potential is found. So, different methods of streamflow estimation on ungauged stations are used and can be mainly be classified into three groups: empirical methods, statistical methods and rainfall-runoff models (also known as catchment modelling) [32], [37], [38].

3.2.4. Battery modelling

Renewables energy are intermittent sources of energy due to continuous changing that occurs in the weather. Therefore, energy storage comes as one of the suitable solutions to resolve this issue thereby when there is a favourable condition the excess of energy produced, is stored and injected back when it is not. In standalone power supply system batteries are widely used as backup to compensate the unavailability of the main source of energy.
Battery sizing depends on the maximum depth of discharge (*DD*), temperature, and battery life [28], [29]. The battery capacity needed for a given load demand and autonomy by the equation 13 and used by [8], [28], [39] in there is work.

$$B(Ah) = \frac{E_C . D_s}{DD_{max} . \eta_t} \tag{13}$$

Where *Ec* is the load in ampere-hour (Ah), Ds is the battery autonomy days, DDmax is the maximum battery depth of, ηt is the temperature correction factor. The battery state of charge (S_c) at any instant is expressed as follows:
During charging process

$$S_C(t+1) = S_c(t)[1-\sigma(t)] + [I_B(t)\Delta t . \eta_c(t)/C_B] \tag{14}$$

While during charging process :

$$S_C(t+1) = S_c(t)[1-\sigma(t)] - \left[I_B(t)\Delta t . \frac{\eta_D(t)}{C_B}\right] \tag{15}$$

where:

S_C state of charge;
$\sigma(t)$ hourly self-discharge rate depending on the battery;
CB the nominal capacity of the battery (Ah);
IB battery current;
η_c charge efficiency (depends on the Sc and the charging current and has a value between 0.65 and 0.85); and
η_D discharge efficiency

Charge quantity of battery bank is subject to constraints expressed as follows:

$$[1 - DD] \leq S_c(t) \leq 1 \tag{16}$$

3.2.5. Diesel Generator modelling

Apart from the battery, Diesel Generator (DG) is used as backup to compensate when low production from other sources is experienced. In various HRES, DG acts as a steady source of power. The DG systems are designed to supply the load and also charge batteries if the renewable energy source along with battery is unable to supply the load [39].
Notton G et al. (1996) presented two cases that should be considered when determining the rated capacity of diesel Generator.

1. The case if DG is directly connected to load, then the rated capacity of the generator must be at least equal to the maximum load, and
2. When the DG is used as a battery charger, then the current produced by the generator should not be greater than CAh/5A, where CAh is the ampere-hour capacity of the battery.

The total efficiency of the DG is expressed as [26],[37],[39]:

$$\eta_T = \eta_b . \eta_g \tag{17}$$

Where η_b, is the brake thermal efficiency and η_g the generator efficiency. In addition, El-Hefnawi SH et.al, 1998 study has shown since diesel generators are modelled in the control of the hybrid power system in order to achieve required autonomy. It is observed that if the generator is operated at 70–90% of full load then it is economical. Generator fulfills the load demand and battery charging if peak load is not available.

The fuel consumption per hour is given the formula following:

$$Consumption\ per\ hour = APg + BPng \tag{18}$$

where Pg and Png are the power generated, and nominal power of the DG while A and B are coefficients of the consumption curve in kWh.

3.2.6. Converter Modeling

In HRES, sources with AC and DC are used. Therefore, an interface is needed to manage the exchange flow among components, and this is played by the converter. The power delivered by an inverter is given by:

$$C_{out} = \frac{(C_{in} - C_{NL})}{B_{out}} \tag{19}$$

$$B_{out} = \frac{(\frac{C_R}{\text{Ŋ}_R} - C_{NL})}{C_R} \tag{20}$$

where *C*out is the output power in kW, *C*in is the input power in kW, C_{NL} is no load power in kW, *B*out is the constant relating input power to output power, *C*R is the rated power output in kW and Ŋ_R is the rated efficiency (Jacob and Arun 2012).

3.3. Software and Methods for designing Hybrid Energy system

For designing the optimal configuration of Hybrid Renewable Energy System to meet specific load demand, various criteria are used. The two main criteria for any hybrid system design are reliability and cost of the systems[29], [41]. The reliability of the system is defined as the ability of electrical power system to supply the system load having reliable continuity and quality of supply[42]. The Loss of Power Supply Probability (LPSP), Loss of Load Expected (LOLE), Loss of Energy Expected (LOEE), Equivalent Loss Factor (ELF) are some reliability indices commonly used in literature. While the Net Present Cost (NPC), Life Cycle Cost (LCC) and the Levelized cost of energy (LCOE) are criteria used relating to the cost of the system. LPSP and LCC are described as examples.
For instance, the LPSP equations are defined as in the equation 21[43].

$$LPSP = \frac{\sum TIME(if\ P_{avail}(t)\ < P_L(t))}{T} \tag{21}$$

where T is the number of hours in the study, P_L is the energy consumed, and Pavail(t) is the sum of the power produced by each of the sources considered in the system sizing.
When $Pavai(t) < PL(t)$, the reliability analysis is significant. If a system in the electrical field has insufficient power to feed the load demand, i.e., has a small LPSP, it is regarded as a reliable system. An LPSP of zero means that the load demand is absolutely satisfied; and a LPSP of one means that the power generated does not meet the demand of the load (W. Dong et al.2016).

The optimal the configuration presenting the lowest Life Cycle cost is selected. The calculation of LCC is as follow:

$$PV = \sum_{k=1}^{t} \frac{C_t}{(1+i)^t} \tag{22}$$

$$PV_D = (C+m)_{pv} + (C+m)_{wind} + (C+m)_{battery} + (C+m)_{diesel} + (C+m)_{......} - D \tag{23}$$

where PV and PV_D are the present value of the system without and with depreciation, t is the time of analysis, i is the interest rate per year, Ct is the cost in year t, m is the maintenance cost of the system, and D is the present value of depreciation[8].

Indeed, various software tools and methods are used for HRES optimisation. HOMER, PVSYS, RETScreen, SOMES, ARES are some of the software tools widely used in literature. While optimisation techniques methods include Graphic construction, Probabilistic, Iterative and Artificial Intelligence (AI). More detailed about each of those methods and software tools can be found in the review done by Y. Sawle et al. 2016, B. Bhandari et al.,2016 and Aeidapu Mahesh et al. 2015. In Table 6 is shown some case studies and methods/software tools used and outcome.

Table 6: Case studies and optimisation techniques used

Author	Indicator optimised/Objective	Algorithm used	Outcome
Francois Giraud et al. (2001)	Reliability, power quality, loss of supply	LPSP	Evaluate performance of hybrid system regarding cost, reliability
Elhadidy et al. (2004)	Load distribution and power generation	Matlab	Investigate the potential of utilizing hybrid energy conversion systems to meet the load requirements
Mariem Smaoui et al. (2015)	Economic	Iterative technique	Evaluate a hybrid system, which is designed to supply seawater desalination
Arnau González et al. (2015)	Minimum life cycle cost	GA (Genetic Algorithm) and PSO (Particle swarm optimisation)	Design a hybrid system to meet the load demand at minimum life cycle cost based on net present cost
M. Alam (2007)	Modelling and analysis of a Wind/PV/ Fuel cell	Fuzzy and HOMER	Based on simulation result it has been found that RES would be a feasible solution for distributed generation of electric power for standalone application at remote location.
Ould. Bilal et al. (2013)	Levelized cost of energy (LCE) and the CO_2 emission	Genetic Algorithm	Author takes variation of three dissimilar load profile for hybrid system and minimized LCE and the CO_2 emission
Weiqiang Dong et al. 2015	minimum annual system cost and maximum system reliability	LPSP and Ant Colony Optimisation (ACO) Algorithm	Decreasing the system cost and increasing the system reliability are paradoxical.

4. Methodology

This study aims to design a reliable and affordable power supply to electrify sustainably the village of Fouay in Benin through a Hybrid Renewable Energy system. To answer the research questions set above, this work is divided into two main parts. The first part discusses the techno-economic analysis and the second Fouay village market analysis.

The techno-economic is performed using HOMER software tools. HOMER is widely used in many literatures worldwide in designing optimal technology for off-grid rural electrification ([10], [35], [44], [45]). Compared to the others software it presents some unique features such as the wider scope of renewable resources input and their possible combinations and the greater selection of system architecture and dispatch [46]. HOMER performs three principal tasks (simulation, optimisation, and sensitivity analysis) while suggesting the suitable system designs. It requires as main inputs potential resource assessment, load assessment, component characteristic, Project economic and sensitivity variables. The power sources considered in this study are Solar, Wind, and micro-hydropower. Solar radiation, ambient temperature and wind speed at 10 m height from 2000-2016 are obtained from the nearest station of Kandi at the Agency for Aerial Navigation Safety in Africa and Madagascar (ASCENA). The rivers streamflow data at the river site is estimated using an empirical method based on the data of surrounding gauged stations to the point (see section 5.3.3) from the National Direction of Water resources (DGEau). The component characteristic including costs and performance specification and project economic information are collected from literature review including technical catalogues of manufacturers, and Benin country market. The load profile is derived from a survey conducted on 50 households selected randomly. The survey questionnaire used (see Appendix 3) is an adapted version of the proposed standard load assessment questionnaire for mini-grid sizing by [47]. Indeed, one of the main output of the techno-economic analysis is the cost of energy of the optimum configuration.

Do inhabitants of Fouay will be able to afford the system at this price? To provide an answer to this question, the market analysis of the village is analysed. In this analysis, two economics value is assessed namely the Willingness To Pay (WTP) and the Ability to Pay (ATP). Baseline information needed for this assessment is included in the survey, and the standardise questions for the WTP. The Willingness To Pay (WTP) is however not a fixed value but strongly depends on the quality of service provided and the available alternatives (RECP,2014). So, a direct approach for the WTP computation is used based on households interviewed answers to some qualitative questions (see Appendix 2). These questions concern their level of satisfaction with the current energy supply, the importance of the kind of service, the technology, motivation to connect and modality of payment. Each answer is rated according to the likelihood of interviewed WTP for electricity (the computation process is detailed in section 5.8.1). The Ability to Pay (ATP) is estimated based on the information gathered from the survey on current energy expenditure, and the individual stated ATP per month. R statistical software and Excel are used for the data processing.

The diagram in Figure 15 gives a general view of the methodology followed and main inputs variables for each analysis of this study.

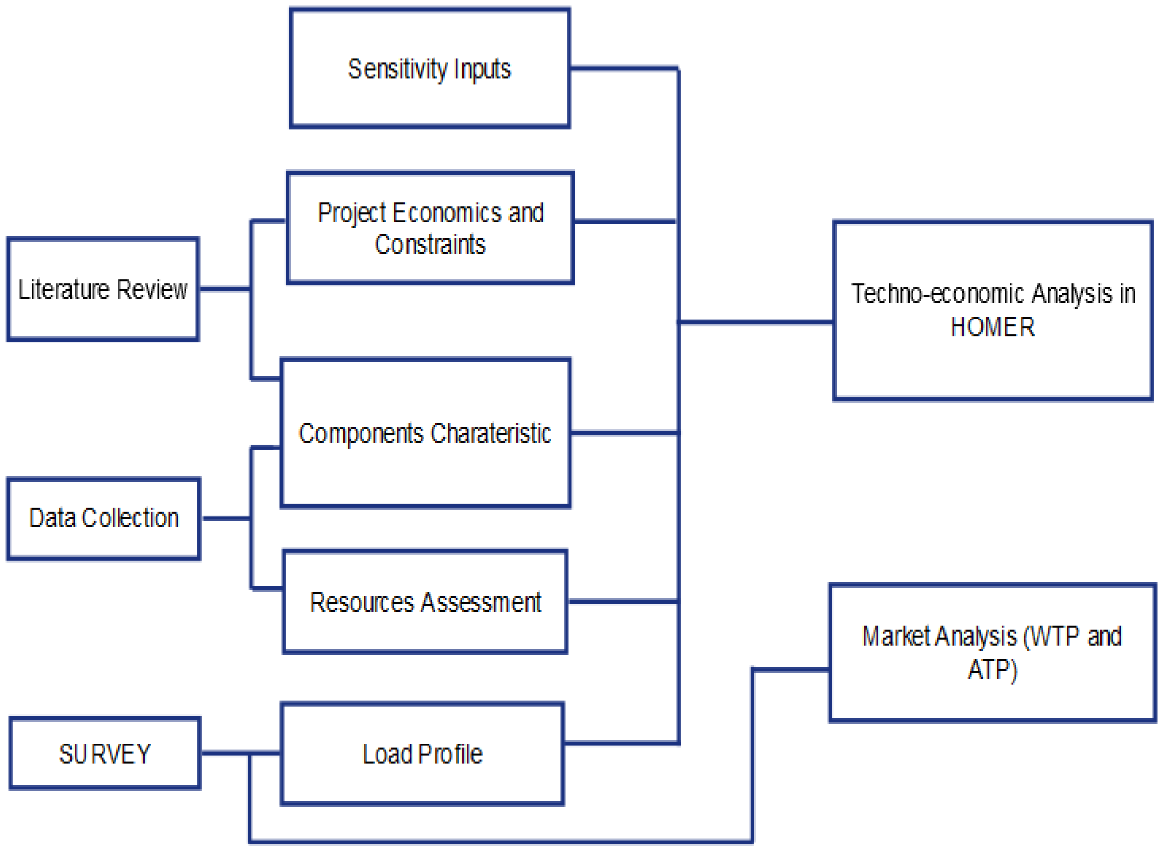


Figure 15: Diagram showing the methodology follows

5. Modelling of Hybrid Renewable power for the electrification of the village of Fouay

5.1. Study Area

Fouay is a remote village in the Alibori Division of Benin. According to 2013 census of Benin, the total household of the village is 333 with 3060 population of inhabitants. Its population is mainly dominated by men who account for 51.05% while and 48.95% for the female with a growth rate of 3.5%. It is geographically located at 11.3°N and 3.17°E with an average elevation of 273 m above the sea level. The annual solar radiation is 7.88 kWh/m²/day (Figure 1), and the wind speed average is 1.59 m/s obtained from the nearest synoptic station of Kandi (District from which Fouay belong to).

Its climate is characterized by two typical climate seasons: the rainy season which extends from June to October and the dry season from November to April. The annual precipitation is 963.7 mm, and the average temperature is 27.5 C. The main source of income is agriculture. The village can also benefit from its power supply of the potential of the river Sota where a potential for micro-hydro power plant was found with a total installed capacity of 494 kW.

The village is not yet connected to the grid and the high scenario of grid extension in the locality is planned for 2018 and for the medium one for 2032[16] which is not certain. The current sources of energy in the area are Diesel Generator, small Solar Home Systems, batteries, candles, and kerosene. Decentralized Energy systems would be one the best option to provide electricity supply to the area.

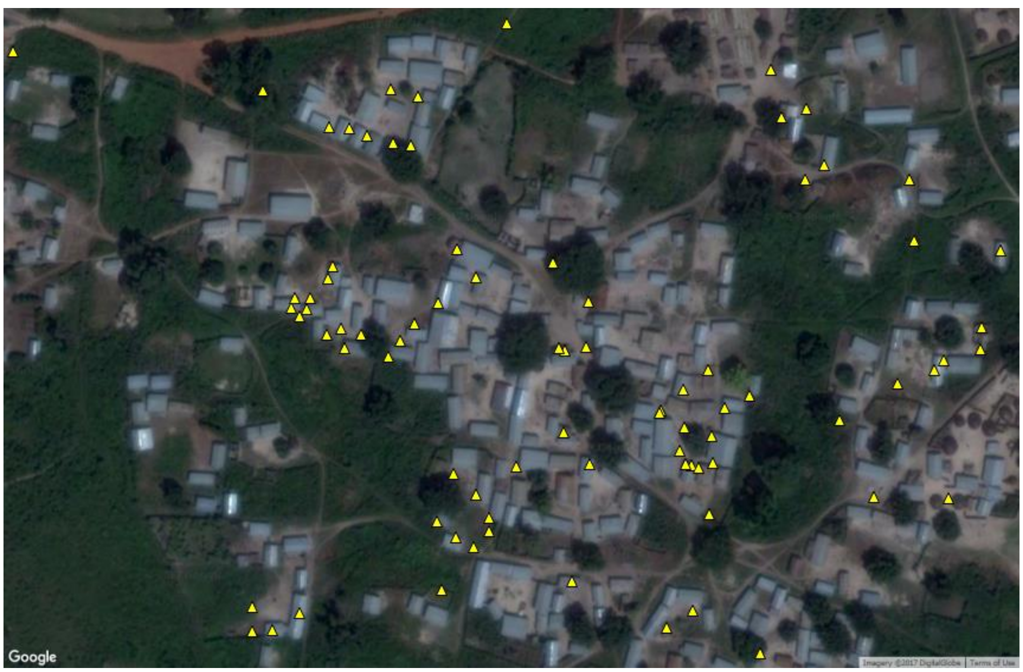


Figure 16: Google map view of the village of Fouay, in yellow triangle represents the household interviewee

5.2. Electricity demand estimation

The demand estimation has been conducted based onsite survey in Fouay village. An adapted version of the standard load assessment questionnaire developed by[47]. This questionnaire comprises a series of questions ranging mainly from the basics information from each customer, their status, current energy supply, planned load demand if they have electricity and finally some questions related to their willingness to pay (WTP). The questionnaire used for the survey can be found in

Appendix *1*. Out the 383 Households in the village, 50 of them were randomly selected as sample for the assessment and six business shop were also interviewed. Also, an estimation of the load demand of each community services was also assessed and commercial based on the interest expressed by household and potential future need.

The electrical load of the village is classified into three main categories: Household load, Community load, and Commercial load. The Household load comprises mainly lighting, Radio/TV, Fan, Phone charging, and Fridge. The Commercial load consists of the load of 6 small business shops, 3 Tailor shops, 3 Barbershops, 1 Printer/Copier Shop, the village store, 5 flour mills and 1 solder Machine. While the community load is composed of street light, School, Health Center, Water Pump, Local administration and religious place (Church and Mosque) load.

Furthermore, some assumptions have been made for seasonal variation of the load profile. The seasonal loads are fans, Water Pumping, and School load. Three main season load variation are defined summer, winter low and winter high (Table 7) and the corresponding daily energy demand is as illustrated in Table 8.

Table 7: Seasonal Variation

Season	Assumptions
Winter low	-Households are not using Fans -Schools load will be only lightning -Water Pumps work for 5hrs (10hrs in Summer)
Winter High	- Households are not using Fans -Water Pump work for 5hrs (10hrs in Summer)
Summer	No variation

Table 8: Seasonal Daily Electricity Consumption

Seasonal Load	**Summer** (NOV-MAY)	**Winter low** (JUN-JUL)	**Winter High** (AUG-OCT)
Daily load(kWh/day)	687.0	668.79	670.20

The total household load of the village is derived from the average of the sample load multiply by the number of households. The household load is dominated by lightning which accounts for 57% followed by radio as can be seen in Table 9. Figure 17 shows how the demand involves throughout the day for a typical day in summer season. From 7:00 AM to 17:00 pm most of the inhabitants are on their farms, less consumption is registered. While early in the night when they are coming from the farm and early in the morning the electricity consumption rises.

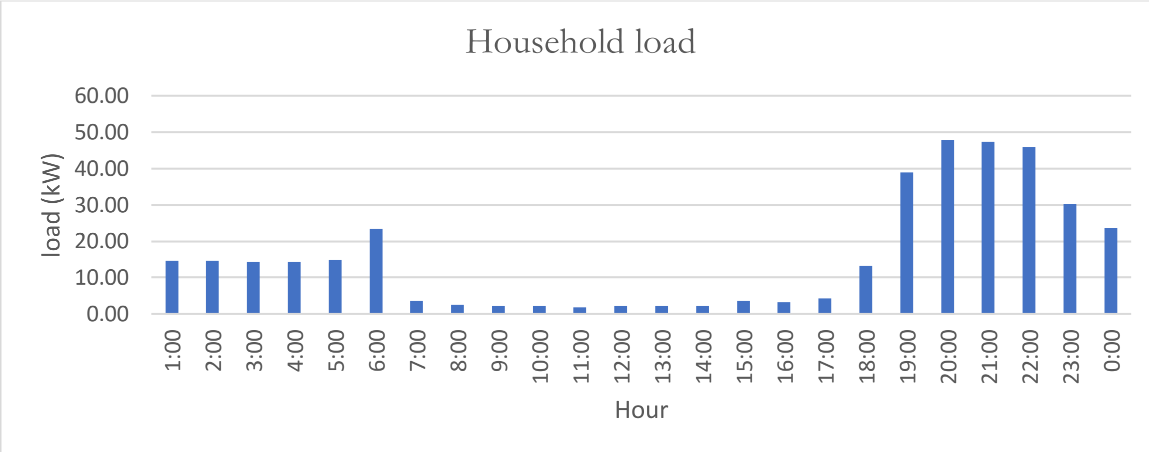


Figure 17: Summer season Household Load Profile

Table 9: Household Load: Appliances load breakdown

Appliances	Radio 30w	TV 120W	CD 24W	Phone 5W	FAN 55W	Fridge 100W	Light 3W/10W	Total
Average Sample load(kWh/day)	0.16	0.12	0.004	0.09	0.01	0.02	0.56	0.97
Foauy Household	383							
Household Load (kWh/day)	62.66	45.04	1.69	35.50	5.06	9.19	213.78	372.91
Percentage (%)	17%	12%	0%	10%	1%	2%	57%	100%

Table 10 presents the daily community demand, dominated by Water Pump (WP), Street Light and Health Center (HC) with respectively 49%, 19%, and 14% of the total demand. Most of the consumption occurs from 08 AM to 5 PM with peak demand at 5 PM of 3.41kW and low of at 7 AM of 0.33kW (Figure 18).

Table 10: Community Load Profile Breakdown by entity

	Mosque	**Church**	**School**	**HC**	**Street Light**	**WP**	**Hall**	**Total**
Total Power (kW)	0.39	0.12	0.38	0.60	0.70	2.20	0.20	4.58
Daily demand (kWh/day)	3.21	0.78	2.79	6.18	8.4	22	1.38	44.74
Percentage (%)	7%	2%	6%	14%	19%	49%	3%	100%

While Flour mill, solder machine and Small Business centre are the major activities driving more power with subsequently 86%, 12% and 4% of the total commercial load demand as can be seen in Table 11. The daily commercial load profile is shown in Figure 19 where the consumption is concentrated from 11 AM to 4 PM with a peak demand of 42.85 kW.

