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Exploring green hydrogen production from the Jebba Hydropower Station for Nigeria's clean energy transition

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ABSTRACT

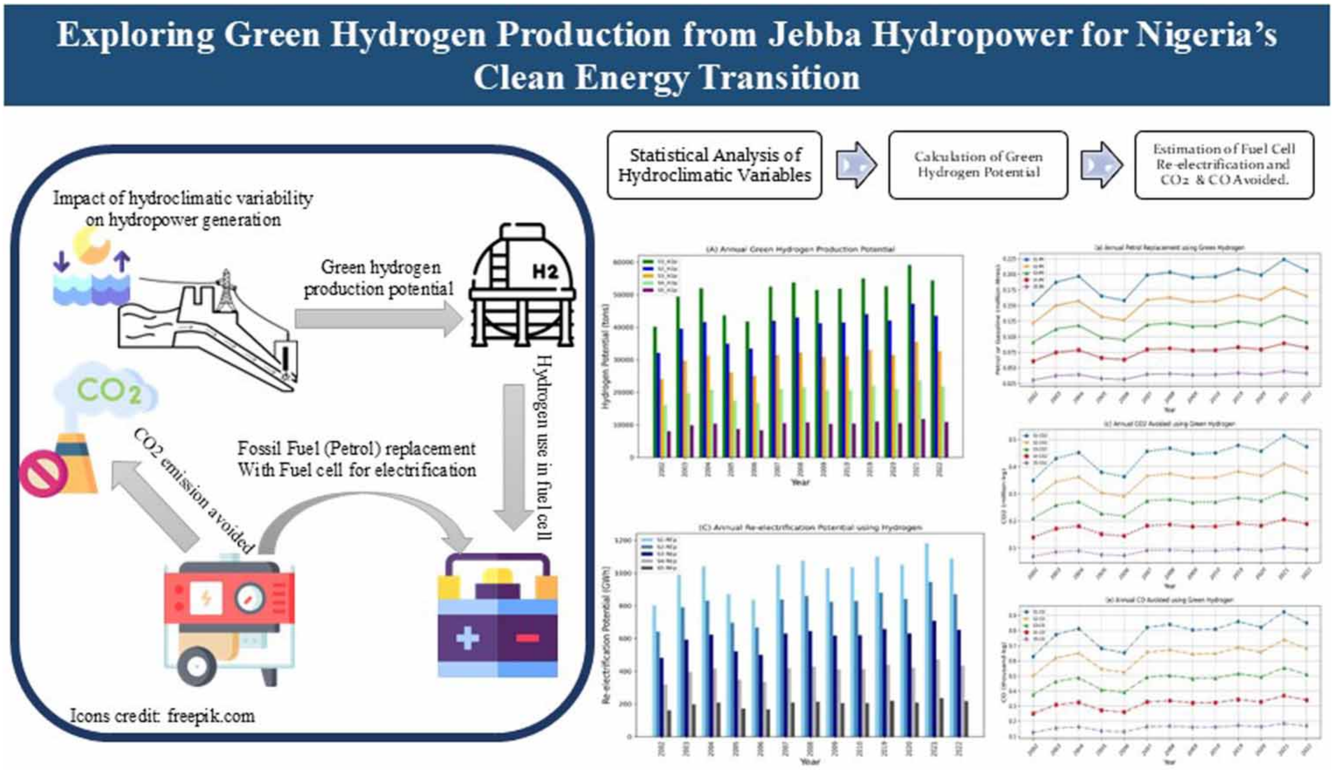
Green hydrogen (GH_2) production from hydroelectricity could enhance clean energy transition. However, hydroclimatic variability could impact the hydropower generation and reliability of GH_2 production. To evaluate this opportunity, we use statistical analysis methods to (i) analyze trends and correlations in Jebba dam's hydroclimatic variables and energy generation, (ii) translate the annual and quarterly energy generation into hydrogen using five scenarios, (iii) estimate the re-electrification potential, and (iv) quantify the amount of petrol that could be replaced, and the CO_2 and CO emissions that would be prevented. The trend analysis shows that hydropower generation has increased significantly in the station. The estimated GH_2 production from the first scenario indicated that the highest potential was 59,111 t and had a re-electrification potential of 1,182 GWh, which could replace 0.224 million liters of petrol, preventing 0.52 million kg of CO_2 and 0.92 thousand kg of CO emissions in the year 2021. The study concludes that hydroclimatic variability influences hydropower generation, which showed a linear relationship with GH_2 production. While we demonstrate that hydropower to hydrogen could serve as a long-storage solution and contribute to achieving the country's fossil fuel replacement goal and rural re-electrification, many more dams would be needed to achieve substantial contributions.

Key words: fossil fuel replacement, green hydrogen, hydroclimatic variability, hydropower generation, Jebba dam

HIGHLIGHTS

- Hydropower dam provides renewable electricity for green hydrogen (GH_2) production.
- Hydroclimatic variability affects the reliability of hydroelectricity for GH_2 production.
- GH_2 fuel cells could support off-grid clean energy access in rural areas.
- Greenhouse gas emission is prevented by replacing fossil fuel usage with GH_2.
- Hydropower to hydrogen can contribute to the country's fossil fuel replacement goal.

GRAPHICAL ABSTRACT



INTRODUCTION

The burning of fossil fuels for the production of energy, transportation, industry, and other purposes has raised concerns around the world since it releases greenhouse gases such as CO_2, CH_4, CO, and N_2O that are responsible for present global warming (Ayodele *et al.* 2019). For instance, carbon monoxide (CO) is one of the harmful gases that can be released when fossil fuels are incompletely burned (Aremu *et al.* 2024). Because of this, several countries are implementing different measures to lower the emissions of these gases and pollutants responsible for causing climate change (Adeoti *et al.* 2014). As a result of this development, the number of countries, including Nigeria, pledging to decrease greenhouse gas emissions to net zero has increased dramatically in recent years (IEA 2021). These actions aim to achieve the highly ambitious global net-zero emission goal to limit the rise in global temperatures to 1.5 °C by 2050 (IPCC 2023). As part of the key strategy for decarbonization, the Federal Government of Nigeria (FGN) has expressed interest in the 100% eradication of all fossil fuel (diesel/petrol) generators through the expansion of its energy generation capacity using renewable energy sources, such as photovoltaic installations, hydropower, and green hydrogen (GH_2), with a target of increasing GH_2 capacity to 34 GW by 2050 to generate GH_2 for the replacement of fossil fuel (diesel/petrol) generators used in the country (NETP 2022).

In the global energy report by the International Energy Agency (IEA 2021), GH_2 has been noted as a clean fuel that could contribute to about 10% climate change mitigation. In nature, hydrogen is found in conjunction with oxygen gas and has a high energy content. However, hydrogen is an energy vector that acts as a medium to store, carry, and transport energy rather than a source of energy, and it may be synthesized using various feedstocks, including fossil fuel (gray hydrogen) and green energy sources through electrolysis (GH_2); electrolysis involves the splitting of water into hydrogen and oxygen using electricity and becomes an essential form of clean energy that might help achieve carbon neutrality (Shari *et al.* 2024). This type of hydrogen produced from renewable energy sources could be used to decarbonize various hard-to-abate sectors, especially where alternative solutions are less developed or more expensive (IRENA 2022). Although the use of GH_2 alone cannot stop global warming without being complemented with other renewable energy applications, it provides an eco-friendly fuel option for the future with a higher energy-to-weight ratio than gasoline or diesel (Shari *et al.* 2024).

