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Green hydrogen production potential in West Africa – Case of Niger

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A B S T R A C T

Niger offers the possibility of producing green hydrogen due to its high solar energy potential. Due to the still growing domestic oil and coal industry, the use of green hydrogen in the country currently seems unlikely at the higher costs of hydrogen as an energy vector. However, the export of green hydrogen to industrialized countries could be an option. In 2020, a hydrogen partnership has been established between Germany and Niger. The potential import of green hydrogen represents an option for Germany and other European countries to decarbonize domestic energy supply. Currently there are no known projects for the electrolytic production of hydrogen in Niger. In this work, potential hydrogen demand across electricity and transport sectors is forecasted until 2040. The electricity demand in 2040 is expected at 2934 GWh and the gasoline and diesel demand at 964 m^3 and 2181 m^3 respectively. Accordingly, the total hydrogen needed to supply electricity and the transport sector (e.g. to replace 1% gasoline and diesel demand in 2040) is calculated at 0.0117 Mt. Only a small fraction of 5% of the land area in Niger would be sufficient to generate the required electricity from solar PV to produce hydrogen.

1. Introduction

The fossil fuels currently serve a gigantic share of the global energy demand. The unrestrained exploitation and use of these nonrenewable resources have an adverse impact on the environment, often causing some irreparable damage. Taking into account the reduced rate at which new oil/gas resources are discovered and the ever increasing energy demand, studies show that we have consumed half of the oil and other fossil resources [1]. Fossil energy use harms renewable based energy consumption in the long run i.e., there is 0.0008% decrease in renewable energy use with every 1% fossil energy consumption [2]. Given these limited resources, transition is required towards greener and cleaner means of producing and using energy. De-carbonizing the energy systems is essential to reduce global warming effects and it can be made possible with the deployment in renewable energy systems [3].

The global energy transition has gained momentum in many parts of the world fueled by the growing use of renewable technologies [4,5]. There has been significant advancements in the renewable energy systems in the field of technology, resource assessment and system design [6,7]. In Ref. [8], Østergaard et al. identified the main trends in the energy system modelling for the energy transition process. Increased modelling of cross-sectoral linkages and focus on temporal detail with respect to planning the future scenarios with high share of renewables were the main trends identified. Majority of the states are interested in creating a low carbon energy infrastructure as a result of which several renewable technologies have grown exponentially in terms of capacity addition [9].

The global renewable generation capacity at the end of 2020 was 2799 GW [10]. At the recent United Nations Climate Change Conference 2021 (COP 26), countries, international banks, lending agencies and public organizations have made commitments to end support to coal and other fossil energy sectors. Some banks will end the international public financing to new coal power plants [11]. This in turn will shift a considerable part of public support to finance the clean energy transition.

There is no second opinion to the fact that renewable energy use is the best route towards a low carbon future. However, with ever-increasing capacities of intermittent renewable energy, managing the grid becomes difficult. The existing power supply and transmission infrastructure is not designed to handle high shares of power from highly intermittent sources. Hence development is being made to integrate appropriate grid energy storage technology to better manage the issue [9]. Ferreira et al. [12] also mention

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the mismatch in energy supplied by renewables and the demand and how the energy storage technologies might be able to address the challenge.

In [13], Duic et al. identified the variable production and integration as the key technical challenges for variable renewable energy sources. They showed that different flexibility options like stationary batteries, hydrogen, pumped hydro storage and high temperature heat storage could work in synergy with variable renewable energy in order to increase the share of renewables in final energy consumed. There are several technologies for grid energy storage like pumped hydro, compressed air energy storage, lithium-ion batteries and hydrogen [1]. Among all these technologies, hydrogen has risen to prominence and is explored as a substitute energy carrier to accelerate the energy transition and mitigate emissions [4].

Hydrogen has gradually become an integral part of the energy transition process as it can be generated with renewable electricity and further can be converted to provide electricity and heat. It can also be stored either for daily or seasonal needs and can be distributed either locally as well as globally [9]. There are different ways of integrating hydrogen with renewable energy sources (RES), as a result of which hydrogen reinforces the contribution from renewables towards mitigating climate change. The different ways in which hydrogen can be coupled with RES are power-to-power, power-to-gas, power-to-fuel and power-to-feedstock [9]. In order to decarbonize hard to abate sectors like transport and heat, flexible solutions are required. Hydrogen is one of the options in which the de-carbonization can be driven forward in all the sectors.

Hydrogen can be produced using a variety of different processes like thermo-chemical processes, electrochemical processes, photochemical processes, photo catalytic processes or photo-electrochemical processes [1]. The raw material for hydrogen production can be either fossils, water or biomass. Hydrogen produced using fossils remains the predominant source in the world markets as this technology has achieved the economies of scale [1]. Although commercially mature and cheap, hydrogen production from fossil-based sources comes with considerable impact on the environment. In the light of the rising concern for sustainable growth, hydrogen production using the cleaner options like water electrolysis is gaining public interest. However, fossil based hydrogen (grey hydrogen) does seem to be unbeatable without carbon tax adjustments and subsidized electricity [14].

In [15], Norouzi examined and ranked the different hydrogen production technologies from different sustainability aspects like economic, social, environmental, energy and exergy. Author found that steam methane reformation (SMR) has significant technical and economic advantage compared to solar or wind based electrolysis, but it is the most destructive for the environment. Wind based electrolysis has a better environmental and social performance as compared to solar photovoltaics (PV) based electrolysis [15]. In case of Niger, the wind resource availability is comparatively low (except to the mountains deep inside Sahara desert, where no large human settlements exist in the periphery of hundreds of kilometers) and the wind energy use sector is not mature at all [16]. On the other hand, Bhandari et al. [17] reported that solar PV in Niger achieved better results on the resource availability and economic dimensions. Hence, it is more favorable to go with the solar PV based electrolysis, which is further considered in this work.

In [18], Valente et al. did the life cycle sustainability analysis (LCSA) and compared the performance of renewable hydrogen (wind powered electrolysis and biomass gasification) against the conventional method (SMR) with Spain as the study area. Compared indicators were environmental (global warming potential (GWP) and acidification potential (AP)), economic (levelized cost of hydrogen (LCOH)) and social (child labor and health expenditure). Authors concluded that renewable hydrogen outperformed the conventional hydrogen in three of the five indicators - child labor, GWP and AP. Due to high production costs and relatively high working time needed per functional unit, the conventional method performed slightly better than the renewable hydrogen methods in health expenditure and levelized cost indicators.

There exist different electrolysis technologies for hydrogen production: alkaline electrolyzers, proton exchange membrane (PEM) electrolyzers and solid oxide (SO) electrolyzers. Alkaline electrolysis is the most commonly used technology in electrolysis of water [19,20]. PEM electrolysis is a relatively new technology but it is quickly gaining grounds in the market because of its ability to adapt to the transient nature of renewables [21,22]. Solid oxide electrolysis is still under development [23]. In order to reach cost parity with the conventional method of hydrogen production, the capital costs of the electrolyzers should decrease significantly [24]. To enhance the efficiency of hydrogen production using electrolysis, several studies have explored the improvement potential in different system components [25].

