Université Cheikh Anta Diop de Dakar

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MASTER THESIS

SPECIALITY: Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic: Hybrid renewable energy system for rural electrification in Togo: Techno-economic assessment (A case study)

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DECLARATIONS

I, PASSAOU Kibaloussinam Ignace, hereby declare that this work has solely been done by me to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics. Throughout the work, I used these software: REF-N-WRITE, DeepL, Google translate to enhance the writing.

PASSAOU K. Ignace	…………………	………………………
(Student)	(Signature)	(Date)

DEDICATION

This work is dedicated to my guardian and all my loved ones.

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ABSTRACT

Globally, access to reliable electricity improves the well-being of people, provides quality education, and ensures good health. In this study, a PV/Wind hybrid renewable energy for rural electrification is designed for the canton of KPASSOUADE in the central region of Togo. The selection of the community was done with the QGIS software. Thereafter, the Hybrid Optimization Model for Electric Renewable (HOMER) software was used to perform the technical and economic analysis. The daily load of the canton of KPASSOUADE is 2617 kWh/d. Three load categories were considered: Household, commercial, and community. The electric mini-bus was considered in the load estimation to cover the transport needs. The findings showed that 450 kW of PV, 10 Wind turbines of 20kW, 253 kW of converter, and 6556 kWh of battery storage is the most optimal configuration compared to other power systems to meet the daily energy needs of the canton of KPASSOUADE. The PV/Wind hybrid energy system will generate annual electricity of 1294813 kWh/ year. The community will consume 26876 kWh of AC load and 85941 kWh of deferrable load. The hybrid renewable energy system has a levelized cost of energy (LCOE) of 0.10 USD/kWh and 4.06 million USD as net present cost (NPC). The LCOE of the HRES is found to be low compared to the cost of energy of the nation's thermal power plant which was 0.11 USD/ kWh in 2021. The sensitivity analysis on the changes in the inflation rate; discount rate; wind speed; capital, replacement, and operation cost are also presented. The development of renewable energy plan with a focus on a hybrid renewable energy system is the key policy recommendation.

Key words: Hybrid renewable energy system, solar PV, Wind, and HOMER.

RESUME

Dans le monde entier, l'accès à une électricité fiable améliore le bien-être des populations, fournit une éducation de qualité et assure une bonne santé. Dans cette étude, un système hybride PV/éolien d'énergie renouvelable pour l'électrification rurale est conçu pour le canton de KPASSOUADE dans la région centrale du Togo. La sélection de la communauté a été faite avec le logiciel QGIS. Par la suite, le logiciel Hybrid Optimization Model for Electric Renewable (HOMER) a été utilisé pour effectuer l'analyse technique et économique. La charge journalière du canton de KPASSOUADE est de 2617 kWh/jour. Trois catégories de charge ont été considérées : Les ménages, les commerces et les collectivités. Le mini-bus électrique a été pris en compte dans l'estimation de la charge pour couvrir le secteur des transports. Les résultats ont montré que 450 kW de PV, 10 éoliennes de 20 kW, 253 kW de convertisseur et 6556 kWh de stockage en batterie constituent la configuration la plus optimale par rapport à d'autres systèmes d'énergie pour répondre aux besoins énergétiques quotidiens du canton de KPASSOUADE. Le système hybride photovoltaïque/éolien produira une électricité annuelle de 1294813 kWh/an. La charge AC que la communauté consommera 26876 kWh et 85941 kWh de charge différée. Le système hybride d'énergie renouvelable a un coût de l'énergie nivelé (LCOE) de 0,104 USD/kWh et un coût actualisé net (NPC) de 4,06 millions USD. Le LCOE du système hybride d'énergie renouvelable est faible par rapport au coût de l'énergie de la centrale thermique nationale, qui était de 0,11 USD/kWh en 2021. L'analyse de sensibilité sur les variations du taux d'inflation, du taux d'actualisation, de la vitesse du vent, du capital, des coûts de remplacement et du coût de l'énergie a montré que le coût de l'énergie est faible. Le développement d'un plan pour les énergies renouvelables, axé sur les systèmes hybrides d'énergie renouvelable, est la principale recommandation politique.

Mots clés : Système hybride d'énergie renouvelable, solaire PV, éolien et HOMER.

ACRONYMS AND ABBREVIATIONS

CAPEX Capital expenditure

EV Electric vehicle

HOMER Hybrid Optimization Model of Electric Renewable

HRES Hybrid Renewable Energy System

IEA International Energy Agency

IRENA International Renewable Energy Agency

LCOE levelized cost of energy

NPC Net present cost

O&M operation and maintenance

QGIS Quantum geographical information system

SDGs Sustainable Development Goals

UN United Nations

USD US dollars

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CHAPTER 1

1.1 Background of the research

Energy is a key component for the socio-economic development of any country. Over the last decade, conventional resources (Coal, natural gas, oil) were solely used to provide energy for mankind's daily energy needs. However, those resources have been found as the sources of greenhouse gas emissions in the atmosphere (Shukla et al., 2022). Increasing worldwide attention to environmental protection and the depletion of conventional energy resources places renewable energy (solar, wind, biomass) as the key drivers of future energy systems. Moreover, according to Arena's world energy transitions outlook (IRENA, 2023), "*a profound and systemic transformation of the global energy system must occur within the next 30 years if the world is to avoid the devastating effects of climate change and a steady erosion of energy security*".

Universal access to reliable, affordable, and modern energy for all is the sustainable goal 7 set by 2030 by the United Nations and the Paris Agreement signed by various countries to keep the global temperature increase well below 2 degrees are worldwide signs of commitment toward the achievement of the energy transition. However, people around the world are living without any access to basic energy requirements. Currently, 600 million people, or 43% of the total population, do not have access to electricity, most of them live in sub-Saharan Africa (IEA, 2022). In addition, it is projected that 679 million people will still be living without electricity in 2030 with regard to the current trend (UN-SDG REPORT, 2022). Furthermore, 970 million of Africans lacks access to clean cooking (IEA,2022). Deploying renewable off-grid energy solutions can expand electricity access, alleviate poverty, create jobs, improve water security, and provide clean cooking (IRENA, 2019).

Togo is one of the developing countries in West Africa with a population estimated at 8,848,699 inhabitants and a population growth rate estimated at 2.3 % per year (*World Bank Open Data*, 2022). The population is unevenly distributed across the country, 42.9 % live in urban areas whereas 58.1% live in rural areas. (NYONI & MUTONGI, 2019), in their study, "Prediction of the total population in Togo" using annual time series data, found that the Togolese population will continue to grow and will reach 14.2 million in 2050. The population growth will be directly linked to an increase in energy demand. Currently, only 58% of the population has access to electricity (ARSE,2021). In 2018, the electricity access rate at the rural level was estimated at 8 % against 88.8% in urban areas (*Energypedia*, 2020).

1.2 Problem statement

The Togolese government aims to deploy more than 300 mini-grids by 2030 (AFD, 2019) to solve the lack of electricity access. Currently, the incorporation of clean cooking and the electrification of transport seems to catch less attention in the rural electrification plans to researchers and governments. On the other hand, high investment costs, inaccessibility, and low density of populations have been found in research as limitations to various developing countries' barriers to their national network expansion in remote areas (Diouf et al., 2013);(Ahlborg & Hammar, 2011). Therefore, a hybrid renewable energy system represents a better solution to curb these obstacles and challenges and provide affordable and reliable energy to rural communities. The off-grid renewable sources are the best option to provide energy to remote areas. These systems do not need too much investment to be implemented and can operate independently from the national grid. Nevertheless, those resources are intermittent and cannot fully satisfy the needs of the community compared to fossil fuels. In this study, we would like to design a hybrid renewable energy system to balance the intermittency. The work will take into account the clean and the electrification of the transport under the umbrella of rural electrification. In the literature, there is a gap in the techno-economic assessment of HRES especially in the context of Togo. So, this work attempts to fill the gap by conducting a case study.

1.2 Research questions

The following research questions have been identified to reach our objectives:

- What is the resource potential in the community?
- What are the techno-economic requirements for the design of hybrid renewable energy system?
- What is the potential impact of the proposed HRES on the local community regarding socioeconomic development and environmental sustainability?

- What policy instruments and recommendations can be provided to foster rural renewable electrification projects in Togo?

1.3 Research hypotheses

- Daily solar global horizontal irradiation (GHI) and average wind speed in the community are sufficient to be converted into sustainable electricity.
- The hybrid renewable power system can supply sustainable electricity to meet the community'`s energy demand.
- The cost of energy from the hybrid renewable energy system will be competitive compared to the cost of energy from the national grid and will positively impact the community.

1.4 Research objectives

The main research objective is to design a hybrid renewable energy system for rural electrification in Togo and evaluate its socio-economic impact on the community.

The specific objectives are:

- Technical and economic assessment of the designed hybrid renewable energy system,
- Review and provision of key recommendations regarding rural electrification policies in Togo.

1.5 Significance of this study

- Provide clean and sustainable electrification for lighting, cooking, transport, and agriculture via a hybrid renewable energy system (HRES) to improve electricity access in remote areas.
- Contribute and consolidate to increase the share of renewables in the national energy mix.
- Alert and inform policymakers about the benefits of a hybrid renewable energy system to speed up the rural electrification processes in Togo.

1.6 Limitation of Research

Due to the limitations of on-site investigations, an interview and assumptions were used to conduct the study. Also, due to the limited data, biomass and hydro were not considered in the case study.

The data concerning the community willingness to pay were not collected so the in-depth economic analysis about their ability to pay was not properly evaluated. It could have an impact on the viability on the HRES.

1.7 Outline of the study

This work is divided into six parts:

The first chapter which is the introductory part of the work covers the background of the research, the research questions, the research objectives, the research hypotheses, the significance of the study, and the limitations of the work. The second chapter gives an overview of the renewable energies and policies in Togo. The third chapter the literature review of hybrid renewable energy systems. Chapter 4 highlights the materials and methods used for the modelling of the HRES. Chapter 5 covers the results of the modelling and the discussions. The last part of the work focuses on the conclusion and recommendations.

CHAPTER 2: Energy situation and Energy policies in TOGO

2.1 Energy Situation and energy policies in Togo

Togo is a West African developing country located on the Gulf of Guinea with a total area of 56 600 km2. It is limited to the north by Burkina Faso, to the east by Benin, to the west by Ghana, and the south by the Atlantic Ocean. It lies between 6° and 11° north latitude and 0° and 2° longitude east of the Greenwich meridian. The capital town is Lomé. The total population estimated in 2022 was 8095498 inhabitants. The population growth of Togo is estimated at 2.3%. Togo has its GDP estimated at 8.13 billion US dollars and a GDP growth of 5.8% per year in 2022(World Bank Open Data, 2022). The country has five administrative regions: Savanes, Kara, centrale, plateaux, and Maritime. Figure 1 shows the delimitation of each region.

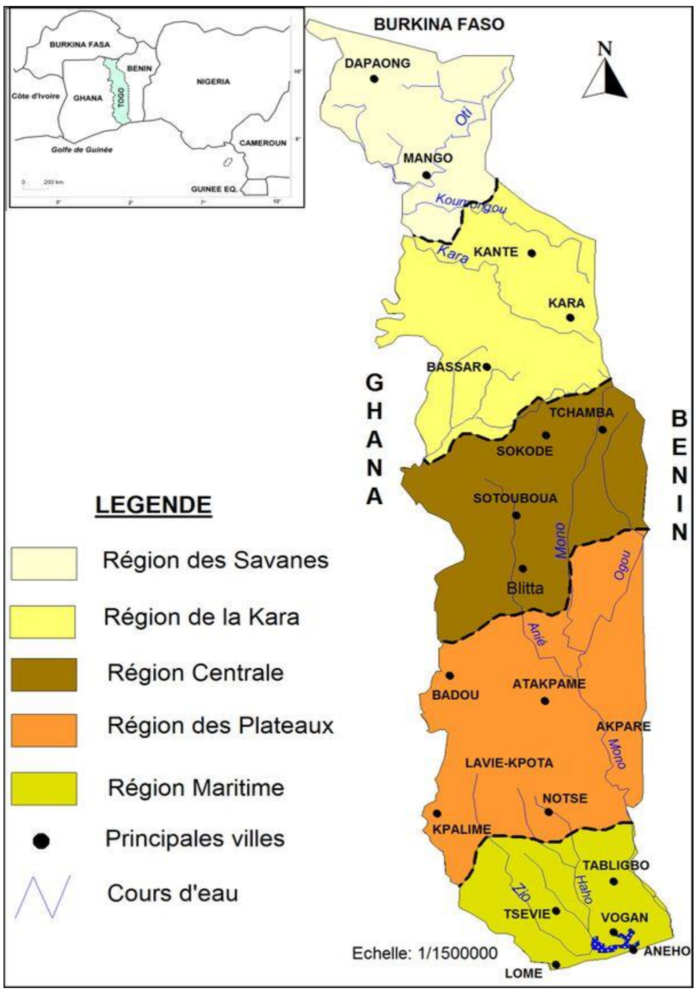


Figure 1: Administrative regions of Togo

Source: Ontheworldmap

Togo's energy consumption comes from three sources: biomass, petroleum products, and electricity. The biomass comes entirely from domestic resources. The biomass resources are firewood, charcoal, and agricultural waste. The firewood is directly used in households and the rest is converted into charcoal. In 2020, 125584 TJ of biofuels and waste were produced in Togo. The petroleum products are imported with a supply of 22396 TJ in 2020 (IEA, 2022). A large part of the petroleum product goes into the transport sector and the rest for electricity production. The electricity production in 2020 was 674.45 GWh. This production comes from the hydraulic and thermal plants of the Communauté Electrique du Benin (CEB) in Togo, from the Compagnie Energie Electrique du Togo (CEET), Contour Global, and other independent producers. It is complemented by imports of up to 814.1 GWh, from the Volta River Authority (VRA) in Ghana and the Compagnie Ivoirienne d'Electricite (CIE) in Cote d'Ivoire and Transmission Company of Nigeria (TCN) in Nigeria. The total supply of electricity was 1488.64 GWh in 2020 (SIE TOGO, 2021).

Togo's energy policy is yet to be adopted by the Government, with anticipation for its adoption by the end of 2014. The preliminary energy policy draft encompasses several provisions aimed at (Ministry of Economy and Finance, 2018):

- Establishing an investment code or law that incorporates taxation and incentives to boost the promotion of renewable energies.
- Formulating regulations outlining the terms for renewable energy production and integration into the national grid at a reduced rate.
- Creating legislation to outline an energy efficiency strategy through the promotion of energy-efficient equipment.
- Crafting specific laws to encourage rural and economically disadvantaged areas' electrification, including the establishment of a national rural electrification agency and a Rural Electrification Fund.
- Executing a plan to liberalize the electricity market to enhance Togo's participation in the ECOWAS Regional Market.

