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Potential of hydrogen production from intermittent renewable energy resources in different locations of Nigeria: Technical, economic and environmental perspective

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Abstract

In this study, ten wind turbines and fourteen solar photovoltaic (SPV) modules were employed to compare the potential of hydrogen production from wind and solar energy resources in the six geopolitical zones of Nigeria. The amount of hydrogen produced was considered as a technical parameter, cost of hydrogen production was considered as an economic index, and the amount of carbon (IV) oxide saved from the use of diesel fuel was considered as an environmental index. The results reveal that ENERCON E-40 turbine yields the highest capacity factor in Lagos, Jos, Sokoto, Bauchi and Enugu sites while FUHRLAENDER, GMBH yields the highest capacity factor in Delta. The mean annual hydrogen production from wind ranged from 2.05 tons/annum at site S6 (Delta) to 17.33 tons/annum at site S3 (Sokoto), and the mean annual hydrogen production from SPV ranged from 64.33 tons/annum at sites S1 (Lagos) to 140.28 tons/annum at site S6 (Delta). The cost of hydrogen production from wind was 6.3679 and 25.9007$/kg for sites S3 and S6, respectively, and the cost of hydrogen production from SPV was 5.6659 and 6.1206$/kg for sites S3 and S1, respectively. The amount of CO_2 saved annually from wind-based hydrogen generation was 137,267 kg/year in site S6 and 504,180 kg/year in site S3, and was used to produce electricity via fuel cells. The amount of CO_2 saved using hydrogen produced from SPV was 615,400 kg/year and 1,341,899 kg/year in sites S1 and S6, respectively. The results also revealed that 75.55%, 88.93%, 80.28%, 80.54%, 85.65%, 98.53% more hydrogen could be produced from SPV for sites S1–S6, respectively, compared to the wind resources. This study serves as a source of reliable technical information to relevant government agencies, policy makers and investors in making informed decisions on optimal investment in the hydrogen economy of Nigeria.

Keywords: Hydrogen; Fuel cell; Solar photovoltaic; Wind energy; Nigeria

0 Introduction

Hydrogen attracted significant attention as an alternative energy resource globally. Hydrogen production has introduced several advantages, such as low grid emissions, hydrogen for industrial use, and regional hydrogen development frameworks, for countries [1]. It has been

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predicted that meeting decarbonization requirements may increase the global demand for hydrogen by approximately seven times by 2050 [2]. Proton exchange membrane (PEM) and alkaline water electrolyzers are used in hydrogen production [3], and thermopile pyranometers and photovoltaic (PV) reference cells are mostly used in solar irradiance measurement [4]. A limitation of reference cells is that they possess non-flat spectral response and do not respond equally to the complete incident wavelength. Reference cells also tend to underestimate the plane of array irradiance values. Nigeria is well endowed with solar energy resources. Because of the presence of aerosols in the arid regions, satellite databases have relatively low accuracies [5]. Solar irradiation is more prevalent in most part of the country than wind. However, few sites in the country have better wind resources. Thus, Nigeria is a good candidate for hydrogen production from these renewable energy resources. Considering the current Nigerian generation capacity of 5000 MW [6], there is need to augment power generation with electricity from hydrogen to improve the security of power supply and increase the share of renewable resources in the generation mix. Hydrogen can also be a potential solution to the problem of intermittency of the renewable energy resources (RESs) in the country. The intermittent sources can be stored in the form of hydrogen during excesses and later be employed for electricity generation via fuel cells during the deficits, thereby augmenting the seasonal variation of intermittent resources.

Several studies have been conducted on hydrogen production from RESs, for instance, Al-Sharafi *et al.* [7] investigated the feasibility of a hybrid PV/wind system for hydrogen production. They study developed two indicators, the station occupancy fraction and social-to-solar fraction (STSF) to measure the level of synchronization between the hydrogen demand and solar potential. The study revealed that a fraction of 0.62 of the refueling events occur during sunshine hours and STSF attains a maximum value in industrial areas. The potential for solar PV (SPV)-dominant 100% renewable grids using a case study of Malaysia was conducted in [8]. The study showed that the deployment of 660-GW of PV and 2200 GWh of pumped hydro-enhanced hydrogen-based gas peaking can potentially fully electrify the region and significantly reduce emissions. To address the issue of intermittency in solar and wind resources, Su *et al.* [9] developed a day-ahead scheduling strategy based on multi-state transitions of alkaline electrolyzers. The study improved the system flexibility by coordinating the operation of the electrolyzer with the battery and showed that the adopted scheduling strategy effectively reduced idle and standby states of the electrolyzer. Moreover, the wind-solar hydrogen system exhibited favorable economic potential. Four cities of Ardebil, Iran were used to evaluate wind energy [10] for electricity generation and hydrogen considering two different sectors, and econometric analysis was performed. The study found that a wind farm containing turbines with rated power of 100 kW was cost-effective for the three cities (Khalkhal, Namin, Meshkinshahr). The hydrogen production cost in a solar-powered refueling station was estimated in [11] for smart city applications in Capo d'Orlando. The study showed that the installed PV plant aids in saving more than 50% of the net electric energy cost, and the battery energy storage system (BESS) aids in saving an additional 11%. Four wind energy conversion systems were used in [12] to obtain a technological platform that allows evaluating emergent technologies for hydrogen production from wind energy. The study revealed that "De Wind D7" can supply electricity and hydrogen with the lowest cost and highest capacity factor. Eight hydrogen production methods were compared in Turkey [13] to assess their economic, social, and environmental impacts. The study showed that out of the six production methods, the thermochemical Copper-Chlorine (Cu-Cl) and Sulphur-Iodine (S-I) cycles have significant potential to produce hydrogen in a cost-effective and environmentally neutral manner. Wind-generated power was used in [14] to access the generation capacity of wind-deployed renewable hydrogen in Pakistan. The study showed that in all studied locations, the hydrogen production capacity was commercially viable. Solar and wind energy was assessed [15] in Algeria to assess the hydrogen production potential. The results of the study showed that the energy supplied by a Solar module UDTS- 50 can supply energy to ten electrolyzer cells. It was also shown that meteorological factors such as temperature, irradiation and wind speed are linked to the renewable electricity generation, and that southern Algeria has more hydrogen potential compared with the northern part. Assessment based on 3E hydrogen fuel cells was performed in [16]. The study used the wind regime of Meme in South Africa to perform energy, economic, and environmental assessment and showed that Meme has the potential to produce 1980 GWh of electricity and 104 tons of hydrogen per annum using PEM fuel cells. Seventy-six sites in Morocco were considered in [17] to conduct a techno-economic capacity assessment of hydrogen production from solar energy. The study showed that Morocco possesses a high potential for hydrogen production, with a yearly production range from 6489 to 8308 tons/km^2. In China, four different hydrogen production methods were used [18] to analyze the production cost, cost structure, and regional differences. The results of the study showed that the levelized cost of hydrogen (LCoH) of the coal-to-hydrogen coupled carbon capture and storage is higher than the coal hydrogen process by 57.6%–128.3%. Another study in Iran [19] used four wind turbines to study the hydrogen production using wind energy in the south-eastern province. The study showed that EWT Direct Wind 500/54 yielded the best capacity factor among the turbines examined, with the highest value of 50.77% for the station at Lutak. In

