Clean Energy, 2024, Vol. 8, No. 2, 156–167
https://doi.org/10.1093/ce/zkae020
Advance access publication 8 March 2024
Research Article

Green hydrogen production from photovoltaic power station as a road map to climate change mitigation

Kehinde Ridwan Kamil[1,2], Bassey Okon Samuel[2,3,*], and Umar Khan[1]

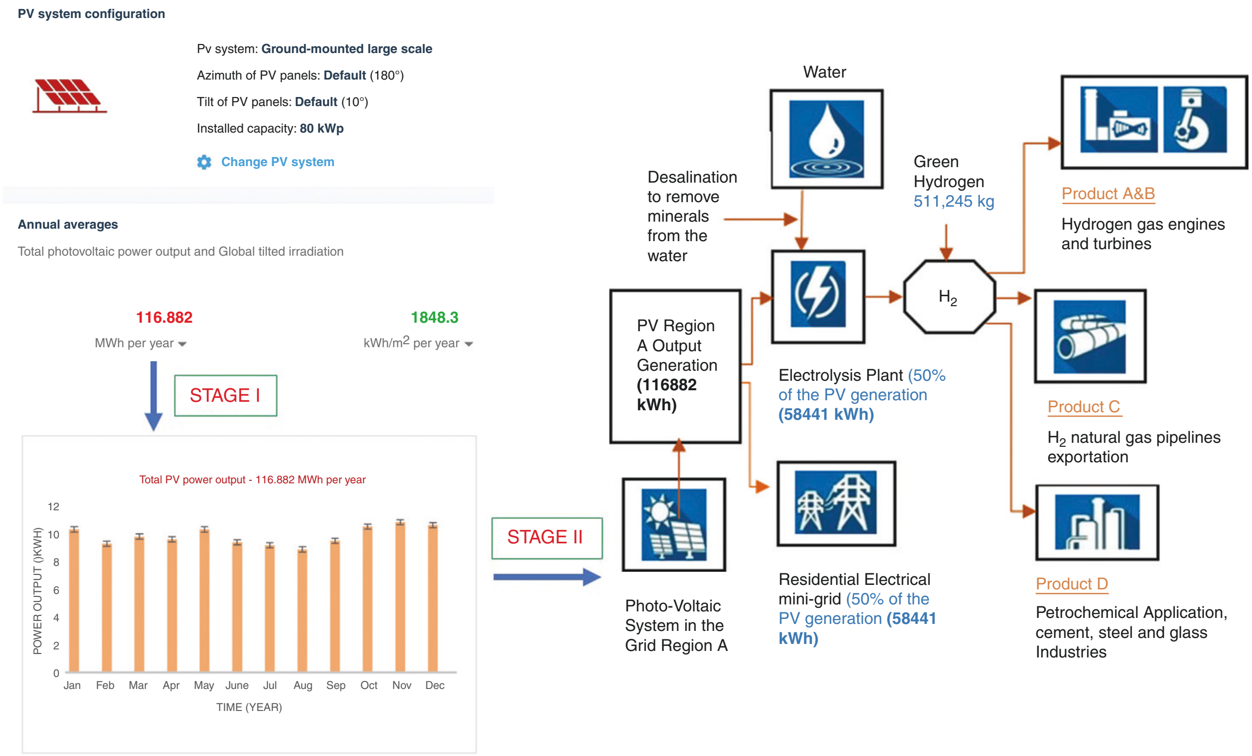
[1]Department of Computer Science and Engineering, Edge Hill University, UK
[2]Enel Green Power, Rome Italy
[3]Materials Research Laboratory, Steelagon Engineering Limited, Kaduna State, Nigeria
[*]Corresponding author. E-mail: basseyokon59@gmail.com

Abstract

The increasing recognition of hydrogen as a critical element in the global net-zero transition and its clear role in decarbonizing challenging sectors coincide with the growing urgency to address climate change. Africa's favourable renewable-energy capacity, ranging from 28% to 36% for solar, has been reported by the global solar irradiance index. However, the majority of hydrogen production today relies on fossil fuels (96%), with only a small fraction (4%) being produced through water electrolysis. Even though there have been many studies on climate change mitigation with a focus on Africa, a green hydrogen production from a photovoltaic power station approach has not been reported. Also, literature with a focus on Nigeria is lacking. This study focuses on the African green hydrogen production industry, utilizing Nigeria as a case study to explore the feasibility of generating clean hydrogen vectors from a percentage of photovoltaic power output in various regions of the country through stand-alone solar grid electrification projects. Analyses of the usage and effectiveness of the produced hydrogen fuel in each region are carried out, with the highest region having an annual output of 12 247 278 kg of green hydrogen and 8 573 094 kg of ammonia and the lowest region having an output of 511 245 kg of green hydrogen and 357 871 kg of ammonia, and the expected production from the proposed usage of 50% of the power generation output of the installed 1.6-MWp and 80-kWp solar power minigrids in the regions is calculated. The analyses were repeated for the other considered regions in the country. The results showcased the enormous advantages of the electrolytic production of hydrogen and how the greener economy project can play a major role in mitigating climate change effects and overreliance on fossil fuels as the driver of the economy in many African countries.

Received: 7 September 2023. **Accepted:** 8 February 2024

Graphical Abstract



Keywords: renewable energy; photovoltaic; climate change; green hydrogen vector; fossil fossil fuels decarbonization electrolysis

Introduction

The escalating dependence on fossil fuels and the accompanying challenges have sparked heightened interest in the development and adoption of cleaner energy alternatives [1]. Non-renewable sources such as gas, oil and coal constitute a significant portion of our energy consumption, leading to various economic, political and environmental concerns [2]. As a result, there has been a growing emphasis on hydrogen as an efficient and eco-friendly energy solution, capable of mitigating the adverse effects of fossil fuel usage on the environment [3]. While the current primary applications of hydrogen involve ammonia production, soil enrichment and the synthesis of various chemical compounds such as methanol, its potential as a viable clean energy source is increasingly gaining recognition [4].

The competitiveness of green hydrogen production varies based on several factors, encompassing local resources, proximity to demand and infrastructure availability, at regional, national and project-specific levels. Sunlight, being a crucial and sustainable energy source, offers an abundance of energy to the surface of Earth, exceeding the total human energy consumption by a substantial margin [5]. Consequently, in addressing global warming concerns and considering the affordability of modern photovoltaic (PV) systems compared with traditional ones, there has been a surge in utilizing PV cells to augment clean energy production. Although the efficiency of PV cells has made remarkable strides, currently reaching ~29%, their practical efficiency in commercial applications lingers in the range of 10–20%, so they are not yet entirely replacing fossil-fuel-based electricity. Elements such as temperature and shading influence PV cell efficiency, underscoring the critical need for accurate forecasting and estimation of PV system efficiency under realistic weather conditions [6].

1 Solar renewable resources potentiality in African countries

The Sustainable Energy for All (SE4All) initiative, led by the United Nations and the World Bank in partnership with other organizations, aims to ensure access to sustainable energy for all by 2030, as part of a global effort. Sub-Saharan Africa's geographic location offers the potential for a significant contribution to the global energy supply through solar energy, provided that adequate infrastructure is available [7, 8].

