Optimizing Hybrid Renewable Energy Systems for Rural Electrification: A Case Study of Selected Villages in Kwara State, Nigeria

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ABSTRACT: The adoption of renewable energy resources for electricity generation usually results in the generation of excessive electrical energy. Efficient utilization of this surplus electrical energy after the battery has been fully charged when in use has the potential to minimize the unit cost of energy generation by these hybrid renewable energy systems. This work presents an optimal sizing methodology for a stand-alone Small Hydro-Solar Photovoltaic (PV)-Battery-Flywheel Energy Storage (FESS) System to electrify three off-grid rural areas: Sangotayo, Budo Umoru, and Idi-Isin in Kwara State, Nigeria. A hybrid optimization model for electric renewable (HOMER) was used to determine the optimum hybrid system configuration with the least levelised cost of energy (LCOE). Interestingly, the optimal system configuration modeled by HOMER, tagged Case 1 is a Small Hydropower-Solar PV-FESS-Converter with Net Present Cost (NPC) of $524, 940 (N 787, 410, 000 at N 1500 to 1USD), LCOE of 0.23$/kWh (N 345), and initial capital cost of $494, 752 (N 742, 128, 000) and composed of 273 kW of CS6U-330P solar PV, 45 pieces of fly100 FESS, 230 kW of Natel49 small hydro generator and 144 kW of PrinDRI100 DC/AC bi-directional inverter.

KEYWORDS: Small hydropower system, Solar photovoltaic, levelized cost of energy, Fuelless energy storage system, Homer, hybrid renewable energy system

[Received Feb. 9, 2024; Revised Sep. 21, 2024; Accepted Sep. 22, 2024] Print ISSN: 0189-9546 | Online ISSN: 2437-2110

I. INTRODUCTION

The Nigerian Government is currently targeting 350GW installed capacity by the year 2043 (Ministry of Budget and Economic Planning, 2024). Currently, the major contribution comes from the combustion of fossil fuel (thermal) with an installed capacity of 10142 MW, which is almost 81% of the total installed capacity. The installed capacity of hydropower is 2380 MW which is almost 19% of the total installed capacity. But, unfortunately, the available generation is about 4000MW which is far below the daily load demand of 180, 000 MW (Sunday, 2019). The electrification rate in rural areas of Nigeria stands at 25% (World Economic Forum, 2023). In Nigeria, the populaces of Ifelodun Local Government Area of Kwara State are mainly subsistence farmers. Plentifully produced food crops include Guinea Corn, Yam, Cassava, Maize, Rice, Soya beans, Locust beans, and Groundnut. From these major crops, reasonable metric tons of agricultural residues are usually being generated in this part of the state which, if properly harnessed can be used to generate the required electricity needed. The major drawback of these residues is their wasteful use. These agricultural residues are normally burnt in an open land area immediately after harvesting the crop, contributing to air pollution and reducing soil fertility and health risks. Hybrid energy systems which comprise renewable sources of energy have recently received weighty awareness as they appear to be environmentally friendly. However, the reliability of the system, power management strategy, and the cost of generating a unit of energy are important issues to be properly addressed while designing a hybrid energy system based on renewable sources of energy. Therefore, an appropriate optimal sizing technique and control scheme are needed to design an effective and economical hybrid system (Singh and Kaushik, 2016). Recently, the feasibility of hybrid energy systems by considering the combination of different renewable sources of energy has been studied for rural electrification by numerous researchers (Patel and Singal, 2018; Pradhan *et al*, 2016; Kusakana *et al*, 2009; Ahmad *et al*, 2018; Asrari *et al*, 2012; Al-Badi and Bourdoucen, 2009; Bekele and Tadesse, 2012; Olatomiwa *et al*, 2015; Chmiel and Bhattacharyya, 2015; Zhao *et al*, 2014; Borhanazad *et al*, 2014; Ashok, 2007; Razmjoo *et al*, 2019; Padrón *et al*, 2019; Filho and Beluco, 2019; Fu *et al*, 2019; Cagnano *et al*, 2020; Rigo-Mariani *et al*, 2020). It is evident from these studies that the operation of hybrid renewable energy systems usually results in the generation of excessive electrical energy, which is the electrical energy produced by the combined renewable energy resources, which is not consumed by the loads in autonomous hybrid renewable energy systems. Efficient utilization of this surplus electrical energy has the potential to minimize the unit cost of energy generation by these hybrid renewable energy systems.

The conventional approach used to overcome this surplus-generated energy was by using dump loads (Mousavi, 2012;

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doi: http://dx.doi.org/10.4314/njtd.v21i3.2359

Jebaselvi and Paramasivam, 2013; Kabalci, 2013; Sreeraj *et al*, 2010; Sebastián and Quesada, 2006; Fux *et al*, 2013; Hafez and Bhattacharya, 2012) to utilize it to prevent the battery from being overcharged. Also, if this excess energy is not properly dumped, it may result in overvoltage which may have negative impacts on the connected load. Load resistors are commonly used for this intention. It is a known fact, that a larger percentage of the energy generated by renewable energy resources would be wasted through the load resistor coupled with the capital cost of purchasing the required load resistors. Some researchers also recommended that the excess energy should be sold to the electric grid (Demiroren and Yilmaz, 2010; Ranjevaa and Kulkarnia, 2012; Krajačić *et al*, 2011; Khatib *et al* 2011). Also, some of the works reported that the excess electrical energy should be utilized through hydrogen storage technology (Ziogou *et al*, 2011; Iverson *et al*, 2013; Agbossou *et al*, 2004; Ipsakis *et al*, 2009; Genovese *et al*, 2023; Khakimov *et al*, 2024; Kumar *et al*, 2024) by converting the excess energy to hydrogen which will be stored in a hydrogen tank. The stored hydrogen will be used as fuel for a fuel cell to satisfy loads in deficient periods. The disadvantage of this approach is also the huge cost required to purchase required hydrogen storage technology equipment. To the best of the authors' knowledge, no work has been reported in the literature that considers the possibility of using FESS and battery banks against the dumping of excess electrical energy when designing hybrid renewable energy systems for off-grid electrification. Likewise, most of the reported works studied the feasibility of a hybrid energy system using a hybrid optimization model for electric renewable (HOMER) (Givler and Lilienthal, 2005; Sen and Bhattacharyya, 2014). HOMER seems to be the preferred tool by the majority of the researchers in the literature. Mathematical modeling of the components of hybrid energy systems is usually neglected by researchers. Hence, to overcome this limitation, this work will majorly focus on detailed mathematical modeling of small Hydropower-Solar PV-FESS hybrid energy systems (HES) and investigate the possibility of modeling and combining the two energy storage systems in Small Hydropower-Solar PV-Battery-Flywheel hybrid energy system to supply continuous electrical energy to a cluster of three off-grid villages using HOMER optimization software. The three communities namely: Sangotayo, Budo Umoru, and Idi Isin are located in the Ifelodun Local Government Area of Kwara State, Nigeria. Presently, there are 86 houses, seven commercial shops, 4 Mosques, 2 Churches, and 273 houses in a cluster of the three rural communities.