Queensland Australia, a techno-economic analysis of renewable hydrogen production [20] was conducted under optimistic, reference, and pessimistic conditions to address the uncertainty in cost predictions. The results of the study showed that AUD 3/kg was obtainable with a properly-sized electrolyzer array. In another study, [21] four Canadian provinces and three alternative hydrogen production methods were studied to assess the life cycle of hydrogen fuel cell passenger vehicles, and the results reveal that thermochemical hydrogen production was most favorable for all provinces.

The study reported in [22] employed Monte Carlo simulations to perform an extensive techno-economic assessment of hydrogen production in some European and North African countries. The study used PEM electrolysis and showed that the lowest levelized cost of energy was obtained in Spain, between 1.66 and 3.12 €/kg. The authors in [23] used a system advisory model to evaluate the techno-economic aspects of PV hydrogen production in Portugal, achieving 30 kg/kWp of hydrogen production with a cost of 4.0 €/kg. An analytical hierarchical process and a geographic information system was used in [24] to evaluate large-scale solar-based hydrogen production facilities from PVs and concentrated solar power (CSP). An annual hydrogen output of 48.5 tons/year was obtained from 1-MW of PV-based hydrogen production with a LCoH of 4.972 $/kg. Wind and solar energy was used in [25] to develop an optimal design of power-to-hydrogen systems. The results showed that the optimal size ratio has a trade-off between the renewable generator and utilization factors of the electrolyzer. The republic of Djibouti was considered in [26] to perform an in-depth techno-economic analysis of green ammonia and green hydrogen production from renewable energy sources. It was shown that the cost of wind-based hydrogen production is significantly lower than that with solar power, and the cost of green ammonia from wind is lower than that from solar.

In the studies discussed above, it can be seen that hydrogen production from RESs is site-specific and varies from one location to another. This shows that hydrogen production assessment from renewable energy needs to be conducted at every potential site around the world. To the best of our knowledge, no such assessment has been conducted in Nigeria. Previous studies have revealed that grid integration of wind and solar electricity is possible in Nigeria, leveraging to the solar and wind resources of the country [27]. Therefore, to identify the best resource, this study aimed to compare hydrogen production from wind and solar resources for electricity generation in different geo-political zones of Nigeria. Therefore, this paper should serve as a valuable source of scientific information in selecting intermittent renewable resources (wind and solar) to obtain the best resource for hydrogen production in developing countries such as Nigeria.

1 Study locations and data collection

The data used in this study were obtained from six different sites in the six geopolitical regions of the country. The data were daily average wind speed and solar irradiation data over a period of one year. The wind speed was obtained at 10-m and 50-m anemometer hub heights. Solar irradiation and wind speed data of the sites were obtained from the National Aeronautics Space Administration using the longitude and latitude of the sites under study. The sites considered and their locations in the corresponding geopolitical zones are presented in Table 1. The wind turbine data were obtained from [28], and the parameters of the wind turbines are presented in Table 2. The technical specifications of the best-performing SPV are presented in Table 3.

2 Modeling and simulation

The methodology employed to achieve the objective of this study is described in this section. Modeling and simulations were performed using MATLAB 2015a.

2.1 Wind speed extrapolation

The wind shear exponent (z) was obtained using the 10 m and 50 m available speed data according to (1).

$$z = \frac{\log\left(\frac{v_{50}}{v_{10}}\right)}{\log\left(\frac{h_{50}}{h_{10}}\right)} \tag{1}$$

The wind speed data were then extrapolated to different turbine hub heights using (2)

$$v_T = v\left(\frac{h_T}{h}\right)^z \tag{2}$$

where h_T is the desired turbine hub height of extrapolation, h is the hub height of the available wind speed, v is the velocity of the available wind speed, and v_T is the velocity of the wind speed at the desired turbine hub height.

2.2 Wind power modeling

The power obtainable from wind [30] can be estimated using (3)

Table 1
Study sites and their geographical locations.

S/N	Sites	Longitude & Latitude	Geopolitical zone
S1	Lagos	6.5244°N, 3.3792°E	South West
S2	Jos	9.8965°N, 8.8583°E	North Central
S3	Sokoto	13.0533°N, 5.3223°E	North West
S4	Bauchi	10.3060°N,9.8404°E	North East
S5	Enugu	6.5364°N, 7.4356°°E	South East
S6	Delta	5.7040°N, 5.9339°E	South

Table 2
Wind turbine specifications from manufacturer data.

Turbine Index	Turbine manufacturers	Turbine operating speed range (m/s)			Rotor diameter (m)	Rated power (kW)	Hub height (m)
		V_{ci}	V_r	V_{co}			
T_1	MICON	4	14	25	30	200	30
T_2	MEPC-MICON	4	15	25	31	400	30.5
T_3	ENERCON E-40	2.5	13	25	44	600	46
T_4	VESTAS V-47	5	15	25	35	660	45
T_5	FIKTIONAL	3.1	16	25	39	700	43
T_6	VESTAS V-52	4	17	25	52	850	55
T_7	FUHRLAENDER, GMBH	2.22	15	26.9	62	1300	50
T_8	GE-1.5S	4	14	25	70.5	1500	64.7
T_9	VESTA V-63	5	16	25	63	1500	60
T_{10}	NEG-NICON	3.5	16	25	60	1650	70

Table 3
Technical specifications of the best (Panasonic solar) SPV module [29].

