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Hybrid off-grid renewable power system for sustainable rural electrification in Benin

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ABSTRACT

Providing power to rural communities, which are far from the grid and suffer from lack of energy access in Africa, especially in Benin, in a sustainable manner requires the adoption of appropriate technology. This paper aims at analysing the techno-economic feasibility of hybrid renewable energy system (HRES) for sustainable rural electrification in Benin, using a case study of Fouay village. HOMER software is used to perform optimization, simulation and sensitivity analysis. The analysis showed that hybrid solar photovoltaics (PV)/diesel generator (DG)/battery (of 150 kW/62.5 kVA/637 kWh) is the least cost optimal system. This system ensures a reliable power supply, reduces battery requirements by 70% compared to PV/battery system and achieves 97% CO_2 emissions reduction compared to a conventional DG. Moreover, the study demonstrated that the most economical HRES depends strongly on the potential energy sources available at a location and power plant's remoteness from the beneficiary. In summary, as solar radiation is an abundant resource across the country, this hybrid PV/DG/battery system can be a suitable model to power remote areas in Benin, and we recommend it for future electrification projects in the country in place of the current widely deployed PV/battery system.

1. Introduction

Access to clean, reliable, and affordable energy services for basic human needs at household level, and productive uses to improve productivity represent the minimum levels required to improve livelihoods in the poorest countries and to drive local economic development on a sustainable basis [1]. This non-access to energy is a major challenge to the African continent, where more than 55% of people do not have access to electricity [2]. At the sub-regional level, Sub-Saharan Africa (SSA) has the largest share of people without access to electricity (62.5%) [3]., Most of that population lives in rural areas that are difficult to access and that are far from the existing power grid [4]. Therefore, the conventional power supply system by grid extension is often economically unviable and unfeasible [5–7]. Increasing worldwide attention to environmental protection, depletion of the conventional energy sources (coal, oil and natural gas) and their increasing cost place renewable energy (RE) at the forefront of the world's energy transition.

In 2016, 62% of added power capacity worldwide was from renewables, with an expected yearly growth rate of about 0.5–1%, which could supply 60% of all our electricity demand by 2050 [8].

Considering the current growth of RE technologies, their decreasing costs and environmental benefits on one hand, and universal access to energy (SDG7) and geographical location of rural dwellers from the main-grid on the other hand, the decentralised energy system (DES) relying on RE offers a unique opportunity to reach the target community in Sub-Saharan Africa. According to the 2017 International Energy Agency (IEA) report, DES will be the most cost-effective solution to provide electricity for 70% of those, who will gain access to electricity in rural areas by 2030 [9].

Nevertheless, in a technological standpoint, the drawback with RE-based DES resides in the intermittent nature of these sources due to weather conditions. Hybrid systems using RE sources together with batteries or a diesel generator (DG) can be used to address the intermittency issues [3]. This mix system is one of the emerging technologies known as hybrid renewable energy system (HRES) to provide a reliable and cost-effective power supply for

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Nomenclature

BGED	Breakeven Grid Extension Distance
BoS	Balance of System
CC	Cycle Charging
COE	Cost of Electricity
DES	Decentralised Energy System
DG	Diesel Generator
DGE	Directorate General for Energy
DNM	National Direction of Meteorology
FCFA	Franc de la Communauté Financière Africaine [French Community of Africa Franc]
HOMER	Hybrid Optimization of Multiple Energy Resources
HRES	Hybrid Renewable Energy System
IRR	Internal Rate of Return
LF	Load Following
LCOE	Levelized Cost of Energy
MV	Medium Voltage
NDR	Nominal Discount Rate
NPC	Net Present Cost
PRODERE	Renewable Energy Development Program
PROVES	Solar Energy Promotion Project
SBEE	Benin Company of Electrical Energy
SHS	Solar Home System
SSA	Sub-Saharan Africa
TOE	Tonnes of Oil Equivalent
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH

communities far from the grid [10,11]. Additionally, HRES on one hand, reduces battery storage and CO_2 emissions [12,13] and on the other hand, increases the energy output of the system [14], which could drive economic development.

1.1. Benin Republic's energy access scenario

Benin Republic is a small country in SSA which extends on a total area of 114,760 km^2 and has a relatively small population of about 10.87 million [15]. Regarding the country's energy sector, more effort is needed to reach the universal energy access goal [16]. Benin Republic currently has one of the lowest national electrification rate in SSA (only about 30.4%), with a strong disparity in favour of urban areas closer to the main grid [17,18]. In rural areas the electrification rate is 6.9% against 54.5% in urban areas [19]. The high investment required to connect rural areas to the national grid as well as the existing low-profit market for the utilities therein are the main reasons that explain such poor grid-extension. Besides, over the last decades, the country's power supply has relied mostly on import, which represents 75–95% of the total electricity supply (Fig. 1). This power comes mainly from neighbouring countries such as Nigeria, Ghana and Togo [19].

However, the country disposes of untapped RE resources, which can serve to improve the demand supply gap and increase the national electricity generation. As an evidence, the average solar radiation across the country varies from 3.9 to 6.1 kWh/m^2/day from the South to the North. The wind speed (at 10 m height) varies from 3 to 5 m/s [17]-thus not quite promising, and theoretical hydropower potential is estimated at 749 MW [16].

The rural communities cannot wait any longer for grid extension projects that are costly and take longer time for implementation. Therefore, isolated mini-grid (cheaper and quick to install) would be a suitable technology to supply power to rural communities in Benin. Conventionally, rural households in the country use DGs to meet their electricity needs. This system of power generation is highly fuel consuming, expensive and highly polluting.

Out of the 12 divisions of Benin, the Alibori division's households have the highest monthly energy expenses for DG [18] and this division has the lowest electrification rate (7.5%) of all divisions (Fig. 2).

Because of its low electrification rate, the Alibori Division should be given special attention by decision makers and investors (public-private). The area has abundant RE potential that is yet to be harnessed such as solar, biomass and small hydropower. Therefore, HRES could be a viable solution to provide sustainable power for the rural communities of Alibori.

This paper purports to bridge a number of knowledge gaps. Although various studies have been conducted on HRES worldwide for rural communities (e.g. Refs. [11,20–26]), to our knowledge no research on the applicability of such system in Benin is reported up to now. Besides, current projects on off-grid rural electrification in Benin, specifically Solar Energy Promotion Project (PROVES) and Renewable Energy Development Program (PRODERE), are based on stand-alone solar PV/battery only. Such a combination makes the

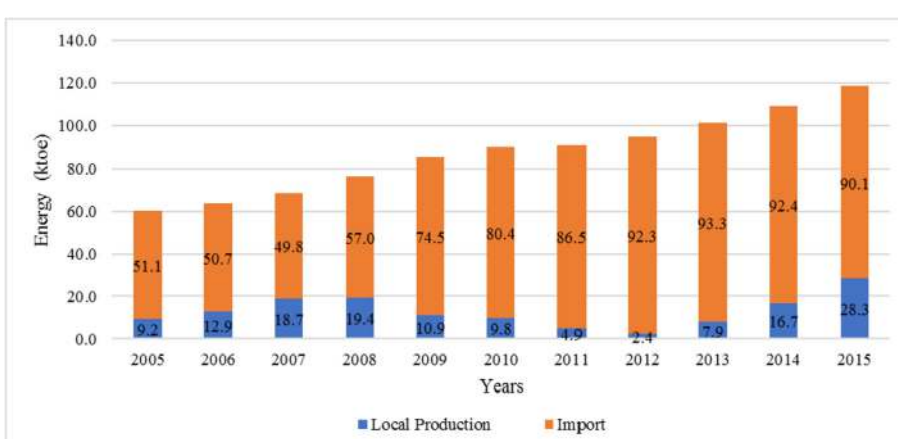

Fig. 1. Benin's electricity supply (2000–2015): national production vs. import [19].