The paper is arranged into six Segments; Section 2, gives the modeling of each of the components of the system. Section 3, presents the optimization problem, and the operating strategy. In Section 4, the input data are presented. In Section 5, results acquired by the HOMER were presented and discussed. Lastly, Section 6 presents the concluding remarks.

II. METHODS

A. Modeling of the System Components

The hybrid generation system includes different components namely, small hydropower units, solar PV panels, power inverters, batteries, and a flywheel energy storage system (FESS). The time step (Δt) used is one hour. The modeling of the components system is given in this section.

1) Small hydropower

In a small hydropower generating system, mechanical energy is utilized to run an electric generator coupled to the turbine. The net head, H_{nh} (m) is assessed with Eqn. (1).

$$H_{nh} = H_{gr} - \left\{ h_{fr} + h_{tr} + h_{be} + h_o \right\} \tag{1}$$

Where H_{gr} is the gross head (m), h_{fr} is a frictional loss (m), h_{tr} is a trash rack loss (m), h_{be} is bend losses due to bends, and h_o is outlet losses (m). The electric power from a small hydropower generating unit in an hour t (P_t^{SHP}) is calculated as presented in Eqn. (2).

$$P_t^{SHP} = \rho \times Q_t \times H_n \times \eta_{tu} \times \eta_g \times 9.81 \tag{2}$$

Where Q_t is the flow rate in m^3/s at time t, ρ is the water density, η_{tu} is the efficiency of the turbine, η_g is the efficiency of the generator, H_n is the net head, and Δt is 1h. The whole electrical energy generated at time t is calculated using Eqn. (3) while the annual electrical energy generated from small hydropower is calculated using Eqn. (4).

$$E_t^{SHP} = P_t^{SHP} \times \Delta t \tag{3}$$

$$E_{AN}^{SHP} = \sum_{t=1}^{8760} E_t^{SHP} \tag{4}$$

2) Solar photovoltaic system

The power produced at time t by a PV panel can be calculated as a function of the solar radiation and the derating factors using Eqn. (5).

$$P_t^P = f_P P_{PR} \frac{G_t}{G_{STC}} (1 + \alpha_T (T_t - T_{STC}) \tag{5}$$

Where P_t^P is the power produced by a solar module at time t, f_P is the de-rating factor, P_{PR} is the rated power of the solar PV, G_t is the hourly solar irradiance, G_{STC} and T_{STC} are the solar irradiance and temperature at standard test conditions, T_t is the temperature at time t, α_T is the temperature coefficient. The expression for the derating factor is given in Eqn. (6).

$$f_p = l_{AC} \times l_{DC} \times l_D \times l_C \times f_{s\_d} \tag{6}$$

Where $l_{AC}, l_{DC}, l_{D\&C}, l_C \; and \; f_{s\_d}$ are AC wiring, DC wiring, diodes, connection, and soiling derating losses respectively.

Total hourly power and energy generation from the entire amount of PV system (E_t^{PV}) can be determined by using Eqns. (7) and (8) as:

$$P_t^{PV} = P_t^{p} \times N_{PV} \tag{7}$$

$$E_t^{PV} = P_t^{PV} \times \Delta t \tag{8}$$

Where N_{PV} is the number of the solar photovoltaic module. The aggregate PV modules (N_{PV}) can be determined by using Eqn. (9).

$$N_{PV} = N_{PV}^{s} \times N_{PV}^{p} \tag{9}$$

The Number of solar modules in series (N_{PV}^{s}) can be calculated using the Eqn. (10) while the yearly energy production can be determined using Eqn. (11).

$$N_{PV}^{s} = \frac{V_{bus}}{V_{PV}} \tag{10}$$

$$E_{PV}^{AN} = \sum_{t=1}^{8760} E_t^{PV} \tag{11}$$

Where V_{bus} bus voltage, V_{PV} is the voltage of a solar PV, N_{PV}^{p} is the number of modules in parallel which is a design variable.

3) Battery output energy

The battery energy storage system is used to regulate any energy excess or deficit produced taking the state of charge of the battery into consideration. The required maximum capacity of the battery bank can be determined with respect to depth of discharge of the battery (DOD) using Eqn. (12). DOD can be defined as the capacity that is discharged from a fully charged battery divided by the battery nominal capacity.

$$E_{bat}^{\max} = \frac{LD_t \times D_A}{(DOD)_{\max} \times \eta_{bat} \times \eta_{inv}} \tag{12}$$

Where D_A is the autonomy days, V_{bus} is the DC bus voltage, $(DOD)_{max}$ is the maximum depth of discharge of the battery bank, η_{bat} is the efficiency of the battery. The minimum state of charge of the battery is expressed by the $(DOD)_{max}$ as given in Eqn. (13).

$$E_{bat}^{\min} = (1 - (DOD)_{\max}) \times C_{bat} \tag{13}$$

Where N_{bat} is the number of batteries as expressed in Eqn. (14).

$$N_{bat} = N_{bat}^{s} \times N_{bat}^{p} \tag{14}$$

Where N_{bat} is the number of batteries in parallel.

