Country	Togo
Request ID#	2017000009
Title	Technical Assistance for the Dissemination of Solar Energy Technology in Togo
Type of document	Deliverable 2: Pre-feasibility study of small-scale solar energy systems
Technical & Lead Partner	Institute for Global Climate Change and Energy Kyungpook National University (82)10-3518-5562 igcce@knu.ac.kr PO BOX: 41566 Daegu, South Korea
NDE	Yaou Mery Head of Climate Change Division Department of the Environment (228) 90-148-744 ymery69@yahoo.fr PO BOX: 4825 Lomé, Togo
Proponent	KOGBE Yaovi Lowanou Executive Director Organization for the Environment and Sustainable Development (228) 90-386-204 yaovikogbe@gmail.com PO BOX: 80867 Lomé 08, Togo

February 17, 2020

Implemented by:

Institute for Global Climate Change and Energy

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1. Introduction

Energy is the backbone for a country's economic growth and development presenting a strong synergy effect across most sustainable development goals. In 2018, only 7% of rural areas in Togo had access to electricity, while 80% of urban areas had access to electricity. However, the national government plans to achieve 100% energy access by 2030. This is ambitious and requires proper planning and efficient deployment of resources if the goal is to be achieved. Togo's new electrification strategy integrates both grid expansion and off-grid alternatives including mini-solar networks. In this context, Togo targets the deployment of more than 317 mini PV solar systems in 317 localities by 2030. This strategy also calls for the electrification of 555,000 households with Solar Kits by 2030.

The technical assistance from the CTCN aims to support the government of Togo in achieving its goals of increasing solar energy adoption to improve access to energy in Togo, as well as helping communities to mitigate and adapt to climate change. This technical assistance specifically focuses on the installation of PAYG models for solar mini-grids. This will be based on benchmarks analysis considering best practices and success models in relevant cases. This study analyzes the techno-economic feasibility environmental sustainability of solar systems in rural communities in Togo. Based on the solar resource potential, an on-grid solar energy system and a PV/battery hybrid solar system was analyzed for both the Northern part and the Southern part of Togo.

1.1. Objectives

1.1.1. General objective

The main objective of this study is to analyze the feasibility of solar energy systems in Togo. The study takes Malfakassa, Hahomegbe, Koumbogou and Kablive as case studies to investigate the techno-economic feasibility of different electricity generation configuration based on a particular set of evaluation criteria. The study achieves its aim through the following specific objectives.

1.1.2. Specific Objectives

- Identify priority areas of solar energy demand ;
- Conduct field surveys of 4 villages in the Northern and Southern part of Togo ;
- To identify the optimal technology configuration for solar energy systems for each location ;
- To mitigate greenhouse gases emissions through the development of the optimal technology configuration.

2. Methodology

2.1. Background of the study

Togo's household electrification rate was at 28% in 2013 with access increasing by 4.8% per year. It is observed that the consumption of energy decreases away from Lomé. This is partly due to the fact that a large part of the industries and populations are located in Lomé. Access to electricity remains very difficult for the poor due to high cost of energy, about 59% of GDP per capita. Electricity consumption by region reflects on the one hand the rural or urban way of life and on the other hand the remoteness or proximity of industrial areas. In 2018, a study by the AT2ER (Rural Electrification Program, AT2ER, 2018) showed that the alternative cost of electricity is expensive for households without electricity when using candles, charcoal, lamp oil or torches. This study showed that rural populations without electricity spend more on energy compared to those having access to energy, not to mention the negative impacts of this energy source they use on the environment and health. However, the current limitations that hinder the promotion of renewable energy in Togo include the perception of commercial and market risks, the low payment capacity of rural customers, uncertainty about the demand of rural customers, insufficient capacity in customer management and monitoring, insufficient community accountability. Four project sites were selected for this study. These sites spread across three economic regions of Togo: Savanes, Central and Plateaux.

2.1.1. Koumbogou

Koumbogou is located in the in Northern region of Togo in the Tandjouaré prefecture and it is also part of the Lion's Pit reserve. This area records its lowest temperatures between July and August, and the warmest temperatures between March-April. Very high sunshine is recorded in March. Population growth is close to the national average of 2.4%. This population is estimated at 500 inhabitants in 2020 composed mainly of the Moba ethnic group. Agricultural activities (millet, rice, maize, yam, cassava and livestock) are dominant and occupy by more than 90% of the village's labor force. Processing and handicrafts are also significant works in this area and the population mainly relies on torches and batteries for energy. Weather data for Koumbogou is presented in the Table 2.1 below:

Table 2. 1. Weather data for the savannah region from RETScreen Expert software

Month	Temperature (°c)	Horizontal sunshine (kwh/m^2/day)	Wind speed (m/s)	Relative humidity (%)
January	26,69	5,41	2,3	21,7
February	28,1	6,05	2,2	27,6
March	29,1	6,20	2,7	46,4
April	28,2	6,14	2,5	65,1
May	27,3	5,91	2,7	72,2
June	25,7	5,33	2,5	79,1
July	24,7	4,90	2,4	82,5
August	24,6	4,68	2,3	82,1
September	25,2	5,07	2,0	79,4
October	26,6	5,70	2,0	67,5
November	27,7	5,66	2,2	44,5
December	26,8	5,58	2,4	26,2

2.1.2. Malfakassa

Malfakassa is located 50 km from Sokodé in the Central Region, Bassar Prefecture in Northern Togo. The village is located on the East side of Fazao Malfakassa National Park. The terrain is very varied and rugged, consisting of vast plains, valleys, mountains. Its climate is tropical with the lowest temperatures recorded between July-August and the warmest temperatures observed between January and March. The average annual precipitation is 1,800 mm. The maximum precipitation occurs between July, August and September. Agricultural activities (cassava and yam) are dominant and occupy more than 75% of the labour force in this area. Malfakassa population is estimated at 350 in 2020, composed mainly of the Kotokoli and Kabyé ethnic groups, and poulation growth is close to the national average of 2.4%. The existing infrastructure consists of religious buildings and public schools. This area does not have a health center nor modern boreholes or wells. The habitat is well grouped and access to the village is made from a paved road on the Sokodé-Bassar axis. The population mainly relies on torches and batteries for energy. Weather data in this village is presented in the Table 2.2 below.

Table 2. 2. Weather data for central region from RETScreen Expert software

Month	Temperature (°c)	Horizontal sunshine (kwh/m^2/day)	Wind speed (m/s)	Relative humidity (%)
Fanuary	26,7	5,60	2,4	42,2
February	26,9	6,03	2,1	50,5
March	26,5	5,93	2,5	70,7
April	25,8	5,82	2,2	80,2
May	25,5	5,54	2,5	82,1
June	24,7	4,94	2,2	83,5
July	23,8	4,45	2,5	84,2
August	23,9	4,19	2,6	83,0
September	24,4	4,62	2,5	83,0
October	24,8	5,21	2,1	79,3
November	25,7	5,63	2,5	67,8
December	26,2	5,65	2,2	49,3

2.1.3. Kablive

Kablive is located in the Plateaux Region, Haho Prefecture. It is located in southern Togo about 80 km from Lomé. The area is marked by vast plains and numerous lagoons. The climate is Sudanese with the lowest average temperatures (25.0^{o}c) recorded between July-August and the warmest average temperatures (28.8^{o}c) observed between January and March. The average annual precipitation is over 2,000 mm, with maximum precipitation in July, August, and September. Population growth is close to the national average of 2.4%. The population is estimated at 1846 in 2020 composed mainly of the Ewe ethnic group. The economy is dominated by agriculture, trade, and other artisanal activities. Existing infrastructure consists of schools (primary and college) and worship places. However, the area does not have a health boreholes nor wells. The habitat is dispersed and access to the village is made from an unpassable rural road. The population mainly uses torches and batteries for energy.

2.1.4. Hahomegbe

Hahomegbe is located in the Plateaux Region, Haho Prefecture. It is located in the south of Togo about 115 km from Lomé. The area is marked by vast plains and numerous lagoons. The climate is Sudanese with the lowest average temperatures (25.0 ^{o}c) recorded between July-August and the warmest average temperatures (28.8 ^{o}c) observed between January and March. The average annual precipitation is over 2,000 mm, with maximum precipitation in July, August and

September. This population is estimated at 1755 in 2020 composed mainly of the Ewe ethnic group. The economy is dominated by agriculture, trade and other artisanal activities. The industrialization around this area is marked by the processing of mining products. Crafts activities are also significant activities. This village has a dispensary and a public elementary school, a college and high school. The habitat is grouped and access to the village is through modern paved road. The population mainly uses torches and batteries for energy. Weather data for this region is presented in the Table 2.3 below.