Nigeria is among the countries that import the most significant number of diesel/petrol generators in the world as a result of its insufficient electrification (Babajide & Brito 2021). The country's national energy mix statistics for 2022, as reported by

IEA (2022), showed that waste and biofuel accounted for 43.4% of the country's total energy supply (TES), while coal, oil, natural gas, and hydro made for 1.1, 32.2, 22.2, and 1.1% of the TES, respectively. Although Nigeria has substantial hydropower resources, with an estimated 24 GW of large hydro potential and 3.5 GW from small hydro, a significant portion remains untapped. By 2015, the country had an installed capacity of approximately 1.9 GW for large hydropower and around 60 MW for small hydropower (ECN 2014; IRENA 2023). Harnessing the unutilized hydropower potential could create new opportunities for both renewable electricity and GH_2 production as an energy carrier. Furthermore, the high percentage of biofuel is caused by the widespread use of biofuel for cooking and heating, where significant advancements in the availability of clean cooking fuels are still needed. The use of off-grid diesel/petrol generators made up about 12% of the country's total emissions reported in 2020, exacerbated by the approximately 90 million people, especially in rural communities, without access to grid electricity. However, achieving the set decarbonization goal through the adoption and utilization of GH_2 technologies, e.g., fuel cells for electrification, requires taking critical initial steps to evaluate the possibility of producing GH_2 from renewable energy resources such as solar, wind, and hydropower (Posso *et al.* 2022, 2023). Hydropower has been a proven hydrogen production pathway, with various hydro-rich nations, including China, Brazil, Norway, Canada, and the United States, producing hydrogen from hydroelectricity by initiating significant hydrogen energy development projects (Dincer 2012; Posso *et al.* 2015; Thapa *et al.* 2021). However, the effect of hydroclimatic variability and climate change impact such as changes in rainfall pattern, temperature, reservoir inflow, evaporation loss, and turbine discharge poses a significant challenge to its stability and efficiency; it could determine the quantity of hydropower energy available for GH_2 production. Although Nigeria possesses a substantial hydropower potential, only about 14% of this potential, equivalent to 1,930 MW, is currently being harnessed with about 86% unharnessed (ECN & UNDP 2005). This potential, if harnessed, could contribute to the country's national energy transition plan and GH_2 development goal, being a promising technology for energy production, transmission, and storage (AbouSeada & Hatem 2022). Conversely, integrating GH_2 production into hydropower generation in Nigeria presents some challenges and limitations that could hinder rapid hydro-to-hydrogen development, which are broadly categorized into technical, economic, environmental, social, and political factors. Some of these factors include aging hydropower plants, variations in water availability for hydropower generation due to climate change, insufficiently skilled workforce with expertise in the management of an integrated system of hydro-to-hydrogen, high initial capital cost, community acceptance and involvement, regulatory framework, and political instabilities. Addressing these challenges and limitations will require a multifaceted approach, such as upgrading existing hydropower infrastructure with modern technology to accommodate hydrogen production, effective water resource management, technological innovation, capacity building, policy framework, financial mechanism development, market development, enhanced focus on research and development, and stakeholder engagements.

In a study conducted by Posso *et al.* (2022, 2023) in Paraguay, the potential for GH_2 production from hydropower resources and other renewables – solar and wind – was assessed; the study reveals an estimated potential of 24,904 t/year from small-hydro resources for end-use applications and fossil fuel replacement. Similarly, Thapa *et al.* (2021) investigated the possibility of producing GH_2 from excess hydropower generation to regenerate electricity and replace petroleum products used in the transportation industry in Nepal. The findings demonstrated that, in the forecasted year 2030, the potential for producing hydrogen spans from 63,072 to 3,153,360 t, using excess hydroelectric energy at 20 and 100%, respectively. In addition, Karayel *et al.* (2023) considered how electricity from hydropower generation could be used to produce GH_2 in Turkey. The study indicated that hydroelectric energy could significantly propel the country toward the forefront of GH_2 production, with a potential of 2.26 Mt. In the factsheet report of H2Atlas Africa (2024), the total renewable energy potential for hydropower in Nigeria was estimated to be 5.28 TWh/year in 2020 and is projected at 33.67 TWh/year by 2050, with highly favorable current and future energy and power sector performance. The total GH_2 production potential toward 2050 from renewable energy resources (wind onshore, open-field photovoltaic, and hydropower) was estimated to be approximately 15,510.08 TWh/year, utilizing all generation potential without economic limitations. Furthermore, contributing to the research and development of GH_2 energy for decarbonization in Nigeria, Shari *et al.* (2024) carried out a study to explore the role of GH_2 as a future low-carbon fuel alongside other technologies in the country's energy mix; the study strongly emphasizes distributed energy access, including GH_2 technologies, to achieve increased electrification and the country's carbon neutrality goal.

Various studies have examined GH_2 development from hydropower resources. However, there is still a gap in knowledge of how hydroclimatic variability will impact hydropower generation and affect the efficiency and potential of GH_2 production for climate change mitigation, which is the aim of this study. This study focuses on filling this research gap by using statistical analysis methods and mathematical equations to achieve the following objectives: (i) analyze the impact of hydroclimatic variables, i.e., precipitation, temperature, evaporation loss, reservoir inflow, outflow, and turbine discharge, on hydropower generation; (ii) estimate the GH_2 production potential for end-use application, i.e., re-electrification using fuel cells; and (iii) evaluate the quantity of petrol that could be replaced in fossil fuel (petrol) generators and the associated preventable greenhouse gas emissions (CO_2 and CO). For this study, the Jebba hydropower dam was selected due to data availability and as one of the significant hydropower dams that considerably enhance the country's energy generation capacity.

MATERIALS AND METHODS

Study area

Nigeria possesses approximately 60 sizable dams, among which are the three most notable, namely, Kainji, Jebba, and Shiroro, located within the Niger River Basin (JICA 2014). This study focuses on Jebba dam, located at latitudes 9° 10'N to 9° 55′N and longitudes 4° 30′E to 5° 00′E, as shown in Figure 1. It is about 100 km downstream of the Kainji dam and has an elevation of 76 m above sea level (m.a.s.l.) (Liman *et al.* 2021). It is an earth dam and Nigeria's third operational hydroelectric power plant, with a capacity of 578.4 MW and six turbines of 96.4 MW each, distributed to approximately 364,000 homes with an operating head of 27.6 m; thus, the turbines generate electrical power through a generator with a maximum continuous rating of 119 MVA and a base load rating of 103.50 MVA (Liman *et al.* 2021). Table 1 shows some of the primary data of the Jebba Hydropower System as recorded in a study by Olukanni *et al.* (2016).

Data collection and quality control

In situ hydroclimatic and energy generation data for the Jebba dam were obtained from Liman *et al.* (2021), which was collected from Mainstream Energy Solution, the company in charge of the Jebba Hydropower Station (JHS). The available data consist of monthly precipitation time series, average maximum temperature, reservoir inflow, reservoir outflow, evaporation loss, turbine discharge, and average energy generation data. The duration of available data is 31 years (1988–2018) for all

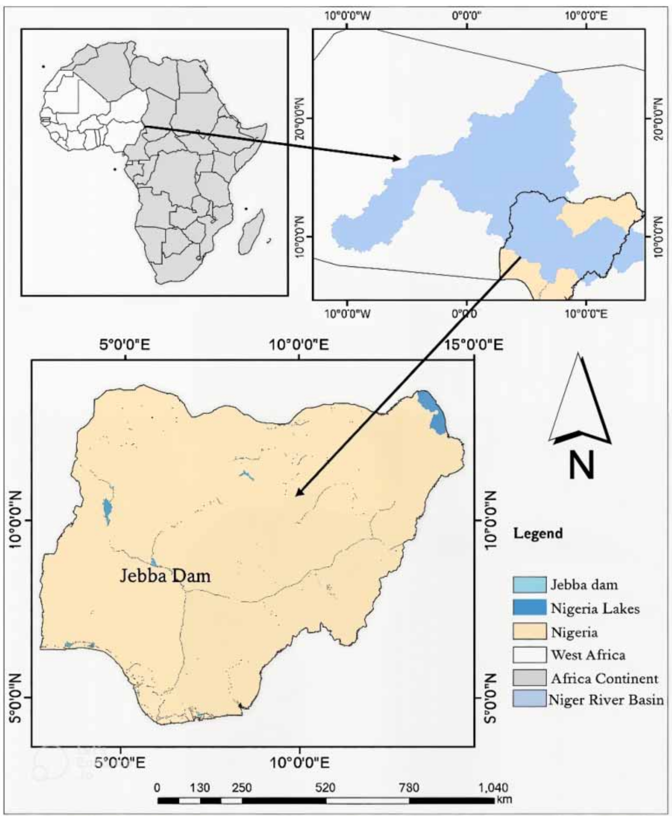


Figure 1 | Study area.