Located in West Africa, Nigeria has a large land area of 923 768 km^2 and is blessed with abundant sunshine year-round due to its proximity to the equator. The country averages ~6.5 hours of sunshine each day, with an average solar flux of 5.55 kWh/m^2 per day. This translates into a remarkable daily solar energy potential of ~4.851 × 10^{12} kWh. Solar radiation intensities in Nigeria range from 3.5 to 7.0 kWh/m^2 per day, increasing from the south to the north. This substantial source of energy is available for roughly 26% of the day, typically from 9:00 am to 4:00 pm. With these promising geographic characteristics, Nigeria holds tremendous potential for significant electrical energy generation through solar power utilization [9]. Table 1 compares the solar potential of Nigeria, Morocco and the other top five African countries based on the geographical location and solar irradiance levels of these countries. Higher solar capacities indicate a better position for these green hydrogen sources, as they are directly proportional.

Table 1: Solar potential of African countries [10]

Country	Solar potential (TWh/year)
Nigeria	15–20
Morocco	45–50
South Africa	20–25
Egypt	50–60
Tunisia	10–15

Table 2: Hydrogen gas in comparison with other fuels [11]

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (–253°C, 1 bar)	1/6 of natural gas
Energy per unit of mass (LHV)	120.1 MJ/kg	3× that of gasoline
Boiling point	–252.76°C (1 bar)	90°C below LNG
Flame velocity	346 cm/s	8× methane
Auto ignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

1.1 Relevant properties of hydrogen

Hydrogen is notable for its higher energy content per unit of mass compared with natural gas or gasoline, which makes it an attractive choice as a transportation fuel, as shown in Table 2. However, as the lightest element, hydrogen has a lower energy density per unit of volume. As a result, to meet the same energy needs as other fuels, it is required in larger volumes. This issue can be addressed by using pipelines that are either larger or have a faster flow rate, and by employing bigger storage tanks [12]. Investment in advanced hydrogen storage solutions that require less space, such as underground salt caverns or advanced materials for compressed or liquefied hydrogen storage, can help to alleviate the large volume requirement of hydrogen during storage [11].

Hydrogen is a gas that poses no toxicity concerns, yet its flammability remains a significant consideration due to its high flame velocity, wide ignition range and low ignition energy. However, its notable buoyancy and diffusivity characteristics facilitate rapid dissipation, offering some measure of risk reduction. One noteworthy challenge lies in the fact that a hydrogen flame is both colourless and odourless, making it invisible to the naked eye, thereby hindering the detection of leaks and fires. Despite this, it is worth noting that the industrial usage of hydrogen has amassed extensive experience, including its safe application in large, dedicated distribution pipelines [13].

Hydrogen is not naturally occurring and must be extracted from other elements such as water or hydrocarbons, and this process requires energy, and has economic and environmental costs. The different types of hydrogen vectors, classified by colour, have varying degrees of CO_2 emissions and environmental impact. Green hydrogen, obtained from water electrolysis powered by renewable energy, has a very low environmental impact and generates zero CO_2 emissions. The colour classification of hydrogen vectors is shown in Table 3.

Table 3: Type and properties of hydrogen vectors [13]

Hydrogen vector type	Properties
Brown hydrogen	Obtained from coal gasification with >20 kg of CO_2 emitted for every kilogram of hydrogen produced
Grey hydrogen	Obtained from steam reforming of natural gas with >9 kg of CO_2 emitted for every kilogram of hydrogen produced
Blue hydrogen	Obtained with the same production method as that for grey hydrogen but with partial capture, transport and storage of CO_2. It emits ≤5 kg of CO_2 not captured for every kilogram of hydrogen produced
Pink hydrogen	Obtained from water electrolysis powered by nuclear energy. It has a high environmental impact due to the production of nuclear waste even if it does not emit CO_2
Green hydrogen	Obtained from water electrolysis powered by renewable energy. It has a very low environmental impact and generates zero CO_2 emissions

1.2 Advantages of green hydrogen as a driver of economic diversification

- Green hydrogen serves as a valuable catalyst for promoting the widespread adoption of renewable energy in an energy system. Such projects necessitate the deployment of renewable energy sources, effectively bolstering the availability of clean energy within a country. The integration of green hydrogen projects with the existing grid infrastructure offers an opportunity to provide additional low-cost clean energy to local communities [14]. Through the strategic implementation of green hydrogen export projects as anchor offtakes and leveraging economies of scale, renewable-energy capacity for hydrogen projects can intentionally be oversized, resulting in the provision of affordable clean energy to local communities. This approach effectively reduces the risk associated with renewable-energy development in Africa, as it facilitates the creation of green hydrogen exports supported by credible foreign offtakes.
- Green hydrogen production facilities play a pivotal role as grid buffers, contributing to the seamless integration of renewable energy sources. By establishing grid-connected green hydrogen projects, the flexibility of the electrolyser comes into play, facilitating the balancing of intermittent electricity systems. During periods of heightened demand, the electrolyser can strategically reduce its load to alleviate demand peaks. Conversely, in situations in which energy supply surpasses demand, the electrolyser can ramp up its production to accommodate the surplus. Such adaptive capabilities significantly enhance the capacity of the grid to effectively integrate and harness the potential of more volatile renewable energy sources [15].
- Green hydrogen projects are of paramount importance in establishing a robust renewable-energy ecosystem and streamlined infrastructure, expediting the rapid deployment of renewables. The development of hydrogen production capacity from renewable sources not only fosters the growth of a skilled local workforce, but also facilitates

> access to cutting-edge technologies such as solar panels and wind turbines [16]. These projects, through the joint subsidization of infrastructure, create an attractive environment for foreign investors, encouraging and enabling the accelerated construction of renewable generation capacity beyond the hydrogen sector. The overarching goal is to establish a sustainable framework that supports the widespread adoption of renewables and drives forward the transformation of the energy landscape.

Producing substantial amounts of hydrogen is a critical aspect of an energy ecosystem that is centred on hydrogen as a fuel for power generation. Two key technologies are prominent for their ability to produce hydrogen in large quantities: steam methane reforming and the electrolysis of water. Currently, steam methane reforming is the technique most commonly used for hydrogen production worldwide. Nonetheless, this process generates CO_2 emissions, necessitating the integration of carbon capture technologies to ensure its participation in a carbon-free ecosystem [17]. The focus lies on striking a balance between efficiency and environmental responsibility, fostering a hydrogen-based energy landscape that aligns with sustainability objectives. Fig. 1 shows the distribution of energy sources in Africa with only 4% for renewable energy sources.

The notion of using water electrolysis to produce hydrogen is well known, but the prospect of generating the substantial volumes required for power generation presents a challenge, as it would demand a considerable amount of energy, subsequently leading to escalated costs of hydrogen and the associated power. To surmount this obstacle, an alternative approach involves producing hydrogen through electrolysis using renewable energy sources [18]. By leveraging on the sustainable potential of renewables, this solution aims to strike a harmonious balance between efficient hydrogen generation and cost-effectiveness while upholding environmental considerations.

Hydrogen can be produced from water through three primary methods: thermolysis (thermal chemical process), electrolysis (electrochemical process) and photocatalysis (photochemical process). In industrial applications, various techniques are employed for hydrogen production, including oil processing, natural gas reforming, coal gasification, and electrolysis. Electrolysis involves using electrical energy to separate hydrogen from water molecules [19].

A prevalent method for generating hydrogen using electricity is through PV cells. In this approach, a PV power plant produces the electricity needed for the electrolysis process. The efficiency of hydrogen production via electrolysis can be significantly increased by using high-performing PV power plants. This method of producing hydrogen with PV power plants is not only clean, but also aligns with environmental sustainability goals, as it offers an environmentally friendly solution [20].