There are a number of applications of green hydrogen, which is the hydrogen produced by carbon free electricity/feedstock. It can be used to store variable renewable energy, using the surplus electricity to produce hydrogen by electrolysis of water [26]. Thus produced green hydrogen can be used as a fuel e.g. in fuel cell electric vehicle, as a feedstock in the chemical industry (e.g. ammonia), for power generation, in steel manufacturing and cement industry, etc. [27]. The global ammonia production is in turn responsible for 1.4% of the global GHG emissions [28]. In order to decarbonize ammonia production, the hydrogen and the energy required for the process should come from renewable sources [28].

Hydrogen can be combined with oxygen in a fuel cell to produce electricity without any direct carbon emission. Hydrogen can be blended with natural gas and be distributed through the natural gas grid. It can be processed further to generate synthetic fuels like methane, ammonia and methanol [29,30]. The methane produced using this method is carbon neutral (e-Methane) and can be used as vehicle fuel in internal combustion engines or even as fuel for the existing gas turbines. The e-Methane can be fed into the natural gas grid [31]. Hence, production of e-Methane solves the dual purpose: storing excess renewable energy by converting it to hydrogen and capturing CO_2.

Africa is a huge continent with a population of 1.3 billion people, where the economy grew at a rate of 3.4% in 2019 [32]. Economic growth and stable development improve the standard of living, which ultimately propels the energy demand. According to International Energy Agency (IEA), the continent's electricity demand in 2019 was 700 TWh with North and South Africa accounting for the most of this demand [33]. This demand is forecasted to double by 2040, because of the emerging economic and population growth. Although 17% of the world's population lives in Africa, the continent accounts only for 3.7% of the global greenhouse gas emissions [32].

Access to clean cooking facilities and electricity are still important aspects that need immediate attention. About 13% of the natural gas and 10% of crude oil consumed in the European Union are imported from Africa [32]. This is a considerable part of Africa's export. However, the recent Covid-19 crisis saw the demand for fossil fuels slump considerably. Thus, dependency on fossil fuel to generate revenue is not a sustainable business strategy, even without mentioning the environmental problems of fossil fuel use. There is a need for some diversification.

Many African countries are blessed with an enormous solar radiation potential [34]. If the available solar energy can be tapped, this energy could electrify the entire continent and still there would be surplus, which makes Africa a potential candidate to produce and export green hydrogen [35]. According to Agenda 2063 of the African Union, if Africa wants to be a global powerhouse, there needs to be a transition to green energy.

The European Union (EU) has set itself an ambitious target of being carbon neutral continent before 2050 [36]. The European Green Deal identifies green hydrogen as a central pillar to achieve this objective. The demand for green hydrogen will surpass supply to a level that import of green hydrogen from other countries would be a necessity. EU's hydrogen strategy clearly scopes an international dimension in the hydrogen roadmap.

This hydrogen strategy and EU's Africa strategy identify Africa as the perfect partner that can support EU in its energy transition by providing green hydrogen because of its renewable potential and close proximity to the EU [37]. Germany was the first country in EU to adopt a hydrogen strategy. In 2030, it is estimated that the hydrogen demand in Germany will be about 110 TWh, but the domestic production will be only around 14 TWh [38]. This also reiterates the fact that green hydrogen will have to be imported from outside the country. As part of the strategy, Germany will invest 2 Billion Euros outside the country in green hydrogen projects [38]. All these facts suggest that hydrogen is set to play an important role in Africa's and EU's energy transition.

Niger is the largest country in West Africa located between Sahara and Sub-Saharan region. Niger's economy is an agriculture dependent one, with agriculture accounting for 40% of the GDP and employing 80% of the population. River Niger flows across the country providing water for domestic and agricultural purposes. Droughts are quite frequent in the region. The economy depends on agriculture, which in turn depends on rainfall. This makes the situation vulnerable.

In 2019, Niger's final annual electricity consumption was 1302 GWh [39]. Out of this demand, 72% was imported from Nigeria [39]. Access to electricity is also a major challenge there with only 17.6% of the population having access to electricity in 2018 [39]. Between 2005 and 2015, the electricity consumption grew at 16%. For the period 2015–2027, the national utility of the country, NIGELEC forecasted the growth in electricity consumption at 32% [40]. These information point to the fact that there is a huge gap between demand and supply and importing a majority of the electricity could be a threat to the energy (electricity) economics and energy security.

The country's final energy consumption is dominated by biomass. Majority of the rural population rely on firewood for cooking [41]. The household sector is the major end user of energy in Niger, followed by transport, industrial and lastly agriculture sector [41,42]. Beside solar energy, Niger has fossil resources reserves for coal, oil, natural gas and uranium [43].

Niger has abundant solar potential, which ranges at 5–7 kWh/m^2/day [41,42,44] with an average daily sunshine duration of 8.5 h [41]. The availability of plentiful solar radiation round the year at majority of the locations makes it a perfect place to harness solar energy. The country has set a target to provide access to electricity to 60% of its population by 2027 and achieve universal electrification by 2035 [40]. The country also wants to increase the share of renewable energy (excluding biomass) in its electricity mix to 30% by 2030 [45].

In [17], authors performed the multi criteria decision analysis to assess the sustainability of different electricity generation technologies using various indicators under different dimensions. They concluded that solar can improve the energy access situation in Niger in the short run, but this technology should be coupled with adequate storage technology to improve reliability in the long run [17]. In an another study [46], authors examined the willingness to pay approach for rural electrification using solar PV in Niger. They found that implementing a rural electrification project based on collaborative consumption and community ownership increased the willingness to pay from 17% to 81% [46]. Increasing the share of renewable sources of energy is possible, but energy generated by these sources is difficult to manage especially when the grid infrastructure is insufficient. Renewable capacity addition alone would be unable to improve the situation, as long as the grid infrastructure is underdeveloped and inefficient.

The country's transmission losses were 15.9% in 2019 [47]. In order to harness the surplus renewable energy, especially solar energy, energy storage is very important and necessary for Niger. If the excess solar energy is used to generate hydrogen, this green hydrogen can help the country in solving its energy crisis and decarbonizing its economy, beside the export earnings.

As mentioned earlier, the need to decarbonize the energy supply is a major concern in recent time. There will be an important role of hydrogen in European Green Deal and in energy transition of both EU and Africa. With ample solar potential in Niger, the energy can be an important player in the production of green hydrogen. And to the best knowledge of the author, no detailed studies are carried out to evaluate the hydrogen potential in Niger. This work aims to present how the challenges of transition to green energy could be addressed with the help of hydrogen produced in West Africa. The objectives of this paper are i) to forecast the hydrogen demand across different sectors until 2040, and ii) to calculate the additional Solar PV capacity needed to generate the required quantity of green hydrogen. Taking into consideration the restrictions on the land use, the theoretical maximum supply of hydrogen is calculated.