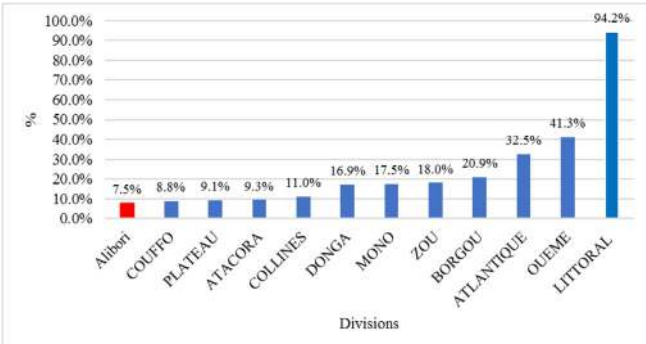

Fig. 2. Electrification rate by division in Benin [19].

overall cost high due to a big battery storage required to ensure reliable power supply. Furthermore, these plants provide a limited power supply, which covers only basic household needs (lighting). And this sense of "inferior" or "temporary" nature of these solutions reduces their acceptability and attractiveness [27]. Thus, upgrading the plant's capacity to allow the community to drive productive activities for income generation have to be taken into account because it plays a key role in the socio-economic status improvement. This will also contribute to refrain the migration of poor rural people to urban areas through local jobs and businesses creation. Likewise, some social infrastructures like health centres, schools, local administration offices, and worship places, which play a predominant role in society, need electric power. Consequently, power plant to be installed should be appropriately designed to cover the needs of the community in order to ensure sustainable electrification and livelihood improvement. Some authors [7] have already warned that off-grid RE technologies do little to significantly improve living standards unless they also enable income generation. Therefore, energy for productive activities should be prioritised.

In this context, this paper seeks to address the above issues by discussing the techno-economic feasibility of HRES for sustainable rural electrification in Benin, especially in the underprivileged regions of the country, namely the Alibori division. A specific case study of the village of Fouay is assessed. Special attention is given to the load demand assessment by considering the commercial and community loads too, particularly the socio-community infrastructure services.

The paper is organised as follows: section 1 discusses the general background of the study and Benin Republic's energy supply scenario. Section 2 describes the study area. Section 3 details the modelling aspect in HOMER. Section 0 presents the results of the techno-economic analysis. And conclusions are drawn in section 5 with some recommendations.

2. Study area

2.1. Site description

Fouay is a remote village in Alibori division in Benin Republic, geographically located at 11.3°N and 3.17°E (273 m above the sea level). According to 2013 census, it counts 333 households with 3060 inhabitants [28]. The population ratio of male/female is 51%/49% in 2013 [28], with an annual population growth rate of 3.5%. Agriculture is the main occupation. The climate of the region is characterized by two regular seasons: the rainy season from June to October and the dry season from November to May. The annual average precipitation is 963.7 mm and the average temperature is 27.5 °C [19]. The village is yet to be connected to the power grid of the Electrical Energy Company of Benin (SBEE) [29]. Current sources of lighting in the village are DGs, small solar home systems (SHSs), batteries, candles and kerosene lamps. The distribution in households in the village is shown in Fig. 3.

2.2. Electrical demand assessment

The electricity demand assessment was conducted based on an onsite survey in the village. An adapted version of the standard load assessment questionnaire developed by a GIZ program was adopted [30]. The survey sample was comprised of 50 households selected randomly; six business (shops) owners and all the community socio-services (health centre, worship places and school). In addition, potential future community services and commercial loads were added based on the high interest expressed by individuals during the survey. It consisted of electric flour mill, soldering unit and water pumping system. An initial assumption was made that the sample size represents and describes the population well. The sample household load is used to derive the village total household demand using the cross-product method based on the ratio sample size to population. Lighting, radio and phone charging drive household's main electricity consumption.

The village load demand is classified into three main categories: household load, community load and commercial load. The demand varies from one period to another depending on the usage of particular appliances. Three sets of assumptions have been made to capture the seasonal load variation: summer, winter low and winter high (Table 1). The seasonal loads are water pumping, school and fans. The daily electrical demand per category and season is illustrated in Table 2.

Daily demand of Fouay during summer and winter low season is

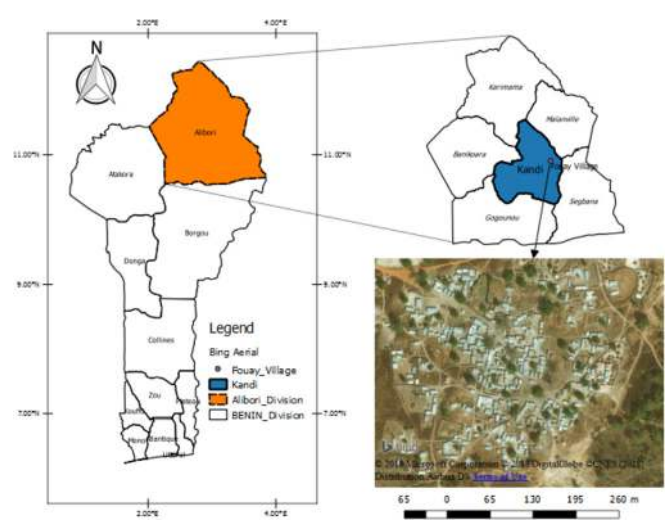

Fig. 3. Study area map.

Table 1
Seasonal load variation assumptions.

Season	Assumptions
Winter low	- No use of fans - Schools load: only lightning (vacation) - Water pump: 5 h of working hours
Winter high	- No use of fans - Water pump: 5 h of working hours
Summer	- Normal usage for all appliances - Water pump: 10 h of working hours

Table 2
Demand per category and season.

Load categories	Loads	Summer (Nov–May) kWh/day	Winter high (Jun–July) kWh/day	Winter low (Aug–Oct) kWh/day
Household load	Radio	62.7	62.7	62.7
	TV	45.0	45.0	45.0
	DVD	1.7	1.7	1.7
	Phone	35.5	35.5	35.5
	Fan	5.1	0.0	0.0
	Fridge	9.2	9.2	9.2
	Light	213.8	213.8	213.8
	Total (kWh/day)	372.9	367.9	367.9
Community load	Worship places	4.0	4.0	4.0
	School	2.8	2.0	0.6
	Health centre	6.2	6.2	6.2
	Street light	8.4	8.4	8.4
	Water pump	22.0	11.0	11.0
	Hall	1.4	1.4	1.4
	Total (kWh/day)	44.7	32.9	31.5
Commercial load	Small business centre	10.3	10.3	10.3
	Village store	0.7	0.7	0.7
	Barber + tailor shops	5.7	5.7	5.7
	Printer shop	0.7	0.7	0.7
	Flour mill + solder	252.0	252.0	252.0
	Total (kWh/day)	269.4	269.4	269.4
Daily load (kWh/day)		687.1	670.2	668.8

displayed respectively in Fig. 4 and Fig. 5. Detailed descriptions of the different categories of load during summer for each time segment are provided in Table 3, Table 4 and Table 5. In all seasons, three major daily peak loads are observed. First, an early peak demand at around 6 a.m. as a result of the inhabitants' behaviour in the morning by turning on lights and preparing for the day. Second, the midday peak load is dominated by commercial load. At this time, heavy appliances like flour mill and soldering engine are activated. Third, is the evening peak load, where the highest demand (51.7 kW) of the day is recorded from 7:00–8:00 p.m. This peak demand is due to a high proportion of the inhabitants' presence at home, back from their daily activities.

2.3. Resources assessment

In this study, solar, wind, and hydro are considered as the primary RE sources. Solar radiation and the wind speed are obtained from the nearest synoptic station of Kandi located at 11°08′ N and 02°56' E. The river stream flow data for gauged stations surrounding the hydropower site is obtained from the National Direction of Water Resources (DGEau).

2.3.1. Solar radiation

Daily average solar radiation data over 16 years collected at Kandi station was used. The location receives high solar radiation ranging from 5.67 to 9.48 kWh/m^2/day, with an annual average of 7.88 kWh/m^2/day. The solar peak months of the year are November and December as shown in Fig. 6.

2.3.2. Wind

The wind speed at the location is measured at 10 m height and is very weak varying from 1 to 2.26 m/s. Therefore, wind power potential is not sufficient and will not be considered further in designing the power system to electrify the village of Fouay.