- Developing an institutional framework to foster public-private partnerships, encompassing favourable tax and customs arrangements for rural electrification initiatives and the creation of a funding mechanism involving external donors and the national financial system.
- Promoting the generation and supply of off-grid energy in remote or isolated regions and offering suitable incentives to enterprises to ensure reasonable investment returns.
- Simplifying the establishment of industrial facilities for local production of electrical equipment.
- Exploring sedimentary basins for petroleum products and gas.

2.2 Solar and wind potentials in Togo

According to the laboratory of Solar Energy at the University of Lomé and the Directorate of National Meteorology, which made measurements made at various latitudes of the country's global sunshine, they found that the average insolation for the whole country is 6.62 hours per day. They estimated the average global solar energy at 4.4 kWh/m2/day in Lomé (capital city of Togo), 4.3 kWh/m2/Day in Atakpamé, and 4.5 kWh /m2/Day in Mango. Solar power is estimated to be 0.7kW/m2, especially in the dry season when the sky is clear with the humidity rate of the air flow (Etse et al., 2019). The northern part of Togo has a photovoltaic power potential than the southern part of the country (See Figure A. 1)

Compared to solar potential, the wind potential is relatively low in Togo. (Amega et al., 2022) , in their study discovered that the wind energy potential in Togo at 50 m above the ground is 4 m/s. This is promising for the development of small-scale wind projects for rural electrification.

CHAPTER 3: LITERATURE REVIEW

3.1 Hybrid renewable energy system for rural electrification

3.1.1 Hybrid renewable energy system: definition

A hybrid renewable energy system is a combination of two or more renewable energy sources that work together to provide a more efficient, sustainable, and reliable power generation system(León Gómez et al., 2023). Renewable resources can be naturally replenished after they have been used. Those resources are Solar, wind, biomass, hydropower, geothermal, and biofuels. The major concern worldwide about renewable resources is that they are intermittent. Thus, hybrid renewable energy systems are the better options to improve renewable based-systems by combining various sources of energy. A hybrid renewable energy system (HRES) matches the differences in generation from its various sources of energy production. For instance, a hybrid system combines solar and wind energies. During the day, when the sun shines, solar panels generate electricity to meet part of the load and charge the batteries. At night, when there is no sun, the wind is converted into additional electricity to meet part of the load. Another example of a hybrid system combines solar and hydro energies. During the day, solar panels generate electricity that is used to pump water from a river or lake to a dam. At night, when there is no sun, the water stored in the dam is released through a hydro turbine to generate additional electricity (Roy et al., 2022).

HRES requires storage systems such as batteries, supercapacitors, flywheel, etc. The storage systems make the hybrid energy system more reliable than the other systems by increasing the efficient supply of energy. Batteries store electricity and are activated when the generation of the renewable energy system is insufficient to meet the load demand. Batteries are an important factor in electricity costs over the life of the project as they need to be replaced regularly, typically every 6 to 8 years. Their duration depends on the manner that they are operated and on the external conditions such as ambient temperature and dirt. Lead-acid are more used in HRES (Come Zebra et al., 2021). On the other hand, lithium-ion batteries are more efficient than lead-acid batteries but more costly. Nevertheless, the cost of lithium-lion batteries is likely to decrease in the future with technology advancement which is estimated between an 8-16% annual decrease annually (Jaiswal, 2017). In his review on the optimal operation of hybrid AC/DC micro-grid under uncertainty of renewable resources, (Pourbehzadi et al., 2019) found that lead-acid batteries are mostly used in hybrid renewable energy systems. While recent advancements in the design of such systems propose the association of batteries and supercapacitors.

3.1.2 Type of Hybrid renewable energy systems

In the field of hybrid energy system configurations, two typologies are often mentioned: AC bar and DC bar. AC bar joins all the components that generate alternating current whereas DC bar joins the components that generate the direct current. For example, PV panels, batteries are connected to DC bar whereas wind turbines are connected to AC bar. The exchange from AC to DC is done through a converter (Roy et al., 2022). A converter can be an inverter or a rectifier. An inverter converts direct current (DC) to alternative current (AC). A rectifier converts the alternative current (AC) into a direct current (DC). Various configurations were seen in the literature: PV/WIND/BATTERY hybrid renewable system (see Figure 2), PV/WIND/ biomass/ battery hybrid energy system, PV/WIND/ biomass/ battery hybrid energy system, PV/WIND/ FUEL CELL/ BATTERY hybrid renewable energy system, PV/ HYDRO/ BATTERY hybrid energy systems, etc.

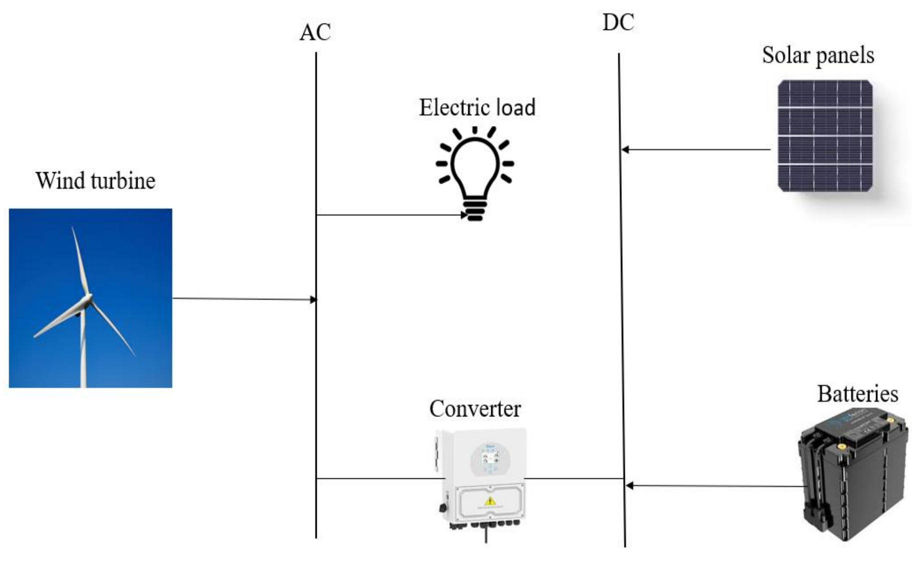


Figure 2: Schematic representation of PV/WIND/BATTERY hybrid renewable system

Source: Roy et al., 2022

3.1.3 Techno-economics assessments of hybrid energy systems

Various studies have been conducted on the hybrid energy system, though the concentration of the work is purely on hybrid renewable energy system for rural electrification, a close look of others system was conducted for the purpose of comparisons and analyses.

In their worked on the analysis of hybrid energy systems for application in southern Ghana Adaramola et al., 2014 evaluated the economic analysis of the feasibility of utilizing a hybrid energy system consisting of solar, wind and diesel generators for application in remote areas of southern Ghana using HOMER Pro software. They found that a PV array of 80 kW, a 100 kW wind turbine, two generators with combined capacity of 100 kW, a 60 kW converter/inverter and a 60 Surrette 4KS25P battery produced a mix of 791.1 MW h of electricity annually and the cost of electricity was 0.28 USD/kWh. This system might have too much generation sources reducing then the integration of renewable (for instance the capacity of solar could have been greater than 80 kW). In comparison , Jain et al., 2022 worked on prefeasibility economic scrutiny of the off-grid hybrid renewable system for remote area electrification. They focused on the feasibility of PV-wind-biomass-diesel generator-battery-converter for a load of a rural town situated in the western area of Gujarat, India using HOMER. The daily load was estimated at 686.00 kWh/day with a peak load of 69.49 KW. The found the optimum system with 139 kW of PV, 112 kW of wind turbine,10 kW of diesel generator, 77 kW of bio generator, 406 kW of lead-acid battery, and 58.2 kW of the converter and the LCOE of 0.26 USD/kWh. Their results showed that rural electrification can be achieved sustainably with renewable resources.

Adaramola et al., 2017 investigated on multipurpose renewable energy resources-based hybrid energy system for remote community in northern Ghana. They focused on the feasibility of using hybrid energy system consisting of solar PV and biodiesel generators in meeting the electricity and domestic water needs of a remote community in Ghana using HOMER software. The daily load is 104kWh/day to meet the need of 100 households, small-scale businesses and a central water pumping system. They considered five different initial investment support scenarios, are considered: 100%, 75%, 50%, 25% and 0%. The results showed a rather poor load profile (load factor of 12.26%) and a levelized cost of electricity (LCOE) of 0.76 USD /kWh at full cost (100% cost) whereas the LCOE declined up to 0.20 USD/ kWh when the project id entirely fully granted. They authors demonstrated that the end consumers will still pay 200% compared to national grid consumers even though the entire is 100% granted. The load factor impacted heavily the cost of energy, an increment on the load factor could have made the system more sustainable than the work of Adaramola et al., 2014. Moreover, the grant could play a major role in the successfulness of hybrid energy systems. Also, Aghapouramin, 2020 researched the technical, economical, and environmental feasibility of hybrid renewable electrification systems for off-grid remote ural electrification areas. They investigated on the application of wind turbine, PV panels, and diesel generator in a hybrid renewable energy system for six off-grid remote villages, with separate locations and various climate statues, for East Azerbaijan province Iran using HOMER. They found one system with the configuration of PV/ WIND/ Battery which had the NPC of 389,822 USD/ kWh and the COE of 0.33 USD/ kWh for Yanbolaghiye Sofla locality and the other five localities had for the same configuration the COE ranging from 0.27 - 0.33 USD/kWh. Hybrid renewable energy systems present the most convenient configurations from environmental and economic viewpoints, though remarkably high expenses are the main trouble reducing the installation possibility in most cases.

In their case study, T. Yeshalem et al., 2017 worked on the design of an off-grid hybrid PV/wind power system for remote mobile base station using HOMER pro. They focused on utilizing a hybrid of photovoltaic (PV) solar and wind power system with a backup battery bank to provide feasibility and reliable electric power for a specific remote mobile base station located at west arise, Oromia. They found that PV array and battery is the most economically viable option with the total net present cost (NPC) of USD 57,508 and per unit cost of electricity (COE) of 0.35 USD/kWh. Their system was designed to meet the need a daily consumption of 41.4 kWh. Their simulations results showed that the hybrid energy systems can minimize the power generation cost significantly and can decrease CO_2 emissions as compared to the traditional diesel generator only. Also, Kebede & Bekele, 2018 researched on the feasibility study of PV-Wind-Fuel cell hybrid power system for electrification of a rural village in Ethiopia with the main interest on the techno-economic feasibility study of emission-free hybrid power system of solar, wind, and fuel cell power source unit for a given rural village in Ethiopia using HOMER. They found up to 26 possible configurations to feed the load. The authors choose the configuration PV/wind/ fuel cell due to its benefits regarding the emissions. The systems had the NPC of 544,550 USD and the LCOE of 0.31 USD/kWh. Etse et al., 2019 worked on the case study of Djarkpanga on a hybrid system for electrification and upliftment of northern rural region of Togo. They found that despite the high cost of biodiesel from Jatropha curcas ($1.6/litter), the proposed hybrid (PV/biodiesel) system had under various climate condition the cost of energy less than 0.21 USD/kWh. Their system showed good performance for power generation and positive socio-economic impact in the local community.

3.2 Electric vehicle in the hybrid renewable energy systems

Transport sector is the third largest contributor of GHG emissions globally (Sanguesa et al., 2021). So, in this study, we considered the electrification of the transport sector under the scheme of rural electrification. The electric vehicle (EV) will be considered as a deferrable load in the model. A deferrable load is an electrical load that requires a specific amount of energy within a specific period of time, although the exact timing is not important; it can wait until power is available. Loads are usually classified as deferrable when associated with storage(*HOMER PRO 3.11-Deferrable load*).

Various studied were conducted in the design of hybrid energy systems with the integration of electric vehicles, (Ruiz et al., 2019) working on the optimal design of a Diesel-PV-Wind-Battery-hydro pumped power system with the integration of electric vehicles in a Colombian community, elaborated two different types of EVs: EVs type 1 performing as additional loads in the grid power balance and EVs type 2 participating as additional storage systems during the parking hours. Their results showed the advantages of the inclusion of EVs as ancillary service providers for the system and also as public transportation agents. Chowdhury et al., 2018 focused their work on the optimization of solar energy systems for the electric vehicle at the university campus in Dhaka, Bangladesh by using Homer software. They proved that using the proposed concept of green transport will ultimately reduce greenhouse gas emissions by 52,944 kg/year for campus public transportation. In the same perspective, Oladigbolu et al., 2023 investigated the technical and economic feasibility of an electrical vehicle (EV) charging scheme based on the availability of renewable energy (RE) sources in six sites representing diverse geographic and climatic conditions in Nigeria using HOMER Pro. The system of PV/WT/battery charging station with a quantity of two WT, 174 kW of PV panels, a quantity of 380 batteries storage, and a converter of 109 kW was the best economic metrics with the lowest NPC, electricity cost, and initial costs of 547,717 USD, 0.211 USD/kWh, and 449,134 USD, respectively.

CHAPTER 4: MATERIALS AND METHODS

This chapter exhibits the methods used to perform this case study and the modelling done in order to answer the research questions. The data used for the calculation in this chapter were collected through secondary sources. The QGIS modelling and the resource assessment with HOMER Pro software helps to answer the first research question. The calculation of the NPC and COE with the HOMER Pro software helps to cover the second question. The results obtained from the HOMER software was analysed in order to answer the research question three. Finally, the current energy policies in Togo and the analysis of the results were used to answer the research question four.

4.1 Steps in the choice of the community

4.1.1 Modelling in QGIS

Prior to conducting the case study, the community selection was the first step. To find the best suitable place, the QGIS software was used. QGIS is an open-source geographic information system (GIS) software used to visualize, analyse, and manage spatial data. It allows one to work with different geospatial data formats, perform spatial analysis, create interactive maps, and customize map layouts. It helps to easily extract the surface area of the community conduct a detailed analysis. The software was used to model an overview of electrification scenario in Togo (distinction of unelectrified areas from the electrified areas). Figure 3 depicts the steps followed for the community selection. The aim was to find an unelectrified settlement for the techno-economic assessment of a hybrid renewable energy system. The research had been desk research entirely as no field survey was conducted during the study, additional interview was performed to verify the information collected. The selection of the settlement was made based on the following criteria: No existing grid network infrastructure, a well-clustered community, an active community with a prospect of economic growth through productive use of energy, an approximate potential in renewable resources: Solar and wind, available infrastructure (roads) to bring the installations materials, 15 km far from the national grid which is considered in the literature (Camblong et al., 2009)(see Figure 3).

A shapefile is a common geospatial vector data format used to represent geographic features and a raster file is a type of spatial data format used to represent continuous data over a two-dimensional grid or matrix. Table 1 shows all the files used in the QGIS modelling.