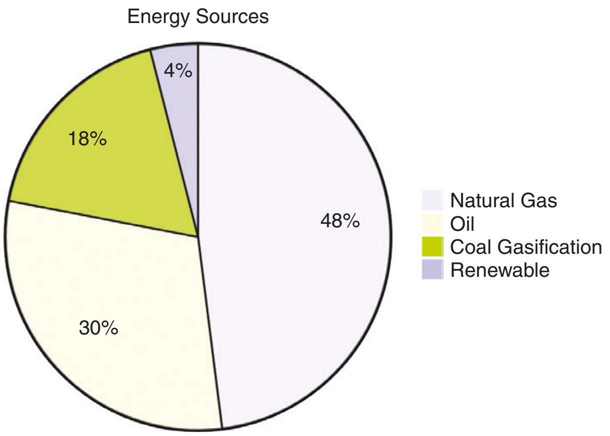


Fig. 1: Distribution of energy sources in Africa [17]

1.3 Green hydrogen as a pathway to sustainable power generation in Africa

Africa, as a continent, maintains a modest contribution to global warming, accounting for <3% of the world's energy-related carbon dioxide (CO_2) emissions thus far. Moreover, it boasts the lowest emissions per capita among all continents [21]. Despite this, Africa bears the brunt of climate change consequences, experiencing heightened vulnerability to extreme weather events such as prolonged droughts, delayed rainy seasons and heavy flooding due to excessive rains. Embracing green hydrogen, which is often hailed as the 'oil of the future', has emerged as an increasingly promising pathway for transitioning towards a cleaner global energy system. Green hydrogen serves as both an energy vector and a versatile industrial feedstock, fostering the development of intricate and resilient economic value chains. Furthermore, it can be processed into finished goods such as renewable fertilizers and chemicals, while effectively decarbonizing highly polluting and challenging-to-abate sectors, including cement, steel and glass production. In Africa, pioneering green hydrogen production projects are already underway, marking a significant step towards sustainable energy innovation [21]. Table 4 shows some pioneering investments of African countries in green hydrogen generation.

By leveraging the abundant renewable resources available in the continent, Africa has the unique opportunity to produce green hydrogen, which, in turn, can act as a catalyst for local socio-economic growth, bolster regional energy security and

Table 4: Pioneering investments of African countries in green hydrogen generation [21]

Country	Project partner and capacity	End use
Egypt	100–3000 MW Renew Power	Mobility and export
	4 GW Masdar Project	Export and industrial feedstock
	100–3000 MW Siemens Project	Mobility and export
	10 MW Alfarnar Green Ammonia	Industrial feedstock
Namibia	100–3000 MW Daures Green Village	Various uses and export
	10 MW Hydrogen Refueling Station	Mobility
South Africa	10 MW Anglo American Mining Truck	Mobility
	ArcelorMittal Direct Reduced Iron Memorandum of Understanding	Industry feedstock
Morocco	3 GW HEVO Ammonia	Industrial feedstock and export
Algeria	Sonatrach and Eni Hydrogen pilot project	Various uses
Mauritania	3 GW AMAN Ammonia	Various uses and export
	3 MW Total and Chariot Nour Green Hydrogen Project	Industrial feedstock and export

alleviate poverty. The development of green hydrogen in Africa holds the potential to yield significant benefits, including the establishment of a green economy in various African nations, facilitating swift and enhanced access to energy, generating employment opportunities and potentially enhancing access to both power and clean water resources. Embracing green hydrogen as an integral part of Africa's energy landscape can usher in a transformative era of sustainable development, paving the way towards a brighter and more prosperous future for the continent [22].

Berga [23] presented the proportional relationship between hydropower and climate change. In the study, it was highlighted that climate change has an inverse relationship with hydropower production capacity and hydropower has an inverse relationship with the production of CO_2. Banianla [24] highlighted the lack of literature on major countries on Africa in a study on climate change adaptation and mitigation in Africa. With the primary objective of developing a rigorous analytical model for conducting a techno–economic assessment of green hydrogen production within the context of a PV power station, Zghaibeh [25] undertook a comprehensive investigation into the feasibility of utilizing solar energy for hydrogen generation within a photovoltaic hydrogen station (PVHS). Notably, the PVHS system exhibits an impressive annual hydrogen production capacity of ~90 910 kg, accompanied by an initial capital cost amounting to €5 301 760. The resultant calculation of the levelized hydrogen production cost yields a figure of €6.2 per kilogram—a calculation made under the consideration of a 2% interest rate. This empirical analysis underscores the significant potential of this innovative approach for the sustainable and economically sound production of green hydrogen. By combining these prospects, Africa stands a chance of not only the mitigation of climate change, but also improvement in its deficient energy infrastructure.

Even though many studies have been centred on the mitigation and adaptation of climate change, and some other studies have presented technical methods of hybrid clean energy production systems, no study has focused on Nigeria's capacity for producing green hydrogen from PV systems. This study uses Nigeria, a country in the western hemisphere of Africa, as the case study to examine the possibility of producing green hydrogen from a percentage of total annual power output from existing PV grid systems in different regions of the country. It discusses how the generated hydrogen fuel can service numerous industrial and commercial needs as an alternative to fossil fuels. The study will expose how green hydrogen can act as an enabler for climate change mitigation and a carbon-free energy ecosystem. This study novelty aims to exploit the potential of producing green hydrogen from proliferating renewable PV grids in different regions in Nigeria to showcase the countries' potential to join African hydrogen-producing nations.

2 Methodology

2.1 Case study analysis and PV system simulation

Renewable electrification initiatives, primarily driven by solar projects, have begun to showcase significant impact in rural areas and alternative electrification efforts across various African countries. This section focuses on the system design that is geared towards generating green hydrogen from PV power plants, with a keen examination of the availability of renewable power to support this innovative concept. As of the end of 2019, Nigeria boasted an estimated installed minigrid capacity of ~2.8 MW, encompassing 59 projects that cater to the energy needs of rural consumers. These minigrids predominantly serve residential areas, with some specifically designed to support productive activities. Additionally, considering the inclusion of fully commercial-served minigrids, the total number of such projects is expected to be higher as seen in Fig. 2 [26]. This ongoing progress reflects the growing momentum towards sustainable energy solutions and electrification in Africa.

According to a spotlight report published by the Rural Electrification Agency in Nigeria showcasing some minigrid PV projects commissioned across the country, this study uses the information to propose the usage of a percentage of the expected PV electrical power outputs to generate sustainable green hydrogen in the same ecosystem [27].

Table 5 shows the specifications and locations of the solar grid projects considered in this study. The PV solar potential in the considered regions is simulated using the Global Atlas SolarGIS Software for different countries. The simulation webpage provides an aggregated and harmonized solar resource and PV power potential from the perspective of different countries and their regions.

