INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 47 (2022) 6437–6452

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

# Hybridized off-grid fuel cell/wind/solar PV /battery for energy generation in a small household: A multi-criteria perspective

O.M. Babatunde [a,*], J.L. Munda [a], Y. Hamam [a,b]

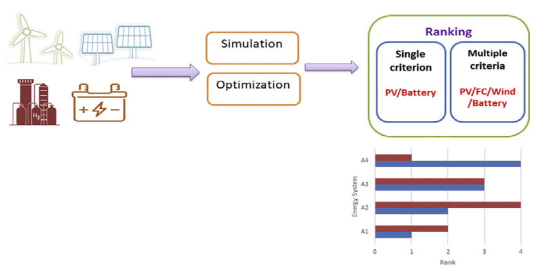
[a] Department of Electrical Engineering, Tshwane University of Technology, Staatsartillerie Rd, Pretoria West, Pretoria, South Africa

[b] École Supérieure d'Ingénieurs en Électrotechnique et Électronique, Cité Descartes, 2 Boulevard Blaise Pascal, Noisy-le-Grand, 93160 Paris, France

## HIGHLIGHTS

- Optimal sizing of off-grid hybrid renewable energy systems for a residential building is presented.
- A combination of hydrogen tank and battery were proposed as backups.
- Energy systems were ranked using complex proportional assessment (COPRAS).
- PV-battery was ranked best using single criterion.
- Hybrid combination of Photovoltaic-Wind Turbine-Fuel cell-Battery was ranked best based on multiple criterion.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 13 August 2021
Received in revised form
6 November 2021
Accepted 2 December 2021
Available online 22 December 2021

*Keywords:*
Fuel cell
COPRAS

## ABSTRACT

In this paper, the robust capability of HOMER and Criteria-COPRAS is deployed to explore the prospect of selecting a renewable energy system. The energy system consisting of wind turbines, solar photovoltaic (PV), fuel cell (FC), electrolyzer, hydrogen storage, and battery energy storage is intended to power a residential load in Lagos Nigeria. Based on the economic metric, the results show that the optimal system is a PV-Battery whose total net present cost (TNPC) and initial investment cost are $9060 and $3,818, respectively. However, if the energy systems are ranked based on multiple criteria (economic, technical and environmental aspects), the most preferred of the feasible energy systems is a hybrid PV-FC-wind-battery (TNPC-$10,324, initial cost: $7670). The study results indicate that, for

* *Corresponding author.*
E-mail address: olubayobabatunde@gmail.com (O.M. Babatunde).

https://doi.org/10.1016/j.ijhydene.2021.12.018

CRITIC
Hydrogen storage
Wind turbine
Photovoltaic

viability in the adoption of hydrogen energy storage as part of the hybrid energy system, the selection metric should be based on more than one criterion.


## Introduction

Adequate energy supply has been identified as inevitable for the sustenance of modern civilization. It is the foundation on which many human activities are laid. It contributes enormously to majority of all human sectors as an employer of labour, purchaser of goods and services, and creator of wealth. Also, energy has been reported to have a significant positive relationship with countries' gross domestic products [1]. Hence, energy availability is very essential and inevitable to human existence. Out of the various forms of energy available for human use, electricity is a major player, and it is the backbone of most industrial, commercial, and residential activities. Electricity access across the globe has been a major subject of discussion in the last few decades. Therefore, the United Nations sustainable development goal number 7 was developed to emphasize that sustainable and affordable energy must be accessible to all by 2030. Since electricity is the most widely used energy source worldwide, adequate efforts are expected to be directed to the electrification process to meet the 2030 target.

Although there have been technological breakthroughs and outstanding success stories in the provision of electricity in many parts of the world, sub-Sahara Africa (SSA) is still seen as being backward in this aspect. Based on available statistics, about 600 million people –two-thirds of people in SSA lack electricity [2], the highest in Africa and the entire world. Despite the massive efforts being made by countries like Rwanda, Ghana, Ethiopia, Nigeria and Senegal to improve electrification rates, the access rates in SSA is not likely to increase since the present and planned efforts aimed at increasing access is small compared to the population growth [2]. For example in Nigeria, a 2012 statistic shows about 93 million people without electricity [3]. In 2019, Nigeria is still home to 15% (90 million) of SSA's population without electricity with about 20 million households not having access to electricity [4,5]. In cases where there is access, it is either inadequate or unreliable [6]. The electricity facilities in Nigeria are plagued with low reliability because they are not properly maintained.

The challenges of reliability and insufficient capacity encountered by utilities in the Nigeria electricity industry have caused many consumers to resort to captive generators (gasoline and diesel) [7]. It is reported that in 2019, there were approximately between 20 million and 60 million captive gasoline and diesel generators operational in Nigeria [8]. Another report specified that on the average, a Nigerian household runs on captive generators for more than 9 h daily and they cumulatively expends about $12 billion annually for self-generated electricity [9]. This means of self-generation has been able to satisfy the electricity demands of many households. However, the recent increase in fuel pump prices has exposed the shortcoming of fossil-fuel-powered captive generators regarding long-term sustainability and affordability. For example, between 2015 and 2019, gasoline pump prices in Nigeria have increased by 67% (from $0.24/l to $0.4/l) [10]. With the proposed efforts of the government to fully deregulate the oil and gas sector in Nigeria, fuel prices will further increase, and this will also increase the operational cost of running fossil powered generators. Apart from this, the additional cost of distributing petroleum products across Nigeria presents a disparity in the final product prices across the country. Furthermore, the country has been through a slow phase in its economic growth and erratic exchange rates, interest rates and inflation rates. The proposed complete deregulation of the oil and gas sector and uncertainties surrounding the exchange rates, interest rates and inflation in Nigeria will further precipitate doubts about the sustainability of using standalone captive fossil fuel-powered generators.

Interestingly, Nigeria is blessed with diverse alternative energy resources such as solar radiation, biomass, hydro and wind that can be harnessed for electricity production [11]. On an annual basis, the average solar radiation received in Nigeria ranges between 7.0 $kWh/m^2/day$ and 3.5 $kWh/m^2/day$, while the wind speed varies between 3.0 m/s in the coastal regions and up to 5.12 m/s in the northern parts of the country. Although the possibility of harnessing these resources has been proposed [12–14], the variability of wind and solar irradiation resource is a big disadvantage in its adoption. One of the ways of mitigating this challenge is the use of energy storage systems [15]. Energy storage devices are classified in terms of storage time frame and medium of storage (Fig. 1) [15]. Since long-term energy storage such as pumped hydro may not be suitable for many locations and applications, medium energy storage devices (e.g., compressed air storage, batteries, and hydrogen) are good alternatives that are widely used.

Due to the technical breakthrough with respect to efficiency, the inclusion of hydrogen for energy production in the energy mix is gradually gaining commercial attention globally. This is evident in the amount of techno-economic feasibility research focused on the subject [16–22]. Production of hydrogen energy through renewable energy sources would limit the dependence on fossil fuel, reduce negative environmental impacts caused by fossil fuel and reduce the health risks involved in the use of fossil fuel. Apart from these, it would help in the decarbonization of the electricity industry through hybridization with other sources.

The idea of hybrid renewable energy design that deploys a hydrogen technology as a storage mechanism is not entirely new. It has been previously presented for various applications such as meeting community load demands [17], residential