S/n	SPV Module Parameters	Ratings
1	Nominal Maximum Power (P_{max})	335 Wp
2	Opt. Operating Voltage (V_{mp})	59.9 V
3	Opt. Operating current (I_{mp})	5.6 A
4	Open circuit voltage (V_{oc})	71.5 V
5	Short circuit current (I_{sc})	6.05 A
6	Module Efficiency ($M\%$)	20%
7	Operating temperature $(T_{op}(-), T_{op}(+))$	−40 °C ~ +85 °C
8	Maximum System voltage (V_{ms})	1000 V
9	Max. Series fuse rating (I_{msf})	15 A
10	Power Tolerance (P_{tol})	±3%
11	Cell Type	Mono-crystalline silicon
12	Temperature Coefficient $(P_{max})(\gamma)$	−0.258%/°C
13	Temperature Coefficient $(V_{oc})(\beta)$	−0.235%/°C
14	Temperature Coefficient $(I_{sc})(\alpha)$	+0.055%/°C
15	Model Number (N_{md})	VBHN335KJ01
16	Degradation rate	3% (first year), 0.45%/year

$$P_{elect}(v) = \begin{cases} P_r \frac{v^2 - v_{ci}^2}{v_r^2 - v_{ci}^2}; & (v_{ci} \leqslant v \leqslant v_r) \\ P_r = \frac{1}{2}\rho A C_p v_r^3; & (v_{ci} \leqslant v \leqslant v_r) \\ 0 & (v \leqslant v_{ci} \& v \leqslant v_{co}) \end{cases} \tag{3}$$

Here, v_{ci} represents the cut-in wind speed, v_r is the rated wind speed, v_{co} denotes the cut-out wind speed, P_r is the rated power, A is the turbine swept area, ρ is the air density, and C_p is the coefficient of performance.

2.3 Capacity factor

The capacity factor is the ratio of the average output power over a definite period of time to the power produced when operated at the rated capacity over the same time period. The capacity factor of the wind turbine can be obtained according to (4), and the capacity factor of the SPV is obtained according to (5);

$$Cf_{wt} = \frac{P_{avg,wt}}{P_{r,wt}} \tag{4}$$

$$Cf_{pv} = \frac{P_{agv,pv}}{P_{r,pv}} \tag{5}$$

Here, Cf_{wt} is the capacity factor of the wind turbine, $P_{avg,wt}$ denotes the average power output of the wind turbine, and $P_{r,wt}$ represents the rated power of the wind turbine. Moreover,Cf_{pv}, $P_{avg,pv}$, $P_{r,pv}$ are the capacity factor, average power output, and rated power respectively of the SPV, respectively.

2.4 Photovoltaic energy output

The energy output [31] obtained from SPV module is given in (6):

$$E_{pv}(j) = \left(1 - \frac{d_{mt}}{100}\right) * \left(1 - \frac{d_{tp}(j)}{100}\right) * \left(1 - \frac{d_{dt}}{100}\right) * G(j) * \eta_{pv,inv} * \eta_{inv} * \eta_{inv,sb} * P_{array} \tag{6}$$

Here, d_{mt}, d_{tp}, d_{dt} are the derations due to manufacturers tolerance, temperature, and dirt, respectively, η_{inv},$\eta_{\mathrm{pv,inv}}$, and $\eta_{inv,sb}$ are the efficiency of the inverter, efficiency of the subsystem between SPV array and inverter, and efficiency of the subsystem between the inverter and the switchboard, respectively.

2.5 Hydrogen production using SPV and wind

The hydrogen derived from SPV [17] can be obtained using (7):

$$M_{\mathrm{H_2}} = \frac{E_{\mathrm{pv}} \times \eta_{\mathrm{ele}}}{\mathrm{HHV}_{\mathrm{H_2}}} \tag{7}$$

where $M_{\mathrm{H_2}}$ is the mass of hydrogen produced, $\mathrm{HHV}_{\mathrm{H_2}}$ denotes the hydrogen higher heating value, E_{PV} represents the energy output from the SPV array, and η_{ele} is the efficiency of the electrolysis system (75%).

The amount of hydrogen that can be obtained from wind energy using the process of water electrolysis is given in [32] (8)

$$M_{\mathrm{H_2}} = \frac{P_{\mathrm{elect}} \times \eta_{\mathrm{rec}}}{E_{\mathrm{ez}}} \tag{8}$$

where P_{elect} is the wind turbine electrical output, η_{rec} denotes the rectifier efficiency, and E_{ez} represents the electrolyzer energy demand.

2.6 Electricity generation of a fuel cell

The amount of electricity that can be obtained from a fuel cell using wind and solar can is given by (9) and (10), respectively.

$$FC_{\mathrm{elect,w}} = M_{\mathrm{H_2,w}} \times \eta_{\mathrm{comp}} \times \mathrm{LHV} \times \eta_{\mathrm{fc}} \times \rho_{\mathrm{VH}} \tag{9}$$

$$FC_{\mathrm{elect},pv} = M_{\mathrm{H_2},pv} \times \eta_{\mathrm{comp}} \times \mathrm{LHV} \times \eta_{\mathrm{fc}} \times \rho_{\mathrm{VH}} \tag{10}$$

Here, $M_{\mathrm{H_2,w}}$ and $M_{\mathrm{H_2,pv}}$ are the mass of hydrogen production from wind and SPV, respectively, η_{comp} is the compression efficiency, LHV represents the lower heating value, η_{fc} denotes the fuel cell efficiency, and ρ_{VH} is the density of compressed hydrogen.