The state of charge of the battery at any point in time should follow the following order: $E_{bat\min 2} < E_{bat\min 1} < E_{bat\max 1} < E_{bat\max 2}$. Where $E_{bat\min 1}$ and $E_{bat\max 1}$ are the operational minimum and maximum bonds of the battery while, $E_{bat\min 2}$ and $E_{bat\max 2}$ are the practical lower and upper bounds of the battery. The major advantage of using the practical maximum and minimum bonds is to elongate the life span of the battery. If satisfactory electrical energy is provided by renewable energy resources then, the net energy would be used to charge the battery bank for $E_t^{bat} < E_{bat\max 2}$. The charging energy of the battery at time t can be calculated by Eqn. (15):

$$E_t^{bat} = E_{t-1}^{bat} + (E_t^{SHP} + E_t^{BM} + E_t^{PV} - LD_t) \times \eta_{cha} \times \eta_{cgc} \tag{15}$$

where E_t^{bat}, E_{t-1}^{bat} are the battery state of charge at present and previous time respectively, LD_t is the overall load demand at time t. Likewise, if the electrical energy generated from renewable resources fails to provide appropriate energy to meet the load, then, the stored energy in the batteries will be considered for $E_t^{bat} < E_{bat\min 1}$ until $E_t^{bat} = E_{bat\max 1}$ or according to Eqn. (16). The netload demand (E_t^{NL}) to be contributed by the battery is computed by using Eqn. (17).

$$E_t^{bat} = E_{t-1}^{bat} - E_t^{NL} / (\eta_{dch} \times \eta_{inv}) \tag{16}$$

$$E_t^{NL} = LD_t - (E_t^{SHP} + E_t^{PV} + E_t^{BM}) \tag{17}$$

where η_{dch} is the battery discharging efficiency, η_{inv} is the efficiency of the inverter, E_t^{NL} is the netload demand.

4) Flywheel energy storage system

If the $E_t^{bat} = E_{bat\max 2}$, then the excess should be used to charge the FESS as presented in Eqns. (18-20) if the speed of the spinning disk reaches its maximum value $(n_{FESS} = n_{\max}^{FESS})$ then, the FESS will be disconnected from the system and operate in standby mode, by maintaining the constant speed for the rotating disk. Also, if $E_t^{bat} = E_{bat\min 1}$ and $E_t^{FESS} > 0$ the energy stored in FESS should be discharged by decelerating the rotating disk and injecting power into the alternating current network. These are computed using Eqns. (18) - (20).

$$E_t^{FESS} = E_t^{cgc\_out} - (E_{bat\max 2} - E_t^{bat}) \tag{18}$$

$$E_t^{cgc\_out} = E_t^{cgc\_in} \times \eta_{cgc} \tag{19}$$

$$E_t^{cgc\_in} = E_t^{SHP} + E_t^{PV} + E_t^{BM} - LD_t \tag{20}$$

B. Problem Formulation

1) Objective function

Levilized cost of energy (LCOE) is the ratio between the present value of the total costs of the system, and the present value of the energy generated by the system during the evaluation period. The LCOE for HES is formulated as the ratio of the total annualized cost (TAC) to the annual electricity generated by the same, as computed in Eqn. (21).

$$LCOE = \frac{TAC}{E^{AEG}} \tag{21}$$

The TAC can be estimated by considering the capital costs of the component of HES via individual capital recovery factors according to their life spans and discount rate; annual operation and maintenance costs of the different components of the HES. The contributions of the annual capital cost (ACC), annual operation and maintenance cost as well as the replacement cost to the total annualized cost can be estimated using the expressions as described in Eqns. (22)– (23).

$$TAC = TAC_{SHP} + TAC_{PV} + TAC_{bat} + TAC_{inv} + TAC_{cgc} + TAC_{FESS} \tag{22}$$

Where TAC_{SHP}, TAC_{PV} and TAC_{bat} are the total annualized cost for small hydropower, and battery banks respectively.

$$\begin{aligned} TAC = {} & P_{SHP} \times \left[(C_{C,SHP} \times CRF_{SHP}) + (C_{SHP}^{v\_mtn} \times E_{SHP}^{AEG}) + (C_{SHP}^{f\_mtn} \times P_{SHP} \times CRF_{SHP}) \right] \\ & + N_{PV} \times \left[(C_{c,PV} \times CRF_{PV}) + (C_{PV}^{mtn} \times E_{PV}^{AEG}) \right] \\ & + N_{bat} \times \left[(C_{c,bat} \times CRF_{bat}) + (C_{bat}^{rep} \times R_{bat} \times SFF) \right] \\ & + N_{inv} \times \left[(C_{c,inv} \times CRF_{inv}) \right] + N_{cgc} \times \left[C_{c,cgc} \times CRF_{cgc} \right] + P_{FESS} \left[C_{c,FESS} \times CRF_{FESS} \right] \end{aligned} \tag{23}$$

Where TAC is the overall total annualized cost of the system, P_{SHP}, P_{inv}, P_{FESS} are the optimal capacity of small hydropower, flywheel energy storage systems, $C_{C,SHP}$, $C_{c,FESS}$ are capital cost per kW for small hydropower, biomass power plant, and FESS, $C_{c,bat}$, $C_{c,PV}$, $C_{c,inv}$, $C_{c,cgc}$ are capital costs per unit for battery, solar PV, inverter, and charge controller, $C_{SHP}^{v\_mtn}, C_{SHP}^{f\_mtn}$ are the variable and fixed maintenance costs for small hydropower, C_{PV}^{mtn} is the maintenance cost per kWh for solar PV, N_{PV}, N_{bat}, N_{inv}, N_{cgc} are the numbers of solar PV, batteries, inverters, and charge controllers, CRF_{SHP}, CRF_{PV}, CRF_{bat}, CRF_{inv}, CRF_{FESS}, CRF_{cgc} are capital recovery factors for small hydropower, solar PV, battery, inverter, FESS, and charge controllers, C_{bat}^{rep} is the replacement cost per unit for the battery.

C. Operational Strategy

The stochastic behavior of renewable resources has prompted different complex power management strategies for optimal combination of renewable resources basically when it is mandatory to generate dependable electricity to satisfy the load demand pattern. Moreover, the installed capacity of the renewable energy generator cannot be instantly increased to meet up with the increase in electrical load demand. Also, when the units of electricity generated from renewable resources are more than the load demand, the usual practice is to dump the excess energy generated to protect the batteries from overcharging. Given this, a proper power management strategy that will consider the possibility of either re-utilization of the excess generated energy using FESS or direct utilization of the FESS as the main energy storage device is considered.

The following strategies will be considered in the simulation.

Strategy 1: if sufficient electrical energy is generated by renewable sources, then, the excess electrical energy should be used to charge the battery bank.

Strategy 2: the same as in strategy 1 but, if the excess electrical energy produced by renewable resources is more than the energy required to power the load and charge the battery then, the remaining energy should be stored in a flywheel energy storage system.

Strategy 3: if the generated energy cannot provide enough energy to satisfy the load demand, then, the energy stored in the battery should be used.