Table 11: Commercial load demand

	Small Business Center	**Village store**	**Barber**	**Tailor**	**Copier Shop**	**Flour Mill**	**Solder**	**Total**
Total Power (kW)	2.2	0.1	1.0	0.4	0.2	37.5	4.5	45.9
Daily demand (kWh/day)	11.6	0.7	4.6	2.1	0.9	232.5	31.5	269.4
Percentage (%)	4%	0.25%	2%	1%	0.34%	86%	12%	100%

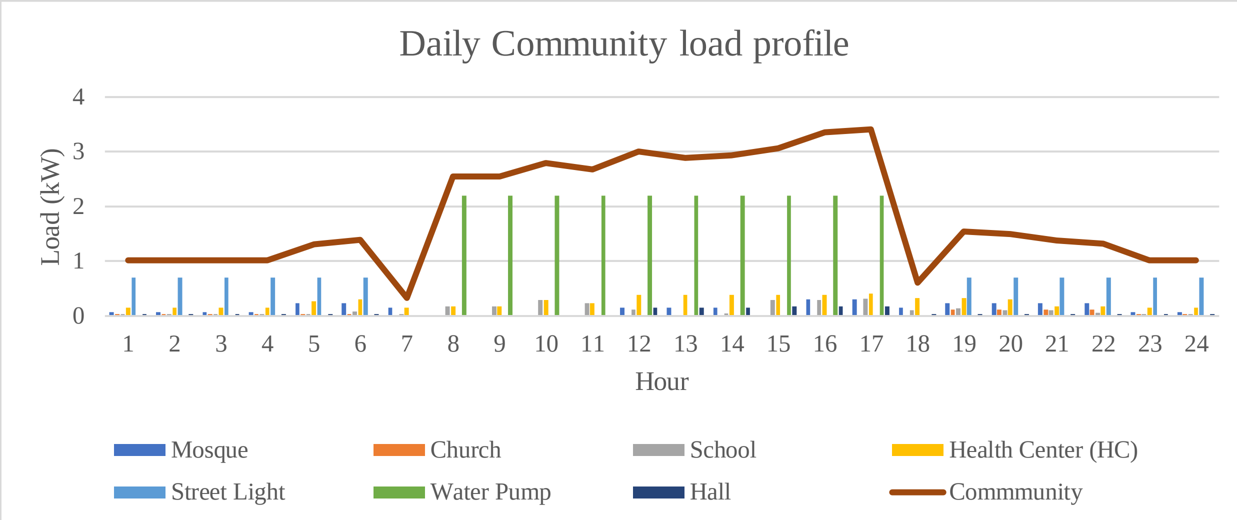


Figure 18: Community load profile

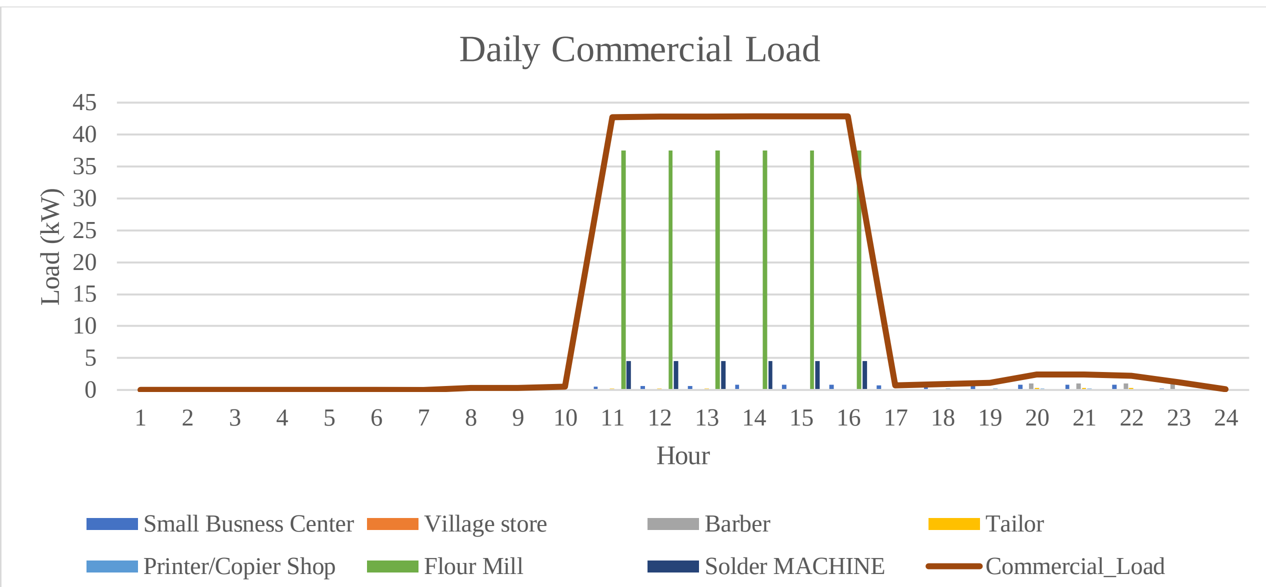


Figure 19: Commercial load Profile

Figure 20 and Table 12 display the total daily load profile of the village in summer season comprising household, commercial and community load. Daily demand is about 686.5 kWh/day with a peak power of 51.7kW which occurs during the night where most of the inhabitants are back from the farm around 8:00 to 9:00 PM. Household dominates the village electricity demand with 54% of the total demand followed by the commercial and community load with respectively 39% and 7% as can be seen in Figure 20 and Table 12. The load profile for winter low and high is in

Appendix 1.

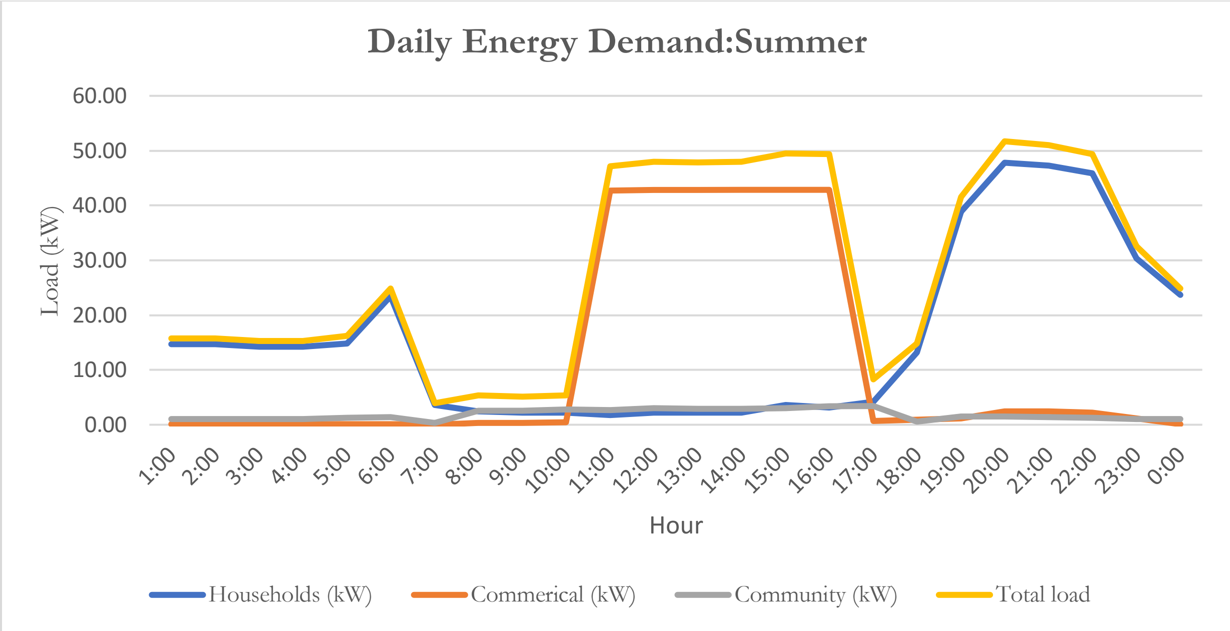


Figure 20: Fouay Village typical load profile

Table 12: Daily Load profile of the village of Fouay during summer season

Time	Households (kW)	Commercial (kW)	Community (kW)	Total load
Daily energy consumption				
1:00	14.68	0.05	1.02	15.75
2:00	14.68	0.05	1.02	15.75
3:00	14.26	0.05	1.02	15.33
4:00	14.26	0.05	1.02	15.33
5:00	14.84	0.05	1.31	16.20
6:00	23.45	0.05	1.39	24.88
7:00	3.60	0.00	0.33	3.93
8:00	2.45	0.35	2.55	5.36
9:00	2.18	0.35	2.55	5.09
10:00	2.14	0.47	2.79	5.41
11:00	1.76	42.69	2.68	47.14
12:00	2.18	42.80	3.01	48.00
13:00	2.18	42.80	2.89	47.88
14:00	2.18	42.85	2.94	47.98
15:00	3.60	42.85	3.06	49.51
16:00	3.18	42.85	3.36	49.39
17:00	4.21	0.69	3.41	8.31
18:00	13.21	0.96	0.61	14.79
19:00	38.84	1.14	1.55	41.53
20:00	47.80	2.41	1.50	51.70
21:00	47.30	2.38	1.38	51.06
22:00	45.88	2.18	1.33	49.38
23:00	30.33	1.19	1.02	32.54
0:00	23.68	0.14	1.02	24.84
Total	372.91	269.41	44.74	687.06

5.3.Resource assessment in Fouay

In this study, Solar, Wind, and Hydro are the main sources of energy considered while battery bank and Diesel Generator are used as back up. Solar radiation and the wind radiation was obtained from the nearest station, the synoptic station of Kandi. The synoptic station of Kandi is geographical located at Latitude: 11°08' N and longitude: 02°56' E, it is 35 km far from the study area and situated 290 m above the sea level. For Hydro resource, streamflow data for Gauged stations around the study area is obtained from the National Direction of Water resources (DGEau). The streamflow rate at the hydropower site has been estimated using an empirical method (see section 5.3.3).

5.3.1. Solar Radiation

The average solar radiation at the synoptic station of Kandi ranging from 5.67 to 9.48 kWh/m^2/day with an annual average of 7.88 kWh/m^2/day with the 15 years obtained (2000-2016) obtained from the National Meteorological Agency. Figure 21 shows the monthly average radiation where from July to September lowest radiation are observed due to cloud cover during the rainy season and higher radiation during the other months and with the highest during November and December.

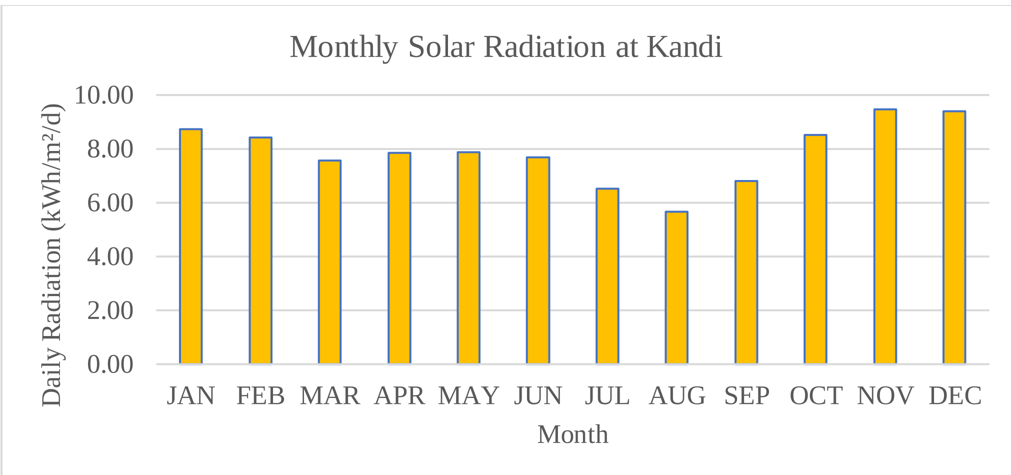


Figure 21:Solar Radiation at Kandi

5.3.2. Wind

The wind speed in the location is very weak and vary from 1 to 2.26 m/s at 10 m height. The peak is obtained during the month of April. A details analysis performed by G. Clarence (2011) on wind power potential in Benin as part of his thesis has also shown that the potential at Kandi site is low and not enough for a small or medium wind turbine. Nevertheless, he has raised the fact that there is a need for increasing on the ground measurement for accurate assessment for the whole location. Therefore, wind power potential is not sufficient to be explored in the design of the current system to electrify the village of Fouay.

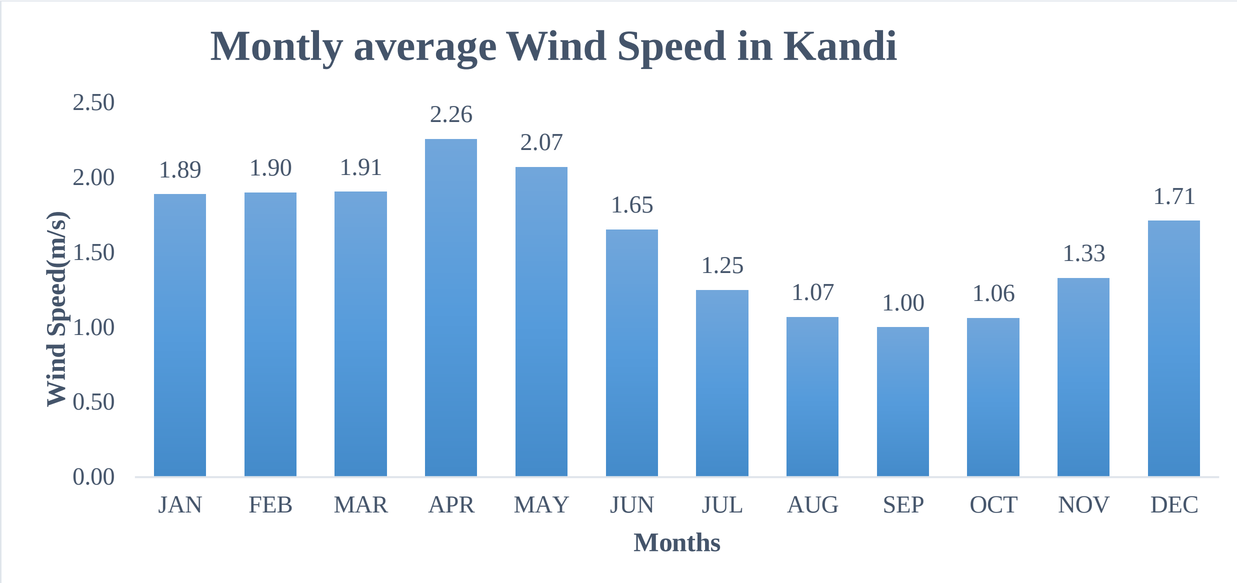


Figure 22: Wind Speed at Kandi

5.3.3. Hydropower Resource

In November 2009, TECSULT Cabinet had come out with the report on the feasibility study of micro-hydropower in the Benin Republic and 6 sites were selected out of 85 potential location at the beginning. The site of ‘’Cascade de Sosso’’is among the 6, which is situated at 11 km of the village of Fouay. The total proposed installed power is roughly 494 kW (2 turbines of 247 kW). Table 13 shows the technical specifications of the hydropower plants. The site is located at the Sota river, a tributary of the Niger river with a catchment area at the dam axis of 10,975 km². The river streamflow at the location of the power plant was estimated since no gauged stations existed directly on the basin cover by the site. According to the World Meteorological Agency (WMO), the flow rate at ungauged sites can be estimated using one of the three methods – Empirical, Statistical and Rainfall-Runoff modelling [32]. Since rainfall-runoff modelling requires key data that are not available for the study area, the empirical method is used. The methods consist of transposing gauged streamflow data from an analogue catchment.

Out the three-gauged stations surrounding the hydropower plant only two analogue gauged stations were considered whereby Gbasse gauged station located at the upstream and the Couberi station at downstream of the ungauged catchment respectively with an area of 8300 km^2 and 13410 km^2. Both stations considered are all situated on the same Sota river and follow the rainfall trends (Figure 23 and Figure 24).

Table 13: Technical Specification of the Hydropower plant [48]

Feasibility study of micro-Hydro plants in Benin: Cascade de Sosso	
Study conducted by:	AECOM TECSULT Inc Cabinet, 2009
Type of Hydropower	Run of the river (with pondage)
Site name	Cascade de Sosso
latitude	11°35'00'
Longitude	03°20'00''
Number of Turbines	2
Type of turbine	S-Kaplan
Power per turbine	247kW
Generated Power	247kW/380V
Installed Power	500kW
Minimum level of the water	174 m
Basin Area	10975km2
Gros head (m)	10
Net head (m)	7
Channel	380m
Penstock	21m
Design flow rate (m3/s)	9

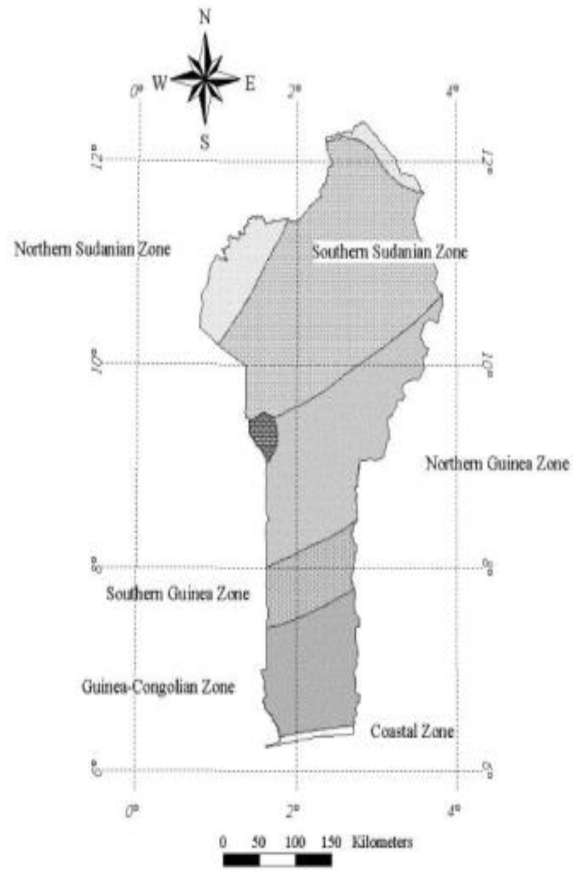


Figure 23: Benin Vegetation Zone [48]

The method formula is as follow: $QX_t = fn\left(\frac{A_T}{A_A}\right) QX_A$ (24)

Where:

QX_t: The flow in the target ungauged catchment of the power plant

QX_A: The corresponding flow in the analogue catchment A

A_T: The catchment area for the power plant site

A_A: The catchment area for the analogue catchment

fn: A scaling constant or a function

Since all the analogue gauged stations considered are all in the same vegetation zone and have the same rainfall trends, the scaling factor (fn) of 1 is taken (Figure 23). Table 6 and Figure 25 show the estimation and the monthly trends of the streamflow rate (m^3/s) at the Cascade de Sosso. The flow is available throughout the year with an annual average flow of 31.076m^3/s.