The paper is organized as follows: in the next section, the country profile of Niger is presented. This is followed by the methodology section. In the results and discussions sections, the main results are presented/discussed. This is followed by conclusions.

2. Niger country profile

Niger is a Sahel Saharan country, landlocked and surrounded by Chad, Nigeria, Mali, Burkina Faso, Benin, Libya and Algeria [45] as shown Fig. 1. It has an area of 1,267,000 km^2 [40,41]. Majority of the country is located in the desert.

The gross domestic product (GDP) per capita was about 554 US Dollar (US $) in 2019 [48]. The GDP per capita from 2009 to 2019 is shown in Fig. 2. After experiencing a strong growth in GDP in 2018 (7%) and 2019 (5.9%), the growth slowed to 1.2% in 2020 because of covid-19 [49].

The country's population in 2020 was about 24 million [50]. The yearly population growth rate in 2020 was 3.8% [17,40]. The rate of electricity access on the national scale remains low with a significant disparity between the urban rate of access to electricity and the rural. The population with access to electricity in Niger is shown in Fig. 3.

In 2018, the total energy supply was 3208 ktoe [51], out of which, the share of biofuels and waste was at 77%, oil at 21% and coal at 2% [51]. The total final energy consumption across all sectors in 2018 was 2990 ktoe [51]. Majority of this consumption was in the residential sector (80%), followed by transport (15%), industry (4%) and lastly commercial and public services (1%) [51]. The industries are not yet well developed, hence the demand for oil and electricity is limited.

Electricity is generated mostly using fossil-based thermal power plants (oil and coal). The total installed electricity generation capacity in 2018 was 284 MW [17]. The electricity consumption, electricity generation (fossil based and renewable energy) and the electricity imports for the period 2012–2019 are shown in Fig. 4. Niger depends significantly on electricity import to meet its electricity needs as the domestic generation is less and the growth in

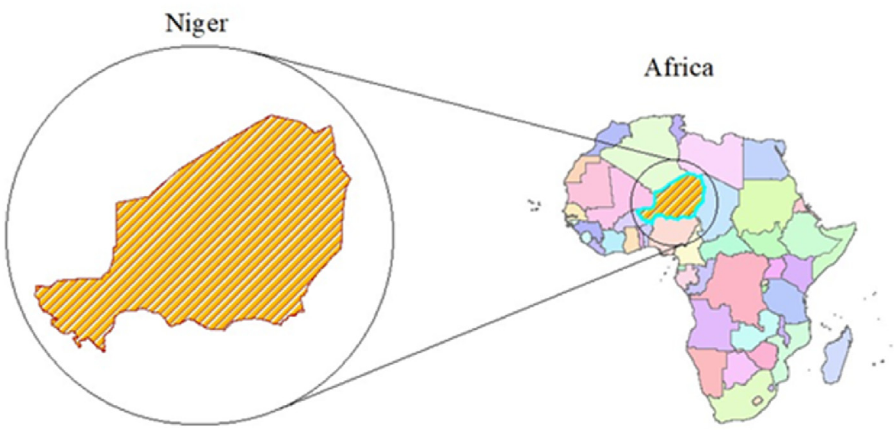

Fig. 1. Map of Niger.

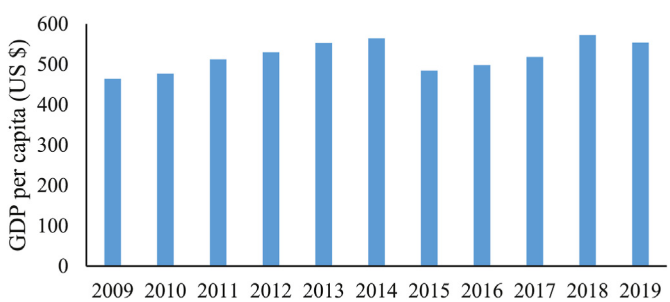

Fig. 2. GDP per capita (current US $).

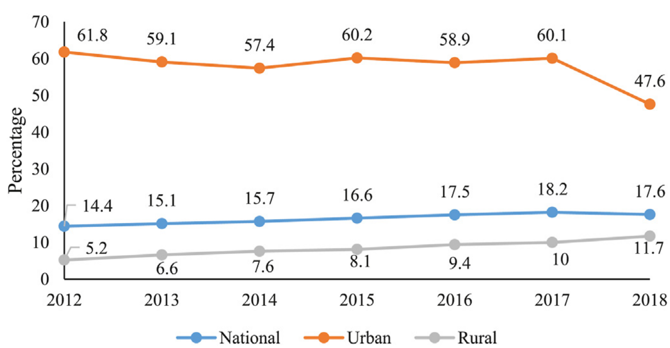

Fig. 3. Percentage of population with access to electricity [39].

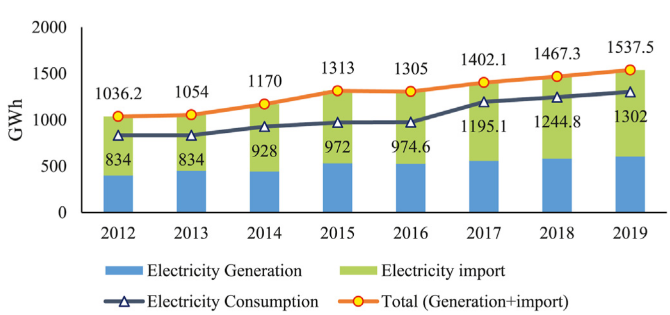

Fig. 4. Electricity consumption, generation and import [39].

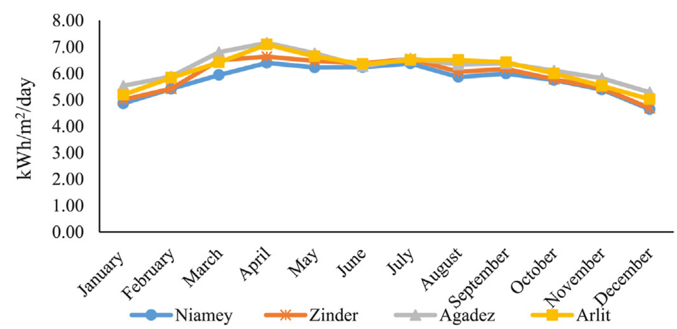

Fig. 5. Average daily radiation in different cities in Niger [44].

electricity consumption has outpaced the rate at which the generation capacity should increase [52]. In addition, the available power plants have exceeded their lifetime, which directly influences their efficiency and hence their electricity output. The difference between total (generation + import) and electricity consumption in Fig. 4 is the transmission loss.

Niger receives profuse amount of solar radiation round the year. The average annual solar radiation across the country is above 2000 kWh/m^2 [44] that makes it an ideal country to utilize solar energy. The average daily solar radiation in different cities is shown in Fig. 5. All the major cities of Niger like Niamey, Zinder, Agadez and Arlit receive maximum solar radiation in the months of April and May and minimum radiation in December and January.