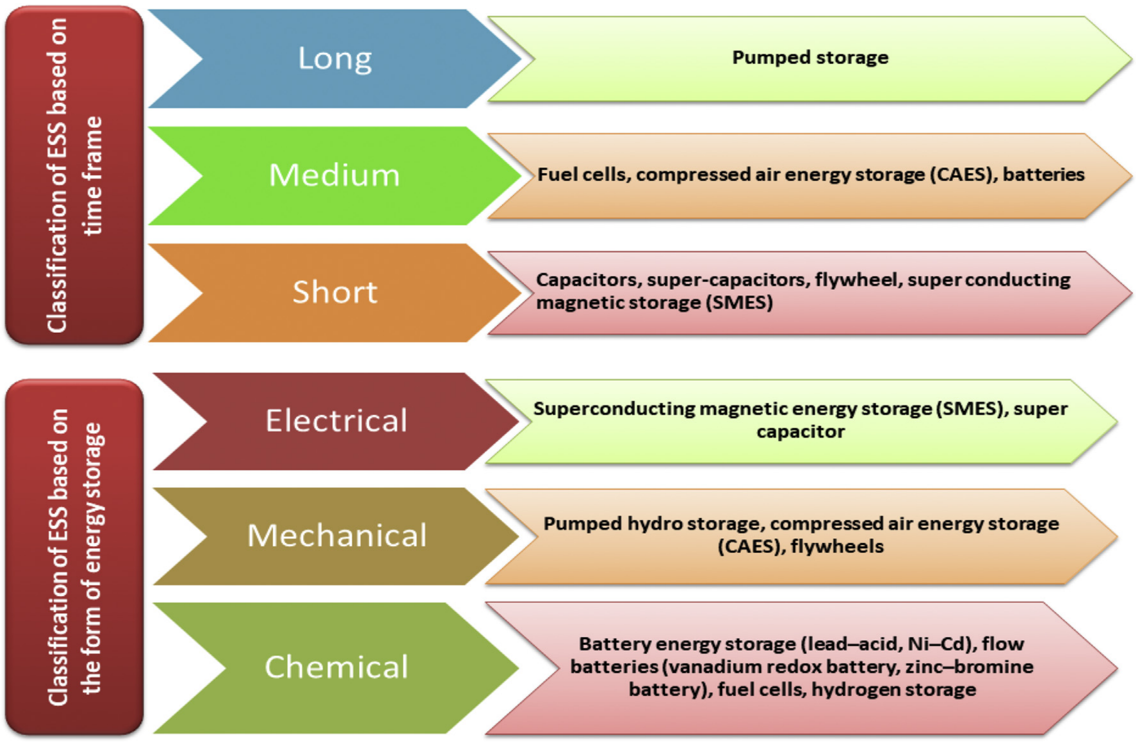



**Fig. 1 – Classification of energy storage [15].**

loads [23,24], educational facility [25], agricultural loads [26], transportation [27] and so on. The work presented by Acar et al. presented a comprehensive evaluation of how energy devices such as high-temperature batteries, conventional batteries, flow batteries, pumped hydro and hydrogen can be made sustainable for residential applications [28]. Based on information available from experts, Ren et al. proposed a two stage MCDM approach to select the most preferred technologies that can be used to produce hydrogen [29]. Also, various aspects of hydrogen energy generation have been explored; for example, using metrics related to social, environmental, and economic aspects of hydrogen production technologies, a framework that identifies, ranks and selects electrolysis technology has been presented using multi-criteria decision making method [30]. The study identified that the most preferred hydrogen production alternative is the proton exchange membrane electrolysis followed by alkaline electrolysis, solid oxide electrolysis and direct electrolysis of seawater respectively. In another study, an economic and thermodynamic assessment of a hybrid geothermal-solar system targeted at freshwater production, hot water, cooling load, hydrogen and electricity was carried out using a multi-objective optimization technique and TOPSIS. At the optimum point selected by TOPSIS, the system's cost rate and exergy efficiency were estimated as 63.89 and 21.63, respectively [31]. Using a MCDM technique and geographical information systems (GIS), an integrated model capable of selecting the best location for the siting of a hydrogen energy production facility using solar energy in Algeria was developed by Messaoudi et al. [32]. The result of the study shows that 21.74% of the land considered is unsuitable, 10.34% is “very low suitable”, 60.75% is a little bit suitable, 6.68% is moderately suitable and only 0.49% of the land is highly suitable. Using 14 conflicting but influential criteria, Rezaei et al. proposed a hybrid wind/solar power plant that can be used for hydrogen generation in 31 capital cities in Middle East, Asia [33]. Using HOMER, the authors proposed an energy alternative with distinct cost and operational characteristics for each of the 39 capital cities. The authors further applied Fuzzy-TOPSIS and concluded that the optimal city for the energy system is Yazd. To enhance power generation exergy efficiency and to utilize the waste heat from a biomass powered solid oxide fuel cell, Gholamian et al. proposed an evolutionary based multi-criteria optimization for hydrogen generation [34]. Optimal results show that the energy cost and the exergy efficiency of the SOFC/GT is 19.01 $/GJ and 33.22% respectively.

To contribute to the subject of hybrid renewable energy adoption in households in SSA, this study explores the sustainability (technical, economic, environmental) aspects of hybridizing PV, wind, diesel generator and hydrogen storage in meeting residential energy demands. Based on literature search, this study is the first of its kind to present a multi-criteria perspective to the ranking of technically and economically feasible energy alternatives consisting of fuel cell, wind turbine, solar PV, battery energy storage and hydrogen storage for a residential application in sub-Saharan Africa. Also presented in this study is the technical performance of system components. Hence, the originality of the research is the simultaneous inclusion of energy systems performance and multi-criteria decision making for selecting a hybrid energy system with hydrogen storage. Although the case study presented is from sub-Saharan Africa, the methods applied in this study can be adopted globally.

## Methodology

To implement the aim of the study, the efficacies of HOMER and CRiteria Importance Through Intercriteria Correlation-weighted complex proportional assessment (COPRAS) methods were deployed. HOMER was used to optimise the energy systems, while CRITIC-COPRAS was used to implement the multi-criteria aspect of the study. The energy system description and the mathematical models of the various components of the energy systems are presented in this section.

### *Case study and system description*

The proposed case study is targeted at a low-income residential area in Akoka - a district of Yaba in Lagos State, Nigeria (6.5270° N, 3.3918° E). Akoka is known for the presence of multiple tertiary academic institutions, and it serves as a transit between the mainland and the island of Lagos. It, therefore, houses many students' and staff accommodation. Because of the presence of educational institutions in Akoka, an adequate and reliable energy system is essential. The average daily photovoltaic power potential for Akoka is about 3.787 kWh/kWp (Fig. 2). Based on the renewable energy potential at the study location, a solar PV, fuel cell, hydrogen storage, wind turbine, battery is designed (Fig. 3). The addition of a battery bank and hydrogen storage is proposed to mitigate the intermittency of both wind and solar resources.

### *Energy system simulation*

The energy modeling tool used to simulate the energy systems is Hybrid Optimization of Multiple Electric Renewables (HOMER). It is an energy modeling software with the technical capabilities of modeling the operational, emission and financial implications of adopting both grid-connected and grid-independent energy systems (renewable and conventional). The software can perform modeling, optimization and uncertainty assessment of grid-connected and grid-independent energy systems [36]. HOMER implements the operational details by performing hourly calculations to ensure energy balance between the various energy sources and energy demand on an annual basis. It then estimates the emissions and the economic implications of the feasible systems. It also replicates the operational features of all components that form the energy system and calculates total annual power generation (Eq. (1)).

$$E_{tot} = \sum_{t=1}^{8760}\left(\sum_{w=1}^{W} P_w^t + \sum_{fc=1}^{FC} P_{fc}^t + \sum_{pv=1}^{PV} P_{pv}^t\right) \tag{1}$$

where $E_{tot}$ is the total electrical production, $P_w^t, P_{fc}^t and\ P_{pv}^t$ are the energy production from the wind turbine, fuel cell and PV panel at time $t$ respectively.

For the optimization process, the feasible energy systems obtained by HOMER is categorized and ranked using TNPC ($C_t$) (Eq. (2)). HOMER also can estimate the average cost per kWh of electricity (Eq. (5)).

$$C_t = \frac{C_{at}}{CRF(i, P_{yr})} \tag{2}$$

where $C_{at}$ is the total annualized cost (\$/yr) and CRF, the capital recovery factor, (i) is the annual real interest rate and $P_{yr}$ is the project lifetime.

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{3}$$

$$i = \frac{i_n - f_a}{1 - f_a} \tag{4}$$

where is the $i_n$ nominal interest rate and $f_a$ is the annualized inflation rate

$$LCOE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}} \tag{5}$$

$C_{ann,tot}$ is the total annualized cost (\$/yr), $C_{boiler}$ i. s the boiler marginal cost $\left(\frac{\$}{kWh}\right)$, $H_{served}$ i s the total thermal load served $\left(\frac{kWh}{yr}\right)$ and $E_{served}$ , is the total electrical load served (kWh /yr).

$$R_{fac} = \frac{E_r + T_r}{E_t + T_t} \tag{6}$$

where $E_r$ is the renewable energy production, $T_r$ is renewable thermal production, $E_t$ is the total energy production, $T_t$ total thermal production.

To capture the various impacts of uncertainties in input parameters, HOMER can carry out sensitivity analysis. HOMER can model systems such as wind, PV, biomass, grid, battery bank, hydro, electrolyzer, conventional generators, etc. HOMER takes inputs related to components' technical details, economic, resources (renewable and non-renewable), constraints and energy demand to give an optimal energy system configuration that meets all conditions specified by the developer.

#### *Wind power*

HOMER estimates the power output of the wind turbine by following 3 steps viz:

1. Adjusting the hourly wind speed from the anemometer height to the proposed hub height using either the power-law or the logarithmic profile
2. It refers to the power curve of the selected wind turbine and estimates the power generated under standard conditions (pressure and temperature)
3. It finally finds the product of the values generated in the 2nd step and air density to calculate the wind power output.