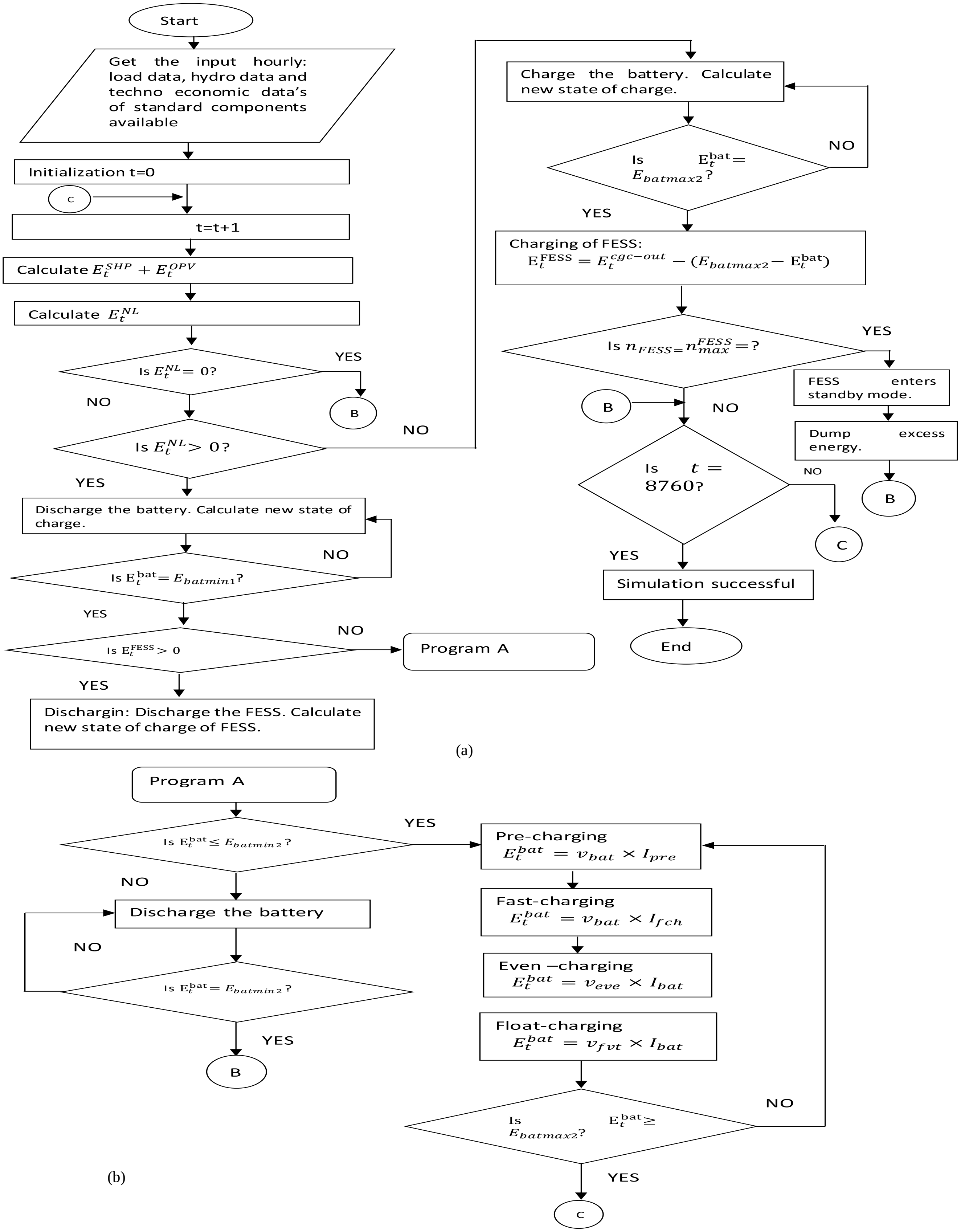
Strategy 4: if the energy generated is insufficient to power the load demand and the energy stored in the battery has been used up, then the energy stored in a flywheel energy storage system should be used to satisfy the net load demand. The whole strategies are represented in Figs. 1 (a) and (b). Where I_{fch} is the fast-charging current, V_{eve} is the even charging voltage, V_{fvt} is the float voltage at time t, I_{pre} is the pre-charging current.

D. Resource Data and Components Selection

The input data used for the design and optimization is divided into three groups namely: 1) stochastic variables which include weather-related and load demand data. 2) economic variables and 3) efficiencies data.

1) Stochastic variables

The stochastic variables that are used are the hourly series solar irradiation in W/m^2, temperature (^{0}C) (data obtained from Nigeria meteorological Station, Ilorin International airport, Ilorin, Nigeria); hourly water discharge (m^3/s) (the measurement was carried out the authors at the proposed case study site); and hourly electrical load demand (data computed based on the interview conducted via structured questionnaires which focused majorly on the respondent’s decisions on the anticipated electrical appliances with pattern of usage if they would love to connect if they had electricity, and the measurements of hourly energy consumption of the similar off-grid rural areas using power analyzer). These data were used as input to determine the hourly potentials of solar PV, hydropower, and electricity demand for the rural areas under study. The load profiles are estimated for the communities and presented in Figs. 2 and 3 for the two predominant seasons. Based on the survey carried out, it has been established as presented in Figs. 2 and 3 that the load demands in rural communities are usually high from the afternoon till around late in the night. The water discharge was assessed and computed as presented in Fig. 4. Fig, 4 has also revealed that the water level in the case study area begins to rise around May and reaches the maximum level between



(a)

(b)

Figure 1 (a) and (b): Flowchart of the Operating Strategy.

