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Techno-Economic Analysis of Geospatial Green Hydrogen Potential Using Solar Photovoltaic in Niger: Application of PEM and Alkaline Water Electrolyzers

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Abstract: This study evaluates the techno-economic feasibility of solar-based green hydrogen potential for off-grid and utility-scale systems in Niger. The geospatial approach is first employed to identify the area available for green hydrogen production based on environmental and socio-technical constraints. Second, we evaluate the potential of green hydrogen production using a geographic information system (GIS) tool, followed by an economic analysis of the levelized cost of hydrogen (LCOH) for alkaline and proton exchange membrane (PEM) water electrolyzers using fresh and desalinated water. The results show that the electricity generation potential is 311,617 TWh/year and 353,166 TWh/year for off-grid and utility-scale systems. The hydrogen potential using PEM (alkaline) water electrolyzers is calculated to be 5932 Mt/year and 6723 Mt/year (5694 Mt/year and 6454 Mt/year) for off-grid and utility-scale systems, respectively. The LCOH production potential decreases for PEM and alkaline water electrolyzers by 2030, ranging between 4.72–5.99 EUR/kgH_2 and 5.05–6.37 EUR/kgH_2 for off-grid and 4.09–5.21 EUR/kgH_2 and 4.22–5.4 EUR/kgH_2 for utility-scale systems.

Keywords: GIS; alkaline; PEM; levelized cost of electricity (LCOE); levelized cost of hydrogen (LCOH)

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1. Introduction

Global energy demand is increasing due to population growth and economic development. However, the world still relies on the fossil fuel energy sources, despite the depletion of natural resources and environmental concerns [1]. The International Energy Agency predicts, through its World Energy Outlook 2023 report, that fossil fuel use will decrease in the upcoming years. The world's primary energy utilization from fossil fuels will decrease from 80% to 73% throughout the next decade. Additionally, electricity generation from fossil fuels is expected to decline from 70% to 40% [2]. Based on the recent trends, renewable energy sources (RESs) will play a significant role in the world energy mix [3]. For instance, in 2028, renewable energy sources will account for over 42% of global electricity generation,

with the share of wind and solar PV energy sources doubling to 25% [4,5]. The use of more renewable energy would similarly reduce Africa's economic vulnerability to the adjustable and rising prices of imported fuels [6]. In the recent decade, renewable energy sources, especially solar and wind energy, have drawn significant attention [7], mostly due to technological advancement and price decreases. Nevertheless, many uncertainties prevent the guarantee of successfully implementing large-scale and off-grid renewable energy technologies into future energy systems [8]. Among these uncertainties is the intermittency, which provokes concerns about grid stability and reliability. Hydrogen derived from renewable energy (RE) presents a versatile option as a medium-to-long-term energy storage, offering an alternative pathway for transitioning to a net-zero energy system.

The world annual hydrogen demand is estimated to increase to between 77 and 212 million tons (Mt) by 2030, and to 148 and 660 Mt by 2050, when considering different scenarios [9]. To achieve the net-zero emissions scenario, the capacity needed for electrolysis will exceed 700 gigawatts [10]. The International Renewable Energy Agency (IRENA) explains that sub-Saharan Africa holds the world's largest promise for competitive green hydrogen manufacturing because it has many solar and wind energy resources, as well as inexpensive land and excellent maritime routes [11]. African Development Bank research shows that the region could generate green hydrogen at 1.8 USD/kg by 2030 if plans succeed [12]. In the optimistic scenario, the region could contribute around 35% of the total hydrogen production potential at a cost below 1.5 USD/kg [11]. As more countries pursue deep decarbonization strategies, hydrogen will have a critical role to play. In this context, hydrogen needs to be low in carbon and, ultimately, green. The largest single cost component for the on-site production of green hydrogen is the cost of renewable electricity, followed by the cost of electrolysis facilities [12]. Subsequently, in order to achieve the energy transition goals, the Economic Community of West African States (ECOWAS) have recently adopted their new energy policy, which promotes the development of renewable energy and energy efficiency, emphasizing the need to promote clean energy, especially green hydrogen, which follows the ECOWAS Green Hydrogen Policy and Strategy Framework [13]. Therefore, the policy and strategy framework of ECOWAS aims to achieve a regional production target of a minimum of 0.5 million tons of green hydrogen annually by 2030, with a further goal of reaching at least 10 million tons by 2050 [14]. Further, in the frame of the Sustainable Energy for All (SE4ALL) initiative, Niger is targeting to boost the share of renewable energy supply to up to 30% of the country's energy mix [15]. However, this target seems unrealistic given the current low electricity access rate in Niger. In the Niger context, fostering hydrogen production through solar PV technology could improve electricity access and address the obstacle of integrating renewable energy into the power grid in the coming decades. In the current scientific and technical sphere, many projects delve into hydrogen and its associated fields, often overlooking the geographical limitations that could impact the cost and scalability of green hydrogen production systems. To tackle these challenges, this study endeavors to explore the techno-economic viability of green hydrogen production.