Niger is a member of the Economic Community of West African States (ECOWAS). Every member of this organization had adopted its renewable energy policy (National Energy Action Plan Renewables (PANER)) under the guidance of Regional Center for Renewable Energy and Energy Efficiency (ECREEE) [53]. The implementation period of this policy is from 2015 to 2030 with the aim of increasing the access to energy in a sustainable manner to achieve energy independence. This policy also supports the fight against climate change as the Sahel region is vulnerable to the impacts of climate change even though their share in the global greenhouse gases emission is minor [53,54]. The policy document highlights the objectives, targets and the growth trajectories of renewable energies. Table 1 shows the targets of the renewable energy policy for grid connected case. Table 2 shows the targets for off grid renewables. It should be noted that the planned hydro capacity for 2020 has not been yet met.

3. Methodology

At first, the method used to forecast the yearly hydrogen

Table 1
Policy targets for grid connected renewables in Niger [53].

Target	2010	2020	2030
Grid connected renewables excluding medium and large hydro (MW)	0	50	150
Installed capacity of medium and large hydro (MW)	0	130	130
Total installed capacity of grid connected renewables-based power plants (MW)	0	180	280

Table 2
Policy targets for off grid renewables in Niger [53].

Target	2010	2020	2030
Total installed capacity of off grid renewables (MW)	4	34	100

demand until 2040 has been presented. This is followed by the method used to assess the theoretical hydrogen supply potential.

3.1. Hydrogen demand

The energy consumption sectors considered for evaluation are electricity and transport. After calculating the quantity of hydrogen needed for both sectors, the additional solar capacity required to produce the needed hydrogen is calculated.

3.1.1. Hydrogen demand for electricity production until 2040

The electricity consumption data for the entire country across all the sectors is the starting point of the analysis. The electricity consumption data for Niger was available for the period 2012 to 2019. Next, three different forecasting techniques are used to forecast the electricity demand from 2021 to 2040 - exponential growth forecasting, moving average method and multiple linear regression model. The chosen models allow in developing proposals for future scenarios with different historical trends. There have been many instances of using these time series methods in forecasting the energy demand as per the review made by Suganthi and Samuel [55].

Lee et al. [56] compared the different time series models for the electricity consumption. The authors carried out the forecast evaluation of those methods with the error analysis. The centered moving average and simple exponential smoothing model showed comparatively less error. The mean absolute percentage error calculated was 11.88% and 12.47% respectively. In Refs. [57,58], the authors have discussed and applied the exponential smoothing forecast methods into their works. Ostertagova and Ostertag [59] implemented simple exponential smoothing method to determine the forecast accuracy with the use of data of primary production of electricity. The smoothing constant used essentially defines the accuracy. The mean absolute percentage error was less than 10% with the selected value of smoothing constant indicating an excellent forecasting accuracy.

Popeanga and Lungu [60] employed centered moving average method to derive final energy consumption. The model achieved a promising result when compared with the degree of fit to historical data. In Ref. [61], a novel approach to forecast the long term electric load is presented. The authors used linear regression model for the analysis and demonstrated a successful forecast with comparatively less mean absolute error. Furthermore, in Ref. [62], the authors carried out the forecasting of electricity consumption with three multiple regression models. Coefficient of determination (R^2) value is used to validate the models. The authors found the regression models to have a good accuracy in the analysis.

These methods are comparatively simpler to implement for the demand analysis and have been proven to provide significantly accurate results in forecasting. In this work, the major project scope is not limited to the demand forecasting alone; rather, it focuses more on the determination of hydrogen production potential in Niger and on how hydrogen can be an important aspect in decarbonizing the energy supply. For this reason, these methods, being simpler yet effective, are applied to demand forecasting.

Exponential growth forecasting method is a classical approach of load forecasting where the load based on the previous data are modeled and the model is used for forecasting future load [63]. With the use of electricity consumption as the dependent variable and year number as the independent variable, an exponential model of the form $y = ae^{bx}$ (where a and b are constants and x is the year number) is developed in this work and used to forecast the yearly electricity demand.

Moving average method tends to estimate the trend that is obtained by averaging the historical trend data within the specific time period. For the moving average method, a two period moving average of the electricity consumption is taken. After this, the centered average is derived. Using the centered average as the dependent variable and year number as the independent variable, a linear equation of the form $y = mx + C$ (where m is the slope of the line, C is the intercept and x is the year number) is developed and used to forecast the yearly electricity demand.

Regression analysis allows the estimation of the relationship between a dependent and one or more independent variable (unlike the exponential and moving average method) for the forecasting. In this work, the electricity consumption is selected as the dependent variable and electricity access rate, GDP per capita and total installed capacity (renewable + fossil based) are the independent variables. Using the data analysis, the multiple linear regression is performed. This analysis gives the regression statistics and the coefficients of different variables. The variables that have p - values greater than 0.1 are eliminated and the regression analysis is performed again. The result of the analysis is a linear equation of the form $Y = a_o X_0 + a_1 X_1 \ldots + a_n X_n + I$ (where Y is the electricity demand, a_o, $a_1 \ldots a_n$ are the coefficients of different independent variables and X_0, X_1 and X_n are the different independent variables). The input variables and the output for different techniques are summarized in Table 3.

R^2(coefficient of determination) measures the fit and strength of correlation between the developed model and the dependent variables. So, the higher the R^2 value, the better the model fits the data [64]. Hence for the analysis, the method that gives the maximum value of R^2 is used for further analysis. Thus, the electricity demand values from 2021 until 2040 are obtained.

A (currently hypothetical) scenario is assumed, where the electricity demand from 2021 onwards is supplied by renewable energy and hydrogen. This assumption is based on [54], where, according to the Agenda 2063, the continent wants to achieve economic development with CO_2 mitigation and deploy maximum renewables (mainly solar) to exploit the solar potential. Using information on the capacity growth trajectory of grid connected and off grid solar PV, the energy generated by grid connected and off grid solar PV is calculated using the equation (1) [53].

Table 3
Input variables and outcomes from different forecasting techniques.

Method	Dependent variable (Y)	Independent variable(s) (x)	Output
Exponential growth forecasting	Electricity consumption	Year number	$Y = ae^{bx}$ where a and b are constants
Moving average	Electricity consumption	Year number	$Y = mx + C$ where m is the slope and C is the intercept
Multiple linear regression	Electricity consumption	Electricity access rate, GDP per capita and total installed capacity	$Y = a_oX_0 + a_1X_1 \ldots + a_nX_n$ where X_0, X_1 and X_n are the different independent variables

$$E_{gen} = \frac{E_c \times 10^3 \times G \times Q}{I_{stc} \times 10^6} \tag{1}$$

E_{gen} - Electricity generated in a year (GWh)
E_c - Energy capacity in (MW)
I_{stc} - Radiation at standard test condition in kW/m^2 (value 1 kW/m^2)
G - Global solar radiation in kWh/m^2/year (2101 kWh/m^2/year [44])
Q - Quality factor or performance ratio (assumed at 0.5 for off grid system and 0.8 for grid connected system)

In [65], authors found that only 44% of the electricity generated by the Solar PV system can be used by the electrolyzer in real time at a case study site in Germany. Based on this, it is assumed that at least 44% of the energy generated by the solar PV systems can be used at the time of generation also in Niger. The remaining 56% of the generated electricity is a surplus. The PANER in Niger provided information on the indicative growth trajectory for energy production from medium and large hydro power plants (>30 MW). Adding together the energy generated by grid connected solar, off grid solar and energy produced by medium and large hydro, the total electricity produced using renewable energy is obtained. The difference between the forecasted electricity demand and the electricity generated by different renewables is the electricity to be generated from green hydrogen.