$$v_{hub} = v_{mes}\left(\frac{H_{hub}}{H_{mes}}\right)^{\beta} \tag{7}$$

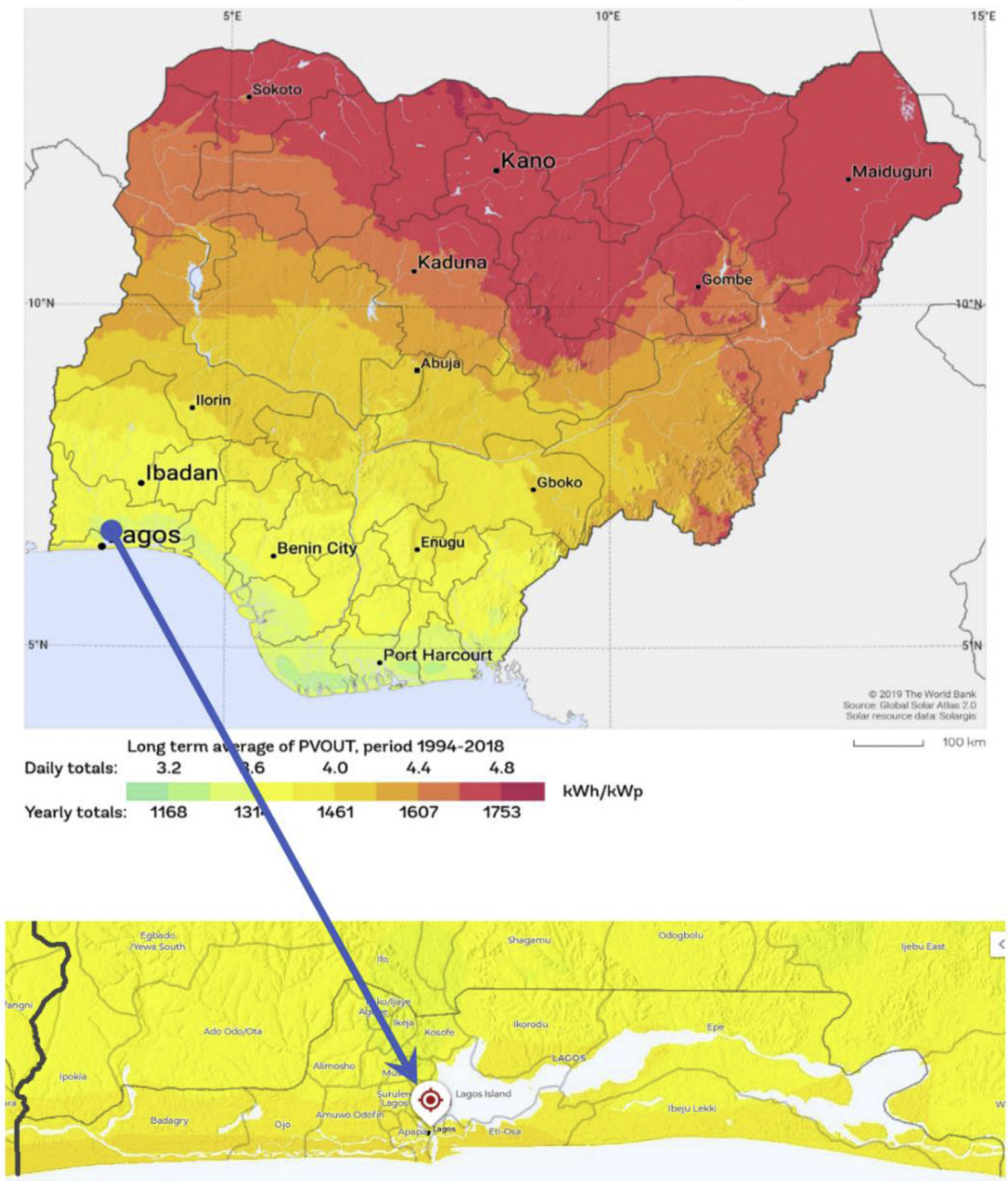



**Fig. 2 – Solar radiation map of Lagos [35].**

$$v_{hub} = v_{mes}\left(\frac{ln[H_{hub}/s_r]}{ln[H_{mes}/s_r]}\right) \tag{8}$$

$$P_{WD} = \frac{\rho}{\rho_o} \times P_{WD,STP} \tag{9}$$

Where the wind speed at the proposed hub height $H_{hub}$ is given as $v_{hub}$, $v_{mes}$ is the wind speed measured at height $H_{mes}$ where the anemometer is placed to take wind speed measurement, $s_r$is the surface roughness length, $\beta$ is the power-law exponent, $\rho$ is the real density of air, $\rho_o$ is the density of air at standard temperature and pressure, $P_{WD,STP}$ is the output of the wind turbine at standard temperature and pressure.

*PV power*

Also, to evaluate the output power of the solar PV panel, HOMER uses the expression given in Eq. (10).

$$P_{pv} = Y_{pv} f_{pv}\left(\frac{\overline{G_T}}{\overline{G_{T,STC}}}\right)[1 + \alpha_P(T_C - T_{C,STC})] \tag{10}$$

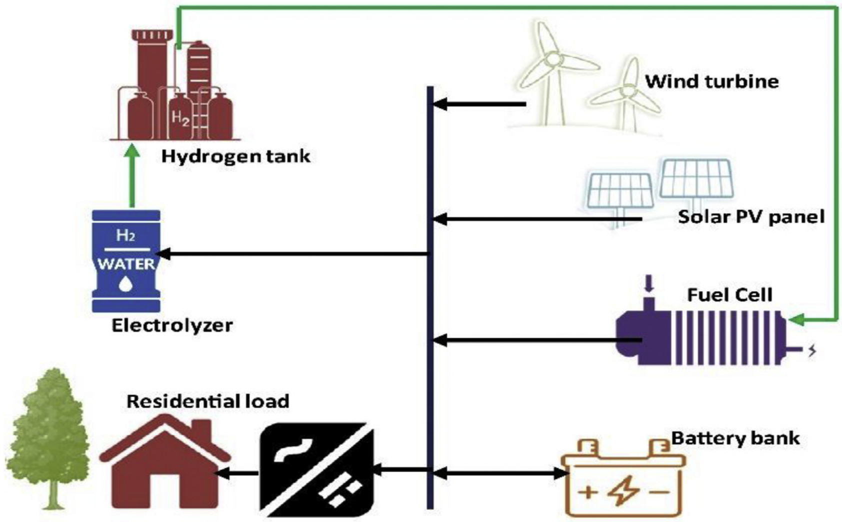



**Fig. 3 – HRES system proposed based on resource potentials at the location.**

Eq. (10) reduces to 11 when temperature effects are neglected. In this study, the effect of temperature on the output of the PV cell is included.

$$P_{pv} = Y_{pv} f_{pv} \left( \frac{\overline{G_T}}{\overline{G_{T,STC}}} \right) \tag{11}$$

*where* $Y_{pv}$ is the rated capacity of PV array, $f_{pv}$ is the PV derating factor (%), $\overline{G_T}$ is the solar irradiation incident on the PV array $\left(\frac{kW}{m^2}\right)$, $G_{T,STC}$ is the solar irradiation incident at standard condition $\left(\frac{1kW}{m^2}\right)$, $\alpha_P$ is the temperature coefficient of power $(\%/^\circ C)$, $T_C$ is PV cell temperature $(^\circ C)$, $T_{C,STC}$ is the PV cell temperature under standard test conditions $(^\circ C)$.

*Storage system*

A combination of battery storage system and hydrogen storage system are used as back up for the proposed energy system. The hydrogen energy system consists of a combination of fuel cell, electrolyzer and a hydrogen storage tank. The expression used to compute the rate of hydrogen generation through an electrolyzer is given in Eq. (12). The hydrogen produced through this process is compressed and stored in a hydrogen tank. The power needed to compress hydrogen gas is expressed in Eq. (13) [22]. The fuel cell is used to convert the stored hydrogen into electricity [49] and the output power of a fuel cell can be obtained using Eq. (14).

$$\alpha \dot{H}_2 = \eta_f \left( \frac{N_s \times I_e}{n \times F} \right) \tag{12}$$

$$P_{com} = \alpha \dot{H}_2 \left[ \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} \right] \left( \frac{\gamma}{\gamma - 1} \right) \left( \frac{T}{\eta_{com}} \right) R \tag{13}$$

$$FC_{ele} = LHV_h \times \alpha \dot{H}_2 \times \rho_h \times \eta_{fc} \tag{14}$$

Where is the $P_1$ and $P_2$ are the inlet and outlet pressure, R is the gas constant, $\gamma$ is the polytrophic coefficient, $\eta_{com}$ is the efficiency of the compressor, $\alpha \dot{H}_2$ is the mass flow rate of hydrogen, $\rho_h$ is the density of compressed $H_2$, $LHV_h$ is the lower heating value of hydrogen gas and $\eta_{fc}$ is fuel cell efficiency.

The number of batteries for the energy system is obtained using Eq. (15), while the capacity of the hydrogen tank $C_{htank}$ is obtained as the ratio of the load demand and the energy content the subject of (Eq. (16)). Apart from electricity, fuel cells generate bye products such as heat, water, and a minimal quantity of Nitrogen Oxides (NOx), depending on the fuel source. Since the energy system considered in this study does not include a fossil-fuel-powered generator, NOx is the only pollutant reported; this is estimated using HOMER.

$$n_b = \frac{Batt_{aut} \times E_d (1000Wh/kWh)}{V_n Q_n \left( \frac{100 - SOS_{min}}{100} \right) (24hr/day)} \tag{15}$$

$$C_{h\ \tan\ k} = \frac{H_{aut} \times E_d (3.6MJ/kWh)}{LHV_h (24hr/day)} \tag{16}$$

Where $Batt_{aut}$ is battery autonomy, $SOS_{min}$i s minimum state of charge (%), $Q_n$ is nominal capacity of a single battery $(Ah)$, $V_n$ is t he nominal voltage of a single battery $(V)$, and $n_b$ is the number of battery, $H_{aut}$ is the autonomy of the hydrogen tank, and $LHV_h$ is the energy content (lower heating value) of hydrogen [120 MJ/kg].

### *Control strategies*

Since the proposed energy system is multi-source, a management strategy is required to coordinate the energy flow between the various components. Two types of dispatch strategies were adopted in this study; these include the load following (LF) and cycle-charging (CC) dispatch strategies [37]. A dispatch strategy is a collection of rules or measures deployed for controlling the operation of the energy sources and storage components, especially each time the power from the renewable energy sources is insufficient to meet the load. For the load following strategy, a power plant generates enough energy to power the load while the storage devices are uncharged. At the same time, in the cycle-charging mode, the generator works at its maximum rated capacity to meet the load and charge the storage system with the excess energy. Since the proposed energy system is not connected to the grid, excess power cannot be evacuated to the grid, hence, the excess energy is only used in charging the energy storage. Excess electricity is extra electrical power that must be discarded because it cannot be used to charge the storage devices or meet any power demand. They usually occur when the energy generated exceeds the demand and the storage devices can no longer absorb the energy. In this case study, since the proposed energy system is an off-grid system, excess electricity is assumed to be dumped through a resistive heater.