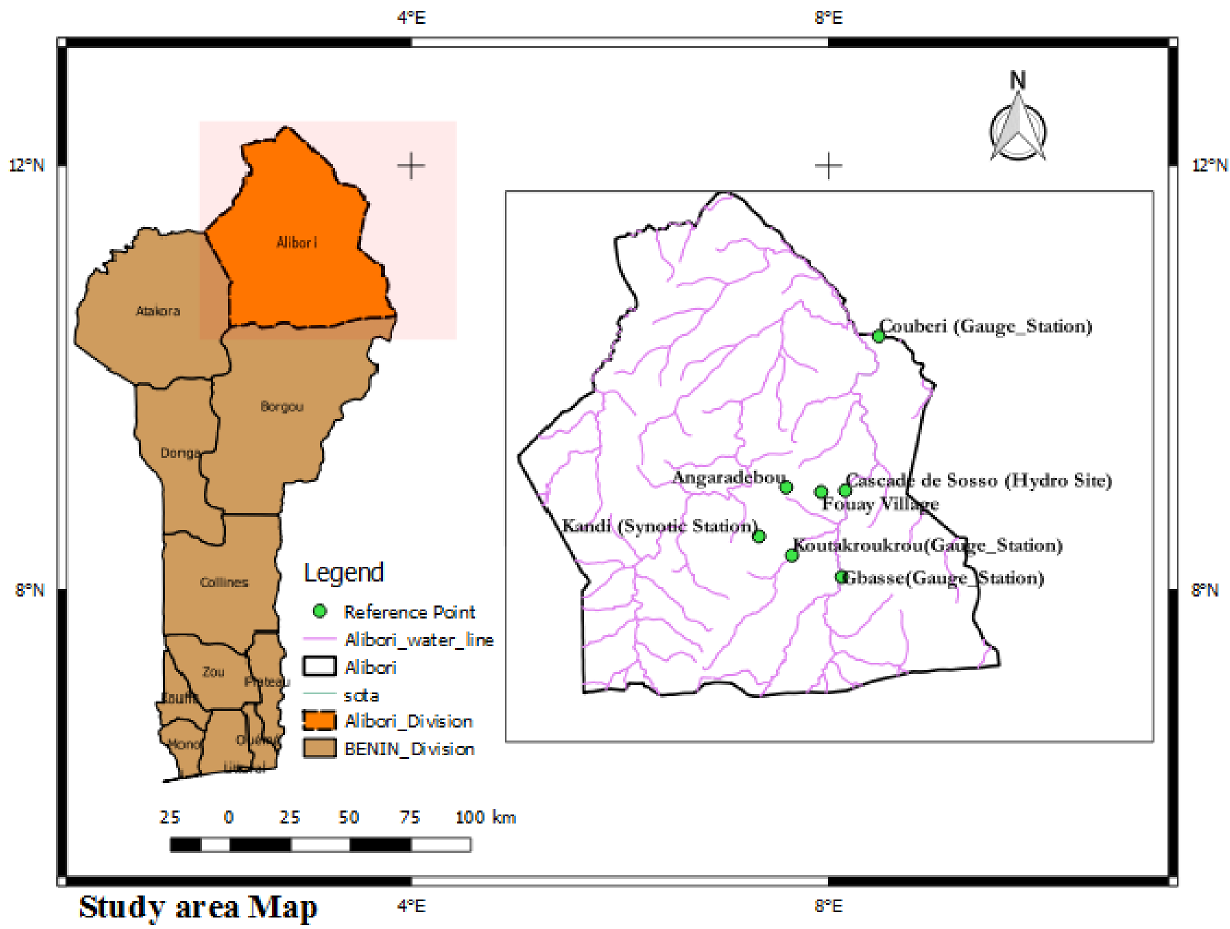


Figure 24: Study Area Map

Table 14: Flow rate estimation at Ungauged point of the hydropower site

Months	Gbasse (m3/s) 3°15'42.17'' E, 11°18'14.49''N	Couberi (m3/s) 03°19'32'' E, 11°44'13'' N	Area Gbasse (km^2)	Area Couberi (km^2)	Area Sosso	$\frac{A_T}{A_A}$ Gbasse	$\frac{A_T}{A_A}$ Couberi	Sosso Estimation (m3/s) Gbasse	Sosso Estimation (m3/s) Couberi	Flow_Sosso (m3/s)	Precipitation Kandi (mm)
JAN	2.6	5.6	8300	13410	10975	1.32	0.82	3.5	4.5	4.01	0.1
FEB	2.2	5.0						3.0	4.1	3.53	2.0
MAR	2.2	4.6						2.9	3.7	3.33	7.4
APR	2.3	4.7						3.0	3.9	3.43	38.0
MAY	6.2	8.5						8.2	7.0	7.59	112.5
JUN	11.1	12.9						14.7	10.6	12.65	151.0
JUL	23.1	28.7						30.6	23.5	27.06	203.7
AUG	65.0	71.7						85.9	58.7	72.28	265.3
SEP	134.6	143.7						178.0	117.6	147.82	186.5
OCT	63.3	73.9						83.7	60.5	72.09	40.8
NOV	11.6	17.4						15.3	14.2	14.77	0.4
DEC	3.8	7.3						5.1	5.9	5.52	0.3

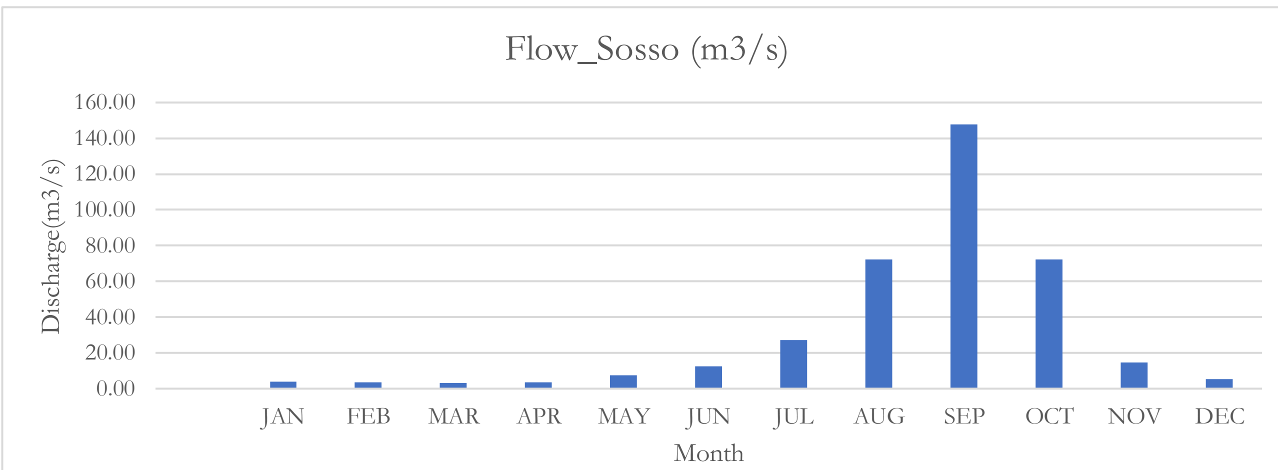


Figure 25: Monthly flow rate at Cascade de Sosso

5.4. Modelling of Hybrid Renewable Power system in HOMER

5.4.1. Introduction to HOMER modelling

As discussed earlier in section 3.3, there are many software and methods based optimisation and simulation of the hybrid energy system, and HOMER is among them. HOMER (Hybrid Optimisation of Multiple Electric Renewables), is the global standard for design in all sectors and has been used for various study worldwide. It is developed by the optimising microgrid National Renewable Energy Laboratory (NREL, USA) which simplifies the task of evaluating designs of both off-grid and grid-connected power systems for a variety of applications. HOMER performs three principal tasks (simulation, optimisation and sensitivity analysis) while suggesting the suitable system designs.

HOMER suggests the best-optimised model design based on the NPC (Net Present Cost) for the given specific load, resources, economic inputs, system control features, constraints and sensitivity variables. It shows simulation results in the form of tables and graphs for comparing configurations and evaluating them on their economic and technical merits.

HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year. It then determines whether a configuration is feasible, and estimates the cost of installing and operating the system over the lifetime of the project. The system cost calculations account for costs such as capital, replacement, operation and maintenance, fuel, and interest.

The sensitivity analysis allows to model the impact of variables that are beyond the designer control, such as Interest rate, fuel costs, streamflow, etc, and see how the optimal system changes with these variations [44], [49] and [35]. The architecture of the software is summarized in the flowchart below (Figure 26).

The total NPC is HOMER's main economic output, the value by which it ranks all system configurations in the optimisation results, and the basis from which it calculates the total [50] annualized cost and the levelized cost of energy[49]. The calculation is as follows [51]:

$$\mathrm{C_{NPC}} = \frac{\mathrm{C_{ann,tot}}}{\mathrm{CRF(i, R_{proj})}} \tag{25}$$

where, Cann,tot is the total annualized cost, i the annual real interest rate (the discount rate), Rproj the project lifetime, and CRF (*i*,N) is the capital recovery factor. The capital recovery factor is calculated using this equation:

$$CRF_{(i,N)} = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{26}$$

Where *N* represents the number of years and *i* the annual real interest rate. Drop of interest rate causes reduction of capital recovery factor and leads to bigger NPC[11]. HOMER defines the levelized cost of energy (COE) as the average cost per kWh of useful electrical energy produced by the system and used the following equation to calculate it:

$$\mathrm{COE} = \frac{C_{ann,tot} - C_{boiler}E_{thermal}}{E_{primm,AC} + E_{prim,DC} + E_{grid}} \tag{27}$$

Where $C_{ann,tot}$ is the total annualized cost of the system ($[1]/yr), C_{boiler} the marginal cost of boiler ($/kWh), $E_{thermal}$the total thermal load served (kW h/yr), $E_{primm,AC}$ the total primary load (kW h/yr), $E_{prim,DC}$ the total DC primary load (kW h/yr), E_{grid} the total grid sales (kW h/yr). For this study, the load served are all AC current, no Thermal load is served, and grid-connected system is not intrinsically inventoried. Then, basically the equation *(27*) is becoming:

$$COE = \frac{C_{ann,tot}}{E_{primm,AC}} \tag{28}$$

Nevertheless, grid extension analysis is performed using the advanced grid Module of HOMER which compares the costs of grid extension with the costs of a standalone system and provides the results in the form of Breakeven Grid Extension Distance (BGED). The BGED is the distance from the grid at which the total net present cost of the grid extension is equal to the total net present cost of the standalone system. The equation used to calculate this is as follows:

$$D_{grid} = \frac{C_{NPC}.CRF(i, R_{proj}) - c_{power}.E_{demand}}{c_{cap}.CRF(i, R_{proj}) + c_{om}} \tag{29}$$

Where c_{cap} =capital cost of grid extension [$/km], c_{om}=O&M cost of grid extension [$/yr/km], c_{power} = cost of power from the grid [$/kWh], E_{demand}=total annual electrical demand [kWh/yr] and C_{NPC}= total net present cost of the standalone power system [$].

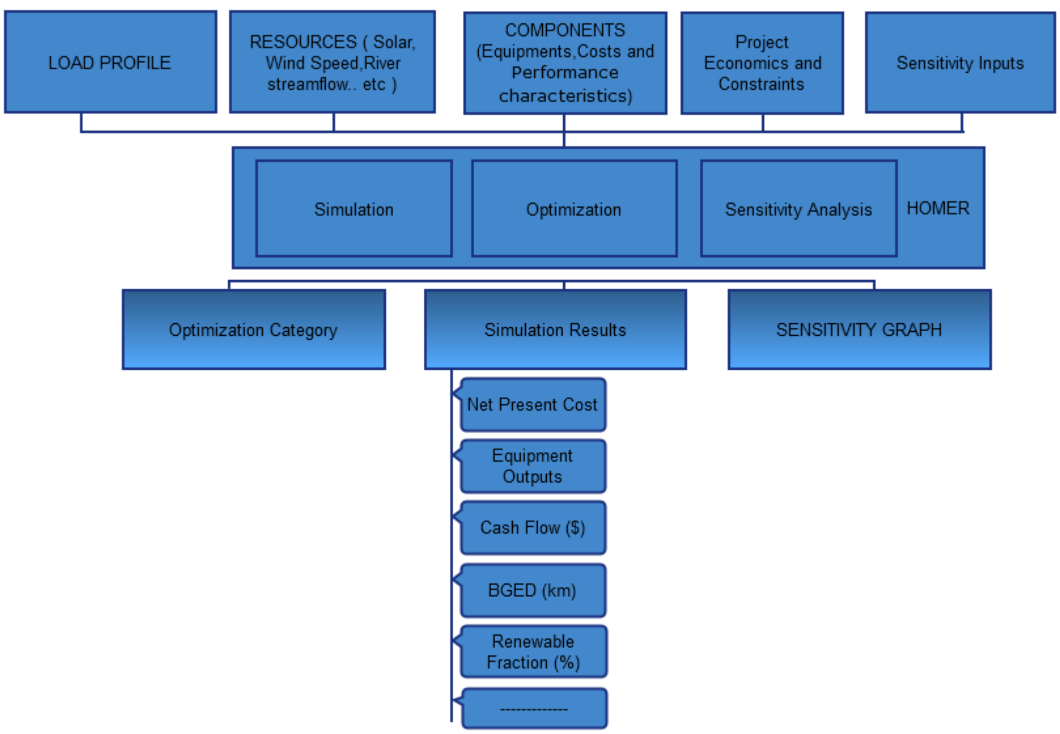


Figure 26: Architecture of HOMER Software.

[1] $ refers to United States Dollars in the document

HOMER Pro version 3.9.2 is used for this assessment.

5.4.2. System setup and inputs to HOMER

5.4.2.1. Components Schematic

As shown in Figure 27 below, for this study, both renewable (solar and small hydropower) and non-renewable (Diesel Generator) energy sources have been considered. The battery is the storage unit. Since there are components with AC and DC, the converter is added. It served as an interface between the two forms of energy, to supply the load and for batteries charging. Grid module is added for comparative analysis with standalone design system.

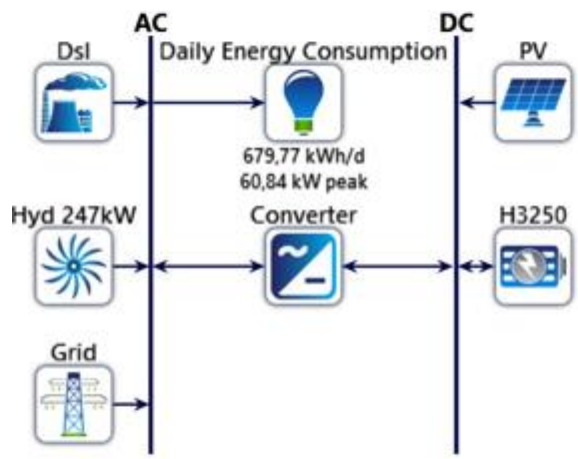


Figure 27: Schematic of the Proposed System in HOMER

5.4.2.2. Inputs to HOMER

5.4.2.2.1. Resource and Load Inputs

The monthly average solar radiation over 16 years (2000-2016) and monthly average streamflow of complete 26 years data ranging of 1953-2012 with an annual average of 31m^3/s as shown in section 5.3.1 and 5.3.3 respectively are entering in resource tab in HOMER. One-year hourly load demand including seasonal variation that occurs from time to time as explained in section 5.2 is imported into the software (see Figure 29). Since that variation was already included in the imported data, therefore random variability of load profile defined case in HOMER is not considered. The monthly average demand is shown in Figure 28. It can be seen from Figure 28 that high demand occurs during summer season majorly from December to May while low demand during the rainy season (fewer hours for water pumping and no use of fans). The difference in magnitude is due to the number of days in each month.

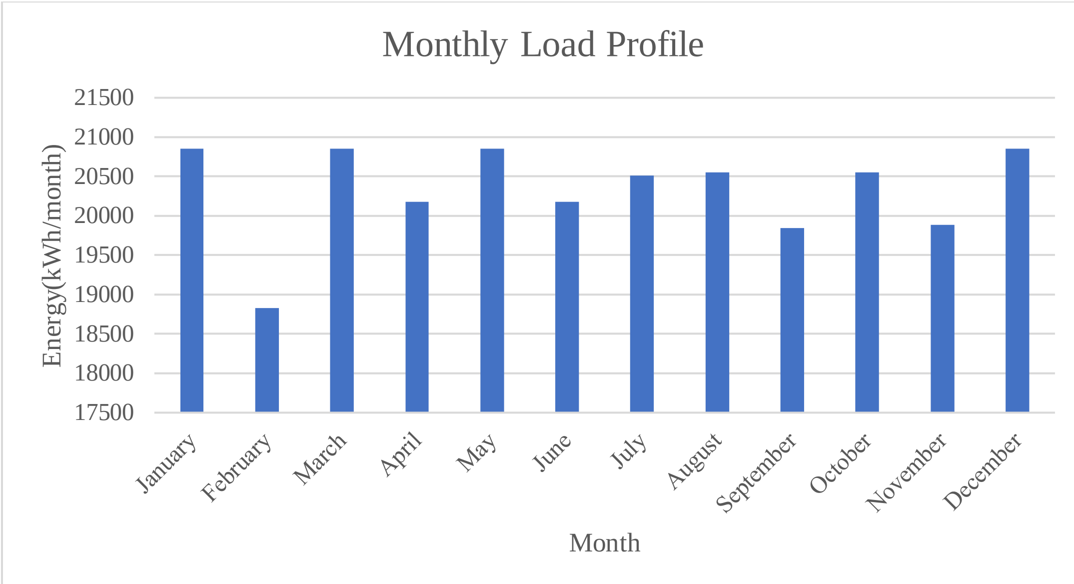


Figure 28: Monthly Load Profile

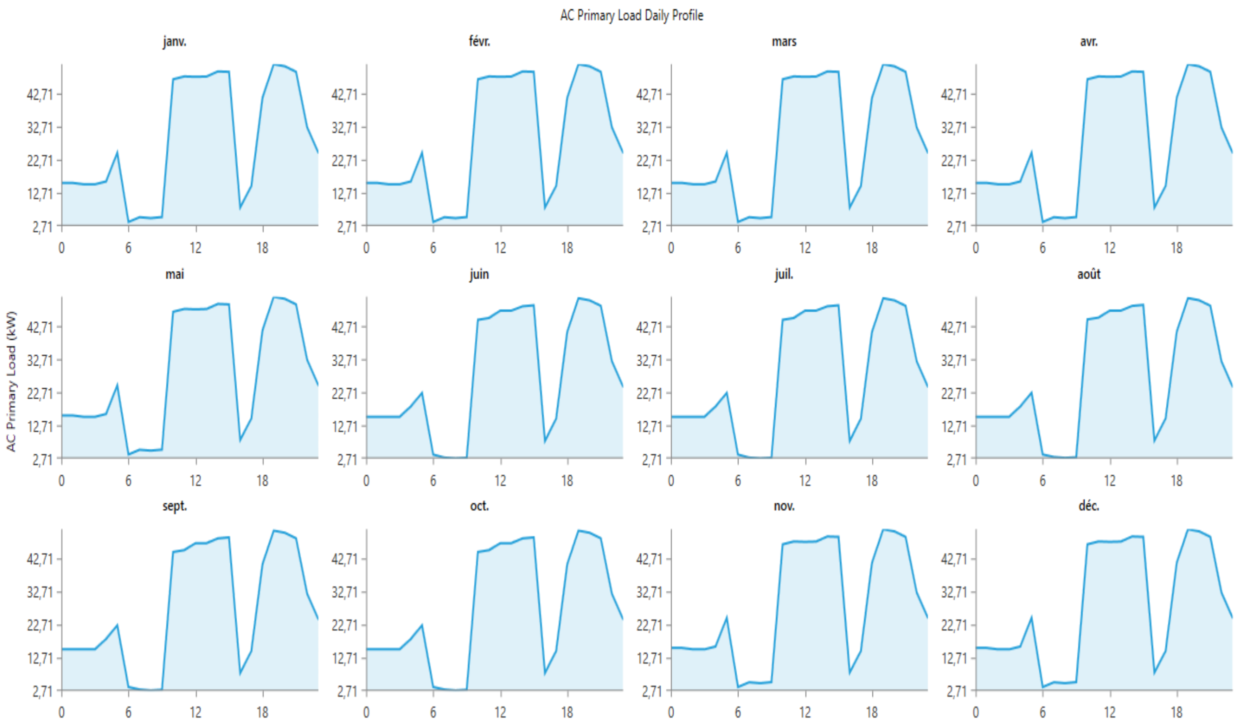


Figure 29: Monthly Load Profile for a year

5.4.2.2.2. Components Costs and Performance characteristics (Techno-economic data)

The main costs (Capital Cost, Replacement Cost, and O&M Cost) of the different components are listed in the table below. The economics of scale is applied to Solar PV, Battery and Diesel Generator. It refers to cost reduction with size so that larger systems will have a lower unit cost compared to a smaller system [30].

Diesel Generator capital cost includes the acquisition and transportation cost obtained from Benin market. The price of Perkins generator (GP22SH/PW-N-C) and Bertoli Brand for different size are collected to make the Table 15. The actual diesel fuel price is 0.8$/l, and the minimum load ratio is set to 30%. The capacity optimised are: 0,40,45,50, 60,70 80kW.

Table 15: Component Inputs: Diesel Generator

Component	Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/hr)	Operating Hours (hr)
Diesel Generator	1	660	660	0.03	15000
	24	20542	20542	0.72	15000
	40	22419	22419	1.2	15000
	48	27024	27024	1.44	15000
Source and Assumptions	Benin market price, December 2017 **0&M:** 3% of the capital Cost				

According to the feasibility study on the hydropower site, two turbines of 247kW were considered. For this study, only one turbine scenario is considered in the simulation with design streamflow of 4500 m^3/s, a minimum flow ratio of 50% while 105% as a maximum. Simulation Systems with and without the hydro turbine is selected in HOMER to see the best configuration in both cases. The pipe loss is set at 15%, 80% for efficiency and the electricity production from hydro is through AC. The annual average streamflow is $31 m^3/s$.

The hydropower power site is 11km far from the village of Fouay, therefore grid extension cost is added to the plant's costs. The grid extension cost comprises the cost of Medium Voltage (MV) line, transformers, protection devices and others hardware cost.

Table 16: Components Inputs: Hydro

	Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/yr)	Lifetime (yrs)
Hydro	247	656287	123500	19689	30
Estimated cost of the plants 2500 CAD $/kW [48] MV line Cost =$14000/km [52] Hardware Cost: 16000 (Local expert) Grid extension Investment=170000 USD ≈15500$/km Replacement Cost: 500$/kW [34] O&M ($/yr): 3% of the capital Cost					

Table 17 shows the costs of the PV system. The PV costs include the module cost and the balance of the system (BoS) cost excluding battery and inverter cost. Local market price is used for the modules cost.

Monthly average temperature (2000-2016) is imported in HOMER with an annual average of 27.43°C to model the effects of temperature on PV modules. Where the temperature effect on power (%/c) is set to -0.5, the nominal operating cell temperature (°C) at 47 % and the PV module efficiency in a standard test condition is 13, and the derating factor set at 80%.

PV array size of 0, 50, 100,125,150,170,190,200,260,300,500 and 700 kW are considered.

Table 17: Component Inputs: PV

Components	Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/yr)	Lifetime (yrs)
PV System	1	2000	2000	40	25
	10	11000	11000	220	25

Table 18 shows the converter cost and efficiency. Converter of 0,5,10,25,50,60,65,75kW in size are considered in search space in HOMER tabs.

Table 18: Components Inputs: Converter

Components	Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/yr)	Lifetime (yrs)	Efficiency
Converter	1	1000	1000	20	15	95 %

Hoppecke OPzS batteries of 3250 Ah/2V as capacity are used for this study. The O&M is assumed to be 2% of the capital cost. The lifetime of Battery as indicated by the manufacturer is 20 years and throughput of 10118.30 kWh. The minimum state of charge is 30 % with an initial of 100%. The cost of the battery is taken from [53]. HOMER Optimizer is used to find the optimal size of the converter for each of the configuration.

Table 19: Components Inputs: Battery

	Quantity	Capital ($)	Replacement ($)	O&M ($/yr)	Lifetime (yrs)
Battery	1	1000	1000	20	20
	24	23947	23947	479	20

To show the cost-effectiveness of the standalone design system compared to grid extension project, a comparative analysis is performed in HOMER which gives in output the Breakeven Grid Extension Distance (BGED). The grid extension modelling feature in HOMER is used. The inputs simulation variables values are in Table 20. The Operation and Maintenance (O&M) cost represents 2% of the capital cost.

Table 20: Components Inputs: Grid Extension

	Capital Cost ($/km)	O&M cost ($/yr/km)	Grid power price ($/kWh)
Grid Extension	15500	310	0.22

5.4.2.2.3. Project Economics

The main economic variables input is summarized in Table 21.

Table 21: Project Economics variables

Nominal Discount Rate	10 %
Expected inflation rate	2%
Project lifetime	25 years

5.4.2.2.4. System operational control and strategies

For this analysis, we considered both the Load following (LF) and the Cycle Charging (CC) dispatch strategy. In LF strategy, the generators will only produce enough power to meet the load demand when operational. Meanwhile, for CC strategy, the generators will operate at full capacity and the excess power will be used to charge the battery bank [30].