Table 1 | Basic data of the Jebba Hydropower Dam

First year of operation	1984
Design power plant factor	0.70
No. of generators	6
Reservoir flood storage capacity (Mm^3)	4,000
Reservoir flood level (m)	103.55
Water surface area (km^2) at EI. 103.0 m	303.00
Maximum operating reservoir elevation (m.a.s.l)	103.00
Minimum operating reservoir elevation (m.a.s.l)	99.00
Maximum active storage capacity (Mm^3)	3,880
Minimum dead storage capacity (Mm^3)	2,880

Source: Jebba Hydro-Electric Power Station (2010) and Olukanni *et al.* (2016).

variables except turbine discharge, which has a length of 1984–2009 due to the nonavailability of data. Total annual and quarterly energy generation data were obtained from the reports of JICA (2012), Nigeria Bureau of Statistics (2023), and Nigerian Electricity Regulatory Commission (2023), as shown in Tables 3 and 4, respectively. The data underwent visual inspection to detect outliers and ensure internal consistency. Table 2 contains the observed data and the corresponding years of record for JHS.

Statistical analysis

The Mann–Kendall (MK) test is a nonparametric trend detection method (Mann 1945; Kendall 1975). It is a commonly used tool for detecting changes in climatic and hydrologic time series (Hamed & Rao 1998). However, the modified MK (MMK) trend test, a modified version of the MK test based on the modified variance (S), is robust in the presence of autocorrelation and does not assume a specific distribution (Hamed & Rao 1998). The MMK trend test, designed to find monotonic trends in time series data, was used to assess the trends of hydroclimatic variables and hydroelectric generation trends in this study. Other studies have used this method for trend detection in many hydroclimatic variables such as runoff, rainfall, and temperature (Pingale *et al.* 2016; Aziz & Obuobie 2017; Abungba *et al.* 2020). The MK statistic (S) was calculated following the method described by Mann (1945) and Kendall (1975):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{Sgn}(x_j - x_k) \tag{1}$$

where x_j and x_k represent consecutive data values for time series data of length n, and the test statistic represents the number of variations between adjacent points in the time series under consideration (Biggs 2009; Kyambia & Mutua 2015) and

Table 2 | Hydroclimatic and energy generation data

Variable	Resolution	Temporal
Precipitation	Monthly	1988–2018
Max. temperature	Monthly	1988–2018
Reservoir inflow	Monthly	1988–2018
Reservoir outflow	Monthly	1988–2018
Evaporation loss	Monthly	1988–2018
Energy generated	Monthly	1988–2018
Turbine discharge	Monthly	1984–2009

equates to t sum of the Sgn series, which is defined as:

$$\operatorname{Sgn}(x_j - x_k) = \begin{cases} 1 & \text{if} \quad x_j > x_k \\ 0 & \text{if} \quad x_j = x_k \\ -1 & \text{if} \quad x_j < x_k \end{cases} \tag{2}$$

The average and variance of S, $E(S)$, and $V(S)$, respectively, under the null hypothesis, H_0, of randomness, provided that there may be ties in the x values (Biggs 2009; Biggs & Atkinson 2011) are given as:

$$E(S) = 0 \tag{3}$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i[(t_i - 1)(2t_i + 5)]}{18} \tag{4}$$

where t is the extent of any given tie. $\sum t_i$ denotes the summation of all ties and is only used if the data series contains ties. The standard normal variate Z is calculated by (Biggs 2009):

$$Z = \begin{cases} \frac{s-1}{\sqrt{\mathrm{VAR}(S)}} & \text{if} \quad S > 0 \\ 0 & \text{if} \quad S = 0 \\ \frac{s+1}{\sqrt{\mathrm{VAR}(S)}} & \text{if} \quad S < 0 \end{cases} \tag{5}$$

There are two advantages to utilizing this test. First, it is a nonparametric test, which means that the data do not have to be normally distributed. Second, because the time series is not homogenous, the test is not sensitive to sudden breaks (Adonadaga 2014). The alternative hypothesis, H_1, which posits a trend, is evaluated against the null hypothesis, H_0, which states that there is no trend (the data are independent and randomly ordered) (Vukialau-Taoi *et al.* 2023). The pyMannkendall package is utilized for the nonparametric trend analysis, which is a Python package developed to assist researchers in checking MK trends and combines nearly all forms of MK tests. To improve its performance, it employs a vectorization technique. The package presently comprises two Sen's slope estimator functions and 11 MK tests. A brief description of all the functions can be found in Hussain & Mahmud (2019). The pyMannkendall python package was used for trend analysis in this study. A Pearson correlation coefficient matrix was constructed between the hydroclimatic variables and hydroelectric generation to examine the importance of the association between hydroelectric generation and each of the hydroclimatic variables (precipitation, temperature, reservoir inflow, reservoir outflow, turbine discharge, and evaporation loss). Other studies like Liman *et al.* (2021) and Obahoundje *et al.* (2022) employed a similar method. The correlation function in Python was used, and the result was displayed using a heatmap. Furthermore, a Random Forest (RF) model was developed using Python to evaluate the sensitivity analysis of the hydroelectric generation at the hydropower station. This approach is used to identify the potential connections between uncertainty in output variables and uncertainties in one or more input variables. In other words, it establishes the extent to which input variables (predictors) can impact the target variable, e.g., energy (Obahoundje *et al.* 2022). Given that it provides a solid, internally cross-validated assessment of the relevance of the variable (Polewko-Klim *et al.* 2020), the RF can be a more trustworthy sensitivity analysis tool in matching production histories (Aulia *et al.* 2019). The most effective and insightful method for extracting critical variables from RF is the percentage increase in Mean Square Error (%IncMSE); more details about the RF are discussed in a study by Polewko-Klim *et al.* (2020). For this study, the percentage increase in %IncMSE is employed to determine which variables are most important or have the most influence on energy generation at the JHS (Polewko-Klim *et al.* 2020; Obahoundje *et al.* 2022).