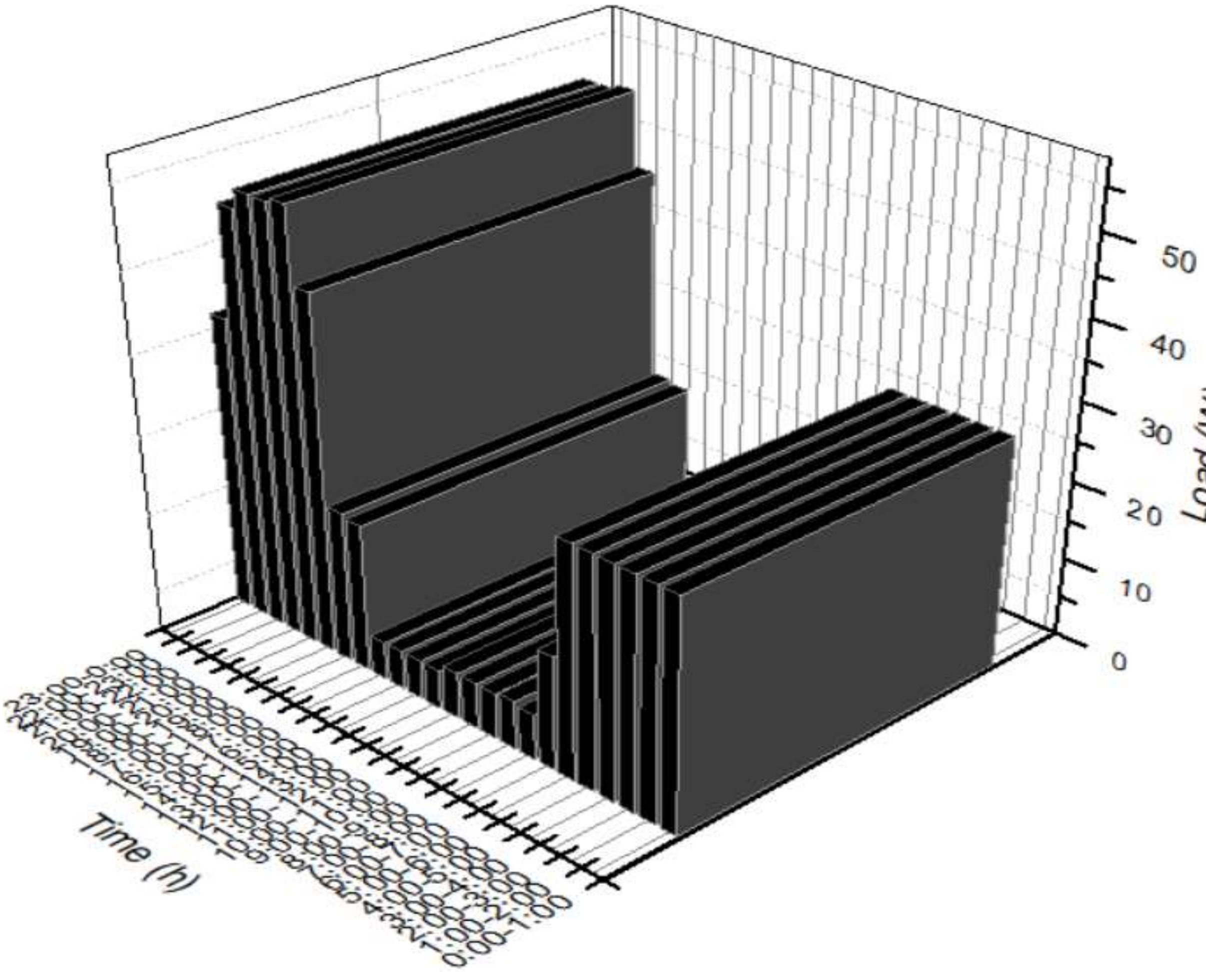


Figure. 2: The Load Profile for the Dry Season.

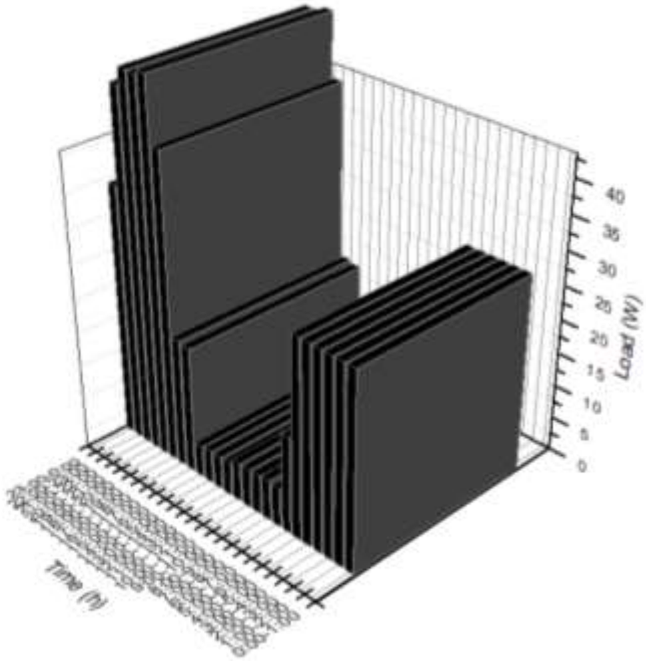


Figure 3: The Load Profile for the Rainy Season.

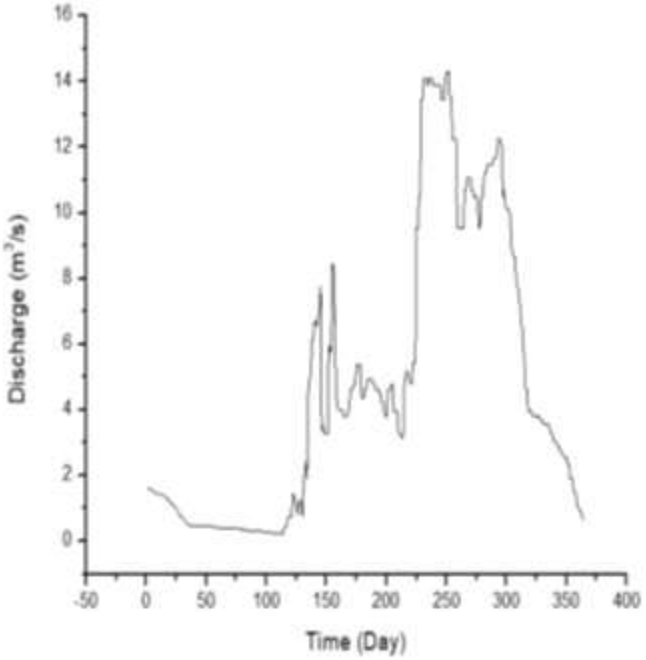


Figure 4: Yearly Water Discharge in the River (Authors' Field Work).