5.4.2.2.5. Sensitivity variables

To monitor the effects of certain variables on the techno-economic analysis of the optimised system, sensitivity analysis is performed. These variables are varying within a given range. The sensitivity variables are defined for annual average load profile, diesel price, annual average stream flow, annual interest rate and project lifetimes.
Since 100 % of Benin petroleum products are imported [19]. This includes diesel fuel which is also dynamic in price. Therefore, Diesel fuel price will significantly affect the cost and the kind of optimal system to choose. Different values of fuel price ranging from 0.8$/l to 1$/l are simulated. In addition, the load demand will not be the same over the project lifetime as the village population grows and other socio-economic condition change in the village. Then, a load demand is taken as sensitivity variable where for multiple values of 679, 750 and 850 kWh/day the system behaviour is observed.
So far, there is no a clear idea about the discount rate applied for renewable energy projects in Benin. Therefore, different values of interest rate 7 to 10% are considered to simulate how it could affect the overall system economics.
Furthermore, the high, medium and low scenario of electrification through grid extension in the locality are subsequently projected in 2018, 2033 and 2032 [16]. So far, the nearest village of Angaradebou where the grid poles are installed now is yet to be powered. So, it is very uncertain that in 2018 that the study area be electrified. Therefore, the more optimistic scenario will be to consider the case of medium projection to 2032. In that perspective, two project lifetimes have been considered: 15 and 25 years. This will help analyse if at any of this project lifetimes whether the optimised system in economic point of view is cost-effective than grid extension.
Finally, multiple values of annual streamflow are simulated since it varies considerably throughout the 26 years of data obtained. The simulated stream flows are 21m^3/s, 31m^3/s, and 70m^3/s. The following table summarizes the sensitivity variables considered and their values.
However, no sensitivity analysis is performed on solar radiation because of the low significant changes.

Table 22: Sensitivity Variables

Sensitivity variables	**Values**
Diesel Fuel Price ($/l)	0.8$/l, 0.95$/l, 1$/l
Load Growth (kWh/day)	679 ,750, 850
Interest Rate (%)	8,9,10%
Annual average Streamflow	21m^3/s,31 m^3/s,70m^3/s,
Project lifetime (years)	15, 25

5.5. Optimisation Results

HOMER simulate all the possible optimal solution and sort them based on the lowest Net Present Cost (NPC). The optimisation results are categorized as shown in Table 23 which comprises the architecture(s), costs and some system variables. The optimal controller strategy varies from one configuration to another either Cycle Charging or Load Following. Out the 13-optimal sizing configuration, six sub-configuration systems are closely analysed namely: PV/DG/Battery, PV/Hydro/DG, Hydro/DG, PV/Battery, Hydro and Diesel Generator as highlighted in Table 23 and presented in Table 24. The initial condition for this simulation is the load demand of 679 kWh/day, Diesel fuel price of 0.80$/l, a nominal discount rate of 10%, 31m^3/s as streamflow and project lifetime 25 years.
Based on that, the least cost system is the hybrid PV/DG/battery with 555492$ as Net Present Cost (NPC) comprising PV panels of 150kW, 50kW Diesel Generator, 98 Hoppecke Battery of 3250AH/2V, 60kW Converter and the dispatch strategy is the load following (Table 23). The cost of electricity (COE), initial capital cost, Operation and Maintenance (O&M) Cost are respectively,0.207$/kWh, 332369$ and 20623$. It is worth noting that those different costs do not include any subsidy or funding. The PV/DG/battery system is cost-effective than grid extension because the COE of 0.207$/kWh is lower than 0.22$/kWh of the national grid and present a breakeven grid extension distance of -1.87 km which is far lower than the village distance to the grid of 15km air. Compared to a non-hybrid PV/Battery system, PV/DG/Battery reduce battery storage by 70%, therefore lowering the NPC. Since the battery is the costliest components in standalone PV system; the hybrid system is a viable solution to minimise its costs. In a technical point of view, PV/DG/Battery provided a reliable power supply with unmet % load and generated the lowest excess of electricity of 7.7% compared to the other systems. While in environmental standpoint, its CO_2 emission of 9590 kg/yr is very insignificant which is roughly only 3% of the CO_2 emissions of a standalone DG system. In contrast, the renewable energy penetration is high of 96.7%.

The second-best hybrid system is Hydro/DG system with a NPC, initial investment and COE respectively of 885302$, 678706$ and 0.33$/kWh. Compared to the PV/DG/battery it has a low 0&M cost of 19095$. Although hydropower has the lowest levelized cost of electricity of 0.0452$/kWh compared to the others power source, the overall COE of hydro/DG system is greater than the cost of the main grid. The additional investment cost added for grid extension so that the generated power could reach the village in the capital cost could explianed it. Furthermore, the breakeven point is 15.63km, slightly higher than 15 km which make grid extension a little bit cost effective than Hydro/DG. Nevertheless, regarding the high renewable energy fraction and especially the quality of power supply with 0% unmet load, Hydro/DG system is viable than grid extension where the continuous power supply is not secured. Moreover, DG as a backup will serve ensuring the load is always meet during low streamflow season. Which would not be the case with standalone hydropower system.

In summary, PV/DG/battery and Hydro/DG are the best hybrid system viable to power the village based on the optimisation results. PV/DG/battery is the overall cost-effective system and provides more reliable power compared to PV/Battery and environmentally friendly than DG. While Hydro/DG is a more secure system as DG will be served as backup compared to standalone hydro. PV/Hydro is disregarded because it is less cost-effective than grid extension.

Table 23: Optimization Results by category

	Architecture						Cost				System			
Rank	**PV (kW)**	**Dsl (kW)**	**H3250**	**Hyd (kW)**	**Converter (kW)**	**Dispatch**	**COE ($)**	**NPC ($)**	**O&M cost ($)**	**Initial capital ($)**	**Ren Frac (%)**	**Excess Elec (%)**	**Unmet load (%)**	**CO2 (kg/yr)**
1	150	50	98		60	LF	0.207	555492	20623	332369	96.7	7.7	0.0049	9590
2	200		328		60	CC	0.286	766965	16518	588247	100	28.6	0	0
3				247		CC	0.323	866193	19401	656287	100	86.0	0	0
4			5	247	5	CC	0.328	880240	19776	666278	100	86.0	0	0
5		40		247		CC	0.330	885302	19095	678706	100	86.0	0	0
6		40	5	247	5	CC	0.335	899349	19470	688697	100	86.0	0	0
7	50			247	5	CC	0.349	935669	20647	712287	100	86.7	0	0
8	50		1	247	5	CC	0.349	936993	20676	713287	100	86.7	0	0
9	50	40		247	5	CC	0.356	954778	20341	734706	100	86.7	0	0
10	50	40	1	247	5	CC	0.356	956102	20371	735706	100	86.7	0	0
11	170	60			60	CC	0.378	1.01$M	70120	255765	42.1	47.1	0	157355.5
12		50	17		25	CC	0.390	1.05$M	90806	65555	0	0.0	0	230508
13		60				CC	0.487	1.31$M	118555	24765	0	10.5	0	293139.5

Table 24: Sub-category

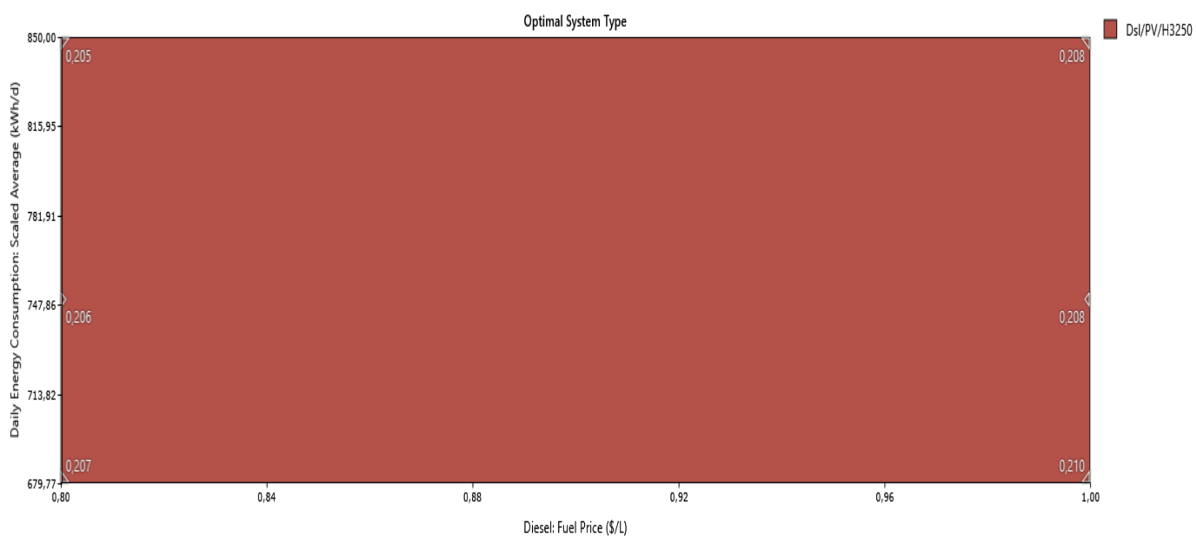
System	**COE ($)**	**NPC ($)**	**O&M cost ($)**	**Initial capital ($)**	**Ren Frac (%)**	**Excess Elec (%)**	**Unmet load (%)**	**CO2 (kg/yr)**	**BGED (km)**
PV/DG/Battery	0.207	555492	20623	332369	96.7	7.7	0	9590	-1.87
PV/Battery	0.286	766965	16518	588247	100	28.6	0	0	9.36
Hydro	0.323	866193	19401	656287	100	86	0	0	14.62
Hydro/DG	0.33	885302	885302	19095	100	86	0	0	15.63
PV/Hydro	0.349	935669	935669	20647	100	86.7	0	0	18.3
DG	0.487	1.31$M	0.487	1.31$M	0	10.5	0	293139.5	38.02

5.6. Sensitivity Analysis

The sensitivity analysis has been performed considering the variables listed in Table 22. In all the sensitivity cases as shown in the different graphs of Figure 30, PV/DG/Battery appeared as the optimal system with the least net present cost to meet the demand load. However, some aspects need to be point out. It can be seen in Figure 30 (a) that, the cost of electricity decreases from 0.207$/kWh to 0.205$/kWh as demand increase [679-850] kWh/day. While when the fuel price increases [0.8-1] $/l the COE tends to slightly increase up to a maximum of 0.210$/kWh. Which is still below 0.22$/kWh applied by the national grid. So, it can be concluded that changes in fuel price and increase in demand will not affect as much the profitability of the system. Furthermore, when decreasing the Nominal Discount Rate (NDR), the COE decrease up to 0.188$/kWh but in contrast, the NPC increase Figure 31.

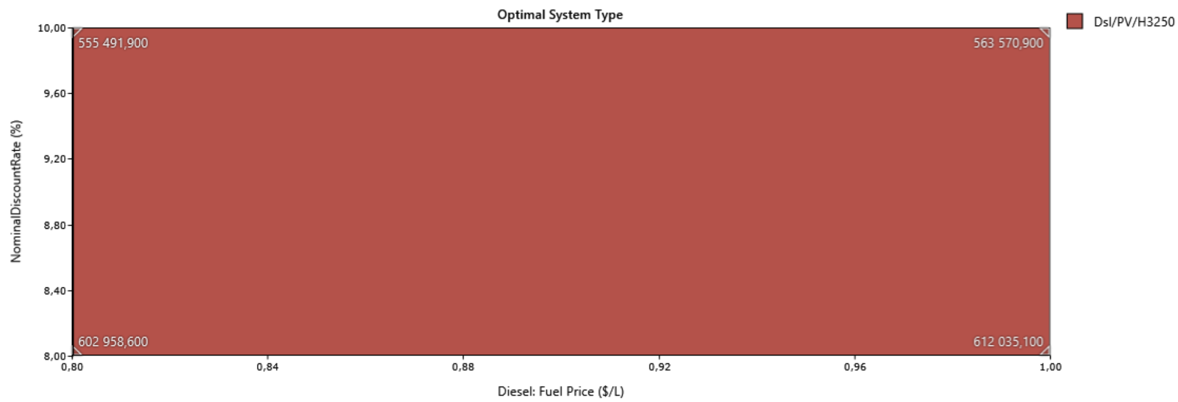
Indeed, sensitivity analysis performed on various river streamflow revealed PV/DG/Battery as the least cost hybrid system (Figure 30, c) followed by Hydro/DG. Nevertheless, Hydro/DG could be cheaper than PV/DG/Battery system and even cost-effective than grid extension if the demand is high enough and the hydropower source is not far from the village. For load demand of 850kWh/day, the cost of electricity is 0.264$/kWh, 0.301$/kWh and a breakeven point of 7.79km 14.44 km respectively for streamflow of 31m3/s and 31m3/s (Table 25).

Moreover, when considering 15 years as project lifetime, hybrid PV/DG/Battery system is the most cost-effective optimal system to meet the load and more viable than an extension project scenario since the breakeven points are below 15km the village distance to Grid (Table 26).



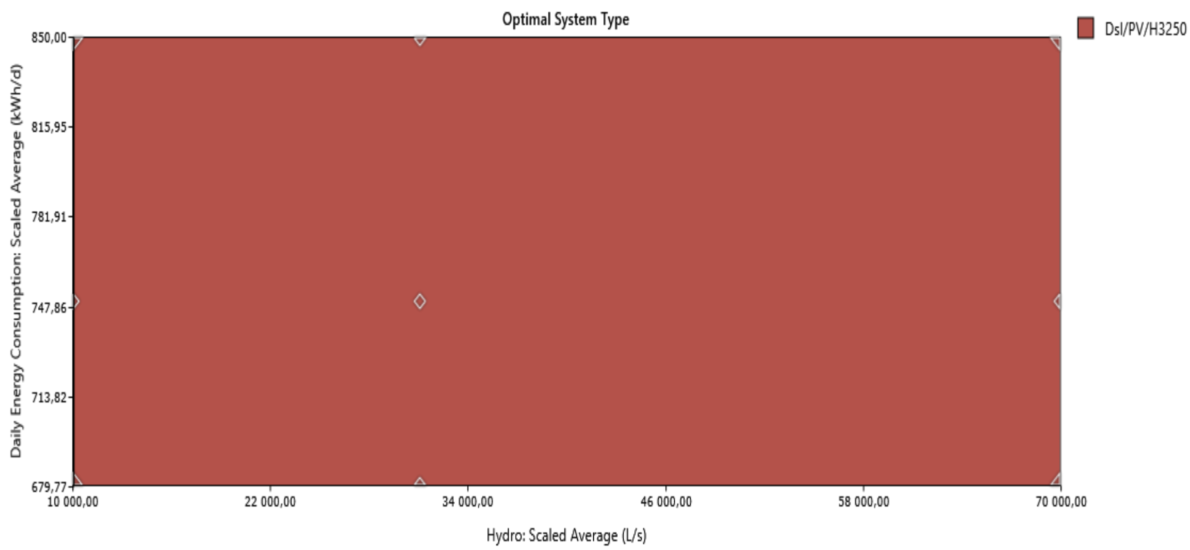
a

Diesel Fuel price vs Load Growth, ND:10%, Project lifetime=25 years



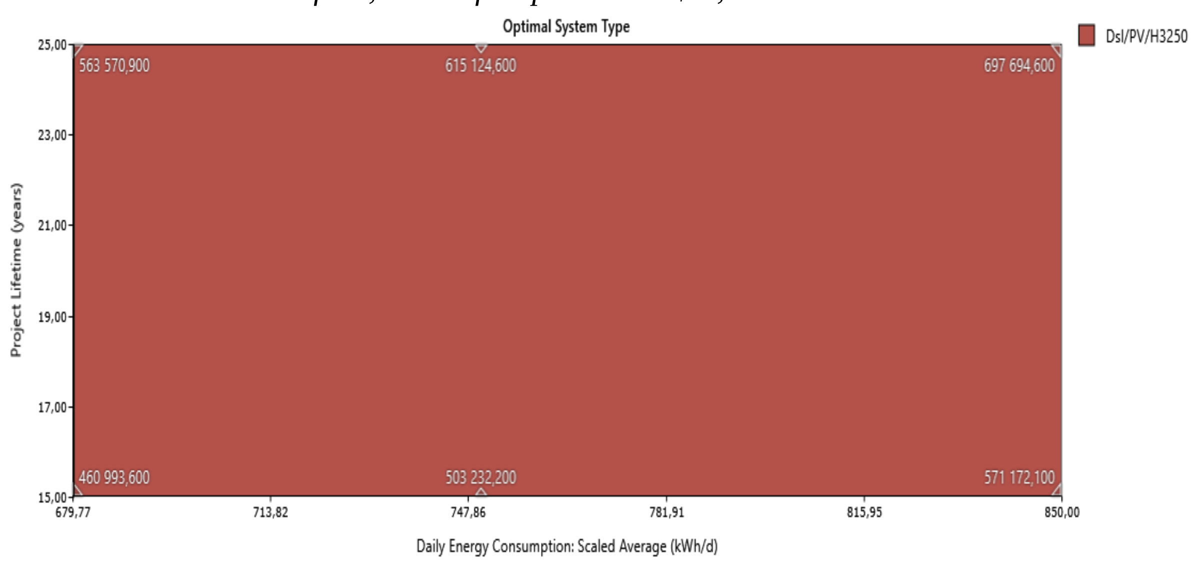
b

Diesel Fuel price vs Nominal Discount Rate, 679 kWh/day, Project lifetime=. 25yrs



c

Load Growth vs Streamflow, Diesel fuel price = 0.8$/l , NDR=10%



d

Project Lifetime vs Load Growth, Diesel Fuel Price=0.8$/l, NDR=10%

Figure 30: Sensitivity analysis

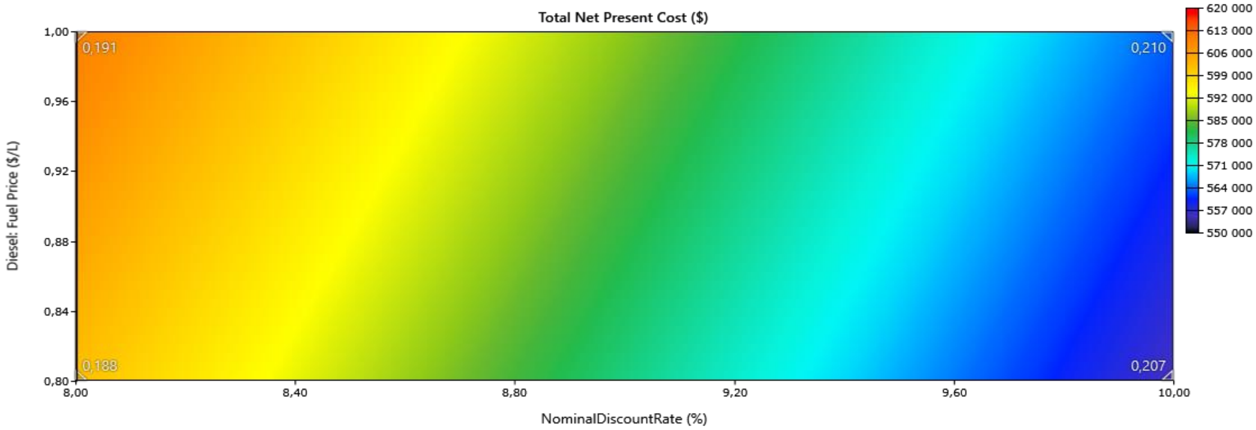


Figure 31: Surface Plot: Net present Cost, Superimposed: Cost of energy.

Table 25: Hydro/DG optimising results-Increase load and Variable streamflow;

Nominal Discount Rate (ND) = 10%, Diesel Fuel price (DFP)=0.8$/l										
Load (kwh/day)	**Stream Flow m^3/s**	**Hyd (kW)**	**Dsl(kW)**	**NPC ($)**	**COE ($/kWh)**	**Ren Frac (%)**	**Exc elec %**	**Unmet Load**	**CO2 (Kg/yr)**	**BGED (km)**
680	31	247	40	885302	0.328	100	86	0	0	15.63
850	31	247	40	885302	0.264	100	82.5	0	0	7.79
680	21	247	60	994071$	0.336	90.7	82.1	0	26186	18.16
850	21	247	70	1.01$M	0.301	90.60%	79.8	0	30125	14.44
680	70	247	40	885302	0.33	100	86	0	0	15.63
850	70	247	40	885302	0.264	100	82.5	0	0	7.79

Table 26: Optimal system for different project lifetime, DFP (Diesel Fuel Price)

	ND=10%									
Architecture	**Proj lifetime**	**DFP ($/l)**	**Load (kwh/day)**	**NPC ($)**	**COE ($/kWh)**	**Ren Frac (%)**	**Exc of elec (%)**	**Unmet Load**	**CO2 (Kg/yr)**	**BGED (km)**
PV/DG/Batt	15	0.8	680	459941	0.212	96.8	7.66	0	9447	-0.92
	15	1	680	460994	0.215	96.9	7.54	0	9021	-0.59
	25	0.8	680	555492	0.207	96.7	7.7	0	9590	-1.87
	25	1	680	563571	0.210	96.8	7.66	0	9447	-1.43

5.7.Optimal Hybrid system: Simulation Results

The optimal hybrid system from the analysis performed above shows that PV/DG/Battery is the best system to power the village over the different sensitivity case.

The proposed hybrid system architecture consists of 150kW PV panels, 50kW Diesel Generator and 98 Hoppecke OPzS battery of 3250 Ah. The electricity production is very dominated by the PV with 97.3% whereas 2.66% for Diesel Generator. Most of Diesel Generator power generation comes in the dominant part of the rainy season where there is a lot cloud cover from July-September and peak during in August (Figure 32).