GH_2 potential from hydropower

According to Thapa *et al.* (2021), two fundamental approaches exist to estimate the GH_2 production potential. The first method was defined as assessing the potential for hydrogen generation by estimating the surplus hydroelectricity that was supposed to be cut back as a result of declining demand or increased generation from a higher volume of water flow rate during the wet or dry season in the hydropower plants. The second method assumes that electrolysis will be utilized to generate hydrogen at a predetermined percentage of the feasible hydroelectric capacity. Posso & Zambrano (2014) used this method in a study conducted in Venezuela. This study employed the later approach. First, the annual electrical energy generated for the years 2002–2010, as presented in JICA (2012) and displayed in Table 3, and quarterly energy generated for years 2019–2022 in the quarterly reports of Nigeria Bureau of Statistics (2023) and Nigerian Electricity Regulatory Commission (2023), as displayed in Table 4, were used in this study; however, the hydroelectricity generated can also be calculated using (Posso *et al.* 2015):

$$E_{EG} = \text{HP} \times \text{CF} \times \text{Op. hrs} \quad (6)$$

E_{EG} is the total electrical energy generated annually (Table 3) and quarterly (Table 4) in GWh, HP is the hydropower potential, CF is the capacity or plant factor, and Op.hrs is the operating hours. Equation (7) was used to obtain the electrical energy utilized for each of the scenarios:

$$E_{sc} = E_{EG} \times \text{Scenario \%} \quad (7)$$

Table 3 | Total annual electrical energy generated (E_{EG}) in GWh at Jebba station

Year	E_{EG} (GWh)
2002	2,087
2003	2,571
2004	2,704
2005	2,268
2006	2,172
2007	2,729
2008	2,795
2009	2,677
2010	2,694

Source: JICA (JICA, 2012).

Table 4 | Total quarterly electrical energy generated (E_{EG}) in GWh at Jebba station

Quarter	E_{EG} (GWh)
2019-Q1	694
2019-Q2	601
2019-Q3	651
2019-Q4	913
2020-Q1	726
2020-Q2	575
2020-Q3	669
2020-Q4	765
2021-Q1	734
2021-Q2	682
2021-Q3	683
2021-Q4	975
2022-Q1	781
2022-Q2	513
2022-Q3	721
2022-Q4	814

Source: Nigeria Bureau of Statistics (2023) and Nigerian Electricity Regulatory Commission (2023).

where Esc represents the electricity generated in GWh that is estimated to be used for the production of hydrogen in each scenario as indicated by a comparative study conducted in Nepal (Thapa *et al.* 2021). To estimate the potential for producing hydrogen from electrical energy, the following five scenarios were postulated (Aremu *et al.* 2024):

- Scenario 1 (S1-H2p) – 100% hydroelectric energy utilized.
- Scenario 2 (S2- H2p) – 80% hydroelectric energy utilized.
- Scenario 3 (S3- H2p) – 60% hydroelectric energy utilized.
- Scenario 4 (S4- H2p) – 40% hydroelectric energy utilized.
- Scenario 5 (S5- H2p) – 20% hydroelectric energy utilized.

Second, Equation (8) is used to estimate the hydrogen potential (H_{2p}) in kg H_2/year. It is assumed that some percentage of the electrical energy produced in each scenario is used to generate GH_2:

$$H_{2p} = \frac{E_{sc}}{\text{Electrolyzer Efficiency}} \tag{8}$$

The IEA (2019) as described in the study by Zhou *et al.* (2020) estimated that 'meeting the current full hydrogen output of (69 MtH2) from electricity is equivalent to an electricity consumption of 3,600 TWh.' This is equivalent to a production efficiency of (3,600 TWh/69 Mt $H_2 = 52$ kWh/kg H_2). Therefore, 52 kWh/kg H_2 is assumed to represent the electrolyzer's energy consumption for this study, not including the energy usage of ancillary machinery required for compression and gas treatment, as explained by Posso *et al.* (2015).

Re-electrification potential using fuel cell

Re-electrification of rural regions could be facilitated by hydrogen energy, especially in communities that do not have access to grid electricity (Aremu *et al.* 2024). Moreover, fossil fuel–based energy sources from the domestic and industrial sectors, like generators that run on gasoline or diesel, could be replaced by electricity produced from hydrogen (Thapa *et al.* 2021). The hydrogen created by hydroelectric energy can be used to generate electricity on its own using fuel cells. The IEA (2019) estimates that, in 2030, if 1% of the world's installed gas-fired power capacity (or 25 GW) were powered by hydrogen (or ammonia), this would provide around 90 TWh of annual energy (40% load factor), requiring 4.5 Mt H_2 of hydrogen. Based on these factors, Zhou *et al.* (2020) calculated that with the current technology, 1 kg H_2 may generate 20 kWh of power (i.e., 4.5 Mt H_2/90 TWh). As a result, considering that fuel cells currently have a 60% efficiency (Thapa *et al.* 2021), the potential for re-electrification using hydrogen is evaluated for this study using Equation (9). This is done by noting that 1 kg H_2 may provide 20 kWh of energy:

$$RE_P = H_{2p} \times 20/1,000 \text{ (GWh)} \tag{9}$$

The hydrogen re-electrification potential, or RE_P, is determined using the same hypothetical scenarios as utilized in the quantification of the hydrogen production from hydroelectric energy (Thapa *et al.* 2021):

- S1-RE_P – Using Hydrogen from 100% hydroelectricity.
- S2-RE_P – Using Hydrogen from 80% hydroelectricity.
- S3-RE_P – Using Hydrogen from 60% hydroelectricity.
- S4-RE_P – Using Hydrogen from 40% hydroelectricity.
- S5-RE_P – Using Hydrogen from 20% hydroelectricity.

Estimation of fossil fuel (petrol) replacement

In the study by Thapa *et al.* (2021), 1 kg of GH_2 can approximately replace 3.785 L of petrol, with 1 kg of hydrogen having the same energy content as one US gallon of petrol (or gasoline) (Ale & Bade Shrestha 2008; United States Department of Energy 2008). In this study, the quantity of petrol fuel in liters that would be displaced is examined using the following equation (Thapa *et al.* 2021):

$$PR = H_{2p} \times 3.785 \text{ (L)} \tag{10}$$

where PR is the petrol (or gasoline) replacement potential; to estimate the amount of petrol that would be replaced, the same five assumed scenarios with the equivalent percentage of hydropower energy utilization as used in the calculation of the hydrogen and the re-electrification potential were used for the estimation. The results were obtained as Sx-PR for each scenario.

Estimation of greenhouse gases avoided

Water is the main byproduct of hydrogen-based fuel cells, which provides minimal environmental concern and has been identified as a feasible solution to the climate change crisis. The study takes into account both CO and CO_2 emissions using Equation (11) to calculate the amount of greenhouse gas emissions (CO_2 and CO) that will be prevented by utilizing H_2-powered fuel cells as an alternative to petrol (or gasoline) fuel combustion (Ayodele *et al.* 2019):

$$CO_2 \text{ or } CO = PR \times SE_F \quad (11)$$

CO_2 or CO is the amount of CO_2 and CO emissions that would be prevented, and SE_F is the specific emission factor of the corresponding greenhouse gas. The CO_2 emission factor of petrol (or gasoline) fuel is 2.3 kg/L (Ayodele & Ogunjuyigbe 2015), whereas the CO emission factor is 0.00413 kg/L (Ayodele & Ogunjuyigbe 2015). To estimate the amount of CO_2 and CO that would be prevented by using hydrogen to replace petrol (or gasoline) fuel, the same five assumed scenarios with the equivalent percentage of hydropower energy utilization as used in the calculation of the hydrogen and the re-electrification potential were used in the estimation. The results were obtained for each scenario as Sx-CO_2 and Sx-CO for CO_2 and CO emissions, respectively.

The estimation of greenhouse gas emissions prevention by petrol (or gasoline) replacement refers to the operation phase only. This is based on the narrow boundary, which only includes emissions from the use phase of the generator, i.e., the combustion of petrol or the consumption of hydrogen in the fuel cell during the generator operation. This was chosen primarily due to its focus on immediate operational impacts and availability of data. While a full life cycle assessment would provide a more comprehensive comparison, this study aims to highlight the direct emissions reduction potentials when switching from petrol to hydrogen in generator operation.