It is assumed that the electricity is generated from hydrogen via fuel cell. The hydrogen required for fuel cell is calculated by assuming that the efficiency of the hydrogen fuel cell at 50% [66]. The quantity of hydrogen required to meet this electricity need is calculated using equation (2).

$$H_{2_{dem}} = \frac{E_{req}}{HV_{H2} \times \eta_{fuel\ cell}} \tag{2}$$

H_{2dem} - Hydrogen requirement in thousand tons.
E_{req} - Electricity required to be produced from hydrogen (GWh)
HV_{H2} - Lower heating value of hydrogen (33.33 kWh/kg)
$\eta_{fuel\ cell}$ - Efficiency of fuel cell (50%) [66].

3.1.2. Hydrogen demand for transport until 2040

The starting point of the analysis is the data on gasoline and diesel consumption for Niger. The PANER provides information on gasoline and diesel consumption in the country and forecasts its value until 2030 to provide an indicative trajectory for the use of biofuels. The consumption and forecast data for gasoline and diesel are used to build the forecast model. With this, the gasoline and diesel consumptions are forecasted from 2030 to 2040.

Linear extrapolation and moving averages methods are used to forecast the demand for gasoline and diesel from 2030 to 2040. Linear extrapolation, also known as linear trend analysis, includes fitting trend curves with the past data that is adjusted to show the growth trend itself. The forecasting is done by considering the trend curve function to the chosen future point. The results from this technique are realistic, even though the procedure is simple [67]. The methods chosen is based on opinions mentioned for electricity demand forecasting in the previous section, i.e., making the analysis simpler yet precise. Table 4 provides the information used to build the forecast model.

The method that gives the maximum value of R^2 is used for further analysis. Thus, the gasoline and diesel demand is calculated for the period from 2030 until 2040.

The direct CO_2 emission from gasoline and diesel is 69.3 kg CO_2/GJ and 74.1 kg CO_2/GJ respectively [68]. Hydrogen can be deployed in the transport sector by deploying the fuel cell electric vehicles. Hence, it is assumed that starting 2030, about 1% of the demand for gasoline and diesel is replaced with hydrogen. Today, the number of fuel cell electric vehicle on road are less than 1% of the total vehicles in most of the developed nations, hence it is assumed that 1% of the gasoline and diesel demand will be replaced with hydrogen from 2030 in Niger. So first 1% of the demand is calculated and correspondingly multiplied with the calorific value for gasoline (46 MJ/kg) and diesel (44 MJ/kg) to get the value of the energy content that needs to be provided by hydrogen [69]. The value of the energy content is divided by the calorific value of hydrogen (142 MJ/kg) to get the quantity of hydrogen required to replace 1% of gasoline and diesel demand respectively.

3.1.3. Solar PV capacity to produce hydrogen

The hydrogen demand for electricity and transport sector are combined together and this leads to the total hydrogen required from 2021 until 2040. The electricity needed to produce one kg of H_2 is 54.6 kWh/kg [20]. Multiplying the quantity of hydrogen with the specific electricity requirement gives us the total electricity needed to produce the hydrogen. As mentioned earlier, 56% of the energy generated by the solar system is a surplus. It is assumed that this surplus is used to produce hydrogen. The additional energy requirement is the difference between the electricity needed to produce hydrogen and the surplus of grid connected and off grid solar. Equation (3) summaries the same.

$$E_{add} = E_{H2} - E_S \tag{3}$$

E_{add} - Additional energy required (GWh)
E_{H2} - Electricity needed to produce hydrogen (GWh)
E_S - Surplus from grid connected and off grid solar PV (GWh)

The additional solar capacity required for each year from 2021 to 2040 is calculated according to the equation (4).

$$SC(t) = \frac{E_{add}(t) \times I_{stc}}{G \times Q} \tag{4}$$

SC(t) - Solar capacity in year (t) (GW)
$E_{add}(t)$ - Additional Electricity required in year t (GWh)
I_{stc} - Radiation at standard test condition in kW/m^2 (value 1 kW/m^2)
G - Global solar radiation in kWh/m^2/year (2101 kWh/m^2/year [44])

Table 4
Input variables and output for gasoline and diesel forecasting.

Method	Dependent variable (Y)	Independent variable(s) (x)	Output
Linear extrapolation	Gasoline/diesel consumption	Year number	Y = mx + C where m is the slope and C is the intercept
Moving average	Gasoline/diesel consumption	Year number	Y = mx + C where m is the slope and C is the intercept

Q - Quality factor (or performance ratio) (assumed to be 0.8 for grid connected system)

3.2. Hydrogen potential by supply scenario

The approach to evaluate the hydrogen potential from the supply side is shown in Fig. 6. In order to calculate the hydrogen potential from supply perspective, first the solar potential is calculated and then the hydrogen production potential.