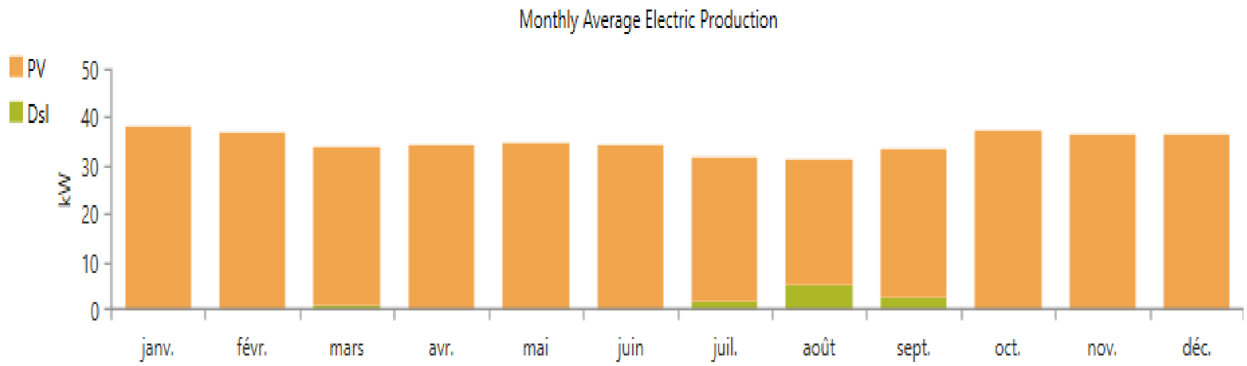


Figure 32: Monthly Electric production

The expected battery life is 7.10 years with an autonomy of 15.7hr. The battery is discharged for serving the base load and sometimes the peak demand as can see in Figure 33. When looking closely, over a day in February, batteries discharged power from 00-06 AM and 5-00 PM while charged back between these two periods from PV panels alone (Figure 34). The optimal controller strategy is Load Following where Diesel Generator cannot be used to charge batteries.

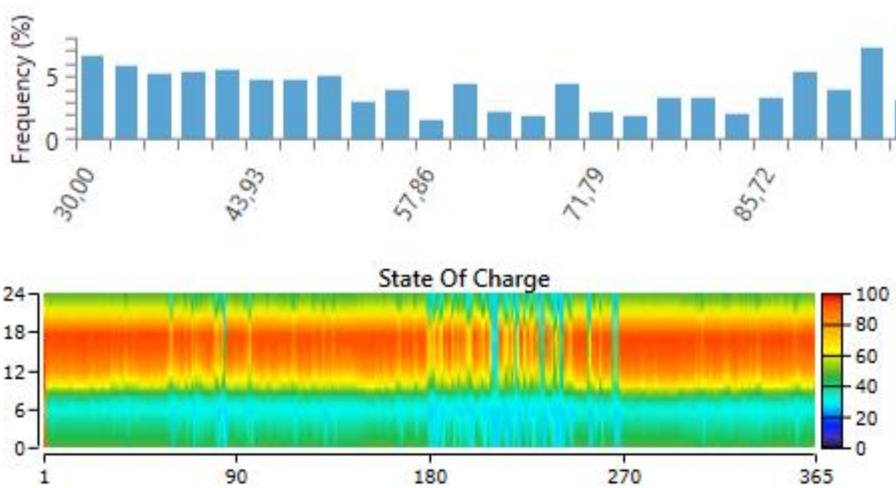


Figure 33: PV/DG/Battery: State of Battery over a year

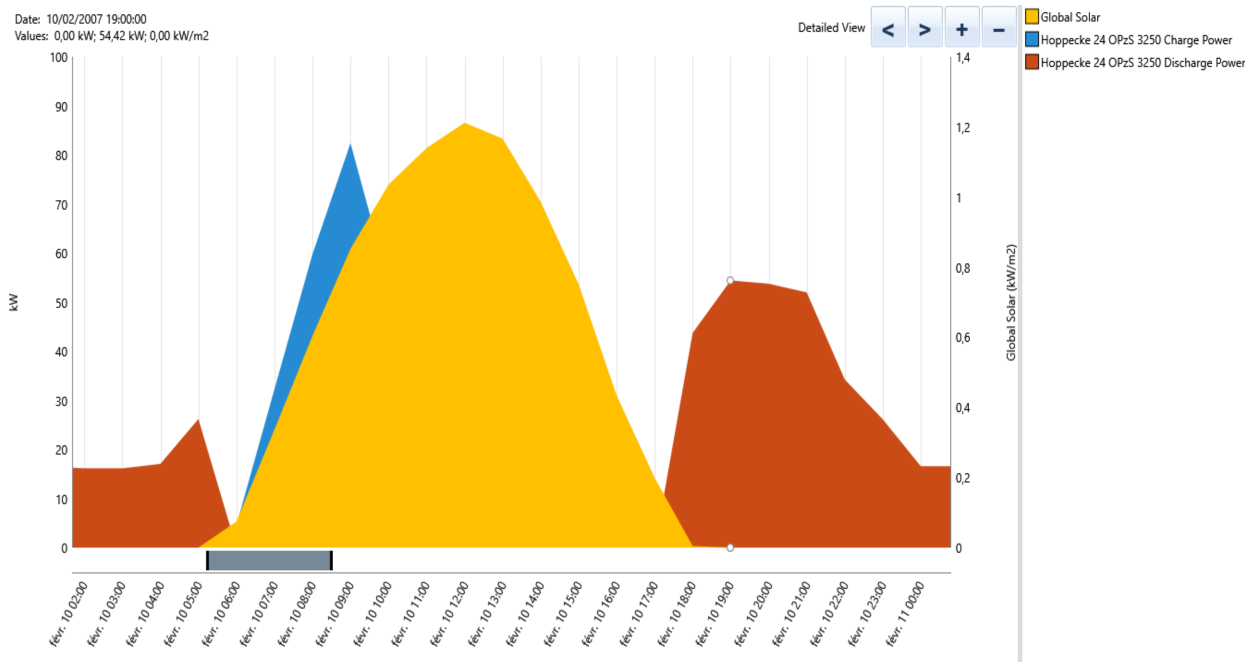


Figure 34: Battery Discharge and Input power in a day

PV panels total electricity production is 296918 kWh/yr with hours of operation of 4380 hrs/yr and levelized cost of 0.0572$/kWh. The PV power output is mainly from 06 AM to 6:00 PM throughout the year with high production during summer and low during peak rainy season month (July-August-September) Figure 35. While maximizing the period of the day when the solar radiation is high to meet the first peak load demand and charge batteries (Figure 36).

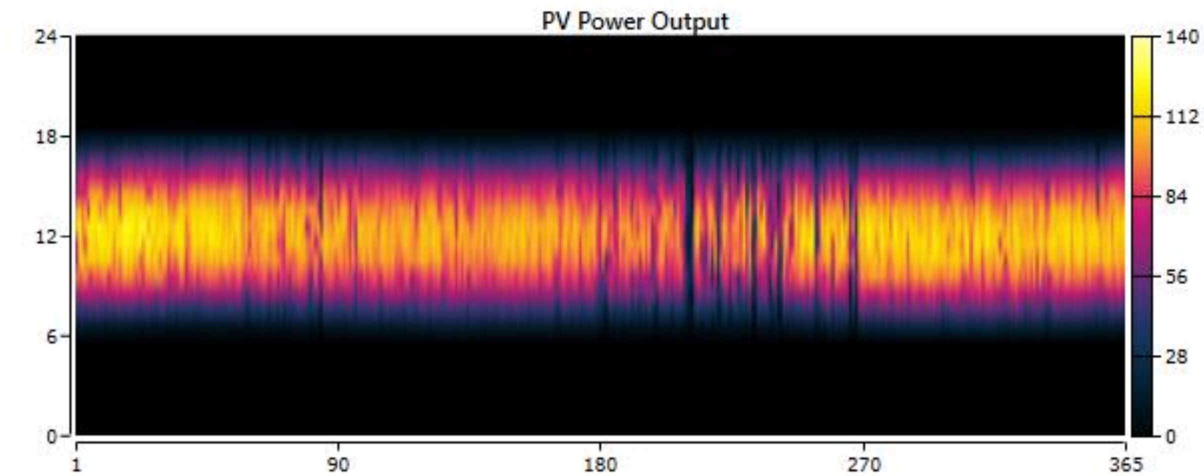


Figure 35: PV/DG/battery: PV power Output over a year

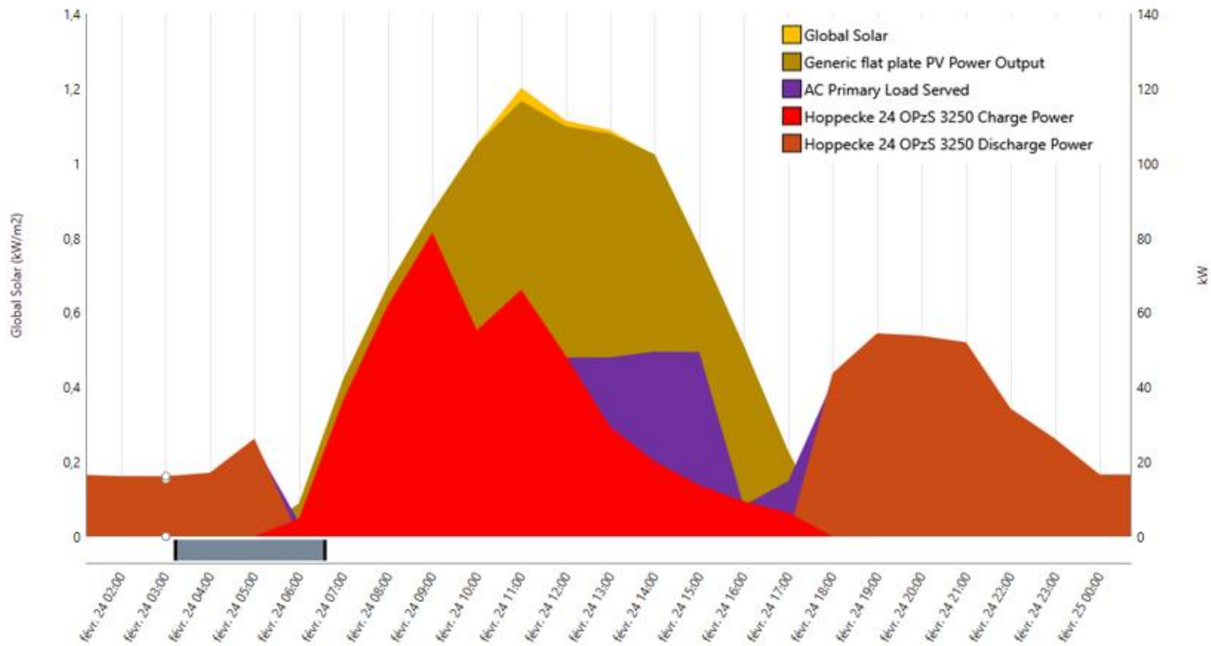


Figure 36: PV/DG/Battery system: PV output over a day, load cover and battery charging

The diesel generator serving as a backup in this configuration of system has only 1.66 % of the total electrical production as mentioned above which decrease its operating hours to a very limited number and increase its lifetime. The DG hours of operation is 403hrs/yr, starts only 87 in a year and an operating lifetime of 37.2 years. The total electrical output production is 8119 kWh/yr, and the engine consumes around of 0.45L/kWh. Also, it has the highest Levelized cost of electricity of 0.2$/kWh. The generator operates mainly in the period of the year where there is peak rainfall due to high cloud cover which reduces the incident solar radiation especially July-Aug-September (Figure 37). Since the collected incident solar radiation has reduced, PV panels are not able to charge enough the battery, so that the based load and peak load demand of the night be met. Therefore, the DG supplement the injected power by batteries (Figure 38). The time of operation of the DG varies from 00-06AM and 6-12 PM.

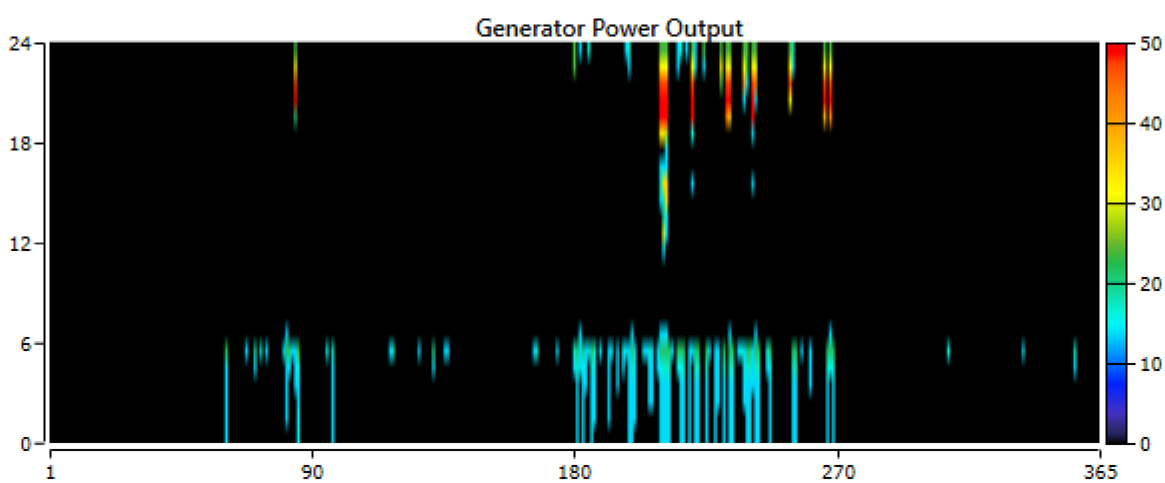


Figure 37: PV/DG/Battery: Diesel Generator power output

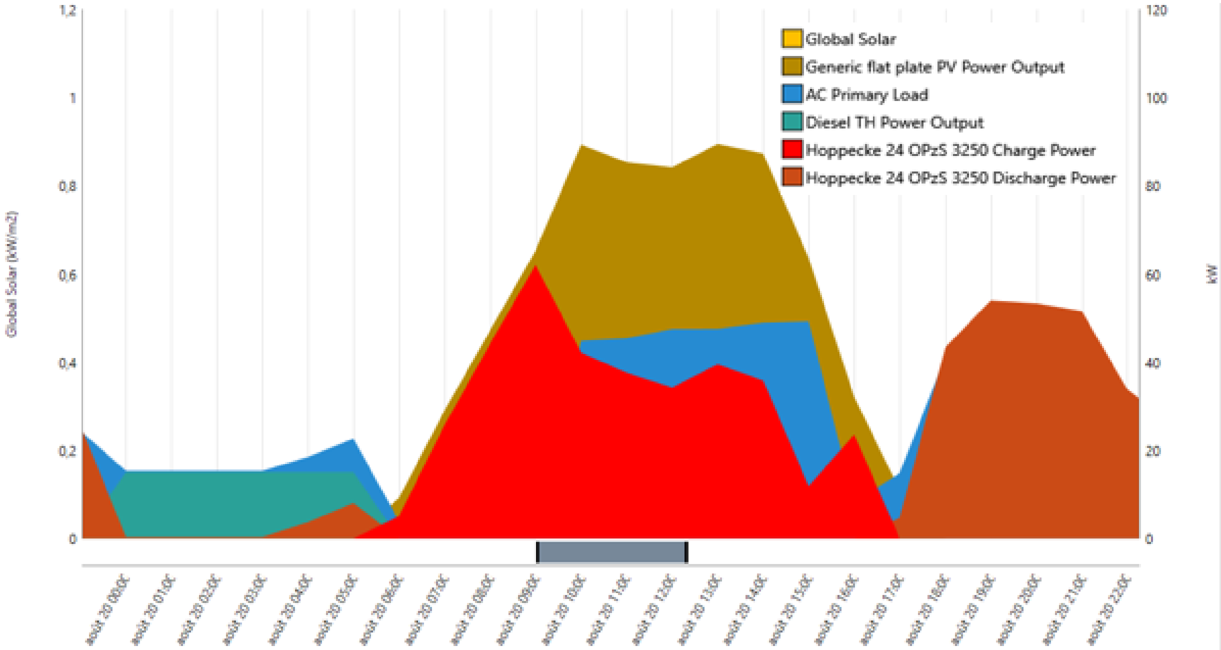


Figure 38: DG Operation over a day in August

The converter operates quite all the time in a year with an operation hour of 8711 hrs/yr with maximum 51.7kW for the inverter and 9.99kW for the rectifier. The rectifier operates less due to the Load Following strategy whereby the excess power produced by DG is not charging the battery. For the inverter, the total energy output against an energy input of 252743kWh/yr is 240105 kWh/day. Figure 39 display the converter output throughout the year.

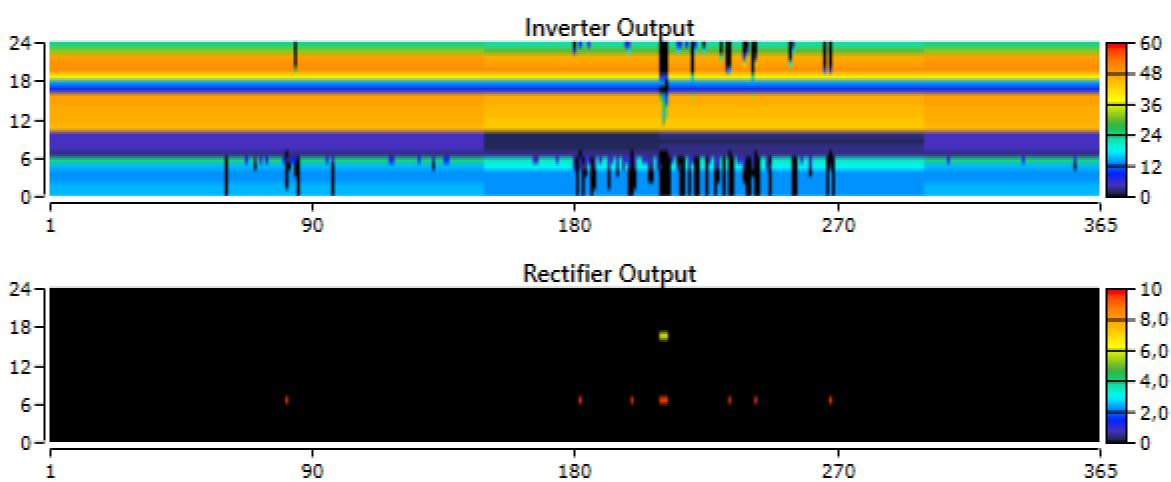


Figure 39: Hybrid PV/DG/Battery-Converter System

The capital, replacement, 0&M, Fuel and Salvage costs throughout the project the lifetime are 3332369 $, 125549 $, 73358 $, 31521 $ and -11305 $ respectively (Table 27). Figure 40 shows the cost summary by components, where Battery has the highest NPC followed by PV panels, Generator and Converter. As shown in Figure 41 presents the nominal cash flow, the replacement of battery occurs three times during the project lifetime, 8th, 15th and 22nd years while the converter one time and in the 15th years of operation.

Table 27: PV/DG/Battery -Cost summary

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
PV	151 000 $	0,00 $	32 675 $	0,00 $	0,00 $	183 675 $
Diesel	23 592 $	0,00 $	6 540 $	31 521 $	-1 173 $	60 480 $
Hoppecke 24 OPzS 3250	97 776 $	110 218 $	21 160 $	0,00 $	-7 103 $	222 051 $
System Converter	60 000 $	19 331 $	12 983 $	0,00 $	-3 028 $	89 286 $
System	332 369 $	129 549 $	73 358 $	31 521 $	-11 305 $	555 492 $

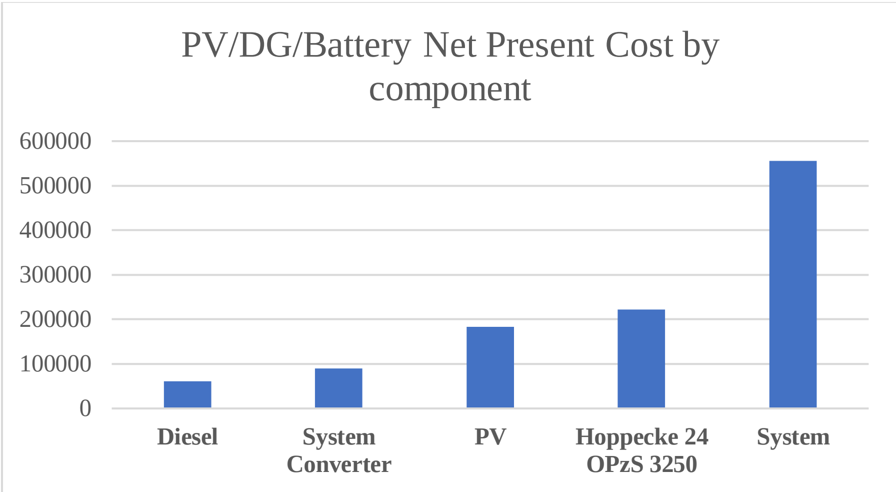


Figure 40: Cost summary: NPC by components

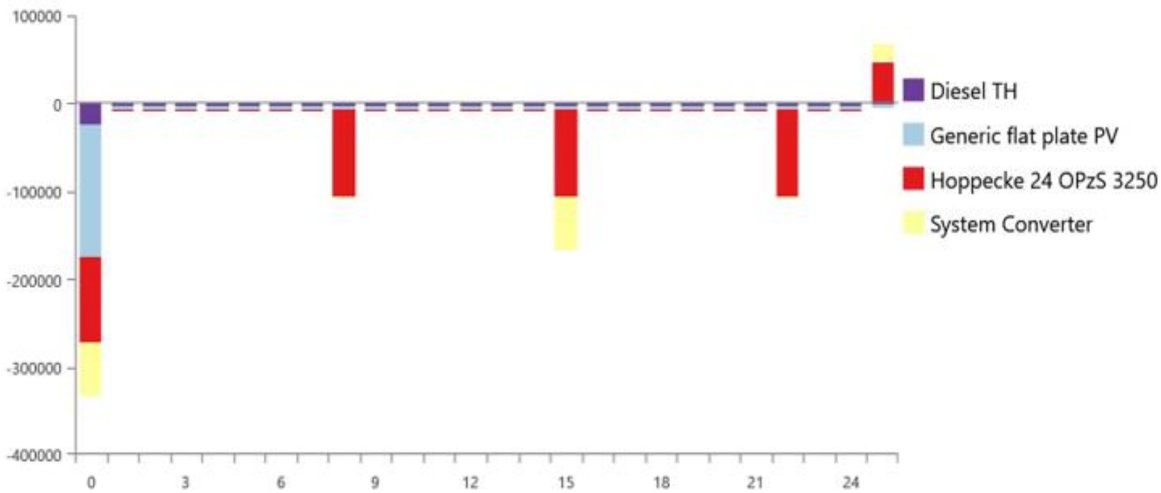


Figure 41: PV/DG/Battery – Cash flow

Standalone Diesel Generator system is taken as the base system for economics comparison, and Table 28 shows some economic metric and value. To recover the difference in investment cost of 751961$ between these two systems, it will take less than four years either discounted or not. With a high-interest rate of return of 33.3% and return on investment of 31.7%.