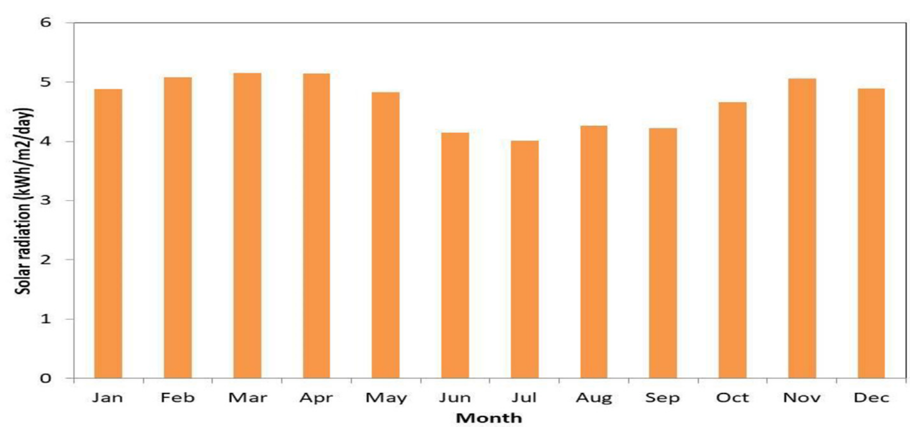
Furthermore, to model the size of the converter in HOMER, the rectifier power, which is the maximum DC power the converter can deliver through rectification is specified; this is usually a fraction of the inverter capacity. The rectifier capacity is therefore not a separate decision variable. HOMER assumes that the rectifier and inverter sizes are not surge capacities that the electronic converter can accommodate for only short periods, but continuous capacities that the device can withstand for as long as necessary.

### Site resources

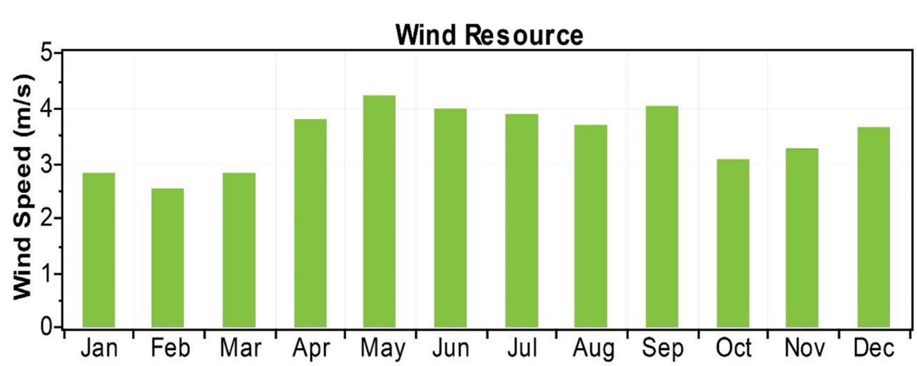
A 22-year average of monthly solar resource (solar radiation and clearness index) for Akoka was obtained from the NASA website. The minimum solar irradiation for the location is 4.0 kWh/m$^2$/day while the maximum radiation (5.2 kWh/m$^2$/day) is noticed to occur in the dry season (May and April) (Fig. 4(a)). The value of the solar irradiation is an indication of a moderate potential for electricity generation from PV panels. Typically, solar irradiation fluctuates relative to location, season, precipitation, cloud conditions, and shading. The monthly wind speed (average of 22 years) for the location under consideration is also extracted from the NASA database. The data shows that a maximum wind speed of 4.21 m/s occurred in May, while the minimum wind speed (2.54 m/s) was recorded in February. The wind speed for Akoka is given in Fig. 4b.

### Energy demand

Typically, residential energy demand in Nigeria depends on the family size, lifestyle, and income level. Most low-income




(a)




(b)

**Fig. 4 – (a) Solar resource (b) wind resource data for the site.**

earners in Nigeria tend to use fewer gadgets that translate to reduced electricity consumption while mid-income and high-income earners usually occupy larger buildings and have access to various gadgets (based on their lifestyle) that tends to increase their electricity consumption. In low-income families in Nigeria, consumers prefer to use kerosene or gas for cooking instead of electricity. Low-income households usually use electricity for lighting, ironing, heating (electric kettle), ventilation (fan), radio, TV, phone charging and some basic electricity use (Table 1). For this case study, a low-income household energy demand was adopted based on Babatunde et al. [7]. For this case, the heating load and cooling load are neglected because in Nigeria, the temperature during the rainy season (cold) is reasonably fair *(with an average of* 24°C*)*, and heating of the spaces is not required. However, during the dry season, many low-income households use fans for cooling and ventilation purposes. To obtain the daily energy consumption pattern, the individual power consumed by each appliance is summed on an hourly basis and plotted against time (Eq. (17)). In developing the energy demand pattern, it is assumed that the consumers occupying the building would not be at home between 8.00 h and 17.00 h as they are expected to be engaged at work [38]. The consumption is expected to increase starting from 16.00 h when the residents retire to their apartment. Fig. 5 shows the pattern of energy consumption of the residential apartment.

$$E_d = \sum_{i=1}^{L} P_L \times m_L \times n_L \tag{17}$$

where $P_L$ is the power rating of the equipment, $m_L$ is the number of each piece of equipment connected and $n_L$ is the duration of the operation.

To carry out the simulations, HOMER requires periodic details of the renewable energy resources, the energy demand to be met, the technical details of all energy system components, the economic details, and the search space. The energy demand used in this case study was adapted from a previous study carried out by Babatunde et al. [7], the technical details were obtained from the technical data sheets of the various components and the literature, the economic details were obtained from the literature and market survey while the renewable energy resource data were obtained from the NASA database.

### *Techno-economic features of energy system components*

In this study, the initial cost for the purchase of a 0.25 kW solar PV panel with a lifespan of 25 years is taken as $298.12 [39], while its replacement cost is assumed to be $200. Other details of the PV panel include derating factor- 80%, efficiency at standard test condition-13%, nominal operating cell temperature- 47 °C, and temperature coefficient of power-(-0.5%/°C) [40]. It is also assumed that the position of the PV panel is fixed throughout its lifetime. As for the wind turbine (0.4 kW DC), its initial cost of procurement is' $1356.66, the replacements cost and operating and cost of maintenance (O&M) are taken as $1300 and 20$/year respectively [41]. Its operational lifetime and hub height are 15 years and 20 m, respectively. The real interest rates based on the prevailing interest rates in Nigeria is approximately 12% [42]. Details of other inputs are presented in Table 2.

### *COPRAS method*

Developed by Zavadskas et al. COPRAS is a compensatory MCDM approach with independent attributes [47]. Details of this method is presented in the literature [47–49], but the summary of the steps in the implementation of COPRAS include:

1 .Formation of decision matrix
2. Normalization of the decision matrix that was developed in step 1
3. Determination of the weight and computation of the weighted normalized decision matrix.
4. Maximization and minimization of the indexes
5. Computation of the relative significance value of the alternatives
6. Ranking and selection of the alternatives based on the relative significance values of obtained from step 5. The smallest relative significance value is ranked last, while the

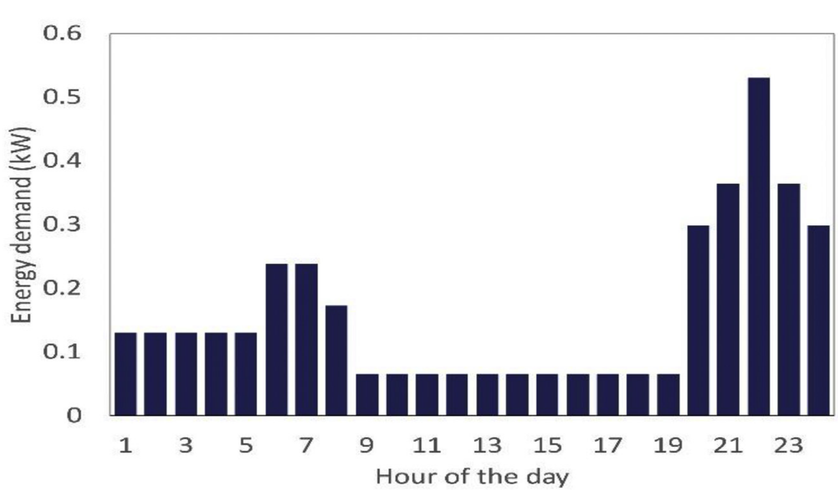



**Fig. 5 – The energy demand of the residential apartment.**

**Table 1 – Electrical appliance and daily energy demand [7].**

| | Quantity | Power (kW) | Total (kW) | Cumulative hour(s)/day | Total energy (kWh/day) |
|---|---|---|---|---|---|
| Television | 1 | 0.065 | 0.065 | 5 | 0.33 |
| Iron | 1 | 1 | 1 | 0.17 | 0.17 |
| Fan | 2 | 0.065 | 0.13 | 12 | 0.98 |
| Lamps | 6 | 0.018 | 0.108 | 8 | 0.59 |
| Fridge | 1 | 0.065 | 0.065 | 6 | 0.39 |
| Others | | 0.050 | 0.050 | 5 | 0.25 |

**Table 2 – Techno-economic details of HRES components.**

| System Component | Capital Cost ($) | Replacement cost ($) | O & M cost | Sizes consider | Life Span |
|---|---|---|---|---|---|
| PV panel (0.25 kW) [39] | 295 | 290 | 0$/year | 0–5 kW | 20 years |
| Battery (12 V,200Ah) [43] | 356.55 | 350 | 2$/year | 0-40 (No) | 4 years |
| Converter (0.3 kW) [44] | 36.83 | 30.00 | 2$/year | 0-4 (kW) | 15 years |
| Wind turbine (0.4 kW DC) [41] | 465.0600 | 400 | 20/year | 0-3 (No) | 15 years |
| Fuel cell (1 kW) [45] | 4000 | 3000 | 0.01 $/h | 0, 0.4 | 30,000 h |
| Hydrogen tank (8 kg) [46] | 3100 | 3100 | 4 | 0–28 kg | 20 years |
| Electrolyzer (8 kW) [46] | 2700 | 2700 | 30$/year | 0–0.8 kW | 25 years |

alternative with the highest relative significance value is the most preferred.