Table 2. 3. Weather data from the plateau region from RETScreen Expert software

Month	Temperature (°C)	Horizontal Sunshine (Kwh/M^2/day)	Wind Speed (m/s)	Relative humidity (%)
January	26,8	5,61	2,7	55
February	26,9	5,88	2,5	61,8
March	26,3	5,80	2,8	76,8
April	26,0	5,66	2,4	82,2
May	25,7	5,40	2,5	83,6
June	24,9	4,84	2,2	84,3
July	24,0	4,44	2,8	83,9
August	24,1	4,22	2,9	82,3
September	24,5	4,58	2,8	83,5
October	24,9	5,18	2,2	82,3
November	25,4	5,50	2,6	76,2
December	26,2	5,53	2,3	62,5

2.2. Load assessment

2.2.1. Data collection tools

A survey was carried out using google forms and survey monkey. This application was installed on each of the tablets of the 4 field personnel to ensure reliable and timely data collection. It also made it easier to compile and process the data. Data collection in the northern villages was very challenging because there was no internet connection. However, data was inputted manually on a sheet of paper and later transferred online.

2.2.2. Electric load

Initially, an interval of 4 households was planned to collect energy demand for the four villages. However, because of the non-availability of most households due to farming and commercial activities necessitated the team to change its technique. The head of every household and head of public offices and shops were randomly surveyed. Table 2.4-Table 2.7 below show the different types of residential clients and the sectorial energy demand for the four villages.

Table 2. 4. Number of different types of customers per village

N°	Region	Prefecture	Canton	Locality	Longitude	Latitude	Population 2020	Household 2020	Types of households		
									household 1 (revenue less than 25$/month)	household 2 (revenue between 25 and 50 $/month)	household 3 (revenue more than 50 $/month)
1	Plateaux	Haho	Hahomegbe	Hahomegbe	1°01'11.32"E	6°56'33.05"N	1755	579	307	191	81
2	Plateaux	Haho	Dalia	Kablive	1°10'36.76"E	6°45'59.10"N	1846	362	116	116	130
3	Central	Bassar	Bassar	Malfakassa	0°58'31"E	9°10'33"N	350	60	16	14	30
4	Savanna	Tandjouare	Tandjouare	Koumbogou	0°13'06"E	10°45'23"N	500	85	45	28	12

Table 2. 5. Number of public, commercial, and professional customers

Prefecture	Canton	Locality	Baber shop	Tailor shop	Carpentry workshop	Mill	Bars/ Shop	Welding shop	Health center	School (Number of classes)	Worship Place
Haho	Hahomegbe	Hahomegbe	3	5	5	2	8	2	1	3 (6)	4
Haho	Dalia	Kablive	3	5	3	4	8	3	0	2 (6)	8
Bassar	Bassar	Malfakassa	0	0	1	1	0	1	0	1 (12)	1
Tandjouare	Tandjouare	Koumbogou	0	0	0	2	3	0	0	1 (4)	2

Table 2. 6. Estimated energy demand for Malfakassa and Hahomegbe

Sector	Electrical appliance	Power consumption (W)	Number in use	Daily cycle (h)	Number of hours	Daily consumption (Wh)
***Domestic Use**	LED bulbs and lamps	10	6	18:00-22:00	4	240
	Radio	15	1	13:00-17:00	4	60
	Phone charger	15	1	18:00-20:00	2	30
	Portable lamp	2	1	19:00-20:00	1	2
	Color TV 19”	26	1	19:00-22:00	3	78
	Fan	70	1	21-00-22:00	1	70
	Total (One home)					**480**

Note: * For Malfakassa with 60 househols, the total energy demand = 60 x 480 = 28,800Wh/day
* For Hahomegbe with 579 housholds, the total energy demand = 579 x 480 = 277,920Wh/day

Table 2. 7. Estimated electricity demand for Kablive

Sector	Electrical appliance	Power consumption (W)	Number in use	Daily cycle (h)	Number of hours	Daily consumption (Wh)
***Domestic Use**	LED bulbs and lamps	10	6	18:00-22:00	4	240
	Radio	15	1	13:00-17:00	4	60
	Phone charger	15	1	18:00-20:00	2	30
	Portable lamp	2	1	19:00-20:00	1	2
	Color TV 19”	26	1	19:00-22:00	3	78
	Fan	70	1	21-00-22:00	1	70
	One home					480
	Total (362 homes)					**173,760**
Commercial Use	*Welding shop (3)*					
	Welding machine	2200	3	10:00-13:00	3	19,800
	Total					19,800
	Carpentry shop (3)					

	Angle grinder	2200	3	9:00-17:00	8	52800
	Sawing machine	1000	3	9:00-17:00	8	24000
	Electric drill	60	3	9:00-17:00	8	1440
	Radio	16	3	9:00-17:00	8	384
	Total					**78,624**
	Tailors (5)					
	Fluorescent lamp	16	5	16:00-18:00	2	160
	Ceiling fan	40	5	13:00-18:00	5	1000
	Total					1,160
	Restaurants/bars (8)					
	Refrigerator	260	8	15:00-19:00	4	8320
	Color TV	70	8	14:00-22:00	8	4480
	LED lamp	9	8	18:00-22:00	4	288
	Total					13,088
	Barber shop (8)					
	Wahl clipper	11	8	11:00-16:00	5	440
	Fluorescent lamp	16	8	15:00-18:00	3	384
	Total					824
	Mill (4)					
	Electric motor	5520	4	10:00-16:00	4	88,320
	Phone multi-charger	15	4	10:00-12:00	2	120
	Total					**88,440**
Public	*School (3)*					
	Desktop computer	70	3	10:00-15:00	5	1050
	Photocopier/Printer	120	3	1 h per day	1	360
	LED 1.20M lamp	18	120	12:00-16:00	4	8640

	LED bulbs	5	45	12:00-16:00	4	900
	2P + T sockets	50	12	10:00-15:00	5	3000
	Total					13,950
	Worship places (8)					
	LED bulbs	5	32	3h per day	3	480
	Microphone/speaker	20	8	3h per day	3	480
	Total					**960**
Others	LED street lamp	20	2	18:00-6:00	12	480
	Miscellaneous	25	10	11:00-14:00	3	750
	Total					**1,230**
Grand total						**391,836**

Note: *The electrical appliances for Kablive and Koumbogou are same. However, Koumbogou has 85 households, 3 restaurant/bars, 2 Milling shops, 1 school and 2 worship places. The total energy demand for Koumbogou is estimated at 84,008Wh/day.

2.2.3. Household classification

Electricity demand in these villages is divided into residential, public and commercial sectors. Residential electricity consumption in the residential sector falls into four categories: Household 1, household 2 and household 3 as shown in Table 2.8-Table 2.10 below. The grouping of these clients is based on average monthly income or by social class. The power rating of each appliances as well as the daily cycle of the appliances, was collected for every sector. However, the specifications may change with time due to increase in house-hold income and availability of electricity.

Table 2. 8. Household 1: Poor household

Appliance	Number of appliances	Power unit (w)
LED bulbs and lamps	4	1
Radio	1	15
Phone multi-charger	1	15
Total power		31

Table 2. 9. Household 2: Average household

Appliance	Number of appliances	Power unit (w)
LED bulbs and lamps	6	2
Radio /huffer	1	15
Phone multi-charger	1	15
Portable lamp	1	2
TV	1	26
Fan	1	70
Total power		130

Table 2. 10. Household 3: Richest household

Appliances	Number of appliances	Power unit (w)
LED bulbs	4	5
Tube led lamp (0.6m)	3	9
Radio /huffer	1	2
Phone multi-charger	1	15
Portable lamp	1	2
TV	1	70
Fan	2	70
Fridge	1	150
Total power		323

3. Case study

A techno-economic feasibility study was conducted for a solar PV energy system and a hybrid PV/battery energy system in the Northern and Southern part of Togo. Data for an average household (Table 2.9) was used for the analysis, including sectorial energy demand as seen in Table 2.7.

3.1. Case study 1: Feasibility analysis of small scale solar energy systems for Malfakassa and Hahomegbe using RETScreen Expert Software

3.1.1 Introduction

This study used RETScreen Expert software to access the viability of installing a 12kW and 120kW grid-connected solar photovoltaic system. The size of the installed solar photovoltaic was determined based on the number of households in the Malfakassa and Hahomegbe villages of Togo. The climatic data for the two locations were calculated by the RETScreen using the National Aeronautics and Space Administration (NASA) data as listed in Table 3.1. The village of Malfakassa has the highest annual solar radiation of 5.30kWh/m^2/d when compared with the village of Hahomegbe with 5.22kWh/m^2/d. Also, the variation of the average monthly solar radiation of the selected locations is shown in Fig. 3.1. A thorough feasibility analysis carried out shows the technical, economic, environmental, and risk/sensitivity analysis result of installing the proposed slat PV technologies in the two locations.