2.7 Economic cost of hydrogen production from wind and solar energy

The cost of electricity from wind turbines can be obtained as given by (11):

$$C_{\mathrm{Elect}(WT)} = \frac{C_{\mathrm{cap}(WT)} + C_{O\&M(WT)} + \sum_{a=1}^{A}\left\{f_{\mathrm{a}} \times C_{\mathrm{cap}(WT)}\right\}}{p_{\mathrm{Elect}}} \tag{11}$$

In the same manner, the cost of hydrogen production from the electrolyzer is given by (12)

$$C_{\mathrm{H_2}} = \left\{\frac{C_{\mathrm{cap}(EZ)} + C_{O\&M(EZ)} + \sum_{\mathrm{b}=1}^{\mathrm{B}}\left\{h_{\mathrm{b}} \times C_{\mathrm{cap}(EZ)}\right\}}{M_{\mathrm{H_2}}}\right\} + C_{\mathrm{Elect}(WT)} \tag{12}$$

where f_{a}, h_{b} and L_{c} are the fractional percentages of the cost of other components with respect to the capital cost of the turbine, electrolyzer, and the fuel cell, respectively, $M_{\mathrm{H_2},pv}$ are the masses of hydrogen production from wind and SPV respectively, η_{comp} is the compression efficiency, LHV represents the lower heating value, η_{fc} denotes the fuel cell efficiency, and ρ_{VH} is the density of compressed hydrogen. The operation and maintenance cost for the system elements are given by (13) [16]

$$C_{O\&M(.)} = C_{O\&M(int)} \times \left(\frac{1+\mathrm{inf}}{1+int}\right) \times \left[\frac{1-\left(\frac{1+\mathrm{inf}}{1+int}\right)^{T}}{1-\left(\frac{1+\mathrm{inf}}{1+int}\right)}\right] \tag{13}$$

where inf and int are the prevailing inflation and interest rate in Nigeria obtained as 29.9% and 22.75%, respectively [33].

2.8 Cost of hydrogen production from SPV

The levelized cost of energy from SPV [34] can be obtained as (14)

$$LCoE = \frac{\sum_{t=0}^{N} C_t/(1+r)^t}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}} \tag{14}$$

In the same manner, the levelized cost of hydrogen generation can be obtained as given in [17] (15)

$$LCoE_{\mathrm{H_2}} = \frac{\sum_{t=0}^{N} (C_{\mathrm{E}} + C_{\mathrm{elec}})/(1+r)^t}{\sum_{t=0}^{N} \frac{M_{\mathrm{H_2,def},t}}{(1+r)^t}} \tag{15}$$

Here, C_t is the net cost of the project for t (year), r is the discount rate for t, C_{elec} is the investment cost of electrolyzer, $M_{\mathrm{H_2,def},t}$ is the defined annual hydrogen production, and C_{E} is the investment cost of electricity generation.

2.9 Environmental benefits of fuel cells

The amount of diesel fuel that can be saved using wind and SPV if the internal combustion engine is replaced by fuel cell is given in (16) and (17), respectively

$$F_{\mathrm{d,w}} = QFC_{\mathrm{elect,w}} + RP_{\mathrm{Gen}} \tag{16}$$

$$F_{\mathrm{d},pv} = QFC_{\mathrm{elect},pv} + RP_{\mathrm{Gen}} \tag{17}$$

Here, $FC_{\mathrm{elect,w}}$, $FC_{\mathrm{elect},pv}$ are the powers produced by the fuel cell system using wind and solar SPV, respectively.

2.10 Emission mitigation

The carbon dioxide and carbon monoxide mitigated per hour using fuel cells instead of diesel generators is given by (18)–(21)

$$F_{\mathrm{CO_2,w}} = S_{\mathrm{E}(CO_2)} \times F_{\mathrm{d,w}} \tag{18}$$

$$F_{\mathrm{CO_2},pv} = S_{\mathrm{E(CO_2)}} \times F_{\mathrm{d},pv} \tag{19}$$

$$F_{\mathrm{CO,w}} = S_{\mathrm{E(CO)}} \times F_{\mathrm{d,w}} \tag{20}$$

$$F_{\mathrm{CO},pv} = S_{\mathrm{E(CO)}} \times F_{\mathrm{d},pv} \quad (21)$$

Here, $F_{\mathrm{d,w}}$ and $F_{\mathrm{d},pv}$ are the amount of diesel fuel saved when wind and SPV are used, respectively. $S_{\mathrm{E(CO_2)}}$ and $S_{\mathrm{E(CO)}}$ are the specific emissions of carbon dioxide and carbon monooxide per liter of diesel fuel, respectively.

The cost of fuel saved per hour when wind and SPV are employed is given by (22) and (23), respectively.

$$C_{\mathrm{Fsav,w}} = F_{\mathrm{d,w}} \times C_{\mathrm{d}} \quad (22)$$

$$C_{\mathrm{Fsav},pv} = F_{\mathrm{d},pv} \times C_{\mathrm{d}} \quad (23)$$

The current price of diesel in Nigeria, represented as C_{d}, is 0.74$/liter.

3 Results and discussion

This section presents the results of the solar and wind characteristics of the six locations considered and their hydrogen generation potentials.

3.1 Solar and wind characteristics of locations under study

Fig. 1 shows that the wind speed ranged from 1.06–5.73 m/s for Delta and Sokoto, respectively. Delta had the lowest wind speed and Sokoto had the highest wind speed in the six locations considered. Site S1 had the highest (3.94 m/s) wind speed in August and the lowest (2.18 m/s) in November. The wind speed at site S2 ranged from 2.10 m/s in August to 5.73 m/s in December. At site S3, the wind speed ranged between 2.19 m/s in August to 5.46 m/s in December. Site S4 had the highest wind speed (4.05 m/s) in December and lowest (1.91 m/s) in November. The wind speed at site S5 ranged from 2.03 m/s in August to 4.59 m/s in April. At site S6, the wind speed ranged between 1.06 m/s in November to 1.81 m/s in August.

Fig. 2 shows that the solar radiation varied from 5.22 to 7.10 k Wh/m^2/day for Delta and Bauchi, respectively. This shows that Delta had the lowest solar irradiation and Bauchi had the highest radiation in the six locations considered. Site S1 had the highest (6.71 kWh/m^2/day) radiation in September and lowest (5.38 kWh/m^2/day) in January. The radiation at site S2 ranged from 5.32 kWh/m^2/day in December to 6.89 kWh/m^2/day in April. At site S3, the radiation was between 5.57 kWh/m^2/day in December to 7.03 kWh/m^2/day in May. Site S4 had the highest radiation (6.76 kWh/m^2/day) in September and the lowest (5.48 kWh/m^2/day) in December. The radiation at site S5 ranged from 5.35 kWh/m^2/day in December to 7.10 kWh/m^2/day in May. At site S6, the radiation was between 5.22 kWh/m^2/day in January to 6.75 kWh/m^2/day in September.