2.3.3. Hydropower

The village of Fouay is 11 km far from the potential hydro site of “Cascade de Sosso” found among the locations as suitable for micro-hydro power plant. The hydropower site is located at Sota River, a tributary of Niger River, with a catchment area at the dam axis of 10,975 km^2. The total proposed power is about 494 kW (2 turbines of 247 kW each) [31]. No stream flow data and direct measurement are available at the site. Therefore, an estimation

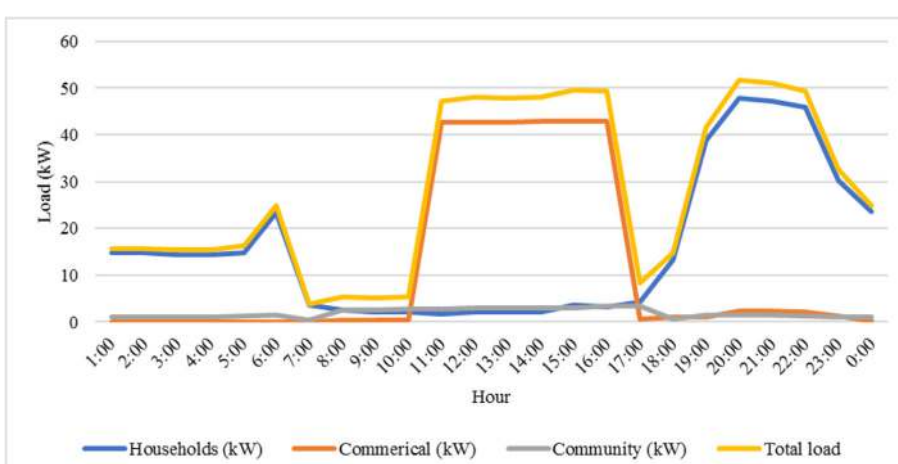

Fig. 4. Daily load profile – summer.

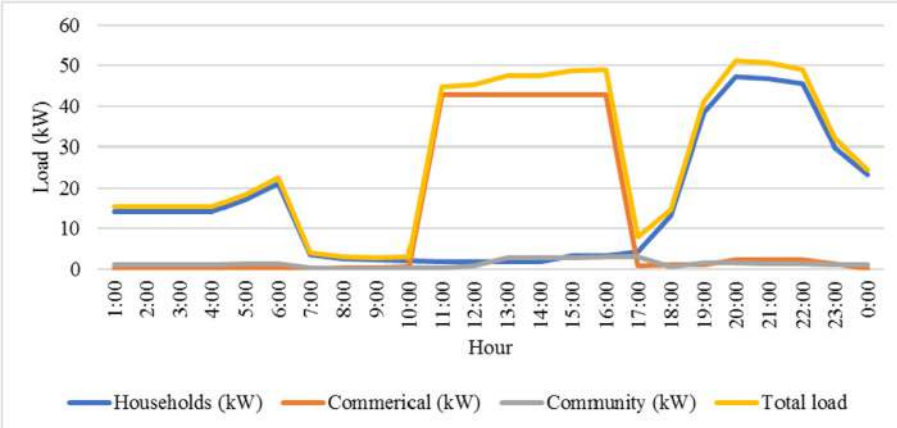

Fig. 5. Daily load profile - winter low.

Table 3
Estimated household load in Summer.

Time	Household load (383)							Total
	Radio (30 W)	TV (120 W)	DVD (24 W)	Phone (5 W)	Fan (55 W)	Fridge (100 W)	Light (3 W/10 W)	
1:00				0.27	0.42		14.0	14.68
2:00				0.27	0.42		14.0	14.68
3:00				0.27			14.0	14.26
4:00				0.27			14.0	14.26
5:00				0.27			16.8	17.11
6:00	1.61			1.23			18.3	21.17
7:00	1.61			1.23			0.8	3.60
8:00	1.61			0.84				2.45
9:00	1.15			1.03				2.18
10:00	1.38			0.77				2.14
11:00	0.23			0.77		0.77		1.76
12:00	0.23			0.77	0.42	0.77		2.18
13:00	0.23			0.77	0.42	0.77		2.18
14:00	0.23			0.77	0.42	0.77		2.18
15:00	0.23			2.18	0.42	0.77		3.60
16:00	0.23			2.18		0.77		3.18
17:00	0.23			3.22		0.77		4.21
18:00	7.74			4.71		0.77		13.21
19:00	10.88		0.15	4.79	0.42	0.77	21.8	38.84
20:00	10.88	9.19	0.34	3.45	0.42	0.77	22.8	47.80
21:00	10.88	9.19	0.34	2.95	0.42	0.77	22.8	47.30
22:00	10.88	9.19	0.34	1.53	0.42	0.77	22.8	45.88
23:00	2.45	9.19	0.34	0.57	0.42		17.4	30.33
0:00		8.27	0.18	0.42	0.42		14.4	23.68
Total (kWh/day)	62.66	45.04	1.69	35.50	5.06	9.19	213.78	372.91
%	17%	12%	0%	10%	1%	2%	57%	100%

method was adopted. According to the World Meteorological Agency (WMO), the flow rate at ungauged sites can be estimated using one of three methods: empirical, statistical and rainfall-runoff modelling [32]. The empirical one has been used here due to data availability and time constraints. The method consists of transposing gauged stream flow data from an analogue catchment using the following equation [32,33]:

$$QX_t = fn(A_T/A_A)*QX_A \tag{1a}$$

Where: QX_t is flow in the target ungauged catchment of the power plant; QX_A is corresponding flow in the analogue catchment A; A_T is catchment area for the power plant site; A_A is catchment area for the analogue catchment; fn is scaling constant or a function.

Out of three-gauged stations surrounding the hydropower site, only two analogue gauged stations (Gbasse and Couberi) were finally considered. Gbasse gauged station which is located at the upstream and the Couberi station is at the downstream of the ungauged catchment (Fig. 7) with an area respectively of 8300 km^2 and 13,410 km^2. Both stations considered are located at the same Sota River, with same vegetation zone and have same rainfall trends. Therefore, the scaling factor (fn) is taken as 1. The stream flow at the location is given by the average estimation values of each analogue station considered. Fig. 8 displays the estimated monthly stream flow rate at Cascade de Sosso. The flow is available throughout the year, with an average annual value of 31 m^3/s.

2.4. Modelling of the hybrid renewable energy system

2.4.1. HRES modelling approach

Hybrid Optimization of Multiple Energy Resources (HOMER) software was used for the modelling of HRES in this study. HOMER Pro version 3.9.2 is used for this assessment. HOMER is the global standard for design in all sectors and has been used for various

Table 4
Estimated community load in Summer.

Clients	Central +3 small mosques		Church		School (4 classrooms)					Health centre						Street light	Water pump	Hall (3 rooms)		Total kWh/day
Appliances	Light	Fan	Light	Fan	TV	Light	Radio	Phone	PC	TV	Light	Radio	Phone	Fan	Fridge	Light	Motor	Light	Fan	
Power (W)	10	75	10	75	120	10	30	5	120	120	10	30	5	75	120	70	2200	10	75	
Number	24	2	4	1	1	8	1	5	1	1	15	1	5	2	1	10	1	5	2	
No of hours	16	5	12	4	5	17	10	6	8	8	12	10	6	6	16	12	10	16	6	
1:00	0.07		0.04			0.03					0.15					0.7		0.03		1.02
2:00	0.07		0.04			0.03					0.15					0.7		0.03		1.02
3:00	0.07		0.04			0.03					0.15					0.7		0.03		1.02
4:00	0.07		0.04			0.03					0.15					0.7		0.03		1.02
5:00	0.24		0.04			0.03					0.15				0.12	0.7		0.03		1.31
6:00	0.24		0.04			0.05	0.03				0.15	0.03			0.12	0.7		0.03		1.39
7:00	0.15						0.03					0.03			0.12					0.33
8:00							0.03	0.025	0.1			0.03	0.025		0.12		2.2			2.55
9:00							0.03	0.025	0.1			0.03	0.025		0.12		2.2			2.55
10:00					0.1		0.03	0.025	0.1	0.12		0.03	0.025		0.12		2.2			2.79
11:00					0.1				0.1	0.12					0.12		2.2			2.68
12:00		0.2							0.1	0.12				0.2	0.12		2.2		0.15	3.01
13:00		0.2								0.12				0.2	0.12		2.2		0.15	2.89
14:00		0.2				0.05				0.12				0.2	0.12		2.2		0.15	2.94
15:00					0.1	0.05			0.1	0.12				0.2	0.12		2.2	0.03	0.15	3.06
16:00	0.15	0.2			0.1	0.05			0.1	0.12				0.2	0.12		2.2	0.03	0.15	3.36
17:00	0.15	0.2			0.1	0.05		0.025	0.1	0.12			0.025	0.2	0.12		2.2	0.03	0.15	3.41
18:00	0.15					0.05	0.03	0.025			0.15	0.03	0.025		0.12			0.03		0.61
19:00	0.24		0.04	0.08		0.08	0.03	0.025			0.15	0.03	0.025		0.12	0.7		0.03		1.55
20:00	0.24		0.04	0.08		0.08	0.03				0.15	0.03			0.12	0.7		0.03		1.50
21:00	0.24		0.04	0.08		0.08	0.03				0.15	0.03				0.7		0.03		1.38
22:00	0.24		0.04	0.08		0.03	0.03				0.15	0.03				0.7		0.03		1.33
23:00	0.07		0.04			0.03					0.15					0.7		0.03		1.02
0:00	0.07		0.04			0.03					0.15					0.7		0.03		1.02
Total (kWh/day)	3.21		0.78		2.79					6.18						8.40	22.00	1.38		44.74
%	7%		2%		6%					14%						19%	49%	3%		100%