Table 3. 1. Climatic data of the selected locations

Location	Malfakassa	Hahomegbe
Latitude	9.0	7.1
Longitude	1.1	1.1
Elevation	337	228
Heating design temperature (^{0}C)	19.7	20.2
Cooling design Temperature (^{0}C)	33.0	32.3
Earth temperature amplitude (^{0}C)	12.3	11.2
Average monthly solar radiation (kWh/m^2/d)	5.30	5.22

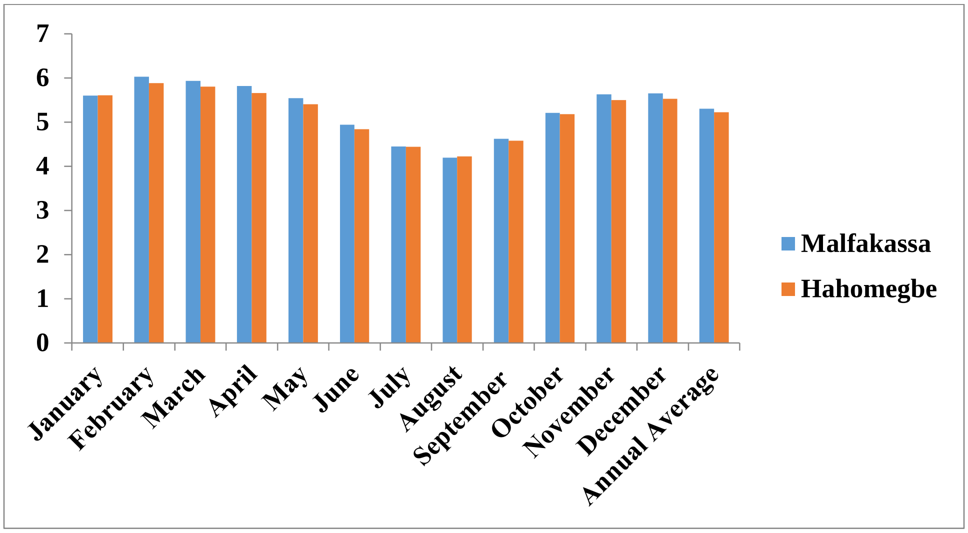


Figure 3. 1. Monthly variation of the daily solar radiation for the six locations

3.1.2 Technical Analysis

In engineering, technical sustainability takes into consideration the product specification upon which the efficiency and efficient utilization of the solar PV depends on. Two axes solar tracking mode was considered for the two locations. These were chosen because the solar irradiance and the electricity exported to the grid for the locations were at the highest when the two-axis panel tracking was compared with both one axis and fixed. The RETScreen Expert software calculated the parametric characteristics of the China Sunergy mono-si-CSUN200-72M solar module as shown in Table 3.2.

Table 3. 2. Parametric characteristics of China Surnegy solar module

Property	Value
PV technology type	mono-Si
Power capacity	6MW
Manufacturer	China Surnegy
Model	mono-Si-CSUN200-72M
Number of units	30,000
Efficiency	15.67%
Nominal operating temperature	45 ^{0}C
Temperature coefficient	0.4%/^{0}C
Solar collector area	38,290m^{2}

The energy produced from any solar photovoltaic module depends on the solar radiation of the location and the number of clear sunny days and this, in turn, affects both the annual energy exported to the grid by the panel and the capacity utilization factor (CUF) which is the ratio of electrical energy generated by the solar photovoltaic plant over the year to the energy output at its rated capacity. For the 12kW solar PV proposed for the village of Malfakassa, 24.6% was gotten as the capacity factor as against 24% for the village of Hahomegbe as shown in Table 3.3. This is as a result of the amount of solar irradiance gotten from the village of Malfakassa. Also, the annual energy exported to the grid for the village of Malfakassa having 12kW installed solar PV was 25,852MWh and that of the village of Hahomegbe with 120kW installed solar PV was 251,947MWh. The values gotten as the annual energy exported to the grid and the capacity factors for the two locations are compatible with the acceptable values and hence it is technically sustainable to build and operate solar photovoltaic plants in the two villages based on the technical viability of the solar system.

Table 3. 3. Solar photovoltaic energy summary per location

Locations	Capacity factor	Annual energy exported	Annual electricity exported revenue
Malfakassa	24.6%	25,852MWh	$5,507
Hahomegbe	24.0%	251,947MWh	$53,665

3.1.3 Financial Analysis

In developing a solar photovoltaic project, the economic analysis is a very important analysis that is done to know if a project will be economically viable and sustainable. The financial analysis worksheet of the software contains some financial parameters to include inflation rate, discount rate, reinvestment rate, debt ratio, debt interest rate as input variables as shown in Table 4 for the two villages. The values used as input variables are standards gotten directly from the software excluding the initial cost and the operation and maintenance cost that was manually inputted. Based on the inputted variables, the Internal Rate of Return (IRR), the Net Present Value (NPV), the annual life savings, and other financial parameters for the two villages are calculated by the RETScreen software as shown in Tables 3.4 and 3.5 below.

Since the economic viability of a project is a measure of its NPV, IRR, and the payback period. For this project, the NPV which is the difference between the present value of cash inflows and the present value of cash outflows over a period for the two locations were positive and this makes the project to be financially and economically feasible. Also, the value of the IRR which is a measure of a project's profitability that is gotten for the two locations is higher than the required rate of return of the project. This makes the projects in the two villages to be economically acceptable given the required rate of return of the project has the discount rate.

Table 3. 4. Financial input variables from RETScreen Expert

Financial parameters	Malfakassa	Hahomegbe
Escalation rate fuel	2%	2%
Inflation rate	3%	3%
Discount rate	6%	6%
Reinvestment rate	9%	9%
Project Life	25yrs.	25yrs.
Debt ratio	60%	60%
Debt interest rate	7%	5%
Debt term	15%	15%
Debt payment	$2,609/yr.	$26,087/yr.
Electricity export rate	$0.21/kWh	$0.12/kWh
Electricity export escalation rate	2%	2%
Initial cost	$39,600	$396,000
Operation and maintenance cost	$600	$6,000
Total annual cost	$3,209	$32,087

Table 3. 5. Financial output variables from the RETScreen Expert

Financial viability	Malfakassa	Hahomegbe
Internal rate of return (%)	19	18.2
Net Present Value (NPV) ($)	35,014	328,078
Annual life cycle savings ($)	2,739	25,664
Benefit-cost (B-C) ratio	3.2	3.1
Debt service charge	1.9	1.9
Energy production Cost ($/kWh)	0.157	0.161

The simple payback period which is the length of time that will take to recoup the project's initial investment in the two locations is illustrated in Fig. 3.2. The proposed 12kW photovoltaic project in the village of Malfakassa has 8.1 years as the payback period while the 120kW proposed project in Hahomegbe has 8.3 years payback period. Irrespective of the break-even year, the solar PV systems in the two locations makes financial sense. The project in Malfakassa will have an equity payback of 6 years and that in Hahomegbe has an equity payback of 6.31 years. This simply means that the project will yield interest in Malfakassa for 18.69 years and the one in Hahomegbe will yield interest for 19 years out of the 25 years designed for the project to work respectively. The profit that each project location will accumulate after recouping the total cost incurred on the project is shown in Fig. 3.3.

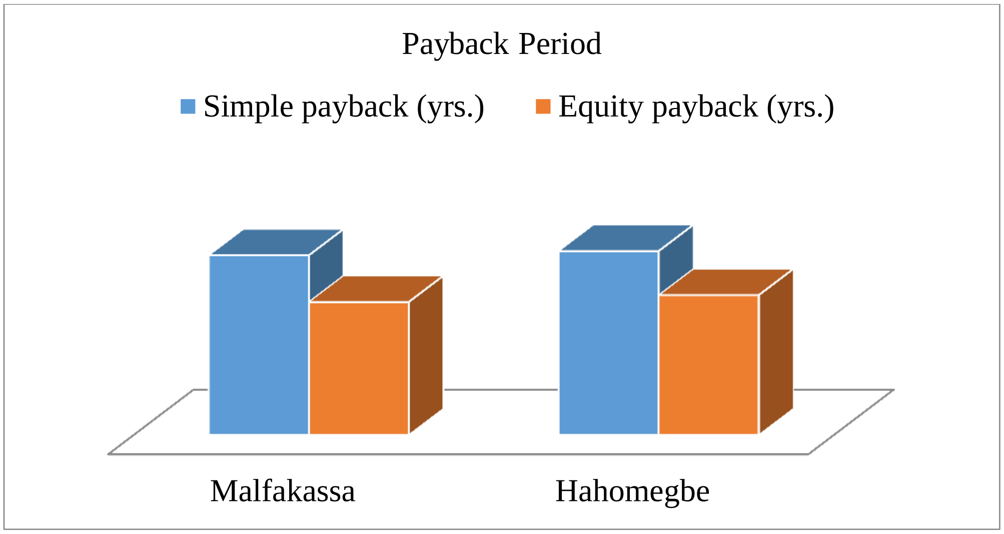


Figure 3. 2. The project payback period for the six locations

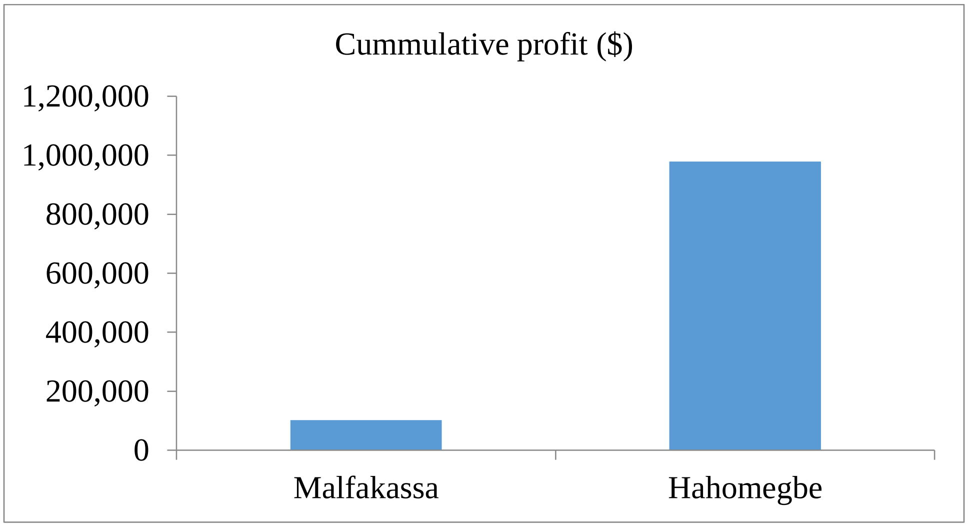


Figure 3. 3. The cumulative cash flow of the project after 25 years for the six locations