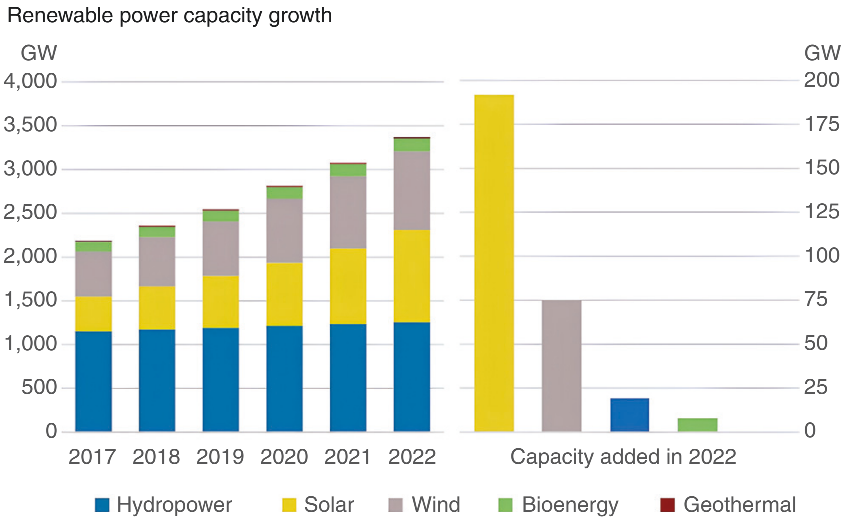


Fig. 2: Scale of renewable energy generation in Nigeria [26]

Table 5: Considered PV stand-alone grids and their capacity [27, 28]

Country location (PV Grid Region)	Size of the photovoltaic minigrid project	SolarGIS annual solar photovoltaic potentiality in the region (kWp)
North Central Region (PV Grid Region A)	80-kWp solar minigrid at an isolated community in Ajaokuta, Kogi State	1448.3
South-South Region (PV Grid Region B)	100-kWp solar–hybrid LGA (Local Government Area), Akwa Ibom State community in Onna	1168
South East Region (PV Grid Region C)	100-kWp solar minigrid at Eka-Awoke community, Ikwo LGA, Ebonyi State	1314
North West Region (PV Grid Region D)	1.6-MWp solar power Sabon Gari Market Grid Project	1607
North East Region (PV Grid Region E)	85-kWp solar minigrid at Dakiti community in Akko LGA, Gombe State	1753
North East Region (PV Grid Region F)	91-kWp solar minigrid in Sarkin Kudu community, Taraba State	1557.5

Table 6: Output of the photovoltaic power output in PV Grid Region A

Ajaokuta, Kogi State Grid Region A output photovoltaic (latitude 07.4631, longitude 0006.6936)		
Map data	**PV generation features**	**Amount (kWh/kWp per year)**
Specific photovoltaic output	PVout	1448.3 kWh/kWp
Direct normal irradiance	DNI	1007.5 kWh/m^2
Global horizontal irradiance	GHI	1831.9 kWh/m^2
Global tilted irradiation	DIF	1063.5 kWh/m^2
Global tilted irradiation at optimum angle	GTIopta	1849.4 kWh/m^2
Optimum tilt of PV modules	OPTA	10/180°
Air temperature	TEMP	28.1°C
Terrain elevation	ELE	94 m

2.2 Simulation for the expected annual power generation in PV Grid Region A

To estimate the quantity of green hydrogen produced through electrolysis, we will rely on the annual performance data from individual PV power projects. The electrolysis process will involve splitting water molecules into their constituent elements. For the initial calculation, we will focus on the power generation of the first considered PV grid system in PV Grid Region A. Table 6 shows the output of the photovoltaic power output in PV Grid Region A. This system comprises an 80-kWp solar minigrid located in an isolated community within Kogi State, with PV resources obtained from SolarGIS for the region. The site-specific PV potentiality obtained from SolarGIS was used in the design simulation carried out on Global Solar Atlas, as shown in Fig 3. To start with, it is important to stress that the efficiency of a solar panel is a matter of area, not power. Installing 300-Wp panels for the 80-kWp solar minigrid will require 267 series-connected 300-Wp solar panels in the region.

Fig. 4 Shows the simulation result for the case study PV Grid Region A in Ajaokuta, Kogi State, Nigeria, where the grid has been commissioned. The grid configuration in the simulated design is ground-mounted, as installed on the site. The simulation result shows that a total of 116.882 MWh or 116 882 kWh per year is the expected generation. The system design will be in a hybridized form whereby an equal percentage of the generated PV power in the considered regions will service the primary needs of the province and supply the proposed green hydrogen generation plant in the area. Figs 5 and 6 show the monthly and November daily PV generation from the stand-alone PV grid system. The highest generation is in November, with a peak hourly PV power output of 55.1 kWh.

The approach presented in this study for green hydrogen production paves the way for carbon-free, sustainable energy solutions. The results gleaned from the annual generation data of the PV power station indicate that utilizing 50% of the PV power output for hydrogen production through electrolysis is viable. During the process of electrolysis, water molecules split into their constituent elements, as depicted in Equation (1). This transformative process exemplifies the potential for harnessing clean hydrogen as an integral component of the clean energy transition:

$$H_2O(liquid) \rightarrow H_2(gas) + 1/2O_2(gas) \tag{1}$$

Electrolysis requires electrical energy to successfully split water molecules into hydrogen. Specifically, to produce 1 g (or 1 kg) of hydrogen, 9 g (or 9 kg) of water are needed, based on stoichiometric values and assuming there are no losses in the electrolysis process. The amount of power required for this is determined by dividing the higher heating value (HHV) of hydrogen by the efficiency of the electrolysis system [29]. This process creates a detailed connection between the input of electrical power and the production of hydrogen. It underscores the importance of efficiency in maximizing hydrogen generation while minimizing the consumption of resources.

$$Electrolyzer\ Power = \frac{HHV}{System\ Efficiency} \tag{2}$$

The HHV for hydrogen stands at 12 756.2 kJ/Nm^3 (141 829.6 kJ/kg), which can be equivalently represented as 3.54 kWh/Nm^3 (39.39 kWh/kg). For this analysis, we assume a 70% efficiency of the proton exchange membrane (PEM) electrolyser system, which is commercially available technology. To fulfil the power demands of the electrolyser, PV power will be harnessed as a clean and sustainable alternative energy source [29, 30].