Table 5
Estimated commercial load in Summer.

Customer	Shops						Store	Printer service (1)			Tailor (3)	Barber (3)	Flour mill (5)	Solder machine (1)	Total (kWh)
Appliances	Fan (55 W)	Light (3 W/10 W)	Radio (30 W)	Phone (5 W)	CD player (24 W)	Fridge (100 W)	Light (10 W)	Copier (35 W)	Computer (120 W)	Light (10 W)			Motor (7500 W)	Motor (4500 W)	
Watts	165	145	90	450	48	100	100	35	120	20	435 W	987 W	37500	4500	
1:00		0.018					0.03								0.05
2:00		0.018					0.03								0.05
3:00		0.018					0.03								0.05
4:00		0.018					0.03								0.05
5:00		0.018					0.03								0.05
6:00		0.015					0.03								0.05
7:00															
8:00			0.03	0.3	0.024										0.35
9:00			0.03	0.3	0.024										0.35
10:00			0.06	0.3	0.024						0.09				0.47
11:00			0.06	0.3	0.024	0.1					0.21		37.5	4.5	42.69
12:00	0.11		0.06	0.3	0.024	0.1					0.21		37.5	4.5	42.80
13:00	0.11		0.06	0.3	0.024	0.1					0.21		37.5	4.5	42.80
14:00	0.165		0.09	0.45	0.048	0.1							37.5	4.5	42.85
15:00	0.165		0.09	0.45	0.048	0.1							37.5	4.5	42.85
16:00	0.165		0.09	0.45	0.048	0.1							37.5	4.5	42.85
17:00			0.09	0.45	0.048	0.1									0.69
18:00			0.09	0.45	0.048	0.1	0.1	0.035	0.12	0.02					0.96
19:00		0.115	0.09	0.45	0.048	0.1	0.1	0.035	0.12	0.02	0.06				1.14
20:00		0.145	0.09	0.45	0.048	0.1	0.1	0.035	0.12	0.02	0.315	0.987			2.41
21:00		0.145	0.06	0.45	0.048	0.1	0.1	0.035	0.12	0.02	0.315	0.987			2.38
22:00		0.145	0.06	0.45	0.048	0.1	0.03		0.02	0.02	0.315	0.987			2.18
23:00		0.122			0.048		0.03					0.987			1.19
0:00		0.084			0.024		0.03								0.14
Total (kWh/day)	0.715	0.861	1.05	5.85	0.648	1.2	0.67	0.14	0.5	0.1	1.725	3.948	225	27	269.41

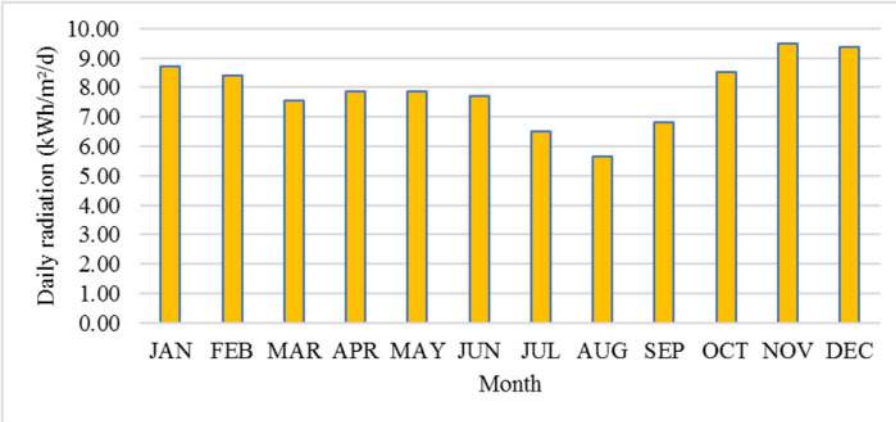

Fig. 6. Average daily solar radiation in different months.

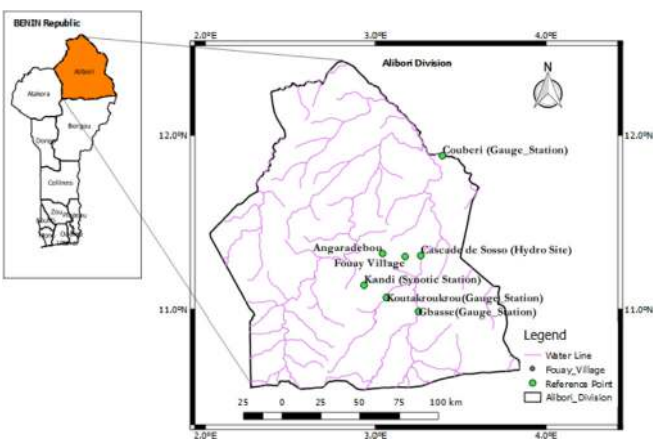

Fig. 7. Geographical location of Gauge stations.

studies worldwide for evaluating designs of both off-grid and grid-connected power systems [13,34–38]. Compared to the other similar software computing techniques such as RETScreen, PVSOL, Hybrid2, TRANSYS, SAMS, RAPSYS and MATLAB, it presents some unique features such as the wider scope of renewable resources input and their possible combinations over varying constraints and the greater selection of system architecture and dispatch [39,40]. HOMER is the most flexible software in terms of systems that can simulate, give more detailed information and perform sensitivity analysis with limited input [41,42]. It performs three principal tasks (simulation, optimization and sensitivity analysis) while suggesting the suitable systems design [36]. It suggests the best-optimised model design based on Net Present Cost (NPC) considering the given inputs. It simulates the operation of a system by making energy balance calculations for each of the 8760 h in a year. It then determines whether a configuration is feasible and estimates the cost of installing and operating the system over the lifetime of the project [35].