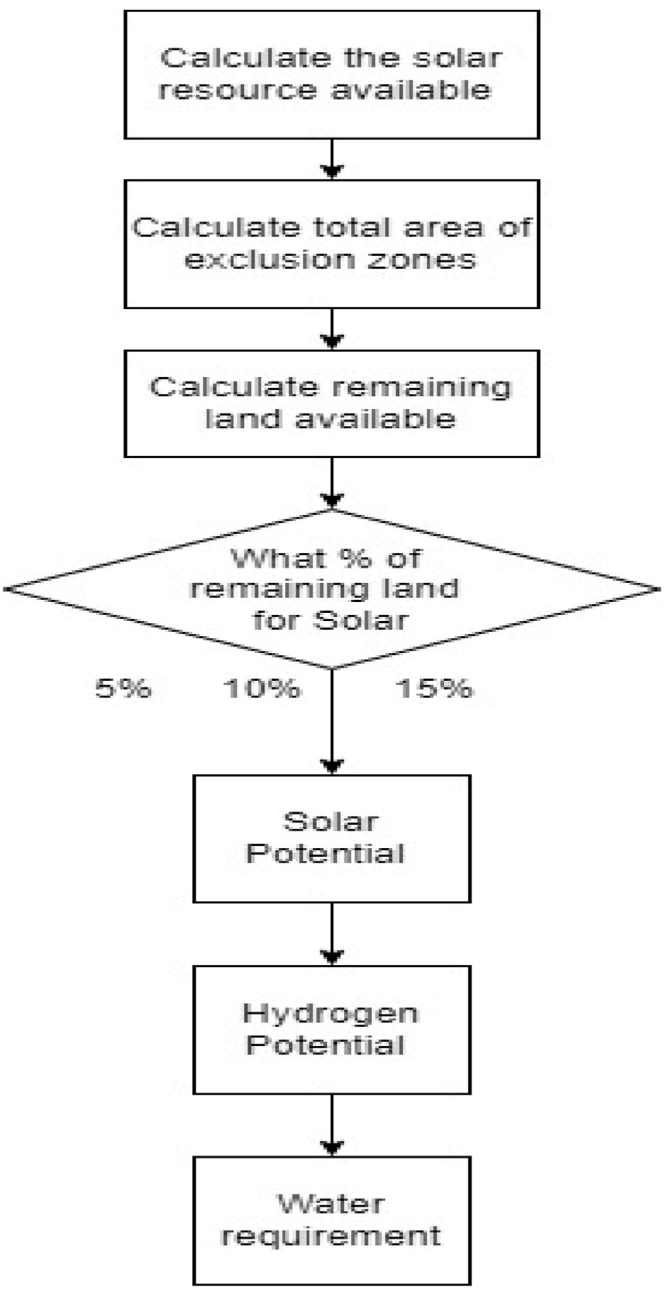

Fig. 6. Flowchart showing the method to calculate the hydrogen potential from supply side.

The solar potential is calculated according to equation (5) [70].

$$SP = \frac{SR \times \eta_{module} \times PR \times L_{avai}}{SF} \tag{5}$$

SP - Solar potential in GWh.
SR - Solar resources available - 2101 kWh/m^2/year [44].
η_{module} - Efficiency of solar PV module (16.5%)
PR - Performance ratio (assumed to be 0.5 for off-grid systems)
L_{avai} - Total area in the country that can used to build solar plants (km^2)
SF - Spacing factor - actual land required compared to area of panels (assumed to be 5 for ground-mounted PV)

The available land is calculated by subtracting the total area of the exclusion zones from the total land area of Niger as shown in equation (6). The total land area of Niger is 1,267,000 km^2 [41,71]. The exclusion zones are defined in Table 5.

$$L_{avai} = L_{total} - L_{excl} \tag{6}$$

L_{avai} - Available land (km^2)
L_{total} - Total area in the country that can used to install solar plants (km^2)
L_{excl} - Total area of exclusion zones (km^2)

As 100% of the available land cannot be realistically used for installing solar PV, different scenarios are used to calculate the solar potential, i.e. 5%, 10% and 15% of the available land. After calculating the solar potential for different scenarios, the respective hydrogen potential is calculated using equation (7) and information from Table 6.

$$H_{prod} = \frac{SP \times 10^6}{E_{H2}} \tag{7}$$

H_{prod} - Hydrogen production (kg/year)
SP - Solar potential (GWh)
E_{H2} - Electricity required to produce 1 kg H_2 (kWh/kg H_2)

The water required to produce the given quantity of hydrogen using a particular electrolysis process is calculated using information from Table 6 and equation (8).

$$W_t = W_{req} \times H_{prod} \tag{8}$$

W_t - Total water required (m^3)
W_{req} - Water requirement per kg H_2 (m^3/kg)

Table 5
Exclusion zones and their area.

Exclusion Zone	Assumption	Area in km^2
Cities and urban areas	30% of the total land area	380100
Protected area	7.7% of the total land area	97559
Water bodies	[71]	300
Slopped and hilly area	[71]	84000
Rural residence area	10% of the total land area	126700
Agriculture land	[71]	660
Forest areas	[71]	12670
Total area of exclusion zones		701,989

Table 6
Water and electricity needs for different processes [19–23].

Process/Pathway	Water requirement (kg/kg H_2)	Energy requirement (kWh/kg H_2)
PEM	18.04	55.05
Alkaline electrolysis	22.47	54.6
Solid oxide electrolysis	9.1	36.14

H_{prod} - Hydrogen produced (kg)

4. Results and discussion

The results for the hydrogen demand for electricity and transport sector until 2040 are presented first followed by the results related to the supply side.

The model equation and the R^2 for different methods mentioned in Table 3 to forecast the electricity demand is summarized in Table 7. For the electricity demand forecasting using multiple linear regression method, the selected independent variables are electricity access rate, GDP per capita and installed capacity. The p values for the independent variables are 0.54877, 0.8595 and 0.108 respectively and the R^2 value is found to be 0.953. As discussed in the methodology section, independent variables with p values > 0.1 are eliminated and the regression analysis is performed again using electricity demand as the dependent variable and installed capacity as the independent variable. The p-value for this iteration is found to be 0.0005. Hence, a linear equation using the installed capacity as the only dependent variable is obtained.

The electricity demand is shown in Fig. 7. As seen in Fig. 7, the forecast values using the exponential growth forecasting method are the highest among the three. The forecasted value for electricity demand in 2040 is 5675 GWh, 2934 GWh and 2189 GWh using exponential growth forecasting, moving average and multiple linear regression methods respectively.

As observed from Table 7, the moving average method has the highest value of R^2 (0.9688), as a result of which the forecasted values of electricity demand using the moving average method are used in our analysis further. Fig. 8 shows the forecasted electricity demand and total generation from renewables (grid connected solar + off grid solar + hydropower) determined with the equation (1). It can be seen that the generation from renewables is insufficient to meet the electricity demand. The growth in demand outpaces the electricity generation from renewables and hence this gap needs to be filled, e.g. by hydrogen.

This deficit is to be covered by hydrogen by generating electricity using fuel cells. In order to cover the electricity deficit, the required hydrogen calculated as per the equation (2) is also shown in Fig. 8 on the secondary Y-axis. As the capacity addition of renewables and correspondingly the electricity generation is relatively lower than the forecasted growth in electricity demand, the deficit is large. This increases the quantity of hydrogen required to produce the electricity from fuel cells. In 2040, the quantity of hydrogen required to generate the remaining electricity is 116.73 thousand tons.

The model equation and the R^2 for different methods to forecast the gasoline and diesel consumption are shown in Table 8. As seen

Table 7
R^2 value and model equation for forecasting electricity demand from 2021 to 2040.

Method	Equation	R^2 value
Exponential growth forecasting	$y = 745.31e^{0.07x}$	0.9415
Moving average	$y = 77.829x + 676.9$	0.9688
Multiple linear regression	$y = 3.13225x+375.5246$	0.923247

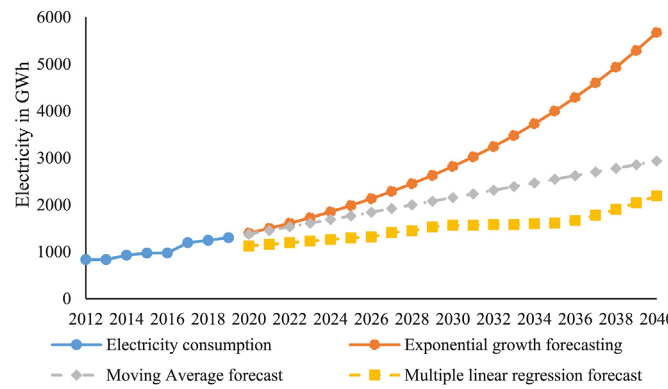

Fig. 7. Electricity demand forecasting results for different techniques.

in the table, for both the cases, moving average method shows greater R^2 value as compared to linear extrapolation method. Hence the values forecasted using moving average method for gasoline and diesel are used further in the analysis.