## Results

The results of the analysis carried out in this study are presented in this section. The output results include size of components, dispatch strategies, cost implications, energy productions and Nitrogen oxides emission results. As earlier discussed in the methodology section, the ranking of the optimal systems is based on the TNPC accrued to the systems. The system with the least TNPC is ranked the best. For this case study, the feasible systems that would power the load as obtained from the process of the simulations are 4 in number; these include PV/Battery ($A_1$), PV/Wind/Battery ($A_2$), PV/FC/Battery ($A_3$), PV/FC/Wind/Battery ($A_4$). Based on the result of the HOMER (economic criterion), it is seen that A1>A2>A3>A4. From Table 3 the most feasible energy system consists of 2 kW PV, 0.8 kW converter and 4 number 200Ah, 12 V battery operating in cycle charging mode. The investment cost needed for this system is $3818, while the annual operating cost and cost of energy (COE) are $410 and 0.726$/kWh, respectively. This system (PV/battery system ($A_1$)) will have a total energy production of 2,923 kWh per annum with an annual capacity shortage and annual excess electricity production standing at 7 kWh and 1592 kWh, respectively. The only pollutant attributed to this system is the one released during the production of the components.

The system ranked 2nd based on TNPC is the combination of PV/Wind/Battery ($A_2$), This alternative requires a 1.5 kW PV panel, while a 0.4 kW DC wind turbine and 6 number 200Ah, 12 V battery would also be needed to meet the load requirement. A 0.8 kW converter would also be needed to convert DC to AC and charge the battery bank. The TNPC, COE and total capital cost of the PV/Wind/Battery system are $9241, 0.742$/kWh and $4407, respectively. Out of the total annual energy production of 2302 kWh offered by the system, the PV panels generated 95% (2192 kWh) while about 5% (110 kWh) is attributed to the wind turbine. If compared to the most feasible system (PV/Battery), its capacity shortage (8 kWh/yr) is slightly higher, while its excess energy is slightly lower (983 kWh/yr).

The next energy system based on TNPC is the PV/FC/Battery system ($A_3$),. The sizes of the various components include PV- 2 kW, fuel cell- 0.4 kW, electrolyzer- 3 kW, hydrogen tank-

**Table 3 – Size, economic and emission results of the feasible energy systems.**

| Description | Unit | ($A_1$) | ($A_2$) | ($A_3$) | ($A_4$) |
|---|---|---|---|---|---|
| PV | kW | 2.0 | 1.5 | 2.0 | 2.0 |
| Wind turbine | Nos. | 0 | 1 | 0 | 1 |
| FC | kW | 0.0 | 0.0 | 0.4 | 0.4 |
| Battery | Nos. | 4 | 6 | 4 | 4 |
| Converter | kW | 0.8 | 0.8 | 0.8 | 0.8 |
| Electrolyzer | kW | 0 | 0 | 3 | 3 |
| H2 Tank | kg | 0 | 0 | 2 | 2 |
| Dispatch strategy | | CC | CC | LF | LF |
| Total capital cost | $ | 3818 | 4407 | 7205 | 7670 |
| Total NPC | $ | 9060 | 9241 | 9687 | 10,324 |
| Operating cost | $/yr | 410 | 378 | 194 | 208 |
| COE | $/kWh | 0.726 | 0.742 | 0.772 | 0.823 |
| LCOH | $/kg | 0 | 0 | 17.30 | 18.8 |
| PV production | kWh/yr | 2923 | 2192 | 2923 | 2923 |
| Wind production | kWh/yr | 0 | 110 | 0 | 110 |
| FC production | kWh/yr | 0 | 0 | 726 | 704 |
| Tot. electrical production | kWh/yr | 2923 | 2302 | 3650 | 3737 |
| Cap. shortage | kWh/yr | 7 | 8 | 1 | 0 |
| Excess electricity | kWh/yr | 1592 | 983 | 557 | 685 |
| NOx emissions | kg/yr | 0 | 0 | 3 | 2 |

PV/Battery ($A_1$), PV/Wind/Battery ($A_2$), PV/FC/Battery ($A_3$), PV/FC/Wind/Battery.($A_4$)

2 kg, battery (220Ah, 12 V)- 4 Nos, all with an initial cost and TNPC of $9687 and $7,205, respectively. Other costs attributed to this system include total annual operation cost- 194$/yr, and COE-0.772$/kWh. Out of the total annual energy production of 3650 kWh, Fuel cell contributed 726 kWh (20%), and PV contributed 2923 kWh (80%). To function optimally, the energy system would have to be operated in a load-following dispatch strategy. It is worth noting that the PV/FC/Battery system will emit 3 kg of NOx annually.

The last system ($A_4$), on the list is one consisting of a 2 kW PV panel, 0.4 kW DC wind turbine, 0.4 kW fuel cell, 4 Nos 12, 200Ah battery, 2 kg Hydrogen tank and 3 kW electrolyzer all operating in the load-following mode. This system has the highest TNPC, which stands at $10,324. Other costs include

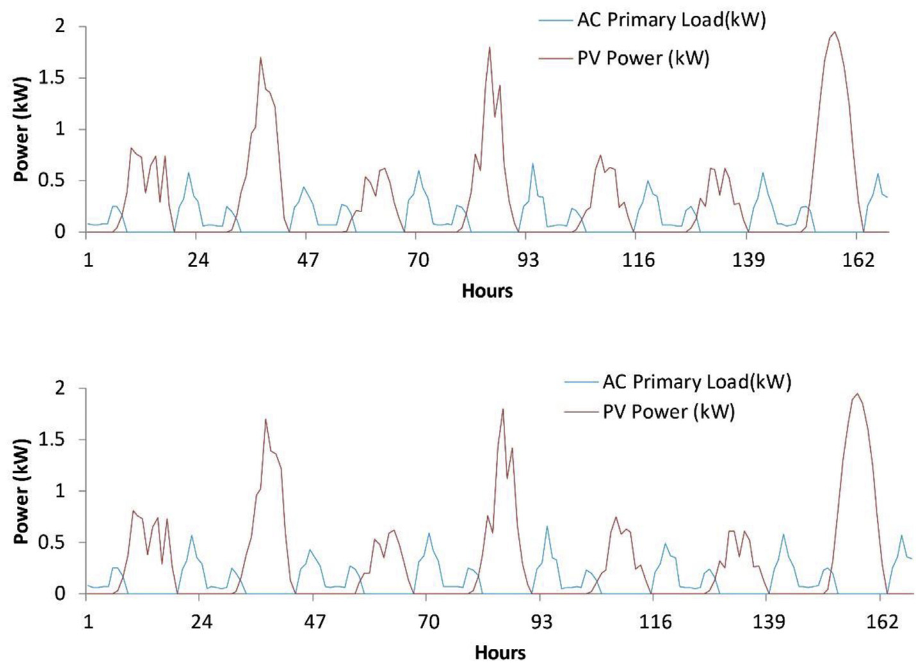



**Fig. 6 – Typical weekly performances of the PV/Battery ($A_1$) energy system (September 19–25 and March 18–25).**

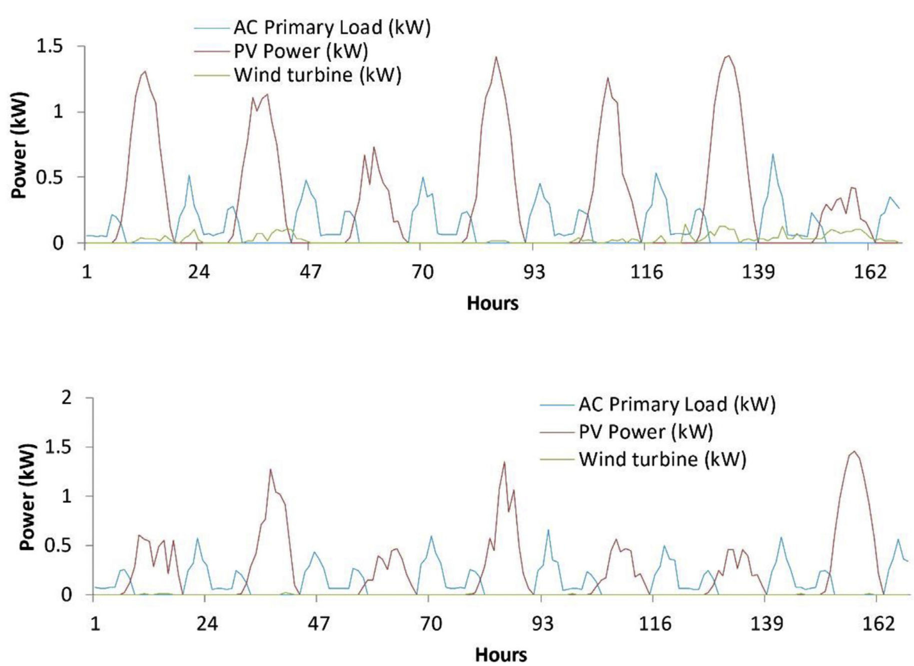



**Fig. 7 – Performances of the PV/Wind/Battery ($A_2$) energy system component for a typical week (September 19–25 and March 18–25).**

total capital cost- $7,670, Total O&M Cost $208, and COE-0.823$/kWh. The energy mix shows that PV contributed 78% (2923 kWh), Fuel cell contributed 19% (704 kWh) and wind contributed 3% (110 kWh). The emission attributed to the PV/FC/Wind/Battery is 2 kg of NOx annually. The performances of the various energy systems for a typical week in both dry and rainy season (September 19–25 and March 18–25) is given in Figs. 6–9. As can be seen in the figure, the PV panel is common to all the energy system configurations, and it produces the bulk of the daily energy.

For all the four feasible energy systems, the PV panel output is higher during the dry season. For the PV/FC/Battery and PV/Wind/FC/Battery energy systems, the FC is seen to produce most of its energy during the evening when the PV power is unavailable. During the day, the excess production from the solar PV panels is used to operate the electrolyzer to produce hydrogen and charging the battery bank (Fig. 10).