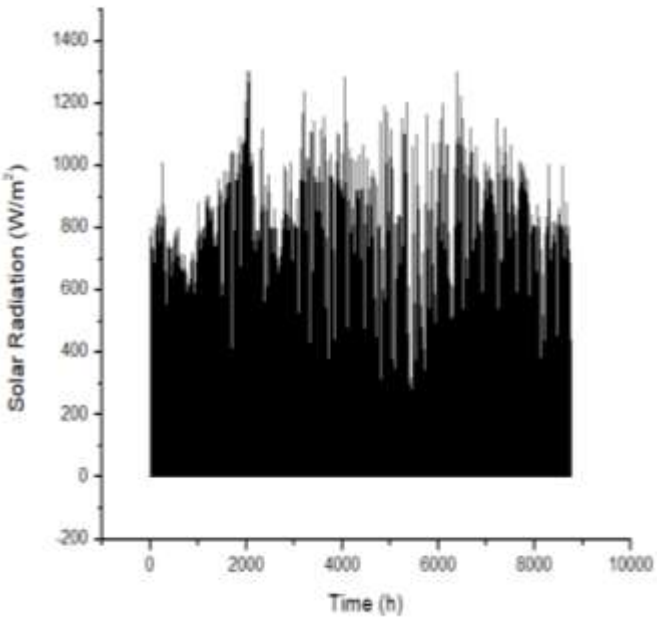


Figure 5: Average Hourly Solar Radiation Data of the Site (2010-2016) (NIMET, 2020)

October and November. On the other hand, the hourly solar insolation and temperature data for the year (2010-2016) were plotted and presented in Figures. 5 and 6 respectively. Figures 5 and 6 have shown that the study area has a reasonable potential for solar photovoltaic systems, with higher irradiance and temperature during the dry season Months.

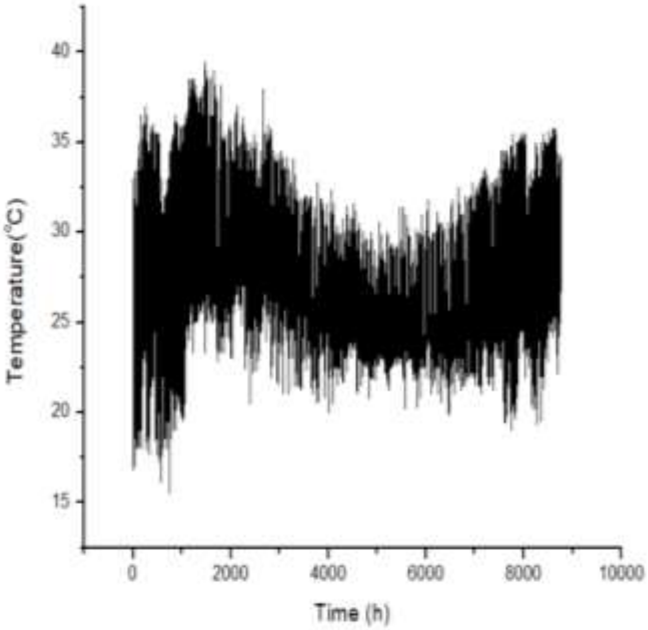


Figure 6: Average Hourly Temperature Data of the Case Study Site (2010-2016) (NIMET, 2020)

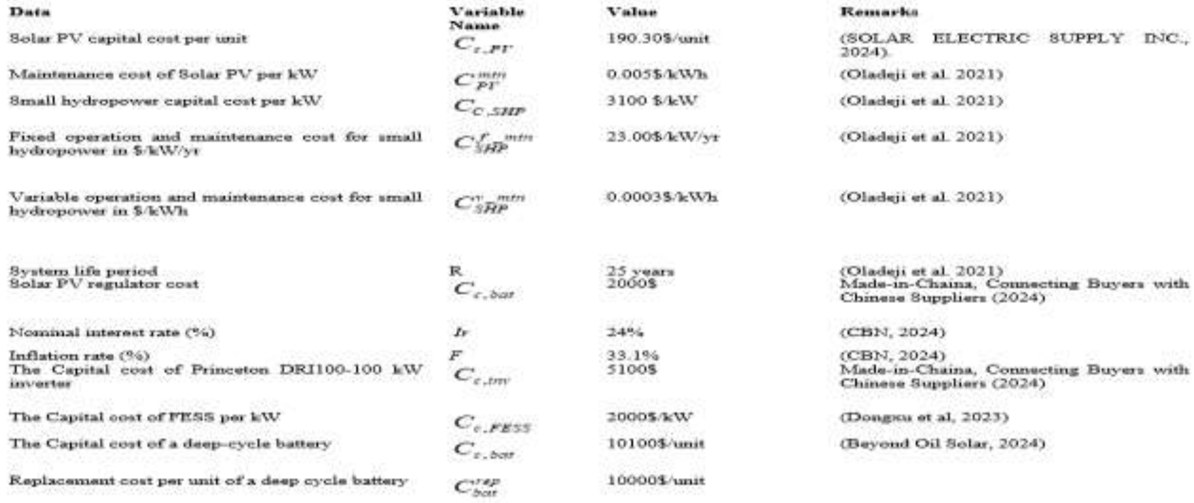
III. RESULTS AND DISCUSSION

The HOMER optimization software has been used in this work for the simulation, optimal sizing as well as techno-economic evaluation of the proposed hybrid renewable energy system for the chosen of-grid rural areas. The optimization of the hybrid energy system component comprises different combinations of small hydropower, solar PV array, DC/AC inverter, batteries, and flywheel energy storage system that satisfies the electrical load demand of the selected off-grid rural communities. The economic feasibility of each configuration is based on the following parameters that were used as performance criteria for the selection of the best configuration which are; net present cost (NPC), LCOE, and renewable energy fraction (RF). The modeled configuration of the components and the load demand in HOMER is presented in Figure 7.

Table 3 presents the optimal results in terms of the number and sizes of hybrid system components in each configuration with their respective initial capital cost, total NPC, LCOE, and the renewable fraction of each configuration. From the results, the best system configuration with the lowest NPC and LCOE which is tagged Case 1 is a hybrid PV-hydro-FESS system having an NPC of $524, 940, LCOE of 0.23$/kWh, and initial capital cost of $494, 752 and composed of 273 kW of CS6U-330P solar PV, 45 pieces of fly100 FESS, 230 kW of Natel49 small hydro generator and 144 kW of PrinDRI100 DC/AC bi-directional inverter. The obtained minimum NPC and LCOE were due to the availability of high solar insolation and water discharge (m^3/s) resources in the case study sites. The next system configuration which has high NPC and LCOE which is tagged Case 2 is a hybrid PV-hydro-battery system having the NPC of $2, 220, 000, LCOE of 0.97$/kWh with an initial capital cost of $1, 360, 000 and composed of 366 kW of CS6U-

2.) Economic variables

The Economic variables used are presented in Table 1.