The forecasted values for gasoline and diesel using the moving average method are shown in Fig. 9. As it can be seen, the demand for diesel is more compared to gasoline. With the economic development, increase in urbanization and GDP per capita, both fuels used in transport are set to grow until 2040. Thus, it is very important to curb the carbon emissions related to the increase in the fuel use. Hydrogen is tested as an alternative to the conventional fuels to meet the transport sector related needs.

Fig. 9 also shows the quantity of hydrogen required in tons to replace 1% of the gasoline and diesel demand from 2030 to 2040 (years are taken rather late, because we assumed that practically it is not realistic to have significant fuel cell vehicles in Niger before 2030). As the forecasted demand for diesel is higher than that of gasoline, correspondingly the hydrogen required is higher.

Adding up the hydrogen demand for electricity and transportation sector, a combined hydrogen demand profile is generated from 2025 to 2040 as shown in Fig. 10. In 2040 about 117 thousand tons of hydrogen will be required to provide electricity and to act as fuel in the transport sector.

The additional solar capacity required calculated through the equation (4) indicates 3.43 GW additional installation solely to produce required hydrogen in 2040 as compared to 1.89 GW in 2025 (Fig. 10). This represents a compound annual growth rate (CAGR) of 4.91%, meaning the solar capacity addition should grow at a rate of 4.91% each year from 2025 until 2040 in order to produce the required quantity of hydrogen to meet the energy needs.

The available land that can be used to install solar PV in Niger is calculated to be 565,011 km^2. The solar potential (equation (5)), the hydrogen potential using different electrolysis technologies (equation (7)) and corresponding water requirements for different scenarios (equation (8)) are summarized in Table 9.

The solar potential is directly proportional to the land area, as a result of which hydrogen potential is also directly proportional to the land area. Among the given scenarios, maximum hydrogen is produced in the 15% scenario. For all the scenarios, maximum

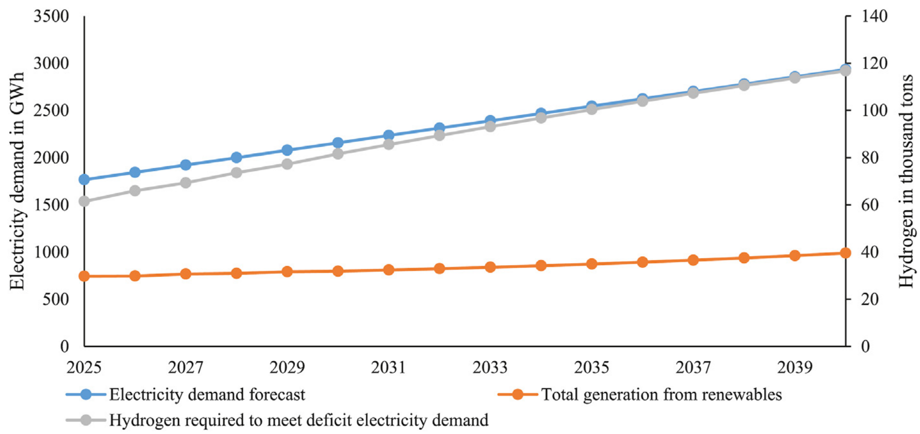

Fig. 8. Electricity demand forecast, total generation from renewables and hydrogen required to meet the deficit electricity demand.

Table 8
R^2 and model equation for different methods to forecast gasoline and diesel consumption from 2030 to 2040.

Fuel	Method	Equation	R^2 value
Gasoline	Linear extrapolation	y = 31752x + 81651	0.9969
	Moving average	y = 31298x + 87773	0.9987
Diesel	Linear extrapolation	y = 72780x + 155500	0.9975
	Moving average	y = 71935x + 167018	0.9988

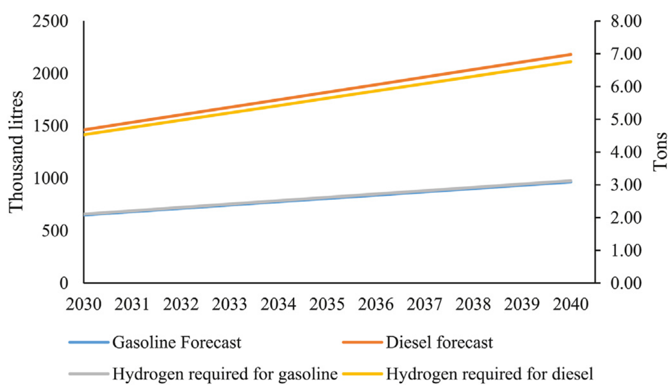

Fig. 9. Forecasted gasoline and diesel demand from 2030 to 2040 and corresponding hydrogen demand.

hydrogen can be produced by employing solid-oxide electrolysis followed by alkaline and PEM electrolysis. The results are justified as solid oxide electrolysis has the least energy demand to produce a kilogram of hydrogen and PEM has the highest. Hence, this study establishes the fact that Niger has good solar hydrogen production potential.

The country experiences very little rainfall round the year and is located in the arid and semi-arid regions of the Sahara and the Sahel. This naturally raises the question regarding the availability of water for human consumption, other domestic uses, industry and so on. In addition, producing hydrogen requires a lot of water depending on the method used to produce hydrogen.

Table 10 summarizes the information on available water resources of Niger. As seen in the table, the total renewable water resource of Niger was 34.05 (billion m^3/year) in 2017. Dependency factor is an indicator, which expresses the percent of total renewable water resources originating outside the country. A country, which receives all its renewable water from upstream countries, without producing any of its own has a dependency ratio of 100%. Dependency ratio for Niger is 89.72% [72].

Niger depends heavily on ground water for water use. There are three aquifer systems with non-renewable groundwater resources - Iullemeden Aquifer System, Chad Basin Aquifer and Murzuk Basin (Algeria, Libya, Niger) [73]. The Iullemeden Aquifer system shared among Mali, Niger and Nigeria has an exploitable water reserve of 2000 km^3 [74]. The Lake Chad Basin Aquifer system is shared among Niger, Nigeria, Chad and Cameroon, 28% of which lies in Niger [75]. The estimated exploitable volume of water is between 170 and 350 billion m^3 [73].

The main sectors of water usage (withdrawal) are agriculture, industrial and municipal. Agriculture water use is for irrigation, livestock and aquaculture purposes. The water used in the industries and factories is accounted in the industrial use sector. Municipal water use refers to the annual water used directly by the population. The total water usage of Niger was 1.251 billion m^3/yr in 2012 and 1.751 billion m^3/year in 2017. Table 11 shows the water usage distribution for 2012 and 2017. The total water withdrawn per capita was 70.30 m^3/year in 2012 and 81.05 m^3/year in 2017. The difference between the available water and water needed is the water that could be used for other applications like hydrogen production. However, a further analysis in competitive water use is necessary, e.g. in drinking and irrigation sector.