RESULTS

Hydropower in Nigeria has strong seasonality

The statistical analysis helps benchmark hydropower's interannual variability and seasonality toward estimating the exposure of hydrogen production to climate variability. The trend test results using the MMK test are shown in Table 5. It shows a positive or an increasing trend in the reservoir inflow, outflow, turbine discharge, and energy generation, while evaporation loss shows a decreasing trend; however, maximum temperature and rainfall have no trend. The results of interannual variability and seasonality of hydropower generation are displayed in Figure 2. The interannual variability reveals that hydropower generation has been fluctuating annually, with the lowest generation of 2,065 MWh in 1993 and the highest generation of 4,150 MWh in 2016, indicating a 50.2% increase; similarly, for the seasonal variation, the highest generation of 2,412 MWh was recorded in the dry season of 2007 while the lowest generation of 684.7 MWh was recorded in the wet

Table 5 | MMK trend analysis statistics (with the *P*-value at 0.05 significant level) and *Z*s (normalized test statistics) show the trend, either increasing (+ve), decreasing (−ve), or no trend (Non) for all variables

Jebba dam variables	*P*-value	*Zs*	Trend
Rainfall (mm/year)	0.0891	1.6996	Non
Max. temperature (°C)	0.2960	1.0449	Non
Reservoir inflow (m^3/s)	0.0000	5.3603	+ve
Reservoir outflow (m^3/s)	0.0005	3.4672	+ve
Evaporation loss (m^3/s)	0.0005	−3.4633	−ve
Turbine discharge (m^3/s)	0.0000	4.7610	+ve
Energy generation (MWh)	0.0001	3.8071	+ve

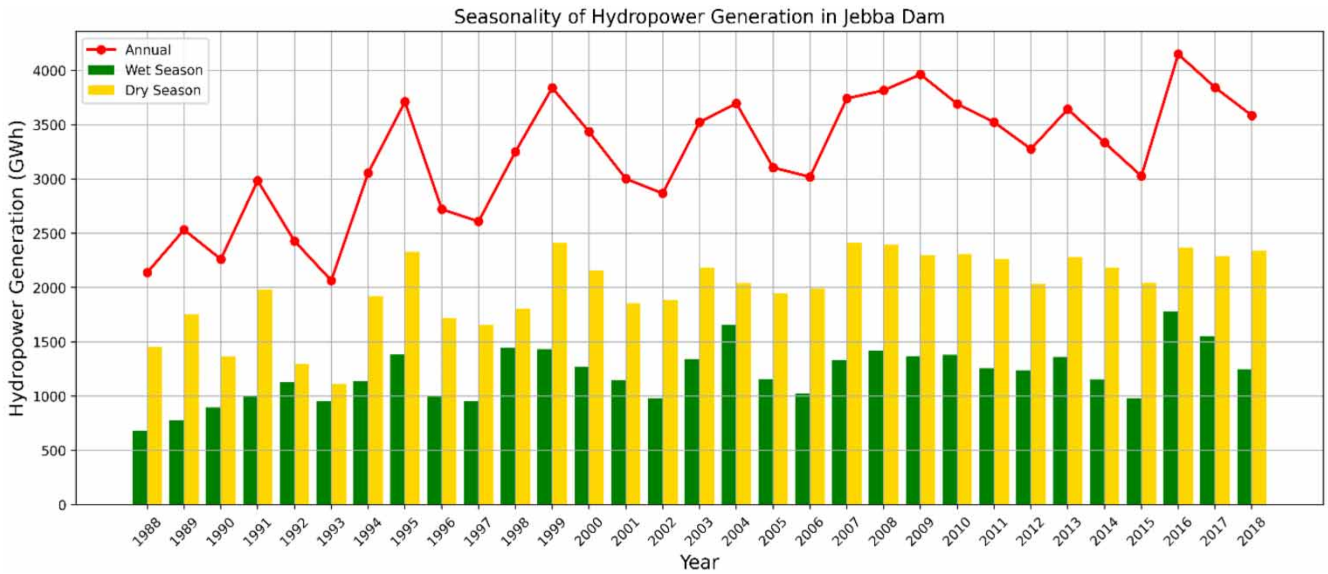


Figure 2 | Interannual variability and seasonality of annual hydropower generation in the wet (green) and dry (orange) seasons at JHS.

season of 1988. The results show an increasing trend in the annual energy generation both annually and seasonally, and this could be a result of the positive trend in the reservoir inflow and turbine discharge, which largely influences the amount of hydropower energy generated. Also, the seasonality shows higher hydropower generation in the dry season (October to April) than in the wet season (May to September). This disparity could be traceable to the flooding in the wet season and the moderate reservoir inflow in the dry season; more details on flooding in the dam are reported in the study by Olukanni *et al.* (2016). Energy output in the dry season (if surplus) is another approach to producing GH_2; however, the approach used in this study utilizes a specific percentage of hydropower generation.

The correlation matrix between hydroelectric energy production and other hydroclimatic variables (rainfall, maximum temperature, reservoir inflow, outflow, evaporation loss, and turbine discharge) was built to evaluate how each of these variables relates to hydroelectric generation using a statistical significance of 0.95. Figure 3(a) shows the correlation matrix for the pairwise variables of the Jebba hydroelectric plant. The result shows that energy generation is significantly and strongly correlated with the inflow, outflow, and turbine discharge, having correlation coefficients of 0.9, 0.9, and 0.99, respectively.

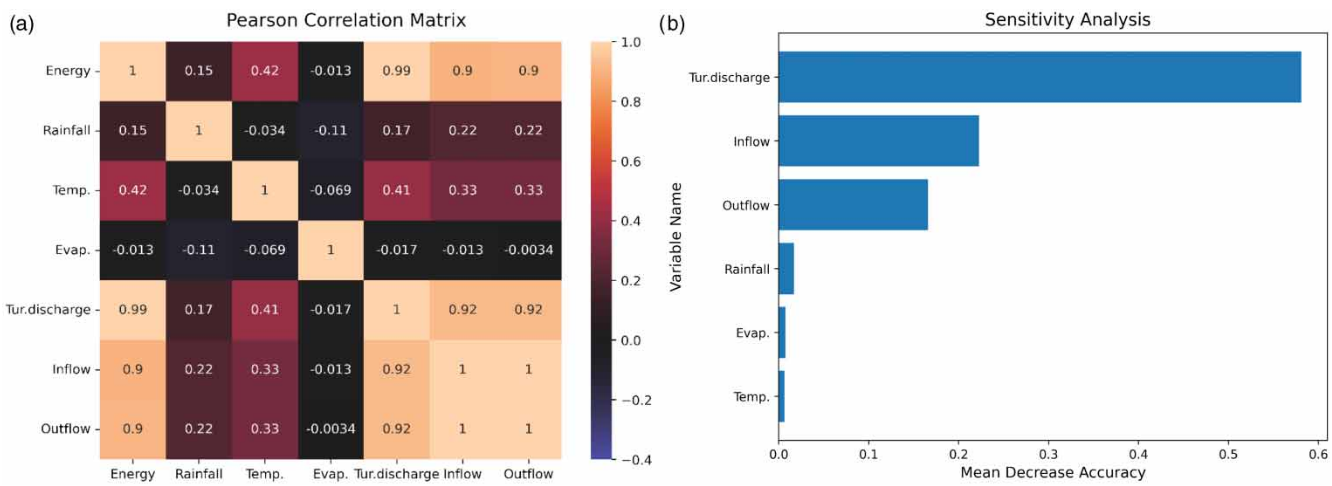


Figure 3 | (a) Pearson correlation coefficient for energy generation and other hydroclimatic variables. (b) Sensitivity analysis of energy generation to other hydroclimatic variables.