3.1.4 Environmental Analysis

The emission analysis worksheet is used to calculate the greenhouse gas (GHG) emission reduction resulting from carrying out the solar PV installation. It is also used to calculate the revenue that may occur from the sales of the GHG reduction emission. The transmission and distribution losses of 18% and GHG emission factor of 0.251tCO_2/MWh were considered as the base case electricity system in Togo. The software calculates the gross annual GHG emission reduction in the two locations by subtracting the calculated emission in the proposed case from the calculated emission in the based case as shown in Table 3.6. This is because the GHG emission during the project operational period is only considered and not during the life cycle of the project.

Table 3. 6. Annual GHG emission for the six locations

Location	Based case (tCO_2)	Proposed case (tCO_2)	Gross annual GHG emission reduction(tCO_2)
Malfakassa	6.4812	0.4537	6.0275
Hahomegbe	63.1635	4.4214	58.742

The project in the village of Malfakassa has the maximum GHG emission reduction of 6.0275 tons of CO_2 that is equivalent to 0.6 Hectares of forest absorbing carbon not cut down for the entire life span of the project if installed and that in Hahomegbe has 58.742 GHG emission reduction that is equivalent to the 5.4 Hectares of forest absorbing carbon not cut down for the entire life span of the project as shown in Fig. 4.4. The Global Forest Resources Assessment (FRA), coordinated by FAO, found that the world's forest area decreased from 31.6 percent of the global land area to 30.6 percent between 1990 and 2015, but that the pace of loss has slowed in recent years because of development of clean energy technology for sustainable development. According to the sustainable development goals (SDGs), countries under the United Nations committed to achieving sustainable development agenda by 2030 to tackle the complex challenges human-faced from ending poverty and hunger and responding to climate change to building resilient communities, achieving inclusive growth, and sustainably managing the Earth's natural resources. Hence this project will help in achieving the set goals if implemented.

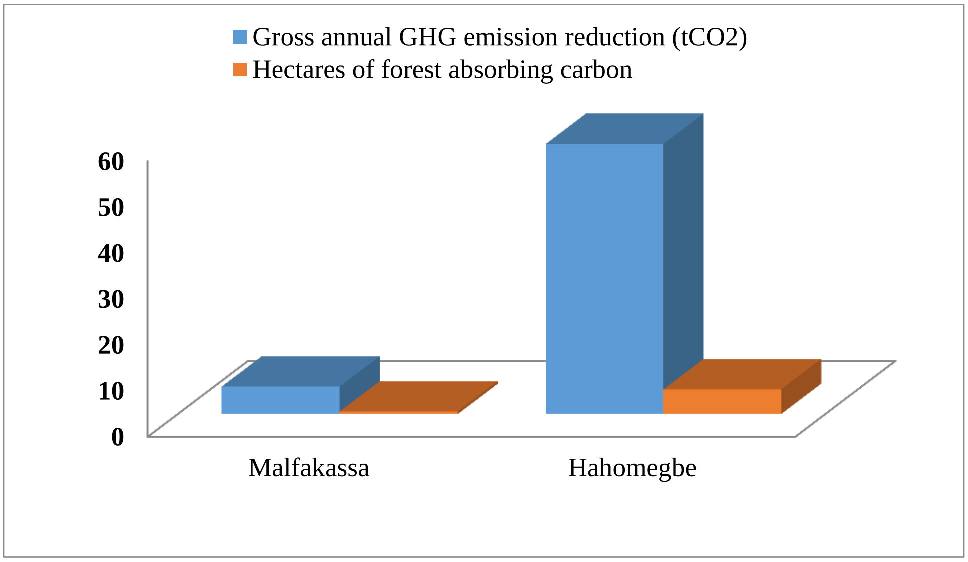
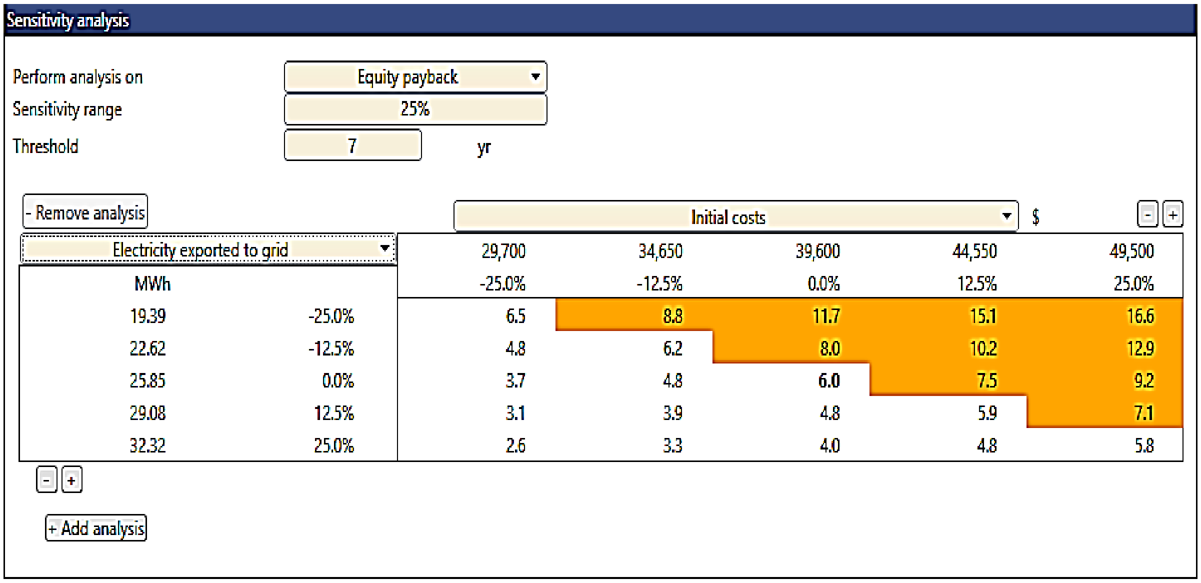


Figure 3. 4. Gross annual GHG emission and the corresponding Hectares of forest absorbing carbon not cut down.

3.1.5 Sensitivity Analysis

The level of uncertainty associated with the project during analysis is a measure of the level of uncertainty of the inputted variables which has effects on the level of uncertainty on the calculated financial variables. The sensitivity analysis worksheet is where the level of uncertainty can be reduced by considering two inputted parameters against the calculated financial variables. The sensitivity analysis was done for the Equity payback of the project by varying the initial cost against the electricity exported to the grid by ±25% for the 12kW proposed solar PV in Malfakassa and 120kW for the project in Hahomegbe as shown in Fig. 3.5 and Fig. 3.6 respectively.

For the case of Malfakassa, the value of the initial cost is given as $39,600 and with a range of ±25%, it will be $49,500 and $29,700 respectively. Also, the electricity exported to the grid is 25.85MWh but with a ±25% it will be 32.32MWh and 19.39MWh respectively. By recalculating the equity payback for the combination of initial cost and the electricity exported to the grid holding all other parameters fixed. The software indicates the values of the equity payback below the threshold of 7 years by yellow. With an increase of 25% to the initial cost and a decrease of 25% to the electricity exported to the grid, the project will be financially not profitable because the equity payback will be 16.6 years. But if the initial cost is reduced by 25% and the electricity exported to the grid is increased by 25%, the project will be financially feasible because the equity payback will be 2.6 years. This means that the equity payback is more sensitive to the initial cost than the electricity exported to the grid for this project. Similarly, the village of Hahomegbe followed the same pattern.