Table 1: Files used in QGIS

File name	Type	Sources
Political Administrative boarders of Togo	shapefile	*GADM*, 2022
Political borders of the five regions of Togo	Shapefile	*GADM*, 2022
Protected areas and reserve areas	Raster file	(*Spatial Data Download | DIVA-GIS*, 2011.)
National transmission line	Shapefile	(*ENERGYDATA.INFO*, 2021.)
Night image of Togo	Raster file	(*Nighttime Lights*, 2010)

Based on the simulation in the QGIS software, three communities were selected. Those three communities were: TOUKOUDJOU, NAGANGOU and KPASSOUADE. In order to decide on which one to work a shallow analysis has been conducted. The analysis was mainly to see the density of the population, the estimate potential in solar and wind, the available land. Table A. 1 and Table A. 2 show the information collected. After the evaluation of the information obtained, the canton of KPASSOADE was selected for the case study of this research work.

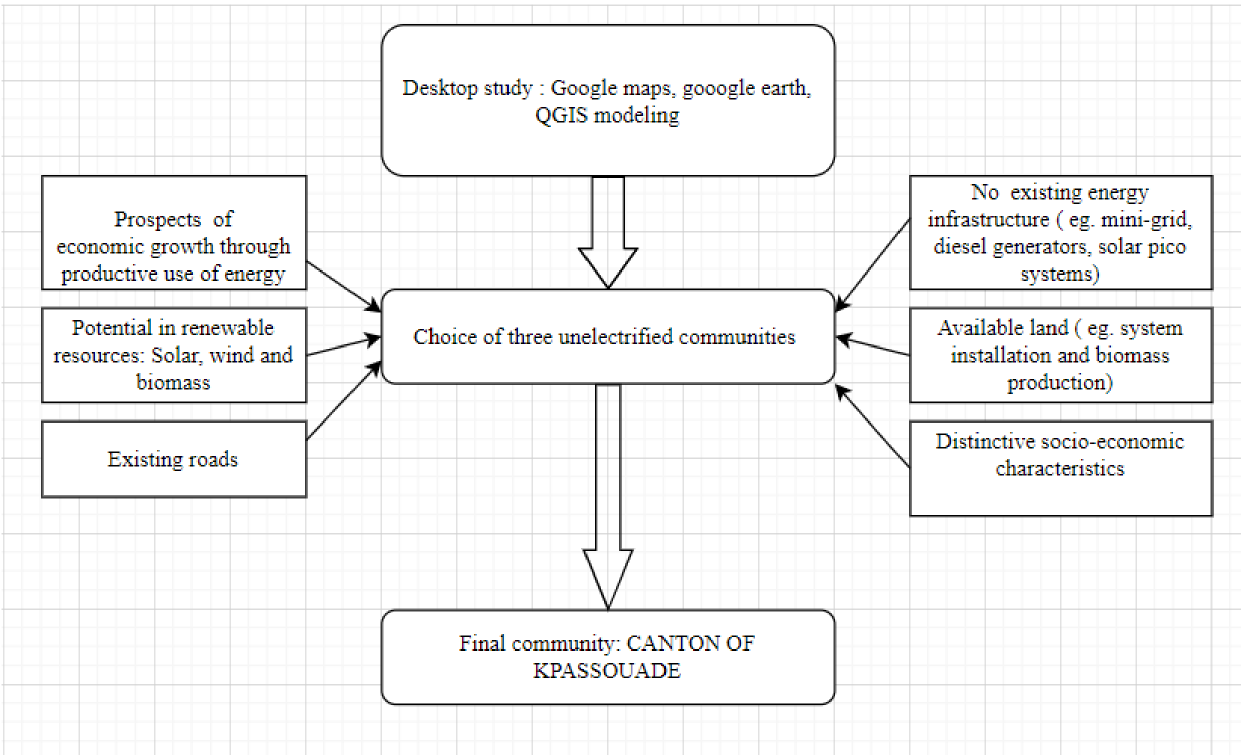


Figure 3: Process in QGIS modelling

Source: Author Owner illustration

4.1.2 Interview and Information collection

The interview was conducted to know more about the community in order to build the load profile and conduct the techno-economic assessment of the hybrid renewable energy system based on their socio-economic activities. It aimed to ascertain the following information: The average persons per household, road and transportation infrastructure linking the community with the main city in the region, existing schools and worship places, existing businesses and their domain of specialization, energy situation of the community, distance to nearest national utility line (see

Table A. 2: Overview of renewable potential in the communities

Community / Parameters	Village of TOUKOUDJOU	Village of NAGANGOU	Canton of KPASSOUADE
Height (m)	100	100	100
Average wind speed (m/s)	3.20	4.74	5.34
Average power density(W/m^2)	44	110	169
Global horizontal irradiation	1932.1 kWh/m2/year	1985.8 kWh/m2/year	1942.5 kW/m2/ year

Sources: Global wind Atlas/ Global solar Atlas

Questionnaire 1). The interview played an important role in the drafting of the community's load profile of the canton of KPASSOUADE.

4.2 Description of the selected area: Canton of KPASSOUADE

KPASSOUADE is a canton in the central region of Togo. The canton is a group of 10 villages: Kpassouade, Wassara-kidereou, Afadade, Avadade, Kpalada, Assamilade, Diboreda, Bande, Djouwada and Talanwezi. The canton is located at the latitude 9.0537487 and longitude 1.2985805. The total population of PKASSOUADE is 3468 inhabitants (INSEED, 2023) with an average of 7 persons in each household. So, the total number of households in the canton is 495 but in this case study 500 households have been considered to cover the error margin of total households' estimation in the canton. Figure 4 shows the two biggest villages (KPASSOUADE, KPALADA) of the canton of KPASSOUADE.

We assume that the canton does not have access to electricity. The cooking in the canton of KPASSOUADE is achieved 100% through firewood and charcoal in all the villages. The main activity in the canton is agriculture. The casava cultivation and cashew nut plantation are most sources of income for the farmers.

Figure 4: Villages of the canton of KPASSOUADE

Source: Google Earth

4.3 Assessment of electricity in the Canton of KPASSOUADE

The load estimation is the most important part of the hybrid renewable energy design (Bekele & Boneya, 2012). It is directly link to the cost of energy. The load was developed based on secondary data. The interview helped to classify the load into three categories: household load, commercial load and community load and provide more details about the consumers energy consumption. In addition, the usage hours of the appliances were collected through the interview. Moreover, the total number of appliances in each load category was estimated through the interview.

The surveys conducted in the context of rural electrification by Odou et al., 2020 and Camblong et al., 2009 gave us an understanding for the current assessment of the electricity access in the canton of KPASSOUADE. Both surveys collected the energy requirement of those communities and propose their load profile. In addition, the survey on the rural household energy consumption conducted in 2014 (*Togo - Enquête Ménage Sur La Consommation d'Energie En Milieu Rural (2013-2014)*) helped to scale it down in the context of Togo's households scenarios. Those three valid sources helped to elaborate the appliances in the three customers categories. The current electricity assess was built with the above-mentioned sources, which helped to forecast the electricity demand for 10 years. Each load category has different consumption patterns in the weekdays and weekends. So, the differentiation in energy consumption was made.

In the household load category: Television(120W), DVD (24W), radio/Bluetooth speaker(30W), electric stove(1000W), iron(2000W), phones (5W), Fan (55W), fridge(100W), laptops(100W) and lamps(10W) are the appliances considered. The wattage of the appliances was taken from the surveys. In the load estimation we assumed that, the televisions will be owned by 250 households which will be on from 10:00 to 13:00 in the morning and from 19:00 to 22:00 in the evening alongside with the DVD. The total number of Radios considered is 450 for the entire canton, which will be work all the day except from 14:00 to 16:00 and in the night when they are sleeping. The electric stoves will be 100 in the entire canton which will be used from 11:00-17:00. According to the interview, there are two major classes of women in the locality: teachers' wives and farmers' wives. The cooking tends to be continuous because teachers' wives cook from 10:00-13:00 for the morning section and 17:00-19:00 in the evening section whereas the farmers' wives cook from 13:00-16:00 for the morning and from 18:00-20:00 in the evening. But for an efficient operation of the HRES, we applied the restriction for the cooking from 11:00-17:00. The weakness of our assumption is that we have not done the business model to see its effectiveness. The laptops will be 30 which will be owned by the teacher in the canton. They will be charged from 5:00-6:00 and from 18:00-19:00. We assumed that the total number of teachers households will be 50 with respect with the current 20 teachers' households. The phones will be charged during the night. The total number of fans considered is 250 which will be used from 12:00 to 15:00. The total number of fridges considered is 80, which will be plugged the entire day. The lamps will be mostly on during the night. For the weekends, the usage of the televisions will be 11 hours which goes along with the DVD usage.

In the community load category: schools, streets light, health centre, water pumping, worship places and local administrations offices were the load categories considered. Currently, there is a primary school and secondary school in the canton, which have lamps, school lamps, printer, photocopier, desktops as appliances. We assumed that there will be a high school with quite the same appliances. In the school, the lamps work mostly during the night whereas during teaching sections they will be used from 8:00-9:00 and 16:00 to 17:00. The health centre has a television, radio, lamps, fans, fridge and microscope which will be working almost the entire day. The large part of the canton inhabitants are muslins. The mosques will be using basically lamps, fans and the sound system: the lamps will be used at the dawn prayer time from 5:00-4:00 and from 18:00 till 7:00; the sound system will work respectively at 5:00, 4:00, 13:00, 15:00 and 19:00; the fans will be used between 12:00-13:00. The motor of the water pumping machine will be used from 11:00-17:00. The churches will have only the fans and the lamps which will work mostly in the evening from 18:00 to 20:00 during weekdays and 8:00 to 12:00 in the weekends. The community load category consumption does not differ much between weekdays and weekends expects the schools that will use only their lamps from 18:00-7:00 during weekends. The wattage of the appliances in the community load category is same in other load categories.

Finally, the commercial load category: groceries, stores, barbershop, sewing salon, restaurant, cassava crushing machine, flour mills, solder machine and Agri water pumping were the sub-load categories. The appliances considered in the groceries are: televisions, DVD, speaker system, lamps, fridge. The television will start working from 10:00-20:00 alongside with the DVD and at some points with the speaker system. The lamps will be on from 18:00-7:00. The stores will have only lamps which will work from 18:00-7:00. Fans, electric scissors (100W), radio/Bluetooth speaker are identified to exist in the barbershop. Radio/ Bluetooth speaker, lamps, fans and sewing machine (100 W) were considered in the sewing salon. The flour mill motor(7500W) will work from 8:00-18:00. The cassava crushing machine (2200W) (mill, 2022) is assumed to be working from 7:00-10:00. The solder machine (4500 W) will be working from 11:00-16:00. The Agri water pump motor is assumed to be working from 9:00-14:00. In the commercial load category, the energy consumption is almost the same both during the weekdays and weekends except some increment due in the weekends in barbershop.

In order, to be more realistic about the energy assessment in the community, few assumptions were made to depict the seasonality with respect to the energy consumption in the community. So, we divided the year into three seasons: Winter low from august to September, Winter high from June to July and the summer from October to May. Table 2 shows the assumption for each season. Those assumptions were applied to the three load categories: household load, commercial load and the community load in order to obtain the yearly load profile.

Table 2: Assumptions for each season

Season	Assumptions
Winter low (Aug-September)	No use of fans
	School load only lighting(outside): school on vacation
	Water pumping: 7 hours only
Winter High (May-July)	No use of fans
	Water pumping: 7 hours only
Summer (Oct-April)	Normal consumption
	Water pumping: 10 hours

Source: Author own representation

4.4 Electric bus as deferrable load

We assume that the local population will adopt the common transportation system both for administrative and commercial purposes in the community. The electric bus selected is "EV star passenger transportation" vehicle which is a multi-purpose, zero-emission, min-bus of the Greenpower MOTOR Company (*EV Star - GreenPower Motor Company | Zero Emission Mini Bus*, 2023.). The mini-bus has the passenger's capacity of 19 seats and one seat for the driver. Its battery capacity is 118kWh and motor capacity of 150 kW maximum. When the EV is fully charged, it could go up to 250 km with fuel economy of 0.48 kWh/km. The EV mini-bus has a lifetime of 10 years (Greenpower, 2023). Figure 5 shows the EV star mini-bus. The EV will basically have three transport itineraries: PASSOUA-SOKOKDE, PASSOUA-AGOULOU and PASSAOUA-TCHAMBA. Figure 6 shows the itineraries of three lines. The total round for one complete trip is 3hours 11 minutes over the distance of 99.2 km. The load of the EV is considered as a deferrable load. We assume the average capacity of the battery is to be the average capacity of the EV deferrable load (Huda et al., 2020). We considered that daily average of the deferrable load to be 236 kwh/d (two round energy requirement of the EV). The charging scheme of the EV is level 2 which takes 11 hours to fully charge the EVs battery with the peak power input of 11 kW. The Table 3 gives the input values in HOMER Pro software.

Figure 5: Electric mini-bus

Source: Green power

Table 3: Input parameters of the deferrable load.

Parameters	Values
Average load (kWh)	236
Storage capacity(kWh)	118
Peak load (kW)	11

Source: Author own estimation

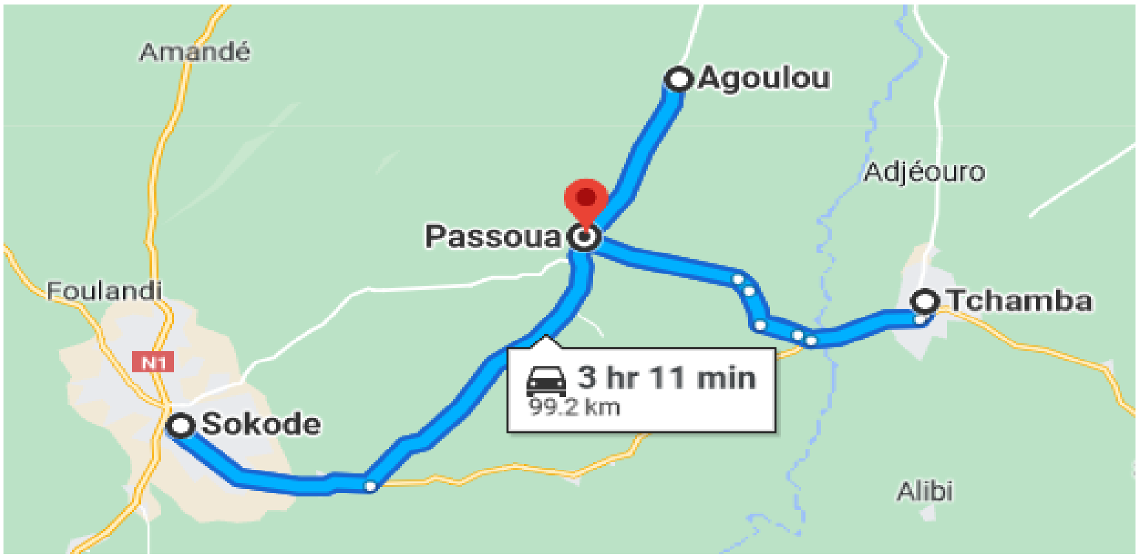


Figure 6: Itineraries of the Transport.