Moreover, temperature and rainfall show a lower correlation, with coefficients of 0.42 and 0.15, respectively. In contrast, evaporation loss showed a very insignificant correlation at the hydropower station with a correlation coefficient of −0.013. Furthermore, turbine discharge strongly correlates with inflow and outflow, with a coefficient of 0.92. Likewise, the sensitivity analysis result is presented in Figure 3(b). It shows that turbine discharge has the highest sensitivity to energy generation with a mean decrease accuracy of 0.59, followed by the reservoir inflow with a mean decrease accuracy of 0.23, then the outflow with an approximate mean decrease accuracy of 0.17, and rainfall with an approximate mean decrease accuracy of 0.04. In contrast, temperature and evaporation loss show the least sensitivity to energy generation in the hydroelectric station with mean decrease accuracy of 0.02 and 0.01, respectively.

Estimation of GH_2 production and re-electrification potential

The hydroelectricity used for the five hypothetical scenarios was computed using Equation (7). The result of the annual and quarterly GH_2 potential estimation is displayed in Figure 4(a) and 4(b), while the yearly and quarterly electricity that could be generated by utilizing hydrogen fuel cells is shown in Figure 4(c) and 4(d), respectively. The first scenario using 100% hydropower energy revealed that the highest and the lowest annual hydrogen production potential are 59,111 and 40,125 tons, which have a re-electrification potential of 1,182 and 803 GWh in the years 2021 and 2002, respectively, while the highest quarterly production potential was recorded in the fourth quarter of 2021 (2021Q4) with a potential of 18,744 t and a re-electrification potential of 374 GWh. The results show that the GH_2 production and re-electrification potential for the five hypothetical scenarios is highly linear and follows the trend of hydropower generation. This suggests that potentially

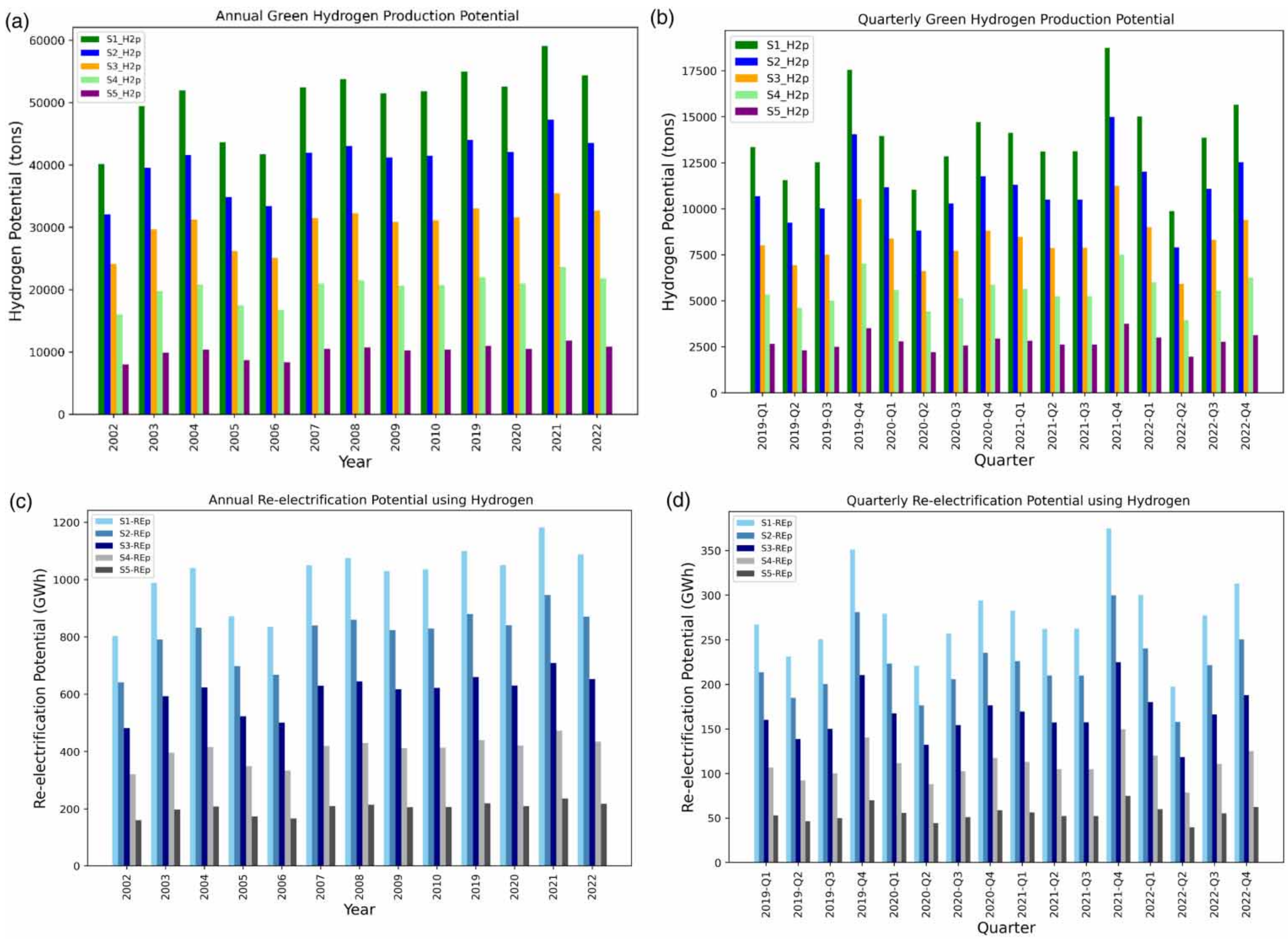


Figure 4 | Scenario 1 (S1) to scenario 5 (S5) estimated (a) annual GH_2 production potential (H2p), (b) quarterly GH_2 production potential (H_{2p}), (c) annual re-electrification potential (RE_p), and (d) quarterly re-electrification potential (RE_p) at JHS.

stable, consistent, and less fluctuating hydrogen production is possible with stable hydropower generation and can be used as a means for energy storage and rural re-electrification of the population without access to grid electricity.

Estimation of petrol (or gasoline) replacement and amount of greenhouse gas emissions prevention

The results of the estimated amount of annual and quarterly petrol (or gasoline) replacement with hydrogen for the five hypothetical scenarios are displayed in Figure 5(a) and 5(b), while the quantity of the annual and quarterly greenhouse gases CO_2 and CO emissions that could be prevented is shown in Figure 5(c)–5(f). The first scenario using hydrogen produced from 100% hydropower energy reveals that the highest and the lowest amounts of petrol that could be replaced with hydrogen are 0.224 and 0.152 million L, utilizing 59,111 and 40,125 tons of hydrogen in 2021 and 2002, respectively. In the same years, this replacement could prevent 0.52 million kg of CO_2, 0.92 thousand kg of CO in 2021, and 0.35 million kg of CO_2, 0.63 thousand kg of CO emissions in 2002. Likewise, the quarterly GH_2 produced from the first scenario shows that 0.0709 million L of petrol could be replaced with 18,744 t of hydrogen. This could prevent 0.163 million kg of CO_2 and 0.293 thousand kg of CO emissions in 2021-Q4. This replacement of petrol with hydrogen for the re-electrification of rural communities without access to sufficient energy can contribute to the reduction of greenhouse gas (CO_2 and CO) emissions in Nigeria. Using the estimated electricity consumption of the country according to the study by Olaniyan *et al.* (2018), the consumption rate of 90–135 kWh per month for an average household of five members and 18–27 kWh per capita per month, an estimated 730–1,094 households and 3,648–5,472 persons in the rural areas could be provided with electricity using the hydrogen production of 59,111 t, which has a re-electrification potential of 1,182,000 KWh (1,182 GWh) for the year 2021. This could contribute to the reduction of the year's total CO_2 emission, which was mainly driven by the burning of fossil fuels, as reported by Climate Watch (2020). This gradual emission reduction, when cut across all sectors, would enhance the climate change mitigation efforts and carbon neutrality goal in the country.