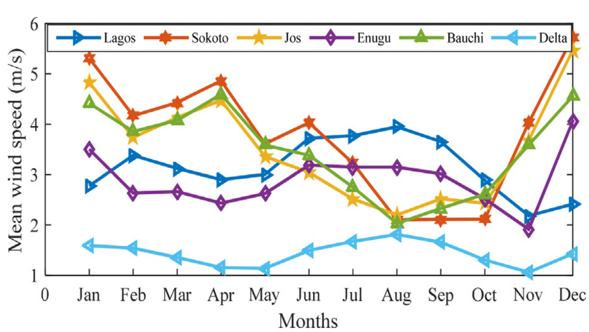

Fig. 1. Monthly wind speed of the sites under study.

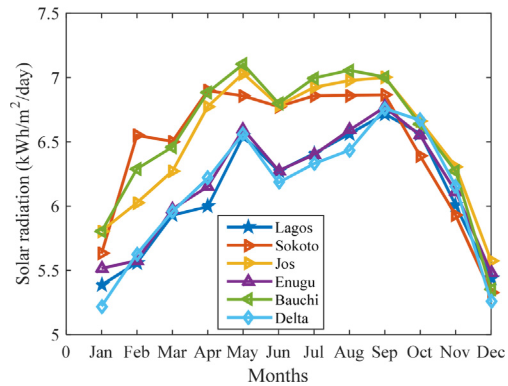

Fig. 2. Monthly solar irradiation of the sites under study.

The wind speed was extrapolated to the turbine height using Eqs. (1) and (2) and the wind speed at the hub height was obtained to obtain the wind power.

3.2 Solar and wind capacity factor for study locations

Tables 4a and b show that the capacity factor varied from 0.00 (at site S6) to 17.88% (at site S3). The capacity factor of site S1 varies from 0.51% (T_4) to 7.34 % (T_3); at site S2, the capacity factor varied between 5.10% (T_4) and 14.10% (T_3). The capacity factor of site S3 varied from 7.64% (T_4) to 17.88 % (T_3); at site S4, the capacity factor was between 4.44% (T_4) and 13.80% (T_3). The capacity factor of site S5 varied from 1.89% (T_4) to 9.70% (T_3); at site S6, the capacity factor was between 0.00 (T_4, T_1, T_2, T_9,) and 2.40% (T_7). This reveals that for sites S1–S5, turbine T_3 (ENERCON E-40) which produces a rated power of 600 kW at 13 m/s (the lowest among the turbines considered), yields the highest capacity factor. Turbine T7 (FUHRLAENDER, GMBH), with the lowest cut-in wind speed of 2.22 m/s, yields the highest capacity factor at site S6. In all the sites considered, site S3 had the highest capacity factor and S6 had the lowest capacity factor. This shows that site S3 is the best candidate for wind energy deployment and S5 is the least-ideal candidate for wind energy deployment.

The rated power (600 kW) of turbine T_3 yielded gives the highest capacity factor, as shown in Tables 4a and b, and was used to obtain the capacity factor of SPV in sites S1–S5, as given in Tables 5a and b. The rated power (1300 kW) of turbine T_7 yielded the highest capacity factor in site S6, as shown in Tables 4a and b, and was used to

Table 4a
Wind turbine performance and the sites considered.

Sites	Parameters	Wind Turbine Performance				
		T_1	T_2	T_3	T_4	T_5
S1	*Cf*/%	1.46	1.29	7.34	0.51	3.45
S2	*Cf*/%	5.99	5.23	14.10	5.10	7.76
S3	*Cf*/%	8.43	7.36	17.88	7.64	10.15
S4	*Cf*/%	5.33	4.67	13.80	4.44	7.47
S5	*Cf*/%	2.48	2.19	9.70	1.89	4.83
S6	*Cf*/%	0.00	0.00	2.12	0.00	0.47

Table 4b
Wind turbine performance and the sites considered.

Sites	Parameters	Wind Turbines Performance				
		T_6	T_7	T_8	T_9	T_{10}
S1	*Cf*/%	1.97	6.27	3.50	0.78	3.90
S2	*Cf*/%	6.42	11.52	10.97	5.74	9.74
S3	*Cf*/%	8.83	14.45	15.04	8.52	12.97
S4	*Cf*/%	6.11	11.34	10.61	5.27	9.62
S5	*Cf*/%	3.66	8.25	6.69	2.63	6.61
S6	*Cf*/%	0.17	2.40	0.63	0.00	1.35

obtain the capacity factor of SPV in site S6, as shown in Tables 5a and b. The results show that the SPV capacity factor varied from 19.34 (at site S6) to 21.69 (at site S2). The capacity factor of site S1 ranged from 19.27% (M_{13}) to 20.23% (M_2), and the capacity factor of site S2 was between 20.77% (M_{13}) and 20.23% (M_2). The capacity factor of site S3 varied from 19.90% (M_{12}) to 21.21% (M_2). At site S4, the capacity factor was between 20.60% (M_{13}) and 21.64% (M_2). The capacity factor of site S5 varied from 19.51% (M_{13}) to 20.44% (M_2); at site S6, the capacity factor was between 19.34% (M_{13}) and 20.24% (M_2). This reveal that the *Panasonic* solar module (M_2) yields the highest capacity factor in all the sites considered, and the *Topsun* solar module (M_{13}) yields the lowest capacity factor in sites S1, S2 and S4–S6. The *Hyundai* solar module (M_{12}) yields the lowest capacity factor in site S3. Site S2 (Jos) has the highest capacity factor of 21.69 for SPVs among all the sites considered.

3.3 Energy analysis and hydrogen production from wind and solar resources

Since turbine T_3 had the highest capacity factor in sites S1–S5 with a rated power of 600 kW, the solar module M_2 of the same rated power (600 kW) was used for energy and hydrogen production from SPV in sites S1–S5. Turbine (T_7) with the highest capacity factor in site S6 with a rated power of 1300 kW was used to obtain the energy and hydrogen production in site S6, as shown in Table 6a and Table 6b. The table shows that the energy obtained from wind was between 111.50 MWh and 939.95 MWh for sites S6 and S3, respectively, and the energy produced from SPV ranged from 24.68 GWh at site S1 to 53.81GWh at site S6. The table shows that the mean amount of hydrogen produced from wind ranged from 2.05 tons/annum at site S6 (Delta) to 17.33 tons/annum at site S3 (Sokoto). Similarly, hydrogen production from SPV was between 64.33 and 140.28 tons/annum in sites S1 (Lagos) and S6 (Delta), respectively. It should however be noted that site S6 was exhibited the highest hydrogen production because a turbine with a higher rated power was used. If the same turbine rating were to be employed for all the sites, site S3 would present the highest hydrogen production from SPV.