Source: Google Maps

4.5 Resources assessment in the canton of KPASSOUADE

4.5.1 Solar potential

The monthly average solar GHI was obtained from National Renewable Energy Laboratory solar database via the HOMER software. The average annual solar radiation of our case study is 5.29 kWh/m2/day. HOMER displays the monthly average radiation and the clearness of the baseline data in the solar resource table and graph. The Figure 7 shows the monthly solar GHI and clearness index data for the canton of KPASSOUADE.

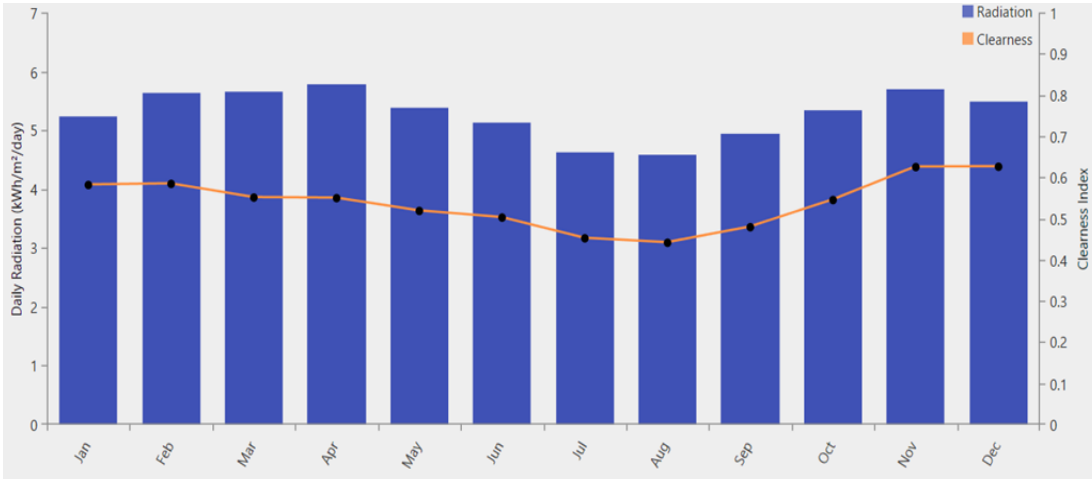


Figure 7:The clearness index and monthly solar radiation

Source: HOMER Pro 3.16.2

4.5.2 Wind potential

The monthly average wind data was download from the NASA prediction of worldwide Energy resource database at 50 m above the surface of earth over 30 years period via HOMER software. The annual average wind speed of the canton of KPASSSOUADE is 4.09 m/s. The Figure 8 shows the monthly average wind speed of our case study.

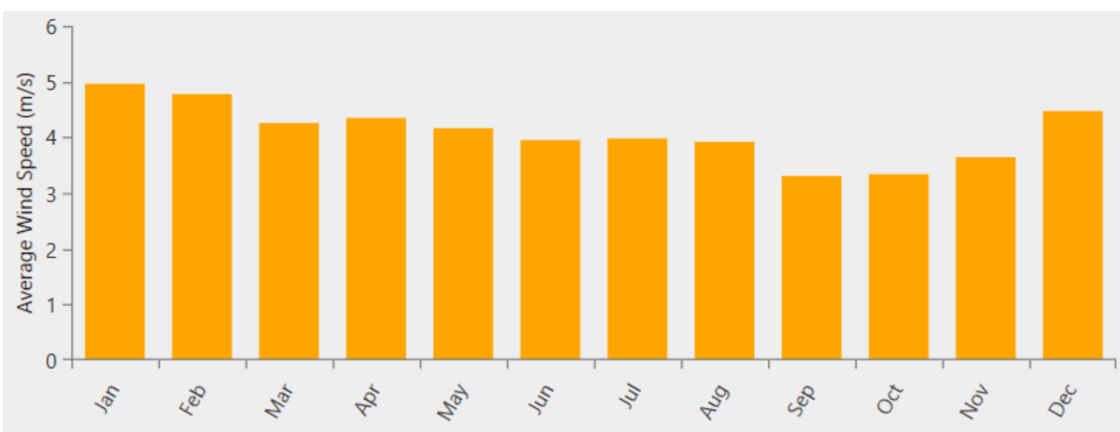


Figure 8:Monthly wind speed

Source: HOMER Pro

4.6 Hybrid renewable energy system design in HOMER

HOMER Pro software is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to support the design of micro-energy systems and compare energy production technologies across a wide range of applications(Lambert et al., 2006). HOMER Pro models the physical behaviour of an energy system and its life cycle costs, i.e., the total costs of installing and operating the system over its lifespan. HOMER Pro allows the modeler to compare many different design options based on their technical and economic merits. HOMER Pro performs three principal tasks: simulation, optimization, and sensitivity analysis. In the simulation process, HOMER Pro models the performance of a particular micropower system configuration each hour of the year to determine its technical feasibility and life-cycle cost. In the optimization process, HOMER Pro simulates many different system configurations in search of the configuration that meets the technical requirements of the lowest life cycle cost. In the sensitivity analysis process, HOMER Pro performs multiple optimizations under different input assumptions to estimate the impact of uncertainties or changes in the model inputs (Farret & Simoes, 2006). The advantage of homer than the other existing modeling tool is that, HOMER Pro is the most flexible in terms of the diversity of systems it can simulate. In addition, HOMER Pro simulation logic is less detailed than that of several other time-series simulation models for micropower systems, such as Hybrid2(Manwell & McGowan, 1994), PV-DesignPro (*PV-Design-PRO (GE)*, n.d.), and PV*SOL (*PV*SOL*, 2023). On the other hand, HOMER is more detailed than statistical models such as RETScreen (RETScreen, 2013), which do not perform time-series simulations.

4.6.1 Solar PV System

The solar PV system is composed of a group of solar modules mounted either in parallel or in serial. Each PV module consists of solar cells. The solar cells inside the PV module converts the sunlight into direct current (DC) through a process called photoelectric effect. The PV panels will be mounted at the corresponding latitude of the case study and oriented towards the south. The solar PV system has no tracking system. Equation 1 represents the power yield calculation of the PV array that HOMER used in the modelling:

$$P_{PV} = P_{STC} * df_{PV} * \left(\frac{G_T}{G_{T,STC}}\right) * \left[1 + \alpha_P * \left(T_C - T_{C,STC}\right)\right] \quad \text{Equation 1}$$

Where:

P_{STC} = Rated capacity of the PV array at the standard test conditions(kW), df = the derating factor of PV (%), GT= the average GHI on PV array (kW/m2),$G_{T,STC}$= the average GHI on PV at the standard test condition (1 kW/m2),α_P= the temperature coefficient of power indicated on PV panel (%/ °C),T_C = the PV cell temperature (°C), $T_{C,STC}$ = the PV cell temperature at the standard test conditions (25°C).

The Sharp ND-250QCS PV panel was chosen in HOMER. The Sharp ND-250QCS PV panel is polycrystalline type solar panel (*Sharp ND-250 QCS*, 2023). The lifetime of the PV panels is 25 years and the derating factor considered is 88% which accounts for losses due to temperature effect, dirt, wire losses, shading, aging, etc. The capital, operating, and maintenance cost was taken from the thesis on the design of a solar PV-biogas hybrid power system for rural electrification in GHANA(Odoi-Yorke, 2018). The author took into account all the costs associated with the PV system: PV panels, mounting hardware, tracking system, control system, wiring and cables, and installation cost. Since the PV covers the lifetime of the project, the replacement cost is USD 0/kW/yr while the capital cost is taken USD1000/kW and the operating and maintenance cost is USD10/kW.

Table 4: Cost specifications of PV Array

	PV Array
Type	Sharp ND-250QCS
Capital cost	USD 1000 / kW
Replacement cost	USD 0 / kW
Operating and maintenance cost	USD 10 / kW
Lifetime	25 years

Source: Odoi-Yorke, 2018

4.6.2 Wind turbine

The wind turbine turns the kinetic energy of wind into electricity. In the literature the lower capacity of wind turbine proved to be more favorable than high capacities for off-grid project (Kebede & Bekele, 2018). Therefore, the wind turbine Eocycle E020 was chosen in the HOMER library. This wind turbine has the cut-in wind speed 2 m/s and a capacity of 20 kW. The Figure 9 shows the power curve of Eocycle E020. Also, the Table 5 depicts the specifications and the cost of the wind turbine. The wind speed data are measured in HOMER at the anemometer height of 10 m. The power law expressed in Equation 2 helps to scale it to the height of the wind turbine height. Then, HOMER assumes that the power curve corresponds to the standard temperature and pressure conditions. It considers the air density of 1.225kg/m3. HOMER calculates the power output of the wind turbine every hour in a four-step process. First, the average wind speed for the hour at the anemometer height is determined using the wind resource data. Second, it calculates the corresponding wind speed at the hub height of the turbine using the logarithmic law or the power law. Third, it refers to the power curve of the turbine to calculate its power output at that wind speed, assuming a standard air density. Fourth, it multiplies this power output value by the air density ratio, which is the ratio of actual air density to standard air density (Lambert et al., 2006).

$$\frac{U_{Hub}}{U_{Anem}} = \left(\frac{Z_{Hub}}{Z_{Anem}}\right)^{\alpha} \qquad \text{Equation 2}$$

Where: U_{Hub}= the wind speed at the hub height of the wind turbine (m/s), U_{Anem}= the wind speed at the anemometer height (m/s), Z_{Hub} = the hub height of the wind turbine (m), Z_{Anem}= the anemometer height (m), α = the power law exponent (α=0.14)

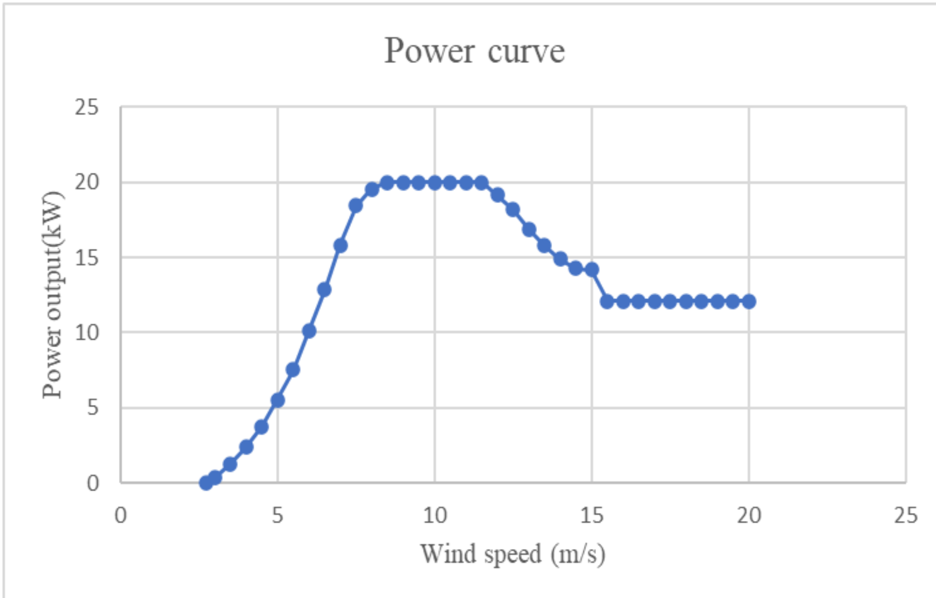


Figure 9: Power curve of the wind turbine Eocycle E020

Source: (*E-20 Ryse Energy HAWT :1–2. - Google Search*, n.d.)

Table 5: Specifications of wind turbine (Al Afif et al., 2023)

	Wind turbine Eocycle EO20
Max hub height	36 m
Rated power	20 kW
Lifetime	20 years
Rated wind speed	7m/s
Capital cost	USD 9000
Replacement cost	USD 4100
O&M	USD 700

4.6.3 Storage system: Battery

The batteries serve as energy storage for night time when there is no solar radiation and the wind turbine is not able to meet the demand. During the day, the battery is charged by the excess energy produced by solar panels and wind turbines. The battery considered in this case study is battery Hoppecke 24 OPzS 3000 which is a lead acid battery. The battery has an excellent charging cycling behaviour; it can sustain high charge and discharge operation load. The table 6 shows its specifications. HOMER software calculates the storage bank autonomy and the battery lifetime using Equation 3 and Equation 4.

$$A_{Batt} = \frac{N_{Batt} V_{Nom} Q_{Nom} \left(1 - \frac{q_{min}}{100}\right)(24\ h/d)}{L_{Prim,ave}(1000\ Wh/d)} \quad \text{Equation 3}$$

Where: A_{Batt}= number of batteries in the storage bank, V_{Nom}= Nominal voltage of a single storage (V), Q_{Nom}=Nominal capacity of a single storage (Ah), Qmin= Minimum state of charge of the storage bank (%), $L_{Prim,ave}$= Average primary load (kWh/d).

$$R_{batt} = MIN\left(\frac{N_{batt} Q_{lifetime}}{Q_{thrpt}}, R_{batt,f}\right) \quad \text{Equation 4}$$

Where: N_{batt}= Number of batteries in the battery bank, $Q_{lifetime}$= Lifetime throughput of a single battery, Q_{thrpt}= The annual throughput, $R_{batt,f}$= The float life of the battery.

Table 6: Battery cost specifications

	Battery Hoppecke 24 OPzS 3000
Nominal voltage	2V
Nominal capacity	7.15 kWh
Initial cost	USD 1300
Replacement	USD 1300
O&M	USD 14/ year
lifetime	20 years

Source: Al Afif et al., 2023

4.6.4 Converter

The converter helps to convert the direct current to alternating current. The Converter helps to charge the battery and supply the AC to the load. In addition, the converter connects the AC and DC sides to convert the DC power to AC power. The converter selected in this case study has a lifetime of 15 years, an inverter efficiency of 95% and a rectifier efficiency of 90%. The capital and replacement cost of the component is 300 USD.

4.7 Economic input and output parameters of the HRES

The discount and inflation rate in Togo considered are 4.25% and 8 % (*World Bank Open Data*, 2023) (*Central Bank Discount Rate - Togo*, 2023). The project lifetime is taken to be 25 years. In this study, we consider that the overall system fixed and operation cost for the transport of equipment to the site, the installation, the transmission and distribution system are respectively USD 45000 and USD 1000 /year. Also, the major economic output metrics to be regarded for the analysis, discussions are the Net present cost (NPC) and the levelized cost of energy (LCOE). The Net present cost of the system takes into account all the costs that the system incurs over the system lifetime, minus the present value of all the revenue that the system earns over its lifetime. The software calculates the total NPC of the project using the Equation 5 (Lambert et al., 2006).