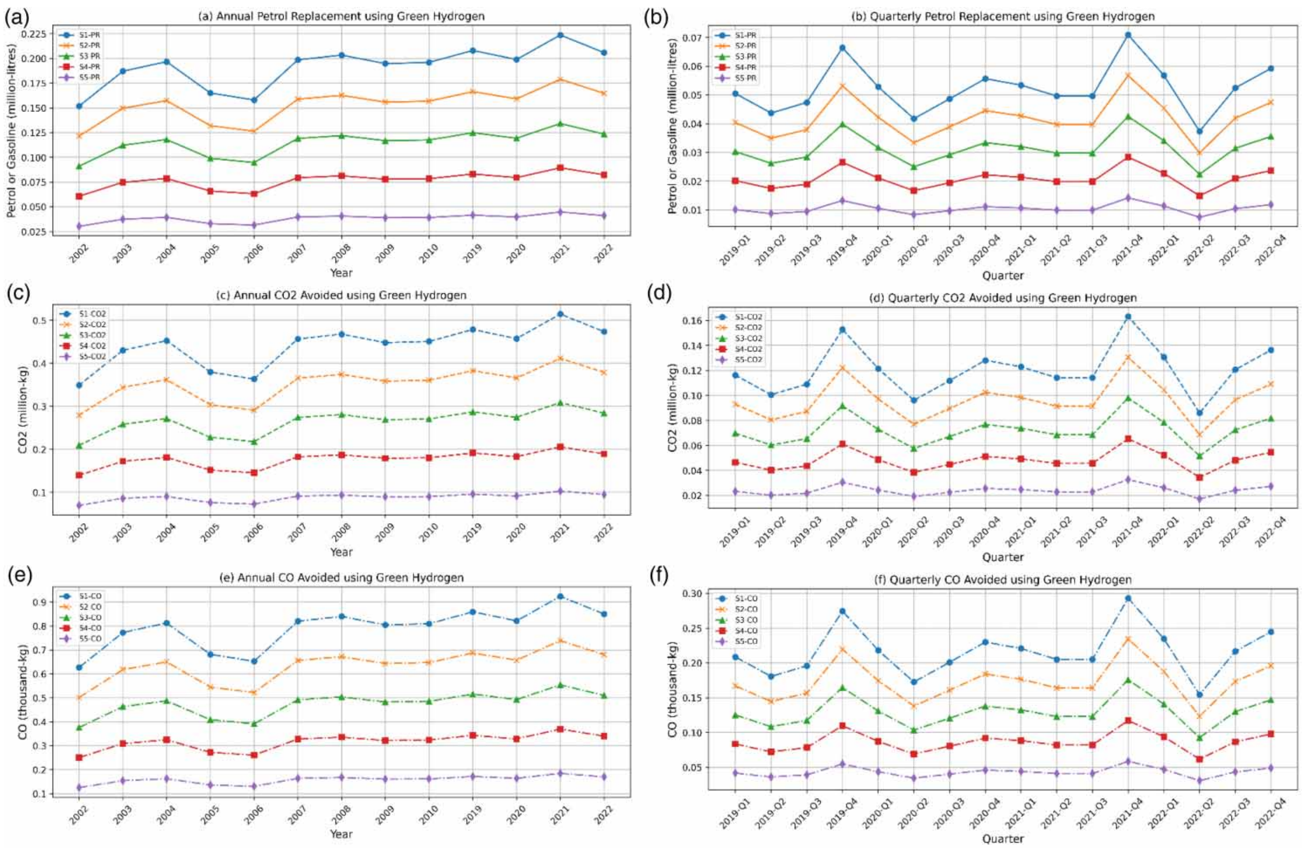


Figure 5 | Scenario 1 (S1) to scenario 5 (S5): (a) annual and (b) quarterly petrol replacement (PR); (c) annual and (d) quarterly CO_2 emissions avoided; and (e) annual and (f) quarterly CO emissions avoided using GH_2 for re-electrification.

DISCUSSION

Hydroclimatic trend and variability

This study shows the effect of hydroclimatic variability on hydropower generation and how it influences the efficiency and stability of GH_2 production for re-electrification and fossil fuel replacement in Nigeria. The trend analysis results show a significant increase in energy generation from 1988 to 2018 due to an increasing trend in reservoir inflow, outflow, and turbine discharge; this indicates that these three variables are the primary drivers of hydropower generation. The sensitivity analysis shows that turbine discharge is the most sensitive variable of these three significant variables responsible for energy production at the station, significantly impacting the amount of electricity produced. The analysis of hydroclimatic trends at the station reveals patterns that are consistent with the results of Salami *et al.* (2010) in their study on the impact of climate change on water resources in the reservoir which shows a significant positive trend in the inflow, outflow, and turbine discharge with a tendency to increase and a negative trend in the evaporation loss with a tendency to decrease over time slightly. Furthermore, the turbine discharge, reservoir inflow, and outflow correlate more strongly with energy generation than other variables like rainfall, temperature, and evaporation loss. These findings align with the findings of Liman *et al.* (2021), which shows that inflow and outflow have a stronger relationship with energy generation than temperature and evaporation loss.

Seasonality of hydropower generation

The seasonality of hydropower production shows that more hydroelectric energy is generated in the dry season than in the wet season, as reported by Liman *et al.* (2021). This is because the Jebba hydropower dam is cascaded downstream of the Kainji dam, which regulates the water releases during the dry season, ensuring consistent flows to Jebba dam and allowing it to generate electricity efficiently; however, priority is given to flood management to avoid flood risk during the wet season, which often reduces controlled water flow and the amount of water passed through the turbines and sent downstream to Jebba dam. This, in turn, limits its capacity to generate power during the wet season. However, the surge in hydropower production concurrently manifested in GH_2 production potential and vice versa. This underscores water resources' significant impact and availability for hydropower and GH_2 production. An increased hydropower output can potentially escalate GH_2 production, which can serve as energy storage during excess energy output and substitute for a substantial amount of fossil fuel usage in the country. This replacement of fossil fuel (e.g., petrol) with cleaner energy – hydrogen energy – can curb greenhouse gas emissions and provide an avenue for mitigating climate change. Furthermore, energy security can be significantly improved by investing in the development of GH_2 technologies and hydropower infrastructure to achieve the GH_2 capacity set for 2050, according to Nigeria's Energy Transition Plan (NETP 2022), as this technology offers a reliable and adaptable energy storage solution that can be applied to a variety of industries and sectors, such as power generation, transportation, and industry. This will decrease Nigeria's reliance on imported fossil fuel through energy source diversification and the improvement of resilience to disruptions in the energy supply, ensuring a more secure energy future and drastically reducing the carbon footprint of the country, thereby enhancing the achievement of the net-zero carbon emission goal of eliminating the use of fossil fuel generators by 2050 as stated in NETP (2022).