Table 5a
Solar modules performance and the sites considered.

Sites	Parameters	Solar Module Performance						
		M_1	M_2	M_3	M_4	M_5	M_6	M_7
S1	*Cf*/%	19.70	20.23	19.56	19.57	19.91	19.61	19.68
S2	*Cf*/%	21.14	21.69	21.42	21.05	21.40	21.09	21.17
S3	*Cf*/%	20.56	21.21	20.49	20.49	20.63	20.55	20.56
S4	*Cf*/%	21.08	21.64	21.29	20.92	21.29	20.97	21.05
S5	*Cf*/%	19.92	20.44	20.14	19.80	20.14	19.84	19.91
S6	*Cf*/%	19.62	20.24	20.00	19.63	19.66	19.70	19.73

Table 5b
Solar modules performance and the sites considered.

Sites	Parameters	Solar Module Performance						
		M_8	M_9	M_{10}	M_{11}	M_{12}	M_{13}	M_{14}
S1	*Cf*/%	19.41	19.77	19.57	19.66	19.31	19.27	19.57
S2	*Cf*/%	20.93	21.27	21.06	21.17	20.80	20.77	21.05
S3	*Cf*/%	20.11	20.50	20.47	20.36	19.90	20.12	20.49
S4	*Cf*/%	20.75	21.14	20.93	21.02	20.61	20.60	20.92
S5	*Cf*/%	19.65	20.00	19.80	19.90	19.55	19.51	19.80
S6	*Cf*/%	19.51	19.59	19.62	19.53	19.34	19.34	19.69

Table 6a
Technical impact of hydrogen production in different study locations.

Parameters	Sites					
	S1		S2		S3	
	Wind	SPV	Wind	SPV	Wind	SPV
Electricity Generation/MWh	385.71	24.68 GWh	740.86	26.55 GWh	939.95	26.90 GWh
Hydrogen production/(tons/annum)	7.12	64.33	13.65	69.22	17.33	70.88

Table 6b
Technical impact of hydrogen production in different study locations.

Parameters	Sites					
	S4		S5		S6	
	Wind	SPV	Wind	SPV	Wind	SPV
Electricity Generation/MWh	725.26	26.39 GWh	509.77	24.97 GWh	111.50	53.81 GWh
Hydrogen production/(tons/annum)	13.39	68.82	9.34	65.09	2.05	140.28

The table also shows that 75.55%, 88.93%, 80.28%, 80.54%, 85.65%, and 98.53% more hydrogen could be produced from SPV than wind in sites S1, S2, S3, S4, S5, and S6 respectively. This shows that more hydrogen was obtained from SPV than wind; a higher rated power turbine also affects the hydrogen production. The daily energy production from wind and SPV in all the six sites are shown in Figs. 3–6. It can be seen that hydrogen production from wind varied from 0 tons/day in all the six sites to 7.8465 tons/day in S2 (Jos). The electricity produced from wind varied from 0Wh/day produced in all the wind sites and 3.77MWh/day (Lagos). Similarly, hydrogen production from SPV is between 3.29 tons/day (Lagos) to 6.7921 tons/day in S2 (Sokoto). The electricity produced from SPV is between 42.940 MWh/day (Bauchi) and 168.99MWh/day (Delta).

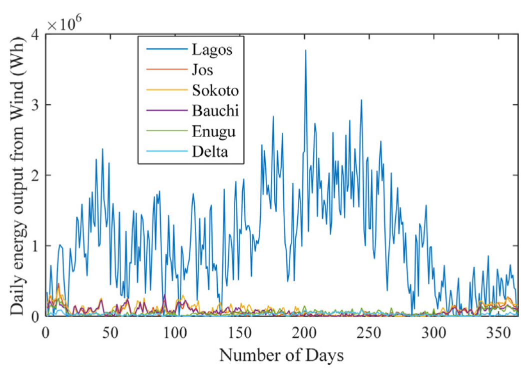

Fig. 3. Daily energy production from wind in all the six sites.

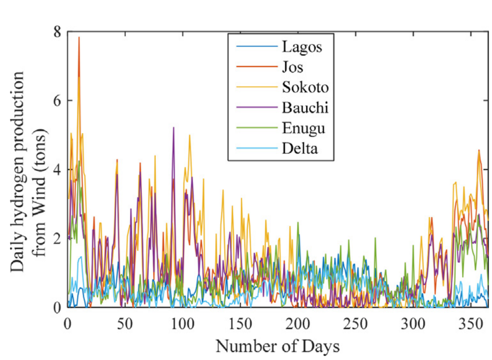

Fig. 4. Daily hydrogen production from wind in all the six sites.

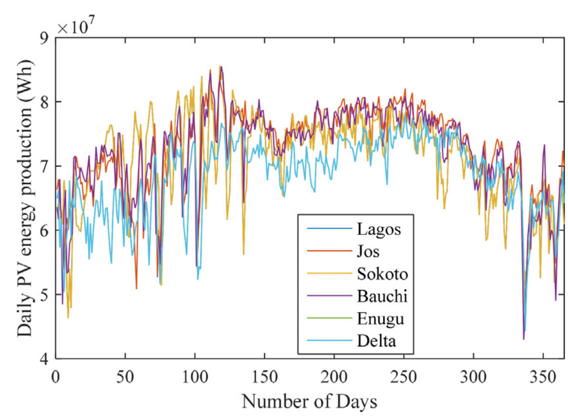

Fig. 5. Daily energy production from SPV in all the six sites.

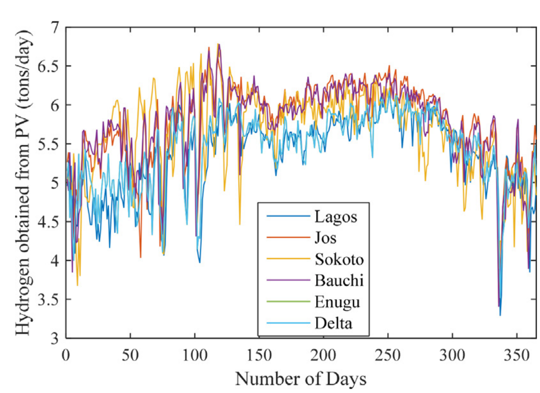

Fig. 6. Daily hydrogen production from SPV in all the six sites.