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i,R_{proj})}$$ Equation 5

Where: $C_{ann,tot}$ = the total annualized cost, i= the annual interest rate, R_{proj} =the project lifetime and CRF(i, N) is the capital recovery factor which is given by Equation 6.

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1}$$ Equation 6

Where: i is the annual real interest rate and N represents the number of years.

Finally, HOMER uses Equation 7 to calculate the levelized cost of energy.

$$COE = \frac{C_{ann,tot}}{E_{Prim}+E_{def}+E_{grid,sales}}$$ Equation 7

Where: $C_{ann,tot}$ = the total annualized cost, E_{Prim} and E_{def} are the total amounts of primary and deferable load, $E_{grid,sales}$ = the amount of energy sold to the grid per year.

4.8 System constraints and sensitivity analysis input variables

The operation reserve in Homer refers to surplus operating capacity which immediately react to unexpected increase in the energy demand or a rapid reduction in the renewable power output. In addition, the operation reserve will ensure the consistent power supply despite the variability in the electrical load and the renewable power supply (Lambert et al., 2006). Moreover, the operating reserve consider a percentage of the electrical hourly and renewable output. In this case study, 10% of the hourly electric load, 25% of solar power output and 50% of wind energy were considered as recommended by Dalton et al., 2008 and Cotrell & Pratt, 2003. The maximum capacity shortage output considered is 0% since the system should meet the daily demand of energy.

The sensitivity variables help to view how the optimal system will operate under the changes of input parameters. We considered the discount rate; inflation rate; wind speed; capital, replacement and O&M cost of PV, Wind and battery.

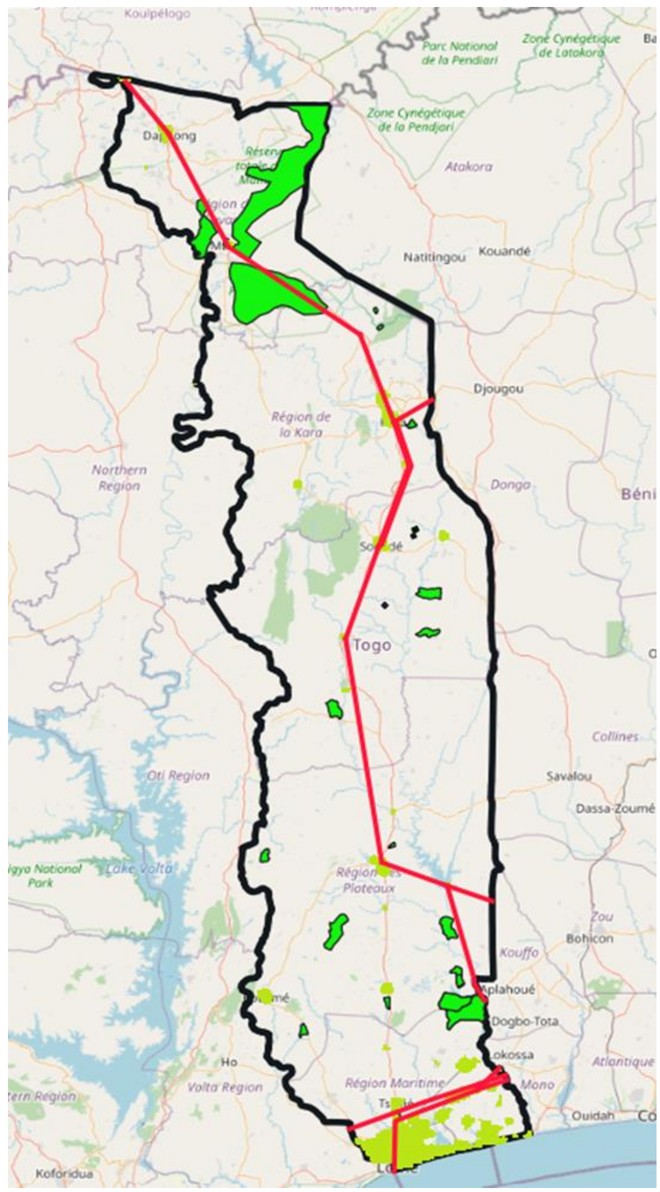
CHAPTER 5: RESULTS AND DISCUSSION

5.1 Result of the QGIS model

The results in the QGIS delimitated the electrified from the unelectrified areas for the country. The model helped in the randon choice of the community. It also shows the protected areas and electrified places.

Figure 10: Result in the QGIS Software

Source: QGIS 3.30.3



Electrified towns

Protected

Electricity grid

5. 2 Load profile of different load categories

5.3 Result of the hybrid energy system in HOMER PRO

HOMER optimization results showed that, out of 1256 solutions which were simulated, only 72 were feasible and 1184 solutions were infeasible due to the capacity shortage constraints. The most economically feasible systems depend on parameters such as NPC, LCOE, operating cost, initial cost, fuel cost, renewable fraction, capacity shortage, unmet load, CO_2 emissions, excess electricity production and annual fuel consumption. HOMER ranks the optimal systems based on the lower NPC, low cost of energy, low initial and operating cost. The Figure 11 shows the HOMER architecture of all components employed in this study to perform the optimization analysis of the most optimal solution.

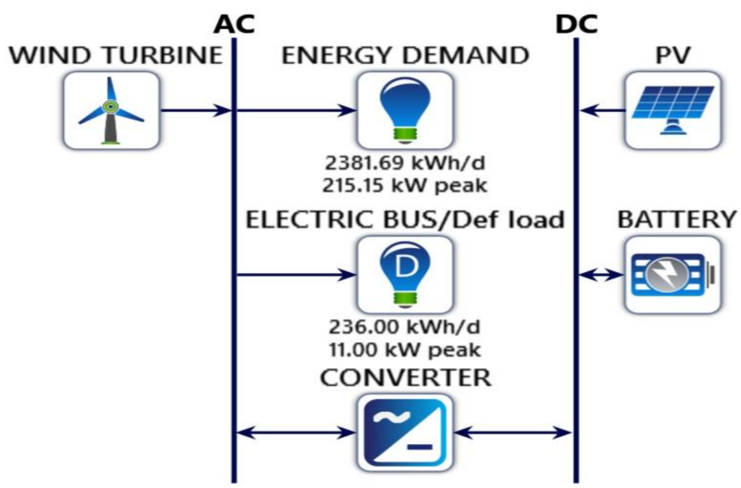


Figure 11 : Schematic design of the hybrid power system

Source: HOMER Pro 3.16.2

HOMER optimizer searched for the optimum solutions between the numerous sizes considered for the estimated electric load demand. The feasible solutions were ranks according to LCOE and NPC (see Figure 12). Optimization results show that, the system configurations that comprises of 450 kW of PV, 10 Wind turbines of 20kW, 253 kW of converter and 6556 kWh of battery is under the load following dispatch is the optimal configuration among other system configurations. The LF prioritizes meeting immediate energy needs and system stability while cycle charging prioritizes extending the life cycle of the battery.

Architecture					Cost			
PV (kW)	WIND TURBINE	BATTERY (#)	CONVERTER (kW)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)
450	10	1,310	253	LF	$4.06M	$0.104	$41,584	$2.36M
450	10	1,310	253	CC	$4.06M	$0.104	$41,584	$2.36M
450	10	1,326	246	LF	$4.09M	$0.105	$41,868	$2.38M
450	10	1,326	246	CC	$4.09M	$0.105	$41,868	$2.38M
450	10	1,324	261	LF	$4.10M	$0.105	$41,928	$2.38M

Figure 12:Optimal hybrid energy systems identified

Source: HOMER Pro 3.16.2

5.2.1 Load profile of different load categories

The Figure 13 shows the load profile of the household load category, Figure 14 shows the load profile of the commercial load category and the Figure 15 shows the load profile of the community load category.

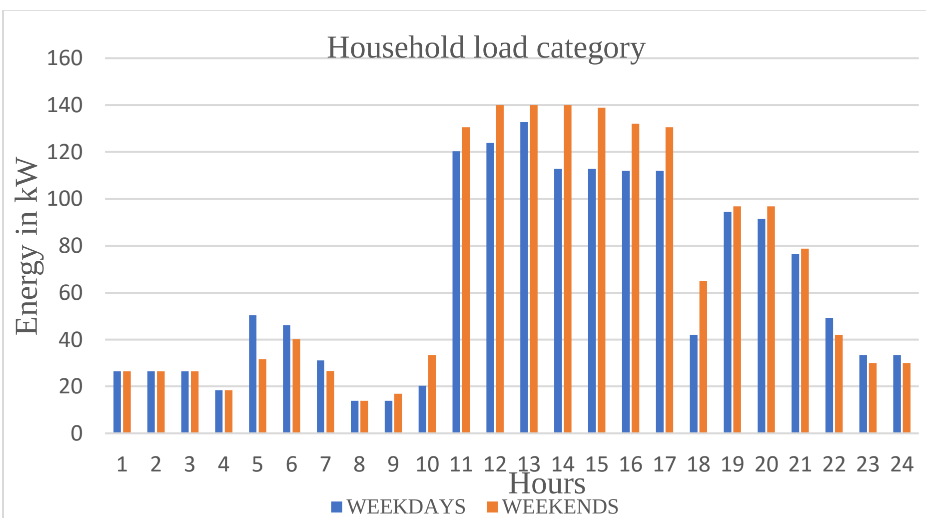


Figure 13: Daily load profile of the household load category

Source: Author own calculation

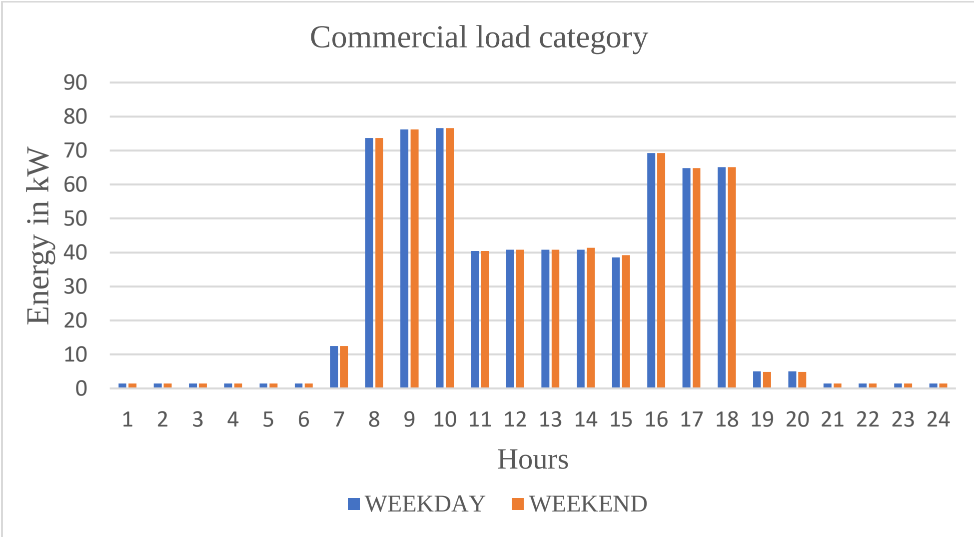


Figure 14: Daily load profile of the commercial load category

Source: Author own calculation

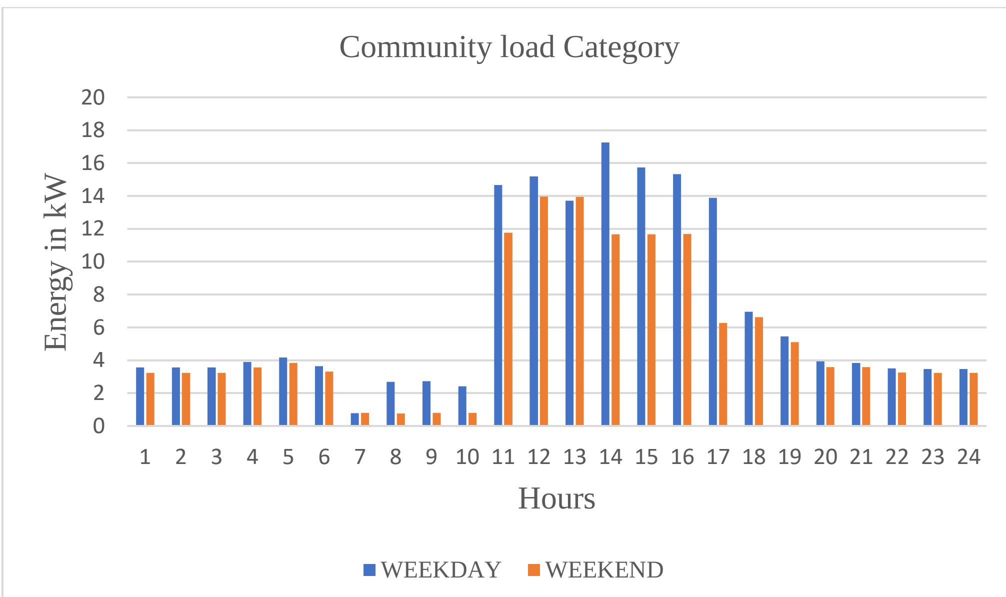


Figure 15: Daily load profile of the community load category

Source: Author own calculation

5.2.2 Synthetic load profile of the community

The daily load demand in KPASSOUADE was estimated at 2381.6 kWh/d. The lowest daily electric load demand during weekday and weekend was respectively 23.69 kW and 23.36 kW. The highest (peak) daily electric load demand during weekday and weekend was estimated respectively at 198.227 kW and 215.147 kW. The hours 23:00-3:00 shows a constant electric load consumption in the various seasons. Around these times almost 95% of the population will be sleeping and only appliances such as streets light, fridges, lamps will be working. Both during the weekdays and weekends at 5:00 a small peak is observed because at this time the population will wake up for the dawn prayer time. Figure 16 and Figure 17 show the daily electric load in the community.

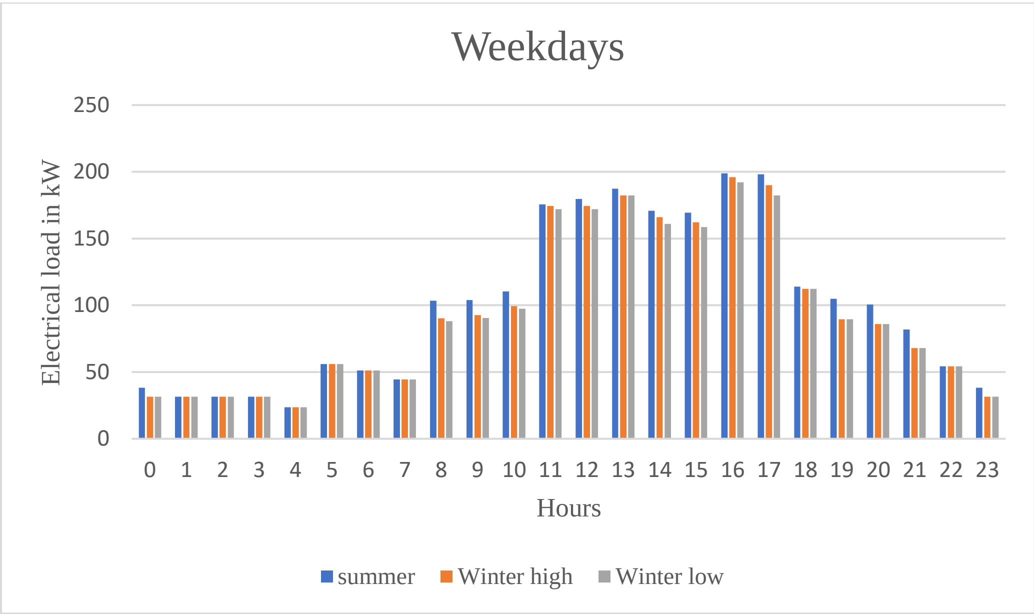


Figure 16: Daily electric load during weekdays in the community.