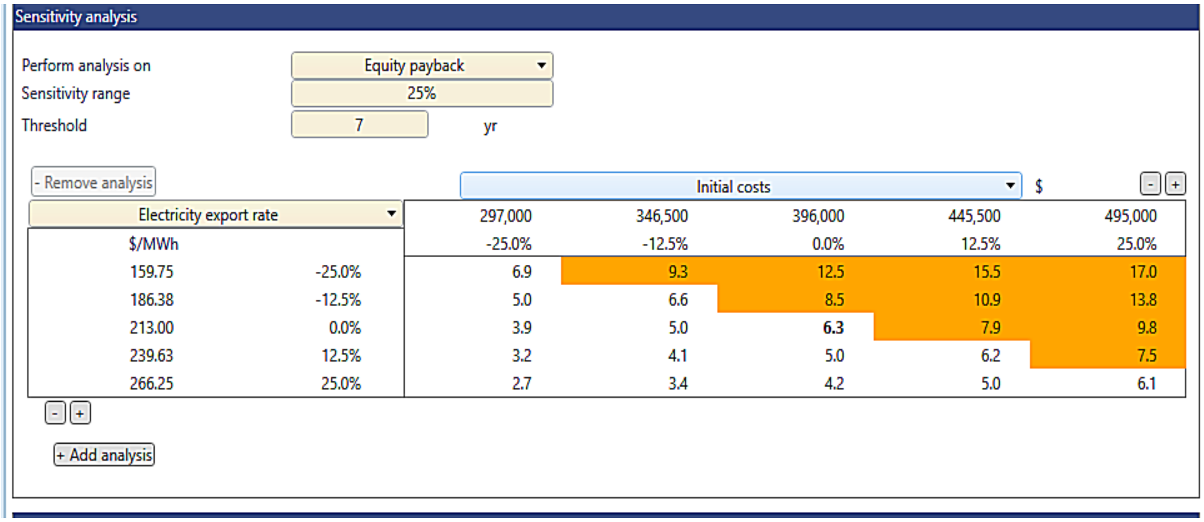
Sensitivity analysis

Perform analysis on: Equity payback
Sensitivity range: 25%
Threshold: 7 yr

Initial costs $

Electricity exported to grid		29,700	34,650	39,600	44,550	49,500
MWh		-25.0%	-12.5%	0.0%	12.5%	25.0%
19.39	-25.0%	6.5	8.8	11.7	15.1	16.6
22.62	-12.5%	4.8	6.2	8.0	10.2	12.9
25.85	0.0%	3.7	4.8	**6.0**	7.5	9.2
29.08	12.5%	3.1	3.9	4.8	5.9	7.1
32.32	25.0%	2.6	3.3	4.0	4.8	5.8

Figure 3. 5. Sensitivity analysis result for the solar photovoltaic project in Malfakassa.



Sensitivity analysis

Perform analysis on: Equity payback
Sensitivity range: 25%
Threshold: 7 yr

Initial costs $

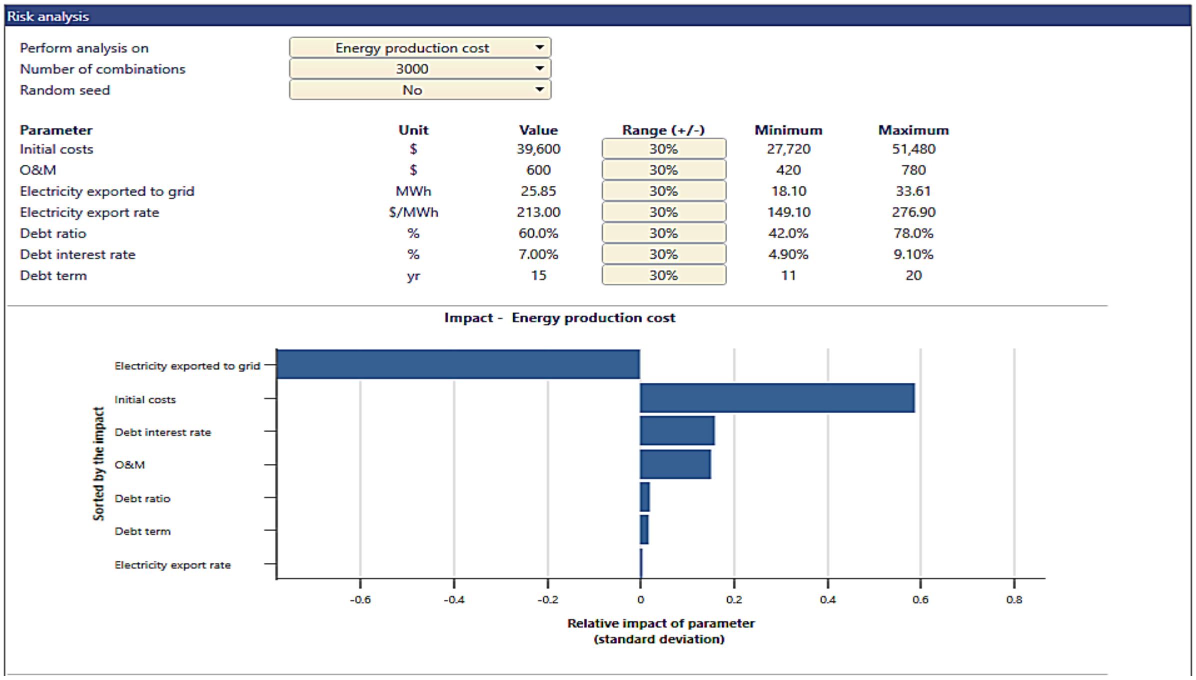
Electricity export rate		297,000	346,500	396,000	445,500	495,000
$/MWh		-25.0%	-12.5%	0.0%	12.5%	25.0%
159.75	-25.0%	6.9	9.3	12.5	15.5	17.0
186.38	-12.5%	5.0	6.6	8.5	10.9	13.8
213.00	0.0%	3.9	5.0	**6.3**	7.9	9.8
239.63	12.5%	3.2	4.1	5.0	6.2	7.5
266.25	25.0%	2.7	3.4	4.2	5.0	6.1

Figure 3. 6. Sensitivity analysis result for the solar photovoltaic project in Hahomegbe

3.1.6 Risk analysis

Risk analysis should be done before the commencement of any solar energy project so that the level of uncertainty in the project will be known the same as in sensitivity analysis. The only difference is that, instead of using two parameters to conclude the case of the sensitivity analysis, all the parameters are allowed to vary with each other during the analysis within a specific range. The energy production cost is selected as the financial indicator for the two locations and the range considered for the two villages was ±30% for all the parameters. The RETScreen software performed Monte Carlo simulation techniques 3000 times for the village of Malfakassa and 4000 times for the village of Hahomegbe by recalculating the energy production cost and the result is displayed as the impact graph as shown in Fig. 3.7 for the village of Malfakassa and Fig. 3.8 for the village of Hahomegbe.

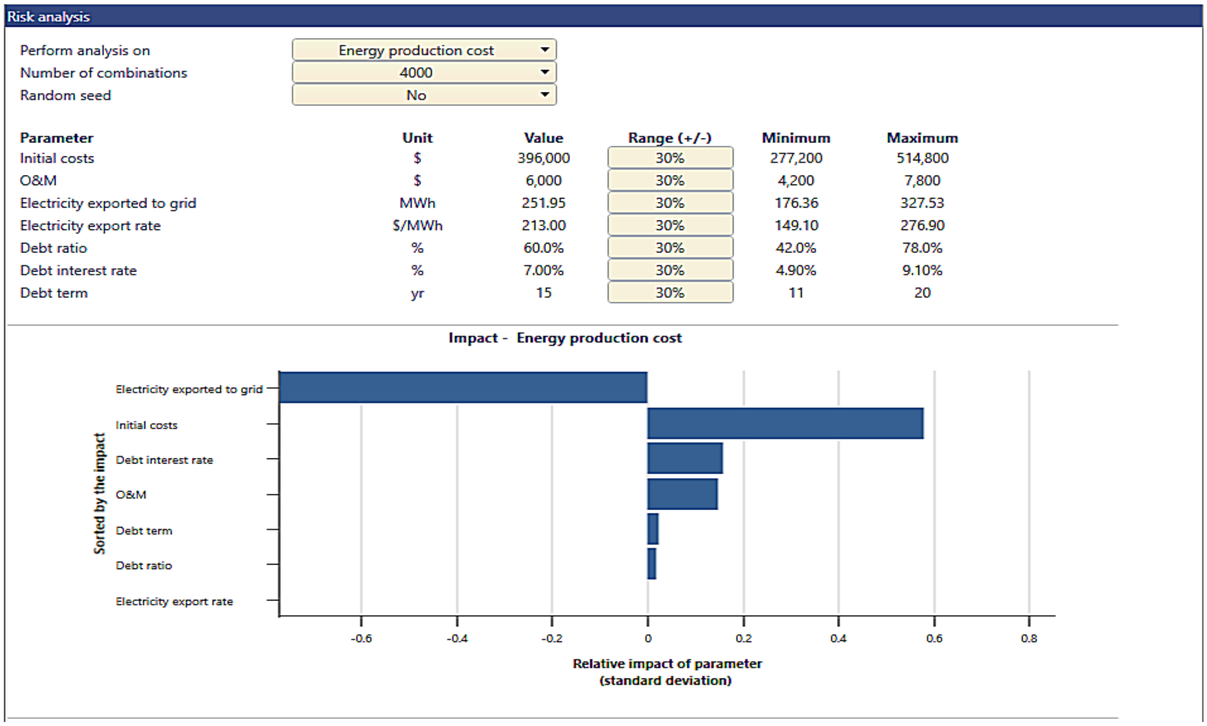
According to the impact graphs for the two locations, the variation in the energy production cost is a result of the variation of the various parameters. The initial cost and the electricity exported to the grid have a great impact on the project but in the opposite direction. An increase in the initial cost of the project in any of the locations increases the energy production cost while an increase in the electricity exported to the grid decreases the energy production cost.