The issue of sustainability is an important factor that is of great interest to investors, decision-makers, consumers, and other stakeholders in the energy sector. For instance, a

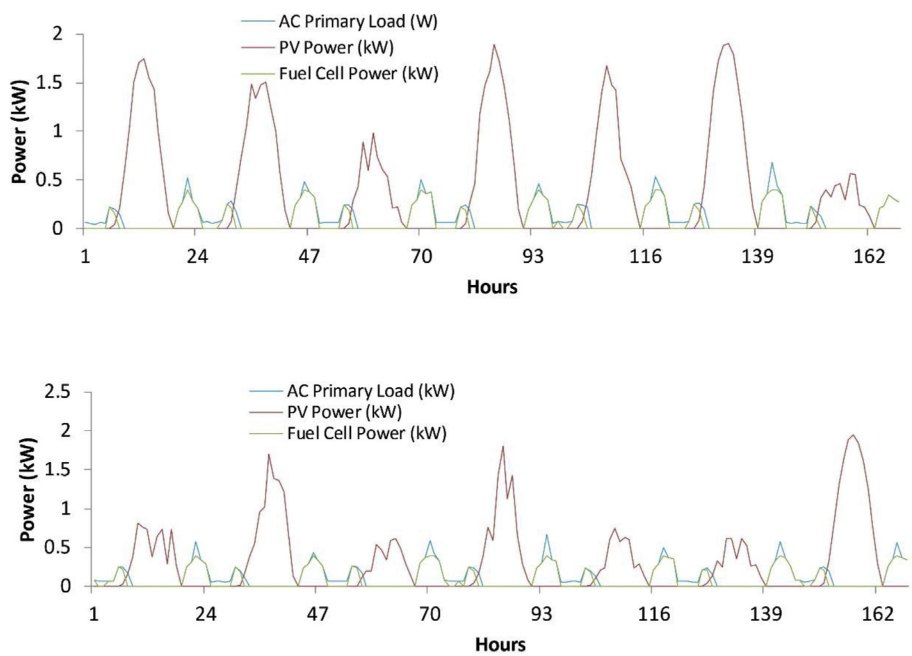



**Fig. 8 – Typical weekly performance of the PV/FC/Battery ($A_3$) energy system (September 19–25 and March 18–25).**

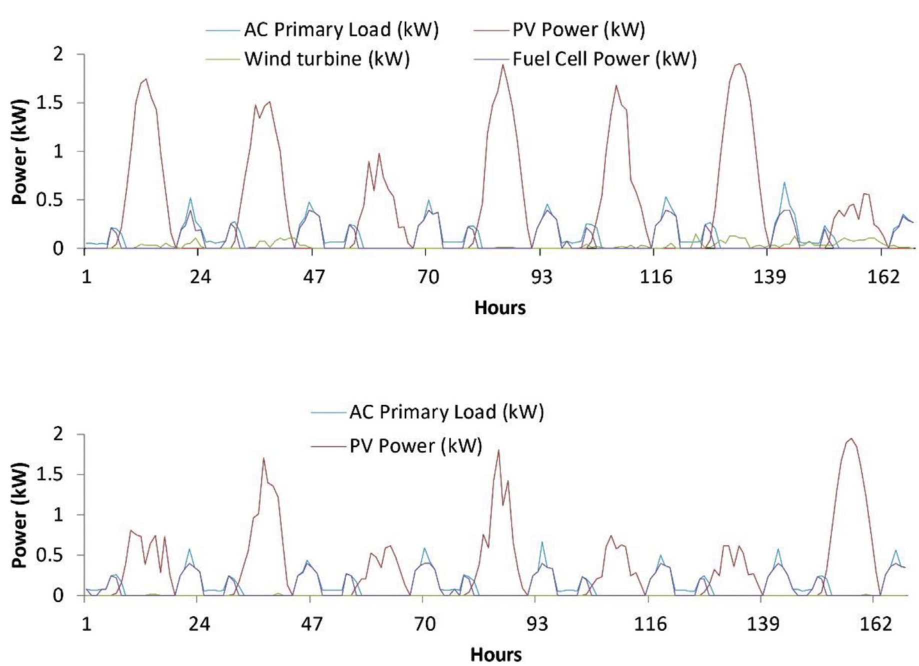
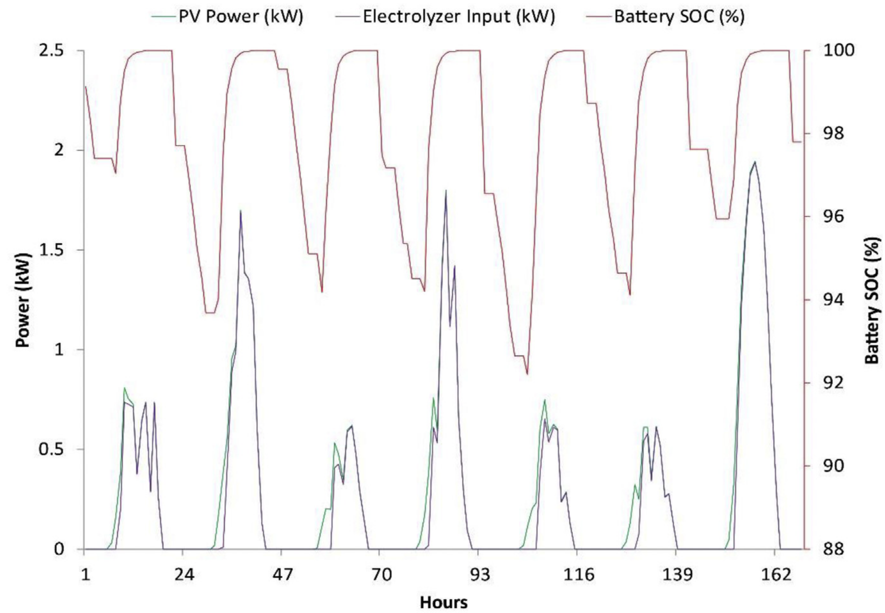
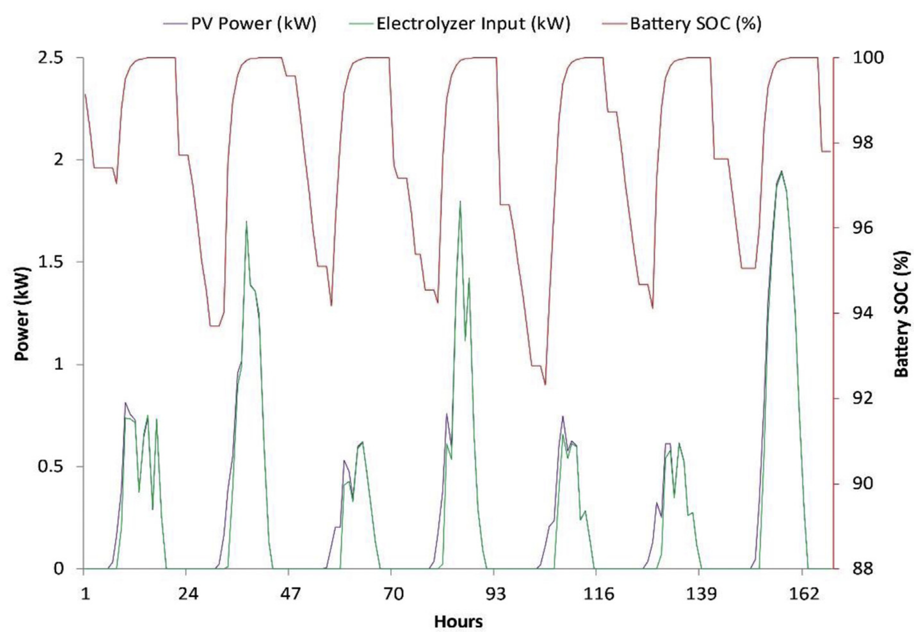



**Fig. 9 – Typical weekly performances of PV/FC/Wind/Battery ($A_4$) (September 19–25 and March 18–25).**




(a)




(b)

**Fig. 10 – Operational features of the PV, battery and electrolyzer for a typical week: (a) September 19–25 and (b) March 18–25).**

consumer would like to purchase a reliable energy system whose unit cost of energy is cheap; an investor may be interested in the number of jobs produced and the profit, while an environmentalist would prefer a system with minimal environmental impact. Therefore, the choice of the most economical energy system alternative depends on multiple sustainability criteria rather than a single criterion. The ranking of the energy system presented in Table 3 is based on a single criterion (TNPC). However, it will be encompassing to rank and select the most feasible energy system using more than one criterion. To handle multiple criteria problems, the use of multi-criteria decision methods have been reported to be effective [50,51]. In this study, because of its capability to estimate both quantitative and qualitative criteria [52], complex proportional assessment (COPRAS) was used in ranking the system alternatives based on multiple criteria [53].

The criteria included in these analyses include economic (total capital cost ($C_1$), TNPC ($C_2$), COE ($C_3$)), technical (capacity shortage ($C_5$), excess electricity ($C_6$), total electrical production ($C_7$)) and environmental (NOx emission $C_4$)). These were all extracted from the results presented in Table 4. Of the attributes of these criteria, excess electricity and total electrical production are regarded as beneficial criteria while capacity shortage, NOx emission, total capital cost, TNPC, and COE are the non-beneficial criteria. Beneficial criteria are criteria whose higher value is desired while non-beneficial criteria are those whose lower value is desired. The alternatives listed in Table 4 are the four energy systems obtained from the HOMER simulation.