The total NPC is HOMER's main economic output, the value by which it ranks all system configurations in the optimization results, and the basis from which it calculates total annualized cost and levelized cost of energy (LCOE) [34,43]. The calculation is done as follows [44]:

$$C_{NPC} = C_{ann,tot} / (CRF(i, R_{proj})) \tag{1b}$$

Where, $C_{ann,tot}$ is total annualized cost, i is annual real interest rate (discount rate), R_{proj} is project lifetime, and CRF (i, N) is capital recovery factor. The capital recovery factor is calculated using the equation:

$$\mathrm{CRF}_{(i,N)} = i(1+i)^N \Big/ \left((1+i)^N - 1\right) \tag{1c}$$

Where, N is number of years and i is annual real interest rate. Drop of interest rate causes reduction of CRF and leads to bigger NPC [14]. HOMER defines the LCOE as the average cost per kWh of useful electrical energy produced by the system and uses the following

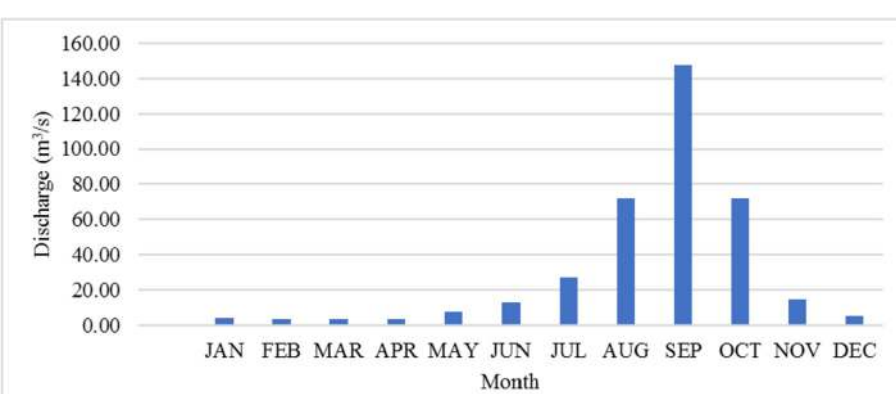

Fig. 8. Monthly streamflow (m^3/s) rate at "Cascade de Sosso"

equation for calculating it:

$$COE = \left(C_{ann,tot} - C_{boiler}E_{thermal}\right) \Big/ \left(E_{primm,AC} + E_{prim,DC} + E_{grid}\right) \quad (2)$$

Where $C_{ann,tot}$ is total annualized cost of the system ($/yr), C_{boiler} is marginal cost of boiler ($/kWh), $E_{thermal}$ is total thermal load served (kWh/yr), $E_{primm,AC}$ is total primary load (kWh/yr), $E_{prim,DC}$ is total DC primary load (kWh/yr), E_{grid} is total grid sales (kWh/yr).

Grid extension analysis is performed using the advanced grid module of HOMER, which compares the costs of grid extension with the cost of optimised stand-alone system and provides results in form of breakeven grid extension distance (BGED). The BGED is the distance from grid at which the total NPC of grid extension is equal to the total NPC of stand-alone system. The equation used to calculate BGED is as follows:

$$D_{grid} = \frac{C_{NPC}.CRF(i, R_{proj}) - c_{power}.E_{demand}}{c_{cap}.CRF(i, R_{proj}) + c_{om}} \quad (3)$$

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

2.5. Modelling in details

2.5.1. Components schematic

In this study, both renewable (solar and small hydropower) and non-renewable (DG) energy sources are considered. The battery plays a role of the storage unit. Since there are AC and DC components, the converter is added to serve as an interface between two currents, which will help first supply the AC load and then charge the batteries. Grid module present in the modelling serves to make a comparative analysis with the stand-alone system. The hybrid system model schematic in HOMER is presented in Fig. 9.

2.5.2. Resource and load inputs

The monthly average solar radiation over 16 years (2000–2016) and monthly average stream flow (annual average of 31 m^3/s) of 26 years (1953–2012) as shown in sections 2.3.1 and 2.3.3, respectively, are entered in resource tab in HOMER. One-year hourly demand including seasonal variation as explained in section 2.2 is imported into the software.

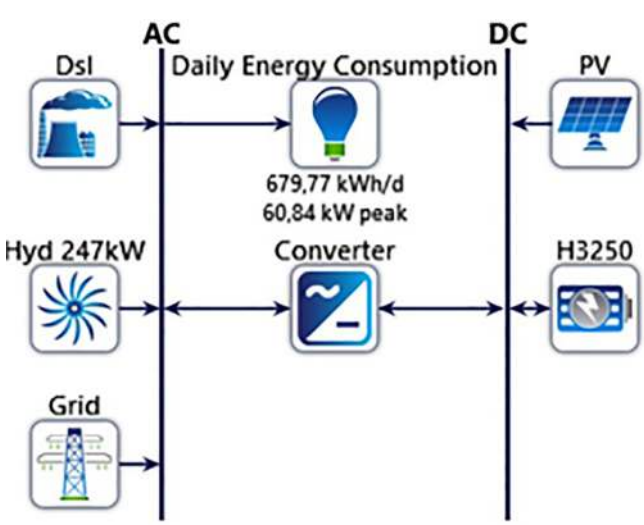

Fig. 9. Schematic of the proposed system in HOMER.

2.5.3. Components cost and performance characteristics

Table 6 shows the components cost summary including the capital, O&M, replacement costs and specifications (capacity and lifetime).

2.5.3.1. Diesel generator. DG capital cost includes the acquisition cost, which is obtained from local Benin market distributors, plus the transportation cost estimated at 200,000 FCFA (equivalent to $363). Bertoli Brand generators of 24, 40 and 48 kW capacity plus the transportation cost in the market would add up respectively to 11,120,115 FCFA ($20,545), 12,354,520 FCFA ($22,419) and 14,892,495 FCFA ($27,024), as presented in Table 6. The price per kW is calculated from the average unit price inferred by each generator cost and was obtained at $660/kW. The replacement cost is considered unchanged and the O&M is equal to 3% of the capital cost. The current diesel price is $0.8/l, and the minimum load ratio is set to 30%. The optimised capacities are: 0, 40, 45, 50, 60, 70, and 80 kW.

2.5.3.2. Hydropower. For this study, only one turbine scenario is considered in the simulation with design stream flow of 4500 m^3/s, a minimum flow ratio of 50% and a maximum of 105%. Pipe loss is set at 15%, 80% for efficiency and electricity production from hydro is through AC. The hydropower site is 11 km far from the village of Fouay. Therefore, grid extension cost is added to that of the plant. The extension cost comprises the costs of Medium Voltage (MV) line, transformers, protection devices and other hardware.

Table 6
Components costs.

Description	Specification
1. PV system [45]	
Capacity (kW)	1 kW, 10 kW
Capital ($)	2000, 11000
Replacement cost ($)	2000, 11000
O&M cost ($/yr)	40/220
Lifetime (years)	25
2. Inverter [45]	
Capacity (kW)	1
Capital ($)	1000
Replacement cost ($)	1000
O&M cost ($/yr)	20
Lifetime (years)	15
3. Diesel Generator [45]	
Capacity (kW)	1, 24, 40, 48
Capital ($)	660, 20542, 22419, 27024
Replacement cost ($)	660, 20542, 22419, 27024
O&M cost ($/hr)	0.03, 0.72, 1.2, 1.44
Lifetime (hours)	15000
4. Hydro [31,46,47]	
Capacity (kW)	247
Capital ($)	656287
Replacement cost ($) [47]	123500
O&M cost ($/yr)	19689
Lifetime (years)	30
5. Battery [48]	
Quantity	1, 24
Capital ($)	1000, 23947
Replacement cost ($)	1000, 23947
O&M ($/yr)	20, 479
Lifetime (years)	20
6. Grid [46,49]	
Capacity cost ($/km)	15500
O&M cost ($/yr/km)	310
Grid power price ($/kWh)	0.22

2.5.3.3. Solar PV. PV cost includes the module cost and the balance of system (BoS) cost excluding battery and inverter. The module prices are obtained at the local market. Temperature effects on the PV modules are modelled in HOMER by importing 2000–2016 monthly average temperatures. PV array sizes of 0, 50, 100, 125, 150, 200, 260, 300, 500 and 700 kW are considered.

2.5.3.4. Inverter. Inverters of 0, 5, 10, 25, 50, 60, 65 and 75 kW sizes are considered in search space in HOMER tab. A 5 kW inverter of Victron Brand costs 2,500,000 FCFA (equivalent to $940/kW) in the market in Benin. It is rounded to $1000/kW to consider the installation costs.

2.5.3.5. Battery. Hoppecke OPzS batteries of 3250 Ah/2 V types are used for this study with throughput of 10,118.30 kWh. The minimum state of charge is 30% and the initial is 100%. The cost of the battery is obtained from solar systems market [48].

2.5.4. Project economics

The main economic variables are nominal discount rate (NDR) set to 10%, expected inflation rate at 2% and project lifetime is 25 years.