Data	Variable Name	Value	Remarks
Solar PV capital cost per unit	C_{c_PV}	190.30$/unit	(SOLAR ELECTRIC SUPPLY INC., 2024)
Maintenance cost of Solar PV per kW	C^{mtn}_{PV}	0.005$/kWh	(Oladeji et al. 2021)
Small hydropower capital cost per kW	C_{C_SHP}	3100 $/kW	(Oladeji et al. 2021)
Fixed operation and maintenance cost for small hydropower in $/kW/yr	$C^{f\_mtn}_{SHP}$	23.00$/kW/yr	(Oladeji et al. 2021)
Variable operation and maintenance cost for small hydropower in $/kWh	$C^{v\_mtn}_{SHP}$	0.0003$/kWh	(Oladeji et al. 2021)
System life period	R	25 years	(Oladeji et al. 2021)
Solar PV regulator cost	$C_{c,bat}$	2000$	Made-in-Chaina, Connecting Buyers with Chinese Suppliers (2024)
Nominal interest rate (%)	Ir	24%	(CBN, 2024)
Inflation rate (%)	F	33.1%	(CBN, 2024)
The Capital cost of Princeton DRI100-100 kW inverter	$C_{c,inv}$	5100$	Made-in-Chaina, Connecting Buyers with Chinese Suppliers (2024)
The Capital cost of FESS per kW	$C_{c,FESS}$	2000$/kW	(Dongxu et al, 2023)
The Capital cost of a deep-cycle battery	$C_{c,bat}$	10100$/unit	(Beyond Oil Solar, 2024)
Replacement cost per unit of a deep cycle battery	C^{rep}_{bat}	10000$/unit	

Efficiency and other Performance parameters are presented in Table 2.

Table 2 Efficiency and other performance parameters

Data	Variable Name	Value
Battery charging efficiency		0.8
Battery discharging efficiency		1.0
The Efficiency of PV Regulator		0.95
Efficiency of turbine		0.91
Efficiency of generator		0.95
Efficiency of inverter		0.92
Net Head (H_n)		7.63
Input DC bus voltage (V_{bus})		240V DC
The nominal capacity of each battery unit	Ah	198
The Nominal voltage of the battery (V)		48V
The Nominal energy capacity of each battery [$E_n = (V_n \times Ah/1000)$]		9.8
The Life span of the battery		10 years
Rated power per unit of solar PV (W)		330
The Nominal voltage of each solar module (V)		40V
Wiring losses factor for the AC		15.0%
DC wiring loss factor		98.0%
Diodes and connection efficiency		99.5%
Connection efficiency		99.5
Soiling de-rate factor		95.0%
Practical maximum and minimum bonds of the battery		100/50

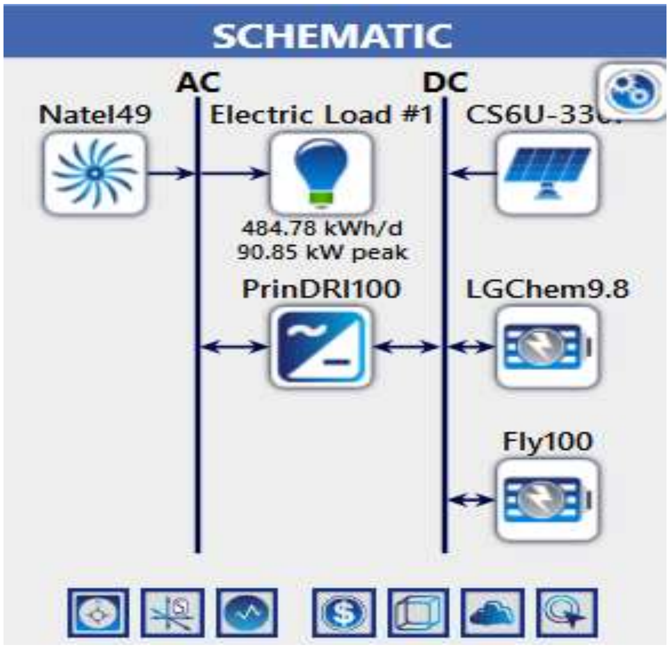
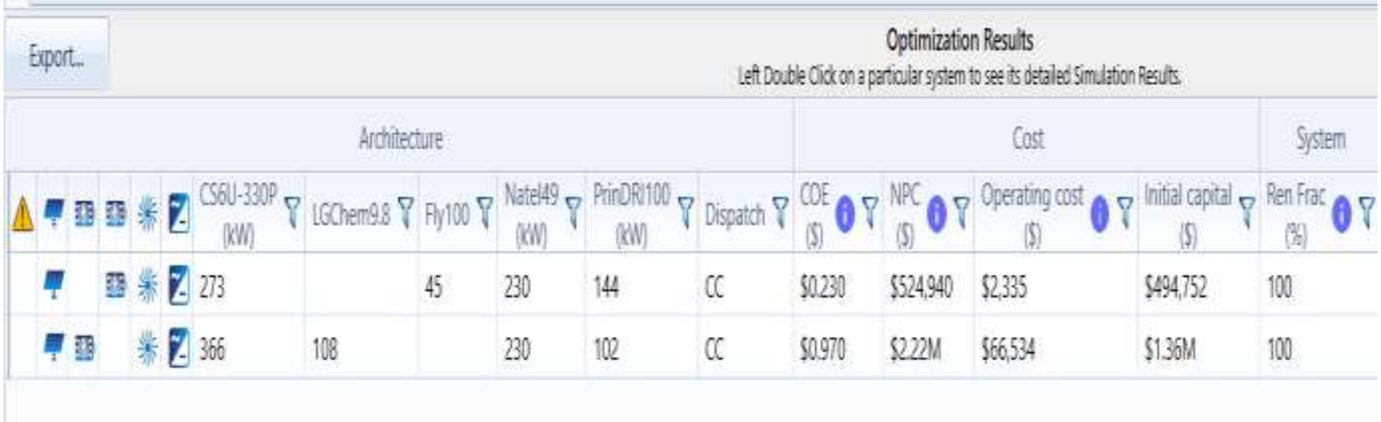


Figure 7: The system modeled in HOMER

330P solar PV, 108 pieces of LGChem9.8 kWh battery, 230 kW of Natel49 small hydro generator and 102 kW of PrinDRI100 DC/AC bi-directional inverter. Case 2 is detected to be one of the costlier configurations with higher NPC, initial capital cost, and LCOE as compared to Case 1 which is a hybrid PV-hydro-FESS system having the NPC of $524, 940, LCOE of 0.23$/kWh with an initial capital cost of $494, 752. However, Case 2 considered the use of batteries as the energy storage devices against the FESS considered in Case 1. It is also observed in Case 1 that the LCOE is 0.74 less than that of

Table 3 Homer Optimization Results.



Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture						Cost				System
CS6U-330P (kW)	LGChem9.8	Fly100	Natel49 (kW)	PrinDRI100 (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)
273		45	230	144	CC	$0.230	$524,940	$2,335	$494,752	100
366	108		230	102	CC	$0.970	$2.22M	$66,534	$1.36M	100

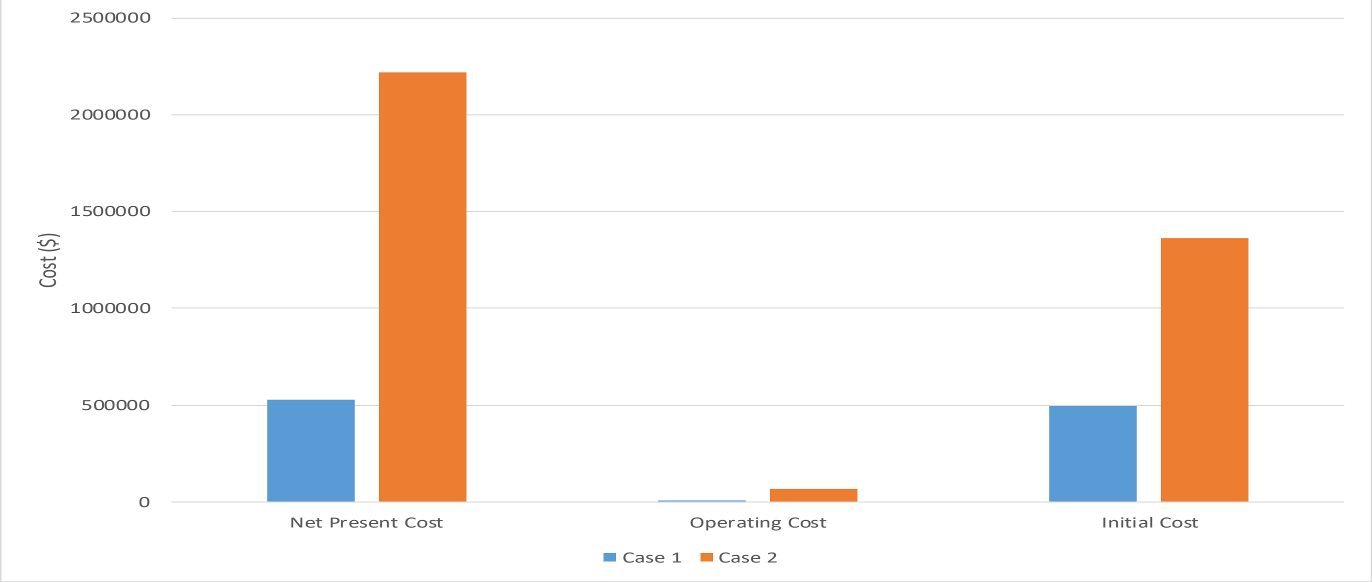


Figure 8: Cost Comparison for Cases 1 and 2

Case 2. This observation has established that the configuration with the lowest NPC and initial capital cost will be the configuration with the lowest LCOE. The cost comparison for the two cases (Cases 1 and 2) is presented in Figure 8 which shows the wide margin in: Net Present Cost ($524,950 against $ 2, 220, 000), Initial Investment cost ($ 494, 752 against $1, 360, 000) and Operation Cost $ 2, 355 against $ 6, 6534). Figure 8 has shown that Case 1 has the lowest LCOE, NPC, Initial investment cost and operating cost. Although, the main objective of this work, which is to see the possibility of storing the excess electrical energy generated by the hybrid generating system in a FESS when the battery is fully charged and the load demand is reliably satisfied using HOMER was not fully achieved. But, Interestingly, HOMER considered each of the energy storage for different configurations with different LCOE, NPC, and initial capital costs. The optimal configuration as computed by HOMER is the one with a FESS as an energy storage device. This implies that the FESS will efficiently and economically convert and store the excess generated energy that would have been either wasted through expensive dump load or by generating hydrogen with the aid of electrolyzes or then storing the hydrogen in an expensive hydrogen tank to be used by fuel cell when there is a deficit in power generation. Hence, using FESS in the optimization of a hybrid energy system will eliminate the need for battery banks, dump load, and the usual headache of how to properly convert excess energy generation to other forms of energy to be used during lean power generation periods.

IV. CONCLUSION

This study has revealed that battery bank and FESS can be modeled and optimized together as energy storage devices system in a hybrid energy system to determine the configuration with the minimum NPC and LCOE. In this study, the optimal system configuration modeled by HOMER tagged Case 1 is a Small Hydropower-Solar PV-FESS-Converter with NPC of \$524, 940, LCOE of 0.23\$/kWh (N 345 at N 1,500 to 1USD), and initial capital cost of \$494, 752 (N 742, 128, 000) and composed of 273 kW of CS6U-330P solar PV, 45 pieces of fly100 FESS, 230 kW of Natel49 small hydro generator and 144 kW of PrinDRI100 DC/AC bi-directional inverter. The study suggests that FESS is worth serious consideration, based on techno-economic grounds, as an energy storage device to minimize excess electrical energy generation when considering hybrid energy systems for the electrification of un-electrified off-grid communities in Nigeria and other developing countries. The outcome of the study based on the solar irradiance which was obtained from Nigeria Meteorological Station, Ilorin, Nigeria, and water discharge data which was computed from the measured water level for one year has also revealed that solar PV and small hydropower have great potential to satisfy the electricity needs of the villages under consideration.

LIMITATION OF THE STUDY

Though the output results satisfy the objective of the work, the development of an appropriate metaheuristic algorithm to handle the mathematical formulation/optimization problem has not been done in this particular study.

FUNDING

The National Centre for Hydropower Research and Development supported and funded all the costs associated with this work.

AUTHOR CONTRIBUTIONS

Conceptualization, **Oladeji, A. S., Atilola, O. F., Olaniyi, J. I.** Methodology, **Oladeji, A. S.; Olaniyi, J. I.** Investigation; **Oladeji, A. S.; Olaniyi, J. I.** Writing-original draft preparation, **Oladeji, A. S.;** Writing review and editing; **Atilola, O. F.** Project administration, **Oladeji, A. S.;** All authors have read and agreed to the published version of the manuscript.

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