Hydrogen is a versatile energy carrier (rather than an energy source) that can be used in many applications. Electrolytic hydrogen produced through renewable energy (green hydrogen) is the most sustainable hydrogen production technology [11]. Despite the green hydrogen potential, only 0.03% of the global hydrogen production in 2020 was derived from renewable energy sources, while more than 96% was generated from natural gas (gray hydrogen) and coal (brown hydrogen) [16]. Green hydrogen is seen as a promising energy carrier that is poised to replace fossil fuels in the near future due to its numerous advantages [17]. With a combustion efficiency that yields approximately 39.4 kWh/kg, hydrogen surpasses other fuels, such as liquid hydrocarbons, by threefold [18]. Broadly, the

following three types of electrolyzers are available: alkaline, proton exchange membrane (PEM), and high-temperature solid oxide electrolyzers [19]. Alkaline water electrolyzers are a mature technology due to their reliability and safety. Consequently, they represent the most widely implemented electrolysis technology on a global commercial scale [20]. In contrast, the proton exchange membrane water electrolyzer is commercially available for low-scale applications, with a hydrogen purity up to 99.999 vol% [21]. One of the main drawbacks of PEM water electrolyzers is the high investment cost associated with the membranes and noble metal electrodes [22]. Conversely, solid oxide electrolyzers (SOEs) represent a sophisticated approach to water, or, more precisely, steam electrolysis, which is performed at elevated temperatures, reaching up to 1000 °C. This method yields greater efficiencies when compared with alkaline and PEM water electrolyzers [21,23]. There are technological challenges related to the materials used in manufacturing electrolyzers which must be overcome to reduce their cost. However, the high potential of renewable energy sources—particularly solar PV—creates an opportunity to produce green hydrogen at competitive prices compared to fossil fuel-based hydrogen [12].

Over time, research attention has steadily increased regarding renewable energy applications for green hydrogen production at a global scale. In his study about decentralized green hydrogen production scenarios, Ramchandra conducted a techno-economic assessment in Germany to evaluate different configurations, which included grid integration. The identification of the most profitable design configuration was the main goal of this study. The research results demonstrated that solar PV and alkaline water electrolyzer systems connected to the grid produced green hydrogen with a minimum levelized cost of hydrogen (LCOH) [24]. Another study was performed in Austria by Povacz, which conducted an analysis of the levelized cost of hydrogen production using solar PV and wind energy sources for off-grid power plants. The work indicated that the model found a cost-efficient portfolio for directly coupled wind power and solar photovoltaic systems [25]. Recently, the use of the geographical information system (GIS) has been discussed by many authors in the literature. In Mexico, Sanchez conducted an eligibility analysis of variable renewable energy sources (VRESs), as well as a techno-economic evaluation [26]. The eligibility analysis was performed using a geospatial land eligibility analysis system (GLAES) tool, including physical, environmental, and socio-political constraint factors. The techno-economic analysis of VRESs was evaluated by using onshore and offshore wind turbines, as well as open-field and rooftop photovoltaic technologies. The study showed that 91% of the electricity would originate from open-field photovoltaic parks, while the overall renewable energy could be produced at a levelized cost of electricity (LCOE) of less than 70 EUR/MWh [26]. In Algeria, Djilali performed a study on potential site selection for solar hydrogen production using GIS-based multi-criteria decision making. The study focused on site suitability analysis and the technical potential; however, the focus was not on performing a hydrogen cost analysis for the country [27]. Conversely, in Morocco, research was carried out on the assessment of the hydrogen production potential from solar energy, focusing on a techno-economic investigation. In the study, the geographical constraints of the system installation did not include an evaluation of the green hydrogen potential. The results showed that the daily annual production of hydrogen varied from 6488.91 to 8308.74 tons/km^2/year, while the LCOE and LCOH ranged from 0.077 to 0.099 USD/kWh and 4.64 to 5.79 USD/kg, respectively [28], without considering the water cost. Furthermore, an analysis of the green hydrogen production potential from biomass, solar, and wind was conducted in Togo by Kitegi [29]. This study evaluated the green hydrogen potential without providing a detailed methodology. Mary conducted a green hydrogen geographical and technical potential assessment in Ghana for utility-scale systems using solar and wind resources. The study revealed that the northern part of the