Perform analysis on: Energy production cost
Number of combinations: 3000
Random seed: No

Parameter	Unit	Value	Range (+/-)	Minimum	Maximum
Initial costs	$	39,600	30%	27,720	51,480
O&M	$	600	30%	420	780
Electricity exported to grid	MWh	25.85	30%	18.10	33.61
Electricity export rate	$/MWh	213.00	30%	149.10	276.90
Debt ratio	%	60.0%	30%	42.0%	78.0%
Debt interest rate	%	7.00%	30%	4.90%	9.10%
Debt term	yr	15	30%	11	20

Figure 3. 7. Impact graph of the risk analysis result for the solar photovoltaic project in Malfakassa



Risk analysis

Perform analysis on: Energy production cost
Number of combinations: 4000
Random seed: No

Parameter	Unit	Value	Range (+/-)	Minimum	Maximum
Initial costs	$	396,000	30%	277,200	514,800
O&M	$	6,000	30%	4,200	7,800
Electricity exported to grid	MWh	251.95	30%	176.36	327.53
Electricity export rate	$/MWh	213.00	30%	149.10	276.90
Debt ratio	%	60.0%	30%	42.0%	78.0%
Debt interest rate	%	7.00%	30%	4.90%	9.10%
Debt term	yr	15	30%	11	20

Figure 3. 8. Impact graph of the risk analysis result for the solar photovoltaic project in Hahomegbe

3.1.7 Conclusion

In this study, a thorough feasibility analysis was conducted to access the viability of installing a 12kW grid-connected solar photovoltaic project in the village of Malfakassa and 120kW grid-connected solar photovoltaic project in the village of Hahomegbe both in Togo by analyzing the technical, financial, risk, sensitivity and environmental impact of the project on the host community. The size of the installed solar photovoltaic was determined based on the number of households in the Malfakassa and Hahomegbe villages of Togo. This was done to have a solar energy road map that will attract solar energy investors from the international organizations and donor countries to invest in the underutilized and abundant clean energy in Togo. This project if implemented will help to reduce the effect of global warming caused by the burning of wood in the regions and also, enhance the sustainable technological development of the region that was hampered and exacerbated by the lack of electricity that can bring about development to Togo. The Climatic data from NASA for the two locations and some financial parameters to include the reinvestment rate, inflation rate, discount rate, and debt interest rate were used for the analysis as input data inside the RETScreen Expert software. Depending on the two locations and the solar panel wattage which was determined based on the number of households. The software accurately calculates the total amount of energy generated by the panel and exported to the grid, the amount of greenhouse gas (GHG) emission that will be reduced annually, the hectares of forest absorbing carbon, the greenhouse gas emission revenue that will be generated during the life cycle of the project, the financial implication of the project to include the amount of revenue that will be generated from the sales of the energy exported to the grid and the risk involved in executing the project.

3.2. Case study 2: Solar hybrid micro-grid energy systems for Koumbogou and Kablive using HOMER

3.2.1. HOMER system modeling

The Hybrid Optimization Model for Multiple Energy Resources (HOMER), developed by the National Renewable Energy Laboratory is the simulation model employed in this study. This tool is powerful for optimizing mini-grid systems in all sectors. HOMER performs a sensitivity analysis to determine the optimal value of each decision variable inputted by the modeler, to ensure the best possible match between energy demand and supply. In this feasibility study, the project lifetime is considered as 25 years, and the nominal discount rate is considered as 6%. The maximum capacity shortage is set at 5%. The methodology utilized for the feasibility analysis is indicated in Fig.3.9.

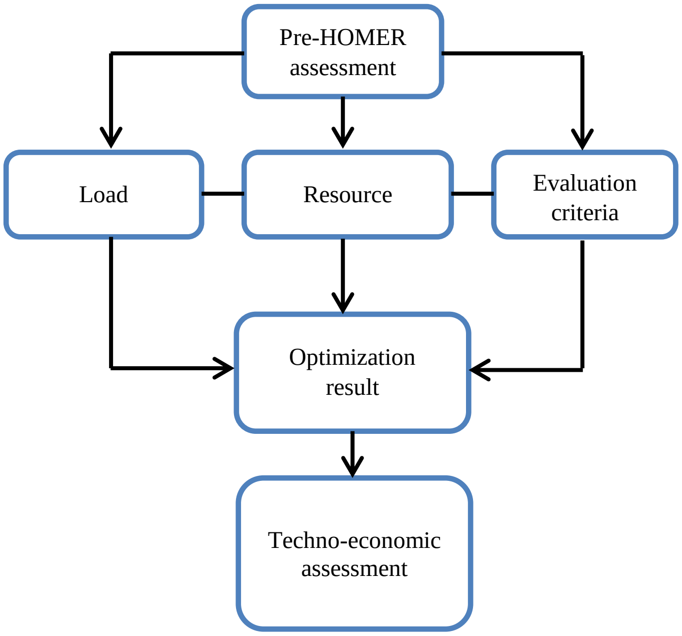


Figure 3. 9. Schematic layout of the study

3.2.2. Input data

3.2.2.1 Electric load

Table 2.7 above gives a breakdown of the electrical appliances considered in this study. A MatLab script using version 9.6, and a random day-to-day (10%) and time-step (20%) variability were considered in HOMER to generate hourly load data for Koumbogou and Kablive. The average electricity consumption for these villages is estimated at 84kWh/day and 390kWh/day respectively. The peak demand was at 23.12kW (Koumbogou) and 92.53kW (Kablive) as shown in Fig.3.10. The daily load profile of both villages is almost similar and represented with a double peak. The peak demand is recorded between 10:00 and 13:00 when public offices and commercial shops switch on appliances. A low peak is also recorded at 21:00 because most people would prefer to switch on their fans about an hour before bedtime. The monthly load profile for both villages is show in Fig. 3.11. However, this may change based on the habits of the population.

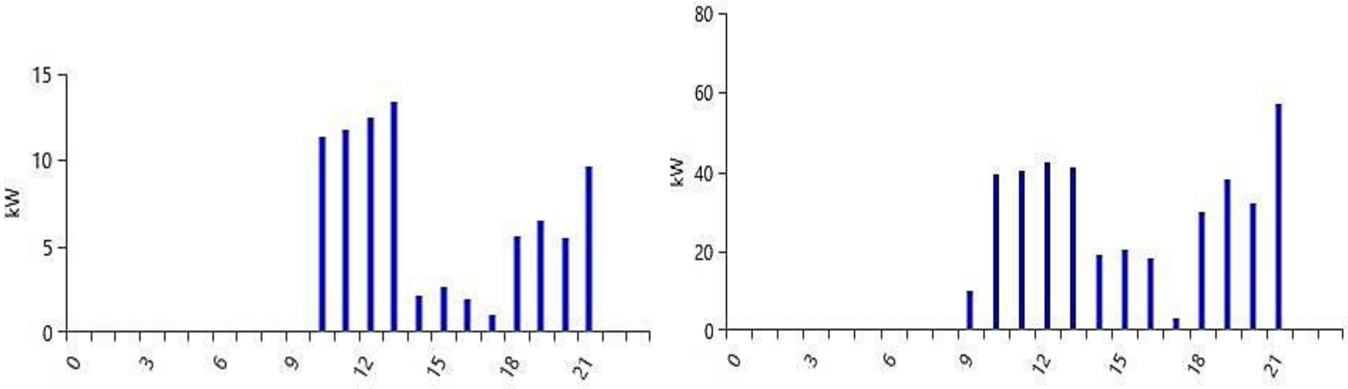
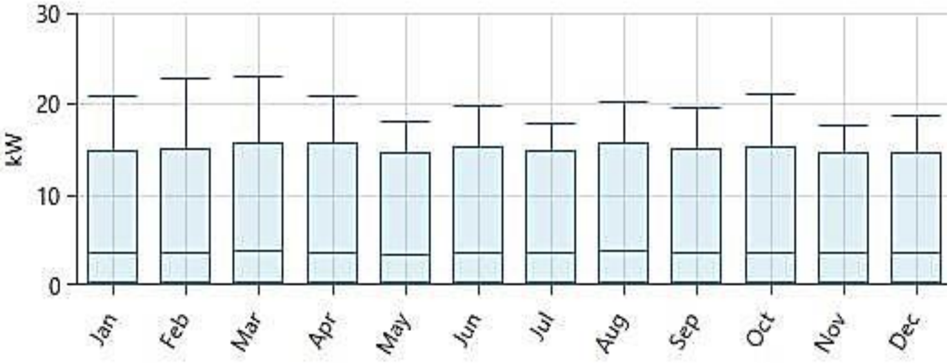
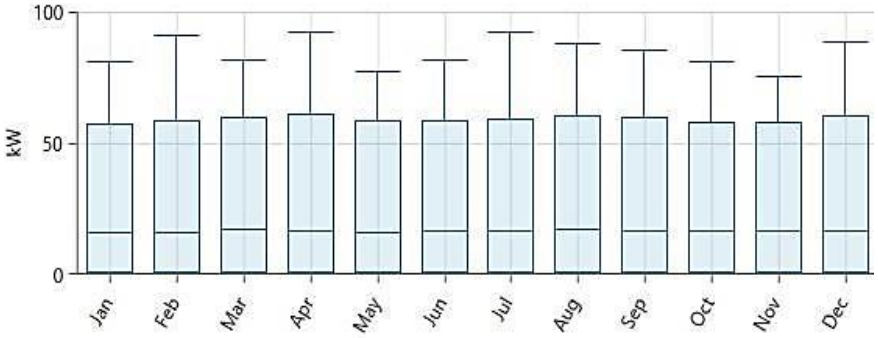