GH_2 production and re-electrification

In addition, the study reveals that integrating hydropower production with GH_2 production for re-electrification and replacing fossil fuel generators with hydrogen fuel cell generators will provide environmental benefits and reduce air pollution, as evidenced by the reduction of CO_2 and CO emissions. With talks on energy transition both at the global and national level, the assessment proposes a strategic incorporation of green energy production into the nation's energy mix by earmarking a five-scenario percentage of hydropower production or excess energy output for the hydrogen production, which can serve as one of the pathways to realizing the nation's energy transition goals and possible reduction in future escalation of greenhouse gas emissions. The study is limited to only one hydropower station located at the Jebba dam due to data availability and the need for site-specific study, even though Nigeria has an estimated 86% untapped hydropower potential, which can be developed to serve as an integrated system for hydropower generation and GH_2 production. This integration can drive the vision of Nigeria's carbon neutrality and net-zero goal by 2060 (Climate Action Tracker 2023), bringing economic benefit through additional revenue generation from GH_2 exports, fostering the development and creation of new jobs within the energy sector, and contributing to the achievement of the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), which emphasized the importance of sustainable energy solutions in achieving broader development objectives. This assessment of Jebba hydropower generation for GH_2 production will catalyze future research endeavors in hydro-to-hydrogen in Nigeria.

The study's results underscore the intricate relationship between hydroclimatic variability, hydropower generation, and GH_2 production potential. Furthermore, the results show the possibility of climate change mitigation by replacing fossil fuels with cleaner energy like hydrogen. However, the study has the following limitations: First, using historical hydropower generation data provides insights into hydropower availability and provides a useful baseline, but it is insufficient for long-term planning, especially in the context of climate change and extreme weather events. Future climate risks such as droughts, floods, and seasonal variability can affect hydropower generation, thus affecting clean hydrogen production. To improve the reliability of hydropower for hydrogen production, historical data can be supplemented with future climate models and risk assessments for climate-resilient hydropower forecasting and hydrogen production planning. Second, it is assumed that sufficient hydroelectricity is generated to support the hydrogen production levels in each scenario; however, seasonal variability may limit the reliability of hydrogen production. Third, optimal efficiency in GH_2 production using hydropower without accounting for potential energy losses in the processes is assumed for each scenario; however, real-world hydrogen production efficiency can vary depending on the electrolysis technology used. Fourth, the scenarios assumed hydrogen utilization in fuel cell generators is nearly 100% efficient; however, this is limited because there could be energy losses during conversion. Finally, the emission factors for petrol are accurate and representative of petrol used in Nigeria; however, the emission factors can vary depending on the source, composition, and local variations of fuel quality being burned, which may result in different emission profiles than those used in our study. In addition, the narrow boundary approach in the analysis of greenhouse gas emission reduction highlights the immediate benefits of hydrogen in reducing direct emissions, but it does not provide a complete environmental assessment. For example, we assume that hydrogen produces zero emissions during the operation phase, but its production (depending on the materials) may involve carbon emissions. Moreover, a key limitation of this method is that it does not account for emissions from other life cycle stages, such as the emissions from extracting, refining, and transporting petrol, as well as producing and distributing hydrogen, the energy and materials needed for hydrogen production, compression, storage, and distribution. Thus, while the narrow boundary approach is useful for assessing direct operational benefits, it may overestimate or underestimate the actual greenhouse gases (GHG) mitigation potential of hydrogen-powered generators compared with petrol generators. Moreover, the study is limited to one reservoir, but the methodology used in the study can be scaled up to include all other reservoirs in the country to foster the development of integrated hydropower dams for clean hydrogen production, fossil fuel replacement, and decarbonization, with emphasis on the continued understanding of these critical issues in the face of a changing climate and global energy landscape.

CONCLUSION

This section presents the study's conclusion, policy implications, and recommendations. It summarizes the findings on the impact of hydroclimatic variability on hydropower generation and its effect on the efficiency and stability of GH_2 production. We demonstrated how hydrogen annual and quarterly potential generation from hydropower is sensitive to hydroclimatic variability and should be considered in implementing Nigeria's hydrogen strategy. The following have been shown:

- The hydropower generation in the dam for the study period (1988–2018) has increased significantly due to the varying hydroclimatic variables, especially the increasing trend in the reservoir inflow and turbine discharge. This has directly influenced the increase in the energy output and produced a similar increasing pattern in the estimated GH_2 potential, re-electrification, the amount of fossil fuel (petrol) that can be replaced, and emissions of CO_2 and CO that could be prevented using hydrogen.
- The production and usage of hydrogen can be utilized to reduce emissions from Nigeria's energy sector, which, according to the country's First National Inventory Report (Federal Republic of Nigeria 2021), saw a rise in emissions from 142,678 Gg CO_2-eq in 2000 to 245,918 Gg CO_2-eq in 2017. The energy sector's overall emissions in 2016 were from fuel combustion activities, accounting for 60.8% of the total, with fugitive processes only contributing 39.2% of the overall emissions (Federal Republic of Nigeria 2021).
- At the current consumption rate of 90–135 kWh per month for an average household of five members and 18–27 kWh per capita per month, leveraging fuel cells could provide electricity, for example, using 59,111 t of hydrogen, which has a re-electrification potential of 1,182 GWh. This would result in access to electricity for an estimated 730–1,094 households

and 3,648–5,472 persons not connected to grid electricity. However, due to aging hydropower plants, the most recommended percentage of hydropower utilization is the lowest percentage of 20%, which can be an initial step to steering the country toward the production and integration of GH_2 into its energy mix till when investment is made in the upgrading of existing hydropower plants and the development of other hydropower sites with huge potentials.
- According to NETP (2022), in 2020, the power sector's total emissions were 48 Mt CO_2, with 12% from off-grid diesel and petrol generators equivalent to 5.76 Mt CO_2. Suppose they were replaced with fuel cell generators. In that case, emissions would be lowered by 0.4576 Mt CO_2, which is a 0.001% reduction of CO_2 emissions. This reduction can increase when other hydropower sites and resources in the country are considered.

Though the integration of hydrogen into hydropower systems holds substantial potential to transform the country's energy landscape and enhance its carbon neutrality goal, several policy interventions and recommendations are crucial to support its development and deployment. A comparison with similar studies conducted in significant hydropower resources countries such as Paraguay, Nepal, and Turkey revealed a potential of 24,904 to 3,153,360 t/year and 2.26 Mt, respectively, considering various forms of hydropower production. However, the highest potential in Jebba dam for the period under study was 59,111 t at 100% hydropower utilization for the only dam considered in the study. Other hydropower-rich countries, such as Norway, Brazil, and Canada's policies and infrastructure-driven strategies also suggest that Nigeria could position itself as a leader in Africa's emerging hydrogen economy.

Furthermore, there are potential challenges that could hinder adoption, including absolute reliance on hydropower for GH_2 production, which may strain existing infrastructure, especially due to competing demands for electricity, highlighting the need for the development of new hydropower dams and renewable energy sources to scale hydrogen production. Likewise, the absence of a clear regulatory framework by the Nigerian government and the lack of technical and logistical skills will require the development of specific policy and capacity-building programs to create an enabling environment and workforce. While competition with fossil fuels can also be a major challenge, the development of strategies to incentivize the fossil fuel industry for clean energy production might be necessary. Energy planners could also consider untapped hydropower potentials estimated at 12,220 MW. These developments can contribute to surplus energy output, which can be converted to hydrogen to build a robust hydrogen economy. This would help the country achieve its carbon neutrality target by 2060 and serve as an export commodity, increasing its revenues. It is, however, best practice to jointly present environmental and socioeconomic assessments to policymakers to develop fully informed regulatory incentives and investment plans.

This study serves as a foundation for future research; further studies can be considered, including assessing the impact of climate change on future hydropower potential and its influence on GH_2 production. Optimization techniques such as techno-economic-environmental analysis can be investigated to enhance cost-effective and environmentally sustainable GH_2 production from hydropower resources in Nigeria. In conclusion, the study's findings show that hydroclimatic variability's impact on hydropower generation has a linear relationship with GH_2 production; these findings could support the policy and regulatory framework and enhance the country's energy transition and climate change mitigation efforts.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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