country had the most favorable solar-based hydrogen potential. However, this potential was hindered by a low population density, which is further limited by inadequate power grid distribution [30].

In Niger, for instance, a study was carried out by Ramchandra [31] on the potential of hydrogen production using solar photovoltaic technology. As a result, the potential of the green hydrogen demand for the electricity and transport sectors were forecasted until 2040. The study showed that the required hydrogen production to replace 1% of the gasoline and diesel demand by 2040 would be 3 and 7 tons, respectively. A total of 0.117 Mt of hydrogen, mostly for electricity production, is needed by 2040 in Niger [31]. The study did not include a cost analysis, which could have provided valuable insights into the competitiveness of green hydrogen production with fossil fuels. Additionally, the study by Ramchandra lacked the integration of a geospatial analysis, thus limiting its relevance for real-world planning and development. It also did not account for regional variations in the solar potential, proximity to infrastructure, or water availability factors, which are critical for identifying viable hydrogen production sites [31]. The International Renewable Energy Agency carried out an assessment of the green hydrogen potential and cost for solar and wind resources in 2022 to meet the 1.5 °C climate goal. Land exclusion and techno-economic feasibility evaluations were conducted over the world using a 1×1 km^2 spatial resolution. The main limitation of the study was related to the cost of hydrogen analysis, which overlooked the increase in the capital expenditure relating to the transport of the equipment and taxes, which reduce the levelized cost of the green hydrogen potential, mostly in Africa.

A comprehensive technical and economic analysis of green hydrogen production remains beyond the scope of many existing studies, particularly due to the limited consideration of geographical constraints. This creates a significant gap for policymakers to establish an enabling environment for green hydrogen economy development across African nations. Furthermore, within the limited number of techno-economic studies on green hydrogen potential, there was a lack of emphasis on the system type, whether off-grid or utility-scale systems. Moreover, there was also a notable absence of attention paid to the implications of the water source type on the cost of green hydrogen production. To address this gap, this study aims to develop a framework for the geospatial techno-economic analysis of the green hydrogen potential in Niger for off-grid and utility-scale solar systems using alkaline and PEM water electrolyzers. Furthermore, this study examines scenarios incorporating two types of water sources, for instance, scenarios including domestic water sources (river and ground water) and desalinated water importation from neighboring countries.

First, a comprehensive literature review is conducted. Then, the methodology section outlines the geospatial techniques and economic analysis methods employed for evaluating the potential of solar-based hydrogen production. Lastly, the study presents the analysis results, including the assessment of the solar PV potential, green hydrogen potential, and the LCOH using PEM and alkaline water electrolyzers for off-grid and utility-scale systems. The study concludes with a summary of the findings.

2. Materials and Methods

2.1. Study Area

Niger is a landlocked country in West Africa characterized by diverse climatic zones, ranging from the Saharan desert in the north to Sahelian and Sudanian zones in the south. It shares borders with Chad, Nigeria, Mali, Burkina Faso, Benin, Libya, and Algeria [32] (Figure 1). Two-thirds of its land area lies within the Saharan zone, while the remaining one-third is situated within the Sudanian and Sahelian zones [32]. The land area is 1,267,000 km^2, with an estimated population of 27,640,265 inhabitants [33]. Despite the abundant solar resources, with irradiance levels ranging between 5 and 7 kWh/m^2/day [34], Niger faces

severe energy access challenges, with the per capita electricity consumption among the lowest globally, around 53.2 kWh/capita, representing 218 times that of the United States, at 11.638 MWh/capita [35]. The country's vast landmass and high solar potential offer a promising foundation for solar-based hydrogen production.