Figure 3. 10. Daily load profile for a) Koumbogou and b) Kablive



a) Koumbogou



b) Kablive

Figure 3. 11. Monthly load profile : a) Koumbogou and b) Kablive

3.2.2.2 Renewable resource

Togo is geographically located in West Africa with great potential for solar energy, but very limited wind energy potential. Thus only solar renewable energy resource was considered in this study. The solar radiation in Koumbogou and Kablive is estimated at 5.55 kWh/day/m^2 and 5.0 kWh/day/m^2 respectively.

3.2.2.3 Techno-economic

In study, a generic flat PV module with ground reflectance of 20% and a derating factor of 80% is considered. The tracking system is not taken into account thus the panel slope is varied to determine the optimal angle. The PV module is connected to the alternating current electrical bus. The capital cost for 1 kW PV is taken as $2800. Operational and maintenance costs for PV array over 25 years lifetime is practically zero since it is negligibly small.

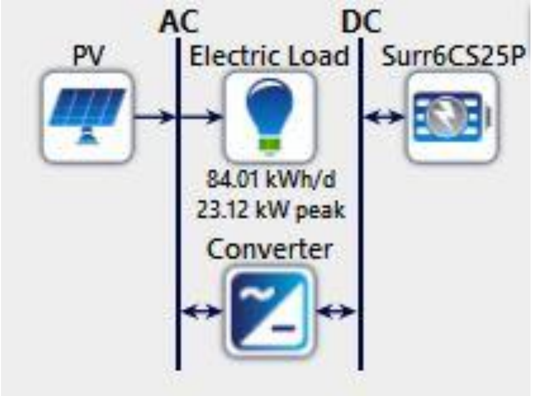
A Surrette 6CS25P 6V battery was used to backup power generation for the system. The battery's minimum state of charge and the initial state of charge is 40% and 100% respectively. The capital cost of the battery is taken as $1250/unit, with replacement cost and O & M cost of $1100 and $50 respectively. The lifetime is 20 years. It is activated when the renewable output is insufficient to meet the load demand.

A converter with an efficiency of 95% functioning both as a rectifier and an inverter is used. The capital and replacement cost for 1kW converter were considered as $300 and $300, respectively.

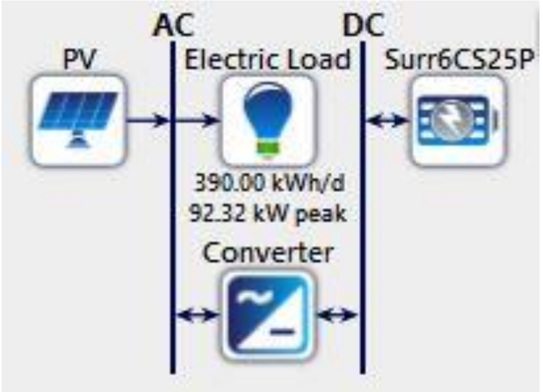
3.2.3. Optimization result

3.2.3.1. Actual scenario

A standard diesel generating system to supply the load demand was considered as the base case. The schematic diagram of the micro-grid power systems are shown in Fig.3.12. Table 3.7 presents a breakdown of the HOMER optimization result of the selected power system configurations for both villages. The costs for the micro-grid components and the cost-type have been presented in Fig. 3.13- Fig.3.16 below.



a) Koumbogou



b) Kablive

Figure 3. 12. Schematic of the proposed power system

Table 3. 7. Optimization result for the micro-grid power systems

Description	Item	Unit	Koumbogou	Kablive
Component	Solar PV	kW	24	130
	Battery Surrette 6CS25P	-	29	178
	Converter	kW	34.3	86.9
Electrical production	Electricity	kWh/yr	40,872	192,146
	Unmet load	kWh/yr	1,124	5,371
	Excess electricity	kWh/yr	7,052	32,531
	Capacity shortage	kWh/yr	1,544	7,193
	Renewable energy fraction	%	100	100
Consumption	Primary load	kWh/yr	29,539	136,979
Emission	Carbon dioxide	kg/yr	0.00	0.00
	Carbon monoxide	kg/yr	0.00	0.00
	Unburned hydrocarbons	kg/yr	0.00	0.00
	Particulate matter	kg/yr	0.00	0.00
	Sulfur dioxide	kg/yr	0.00	0.00
	Nitrogen oxides	kg/yr	0.00	0.00
Cost ($)	Capital cost	$	113,066	612,562
	Total net present cost	$	160,758	776,965
	Operating cost	$/yr	3,731	25,727
	Operation & Maintenance cost	$/yr	35,173	113,771
	Replacement cost	$/yr	15,389	75,747
	Levelized cost of electricity	$/kWh	0.4257	0.4437