3.4 Economic analysis of energy and hydrogen production from wind and solar power

The cost of energy and hydrogen production from wind and solar power in the study locations is presented in Table 7a and Table 7b.

The table shows that the unit cost of electricity from wind turbine ranged from 0.6644 in site S3 to 4.9517$/kWh in site S6. Similarly, the unit cost of electricity from SPV was between 0.0975 and 1.6191 $/kWh, which corresponds to sites S3 and S1, respectively. The table also shows that the cost of hydrogen production from wind is between 6.3679 and 25.9007 $/kg corresponding to sites S3 and S6, respectively, and the cost of hydrogen production from SPV ranges from 5.6659 in site S3 to 6.1206$/kg in site S1. This shows that the cost of energy and hydrogen production from SPV is lower than that obtained from wind in all the locations under study. This is because higher electricity production is realized with SPV than with wind. The results of the levelized cost of energy (LCoE) and levelized cost of hydrogen (LCoH) obtained in this study were compared with that obtained from previous studies in other countries, as shown in Table 8. The table shows that the cost of hydrogen production obtained in this study is comparable to that obtained in other countries of the world. For example, site S3 produced hydrogen from wind and solar energy at a cost of $6.3679 and $5.6659, respectively. Other sites produced hydrogen at higher cost as a result of lower wind speed and solar resources.

3.5 Fuel cell electricity generation

Fig. 7 shows the annual fuel cell electricity generation from SPV and wind in all study locations. The figure shows that fuel cell electrical energy production using wind varied from 155.26 MWh in S6 to 570.27 MWh in S3, and that obtained from SPV was between 696.06 MWh and 1.51 GWh for site S1 and S6, respectively. This suggests that site S6 produces the highest electricity and site S3 produces the lowest electricity from fuel cells when wind energy is used. In the same manner, site S6 produced the highest electricity and site S1 produced the lowest electricity from fuel cells when SPV was used. Site S6 is expected to produce the highest fuel cell electricity production as the operational wind turbine has a higher rated power.

3.6 Environmental assessment of hydrogen-based electricity production

The environmental benefits of using fuel cells for electricity generation instead of diesel generators of equal capacity are discussed in this section. Fig. 8 shows the annual diesel fuel that can be saved when fuel cells are employed using wind energy and SPV. The figure shows

Table 7a
Economic impact of hydrogen production in different study locations.

Parameters	Sites					
	S1		S2		S3	
	Wind	SPV	Wind	SPV	Wind	SPV
LCoE/($/kWh)	1.6191	0.1063	0.8429	0.0988	0.6644	0.0975
LCoH/($/kg)	15.5182	6.1206	8.0791	5.7321	6.3679	5.6659

Table 7b
Economic impact of hydrogen production in different study locations.

Parameters	Sites					
	S4		S5		S6	
	Wind	SPV	Wind	SPV	Wind	SPV
LCoE/($/kWh)	0.8611	0.0994	1.2251	0.1051	4.9517	0.1057
LCoH/($/kg)	8.2530	5.7637	11.7417	6.0566	25.9007	6.0868

Table 8
LCoE and LCoH in literature.

Country	Resource	LCoE	LCoH
Oman [35]	SPV (1000 kW) + Wind (660 kW) + Electrolyzer (500 kW) + Battery (1001 kWh)	0.0158$/kWh	0.401$/kg
Saudi Arabia [36]	Wind and SPV	0.1720$/kWh	4.23$/kg
China [18]	Wind		3.72–4.97$/kg
	SPV		5.72–7.25$/kg
Iraq [3]	Solar, Wind and hybrid SPV/WT		1.98$/kg (AWE electrolyzers). 2.72$/kg, (PEM electrolyzers)
Republic of Djibouti [26]	Wind		2.25$/kg
	SPV		4.17$/kg

that the annual diesel fuel saved using fuel cells and wind is between 186,730 L in site S3 to 147,183,095 L in site S2, and the annual diesel fuel saved using fuel cells with SPV ranges from 248,652 L to 496,999,760 L corresponding to sites S3 and S6, respectively. Fig. 9 shows the annual fuel cost savings from wind and SPV in the study locations. The figure shows that the annual diesel fuel cost saving using fuel cells from wind is between 37,621 $/year in site S6 to 138,182 $/year in site S3, and that using fuel cells with SPV ranges from 168,665 $/year to 367,779 $/year corresponding to sites S1 and S6, respectively. The annual CO_2 saved using wind and SPV is shown in Fig. 10a. It can be seen that the annual CO_2 saved using fuel cells with wind is between 137,267 kg/year in site S6 to 504,180 kg/year in site S3, and that while using fuel cells from SPV ranges from 615,400 kg/year to 1,341,899 kg/year in sites S1 and S6, respectively. Fig. 10b shows the annual CO saved using wind and SPV. The figure shows that the annual CO saved using fuel cells and wind is between 389 kg/year in site S6 to 1430 kg/year in site S3, and that using fuel cells from SPV ranges from 1745 kg/year to 3807 kg/year corresponding to sites S1 and S6, respectively. This shows that more diesel fuel, CO_2, CO, and cost can be saved using fuel cells with SPV than that with wind.

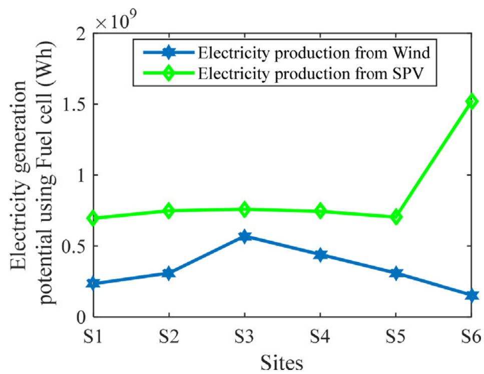

Fig. 7. Fuel cell electricity production potential from hydrogen obtained using wind and solar in different locations under study.

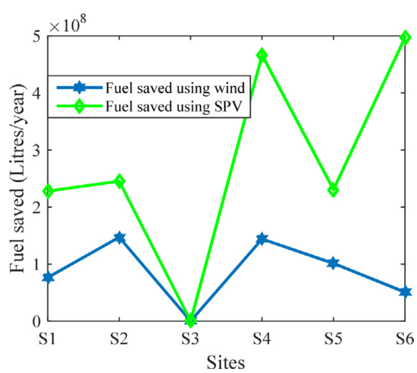

Fig. 8. Fuel saved using wind and solar.