2.5.5. System operational control and strategies

For this analysis, consideration was given to both the Load Following (LF) and the Cycle Charging (CC) dispatch strategies. In LF strategy, the generators will only produce enough power to meet the demand when operational. Meanwhile, in CC strategy, the generators will operate at full capacity and excess power will be used to charge the battery bank [50].

2.5.6. Sensitivity variables

Sensitivity analysis permits to monitor the effects of certain variables on the techno-economic analysis. Different values are assigned to these variables within a given range in order to assess their influence on the optimised system.

According to the different scenarios in the master plan of electrification, the village is supposed to be electrified in high, medium and low scenarios through grid extension by 2018, 2033 and 2032, respectively [46]. However, with regards to current situation of the nearest town where grid is yet to be connected, the electrification scenario of 2018 in the village is improbable. Therefore, more optimistic scenarios will be to consider the projection in 2032 or above. In that perspective, two project lifetimes were considered: 15 years (justifying low and medium scenario of [46]) and 25 years (average operative lifespan for RE projects). This will help to observe if the optimised system is more cost-effective than the grid extension or not at any of these project lifetimes. Various values of annual stream flow are simulated as it varies considerably throughout the year.

In addition to project lifetime and annual stream flow, the sensitivity analysis is defined for annual average demand, diesel price and annual interest rate. Table 7 presents the sensitivity variables considered. However, no sensitivity analysis is performed on solar radiation because of its low significant changes observed on the 16 years dataset.

Table 7
Sensitivity variables.

Sensitivity variables	Values
Diesel fuel price (DFP) ($/l)	0.8, 0.95, 1
Load growth (kWh/day)	679,750, 850
Interest rate (IR) (%)	8, 9,10
Annual average stream flow (m^3/s)	21, 31, 70
Project lifetime (years)	15, 25

3. Results and discussions

3.1. Optimization results

Optimization output is categorized into three parts comprising the architecture(s), costs and some system variables as shown in Table 8. Optimal controller strategy varies from one configuration to the other, either CC or LF. Out of 13-optimal sizing configurations, six are closely analysed, namely: PV/DG/battery, PV/hydro/DG, hydro/DG, PV/battery, hydro and DG as highlighted in Table 8 and presented in Table 9. The initial simulation conditions are: load demand = 679 kWh/day, DFP = $0.80/l, IR = 10%, stream flow = 31 m^3/s and project lifetime of 25 years.

Based on these conditions the hybrid PV/DG/battery is the least cost system with $555,492 NPC among the system architectures. This system comprises solar PV of 150 kW, DG of 50 kW, 98 Hoppecke batteries of 3250 Ah/2 V, 60 kW converter and LF as dispatch strategy. The COE, initial capital cost, O&M cost are respectively $0.207/kWh, $332,369 and $20,623 (Table 8). It is worth noting that these different costs do not include any subsidies or other funding.

The PV/DG/battery system is more cost-effective than grid extension because its COE of $0.207/kWh is lower than the national grid electricity tariff ($0.22/kWh). It has a BGED of −1.86 km, which is shorter than the village's distance to the next grid (15 km). Compared to an only PV/battery, the PV/DG/battery system reduces battery storage by 70%, therefore lowering the NPC. Since battery is one of the costliest components in a standalone PV system, the proposed hybrid system is a viable solution to minimise its cost by backing up with DG. From a technical point of view, PV/DG/battery provides a reliable power supply with 100% met load and generates the lowest excess electricity of 7.7% compared to the other configurations. From an environmental standpoint, it produces 9590 kg/yr of CO_2 emission, which is not that significant. Its CO_2 emission is about 3% of the total CO_2 emission of a standalone DG system. The renewable energy penetration in the system is as high as 96.7%.

Aside the PV/DG/battery, the next best hybrid system is hydro/DG system with an NPC, initial investment and COE of respectively $885,302, $678,706 and $0.33/kWh. Compared to PV/DG/battery system it has lower O&M cost of $19,095. Although hydropower has the lowest COE ($0.0452/kWh), overall COE of hydro/DG system is higher than the tariff of the main grid. This is due to the additional costs for extending the generated power to the village. Furthermore, the BGED is 15.63 km, slightly higher than 15 km, which makes grid extension a little bit more cost effective than the hydro/DG system. Nevertheless, with regard to the high renewable energy fraction, and especially the quality of power supply with 0% unmet load, hydro/DG system remains more viable than grid extension where an interrupted power supply is not necessarily secured. DG as a backup will ensure that the load is always met even during low stream flow periods and therefore makes it a more secure system than stand-alone PV/hydro.

Based on the optimization results, one can summarize that PV/DG/battery and hydro/DG are the best hybrid systems viable to power the village of Fouay. PV/DG/battery is the most cost-effective system. It provides more reliable power compared to PV/battery and is more environment friendly than DG. Hydro/DG system provides secure power than stand-alone hydro. PV/hydro is disregarded because grid extension appears to be cheaper over this option.

3.2. Sensitivity analysis

Sensitivity analysis has been performed considering the variables listed in Table 7. In all the cases, PV/DG/battery appeared to be the most optimal system with the least NPC to meet demand

Table 8
Optimization results by category.

Rank	Architecture						Costs			System		
	PV (kW)	Diesel (kW)	H3250	Hyd (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	O&M cost ($)	Ren frac. (%)	Excess elect. (%)	CO_2 (kg/yr)
1	150	50	98		60	LF	0.207	555492	20623	96.7	7.7	9590
2	200		328		60	CC	0.286	766965	16518	100	28.6	0
3				247		CC	0.323	866193	19401	100	86.0	0
4			5	247	5	CC	0.328	880240	19776	100	86.0	0
5		40		247		CC	0.330	885302	19095	100	86.0	0
6		40	5	247	5	CC	0.335	899349	19470	100	86.0	0
7	50			247	5	CC	0.349	935669	20647	100	86.7	0
8	50		1	247	5	CC	0.349	936993	20676	100	86.7	0
9	50	40		247	5	CC	0.356	954778	20341	100	86.7	0
10	50	40	1	247	5	CC	0.356	956102	20371	100	86.7	0
11	170	60			60	CC	0.378	1.01$M	70120	42.1	47.1	157355.5
12		50	17		25	CC	0.390	1.05$M	90806	0	0.0	230508
13		60				CC	0.487	1.31$M	118555	0	10.5	293139.5

Table 9
Optimization results-sub-category.

System	COE ($)	NPC ($)	O&M cost ($)	Initial capital ($)	Ren frac (%)	Excess elec (%)	Unmet load (%)	CO_2 (kg/yr)	BGED (km)
PV/DG/battery	0.207	555492	20623	332369	96.7	7.7	0	9590	−1.87
PV/battery	0.286	766965	16518	588247	100	28.6	0	0	9.36
Hydro	0.323	866193	19401	656287	100	86	0	0	14.62
Hydro/DG	0.33	885302	885302	19095	100	86	0	0	15.63
PV/hydro	0.349	935669	935669	20647	100	86.7	0	0	18.3
DG	0.487	1.31$M	0.487	1.31$M	0	10.5	0	293139.5	38.02

(Fig. 10). It can be seen from Fig. 10 that, the COE decreases from $0.207/kWh to $0.205/kWh as the demand increases from 679 to 850 kWh/day. When the fuel price increases [0.8–1] $/l the COE tends to slightly increase up to a maximum of $0.210/kWh, which is still below the national grid tariff. Thus, it can be concluded that changes in fuel price and an increase in demand will not affect the profitability of the system. When decreasing the NDR, the COE decreases down to $0.188/kWh, but the NPC increases (Fig. 11).

Sensitivity analysis performed on various river stream flows revealed that PV/DG/battery is still the least cost system followed by hydro/DG. Nevertheless, hydro/DG could be cheaper than PV/DG/battery system and even more cost-effective than grid extension if demand is high enough and hydropower plant is not far from the village. For demand of 850 kWh/day, COE would be $/0.264 kWh and $0.301/kWh, while BGED would be 7.79 km and 14.44 km for stream flow values of respectively 31 m^3/s and 21 m^3/s (Table 10). When considering 15 years as project lifetime, PV/DG/battery system remains the most cost-effective to meet load and is economically more viable than a grid extension scenario as the BGED is below 15 km (Table 11).