Source: Author based on own calculation

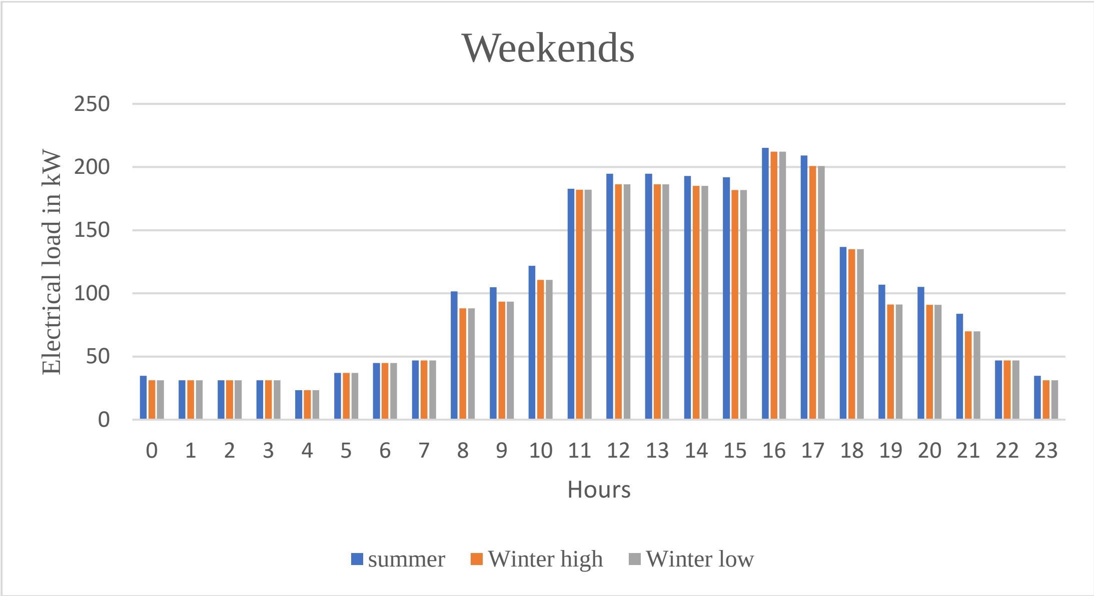


Figure 17: Daily electric load during weekends in the community

Source: Author based on own calculation

5.2.3 Load profile of the electric vehicle

The daily consumption of the electric vehicle is 236 kWh in each month.

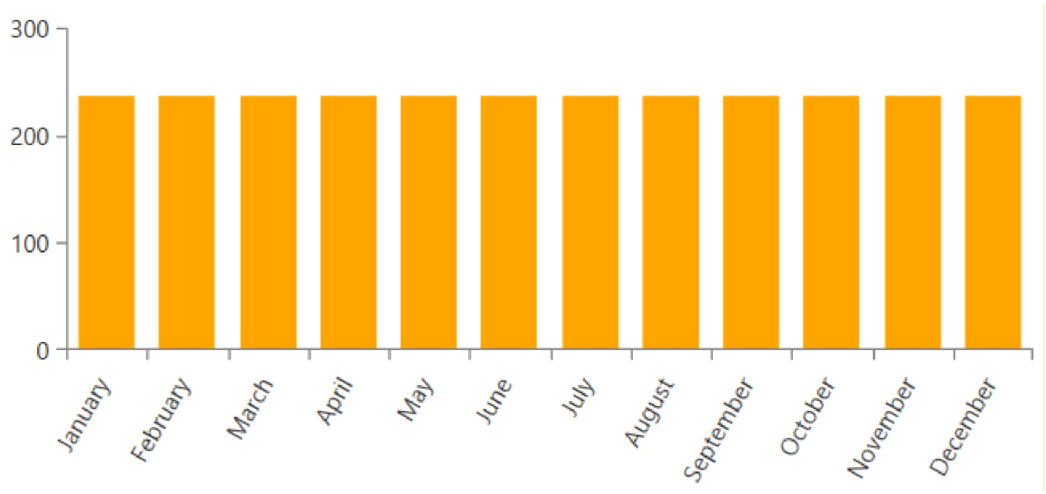


Figure 18: Load profile of the electric vehicle

Source: HOMER Pro 3.16.2

5.4 Energy output of the hybrid energy system

The total annual electricity production from the optimal power system is estimated at 1294813 kWh/ year, where the PV system and wind turbines contribute respectively 700 730 kWh/ year (54%) and 594 083 kWh (45.9%)(See Chart 1)

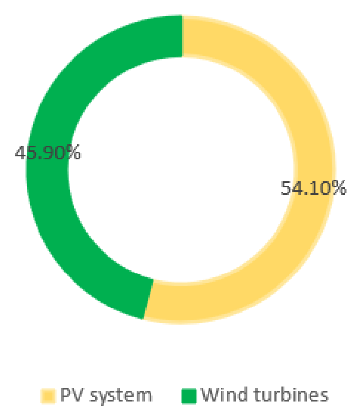


Chart 1: Share of electricity production by technology

Source: Author own illustration

This annual electricity production covers 8686245 kWh/ year of AC load (91%) and 85941 kWh of deferrable load (9%). Though the wind speed is low in the area, the production of wind turbines production shares almost half of the energy demand. This is due to the characteristics of the wind turbine which operates at a cut-in speed of 2m/s. The production from both resources are low during the months of September and October due to the low sun irradiation and low wind speed during these periods (see Figure 19).

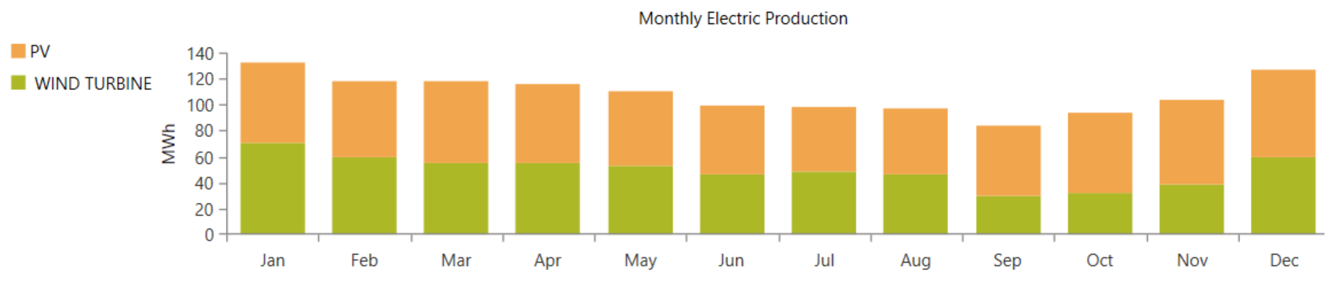


Figure 19:Monthly average electricity production

Source: HOMER Pro 3.16.2

The optimal power system generates excess electricity of 268276 kWh/ year (20%) with the unmet electric load of 775 kWh/year (0.0811%) and a capacity shortage of 936 kWh (0.0980 %).

5.4.1 Optimal performance of the solar PV system

The rated capacity of the PV system is 450 kW with the mean energy output of 1920 kWh/ day and the capacity factor of 17.8 %. The PV penetration which accounts for PV system output divided by the average primary electric load is found to be 80%. This PV system is expected to operate 4432 hours /year. It produces energy from 6 AM till 5 PM in the evening with peak production of energy during noon. Moreover, the levelized cost of energy of the PV system is 0.0221 USD/ kWh. The production during the months of July and august are low due to the low average sun irradiation.

5.4.2 Optimal performance of the Wind turbines

The rated capacity of wind turbines is 200 kW with a capacity factor of 33.9 %. The wind turbines produce a total energy of 594083 kWh/ year. Moreover, the levelized cost of energy from the wind turbines is 0.0158 USD/ kWh. The energy production of wind varies depending on the wind availability. The Figure 20 shows the wind turbines output over the year. The production during the months of October and September tends to be the lowest due to the low average wind speed during those periods.

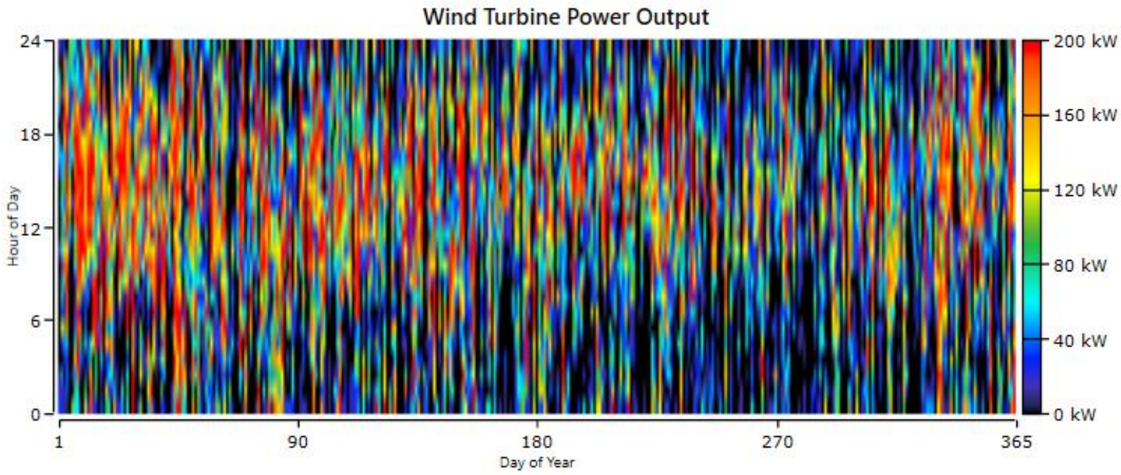


Figure 20: Wind turbine power output

Source: HOMER Pro 3.16.2

5.4.3 Performance of the battery and converter.

The storage of the system is 6556 kWh which is made up of the total quantity of batteries of 1310 strings connected in parallel by 2V bus voltage. The autonomy of the battery is 60.1 hours, making the hybrid energy system stable, reliable and efficient. This implies that the hybrid energy system can respond to a sudden increase in the energy demand. The annual throughput of the storage system is 266421 kWh/ year. The total battery storage energy in an energy out are respectively 289914 kWh/ year and 247068 kWh/year. In addition, it has losses of 40193 kWh/year and the annual throughput of 266421kWh/ year. The batteries are generally fully charged throughout the year except from the august to November where the potential of solar and wind are low. The nominal capacity is 9366 kWh and the storage wear cost is 0.139 USD/ kWh. The Figure 21 shows the state of charge of the battery.

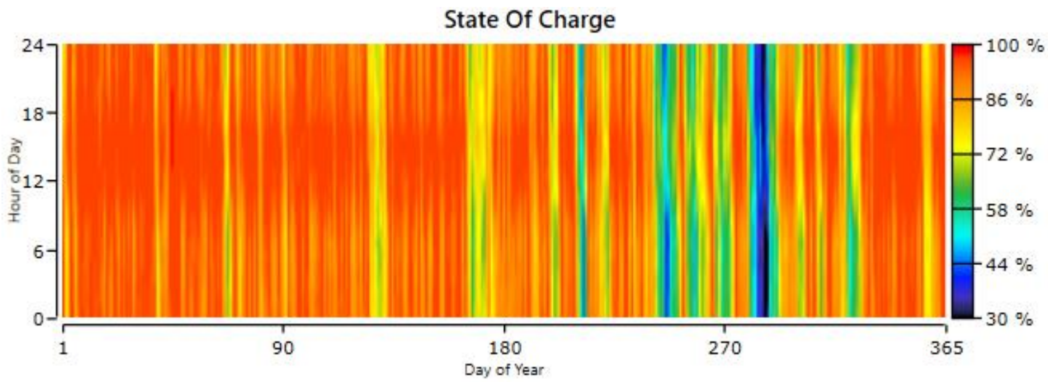


Figure 21: State of charge of the battery.

Source: HOMER Pro 3.16.2

The rated capacity of the converter is 253 kW and the mean output of 55.8 kW. Its capacity factor is 22.1%. The inverter works more than the rectifier. The operation hours of the inverter and rectifier are respectively 6467 hours/ year and 1685 hours/ year. The quantity energy out from the inverter and rectifier are respectively 489033 kWh/year and 57477 kWh/year. Also, the quantity of energy in in the inverter and converter are respectively 514772 kWh/ year and 63863 kWh/ year. The losses from the inverter and rectifier are respectively 25739 kWh/year and 6386 kWh/year. The Figure A. 2 shows the performance of inverter and rectifier.

5.5 Economic analysis of the hybrid renewable energy system

The optimal hybrid renewable energy system has the net present cost (NPC) of 4.06 million USD, the levelized cost of energy (LCOE) of 0.10 USD/ kWh, the operation cost of 41584 USD/ year and the CAPEX of 2.36 million USD. Out of the total net present cost, the batteries have the highest percentage 69.28%, the PV system takes 15.60%, wind turbines 9.47% and other (the construction of the overall system including the transmission lines and the maintenance) 2.11% and the system converter 3.53%. The storage system covers more than the half of the overall system cost. This is due to the lack of dispatchable source of energy, the HRES solely rely on the storage. Solar and wind energy are intermittent and non-dispatchable so the large storage makes the system strong and reliable despite have an impact on the cost of energy. Chart 2 shows the cost of each component of the hybrid energy system.