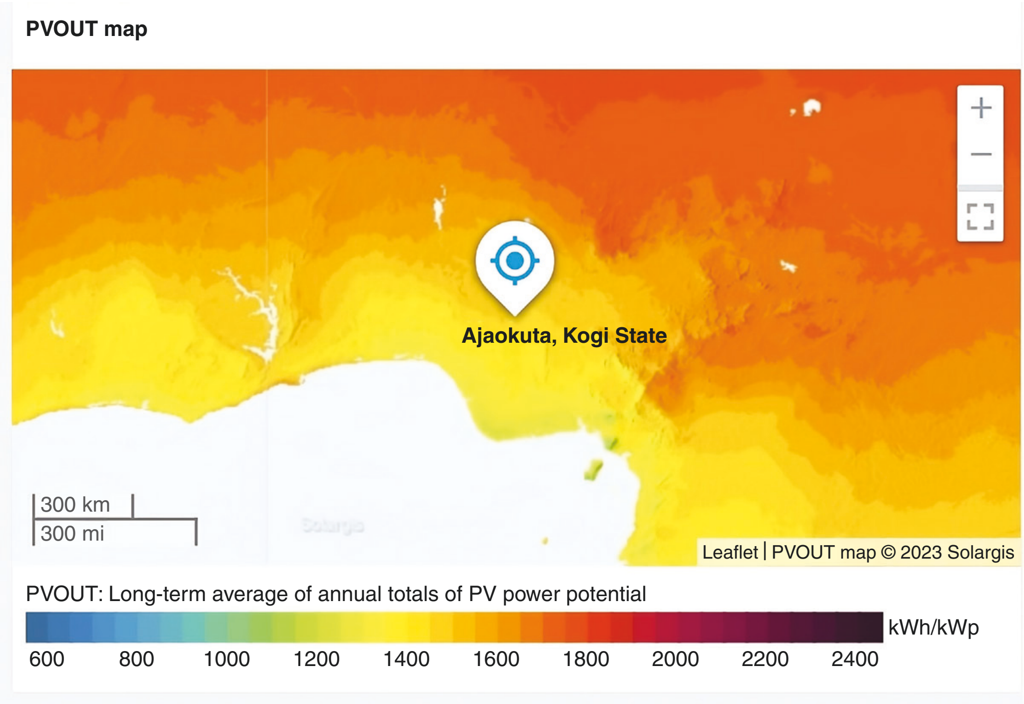
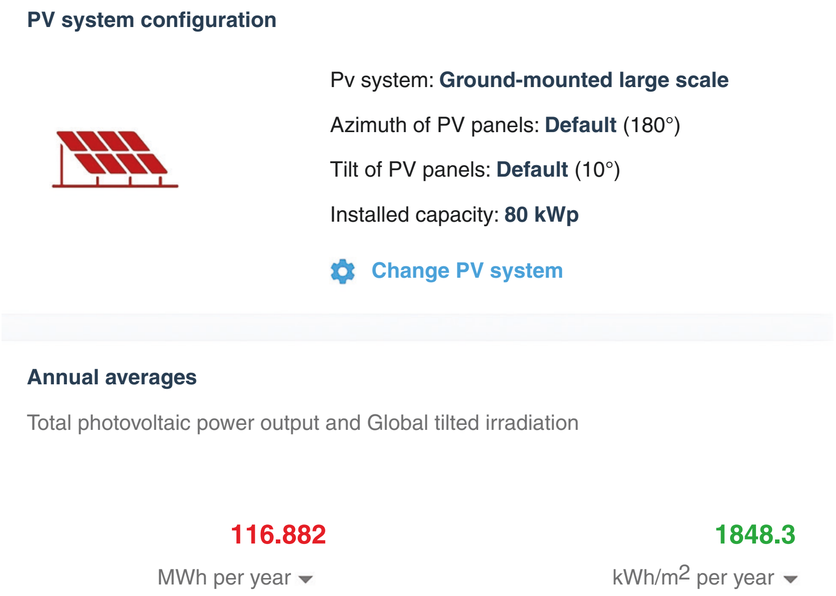


Fig. 3: ESMAP SolarGIS annual specific photovoltaic power output in PV Grid Region A



PV system configuration

Pv system: **Ground-mounted large scale**

Azimuth of PV panels: **Default** (180°)

Tilt of PV panels: **Default** (10°)

Installed capacity: **80 kWp**

Annual averages

Total photovoltaic power output and Global tilted irradiation

116.882
MWh per year

1848.3
kWh/m^2 per year

Fig. 4: Simulation result for the 80-kWp grid system in PV Grid Region A as designed for ESMAP

Therefore, in PV Grid Region A, using 50% of the power output of the 80-kWp PV grid system, the power used for the hydrogen production will be:

$$116\,882 \text{ kWh} \times 50\,\% = 58\,441 \text{ kWh} \tag{3}$$

The formula for calculating the hydrogen production from electrolysis can be given as:

$$m = \frac{z * F * I}{96485 * V} \tag{4}$$

where m represents the mass of hydrogen produced in grams, z denotes the number of electrons participating in the electrolysis reaction, F stands for the Faraday constant (96 485 C/mol), I represents the current flowing through the electrolytic cell in amperes and V indicates the voltage applied across the electrodes in volts. The formula assumes 100% Faraday efficiency, which is not realistic in the industrial production of hydrogen. Since we have the PV energy output instead, hydrogen production can be given as:

$$m = \frac{P}{\eta * E\_H} \tag{5}$$

where m is the mass of hydrogen produced (in grams), P is the PV energy input (in kWh) and E_H is the energy required to produce 1 mole of hydrogen (in kJ/mol).

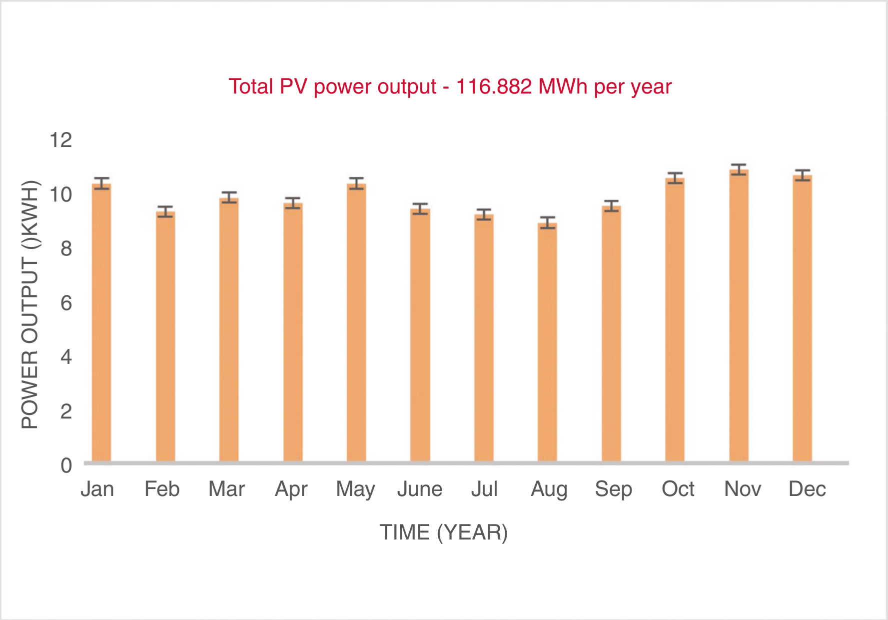


Fig. 5: The monthly distribution of the photovoltaic power output in PV Grid Region A

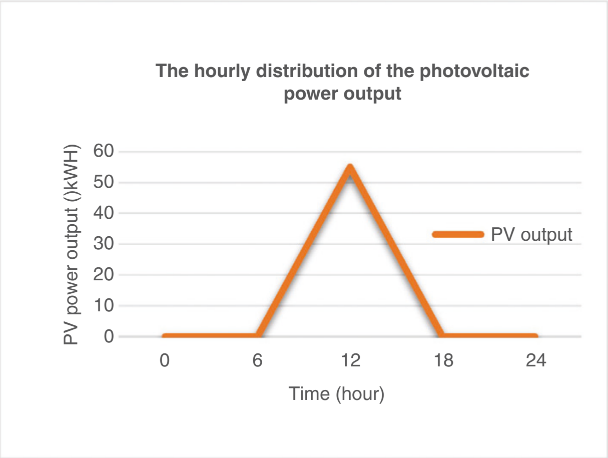


Fig. 6: The hourly distribution of the photovoltaic power output in PV Grid Region A for November

$$E\_H = \frac{\Delta H°f}{\eta_{electrolysis} * \left(\frac{1}{molar} mass\ of\ hydrogen\right)} \tag{6}$$

where $\Delta H°f$ represents the standard enthalpy changes of the formation of hydrogen (~285.8 kJ/mol). The efficiency (η) of a PEM electrolyser can be assumed to be 70%, depending on the operating conditions of the temperature of the electrolysis water, pressure and current density. The molar mass of hydrogen is in grams/mol (~1.0079 g/mol) [29].

$$E\_H = \frac{285.8}{0.7 * \left(\frac{1}{1.0079}\right)} = 411.52 kj/kg \tag{7}$$

Therefore, the hydrogen production in PV Grid Region A with a PV power out of 58 441 kWh, or 210 387 600 kJ (as we are working with energy values from the direct source and the standard unit of energy in the International System of Units is the joule) is:

$$m = \frac{58441 * 3600}{411.52} = 511,245\ kg \tag{8}$$

Using PV energy of 58 441 kWh, we can estimate a production of ~511 245 kg of green hydrogen from PEM electrolysis. Since the electricity for the electrolysis process comes from renewables (solar), there is no 'direct' release of CO_2 when generating or burning hydrogen. The schematic below shows how the produced hydrogen gas can be utilized in different sectors of the country's economy.