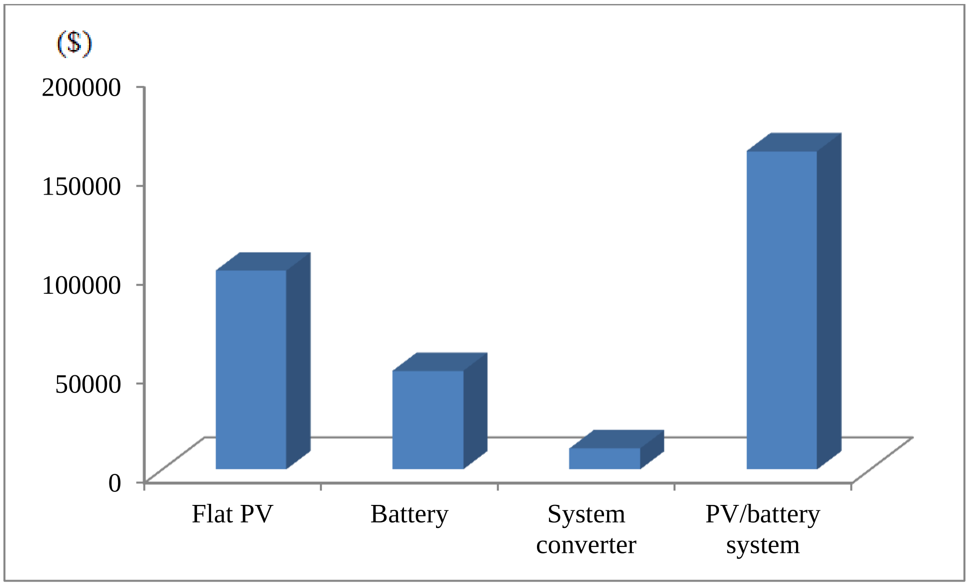


Figure 3. 13. Cost of micro-grid components in Koumbogou

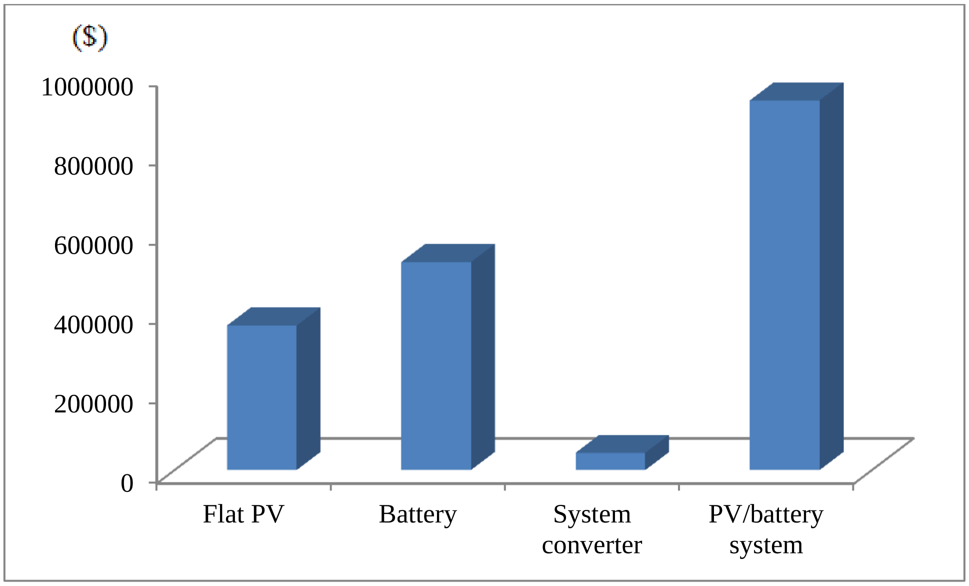


Figure 3. 14. Cost of micro-grid components in Kablive

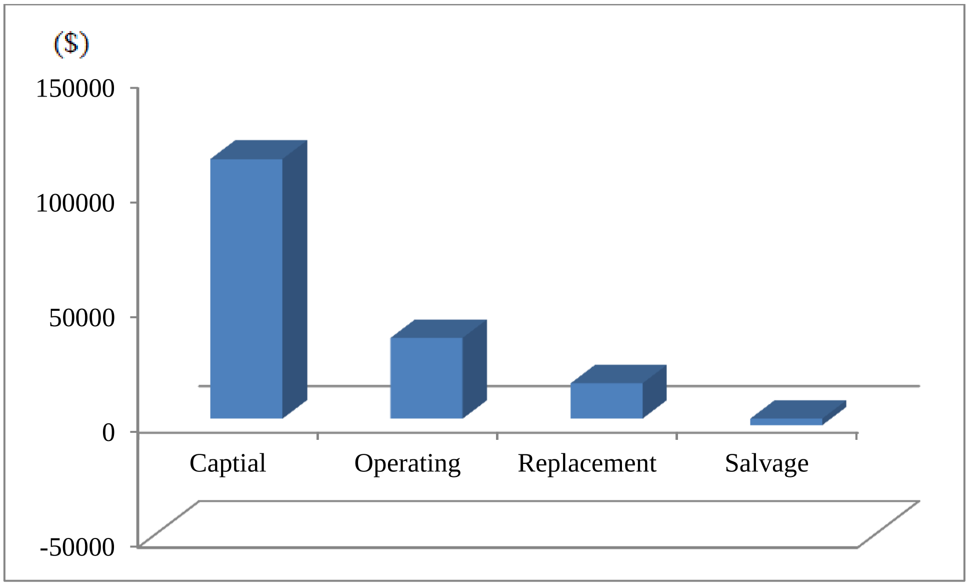


Figure 3. 15. Cost type of the micro-grid power system in Koumbogou

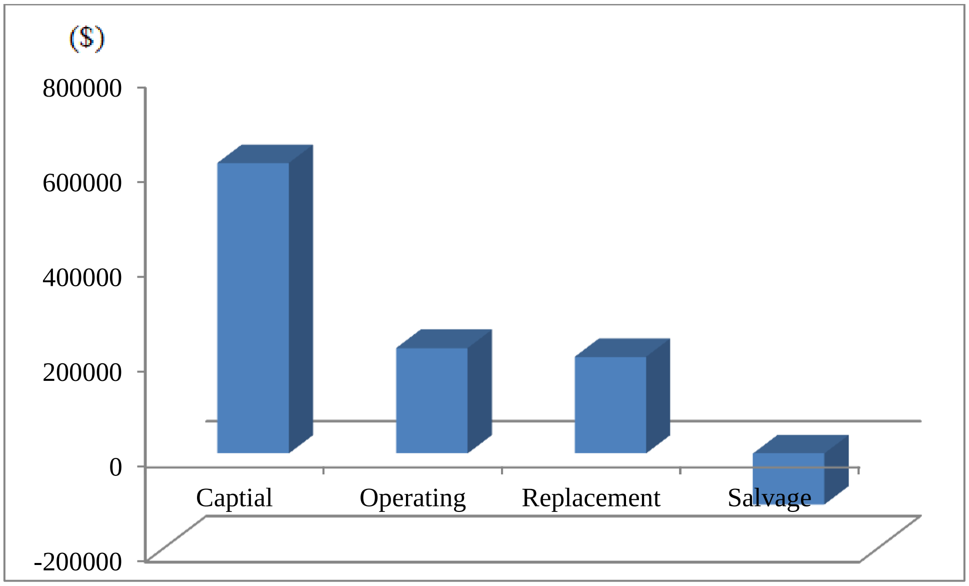


Figure 3. 16. Cost type of the micro-grid power system in Kablive

3.2.3.2. Sensitivity input

The sensitivity analysis has been performed to investigate the impact of changes in variables on the cost of energy (COE) because key variables for micro-grid power systems are, however, often uncertain. This needs to be taken into account when designing especially off-grid power systems. The sensitivity entered for this project includes 0% discount rate, assuming that this project would be funded by the state government and money would not be burrowed to realize this project. The sensitivity result (Fig. 3.17) shows that the COE for Koumbogou and Kablive would drop to 0.279$/kWh and 0.272$/kWh respectively if the nominal discount rate is at 0%.

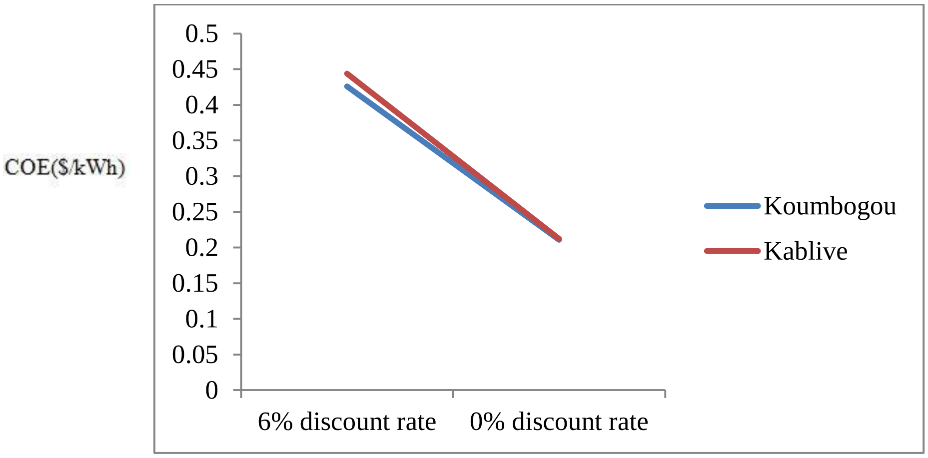


Figure 3. 17. Results of sensitivity analysis based on cost of energy

3.2.4. Conclusion

In this study, it was noted that the average wind speed in Koumbogou and Kablive is below the standard average wind speed of 4 m/s recommended for a wind system. Consequently, a hybrid PV/battery energy system was analyzed and the main findings of the current work are as follows:

- To meet the 84kWh daily load requirement for Koumbogou, analyses of the various system designs recommend a hybrid PV/battery of 24kW PV size and a battery of 200kWh nominal capacity.
- To meet the 390kWh daily load requirement for Kablive, analyses of the various system designs recommend a hybrid PV/battery of 130kW PV size and a battery of 1,230kWh nominal capacity.
- The COE for Koumbogou and Kablive was recorded at 0.4257$/kWh and 0.44374/kWh respectively, based on a nominal discount rate at 6%. With a decrease in the discount rate to 3%, the COE for Koumbogou and Kablive equally decreased to

0.292$/kWh and 0.298$/kWh respectively. This is the rate at which the government of Togo could borrow money to implement the project. However, incase this project is supported by the national government or local government, the COE for both localities would be 0.2112$/kWh and 0.2125$/kWh respectively.

- In case this project is funded by the government of Togo, The COE for both localities are lower than the price of electricity (0.213$/kWh) in Togo.

4. General Conclusion

Togo has abundant solar energy potential but regrettably this resource still remains unexploited leaving most communities either underserved or unserved with electricity. Consequently, these communities greatly rely on fuel wood and diesel for energy. Continuous burning of these fuel does not only emit large amount of GHGs into the atmosphere but also has attendant health effects. Renewable energy can play big role in improving energy access but this energy source has not been reliable due to the seasonal pattern of natural resources. Consequently, connecting a renewable energy system to a grid or developing a hybrid energy system should be considered to take care of this intermittency. Hybrid renewable energy systems have been developed by combining multiple renewable energy resources or a renewable energy resource and a power storage system. In this study, a simple solar technology and a hybrid system have been analyzed in both the Northern and Southern part of Togo. Our results show that Malfakassa , Hahomegbe, Koumbogou and Kablive are feasible for the installation of a solar PV system and a hybrid PV/battery system from all the available indices.

It is suggested that the Togolese government partners with the Rural Electrification Agency (REA) to promote solar energy investment in the localities based on the energy demand of each location. This will promote economic growth in these localities as well as mitigate GHGs emissions resulting from the burning of firewood and diesel for energy. The project is in line with the objectives of the Togolese government, and therefore deserves rapid implementation for the benefit of the targeted villages. The following are the recommendations:

- The deployment of mini-grids and solar kits based on Pay-As-You-Go model in areas with scattered population (Kablive and Koumbogou). Solar kits should include light bulbs, phone charger, radio and TV, etc.
- Raise awareness on the use and acquisition of less energy-intensive equipment while educating them on the cost for every kWh of energy consumed.