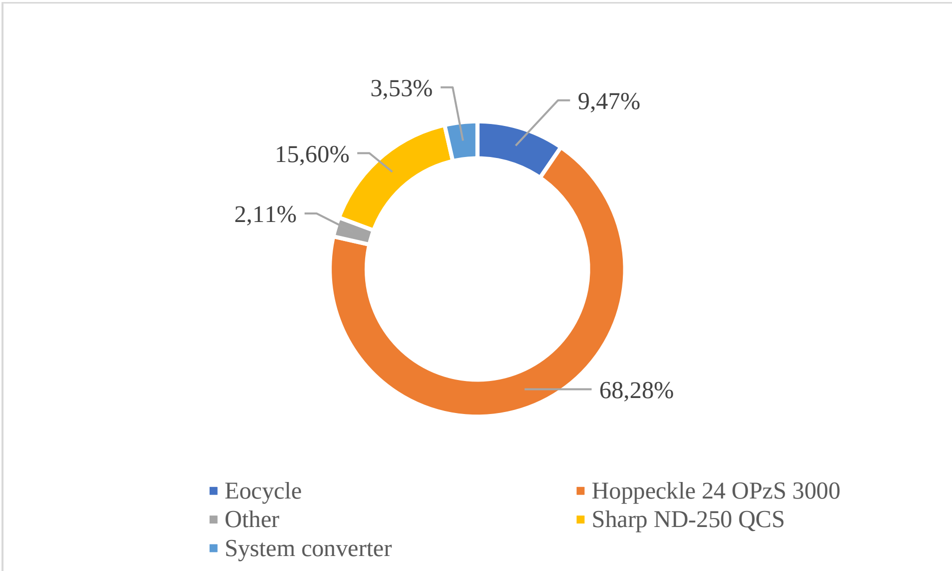


Chart 2: Percentage of each component in the total NPC

Source: HOMER Pro 3.16.2

The cash flow of the HRES is negative for the 24 years of the project and positive on the 25th year of the project. The negative cash flows characterize the outflow of money from the project (capital cost, replacement cost, O&M) whereas the positive cash flow is the salvage cost of the components (see Figure A. 3).

5.6 Results for the sensitivity analysis

The sensitivity variables are plotted using HOMER surface plot and the line plot. Homer surface plot helps to display the total net present cost (NPC) and the levelized cost of energy as superimposed plot. Also, HOMER plot line displays the LCOE and the NPC on the vertical axis against the sensitivity variable on the horizontal axis.

5.6.1 Effect of nominal discount rate and inflation rate, wind speed on the NPC and LCOE

The sensitivity analysis was applied on the two different discount rates:4.25% and 7% with two different inflation rates: 8% and 10%. The NPC and the LCOE have symetric evolution, when the LCOE is low the NPC is high. The increase in inflation rate up to 7% lows the LCOE (0.081 USD/ kWh) whereas the increase in the discount rate increase the LCOE(0.139USD/ kWh). This means that higher discount rate will affect the LCOE reducing then the ability to pay from the consumer's side. In addition, it will not attract investors. We also considered the sensitivity analysis on the average wind speed: 4.09m/s and 5 m/s. The increase of the wind speeds up to 5 m/s reduces the LCOE 0.0728 USD/kWh (see Figure A. 4).

5.6.2 Sensitivity analysis on PV, Wind capital, replacement and replacement cost.

The sensitivity analysis was applied on the capital cost of wind and solar with the cost multiplier of: 0.5, 1, 2. The cost multiplier 0.5 halves, 1 keeps the inputted values and 2 doubles the capital cost of components. We maintained the wind speed at 4.09 m/s. The simulation showed that the reduction of the capital of PV and Wind will bring down the LCOE to 0.09 USD/ kWh(See Figure 22) which will make the electricity cost cheaper than the electricity sold by the largest thermal power plant of Togo (Contour global) in 2021(0.11 USD/kWh). In the other hand, the cost multiplier 2 of the capital cost of component gave the LCOE of 0.12 USD/ kWh. The increase in the cost of component could negatively affect the HRES. In conclusion, the cost reduction of the components will increase the affordability in the community level.

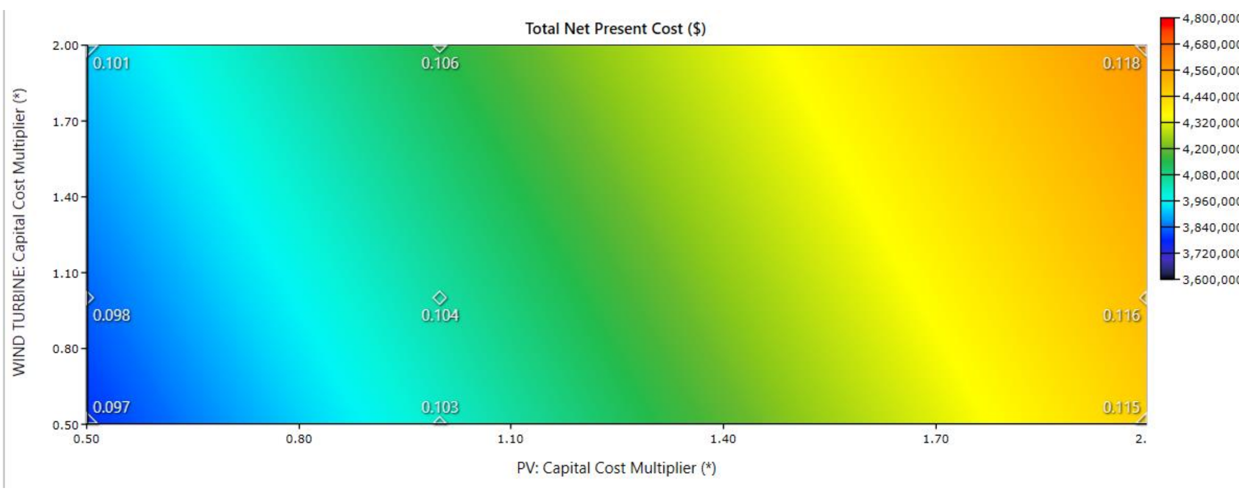


Figure 22: Sensitivity analysis on PV and Wind cost

Source: HOMER Pro 3.16.2

5.7 Discussion

Our work focused on the design of hybrid renewable energy systems for rural electrification which received less attention in the past years. We conducted the tecno-economic assessment of the designed HRES after the resources assessment. We found that the optimal hybrid energy system for the electrification of the canton of KPASSOUADE is made up of 450 kW of PV, 10 Wind turbines of 20kW, 253 kW of converter ,6556 kWh of battery and the LCOE of 0.10 USD/kWh.

The hybrid renewable energy system showed a great production complementary from solar and wind. Instead of having the production during the day like most of PV/batteries systems, the designed hybrid system is capable of producing energy during night time from the wind turbines (see Figure 23). Compared with the current strategies of the Togolese government to increase the energy access through PV/Diesel/ battery mini-grid and solar home systems, the HRES designed can be more efficient and reliable than those systems. Moreover, the EV which works as deferrable load helps to reduce considerably the excess of electricity from 64% to 20% reduce considerably the emissions from in the transport sector.

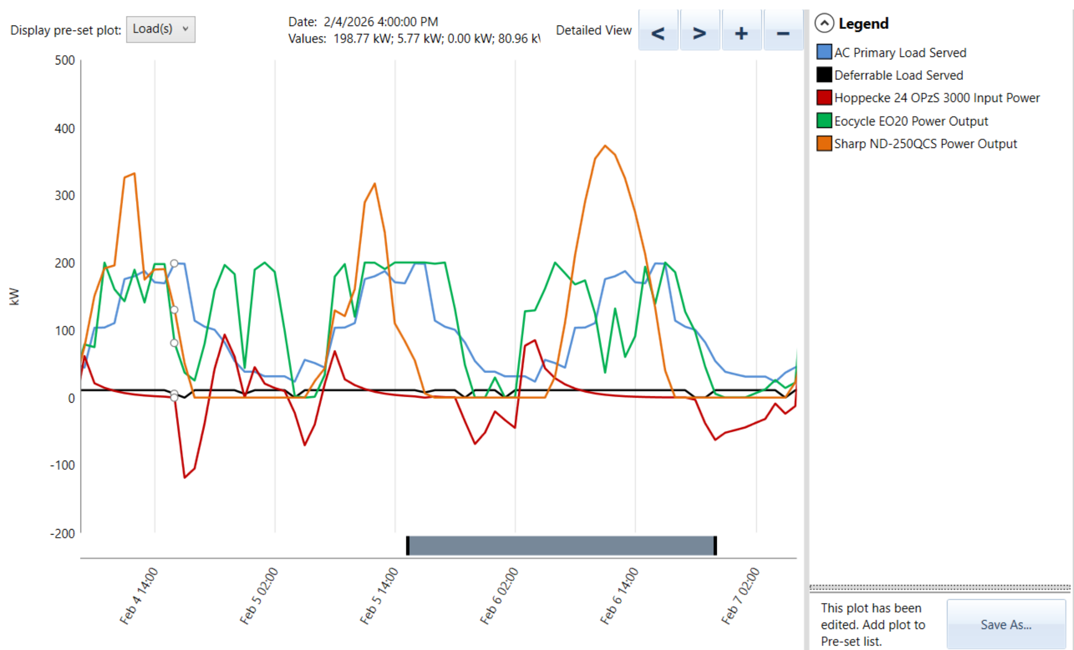


Figure 23: Operation of the HRES

Source: HOMER Pro 3.16.2

The unmet electricity demand of 775 kWh/year during the month of October where the potentials of both resources are low at the same time, could be met by the integration of a small biogas generator or a small fuel cell for the production of hydrogen. The system requires a lot of storage because the renewable resources are intermittent. Though the electric vehicle helps to balance the system, the size of the storage is still high 1310 *7.15 kWh. This large part of the storage capacity increased the cost of energy. In order to cope with it, more sector coupling could help to reduce the high dependency on the batteries only. Application of more robust demand side management in each sector for an efficient energy management. For example, the high energy consuming appliances should be used during the peak generation from the renewable resources. The tariff should be set based on the availability of potential generation from wind and solar. A robust forecast of energy generation could assist in the adjustment of the overall consumption. More integration of V2G in the households and health centre.

In their investigation using the multi-tier frameworks, they proposed the least-cost means of energy access provision in the context of rural electrification. They estimated that the diesel mini-grid energy system which capital cost was 1.52 million USD and the LCOE of 0.51 USD/kWh(*Poor People's Energy Outlook 2016*, 2016) for electrification of one rural area in Togo. Looking at the proposed solution, opting for hybrid renewable energy system (for example our case) will reduce the dependency on the fluctuating cost of diesel and contribute the energy production without any emissions. In comparison of the case study to the previous studies, Etse et al., 2019 proposed a hybrid energy system (PV/biodiesel) for rural electrification which had the LCOE of 0.21 USD/kWh in the context of Togo. Oladigbolu et al., 2023 found the LCOE of 0.21 USD/kWh in the conception of stations for electric vehicle charging station in Nigeria. Also, Kebede & Bekele, 2018 found in their design of emission-free hybrid power system of solar, wind, and fuel cell power source a LCOE of 0.31 USD/kWh. Despite those systems may have different capacities compare to our system, the designed HRES is 50% less costy than the previous studies. It means, the HRES are becoming more economic than the previous years and can accelerate the scheme of rural electrification.

5.8 Implication for the society and policies recommendations

The first impact on the community will be the socio-economic development. Currently the community has 12 agricultural cooperatives aiming at the production and commercialization of gari. Based on the interview, those cooperatives need energy for their activities. Moreover, those cooperatives have the local tontine among themselves for their socio-economic activities. Our HRES will provide water for their agricultural activities regardless of the season. The revenues from the farming could be used to pay for our electricity consumed. In addition, there is many productive uses like the flour mill, store, restaurant, that will be able to pay our electricity. Overall, there will be job creation and new opportunities in the community. Secondly, the HRES will contribute to increase the rural electricity access in Togo. The data concerning the willingness to pay in the community was not thoroughly assessed nevertheless, the interviewee confirmed the need in the community for productive usage of energy.

In term of policy recommendation based on the results, the government of Togo should develop the comprehensive renewable energy plan in the context of rural electrification. In the development of the renewable energy plan, the wind atlas should be developed in order to identify the most suitable places for the implementation of HRES. The government should provide the financial incentives and support into the adoption of HRES. The capacity building should be incorporated for the local skills and expertise in the field of HRES.

CONCLUSION AND RECOMMENDATION

The transition from fossil-based energy production to cleaner sources boosted the interest of renewable energies as key players. Moreover, the countries that still have low electricity access are opting for distributed energy systems to speed their electrification rate. The Togolese' government set the goal of achieving 100% electricity access by 2030 has prompted innovation, research into the analysis and development of reliable and cost-effective energy from the renewable energy sources.

In this study, a hybrid renewable power system which consists of solar PV system and wind turbines has been modelled and optimized successfully. The selection of the community for the case was done by a brief modelling in QGIS. An interview was conducted in order to build the energy demand through the secondary data. The solar global horizontal irradiance and the wind speed for the canton of KPASSOUADE was retrieved from the NASA surface meteorology database. HOMER Pro software was used to carry out the design, simulation and optimization of the PV/Wind hybrid renewable energy system.

Results from the HOMER optimization depicted that the hybrid renewable power system of 450 kW of PV, 10 Wind turbines of 20kW, 253 kW of converter and 6556 kWh of battery storage is the optimal and ideal power system that can meet KPASSOUADE's daily electricity load of 2617.6 kWh/d. The technical and economic analysis shows that the optimal will annually produce 1294813 kWh/ year electricity. The PV panels produce 54.1% and the wind turbine 45.90 % of the annual electricity. The AC load served is 268276 kWh and 85941 kWh of deferrable load. The optimal system has an excess electricity of 268276 kWh/ year with the unmet electrical load of 775 kWh/ year and a capacity shortage of 936 kWh. The HRES does not any emissions.

The hybrid renewable energy system has the NPC of 4.06 million USD and the levelized cost of energy of 0.10 USD/kWh. However, the LCOE is lower compared to the cost of energy which is 0.11 USD/kWh in 2021 from the national thermal power plant. With a close look at one investigation in the process of rural electrification which proposed a diesel mini-grid with the cost energy (0.51 USD/kWh), the designed HRES more cost effective and sustainable in the scheme of rural electrification in Togo. Furthermore, the sensitivity analysis performed showed that the increase of inflation rate lows the LCOE whereas the increase of the discount rate increases the LCOE. In addition, the sensitivity on the wind speed shows that higher wind speed could lower more the LCOE. In addition, the sensitivity on the capital, replacement and operation cost of component shows that the decline in the cost of energy when the cost components reduce. In line with the community ambition in cooperative group, the HRES will contribute to the socio-economic development of the canton of KPASSOUADE.

Recommendations:

- This study used secondary data, an on-ground data collection should be conducted for more accurate decision
- Future studies can consider the application of smart management of the system and demand side management in the process of demand assessment
- Assess the local community willingness to pay both for the public transportation and the energy.