Table 28: PV/DG/Battery: Compare Economics

PV/DG/Battery	
Metric	**Value**
Present worth ($)	751961$
Annual worth($/yr)	82842$
Return on investment (%)	31.7
Internal rate of return (%)	33.3
Simple payback(yr)	2.97
Discounted payback (yr)	3.45

This system is far away more economical than grid extension, with a breakeven grid extension distance of -1.86km (Figure 42) while the Village of Fouay is 15km far from the grid.

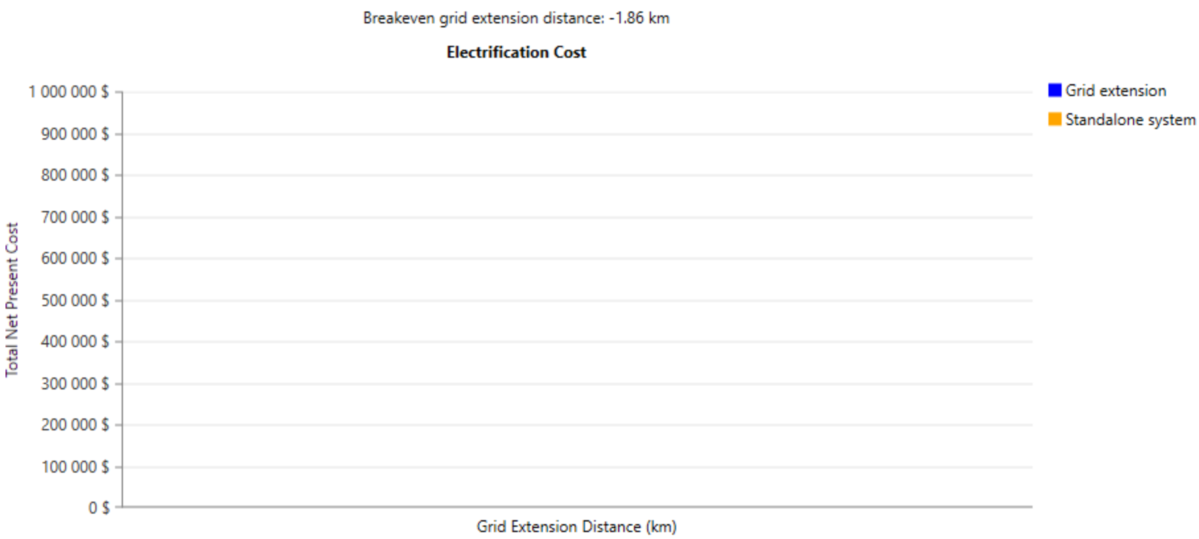


Figure 42: Breakeven-grid extension distance

The proposed optimal system PV/DG/battery pollutes less compared to the DG as presented in Table 29.

Table 29: Emissions summary- PV/DG/Battery vs DG

	Value	
Quantity	**PV/DG/Battery**	**DG**
Carbon Dioxide (kg/yr)	9590	293139
Carbon monoxide (kg/yr)	23.7	724
Unburned Hydrocarbons (kg/yr)	2.62	80.1
Particulate Matter (kg/yr)	1.78	54.5
Sulfur Dioxide (kg/yr)	23.3	714
Nitrogen Oxides (kg/yr)	211	6457

5.8.Fouay Market Analysis

This section of the thesis discusses the current energy scenario in the village, the socio-economic characteristics of household (source of income, expenditure, household size etc..), the electricity need, the Ability To Pay (ATP) and the Willingness To Pay (WTP) for electricity. The primary information is obtained from literature review and field survey questionnaire on a face-to-face basis with 50 households. Those households were randomly selected to be part of this assessment in the village, and the questionnaire was administrated to the head of each household. The questionnaire form used is included in the appendix.
Fouay village market analysis is conducted in the essence of looking at if the community can afford for the system. Also, the viability of any renewable energy projects resides on the ability of the beneficiary to appropriate themselves the system. An assessment of the village financial status is, therefore important, to make sure a return on investment of the project.

The average people per household from the sample of respondents is 11. Most of the Household size are in the range of 5-10 people with a highest relative frequency of 32%. Followed by those in the range of [10-15], [0-5], [15-20] and above 20 people which represents respectively 22%, 20%,18% and 8% (Table 29) of the total household interviewed. The monthly average income of respondents is 147 USD/month, slightly below the average income of people in rural areas in Benin of 151 USD/month (INSAE, 2015). The average monthly expenditure, energy expenditure, and daily electricity demand are respectively 75.1$, 11.4$ and 0.97kWh/day (Table 31). A positive correlation is observed whereby a family with high size tend to have a high income, monthly expense, and energy demand as can be seen in Figure 42.

Table 30: Household size distribution of sample

Person per Household	Number	Relative frequency (%)
0-5	10	20%
5-10	16	32%
10-15	11	22%
15-20	9	18%
>20	4	8%

Table 31: Descriptive summary of household

Person per Household	Average Monthly income ($)	Average Monthly expenditure ($)	Average Energy demand (kWh/day)	Average Energy expenditure ($)
0-5	108.0	71.7	0.51	5.6
5-10	135.0	58.8	0.81	7.9
10-15	94.9	56.1	0.84	11.4
15-20	187.5	97.8	1.22	20.2
> 20	340.3	149.7	2.61	20.4
Total	146.6	75.1	0.97	11.4

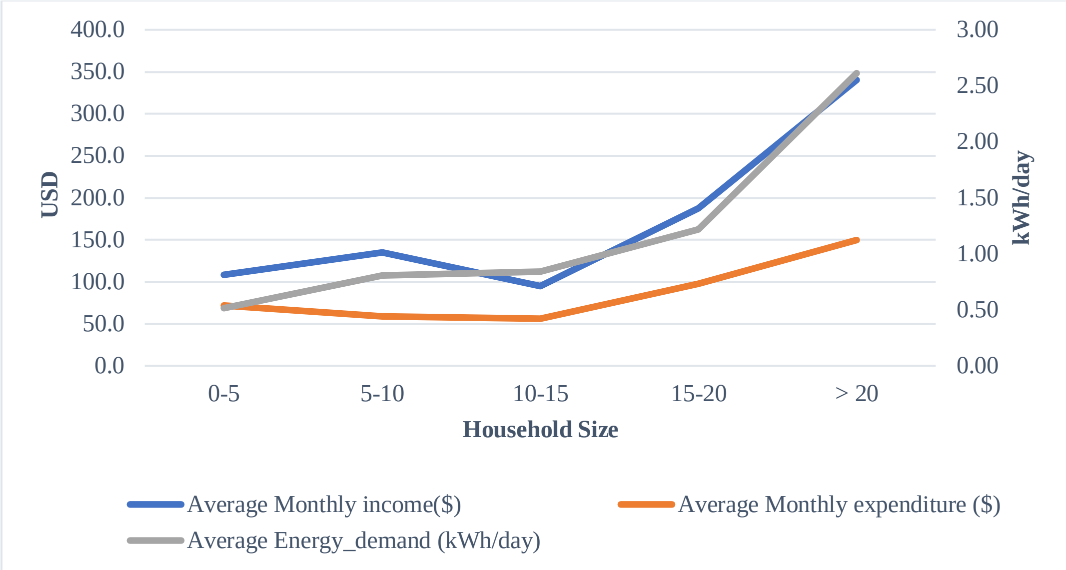


Figure 43: Key Socio-economic variables trend against the income distribution

The monthly income of households in Fouay is ranging from the lowest amount of 9 $/month to the highest of 554 $/month. The distribution of household income is shown in the histogram below (Figure 44). It shows that 60% of the households have their income below 110 $, 20% within [110-220], 10% in [330-440] and 10% above 330 USD/month.

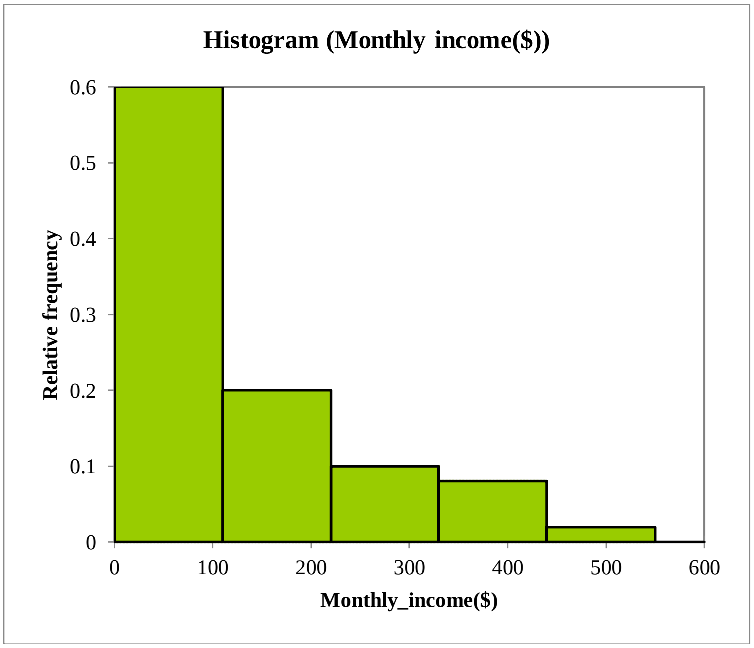


Figure 44: Fouay Income distribution

The current energy used in the village is dominated by battery[2], Solar Home Systems (SHS) and Diesel Generator. The current energy supply in the village are used for lightning, phone charging,

[2] Battery refers to disposable battery

Television, and fan. In parallel the main source of energy for cooking in firewood, which is collected mostly by woman and children from nearby areas. All households use battery as their main source of energy for lightning, whereas 58% relies only on battery, 19 % use a mix of Battery and SHS and 6% use a mix of battery and Diesel generator (Table 32).

Table 32: Type of energy used by income level

Income Level	**Number of Households**	**Relative frequency**	**Type of Energy group**		
			Battery	Mix(Battery+ SHS)	Mix(Battery+ GEN)
[0-110]	30	60%	17	12	1
[110-220]	10	20%	6	3	1
[220-330]	5	10%	3	1	0
[330-440]	4	8%	1	3	1
[440-550]	1	2%	1	0	0
Total	50	100%	28	19	3
		%	56%	38%	6%

Households group with a mix (Battery+ GEN) have a high income, monthly energy expense and energy demand compared to the others group of households having a mix (Battery + SHS) and Battery only as a source of energy. For instance, the average monthly energy expense for households with a generator is 43.56 $/month while 10.94 $/month for households with mix SHS and 8.32 $/month for those using only Battery (Figure 45). This trend can be explained by GEN is high in price comared to SHS and battery, so thereforee only hosehold with high incomc can affford apaying for that ..herefore they will use appliance for more comfort.

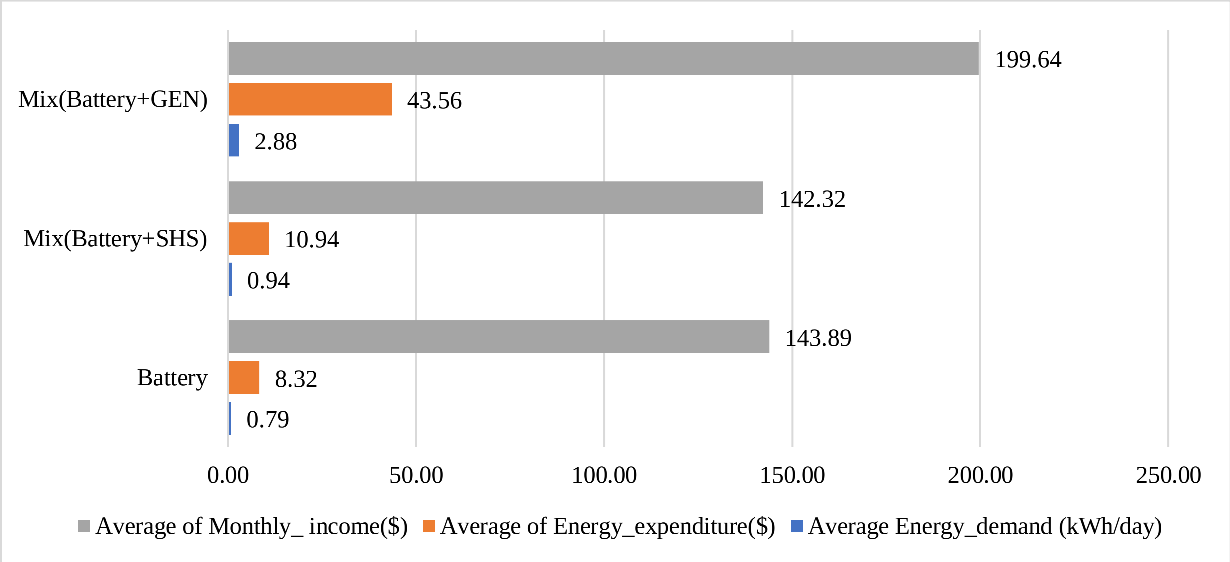


Figure 45: Energy Demand Trend versus Monthly Energy Cost and Monthly Income

In general, the current energy used in the village are Battery, SHS, and Generator for lightning, phone charging, and to power some comfort appliance like Television and Fan. All households use at least battery, but few dispose of Generator and SHS as an additional source. In an economic point of view, 60% of the households have a low income below 110 USD/month and relies mainly on Battery. The target customer that will likely change their behaviour in the way using electricity when electrify will be those with Battery alone as main source of power. In addition, the average energy need per category is high for those using a mix (Battery+GEN) with 2.88 kWh/day, medium 0.94kWh/day for those with the mix (Battery+SHS) and 0.79 kWh/day for Battery users only. However, in regard of this different need, there is a need of performing a willingness to Pay and the ability to Pay analysis to see if they can pay and afford when the proposed hybrid system is installed.

5.8.1. Willingness To Pay **(WTP)**

According to the constructive preference view, consumer willingness to pay is a context-sensitive construct, that is, a consumer's maximum WTP for a product depends on the concrete decision context [54]. Furthermore, WTP is very subjective because its calculation is based on the individual answers to qualitative questions [47]. WTP for electricity, it is however not a fixed value but strongly depends on the quality of service provided and the available alternatives [55]. In any case, it is important to obtain specific local data to assess the actual willingness to pay (World Bank, 2008). A revealed WTP method through an indirect survey is used whereby customers answered to some qualitative questions as listed in Table 33. The questions are an adapted version of the standard questionnaire proposed by [47]. A factor indicating the WTP of the customer is then calculated based on the given answers.
The interviewee answers are weighted from 0 to 3 so that answers that increase the likelihood of people WTP for electricity are rated with a higher figure than answers that show that there is little interest in electricity.

Table 33: Willingness to Pay (WTP) questions Weighting

N°	Questions	Answers	Rate
1	What is important to you?	The cost of electricity	0.5
		The quality of electricity	3
		The duration of the supply	1
2	What will most likely drive you to connect?	Neighbors connected	0.5
		Own need for electricity	3
		Low connection fee	1
3	Will electricity from a hybrid off-grid system improve your life or business somehow?	Yes	3
		NO	0.5
		Don't Know	1
4	On which basis, do you think the provision of electricity should be?	On a free basis	0.5
		On a commercial basis	2
		Others (With subsidy…)	1
5	Who decides for you to pay for electricity?	Myself	3
		My boss	1
		Elders/family	1
6	Do you already have an individual solar system?	Yes	2
		No	0.5
		Under consideration	1
7	How satisfied are you with your current electricity supply?	Very satisfied	0.5
		Not satisfied	2

		Can live with it	1
8	Does your current electricity supply cover your needs?	Yes	0.5
		No	3
		Percentage (if partially):	1

Based on the weights assigned to each qualitative question answers, the interviewees' WTP is computed by taking the total sum of all weighted answers, divided by the maximum possible score of answers (the highest answers out of each question) equal to 21. The result is a percentage figure that indicates the WTP of every interviewee. The interviewee WTP is then clustered into four groups: >90%, [90-75%], [75-50] and < 50% as shown in Table 34 and the percentage of respondents per questions is shown in Table 35.

Table 34: Willingness to Pay (WTP) for electricity at Fouay

	>90%	**75-90%**	**75-50%**	**< 50%**	**Total**
Household	5	32	13	0	50
Percentage (%)	10%	64%	26%	0%	100%

Table 35: Percentage of respondents for each WTP questions

Question	Answers	% respondents	Question	Answers	% respondents
1	The cost of electricity	8%	5	**Myself**	**98%**
	The quality of electricity	**72%**		My boss	2%
	The duration of the supply	20%		Elders/family	0%
2	Neighbors connected	4%	6	**Yes**	**62%**
	Own need for electricity	94%		No	38%
	Low connection fee	2%		Under consideration	0%
3	**Yes**	**80%**	7	Very satisfied	2%
	NO	4%		**Not satisfied**	**90%**
	Don't Know	16%		Can live with it	8%
4	On a free basis	0%	8	Yes	0%
	On a commercial basis	**86%**		**No**	**98%**
	Others (With subsidy.)	14%		Percentage (if partially):	2%

Table 34 is shown a positive sign towards an approximately absolute willingness to pay for the electricity of the community. Since no mention of WTP below 50% is found and 64% of the interviewed households have a WTP to pay within the range of 75-90%. Moreover, 94% of the respondents have declared 'Own need for electricity'' as the main reason that will likely drive them to connect to the system and 72% that, the quality of the electricity is very important for them (see Table 35). The above results from the WTP calculation are reflecting a high disposition for households to pay for reliable and better-quality power supply which is secured by the hybrid system design with 0% unmet load. However, the highest COE for the design Hybrid mini-grid is

0.210 $/kWh, so notwithstanding the fact that their expressed high willingness to Pay, it is important to assess there are ability to Pay if powered by the proposed power supply system.

5.8.2. Ability to Pay (ATP)

ATP for modern energy can be estimated based on current expenditure in energy (kerosene, batteries, diesel, etc.) and the individual customers' stated ATP per month, which is entered into the questionnaire in absolute values. In the questionnaire used during the survey, households were also asked to mention how much they would like to pay per month for electricity and alternatively the current energy expenditure is also computed. To have an accurate answer, the stated monthly ATP for electricity is cross-checked with the computed energy expenditure to avoid a declaration of an amount below the actual energy expense because some tend to respond strategically. Therefore, more explanation and information were provided to allow them to declare an amount that is correlated to the electricity need expressed and which reflects their real standard of living.

The range of ability to pay is divided into five equal range from the minimum to the maximum using Gauss-distribution of ATP for electricity on a monthly basis as used here [47]. The average monthly ability to Pay for respondents is roughly 15.7 $/month and vary from a minimum of 1.82$/month to a maximum value of 55 $/month. Table 36 shows that most of the households ATP fall within the range of 0-22 $/month where 54% are in the range of [0-11] and 26% in [11-22] while the remaining are spread over the others range.

Table 36: Frequency distribution of Ability To Pay (ATP) level

ATP Level ($/month)	0-11	11-22	22-33	33-44	44-55
Number of Household	27	13	4	2	4
Percentage	54%	26%	8%	4%	8%
Average Monthly Income ($)	124.69	143.10	204.17	226.86	208.71
Average Energy Expenditure ($)	6.47	16.82	14.34	28.13	16.11
Average COE ($/kWh)	0.45	0.89	0.63	0.97	1.94
Energy demand (kWh/day)	0.62	0.97	2.04	2.65	1.48
WTP (%)	85	81	82	87	82

Each household provides an estimation of his daily electricity needs, from that the monthly electricity need is derived. The cost of electricity is computed by dividing the expressed ATP by the monthly electricity need. The COE with the highest proportion number of household belong to is taken as a reference to be compared to the COE of the design Hybrid System. Most of the household has their income below 110 USD/month (see Table 32) and belong to the ATP level ranging of [0-11] $/month for electricity as can be seen in Table 36. The willingness to Pay of respondents within this range is found to be 85% in average and would like to pay for a cost of electricity of 0.45$/kWh. While as mentioned in section 5.6, the highest cost of electricity of the proposed Hybrid PV/DG/Battery is 0.21$/kWh. Since the COE expressed by the households is above the COE of the designed system, therefore the community can afford for the Hybrid system

design. So, some electricity sales at a price between 0.22-0.45 $/kWh can be both suitable for the customers and project developer.
Furthermore, it worth noting that, the Net Present Cost of the proposed system, no funding or subsidy is included. If it is so, it will decrease more the overall cost of the system leading to a more cheaper cost of electricity and then more affordable for Fouay inhabitants.

However, Fouay inhabitants have seasonal ability to pay because agriculture is the main source of income and this can be a serious constraint the sustainability of the project if it is not well handled. In fact, their revenue is strongly dependent of the outcomes of the harvesting period, and during seeding time most of their income goes in buying agricultural inputs (fertiliser, pesticide, land preparation…) to ensure a good yield at the end of the season. Although, they have shown a high willingness to pay and can afford for the system, a deep analysis on the kind of tariff scheme to put in place is important to ensure the sustainability of the project. Tariff setting scheme is not in the scope of this work.

5.9. Results and Discussions

The main outcome of the techno-economic, with Solar and Hydro as the main source of power and where battery and Diesel Generator working as backup revealed hybrid PV/DG/Battery and Hydro/DG configuration systems as a viable possible hybrid solution for the electrification of the village of Fouay. When considering the Breakeven Grid Extension Distance (BGED) as an additional key criterion of system selection and the actual demand load, grid extension is more economically feasible than Hydro/DG. Since the BGED is 15.63km greater than 15km the village distance to the grid (VDG). It is only when the demand starts to increase that BGED of Hydro/DG becomes lower than the VDG as shown in Table 25 but the COE proposed is still higher than the national tariff. Although hydropower has the lowest LCOE of all the power source of 0.0452$/kWh. The remoteness of the power source which implies an additional cost to reach the village (11km grid extension cost added to the hydropower capital cost) and the high installed capacity of the turbine could justify such results.

However, in all the sensitivity case, hybrid PV/DG/Battery is the optimal system. As the load demand increase, the Net Present Cost increase but the cost of electricity decrease. While changes in fuel price do not affect the rentability of the system where the COE is still below the national grid tariff. For instance, when varying the fuel price from 0.8 to 1$/l, the maximum COE is 0.21$/kWh which is below 0.22$/kWh the COE of the National grid.