Hydrogen production for the conventional steam methane reforming (SMR) and electrolysis of water involves the release of carbon dioxide into the atmosphere during the process. Green hydrogen production from electrolysis of water as proposed in this study will help in alleviating the environmental threats associated with hydrogen production for commercial and industrial use [31].

The procedure was repeated for the other commissioned solar grid projects in the remaining five geopolitical zones. Table 7 gives the output of green hydrogen generation when 50% of the annual output PV power output was used for hydrogen production.

3 Results

3.1 Hydrogen gas as a motor fuel (Product A)

When comparing hydrogen and diesel as motor fuels, several factors must be considered, including their energy content, efficiency and emissions [32]:

- Energy content: On a mass basis, diesel fuel has a higher energy content than hydrogen, with an energy density of ~44 kWh/kg compared with ~33 kWh/kg for hydrogen. However, since hydrogen is a gaseous fuel, it can be stored in larger volumes, thus increasing its energy content compared with liquid fuels such as diesel.

Table 7: Green hydrogen gas production from PV output in different regions

Photovoltaic project	Expected annual PV electricity utilized (50% of the total PV output)	Expected hydrogen production (kg)
80-kWp solar minigrid at an isolated community in Ajaokuta, Kogi State	58 441 kWh	511 245 in PV Grid Region A
100-kWp solar–hybrid LGA, Akwa Ibom State community in Onna	63 899 kWh	558 992 in PV Grid Region B
100-kWp solar minigrid at Eka-Awoke community, Ikwo LGA, Ebonyi State	63 899 kWh	558 992 in PV Grid Region C
1.6-MWp solar power Sabon Gari Market Grid Project	1400 MWh	12 247 278 in PV Grid Region D
85-kWp solar minigrid at Dakiti community in Akko LGA, Gombe State	72 182 kWh	631 452 in PV Grid Region E
91-kWp solar minigrid in Sarkin Kudu community, Taraba State	71 373 kWh	624 375 in PV Grid Region F

- Efficiency: Regarding efficiency, fuel cell vehicles utilizing hydrogen can be more efficient than diesel vehicles. Hydrogen fuel cell vehicles can transform a larger portion of the stored energy in hydrogen into useful work compared with diesel vehicles, which usually experience energy losses due to factors such as friction.
- CO_2 emissions: In the regions examined in the study, hydrogen generated from renewable energy sources is classified as a green fuel because it produces zero greenhouse gas emissions during combustion. In contrast, diesel fuel, when burned, emits CO_2 and other harmful pollutants into the atmosphere.

Deducing from the established relationship, 511 245 kg of hydrogen produced from PEM electrolysis in PV Grid Region A can supply more energy compared with the equivalent amount of diesel fuel and the use of hydrogen as a motor fuel has a lower environmental impact, as it produces no greenhouse gas emissions during combustion.

3.2 Green hydrogen in the production of ammonia (Product D)

Most hydrogen generated globally for ammonia production for fertilizers or petrochemicals comes from SMR, which releases carbon dioxide. However, the production of green ammonia involves a 100% renewable and carbon-free process. The Haber–Bosch process is a commonly used method for producing ammonia from hydrogen and nitrogen, in which they are reacted under high pressure and temperature conditions to yield ammonia. The reaction can be expressed as follows:

$$N_2 + 3H_2 \rightarrow 2NH_3 \tag{9}$$

where N_2 stands for nitrogen, H_2 is hydrogen and NH_3 represents ammonia. The conversion efficiency of the Haber–Bosch process is typically ~70–80%. This means that, for every 100 kg of hydrogen, 70–80 kg of ammonia can be produced [10].

Table 8: Ammonia production from the available hydrogen gas in each region

Green hydrogen produced	Green ammonia equivalent production (kg)
PV Grid Region A production of 511 245 kg of hydrogen	357 871.5 to 408 996
PV Grid Region B production of 558 992 kg of hydrogen	391 294.4 to 447 193.6
PV Grid Region C production of 558 992 kg of hydrogen	391 294.4 to 447 193.6
PV Grid Region D production of 12 247 278 kg of hydrogen	8 573 094 to 9 797 822.4
PV Grid Region E production of 631 452 kg of hydrogen	442 016.4 to 505 161.6
PV Grid Region F production of 624 375 kg of hydrogen	437 062.5 to 499 500

Table 8 shows ammonia production from the available hydrogen gas in each region. Given that the amount of green hydrogen produced in PV Grid Region A from PEM electrolysis is 511 245 kg, then the amount of green ammonia that can be produced using the Haber–Bosch process can be calculated as follows:

$$\textit{Green ammonia} = 0.70\,\text{to}\,0.80 \times 511\,245\ \text{kg} \tag{10}$$

$$= 376\ \ 810.3\ \textit{to}\ 454\ 095.6\ \text{kg} \tag{11}$$

3.3 Green hydrogen usage in gas turbine engines (Product B)

Gas turbine engines fuelled by green hydrogen exhibit notably superior energy efficiency compared with those powered by fossil fuels. The higher energy density per unit of volume and lower ignition temperature of hydrogen facilitate a more effective combustion process, thereby contributing to enhanced efficiency. It is noteworthy that, by using a blend of hydrogen and natural gas to operate a gas turbine instead of pure hydrogen, the volume of hydrogen required can be reduced. This approach optimizes resource utilization, as highlighted in [23, 24].

Considering power generation volumes, a single General Electric (GE) 6B.03 gas turbine operating for 8000 hours annually would necessitate ~33 million kg of H_2 per year. However, if the hydrogen were to be produced via SMR, this process would generate ~178 000 metric tons of CO_2 annually [33]. This stark comparison underscores the significance of transitioning towards green hydrogen production to mitigate environmental impact and foster sustainable energy practices in the power generation sector.