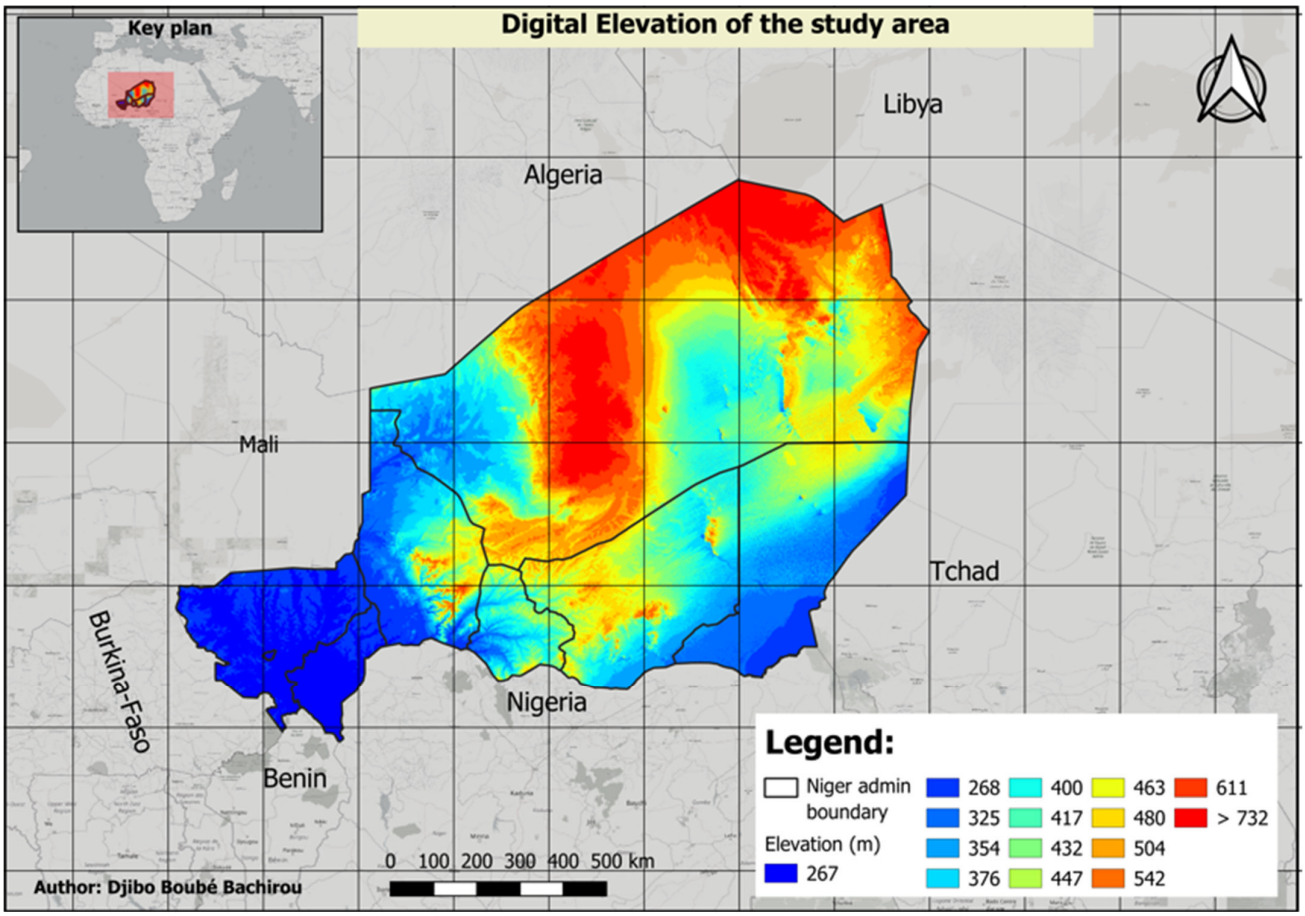

Figure 1. Digital elevation map of Niger.