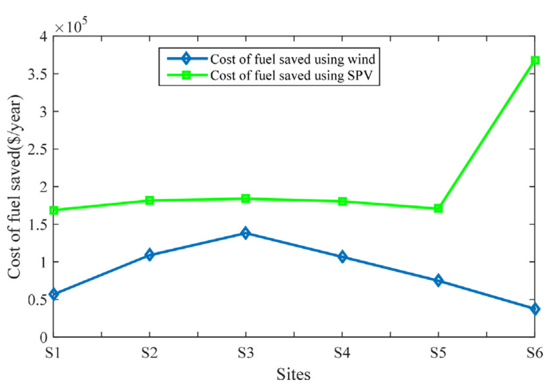

Fig. 9. Cost of fuel saved using wind and solar.

3.7 Impact of wind speed on cost of hydrogen production

To investigate the impact of wind speed on the cost of hydrogen production, the behavior of the annual average wind speed was carefully observed against the cost of hydrogen production, as given in Fig. 11. The figure shows that site S3 possess the highest wind speed while site S6 has the lowest wind speed; site S3 has the lowest cost of hydrogen production and site S6 possess the highest cost of hydrogen production. This shows that locations with high wind speed have a tendency to produce hydrogen at a lesser cost from wind energy.

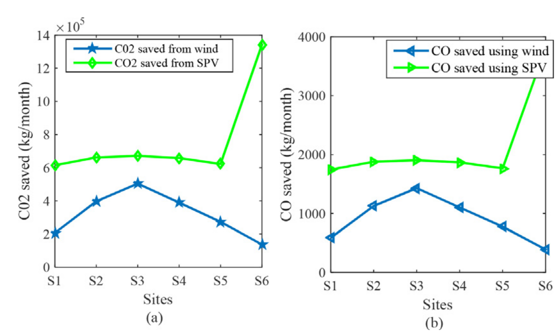

Fig. 10. Carbon (IV) and Carbon (II) oxide saved from all the six sites.

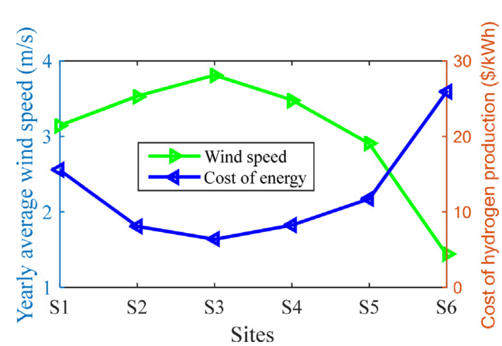

Fig. 11. Year 2015 average wind speed and cost of energy.

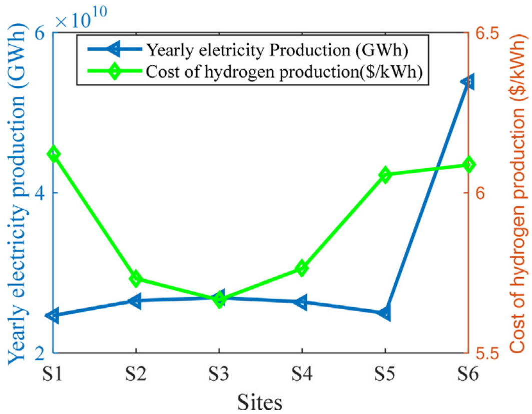

Fig. 12. Average electricity production and cost of energy.

3.8 Impact of electricity production on cost of hydrogen productions

To investigate the impact of electricity production on the cost of hydrogen production, the behavior of the annual SPV electricity production was carefully observed against the cost of hydrogen production, as shown in Fig. 12. The figure reveal that site S6 and S1 possess the highest and lowest electricity production and sites S1 and S3 have the highest and lowest cost of hydrogen production from SPV, respectively. It should however be noted that site S6 was able to produce the highest electricity production because it has a higher rated capacity. If the same SPV capacity (600 kW) is also employed for site S3, it would produce the highest electricity. It can therefore be inferred that sites with higher SPV electricity production are good candidates for higher hydrogen production.

4 Conclusion

A comparative assessment of hydrogen production from wind and solar resources was performed in the six geopolitical zones of Nigeria. The effect of different wind turbines and SPV modules on the capacity factor, influence of wind and solar SPV on electricity and hydrogen generation, possible impact of electricity and hydrogen generation on levelized cost of energy and the influence of hydrogen production from wind and SPV on diesel fuel saved, cost of diesel fuel saved, and carbon (IV) oxide and carbon (II) oxide saved from the use of diesel fuel were studied.

The analyses in the study show that the rated wind speed and cut-in wind speed should be given higher priority for obtaining a high capacity factor of a given site, and lower temperature coefficient of power of an SPV module is a better candidate for obtaining a high capacity factor of a given site. Moreover, 75.55%, 88.93%, 80.28%, 80.54%, 85.65%, and 98.53% more hydrogen could be produced from SPV than wind in sites S1, S2, S3, S4, S5, and S6, respectively. This shows that more hydrogen can be obtained from SPV than with wind in all the locations. The unit cost of electricity from SPV is considerably lower than that from wind turbines. In the same manner, the cost of hydrogen production from SPV is lower than that obtained from wind. The annual diesel fuel saved using fuel cells from SPV, annual diesel fuel cost saving using fuel cells from SPV, annual CO_2 saved using fuel cells from SPV, and annual CO saved using fuel cells from SPV are higher than that obtained from their wind counterparts.

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CRediT authorship contribution statement

Richard Oladayo Olarewaju: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Ogunjuyigbe Ayodeji Samson Olatunji:** Writing – review & editing, Visualization, Supervision. **Ayodele Temitope Raphael:** Writing – review & editing, Visualization, Supervision. **Samson Oladayo Ayanlade:** Writing – review & editing, Visualization. **Yuming Feng:** Writing – review & editing, Visualization. **Chaoran Liu:** Writing – original draft, Visualization.

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.

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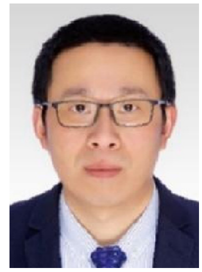

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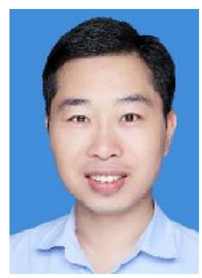

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