5. Conclusion

This study aimed to incorporate hydrogen in the electricity and transport sector by forecasting the electricity and transport related gasoline and fuel demand until 2040 and analyzing the quantity of hydrogen required for the same. The electricity demand in 2040 is forecasted to be 2934 GWh. Working under different assumptions, it is found that the growth in renewables would be insufficient to match the growing electricity demand in the year 2040 and correspondingly flexible energy solutions like hydrogen would be required. Altogether, in 2040, about 0.117 Mt of hydrogen is needed in the country, most of it to produce electricity from fuel cell. The gasoline and diesel demand in the year 2040 are forecasted as 964 and 2181 m^3 respectively. Under the assumption of replacing 1% of gasoline and diesel demand in 2040, the hydrogen required would be 3 and 7 ton respectively..

Looking at the supply side, even if 5% of the land area is allocated to produce solar electtricity for hydrogen production, the production (17.8 Mt) would be far beyond sufficient to meet the hydrogen demand for electricity and transport related use in 2040. This opens the scope to sell hydrogen in the international market especially in

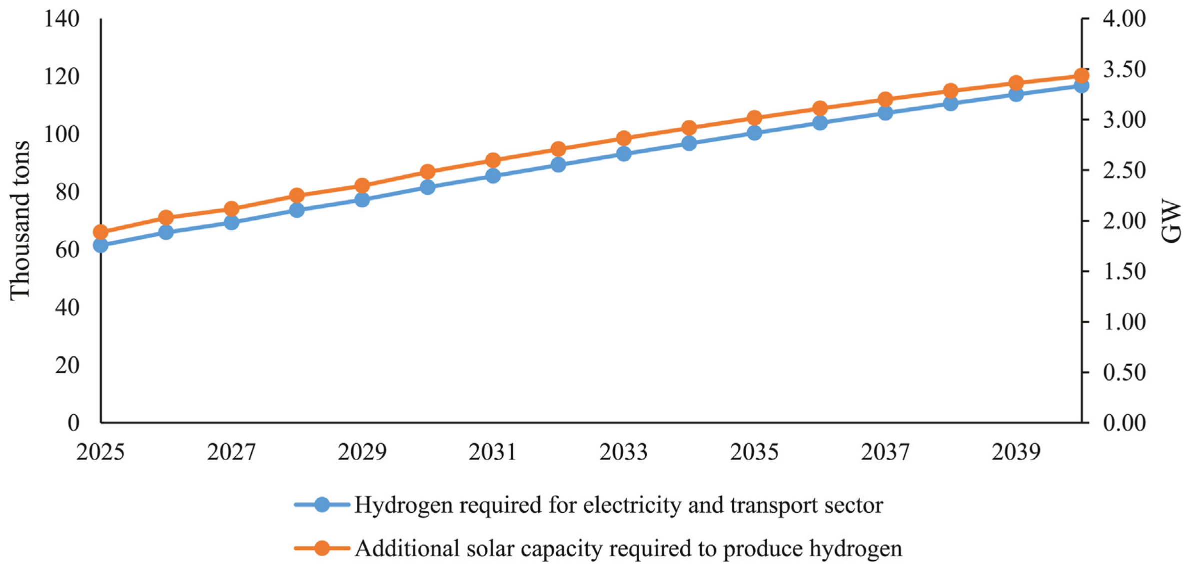

Fig. 10. Hydrogen required for electricity and transport sector and additional solar capacity required to produce hydrogen.

Table 9
Results of solar potential, hydrogen production and water requirement under different scenarios.

Hydrogen production - 5% land area		
Solar electricity potential	979 TWh	
Technology	Hydrogen production in million tons	Water requirement in million m^3
PEM	17.79	320.93
Alkaline electrolysis	17.94	403.04
Solid oxide electrolysis	27.10	246.60
Hydrogen production - 10% land area		
Solar electricity potential	1959 TWh	
Technology	**Hydrogen production in million tons**	**Water requirement in million m^3**
PEM	35.58	641.87
Alkaline electrolysis	35.87	806.08
Solid oxide electrolysis	54.20	493.20
Hydrogen production - 15% land area		
Solar electricity potential	2938 TWh	
Technology	**Hydrogen production in million tons**	**Water requirement in million m^3**
PEM	53.37	962.80
Alkaline electrolysis	53.81	1209.12
Solid oxide electrolysis	81.30	739.80

Table 10
Available water resources of Niger [72].

Parameter	Unit	2012	2017
Precipitation			
Long-term average annual precipitation in depth	mm/year	151	151
Internal renewable water resources (IRWR)			
Surface water produced internally	billion m^3/yr	1	1
Groundwater produced internally	billion m^3/yr	2.5	2.5
Total internal renewable water resources (IRWR)	billion m^3/yr	3.5	3.5
Total internal renewable water resources per capita	m^3/capita/yr	197	162
External renewable water resources			
Surface water: entering the country (total)	billion m^3/yr	29.2	29.2
Groundwater: entering the country (total)	billion m^3/yr	0	0
Water resources: total external renewable	billion m^3/yr	30.55	30.55
Total renewable water resources			
Total renewable surface water	billion m^3/yr	31.55	31.55
Total renewable groundwater	billion m^3/yr	2.5	2.5
Total renewable water resources	billion m^3/yr	34.05	34.05
Dependency ratio	(%)	89.72	89.72

Table 11
Water usage by sector for 2012 and 2017 [72].

Usage sector	2012		2017	
	Billion m^3/year	Percentage	Billion m^3/year	Percentage
Agricultural water withdrawal	1.176	93.97	1.536	87.73
Industrial water withdrawal	0.014	1.10	0.036	2.06
Municipal water withdrawal	0.062	4.93	0.179	10.22
Total water withdrawal	1.251	100.000	1.751	100.000

the time where most of the nations are setting action plans and road maps to employ hydrogen to decarbonize the economy. Yet, the economic analysis of hydrogen production needs to be checked before the related earnings are quantified.

Although the present study is a first step to calculate the hydrogen potential in Niger, it faces some limitations. The data used to create the model to forecast the demand until 2040 is very limited. Although it gives a good value of R^2, the results would have been different with less uncertainty, if a larger data set was used to create the forecast model. Correspondingly, to calculate the hydrogen potential from supply side, theoretical data from literature was used to quantify the potential. A more accurate and detailed analysis using tools like GIS and accounting for different land use planning policies is required to arrive at the true hydrogen potential from supply side. There is now no large-scale demonstration plant of such kind in Niger or in the region, therefore the validation of the results for economic indicators has been left out of the scope of this article. Our work is a starting point of the analysis for decision makers responsible for the energy transition and climate change mitigation policies. Using vast data and the methods presented here, the true hydrogen potential can be easily calculated and relevant policies be implemented.

Declaration of competing interest

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

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