4 Economic viability of green hydrogen production plant

4.1 Availability of water source to support electrolysis process

The enormous availability of water resources in Nigeria favours the consideration of green hydrogen projects in the country. However, it is advisable to extract the water required from the widespread streams and rivers in different regions of the country to avoid water resources competition with residential usage of water at any point of construction of green hydrogen plant projects. As shown in the schematic in Fig. 7, the desalination process helps in removing impurities or minerals that may be present in

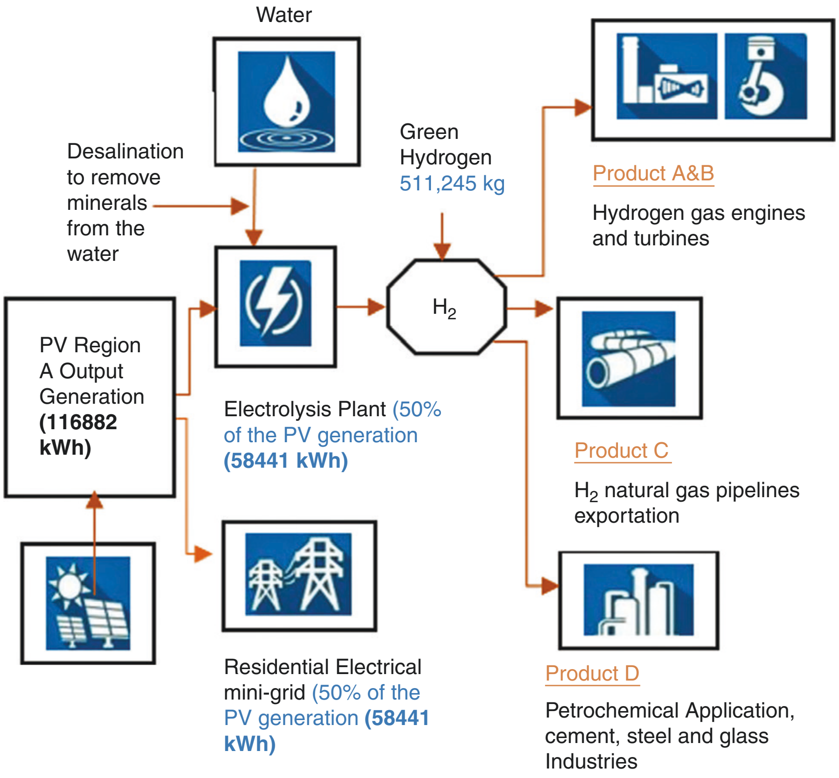


Fig. 7: Schematic showing the distribution of PV Grid Region A power output

the water, as these can have a negative impact on the efficiency and performance of the electrolysis process.

PV Grid Region A is located in Ajaokuta, where there are abundant water bodies, including rivers and streams. Some of the major rivers in the area include the Niger River and its tributaries, such as the Anambra River and the Benue River. Furthermore, PV Grid Region B is located in Onna, Akwa Ibom, where some of the major rivers in the area include the Cross River, which is the largest river in the region, and its tributaries, such as the Kwa River and the Imo River. These rivers provide a source of water for domestic and agricultural purposes, and can serve for industrial usage in green hydrogen production plants.

As a general estimate, the production of 1 g of hydrogen through electrolysis necessitates ~9 g of water, considering stoichiometric values and assuming zero losses throughout the process. This estimation provides a foundational understanding of the water requirements involved in hydrogen generation. This is because the reaction of splitting water into hydrogen and oxygen requires a certain amount of energy, and the amount of water used in the process reflects the amount of energy required [29]. However, the actual energy consumption may be higher due to the energy losses during the process, so the energy efficiency of electrolysis can vary.

4.2 Cost-effectiveness of electrolysers

There are six main types of electrolyser technologies that show potential for hydrogen production: alkaline, acidic, acidic/alkaline amphoteric, solid-oxide, microbial and photo electrochemical. Each category has its specific benefits and limitations, and not all are currently suitable for industrial-scale applications. Additionally, not all these technologies can be smoothly integrated with intermittent renewable energy sources to create a stable power–hydrogen nexus [34].

Furthermore, while academic literature extensively covers the alkali (alkaline) and PEM (acidic) systems, which have already been commercialized, not all the technologies are particularly well suited for coupling with intermittent renewable energy sources to create an efficient and synergistic power–hydrogen relationship [35].

4.2.1 *Alkaline electrolysers*

Alkaline water electrolysis is recognized as the most technologically advanced method and is frequently regarded as the benchmark for large-scale industrial hydrogen (H_2) production. It enables the highest capacity for 'green' hydrogen production while demanding the lowest investment costs. The system size typically ranges from 1.8 to 5300 kWh, resulting in investment costs that vary between US$800 and US$1500 per kilowatt [10]. As an example, in this study, the estimated production of 511 245 kg of hydrogen gas in PV Grid Region A utilizes a PV power output of 58 441 kWh. Consequently, the cost of the electrolyser system will be:

$$1\ \text{kWh} - \text{US}\ \$444/\text{kWh} \tag{12}$$

Generating 58 441 kWh using the alkaline electrolyser will result in an estimated cost of US$2 571 404. This cost is approximately 2–2.5 times lower than the typical investment costs associated with PEM electrolyser technology. Over time, the hydrogen production price has decreased due to the declining costs of electrolysers and renewable energy, with the unit cost of solar electricity production calculated at US$0.084/kWh.

Generally, while alkaline electrolysers offer cost advantages and are considered a mature technology for large-scale hydrogen production, they do have the drawback of producing hydrogen of lower purity compared with other power-to-hydrogen options, such as PEM electrolysers, which are more efficient in terms of hydrogen purity. Nonetheless, the decreasing costs and technological advancements in the hydrogen production sector are paving the way for a promising future of more efficient and economically viable green hydrogen production.

4.2.2 *PEM acidic polymer electrolysers*

The effort to address the significant limitations of alkaline electrolysers ultimately paved the way for development of the first systems founded on a solid polymer electrolyte concept [33]. This concept has seen significant improvements over subsequent decades and has evolved into what is now known as PEM facilities, emerging as the most promising option for coupling hydrogen production with solar and wind power sources at present. When evaluating the cost-effectiveness of electrolyser types in green hydrogen production from PV systems, several factors come into play, including the technology employed, the operating conditions and the size of the production facility. Due to their high efficiency and rapid hydrogen production time, PEM electrolysers are generally considered the most cost-effective option for green hydrogen production from PV systems [36]. The continuous advancements in PEM electrolyser technology are shaping a more sustainable and economically viable future for green hydrogen production, aligning with the ever-increasing demand for renewable-energy solutions.

5 Conclusion

Electrolysis itself is not a novel concept, but the utilization of renewable energy sources to power hydrogen production through electrolysis has garnered significant investment interest in various countries worldwide. To remain at the forefront of sustainable energy advancements, African nations must also proactively explore opportunities in this domain. Many African countries possess an abundance of renewable PV energy resources, presenting a clear pathway to follow the lead of developed nations and invest in green hydrogen production. As evidenced in this study, Nigeria has yet to embrace this direction, with only little research carried out in the conceptualization stage. However, the analysis carried out in the study showcases the viability of generating green hydrogen in different regions of the country.

Six different regions were analysed for green hydrogen production, and it was found that PV Grid Region D, situated in the northern part of the country, where solar intensity is highest, emerged as the most prolific producer of green hydrogen among all the regions studied. This region boasts an impressive annual output of 12 247 278 kg of green hydrogen, with an additional 8 573 094 kg of ammonia production potential. Given the abundant availability of water resources in African countries and the ongoing decline in the price of deploying renewable-energy projects, Nigeria and other African nations should seize the opportunity to invest more in this sector to drive carbon neutrality. Embracing green hydrogen production powered by renewable energy can serve as a transformative step towards a sustainable and greener future for the continent.

Funding

We would like to thank the Petroleum Technology Development Fund (PTDF) in Nigeria for its support towards this research.

Conflict of interest statement

None declared.

Data Availability

The data sets were derived from sources in the public domain: https://globalsolaratlas.info/download/nigeria; https://rea.gov.ng/reference-document/.