Based on the techno-economic analysis and sensitivity analysis, hybrid PV/DG/battery is the best hybrid system to electrify the village. When considering a Nominal Discount rate of 10%, fuel price at 0.8$/l and project lifetime as 25 years, the architecture of the hybrid system consists of PV panels of 150kW, 50kW Diesel Generator, 98 Hoppecke Battery of 3250AH/2V and 60kW Converter. The system is far away more economical than grid extension projects with BGED of -1.87 km below 15km (VDG) and cheaper COE than the one applied for the national grid. More environmentally friendly than DG by producing only 3% of DG system CO_2 emissions with 96.7 % penetration of renewable energy due to a very good solar irradiation at the location averaging 7.88kWh/m^2/day. It reduces the battery storage costs. For the design system, 98 Hoppecke battery of 3250Ah are used compared to 328 in PV/battery system which is about 70% reduction for the hybrid case. Since Battery is one of the costliest components PV system with battery as storage and needs replacement sometimes during the project lifetime, reduction in number implies decreasing in the overall cost of the system. Furthermore, the optimal system has a short payback period of below four years and high-interest rate of return of 33.3% when taking the DG system as base case system. The hybrid system is economically more viable that grid extension regardless 15 or 25years as project lifetimes (Table 26). So, PV/DG/Battery system is more suitable than grid extension projects as projected by the government in the locality.

Most of the village inhabitants' practice farming as the main source of income, with an average income of 147 USD/month. Where 56% of them relying on disposal battery only, 38% in mix (Battery+SHS) and 6% for the mix (Battery+GEN) as a source of electrical energy excluding. Households with a mix (battery+GEN) have high income, expenditure, energy expenditure than the others group. From the WTP analysis, it is found that households have a very high willingness to pay (all the WTP is above 50%) for the electricity and point out the good quality of electricity as essential aspect for them. The design hybrid system provides a reliable power supply with 0% unmet load, therefore in term of quality will meet the inhabitant's will.
Secondly, the Ability to Pay (ATP) analysis showed that 54% of households have their ATP for the electricity no more than 11$/month and are willing to pay in average a cost of electricity of 0.45kWh/day. This COE is below the highest COE of the design system which is 0.210 kWh/day in the worst-case scenario. Based on the above analysis, the inhabitants of Fouay can afford for the design system. Moreover, subsidy or grants from the government or donors is not included in the NPC calculation of the system. Therefore, if it is so, the COE could be lower and make it more affordable for both the supplier and the population.

6. Conclusions and recommendation

6.1. Conclusions

This study aims to discuss the techno-economic feasibility of Hybrid renewable power system for sustainable rural electrification in Benin where the village of Fouay is selected as a case study. Secondly analyse the affordability of the design system through the market analysis based on two economic value, the willingness to pay and Ability to pay for affordability assessment.
Different datasets were used to conduct this assessment namely data collection from energy agency, meteorological centre and market prices, a literature review of reports, articles and books, and finally onsite survey.

Through literature review and data collection from the Directorate General of Energy, the energy supply scenario of the country is discussed. The country has a low power supply and strongly dependent on importation. A part of from the economic capital city, none of the others division has an electrification rate higher than 50%. Furthermore, rural areas are abandoned at the expense of nearby areas to the grid. Though the country has an enormous renewable energy potential that can be harnessed as developed in section 2.3 10 of the document to provide power to the major part of the country population living far from the grid and to step in this challenge of lack of electricity access. There is no single solution to resolve this deficit in electricity as also the demand increase. An integrated approach with large projects of construction of power plants to scale up electricity power supply and decentralised energy systems to reach rural community where grid extension is costly with the right technology could be the right way for the country to overcome that challenge. Also, such approach should include the vulgarisation of efficient cooking stoves since firewood and charcoal are the forms of energy still mostly consumed in the country. The focus of this assessment is to show hybrid renewable power systems as a suitable technology for sustainable rural electrification in Benin.

The village of Fouay in the Alibori Division is the case study for techno-economic analysis for the designing of the optimal HRES and market analysis. Load assessment with seasonal variation through the onsite survey, resource assessment at the location (Solar and Hydro), project economics, components specifications and costs and constraints were uploaded into the Hybrid Optimisation of Multiple Electric Renewables software tool (HOMER). HOMER design the best optimisation system that meets load of the village based on the Net Present Cost (NPC). Sensitivity analysis for different values of annual streamflow, load demand, Diesel fuel price, Project lifetime and interest rate were used to evaluate the strength of the optimised system.

Hybrid PV/DG/Battery is the best optimal system to electrify the village of Fouay and under the different sensitivity cases cited above. The keys finding of the techno-economic analysis are as follows:

- PV/DG/battery provide a reliable power supply with 0% unmet load
- The system reduces battery storage costs. For instance, it requires only 30% of the battery storage of PV/battery standalone system.

- The design system is environmentally friendly compared to DG standalone system; it generates only 3% DG system CO_2 emissions with a high renewable energy penetration of 96.7%.
- The PV/DG/battery is more economically viable than grid extension project over both 15 or 25 years as project lifetime with a breakeven grid extension distance of -1.85km and provides a cost electricity of 0.207$/kWh lower than the COE applied for the national grid.
- Regarding the profitability, when taking DG as base case system, Hybrid PV/DG/Battery system has a shorter payback period of 3.45 years with high IRR of 33.3%.

Moreover, the optimal least cost hybrid system in a location depends strongly on the potential of power available and the distance of the source from the serving load point. Wind power was disregard for instance because of low wind speed at the place, and Hydropower is a little bit expensive whereby the power source is far from the village which increases the capital cost with an investment cost to extend the grid to the village.

Given the results above, off-grid Hybrid PV/DG/battery is a suitable technology for sustainable electrify the village in contrast to grid extension as projected in the Master plan of rural electrification of the country.

Through the onsite survey conducted information concerning the household financial status, energy situation, electricity need, ability to pay and with qualitative questions related to their willingness to Pay was collected to analyse the village market. Two economic value have been analysed the Ability to Pay (ATP) and the Willingness to Pay (WTP). The average income for the village is 147 USD/month; disposal battery is the main source of lighting and agriculture is the primary activity practised. In overall, the village inhabitants have a high willingness to Pay for the electricity and most of them can pay for 0.45$/kWh as the cost of electricity. At this cost, the community can highly afford for the design hybrid system since it is two times greater than the COE of the proposed PV/DG/Battery which is 0.207$/kWh. The COE computed by HOMER do not include subsidy or fund from governments and international partners. So, if included, it will make the cost of electricity more cheap and affordable for the population as well as the owner of the mini-grid or developer. Based on the results of the market analysis, the off-grid PV/DG/battery design is very affordable by Fouay inhabitants.

However, the community has seasonal ability to pay, and during the day the load demand is dominated by the commercial and industrial load. Therefore, applying a flexible tariff scheme could be appropriate for the village. This scheme of tariff could comprise a pre/post-payment to allow customers (household) to advance cash to cover bill during low season and also a time-based tariff to differentiate the typical group of customers (Commercial, Household, Industrial, and community). Furthermore, renewable energy projects have a high initial investment cost, so government providing subsidy and funds which can drive more investors to it.

In general, this study shows that hybrid off-grid renewable power system is the suitable and cost-effective option for providing a reliable power supply with an intermittent energy source for rural electrification in Benin. Furthermore, the design system is very affordable for the community and can be profitable for a project owner.

Moreover, the HRES design if implemented will have a double benefit in environmental view. First, it will reduce CO_2 emissions as shown compared to a conventional Diesel Generator and reducing the amount of battery disposal in the environment.

6.2. Limitation and Suggestion for future work

This work, far from being a perfect job, some limitations need to be considered, and further research should be carried out to overcome these limitations.

The resources assessed in this study are solar, wind and hydropower. While, the village is among one of the big producers of cotton and Maize in the Division, so huge deposit of crops residues are available which can be used as a potential source of energy. Then, further work should consider adding biomass as energy generation sources in the modelling.

Due to the fact, there is no gauged station on the hydropower site; an empirical method was used for streamflow estimation which has his weakness. Further research should look at a comparative methods analysis for accurate estimation of the streamflow since it is a crucial input for the optimisation. Also, future streamflow can also be simulated to show how climate change will affect this variable in the years to come and could be a useful input as sensitivity case.

HOMER software was used for the optimisation of the optimal Hybrid Renewable Energy System. So, there is a need to compare the results with other methods or algorithm such as Game theory, Particle Swarm Optimisation or others optimisation techniques.

The economic analysis in this study was limited to the Willingness to Pay (WTP) and the Ability to Pay (ATP) while tariff setting, the kind of business models and the financial aspect are also some important points that need to be discussed further. The customers of the design project also include commercial and institutional provider services. The WTP and ATP analysis only focused on household; then it will be preferable to access also for commercial and community load customers.

Sustainability assessment of rural electrification involves others dimensions apart from the techno-economic and environmental aspects, like the institutional and the socio-cultural aspects which play a significant role and has to be discussed. A more holistic approach to this study should integrate all these aspects.

Optimal design of decentralised energy systems is site-specific, so replicability of such works in other areas will permit to generalise HRES as a viable solution for rural electrification in Benin.

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Appendix

Appendix 1: Typical Load Profile Winter Season

Time	Typical Daily Profile: Winter								
	Winter low					Winter High			
	Households (kW)	Commercial (kW)	Community (kW)	Total load		Households (kW)	Commercial (kW)	Community (kW)	Total load
	Daily energy consumption					Daily energy consumption			
1:00	14.26	0.05	1.02	15.33		14.26	0.05	1.02	15.33
2:00	14.26	0.05	1.02	15.33		14.26	0.05	1.02	15.33
3:00	14.26	0.05	1.02	15.33		14.26	0.05	1.02	15.33
4:00	14.26	0.05	1.02	15.33		14.26	0.05	1.02	15.33
5:00	17.11	0.05	1.31	18.47		17.11	0.05	1.31	18.47
6:00	21.17	0.05	1.36	22.58		21.17	0.05	1.39	22.61
7:00	3.60	0.00	0.30	3.90		3.60	0.00	0.33	3.93
8:00	2.45	0.35	0.18	2.98		2.45	0.35	0.35	3.16
9:00	2.18	0.35	0.18	2.71		2.18	0.35	0.35	2.89
10:00	2.14	0.47	0.30	2.91		2.14	0.47	0.47	3.09
11:00	1.76	42.69	0.24	44.70		1.76	42.69	0.36	44.82
12:00	1.76	42.80	0.69	45.26		1.76	42.80	0.81	45.38
13:00	1.76	42.80	2.89	47.46		1.76	42.80	2.89	47.46
14:00	1.76	42.85	2.89	47.50		1.76	42.85	2.89	47.50
15:00	3.18	42.85	2.77	48.80		3.18	42.85	2.89	48.92
16:00	3.18	42.85	3.07	49.10		3.18	42.85	3.19	49.22
17:00	4.21	0.69	3.10	8.00		4.21	0.69	3.24	8.14
18:00	13.21	0.96	0.56	14.73		13.21	0.96	0.61	14.79
19:00	38.42	1.14	1.49	41.05		38.42	1.14	1.55	41.11
20:00	47.38	2.41	1.47	51.25		47.38	2.41	1.50	51.28
21:00	46.88	2.38	1.35	50.60		46.88	2.38	1.38	50.63
22:00	45.46	2.18	1.30	48.93		45.46	2.18	1.33	48.96
23:00	29.91	1.19	1.02	32.12		29.91	1.19	1.02	32.12
0:00	23.26	0.14	1.02	24.41		23.26	0.14	1.02	24.41
Total	367.86	269.41	31.53	**668.79**		367.86	269.41	32.94	**670.20**

Appendix

Appendix 2: load demand assessment by appliances and by customers

Time	Household Load							Community Load							Commercial Load							Total Electricity Load (kWh)
	Radio (30W)	Television (120W)	DVD (24W)	Phone (5W)	FAN (55W)	Fridge (100W)	Light (3W/10W)	Mosque (85W)	Church (85W)	School (285 W)	Health Center (360W)	Street Light (70 W)	Water Pump (2200W)	Hall (85W)	Small Business Center (1228W)	Village store (10W)	Barber (657W)	Tailor (345W)	Copier Shop (165 W)	Flour Mill (7500 W)	Solder (4500 W)	
1:00				0.27	0.42		13.99	0.07	0.04	0.03	0.15	0.7		0.03	0.02	0.03						15.75
2:00				0.27	0.42		13.99	0.07	0.04	0.03	0.15	0.7		0.03	0.02	0.03						15.75
3:00				0.27			13.99	0.07	0.04	0.03	0.15	0.7		0.03	0.02	0.03						15.33
4:00				0.27			13.99	0.07	0.04	0.03	0.15	0.7		0.03	0.02	0.03						15.33
5:00				0.27			16.84	0.24	0.04	0.03	0.27	0.7		0.03	0.02	0.03						18.47
6:00	1.61			1.23			18.34	0.24	0.04	0.08	0.3	0.7		0.03	0.02	0.03						22.61
7:00	1.61			1.23			0.77	0.15		0.03	0.15											3.93
8:00	1.61			0.84						0.18	0.175		2.2		0.35							5.36
9:00	1.15			1.03						0.18	0.175		2.2		0.35							5.09
10:00	1.38			0.77						0.30	0.295		2.2		0.38			0.09				5.41
11:00	0.23			0.77		0.77				0.24	0.24		2.2		0.48			0.21		37.5	4.5	47.14
12:00	0.23			0.77	0.42	0.77		0.15		0.12	0.39		2.2	0.15	0.59			0.21		37.5	4.5	48.00
13:00	0.23			0.77	0.42	0.77		0.15			0.39		2.2	0.15	0.59			0.21		37.5	4.5	47.88
14:00	0.23			0.77	0.42	0.77		0.15		0.05	0.39		2.2	0.15	0.85					37.5	4.5	47.98
15:00	0.23			2.18	0.42	0.77				0.29	0.39		2.2	0.18	0.85					37.5	4.5	49.51
16:00	0.23			2.18	0.00	0.77		0.3		0.29	0.39		2.2	0.18	0.85					37.5	4.5	49.39
17:00	0.23			3.22	0.00	0.77		0.3		0.32	0.415		2.2	0.18	0.69							8.31
18:00	7.74			4.71	0.00	0.77		0.15		0.11	0.325			0.03	0.69	0.1			0.18			14.79
19:00	10.88		0.15	4.79	0.42	0.77	21.84	0.24	0.115	0.14	0.325	0.7		0.03	0.80	0.1		0.06	0.18			41.53
20:00	10.88	9.19	0.34	3.45	0.42	0.77	22.76	0.24	0.115	0.11	0.3	0.7		0.03	0.83	0.1	0.99	0.32	0.18			51.70
21:00	10.88	9.19	0.34	2.95	0.42	0.77	22.76	0.24	0.115	0.11	0.18	0.7		0.03	0.80	0.1	0.99	0.32	0.18			51.06
22:00	10.88	9.19	0.34	1.53	0.42	0.77	22.76	0.24	0.115	0.06	0.18	0.7		0.03	0.80	0.03	0.99	0.32	0.04			49.38
23:00	2.45	9.19	0.34	0.57	0.42		17.36	0.07	0.04	0.03	0.15	0.7		0.03	0.17	0.03	0.99					32.54
0:00	0.00	8.27	0.18	0.42	0.42		14.38	0.07	0.04	0.03	0.15	0.7		0.03	0.11	0.03						24.84
																					Total	687.059

Appendix

Appendix 3: Survey: Household Information, load Assessment and WTP

Name of interviewer		**Contact of the interviewer**		
Name of the village		Date:	Questionnaire number:	
Type of electricity consumer	Household ☐ Business ☐ Institution ☐ Anchor client ☐			
Reference data	Head household name:	Contact		

Household characterization

Size of the Household	Number of people in Exodus	Current Monthly expenditure	Current Energy expenditure per month

Current energy expenses

Type of energy	Quantity	Hour(s) of use per day	Distance purchase Place	Freq. of purchase in day	Unit price	Transport Cost
Oil						
Candles						
Kerosene						
Gas						
Batteries						
Firewood						
Diesel/fuel						

Type of habitat

House	Number of room	Type of construction (straw, bamboo, banco, hard, others)	Type of roof (straw, zinc, tile, concrete, other)

Source of income

N°	Income source	Amount per month
Total:		

Stated ability to pay

Amount per month	

Daily consumption

Appliance	Power (W)	Numbers	Daily in use (hr)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Fridge																											
Television																											
Radio/CD																											
Lamps																											
Radio (20-60)																											
Phones (2-5)																											
Computer																											
Others																											
Total																											

Appendix 2: Survey: Household Information, load Assessment and WTP (Cont'd)

Willingness to Pay				
		Please tick one option		
1	What is important to you?	The cost of electricity	The quality of electricity	The duration of the supply
2	What will most likely drive you to connect?	Neighbors connected	Own need for electricity	Low connection fee
3	Will electricity from a hybrid mini-grid improve your life or business somehow?	Yes	No	Don't know
4	On which basis, do you think the provision of electricity should be?	On a free basis	On a commercial basis	
5	Who decides for you to pay for electricity?	Myself	My boss	Elders/family
6	Do you already have an individual solar system?	Yes	No	Under consideration
7	How satisfied are you with your current electricity supply?	Very satisfied	Not satisfied	Can live with it
8	Does your current electricity supply cover your needs?	Yes	No	Percentage (if partially):

Date of the Interview: ______________________________ Signature of the Respondent: ____________________________

Appendix 4: Yearly Discharge of Cascade de Sosso 1956-2006

Years	Cascade sosso streamflow (m^3/s)
1956	27.63
1957	68.72
1958	7.16
1960	51.47
1961	16.99
1964	34.01
1965	15.42
1966	21.68
1967	46.69
1968	39.85
1969	40.32
1972	13.22
1973	21.67
1974	18.46
1975	20.53
1976	5.84
1989	39.43
1990	23.48
1991	77.19
1992	27.10
1994	47.06
2003	32.41
2004	47.38
2005	39.95
2006	29.87

Appendix 5: Solar Radiation at Kandi (kWh/m^2/day) 2000-2016, Source: DNM

Years	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Mean**
2000	8.31	9.24	7.43	9.27	8.49	8.22	5.83	5.47	7.05	8.41	9.47	9.24	8.02
2001	9.41	8.84	8.46	7.47	8.50	7.81	6.76	4.90	6.80	8.80	10.01	10.22	8.16
2002	8.16	9.09	7.38	7.89	8.70	7.26	7.01	7.52	7.76	7.54	9.54	9.83	8.13
2003	8.98	8.88	7.82	8.15	8.54	7.81	6.88	5.23	7.20	8.97	9.26	9.40	8.09
2004	8.69	8.21	6.90	7.59	7.52	7.69	6.87	6.09	7.12	9.60	8.71	9.23	7.85
2005	7.72	7.42	7.24	8.18	7.86	8.22	6.78	6.05	7.58	8.63	9.15	9.94	7.90
2006	8.91	8.78	7.50	8.59	7.16	7.95	7.44	5.72	6.62	9.32	9.80	9.16	8.07
2007	7.99	9.03	7.95	6.71	7.02	8.21	6.39	6.14	7.13	8.21	9.16	8.37	7.68
2008	8.96	7.75	8.86	7.99	8.55	8.82	6.10	5.99	6.15	8.25	9.69	8.86	8.00
2009	8.69	6.61	6.50	7.99	7.70	6.68	6.14	5.60	6.63	8.02	8.98	9.94	7.46
2010	9.94	9.53	5.85	6.19	7.67	7.78	5.85	5.32	6.21	7.65	8.95	9.91	7.56
2011	8.64	7.57	8.66	8.22	8.17	8.31	7.55	5.99	6.09	8.43	10.11	9.36	8.09
2012	8.93	7.68	7.27	7.89	6.60	7.39	5.51	5.29	6.46	8.26	9.58	9.46	7.52
2013	7.92	6.64	8.11	7.38	7.57	6.79	6.73	4.80	6.95	8.78	9.86	9.17	7.56
2014	9.13	8.91	8.36	7.17	7.24	7.00	6.28	5.59	6.26	8.51	9.74	9.65	7.81
2015	8.76	9.38	6.39	7.87	8.08	8.41	6.61	5.31	7.16	8.36	9.85	8.71	7.89
2016	9.13	8.33	8.02	8.94	8.59	6.37	6.15	5.41	6.43	8.97	9.29	9.13	7.89

Appendix 6: Wind Speed at Kandi (m^3/s) 2000-2016, Source: DNM

Years	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Mean
2000	2.7	4.1	3.2	3.9	3.6	1.9					1.9	2.1	2.9
2001	2	2.6	2.2	3	2.8	2.2	1.3	1.5	1.5	1.4	1.7	2.3	2.0
2002	2.8	2	1.9	2.6	2.2	1.8	1.4	1	1.4	1.2	1.6	2	1.8
2003	1.6	1.9	2.3	2.1	2.1	1.3	1.4	0.9	0.9	1.1	1.3	1.8	1.6
2004	1.9	2.5	2.5	2.4	2	1.6	1.2	1	0.8	0.9	1.3	1.1	1.6
2005	2.1	1.8	1.5	1.9	2	1.3	1.1	1	0.9	0.8	1.2	1.5	1.4
2006	1.1	1.3	1.4	1.6	1.9	1.5	1.4	1	0.9	0.8	1.4	1.5	1.3
2007	2	1.4	1.4	2	1.3	1.5	1.1	0.9	0.6	0.7	0.7	1	1.2
2008	2.2	1.9	1.2	1.3	1.2	1.1	0.8	0.6	0.7	0.7	0.8	1	1.1
2009	1.1	0.9	0.9	1.8	1.4	1.2	0.9	0.5	0.4	0.7	0.8	0.8	1.0
2010	1.1	1.1	1.4	1.2	1.2	1	0.9	1.1	1.4	1.7	1.5	1.8	1.3
2011	2.3	2.1	2.4	2.8	2.5	2.5	1.6	1.4	0.8	0.8	0.9	1.9	1.8
2012	1	1	1.8	2.3	2.2	1.2	1	1.1	1.2	1	1	1.7	1.4
2013	1.4	1.4	1.8	1.7	1.6	1.5	1.1	1.2	1.1	1.3	1.7	1.9	1.5
2014	2.2	2.4	2.4	3	2.3	2.1	1.9	1.5	1.3	1.5	1.9	2.1	2.1
2015	2.3	2.1	2.3	2.5	2.5	2.5	1.5	1.1	1.1	1.2	1.6	2.7	2.0
2016	2.3	1.8	1.8	2.3	2.4	1.9	1.4	1.3		1.2	1.3	1.9	1.8

Appendix 7: Optimisation results for Hybrid System with, Q=31m^3/s, Proj lifetime=25years