2.2. Methodology

This study utilizes a GIS-based geospatial and techno-economic framework to evaluate the green hydrogen potential in Niger. The analysis begins by identifying eligible land areas for solar PV installation using the Python-based GLAES tool version 1.3.0, which filters out ineligible zones based on socio-technical and environmental constraints [8]. Subsequently, the electricity generation potential is estimated based on specific irradiance data and solar PV specifications. The following two system types are evaluated: off-grid and utility-scale systems, each with specific performance ratios [36]. The geospatial input layers are processed using the Quantum GIS (QGIS) software package version 3.34.2. The input raster data are resampled to a 100 m $\times$ 100 m grid cell resolution. The green hydrogen potential is calculated using the electrolysis efficiency values for proton exchange membrane (PEM) and alkaline water electrolyzers, with both domestic and desalinated water sources considered. The results of the analysis are extracted by using the zonal statistic tool in an Excel spreadsheet form. Furthermore, desalinated water implication on the cost of green hydrogen is investigated only for the utility-scale system. The methodology framework is summarized in Figure 2.

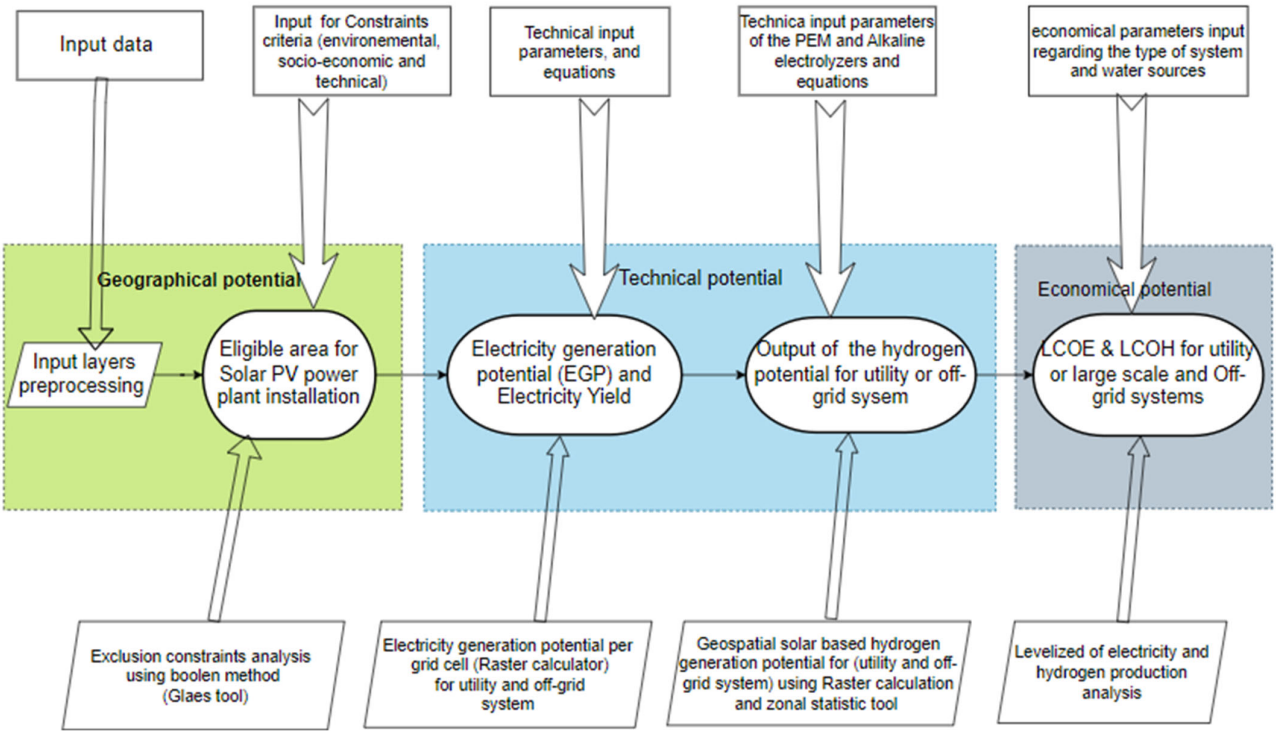

Figure 2. Geospatial analysis of the techno-economic feasibility of the solar-based hydrogen production workflow.

2.2.1. Technical Potential Evaluation of Solar-Based Hydrogen Production

The electricity generation potential of the eligible area is determined by using Equation (1) through a sample monocrystalline solar panel [36], as follows:

$$E_{GP} = GHI_{(xy)} \times \eta_{PV} \times PR \times AvailArea_{(xy)} \quad (1)$$

where

E_{GP} (kWh/m^2/year): the electricity generation potential;
GHI: the global horizontal solar irradiance values for the cell at xy coordinates in (kWh/m^2/year);
η_{PV}: the efficiency of the PV panel in (%);
PR : the PV panel performance ratio in (%).