Usually, the criteria and their attributes do not have the same contribution and preferential value, it is therefore, important to obtain the weight of each criterion. To determine the influence of each attribute in the initial decision matrix, the CRiteria Importance Through Intercriteria Correlation (CRITIC) method was used, and the results are presented in Fig. 11. According to Diakoulaki et al., "the CRITIC method is based on the contrast intensity of criteria, quantified employing the standard deviation of the scores criterion" [54]. Based on the CRITIC method, the attribute that contributed the highest weight is the total electrical production (33.1%), followed by the capacity shortage (21.7%), NOx emission (10.4%), total capital cost (9.5%), TNPC (8.6%), COE energy (8.5%), and excess electricity (8.2%) (see Fig. 11). The technical criteria contributed 63%, the economic criteria contributed 26.6%, while the environmental criteria contributed 10.4%. The weights of these criteria are part of the input for the COPRAS method. Details of these methods are available in the literature [55,56].

The first step in the implementation of the COPRAS method is the formation of decision matrix. Based on the selected criteria, an initial decision matrix showing the non-beneficial and beneficial criteria was developed (Table 4). The initial decision matrix is then normalized and the weighted normalized matrix is calculated. The results of these two steps are given in Tables 5 and 6, respectively.

From the weighted normalized matrix, the sum of benefit criteria values ($B_i$), sum of cost criteria values ($C_i$), relative significance of each alternative ($Q_i$) and utility degree ($U_{di}$) for each alternative are obtained (Table 7). The utility degree is used to rank the energy system alternatives. The alternative with the highest utility degree is the most preferred alternative, while the alternative with the least utility degree is the least preferred option. From the results of the multi-criteria method (COPRAS), the system alternatives are ranked as $A_4 > A_1 > A_3 > A_2$; this contrasts with the ranking from HOMER ($A_1 > A_2 > A_3 > A_4$) which is based on a single criterion (TNPC).

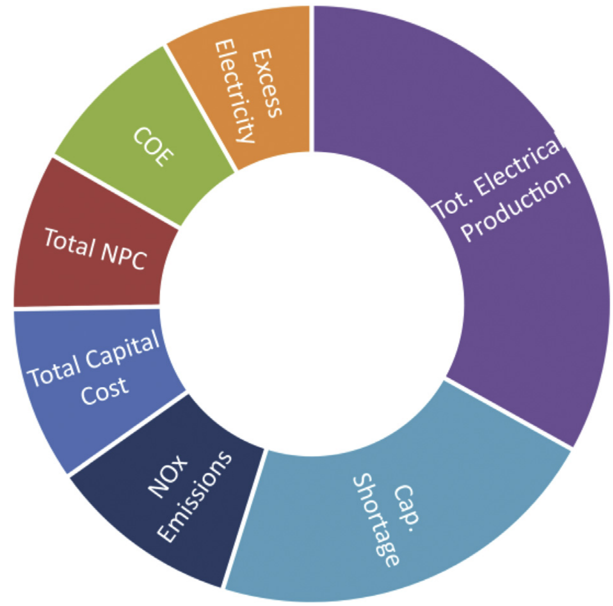



**Fig. 11 – Contribution of each attribute (weights).**

**Table 5 – Normalized matrix.**

| Alternatives | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ |
|---|---|---|---|---|---|---|---|
| $A_1$ | 0.17 | 0.24 | 0.24 | 0.00 | 0.44 | 0.42 | 0.23 |
| $A_2$ | 0.19 | 0.24 | 0.24 | 0.00 | 0.50 | 0.26 | 0.18 |
| $A_3$ | 0.31 | 0.25 | 0.25 | 0.60 | 0.06 | 0.15 | 0.29 |
| $A_4$ | 0.33 | 0.27 | 0.27 | 0.40 | 0.00 | 0.18 | 0.30 |

## Discussion

The possibility of deploying a HRES that consists of PV, wind turbine, fuel cell, hydrogen tank and battery to supply a residential load was implemented, and the simulation results shows that if the TNPC is used to rank the energy systems, the most feasible is the PV/battery ($A_1$), followed by the PV/Wind/Battery ($A_2$), PV/FC/Battery ($A_3$) and PV/FC/Wind/Battery ($A_4$) respectively. Hence, based on single criterion, the ranking of the energy system can be expressed as $A_1 > A_2 > A_3 > A_4$. However, when the feasible energy systems were subjected to multiple criteria, the order of ranking changed to $A_4 > A_1 > A_3 > A_2$. When compared to each other, energy system $A_1$ has the least economic implication (TNPC, COE and initial investment); however, energy system $A_4$ included hydrogen storage and had the advantage of being more reliable with a lower capacity shortage and more energy

**Table 4 – Initial decision matrix.**

| Alternatives | Non-beneficial | | | | | Beneficial | |
|---|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ |
| $A_1$ | 3818.00 | 9060.00 | 0.73 | 0.00 | 7.00 | 1592.00 | 2923.00 |
| $A_2$ | 4407.00 | 9241.00 | 0.74 | 0.00 | 8.00 | 983.00 | 2302.00 |
| $A_3$ | 7205.00 | 9687.00 | 0.77 | 3.00 | 1.00 | 557.00 | 3650.00 |
| $A_4$ | 7670.00 | 10324.00 | 0.82 | 2.00 | 0.00 | 685.00 | 3737.00 |

Table 6 – Normalized weighted matrix.

| Alternatives | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ |
|---|---|---|---|---|---|---|---|
| $A_1$ | 0.01572 | 0.02028 | 0.02009 | 0.00000 | 0.09504 | 0.03431 | 0.07671 |
| $A_2$ | 0.01815 | 0.02068 | 0.02053 | 0.00000 | 0.10861 | 0.02119 | 0.06042 |
| $A_3$ | 0.02967 | 0.02168 | 0.02136 | 0.06234 | 0.01358 | 0.01201 | 0.09579 |
| $A_4$ | 0.03158 | 0.02311 | 0.02277 | 0.04156 | 0.00000 | 0.01476 | 0.09808 |

Table 7 – *Bi, Ci, Qi, and Udi* for each alternative.

| Alternatives | $C_i$ | $B_i$ | $Q_i$ | $U_{di}$ | Rank |
|---|---|---|---|---|---|
| $A_1$ | 0.15 | 0.11 | 0.29 | 85.22 | 2 |
| $A_2$ | 0.17 | 0.08 | 0.24 | 71.34 | 4 |
| $A_3$ | 0.15 | 0.11 | 0.29 | 85.17 | 3 |
| $A_4$ | 0.12 | 0.11 | 0.34 | 100.00 | 1 |

production. While a single criterion may be sufficient for ranking energy system from the perspective of a single stakeholder, when multiple metrics and stakeholders are involved, multi-criteria decision-making methods would be more appropriate. The initial cost of energy system $A_1$ is $3818, and that of $A_4$ is $7670; looking at initial cost of both systems, $\mathbf{A_4}$ is more than 100% the initial cost attributed to $\mathbf{A_1}$. The high initial cost of energy system $\mathbf{A_4}$ is mostly due to the hybrid nature of the system and the expensive nature of the fuel cell and hydrogen tank. In a country like Nigeria, since both energy systems serve the same purpose, consumers would prefer to purchase $A_1$ rather than $A_4$. However, if the right policies that encourage the sale of electricity to the grid are implemented, consumers may likely deploy system $A_4$. Both systems are capable of supplying 100% renewable energy, thereby mitigating emissions and climate change.

## Conclusions

A framework that can be used for the proliferation of hydrogen storage systems in residential renewable energy applications has been presented in this study. First, possible energy systems consisting of a combination of solar PV, small wind turbine, battery and hydrogen energy storage were simulated and ranked based on TNPC. These feasible systems were then re-ranked using multiple criteria, namely economic, technical, environmental. The attributes considered during the multicriteria ranking include total capital cost, total net present cost, cost of energy, capacity shortage, excess electricity, total electrical production, and NOx emission. The study results show that to aid the inclusion of hydrogen storage in a residential applications; stakeholders cannot neglect the multicriteria aspects of energy technologies. For example, the result of the study was able to show that if a consumer wants to purchase or acquire an energy system considering total net present cost, the best system would be PV/Battery (a system that does not include hydrogen energy storage), however, if more than one metric is considered, the best energy system choice would change to PV/FC/Wind/Battery (a system that included hydrogen energy storage). Hence, for a comprehensive analysis of energy systems, various perspectives related to both technical and non-technical must be considered. Future studies would include the dynamic modeling of the proposed energy systems and its effect on the sustainability criteria. Also, the effect of variations in the costs associated to fuel cell can be investigated to monitor the economic and operational features of the feasible systems.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## REFERENCES


[1] Chefurka P. World energy and population: trends to 210017. Canada: Oil Drum; 2007.

[2] Blimpo MP, Cosgrove-Davies M. Electricity access in sub-Saharan Africa: uptake, reliability, and complementary factors for economic impact. World Bank Publications; 2019.

[3] Saifuddin N, Bello S, Fatihah S, Vigna K. Improving electricity supply in Nigeria-potential for renewable energy from biomass. Int J Appl Eng Res 2016;11(14):8322–39.

[4] United States Agency for International Development. Nigeria power Africa fact sheet. 2020 (accessed Apr. 18, 2020), https://www.usaid.gov/powerafrica/nigeria.

[5] Adeyemi M. Nigeria: 90 million Nigerians lack electricity supply, says fashola,. 2019 (accessed Feb. 19, 2020), https://allafrica.com/stories/201803060005.html.

[6] IEA – International Energy Agency. SDG7: data and Projections Access to affordable, reliable, sustainable and modern energy for all," *Flagship report*. 2019 (accessed Feb. 19, 2020), https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity.

[7] Babatunde OM, Munda JL, Hamam Y. Hybrid energy system for low-income households. 2017. https://doi.org/10.1109/AFRCON.2017.8095625.

[8] Adeleru-Balogun T. Nigeria's ever-present hum (of generators)," South Africa. Oct. 2019.

[9] Osae-Brown A, Olurounbi R. "Nigeria runs on generators and nine hours of power a day," Nigeria. Sep. 2019.