NDR (%)	DFP ($/L)	Load (kWh/day)	PV(kW)	Dsl (kW)	Battery	Hydro	Con (kW)	Dispatch	COE ($)	NPC ($)	Ren Frac (%)	Excess Elec (%)	Unmet load (%)	CO2 (kg/yr)
8	0.8	680	150	50	99		60	LF	0.188	602958.6	97	7.6	0.00	9447
8	0.8	680	200		328		60	CC	0.252	806546.8	100	28.6	0.09	0
8	0.8	680				247		CC	0.282	905886	100	86.0	0.00	0
8	0.8	680			5	247	5	CC	0.287	920876.5	100	86.0	0.00	0
8	0.8	680		40		247		CC	0.288	923068.6	100	86.0	0.00	0
8	0.8	680		40	5	247	5	CC	0.292	938059.1	100	86.0	0.00	0
8	0.8	680	50			247	5	CC	0.305	978086.9	100	86.7	0.00	0
8	0.8	680	50		1	247	5	CC	0.305	979484.6	100	86.7	0.00	0
8	0.8	680	50	40		247	5	CC	0.310	995269.5	100	86.7	0.00	0
8	0.8	680	50	40	1	247	5	CC	0.311	996667.2	100	86.7	0.00	0
8	0.8	680	170	60			60	CC	0.363	1163897	42	47.1	0.00	157356
8	0.8	680		50	17		25	CC	0.387	1240774	0	0.0	0.00	230508
8	0.8	680		60				CC	0.485	1557159	0	10.5	0.00	293140
8	0.8	750	170	50	112		65	LF	0.186	658742.3	97	9.6	0.05	8178
8	0.8	750	260		323		65	CC	0.250	883102.2	100	39.4	0.08	0
8	0.8	750				247		CC	0.256	905886	100	84.6	0.00	0
8	0.8	750			5	247	5	CC	0.260	920876.5	100	84.6	0.00	0
8	0.8	750		40		247		CC	0.261	923068.6	100	84.6	0.00	0
8	0.8	750		40	5	247	5	CC	0.265	938059.1	100	84.6	0.00	0
8	0.8	750	50			247	5	CC	0.276	978086.9	100	85.3	0.00	0
8	0.8	750	50		1	247	5	CC	0.277	979484.6	100	85.3	0.00	0
8	0.8	750	50	40		247	5	CC	0.281	995269.5	100	85.3	0.00	0
8	0.8	750	50	40	1	247	5	CC	0.282	996667.2	100	85.3	0.00	0
8	0.8	750	190	70			65	CC	0.368	1304077	41	47.8	0.00	178593
8	0.8	750		50	21		25	CC	0.388	1374679	0	0.0	0.00	255058
8	0.8	750		70				CC	0.497	1758828	0	11.8	0.00	333402
8	0.8	850	190	60	122		75	LF	0.186	747228.3	97	8.7	0.02	10985
8	0.8	850				247		CC	0.226	905886	100	82.5	0.00	0
8	0.8	850			5	247	5	CC	0.230	920876.5	100	82.5	0.00	0
8	0.8	850		40		247		CC	0.230	923068.6	100	82.5	0.00	0
8	0.8	850		40	5	247	5	CC	0.234	938059.1	100	82.5	0.00	0
8	0.8	850	50			247	5	CC	0.244	978086.9	100	83.4	0.00	0
8	0.8	850	50		1	247	5	CC	0.244	979484.6	100	83.4	0.00	0
8	0.8	850	50	40		247	5	CC	0.248	995269.5	100	83.4	0.00	0
8	0.8	850	50	40	1	247	5	CC	0.248	996667.2	100	83.4	0.00	0
8	0.8	850	500		168		75	CC	0.276	1105441	100	64.3	0.09	0

NDR (%)	DFP ($/L)	Load (kWh/day)	PV(kW)	Dsl (kW)	Battery	Hydro	Con (kW)	Dispatch	COE ($)	NPC ($)	Ren Frac (%)	Excess Elec (%)	Unmet load (%)	CO2 (kg/yr)
8	0.8	850	200	80			70	CC	0.368	1474148	40	45.5	0.00	208262
8	0.8	850		60	21		25	CC	0.381	1528180	0	0.0	0.00	289384
8	0.8	850		80				CC	0.495	1983866	0	12.0	0.00	379614
10	0.8	680	150	50	98		60	LF	0.207	555491.9	97	7.7	0.00	9590
10	0.8	680	200		328		60	CC	0.286	766964.9	100	28.6	0.09	0
10	0.8	680				247		CC	0.323	866192.9	100	86.0	0.00	0
10	0.8	680			5	247	5	CC	0.328	880239.9	100	86.0	0.00	0
10	0.8	680		40		247		CC	0.330	885302.1	100	86.0	0.00	0
10	0.8	680		40	5	247	5	CC	0.335	899349.1	100	86.0	0.00	0
10	0.8	680	50			247	5	CC	0.349	935669.3	100	86.7	0.00	0
10	0.8	680	50		1	247	5	CC	0.349	936992.9	100	86.7	0.00	0
10	0.8	680	50	40		247	5	CC	0.356	954778.4	100	86.7	0.00	0
10	0.8	680	50	40	1	247	5	CC	0.356	956102.1	100	86.7	0.00	0
10	0.8	680	170	60			60	CC	0.378	1014423	42	47.1	0.00	157356
10	0.8	680		50	17		25	CC	0.390	1048021	0	0.0	0.00	230508
10	0.8	680		60				CC	0.487	1307453	0	10.5	0.00	293140
10	0.8	750	170	50	112		65	LF	0.206	608404.8	97	9.6	0.05	8178
10	0.8	750	260		323		65	CC	0.284	840785.3	100	39.4	0.08	0
10	0.8	750				247		CC	0.292	866192.9	100	84.6	0.00	0
10	0.8	750			5	247	5	CC	0.297	880239.9	100	84.6	0.00	0
10	0.8	750		40		247		CC	0.299	885302.1	100	84.6	0.00	0
10	0.8	750		40	5	247	5	CC	0.304	899349.1	100	84.6	0.00	0
10	0.8	750	50			247	5	CC	0.316	935669.3	100	85.3	0.00	0
10	0.8	750	50		1	247	5	CC	0.316	936992.9	100	85.3	0.00	0
10	0.8	750	50	40		247	5	CC	0.322	954778.4	100	85.3	0.00	0
10	0.8	750	50	40	1	247	5	CC	0.323	956102.1	100	85.3	0.00	0
10	0.8	750	190	70			65	CC	0.384	1135907	41	47.8	0.00	178593
10	0.8	750		50	21		25	CC	0.392	1160727	0	0.0	0.00	255058
10	0.8	750		70				CC	0.498	1476435	0	11.8	0.00	333402
10	0.8	850	190	60	121		75	LF	0.205	688553.3	96.90	87.3	0.02	11183
10	0.8	850				247		CC	0.258	866192.9	100	82.5	0.00	0
10	0.8	850			5	247	5	CC	0.262	880239.9	100	82.5	0.00	0
10	0.8	850		40		247		CC	0.264	885302.1	100	82.5	0.00	0
10	0.8	850		40	5	247	5	CC	0.268	899349.1	100	82.5	0.00	0
10	0.8	850	50			247	5	CC	0.279	935669.3	100	83.4	0.00	0
10	0.8	850	50		1	247	5	CC	0.279	936992.9	100	83.4	0.00	0
10	0.8	850	50	40		247	5	CC	0.284	954778.4	100	83.4	0.00	0
10	0.8	850	50	40	1	247	5	CC	0.285	956102.1	100	83.4	0.00	0

Appendix

NDR (%)	DFP ($/L)	Load (kWh/day)	PV(kW)	Dsl (kW)	Battery	Hydro	Con (kW)	Dispatch	COE ($)	NPC ($)	Ren Frac (%)	Excess Elec (%)	Unmet load (%)	CO2 (kg/yr)
10	0.8	850	500		168		75	CC	0.310	1041073	100	64.3	0.09	0
10	0.8	850	200	80			70	CC	0.382	1280803	40	45.5	0.00	208262
10	0.8	850		60	21		25	CC	0.384	1289336	0	0.0	0.00	289384
10	0.8	850		80				CC	0.496	1664975	0	12.0	0.00	379614
8	1	680	170	45	96		60	LF	0.191	612035.1	98.12	17.3	0.04	5200
8	1	680	200		328		60	CC	0.252	806546.8	100	28.6	0.09	0
8	1	680				247		CC	0.282	905886	100	86.0	0.00	0
8	1	680			5	247	5	CC	0.287	920876.5	100	86.0	0.00	0
8	1	680		40		247		CC	0.288	923068.6	100	86.0	0.00	0
8	1	680		40	5	247	5	CC	0.292	938059.1	100	86.0	0.00	0
8	1	680	50			247	5	CC	0.305	978086.9	100	86.7	0.00	0
8	1	680	50		1	247	5	CC	0.305	979484.6	100	86.7	0.00	0
8	1	680	50	40		247	5	CC	0.310	995269.5	100	86.7	0.00	0
8	1	680	50	40	1	247	5	CC	0.311	996667.2	100	86.7	0.00	0
8	1	680	170	60			60	CC	0.411	1318394	42	47.1	0.00	157356
8	1	680		50	17		25	CC	0.457	1467096	0	0.0	0.00	230508
8	1	680		60				CC	0.575	1844975	0	10.5	0.00	293140
8	1	750	170	50	112		65	LF	0.188	666771.5	97	9.6	0.05	8178
8	1	750	260		323		65	CC	0.250	883102.2	100	39.4	0.08	0
8	1	750				247		CC	0.256	905886	100	84.6	0.00	0
8	1	750			5	247	5	CC	0.260	920876.5	100	84.6	0.00	0
8	1	750		40		247		CC	0.261	923068.6	100	84.6	0.00	0
8	1	750		40	5	247	5	CC	0.265	938059.1	100	84.6	0.00	0
8	1	750	50			247	5	CC	0.276	978086.9	100	85.3	0.00	0
8	1	750	50		1	247	5	CC	0.277	979484.6	100	85.3	0.00	0
8	1	750	50	40		247	5	CC	0.281	995269.5	100	85.3	0.00	0
8	1	750	50	40	1	247	5	CC	0.282	996667.2	100	85.3	0.00	0
8	1	750	190	70			65	CC	0.418	1479427	41	47.8	0.00	178593
8	1	750		50	21		25	CC	0.459	1625105	0	0.0	0.00	255058
8	1	750		70				CC	0.589	2086175	0	11.8	0.00	333402
8	1	850	200	60	121		75	LF	0.189	757528.4	98	12.6	0.02	8591868
8	1	850				247		CC	0.226	905886	100	82.5	0.00	0
8	1	850			5	247	5	CC	0.230	920876.5	100	82.5	0.00	0
8	1	850		40		247		CC	0.230	923068.6	100	82.5	0.00	0
8	1	850		40	5	247	5	CC	0.234	938059.1	100	82.5	0.00	0
8	1	850	50			247	5	CC	0.244	978086.9	100	83.4	0.00	0
8	1	850	50		1	247	5	CC	0.244	979484.6	100	83.4	0.00	0

NDR (%)	DFP ($/L)	Load (kWh/day)	PV(kW)	Dsl (kW)	Battery	Hydro	Con (kW)	Dispatch	COE ($)	NPC ($)	Ren Frac (%)	Excess Elec (%)	Unmet load (%)	CO2 (kg/yr)
8	1	850	50	40		247	5	CC	0.248	995269.5	100	83.4	0.00	0
8	1	850	50	40	1	247	5	CC	0.248	996667.2	100	83.4	0.00	0
8	1	850	500		168		75	CC	0.276	1105441	100	64.3	0.09	0
8	1	850	200	80			70	CC	0.419	1678628	40	45.5	0.00	208262
8	1	850		60	21		25	CC	0.452	1812308	0	0.0	0.00	289384
8	1	850		80				CC	0.588	2356586	0	12.0	0.00	379614
10	1	680	150	50	99		60	LF	0.210	563570.9	97	76.6	0.00	9447
10	1	680	200		328		60	CC	0.286	766964.9	100	28.6	0.09	0
10	1	680				247		CC	0.323	866192.9	100	86.0	0.00	0
10	1	680			5	247	5	CC	0.328	880239.9	100	86.0	0.00	0
10	1	680		40		247		CC	0.330	885302.1	100	86.0	0.00	0
10	1	680		40	5	247	5	CC	0.335	899349.1	100	86.0	0.00	0
10	1	680	50			247	5	CC	0.349	935669.3	100	86.7	0.00	0
10	1	680	50		1	247	5	CC	0.349	936992.9	100	86.7	0.00	0
10	1	680	50	40		247	5	CC	0.356	954778.4	100	86.7	0.00	0
10	1	680	50	40	1	247	5	CC	0.356	956102.1	100	86.7	0.00	0
10	1	680	170	60			60	CC	0.426	1143726	42	47.1	0.00	157356
10	1	680		50	17		25	CC	0.461	1237436	0	0.0	0.00	230508
10	1	680		60				CC	0.577	1548333	0	10.5	0.00	293140
10	1	750	170	50	112		65	LF	0.208	615124.6	97	9.6	0.05	8178
10	1	750	260		323		65	CC	0.284	840785.3	100	39.4	0.08	0
10	1	750				247		CC	0.292	866192.9	100	84.6	0.00	0
10	1	750			5	247	5	CC	0.297	880239.9	100	84.6	0.00	0
10	1	750		40		247		CC	0.299	885302.1	100	84.6	0.00	0
10	1	750		40	5	247	5	CC	0.304	899349.1	100	84.6	0.00	0
10	1	750	50			247	5	CC	0.316	935669.3	100	85.3	0.00	0
10	1	750	50		1	247	5	CC	0.316	936992.9	100	85.3	0.00	0
10	1	750	50	40		247	5	CC	0.322	954778.4	100	85.3	0.00	0
10	1	750	50	40	1	247	5	CC	0.323	956102.1	100	85.3	0.00	0
10	1	750	190	70			65	CC	0.433	1282662	41	47.8	0.00	178593
10	1	750		50	21		25	CC	0.463	1370315	0	0.0	0.00	255058
10	1	750		70				CC	0.591	1750400	0	11.8	0.00	333402
10	1	850	190	60	122		75	LF	0.208	697694.6	97	8.7	0.02	10985
10	1	850				247		CC	0.258	866192.9	100	82.5	0.00	0
10	1	850			5	247	5	CC	0.262	880239.9	100	82.5	0.00	0
10	1	850		40		247		CC	0.264	885302.1	100	82.5	0.00	0
10	1	850		40	5	247	5	CC	0.268	899349.1	100	82.5	0.00	0
10	1	850	50			247	5	CC	0.279	935669.3	100	83.4	0.00	0
10	1	850	50		1	247	5	CC	0.279	936992.9	100	83.4	0.00	0

Appendix

NDR (%)	DFP ($/L)	Load (kWh/day)	PV(kW)	Dsl (kW)	Battery	Hydro	Con (kW)	Dispatch	COE ($)	NPC ($)	Ren Frac (%)	Excess Elec (%)	Unmet load (%)	CO2 (kg/yr)
10	1	850	50	40		247	5	CC	0.284	954778.4	100	83.4	0.00	0
10	1	850	50	40	1	247	5	CC	0.285	956102.1	100	83.4	0.00	0
10	1	850	500		168		75	CC	0.310	1041073	100	64.3	0.09	0
10	1	850	200	80			70	CC	0.433	1451937	40	45.5	0.00	208262
10	1	850		60	21		25	CC	0.455	1527131	0	0.0	0.00	289384
10	1	850		80				CC	0.589	1976914	0	12.0	0.00	379614

Appendix 8: Household Sample characterization

Appendix

Nº	Household Size	Monthly income ($)	Monthly expenditure ($)	Energy expenditure ($)	ATP ($)	Type of energy	Source of Income	Energy demand (kWh/day)
1	30	363	181	15	27	(Battery+SHS)	Farmer	4.47
2	5	127	54	4	4	Battery	Government Worker	0.79
3	12	109	91	9	9	Battery	Farmer	0.83
4	5	272	91	5	5	Battery	Farmer	1.41
5	21	127	109	3	15	(Battery+SHS)	Farmer	1.82
6	2	381	363	7	18	Battery	Government Worker	0.43
7	6	73	9	9	18	(Battery+SHS)	Farmer	1.04
8	6	27	9	4	6	Battery	Farmer	0.68
9	6	127	36	5	7	(Battery+SHS)	Farmer	1.37
10	4	73	54	9	9	(Battery+SHS)	Farmer	0.38
11	9	145	36	9	18	(Battery+GEN)	Government Worker	2.47
12	9	109	73	22	18	Battery	Farmer	0.68
13	14	45	18	4	4	Battery	Farmer	0.77
14	4	54	36	9	15	Battery	blacksmith	0.92
15	2	36	13	4	4	Battery	Mechanic	1.01
16	16	54	27	20	18	(Battery+SHS)	Farmer	0.359
17	9	91	54	7	5	Battery	Farmer	0.72
18	12	109	73	6	9	Battery	Farmer	0.86
19	15	181	91	6	7	Battery	Farmer	0.835
20	9	145	73	6	6	Battery	Farmer	0.665
21	10	18	9	4	9	(Battery+SHS)	Farmer	0.338
22	1	91	64	7	9	(Battery+SHS)	Business	0.57
23	16	181	91	21	27	Battery	Farmer	1.625
24	29	272	91	9	6	(Battery+SHS)	Farmer	1.03
25	20	363	181	22	9	(Battery+SHS)	Farmer	0.37

Appendix

Nº	Household Size	Monthly income ($)	Monthly expenditure ($)	Energy expenditure ($)	ATP ($)	Type of energy	Income	Energy demand (kWh/day)
26	12	73	54	12	45	(Battery+SHS)	Farmer	0.374
27	18	91	36	85	18	(Battery+GEN)	Farmer	1.6
28	20	363	145	36	36	(Battery+GEN)	Farmer	4.58
29	15	109	36	9	54	Battery	Farmer	2.54
30	2	91	54	2	9	Battery	Farmer	0.39
31	17	73	36	9	4	(Battery+SHS)	Farmer	0.269
32	5	45	18	9	18	Battery	Farmer	0.427
33	10	181	91	15	27	Battery	Farmer	1.045
34	7	73	54	12	13	Battery	Farmer	0.81
35	12	91	54	7	27	Battery	Farmer	1
36	13	109	54	15	20	Battery	Farmer	0.65
37	15	327	272	15	18	(Battery+SHS)	Farmer	1.07
38	19	544	181	15	54	Battery	Farmer	0.845
39	6	109	45	9	5	Battery	Farmer	0.615
40	3	91	45	9	5	Battery	Farmer	0.535
41	1	73	45	3	2	(Battery+SHS)	Government Worker	0.42
42	14	91	45	20	36	(Battery+SHS)	Farmer	0.719
43	10	181	36	4	7	(Battery+SHS)	Farmer	0.27
44	1	9	5	2	2	Battery	Farmer	0.22
45	15	109	54	29	54	(Battery+SHS)	Farmer	2.152
46	9	272	42	5	18	Battery	Farmer	0.288
47	5	181	109	4	9	Battery	Farmer	0.18
48	6	254	181	7	9	Battery	Farmer	0.346
49	8	109	54	9	4	(Battery+SHS)	Farmer	0.408
50	12	109	73	6	5	(Battery+SHS)	Farmer	0.488

Appendix 9: WTP Coding

Household	What is important to you?	What will most likely drive you to connect?	Will electricity from a hybrid off-grid improve your life or business somehow?	On which basis, do you think the provision of electricity should be?	Who decides for you to pay for electricity?	Do you already have an individual solar system?	How satisfied are you with your current electricity supply?	Does your current electricity supply cover your needs?	WTP
1	0.5	0.5	1	2	3	2	2	3	67%
2	3	3	0.5	2	3	0.5	2	3	81%
3	3	3	1	1	3	0.5	2	3	79%
4	3	3	1	1	3	2	1	3	81%
5	0.5	0.5	3	1	3	2	2	3	71%
6	1	3	1	2	3	0.5	1	1	60%
7	1	3	3	2	3	2	2	3	90%
8	3	3	0.5	1	3	0.5	2	3	76%
9	3	3	1	1	3	2	1	3	81%
10	1	3	3	2	3	2	1	3	86%
11	1	3	3	2	3	0.5	2	3	83%
12	1	3	3	2	3	0.5	2	3	83%
13	1	3	3	2	3	0.5	2	3	83%
14	0.5	3	3	2	3	0.5	2	3	81%
15	1	3	3	2	3	0.5	2	3	83%
16	1	3	3	2	3	2	2	3	90%
17	1	3	3	2	3	0.5	2	3	83%
18	1	3	3	2	3	0.5	2	3	83%
19	1	3	3	2	3	0.5	2	3	83%
20	1	3	3	2	3	0.5	2	3	83%
21	1	3	3	2	3	0.5	2	3	83%
22	1	3	3	2	3	2	2	3	90%
23	3	3	3	2	3	0.5	2	3	93%
24	1	3	3	2	3	2	2	3	90%
25	1	3	3	2	3	2	2	3	90%
26	1	1	1	2	3	2	2	3	71%
27	1	3	3	2	3	0.5	2	3	83%
28	1	3	3	2	3	0.5	2	3	83%
29	1	3	3	2	3	0.5	2	3	83%

30	3	3	3	2	3	0.5	2	3	93%
31	3	3	3	2	3	2	2	3	100 %
32	1	3	3	2	1	0.5	2	3	74%
33	1	3	3	2	3	0.5	2	3	83%
34	1	3	3	2	3	0.5	2	3	83%
35	1	3	3	2	3	0.5	2	3	83%
36	1	3	3	2	3	0.5	2	3	83%
37	1	3	3	2	3	2	2	3	90%
38	1	3	3	2	3	0.5	2	3	83%
39	1	3	3	2	3	0.5	2	3	83%
40	1	3	3	2	3	0.5	2	3	83%
41	1	3	3	2	3	2	2	3	90%
42	1	3	3	2	3	2	2	3	90%
43	1	3	3	2	3	2	2	3	90%
44	0.5	3	3	2	3	0.5	2	3	81%
45	1	3	3	2	3	2	2	3	90%
46	1	3	3	2	3	0.5	2	3	83%
47	1	3	3	2	3	0.5	2	3	83%
48	3	3	1	1	3	2	2	3	86%
49	3	3	1	1	3	2	2	3	86%
50	1	3	3	2	3	0.5	2	3	83%