The performance ratio is 75% and 85% for the off-grid and utility-scale systems, respectively, according to the optimal range of the system [36]. A monocrystalline panel of 370 Wp is considered, with a 1.82 m^2 area and an efficiency of 20.3% [37]. The $availArea_{(xy)}$ is the geographical potential representing the available area by excluding the land constraints, represented by one for an eligible area and zero otherwise. Additionally, another crucial factor is the specific PV yield in the area, using Equation (2) [38,39] as follows:

$$E_{yield} = \frac{E_{GP} \times A}{P_p} \quad (2)$$

where

E_{yield}: the specific PV electricity yield (kWh/kWp/year);
A: the area of the PV panel in (m^2);
P_p: the nominal peak power of the panel (kWp).

The efficiency of the electrolyzers is considered according to the higher heating value of hydrogen production, which is 39.4 kWh/kg [12], representing the minimum energy required to produce 1 kg of hydrogen based on enthalpy [40]. The electrolytic production rates are 52.5 kWh/kg and 54.7 kWh/kg for the proton exchange membrane (PEM) and alkaline water electrolyzers, respectively. These values correspond to a 75% [30] and 72% efficiency [27,41]. The density of the green hydrogen potential can be determined by Equation (3). The total amount of hydrogen potential per region is obtained by summing up the density of the green hydrogen potential, as follows:

$$M_{H_2} = \frac{E_{GP} \times \eta_{elec}}{HHV_{H_2}} \tag{3}$$

where

M_{H_2} is the density of the green hydrogen potential in (kg/m^2);
η_{elec} is the efficiency of the electrolysis system (%);
HHV_{H_2} is the higher heating value (kWh/kg of H_2).

2.2.2. Economic Analysis of Solar-Based Hydrogen Production

An economic analysis of the green hydrogen potential was carried out by using the levelized cost method. The levelized cost of electricity (or hydrogen) is the ratio of total lifetime costs (capital, variable, and fixed operating conditions) to the total production [42,43]. The levelized cost of electricity (LCOE) calculation formula is given in Equation (4), as follows:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{CAPEX_t + OPEX_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{GP}}{(1+r)^t}} \tag{4}$$

where $CAPEX$ represents the capital expenditure, $OPEX$ is the operation expenditure, F_t represents the fuel expenditure (set to zero in this case), E_{GP} is the electricity generation, r is the discount rate in %, and n is the lifetime of the system in years. The discount rate is assumed to be constant, while the Opex and the generated electricity are considered to be unchanged annually [44]. The present value factor (PVF) is used to discount future cash flows, ensuring accurate long-term cost estimation for each scenario.

$$LCOE = \frac{\frac{CAPEX}{PVF} + OPEX}{E_{yield}}$$

where PVF represents the present value factor.

$$PVF = \frac{(1+i)^t - 1}{(1+i)^t \cdot i}$$

In the above equation, i represents the interest rate.

The parameters of the evaluation are summarized in Table 1; the technology cost of a solar power plant is evidenced from the project carried out in the country [45]. The economic input of the electrolyzers was obtained from the Fraunhofer Institute for Solar Energy Systems so to analyze the LCOH by 2030 [46] by using Equation (5) [28,47–50] (see Table 2), as follows:

$$LCOH = \frac{\sum_{t=0}^{n} \left(\left(C_E + C_{elec} \right) (1+r)^{-t} \right)}{\sum_{t=0}^{n} \left(M_{H_2,t} (1+r)^{-t} \right)} \tag{5}$$

where

C_E is the investment cost of the electricity generation in (EUR/kWh);
r and n represent, respectively, the discount rate and the projected lifetime;
C_{elec} is the investment cost of the electrolysis system (in EUR);
$M_{H_2,t}$ is the annual hydrogen production potential (kg/year) in the year t.

The investment cost of the electrolysis system is determined by using Equation (6), as follows:

$$C_{elec} = C_{el} + C_{O\&M} + C_{rep} + C_{water} \quad (6)$$

C_{el} is the electrolyzer capital cost, which is calculated by Equation (7) [28], as follows:

$$C_{el} = C_{el,\,u} \times \left(\frac{M_{H_2} HHV}{8760 \eta_{elec}} \right) \quad (7)$$

where

$C_{el,\,u}$ is the unit price of the electrolyzer (EUR/kW_e);
HHV represents the higher heating value (kWh/kg).