[10] Nigerian Prices, "Petrol prices in Nigeria today (April 2019). 2019 (accessed April. 27, 2019), https://nigerianprice.com/petrol-price-in-nigeria/.

[11] Akinyele D, et al. Possibility of solar thermal power generation technologies in Nigeria: challenges and policy directions. Renew Energy Focus 2019;29:24–41.

[12] Ohijeagbon OD, Ajayi OO. Solar regime and LVOE of PV embedded generation systems in Nigeria. Renew Energy 2015;78:226–35.

[13] Ayodele TR, Ogunjuyigbe ASO, Amusan TO. Wind power utilization assessment and economic analysis of wind

turbines across fifteen locations in the six geographical zones of Nigeria. J Clean Prod 2016;129:341–9.

[14] Adeyeye A, Tsado J, Olatomiwa L. Techno-economic analysis of PV/Diesel/Battery hybrid renewable system for remote primary healthcare center. In: *International Conference of mechanical engineering, energy Technology and management*, IMEETMCON 2018. vol. 30; 2018. p. 1. 1.

[15] Babatunde OM, Munda JL, Hamam Y. A comprehensive state-of-the-art survey on hybrid renewable energy system operations and planning. " *IEEE Access*; 2020.

[16] Sun C. And others, "A novel joint bidding technique for fuel cell wind turbine photovoltaic storage unit and demand response considering prediction models analysis Effect's. Int J Hydrogen Energy 2020;45(11):6823–37.

[17] Ghenai C, Salameh T, Merabet A. Technico-economic analysis of off grid solar PV/Fuel cell energy system for residential community in desert region. Int J Hydrogen Energy 2020;45(20):11460–70.

[18] Singh A, Baredar P, Gupta B. Techno-economic feasibility analysis of hydrogen fuel cell and solar photovoltaic hybrid renewable energy system for academic research building. Energy Convers Manag 2017;145:398–414. https://doi.org/10.1016/j.enconman.2017.05.014.

[19] Abdin Z, Mérida W. Hybrid energy systems for off-grid power supply and hydrogen production based on renewable energy: a techno-economic analysis. Energy Convers Manag 2019;196:1068–79.

[20] Abe JO, Popoola API, Ajenifuja E, Popoola OM. Hydrogen energy, economy and storage: review and recommendation. Int J Hydrogen Energy 2019;44(29):15072–86.

[21] Ayodele TR, Mosetlhe TC, Yusuff AA, Ntombela M. Optimal design of wind-powered hydrogen refuelling station for some selected cities of South Africa. Int J Hydrogen Energy 2021;46(49):24919–30.

[22] Ayodele TR, Mosetlhe TC, Yusuff AA, Ogunjuyigbe ASO. Off-grid hybrid renewable energy system with hydrogen storage for South African rural community health clinic. Int J Hydrogen Energy 2021;46(38):19871–85.

[23] Lokar J, Virtič P. The potential for integration of hydrogen for complete energy self-sufficiency in residential buildings with photovoltaic and battery storage systems. Int J Hydrogen Energy 2020;45(60):34566–78.

[24] Karunathilake H, Perera P, Ruparathna R, Hewage K, Sadiq R. Renewable energy integration into community energy systems: a case study of new urban residential development. J Clean Prod 2018;173:292–307.

[25] Hong T, Koo C, Kwak T, Park HS. An economic and environmental assessment for selecting the optimum new renewable energy system for educational facility. Renew Sustain Energy Rev 2014;29:286–300.

[26] Carroquino J, Bernal-Agustin J-L, Dufo-López R. Standalone renewable energy and hydrogen in an agricultural context: a demonstrative case. Sustainability 2019;11(4):951.

[27] Salvi BL, Subramanian KA. Sustainable development of road transportation sector using hydrogen energy system. Renew Sustain Energy Rev 2015;51:1132–55.

[28] Acar C, Beskese A, Temur GT. A novel multicriteria sustainability investigation of energy storage systems. Int J Energy Res 2019;43(12):6419–41.

[29] Ren X, Li W, Ding S, Dong L. Sustainability assessment and decision making of hydrogen production technologies: a novel two-stage multi-criteria decision making method. Int J Hydrogen Energy 2020;45(59):34371–84.

[30] d'Amore-Domenech R, Santiago Ó, Leo TJ. Multicriteria analysis of seawater electrolysis technologies for green hydrogen production at sea. Renew Sustain Energy Rev 2020;133:110166.

[31] Alirahmi SM, Rostami M, Farajollahi AH. Multi-criteria design optimization and thermodynamic analysis of a novel multi-generation energy system for hydrogen, cooling, heating, power, and freshwater. Int J Hydrogen Energy 2020;45(30):15047–62.

[32] Messaoudi D, Settou N, Negrou B, Settou B. GIS based multi-criteria decision making for solar hydrogen production sites selection in Algeria. Int J Hydrogen Energy 2019;44(60):31808–31.

[33] Rezaei M, Khalilpour KR, Jahangiri M. Multi-criteria location identification for wind/solar based hydrogen generation: the case of capital cities of a developing country. Int J Hydrogen Energy 2020;45(58):33151–68.

[34] Gholamian E, Hanafizadeh P, Habibollahzade A, Ahmadi P. Evolutionary based multi-criteria optimization of an integrated energy system with SOFC, gas turbine, and hydrogen production via electrolysis. Int J Hydrogen Energy 2018;43(33):16201–14.

[35] Solar atlas. https://globalsolaratlas.info/.

[36] Babatunde O, Akinyele D, Akinbulire T, Oluseyi P. Evaluation of a grid-independent solar photovoltaic system for primary health centres (PHCs) in developing countries. Renew Energy Focus 2018;24:16–27.

[37] Ramesh M, Saini RP. Dispatch strategies based performance analysis of a hybrid renewable energy system for a remote rural area in India. J Clean Prod 2020;259:120697.

[38] Babatunde OM, Munda JL, Hamam Y. Selection of a hybrid renewable energy systems for a low-income household. Sustainability 2019;11(16):4282.

[39] Kara, Ruby ". Solar panel 250W/24V. 2020 (accessed Mar. 21, 2021), https://kara.com.ng/ruby-solar-panel-250w-24v.

[40] Babatunde OM, Munda JL, Hamam Y. Photovoltaic system sizing for household use: effects of temperature, orientation and sun tracking. In: 2019 open innovations (OI); 2019. p. 190–5.

[41] Jumia. Tumo int 400W 5 Blades wind turbine with controller (12/24V. 2020 (accessed Mar. 21, 2021), https://www.jumia.com.ng/tumo-int-400w-5blades-wind-turbine-with-controller-1224v-22064264.html.

[42] TRADING ECONOMICS. Nigeria interest rate. 2021 (accessed Oct. 04, 2021), https://tradingeconomics.com/nigeria/interest-rate.

[43] Jumia. Ritar 12V 200AH AGM inverter battery. 2020 (accessed Mar. 21, 2021), https://www.jumia.com.ng/ritar-12v-200ah-agm-inverter-battery-32840328.html.

[44] Jumia. "300W power inverter with digital foot correction sine wave 12V/24V to 220V-240V black,". 2020 (accessed Mar. 21, 2021), https://www.jumia.com.ng/generic-300w-power-inverter-with-digital-foot-correction-sine-wave-12v24v-to-220v-240v-black-42127420.html.

[45] Luta DN, Raji AK. Decision-making between a grid extension and a rural renewable off-grid system with hydrogen generation. Int J Hydrogen Energy 2018;43(20):9535–48.

[46] Jahangiri M, Shamsabadi AA, Mostafaeipour A, Rezaei M, Yousefi Y, Pomares LM. Using fuzzy MCDM technique to find the best location in Qatar for exploiting wind and solar energy to generate hydrogen and electricity. Int J Hydrogen Energy 2020;45(27):13862–75.

[47] Zavadskas EK, Kaklauskas A, Peldschus F, Turskis Z. Multi-attribute assessment of road design solutions by using the COPRAS method. Baltic J Road Bridge Eng 2007;2(4):195–203.

[48] Alinezhad A, Khalili J. "COPRAS method," in *new Methods and Applications in multiple attribute decision making (MADM)*. Springer; 2019. p. 87–91.

[49] Chatterjee N, Bose G. A COPRAS-F base multi-criteria group decision making approach for site selection of wind farm. Decis Sci Lett 2013;2(1):1–10.

[50] Ghorabaee MK, Zavadskas EK, Olfat L, Turskis Z. Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS). Inform 2015. https://doi.org/10.15388/Informatica.2015.57.
[51] Juanpera M, Blechinger P, Ferrer-Mart\\'\\i L, Hoffmann MM, Pastor R. Multicriteria-based methodology for the design of rural electrification systems. A case study in Nigeria. Renew Sustain Energy Rev 2020;133:110243.
[52] Organ A, Yalç\\in E. Performance evaluation of research assistants by COPRAS method. Eur Sci J 2016;12(10):102–9.
[53] Ighravwe DE, Oke SA. An integrated approach of SWARA and fuzzy COPRAS for maintenance technicians' selection factors ranking. Int J Syst Assur Eng Manag 2019;10(6):1615–26.
[54] Diakoulaki D, Mavrotas G, Papayannakis L. Determining objective weights in multiple criteria problems: the critic method. Comput Oper Res 1995;22(7):763–70. https://doi.org/10.1016/0305-0548(94)00059-H.
[55] Hezer S, Gelmez E, Özceylan E. Comparative analysis of TOPSIS, VIKOR and COPRAS methods for the COVID-19 regional safety assessment. J Infect Public Health 2021;14(6):775–86.
[56] Ighravwe D, Babatunde M. Selection of a mini-grid business model for developing countries using CRITIC-TOPSIS with interval type-2 fuzzy sets. Decis Sci Lett 2018;7(4):427–42.