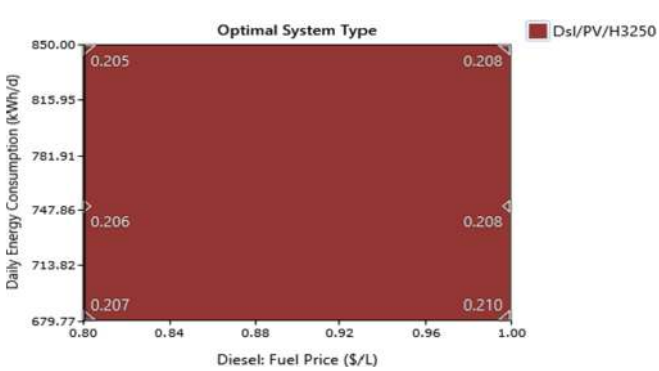

Fig. 10. Sensitivity analysis: diesel price vs. load growth, NDR = 10%, project lifetime = 25 years.

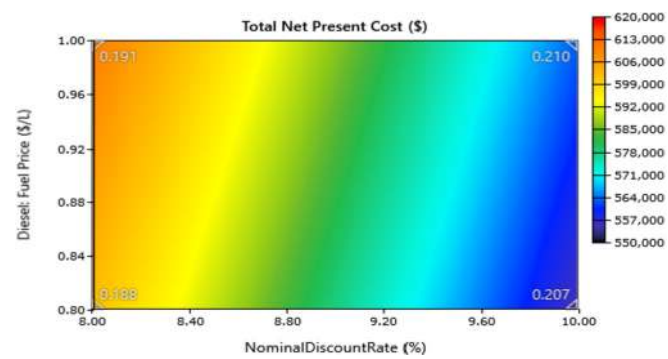

Fig. 11. Surface plot: net present cost, superimposed: cost of energy.

3.3. Optimal hybrid system: simulation results

Optimal hybrid system from the analysis performed above shows that PV/DG/battery is the best system to power the village over the different sensitivity analysis cases. The proposed system architecture remains the same (150 kW PV, 50 kW DG and 98 batteries of 3250 Ah/2 V). PV panels dominate the electricity production (97.3%), whereas DG accounts for 2.66%. DG will serve as a backup during the dominant part of rainy season when cloud coverage is intense from July to September (peaks during August) and some also in March (Fig. 12). Expected battery life is 7.10 years with an autonomy of 15.7 h. Discharge of the battery occurs during the early morning and at night (peak load periods) while they are recharged in-between periods as represented in Fig. 13.

The system's electricity production during a day in a cloudy month (eg. August) and in summer (eg. November) is presented in Fig. 14 and Fig. 16 respectively. As shown in Fig. 14, DG operates late in the evening as well as in the early morning (22:00-midnight and 3:00–7:00 a.m.) during winter to meet the peak demand and also

Table 10
Hydro/DG optimization results-increased load and variable stream flow.

Load (kWh/day)	Stream flow (m^3/s)	Hydro (kW)	DG (kW)	NPC ($)	COE ($/kWh)	BGED (km)
680	31	247	40	885302	0.328	15.63
680	21	247	60	994071$	0.336	18.16
680	70	247	40	885302	0.33	15.63
850	31	247	40	885302	0.264	7.79
850	21	247	70	1.01$M	0.301	14.44
850	70	247	40	885302	0.264	7.79

NDR = 10%, DFP = 0.8 $/l.

Table 11
Optimal system for different project lifetime, diesel fuel price (DFP).

Architecture	Project lifetime	DFP ($/l)	Load (kWh/day)	NPC ($)	COE ($/kWh)	CO_2 (kg/yr)	BGED (km)
PV/DG/battery	15	0.8	680	459941	0.212	9447	−0.92
	15	1	680	460994	0.215	9021	−0.59
	25	0.8	680	555492	0.207	9590	−1.87
	25	1	680	563571	0.21	9447	−1.43

NDR = 10%.

to recharge the batteries. PV panels generate power from 6 a.m. to 7 p.m. to meet the mid-day load and the excess power generated is used to charge the battery (Figs. 14 and 15).

In contrast to winter, no power output from DG is observed in summer, as shown in Fig. 16. This is due to high PV power production, -a consequence of the high incident radiation received (less cloud coverage). As a matter of fact, peak PV power production in winter is 90 kW, while it is 112 kW in summer (Figs. 14 and 16). Therefore, batteries are charged enough from the surplus power from PV (Fig. 17) to meet load at times with no PV output (Fig. 16). Hence no power from DG is required.

Solar PV's total electricity production is 296,918 kWh/yr with operating hours of 4380 h/yr and COE of $0.0572/kWh. The DG operates 403 h in a year; it starts only 87 times and has an operating lifetime of 37.2 years. Total electrical output from DG is 8119 kWh/yr, and it consumes around 0.45 l/kWh. It has the highest COE of $0.2/kWh.

Converter operates almost all the time, i.e. 8711 h/yr because most of the loads served are in AC mode. The maximum output capacity for inverter is 51.7 kW and that is 9.99 kW for rectifier. Fig. 18 presents cost summary of the system components. Battery has the highest NPC followed by PV, generator and converter. As

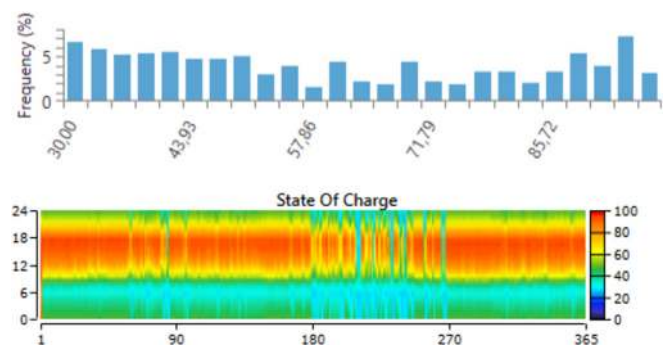

Fig. 13. PV/DG/battery: state of the battery over a year.

shown in Fig. 19, the replacement of battery occurs three times during the project lifetime, i.e. in 8th, 15th and 22 nd years, whereas the converter is replaced only once in the 15th year.

For economic comparison, the base case system selected is DG as shown in Table 12. The difference in investment of $751,961 between conventional DG and optimal PV/DG/battery system can be recovered within four years, whether discounted or not, with a

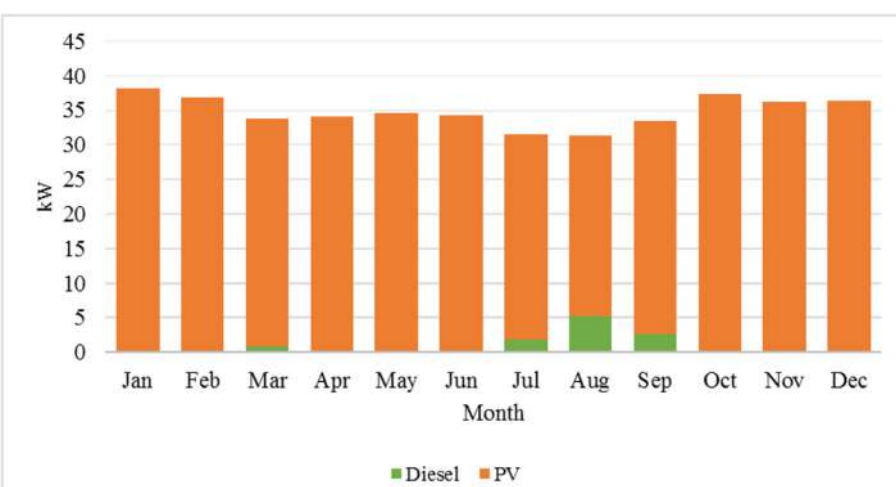

Fig. 12. Monthly electricity production.