References

[1] Bhattacharya P, Prokopchuk DE, Mock MT. Exploring the role of pendant amines in transition metal complexes for the reduction of N2 to hydrazine and ammonia. *Coord Chem Rev*, 2017, 334:67–83.

[2] Hydrogen Council. *Hydrogen Scaling Up 2017*. https://hydrogencouncil.com/en/study-hydrogen-scaling-up/ (30 March 2023, date last accessed).

[3] Wang H, Tong Z, Zhou G, *et al*. Research and demonstration on hydrogen compatibility of pipelines: a review of current status and challenges. *Int J Hydrog Energy*, 2022, 47:28585–28604.

[4] Hydrogen Council, McKinsey Company. *Hydrogen Insights*. 2021. https://hydrogencouncil.com/en/hydrogen-insights-2021/ (23 July 2022, date last accessed).

[5] Energy Information Administration, US Department of Energy. *Electricity Generation, Capacity, and Sales in the United States*. https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php (11 December 2023, date last accessed).

[6] Mikhaylov K, Tervonen J, Fadeev D. Development of energy efficiency aware applications using commercial low power embedded systems. In: Tanaka K (ed). *Embedded Systems: Theory and Design Methodology*. Rijeka, Croatia: InTech, 2012, 407–430.

[7] NASA. *Prediction of Worldwide Energy Resources*. https://power.larc.nasa.gov/ (10 November 2022, date last accessed).

[8] Beyoud A, Bouhaouss A. An investigation into the feasibility of a hybrid generator–photovoltaic–wind farm with variable load profile: case of headland south-west of Morocco. *Clean Energy*, 2022, 6:484–495.

[9] Kamil KR, Yusuf AO, Yakubu SA, *et al*. Renewable energy ree sources hybridization as an efficient and cost-effective alternative for electrification. *NJTD,* 2022, 18:174–183. https://doi.org/10.4314/njtd.v18i3.2.

[10] Barhoumi EM, Okonkwo PC, Belgacem IB, *et al*. Optimal sizing of photovoltaic systems based green hydrogen refueling stations case study Oman. *Int J Hydrogen Energy*, 2022, 47:31964–31973.

[11] Gandhi K, Apostoleris H, Sgouridis S. Catching the hydrogen train: economics-driven green hydrogen adoption potential in the United Arab Emirates. *Int J Hydrog Energy*, 2022, 47:22285–22301.

[12] Feng Z, Wang Y, Lim YC, *et al*. *Steel Concrete Composite Vessel for 875 Bar Stationary Hydrogen Storage: DOE Hydrogen and Fuel Cells Program Annual Progress Report*. Oak Ridge, TN: US Department of Energy, 2016.

[13] International Renewable Energy Agency. *Hydrogen from Renewable Power: Technology Outlook for the Energy Transition*. Abu Dhabi: International Renewable Energy Agency, 2018.

[14] Singh S, Chauhan P, Singh NJ. Capacity optimization of grid connected solar/fuel cell energy system using hybrid ABC-PSO algorithm. *Int J Hydrog Energy*, 2020, 45:10070–10088.

[15] Schmidt O, Gambhir A, Staffell I, *et al*. Future cost and performance of water electrolysis: an expert elicitation study. *Int J Hydrog Energy*, 2017, 42:30470–30492.

[16] Hydrogen Council. *Hydrogen Insights*. 2021. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf (23 August 2023, date last accessed).

[17] Natural Hy. *Using the Existing Natural Gas System for Hydrogen*. 2009. https://www.fwg-gross-bieberau.de/fileadmin/user_upload/Erneuerbare_Energie/Naturalhy_Brochure.pdf (6 August 2021, date last accessed).

[18] Schwarze K, Posdziech O, Kroop S, *et al*. Green industrial hydrogen via reversible high-temperature electrolysis. *ECS Trans*, 2017, 78:2943.

[19] Borm O. Steam electrolysis as the core technology for sector coupling in the energy transition. In: *International Conference on Electrolysis*, Copenhagen, Denmark, 12–15 June 2017.

[20] Chen XZ, Li N, Kong ZZ, *et al*. Photocatalytic fixation of nitrogen to ammonia: state-of-the-art advancement and future prospects. *Mater Horiz*, 2018, 5:9.

[21] Zhang S, Zhao YX, Shi R, *et al*. Photocatalytic ammonia synthesis: recent progress and future. *EnergyChem*, 2019, 1:100013.

[22] Horizon Power. *Hybrid Systems Awarded Australian First Renewable Hydrogen Microgrid Project*. 17 December 2020. https://www.horizonpower.com.au/our-community/news-events/news/hybrid-systems-awarded-australian-first-renewable-hydrogen-microgrid-project/ (16 April 2022, date last accessed).

[23] Berga L. The role of hydropower in climate change mitigation and adaptation: a review. *Engineering*, 2016, 2:313–318.

[24] Banianla Y, Sharifi A, Allam Z, *et al*. An overview of climate change adaptation and mitigation research in Africa. *Frontiers in Climate*, 2022, 4:976427.

[25] Zghaibeh M, Okonkwo PC, Belgacem IB, *et al*. Analytical model for a techno-economic assessment of green hydrogen production in photovoltaic power station case study Salalah City—Oman. *Int J Hydrog Energy*, 2022, 4731:14171–14179.

[26] Korkovelos A, Zerriffi H, Howells M, *et al*. A retrospective analysis of energy access with a focus on the role of mini-grids. *Sustainability*, 2020, 12:1793.

[27] Rural Electrification Agency (REA). *NEP's Achievement in the Last Two Years: Spotlight on Rural Electrification Agency*. https://rea.gov.ng/reference-document/ (3 November 2023, date last accessed).

[28] Global Solar Atlas. *Energy Data Info*. https://globalsolaratlas.info/download/nigeria (11 October 2023, date last accessed).

[29] Enapter. *Hydrogen Seasonal Storage—Electrolyser Use Cases*. https://www.enapter.com/use-cases/hydrogen-seasonal-storage (16 April 2021, date last accessed).

[30] Raab M, Körner R, Dietrich RU. Techno-economic assessment of renewable hydrogen production and the influence of grid participation. *Int J Hydrog Energy*, 2022, 47:26798–26811.

[31] Smith C, Torrente-Murciano L. Guidance for targeted development of ammonia synthesis catalysts from a holistic process approach. *Chem Catalysis*, 2021, 1:1163–1172.

[32] Chen Z, Yiliang X, Hongxia Z, *et al*. Optimal design and performance assessment for a solar powered electricity, heating and hydrogen integrated energy system. *Energy*, 2023, 262:125453.

[33] Temiz M, Javani N. Design and analysis of a combined floating photovoltaic system for electricity and hydrogen production. *Int J Hydrog Energy*, 2020, 45:3457–3469.

[34] Natarajan SK, Kamran F, Ragavan N, *et al*. Analysis of PEM hydrogen fuel cell and solar PV cell hybrid model. *Mater Today Proc*, 2019, 17:246–253.

[35] Hirakawa H, Hashimoto M, Shiraishi Y, *et al*. Photocatalytic conversion of nitrogen to ammonia with water on surface oxygen vacancies of titanium dioxide. *J Am Chem Soc*, 2017, 139:10929–10936.

[36] International Renewable Energy Agency. *Green Hydrogen Cost Reduction*. Abu Dhabi: International Renewable Energy Agency, 2020.