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APPENDIX

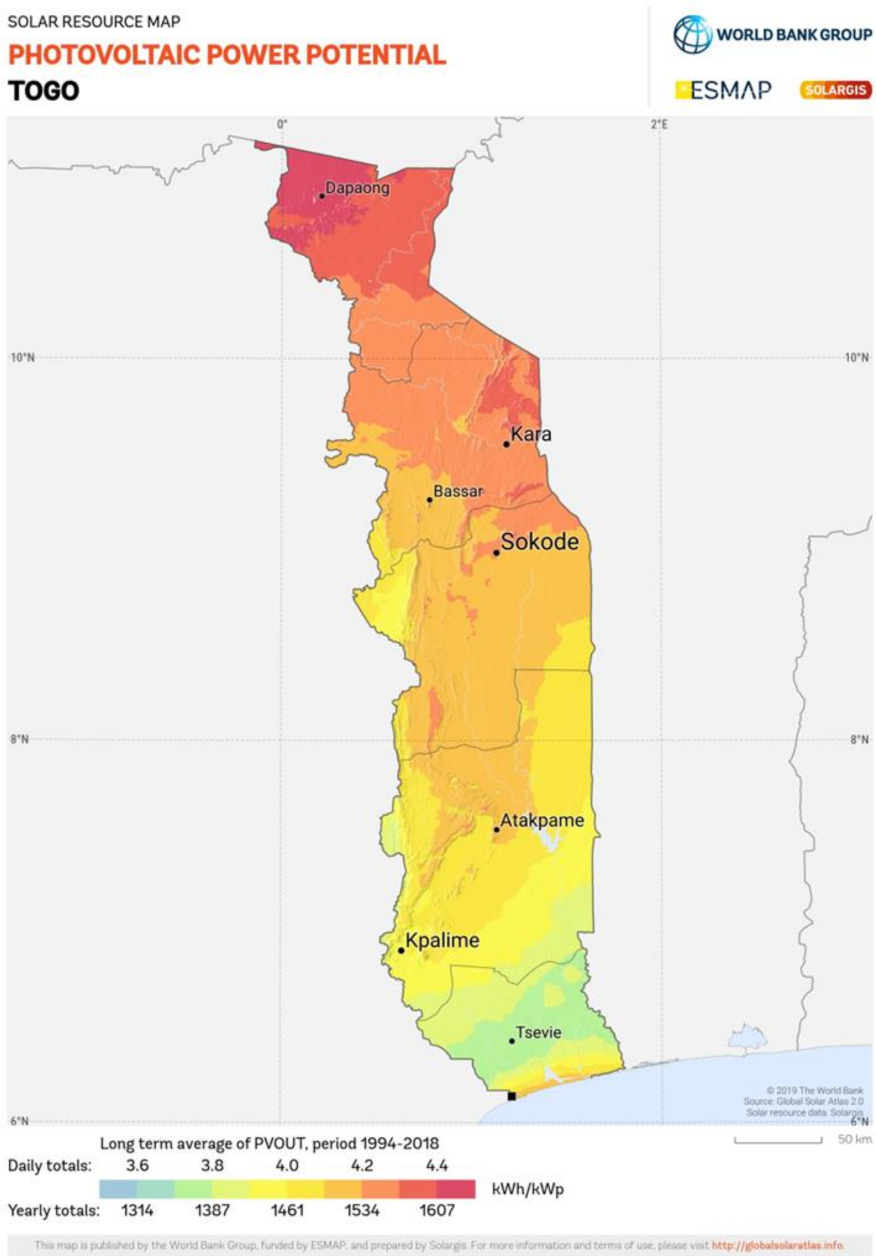

Figure A. 1 Solar power potential of Togo

Source: Global solar Atlas

Table A. 1 Collected information about the three communities

Localities / criteria	Village of TOUKOUDJOU	Village of NAGANGOU	Canton of KPASSOUADE	
Region	Centrale	Savane	Centrale	
Latitude	8.7100012	10.1108892	9.0537487	Source: google earth, google maps(*Google Maps*, 2023)
Longitude	1.1555514	0.375737	1.2985805	
Distance from the asphalted road	24 km	8 103.33 m	9 972.63 m (Sokode-Tchamba)	
Distance from the National grid	23 km	27.22 km	13.66048 km	
Waterway distance from the village	4.4 km	2 178.18 m (water pots in the dry season)	450.39 m (completely dry during dry season)	
Types and existing buildings	- Primary school - Market - kindergarten - Secondary school	– Primary school – Market – Kindergarten	- 3 mosques - 1 primary school - 1 secondary school - Rectangular construction - One market	Source: QGIS, Google Earth

The approximate number of households	110	82	300	Source: google earth
The population density in the region (persons/km2)	41-50	81-120	70-100	(INSEED, 2023)
The area occupied by all households	124708.2 m2	328227.262 m2	328213.193 m2	QGIS (area calculatio n)
The total area of research interest…	908 647.29 m²	23,35 km²	81061514.36 m2	Google Earth, QGIS cloud(Tog o, n.d.)
Total population of the community (inhabitants)	4950 (considering 50 persons/ km2)	2802 (considering 120 persons/km2)	3468 [men:1 691, Women:1 777] (INSEED,2023)	I first approach to view the number of inhabitant s
Average area coverage by each household	470 m2	533.52 m²	602.33 m2	Source: Google Earth

Available cultivable land	840497 m2	16 km2	77773301.16 m2	I calculated those values by assuming a specific area of research interest on Google Earth.
Sources of income	-Agriculture -commerce	-Agriculture -Commerce -fishing	-Agriculture -Commerce -Fishing	

Table A. 2: Overview of renewable potential in the communities

Community / Parameters	Village of TOUKOUDJOU	Village of NAGANGOU	Canton of KPASSOUADE
Height (m)	100	100	100
Average wind speed (m/s)	3.20	4.74	5.34
Average power density(W/m^2)	44	110	169
Global horizontal irradiation	1932.1 kWh/m2/year	1985.8 kWh/m2/year	1942.5 kW/m2/ year

Sources: Global wind Atlas/ Global solar Atlas

Questionnaire 1: QUESTIONNAIRE DEVELOPED FOR THE INTERVIEW:

Interviewee: OURO SAMA Abdoulaye

A request of interview was addressed to the Mayer of the prefecture of Tchaoudjo4 in the context to have more information on the canton of KPASSOUADE. In response, the put us in contact with a key person for the interview.

Conversations and questions

1. This interview is mainly done in the context of my research work. There is no any other interest apart from my desire to gather information in order to complete my research work. Can give more information about the canton of KPASSOUADE?

2. What is the current status of the community in term of energy access?

3. What are the means to cope with the unavailability of electricity in the community?

4. What do you think that the availability of electricity could help in the community?
5. What are the schools available in the canton?
6. What are the future plans about the school's construction in the community?
7. What are the existing worship places?
8. Since the large proportion of the population are muslins, what are their behaviour regarding prayer time? How about the churches?
9. What are main behaviours regarding the prayer section during weekdays and weekends?
10. How many markets do you have in the community?
11. What are the socio-economic activities in the community?
12. What are the transportations means in the community?
13. What are appliances that a typical household have?
14. At which time do the businesses open in the morning and close in the evening?
15. What type of appliances do the groceries have?
16. Which types of businesses could be implemented in future in the community?
17. What do the community do during the weekends?
18. Are there recreation centres in the community?
19. Which type of challenges could be expected if the community get access to electricity?
20. What were the sensitizations campaigns conducted in the community? what was the theme?

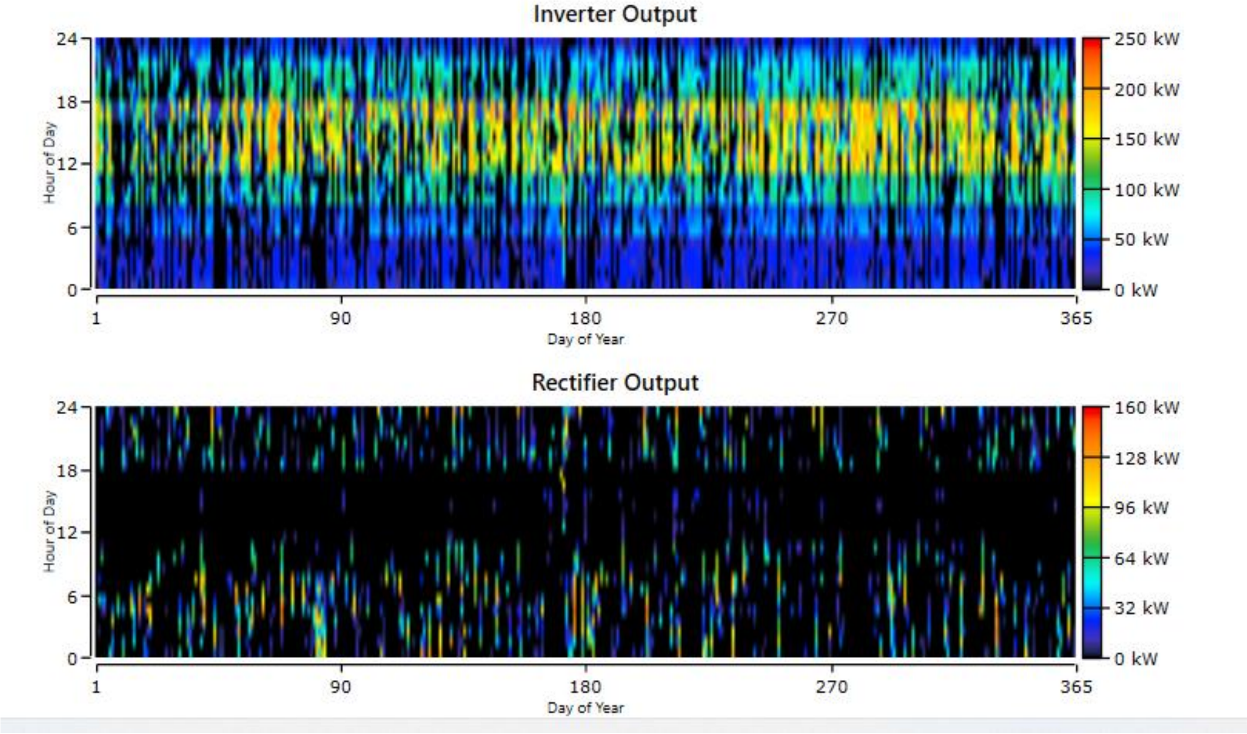

Figure A. 2: Performance of inverter and rectifier.

Source: HOMER Pro 3.16.2

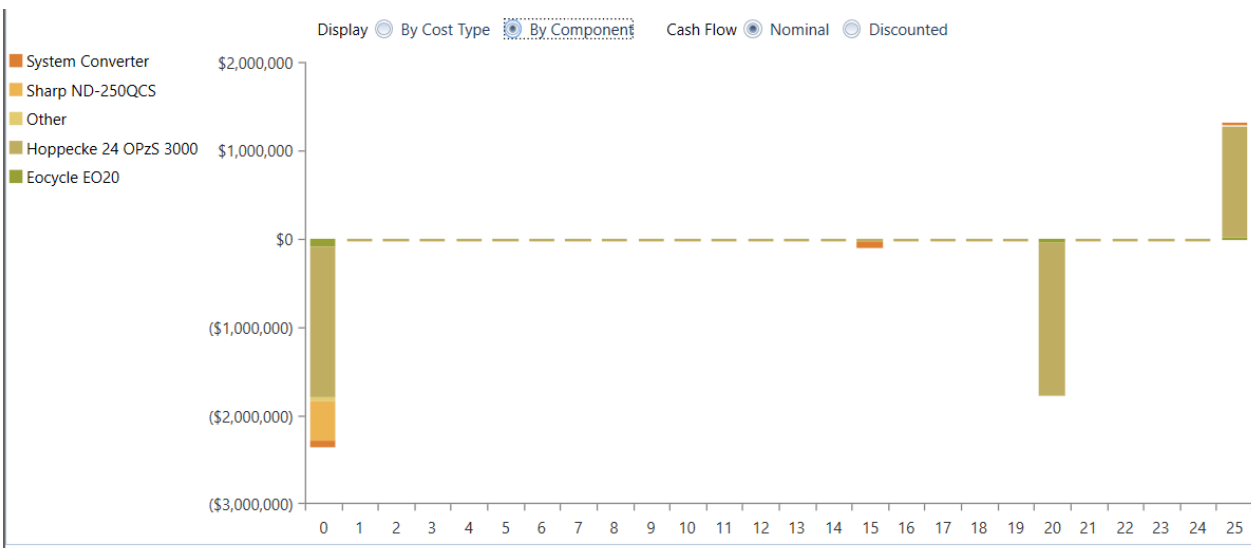

Figure A. 3: Nominal cash flow of each component

Source: HOMER Pro 3.16.2

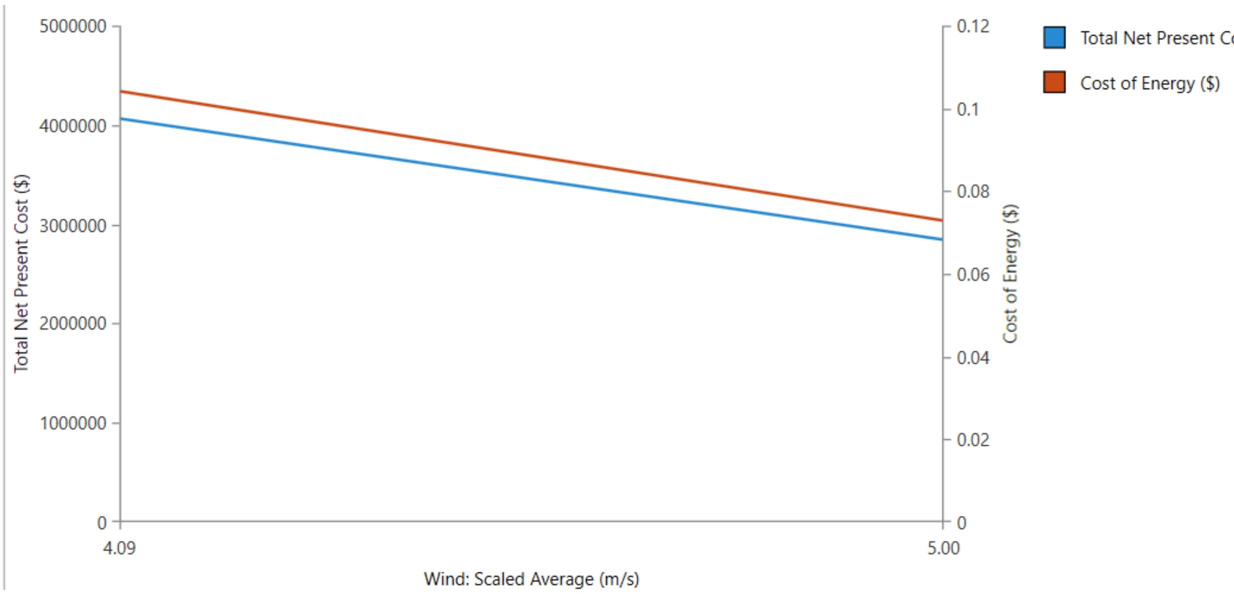

Figure A. 4: Effect of wind speed on the NPC and LCOE

Source: HOMER Pro 3.16.2