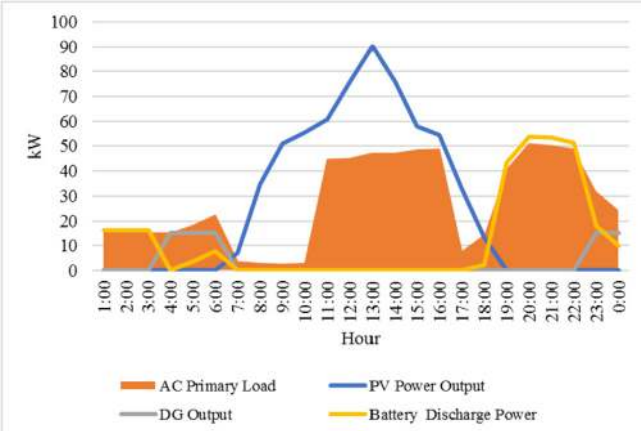

Fig. 14. Daily system operation in a day of August.

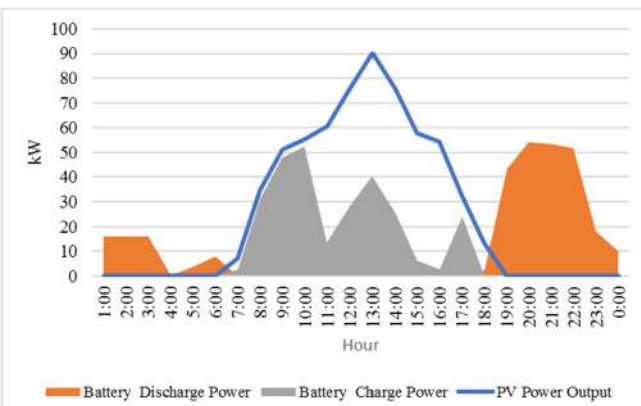

Fig. 15. Battery charge and discharge power profile during winter.

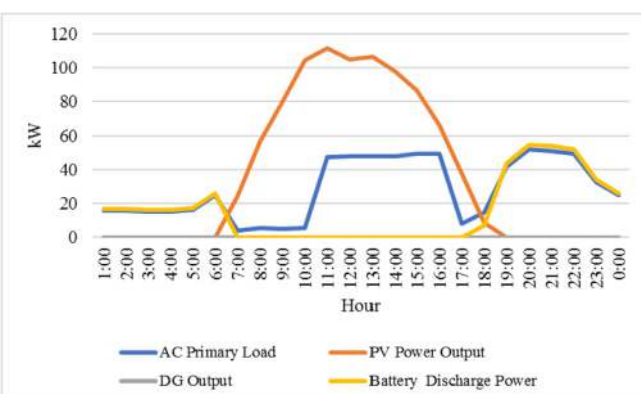

Fig. 16. Daily system operation in a day of November.

high rate of return of 33.3% and return on investment of 31.7%. PV/DG/battery system is far more economical than grid extension, where the BGED is −1.86 km. In terms of emissions, the proposed optimal system pollutes less compared to DG as can be seen in Table 13. Based on the reduction of CO_2 and other harmful gases and exhaust fumes, the PV/DG/battery system not only contributes to the country's mitigation strategy but also can, at a certain extent, improve local population health conditions regarding respiratory problems.

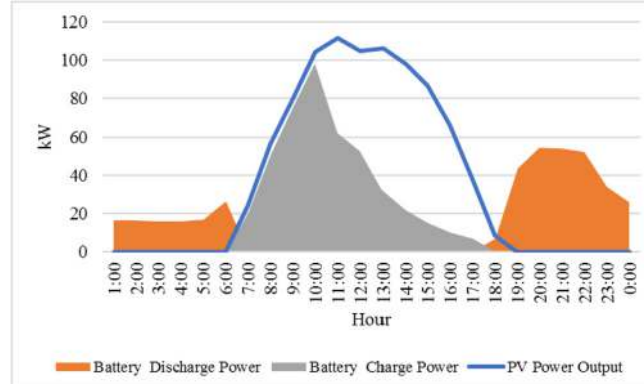

Fig. 17. Battery charge and discharge power profile during summer.

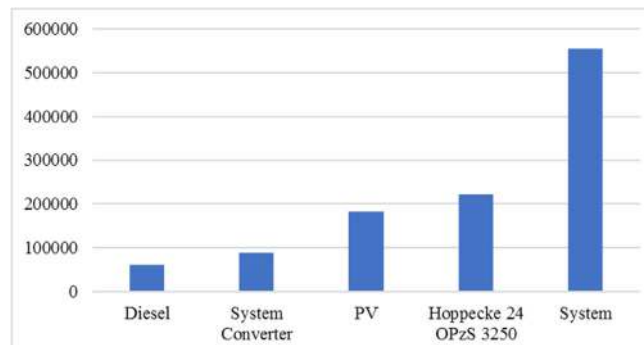

Fig. 18. PV/DG/battery: cost summary by components.

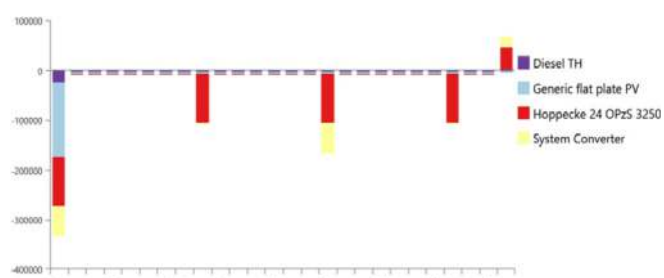

Fig. 19. PV/DG/battery – cashflow.

Table 12
PV/DG/battery: economics comparison.

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

4. Conclusion and recommendations

This paper analysed the techno-economic feasibility of HRES for sustainable rural electrification using a case study village of Fouay in Benin Republic. The analysis showed that hybrid PV/DG/battery is the best optimal system amongst different cases considered to

Table 13
Emissions summary- PV/DG/battery vs. DG

Quantity	PV/DG/battery	DG
Carbon dioxide (kg/yr)	9590	293139
Carbon monoxide (kg/yr)	23.7	724
Unburned hydrocarbons (kg/yr)	2.62	80.1
Particulate matter (kg/yr)	1.78	54.5
Sulphur dioxide (kg/yr)	23.3	714
Nitrogen oxides (kg/yr)	211	6457

electrify the village in a sustainable manner. Main findings of this assessment are summarized below:

- PV/DG/battery has the lowest NPC and provides a reliable power supply with 0% unmet load.
- It reduces battery storage cost. Its battery requirement is only 30% of that of a standard PV/battery standalone system.
- The proposed system is environment friendly compared to DG stand-alone system, CO_2 emission represents only 3% of a DG system due to a high renewable energy penetration of 96.7%.
- The PV/DG/battery is economically more viable than grid extension project over considered project lifetime (with a breakeven grid extension distance of −1.86 km) and the system has a COE of $0.207/kWh, which is lower than the current national grid tariff.
- From profitability standpoint, when taking DG as base case system, hybrid PV/DG/battery system has a shorter payback period of 3.45 years and an IRR of 33.3%.

Furthermore, optimization results showed that the most economical hybrid system in a location depends strongly on the potential of available different power sources and the distance of the source from the load point. As an illustration, hydropower potential at the location is high, but because of remoteness of site to the village, an extra investment cost for grid extension makes such a system less cost-effective than the PV/DG/battery.

Considering the current overall system cost, which is still quite high, the availability of incentive measures or supporting schemes through grants or subsidies can reduce the investment costs as well as the COE proposed to the villagers. This also makes it more attractive for investors during its implementation phase.

Given the above results, off-grid hybrid PV/DG/battery is a suitable technology to sustainably electrify the village of Fouay in contrast to grid extension as projected in the country's master plan for rural electrification. As solar energy is abundant across the country, this model can be suitable to power rural communities far from the grid in Benin. Compared to currently deployed PV/battery systems, the present study, recommends the off-grid hybrid PV/DG/battery system for future electrification projects in Benin.

Moreover, the sustainability of rural electrification projects integrates other dimensions like institutional and socio-cultural aspects, which play a crucial role, and where future research could explore. The same also applies to affordability of the system through the analysis of the community willingness and ability to pay for the system.

Conflicts of interest

The authors declare no conflict of interest.

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