Green hydrogen generation involves the utilization of electricity to split water (H_2O) into dihydrogen (H_2) and oxygen (O_2) using electrical energy, as demonstrated by the chemical equation [51] shown in Equation (8), as follows:

$$2H_2O \rightarrow 2H_2 + O_2. \quad (8)$$

The water and electricity generated from renewable energy sources are the main key feedstock for green hydrogen production [12]. While the purity level required varies depending on the technology, the cost of water purification is marginal, starting from desalinated seawater [52]. In green hydrogen production from large-scale systems for export, desalinated seawater could be a better option in a water-stressed region, which can be a benefit for other end-users. Therefore, an average distance of 800 Km outside of the country and a 500 km in-country distance are proposed as desalinated water importation routes, assuming a linear increase in the water cost with the distance. The water cost is calculated using Equation (9), including the energy and demineralization costs [44]. The input data are presented in the Table 2.

$$c_{Water} = c_{H_2O_{spec}} + C_{H_2O_{transport}} + E_{H_2O} \times LCOE \quad (9)$$

where

C_{H_2Ospec}: the specific water costs;
$C_{H_2O_{transport}}$: the water transport cost;
E_{H_2O}: the water purification energy.

Furthermore, a sensitivity analysis was conducted to evaluate how the variations in the key parameters affect the levelized cost of hydrogen. The parameters examined include the solar photovoltaic (PV) efficiency, with a baseline value of 20.3%, and the electrolyzer efficiency, set at 75% for proton exchange membrane systems and 72% for alkaline electrolyzers. Each parameter was independently varied by ±10% while keeping all other variables constant in order to isolate and quantify the specific impact on the LCOH.

Sensitivity scenarios were developed for both off-grid and utility-scale hydrogen production systems. Sensitivity analysis is a widely adopted practice in techno-economic evaluations of green hydrogen system analyses [53].

Table 1. Economic input parameters of the levelized cost of electricity calculation.

	Unit	Value	Reference
Capex (2020 and 2030)	EUR/kW_p	1448.02 1346.64	[45]
Opex	EUR/kWp	15.28	[45]
Lifetime	a	25	[53]
Interest rate	%	4.9%	[54]

Table 2. Economic input parameters of the levelized cost of green hydrogen calculation.

	Unit	Value			Reference
Opex	% Capex/a	2% capex			[55]
Cost of stack replace	EUR/kW_{el}	30% capex			[12]
Water demand	L/kg_{H2}	21			[12]
General water bodies	kWh/m^3	0.4			[56]
Water purification of ocean water	kWh/m^3	3.7			[57]
Specific water costs	EUR/m^3	0.73			[58]
Water transport	EUR/m^3/100 km	0.1			[59]
Discount rate	%	4.9			[54]
Lifetime of the system	year	20			[44]
	2020		2030		Reference
	5 MW	100 MW	5 MW	100 MW	[46]
Capex PEM water electrolyzer (EUR/KW)	980	720	730	500	
Capex alkaline water electrolyzer (EUR/KW)	949	663	726	444	

3. Results and Discussion

This part of the study presents the results of the techno-economic analysis. Initially, a geospatial analysis presents the electricity generation potential, yield, and green hydrogen production potential. The analysis was carried out using PEM and alkaline water electrolysis for off-grid and utility-scale solar power plants across all eight regions of Niger, providing a comprehensive overview. Subsequently, the study evaluated the economic analysis of green hydrogen production, highlighting the various water sources considered for each system type and electrolysis technology.

3.1. Technical Potential for Solar-Based Electricity Generation

The spatial analysis in this study revealed that Niger has a total electricity generation potential of approximatively 311,617 TWh/year for off-grid systems and 353,166 TWh/year for utility-scale solar PV systems, as illustrated in Figure 3. These values were derived by excluding 32.11% of the land area deemed unsuitable for PV installation. This is due to socio-economic and environmental constraints, as depicted in the white legend (Figures 4 and 5). Whereas, in the remaining area, 67.89% (888,834 km^2) of Niger's total land mass was deemed eligible for solar PV system deployment.

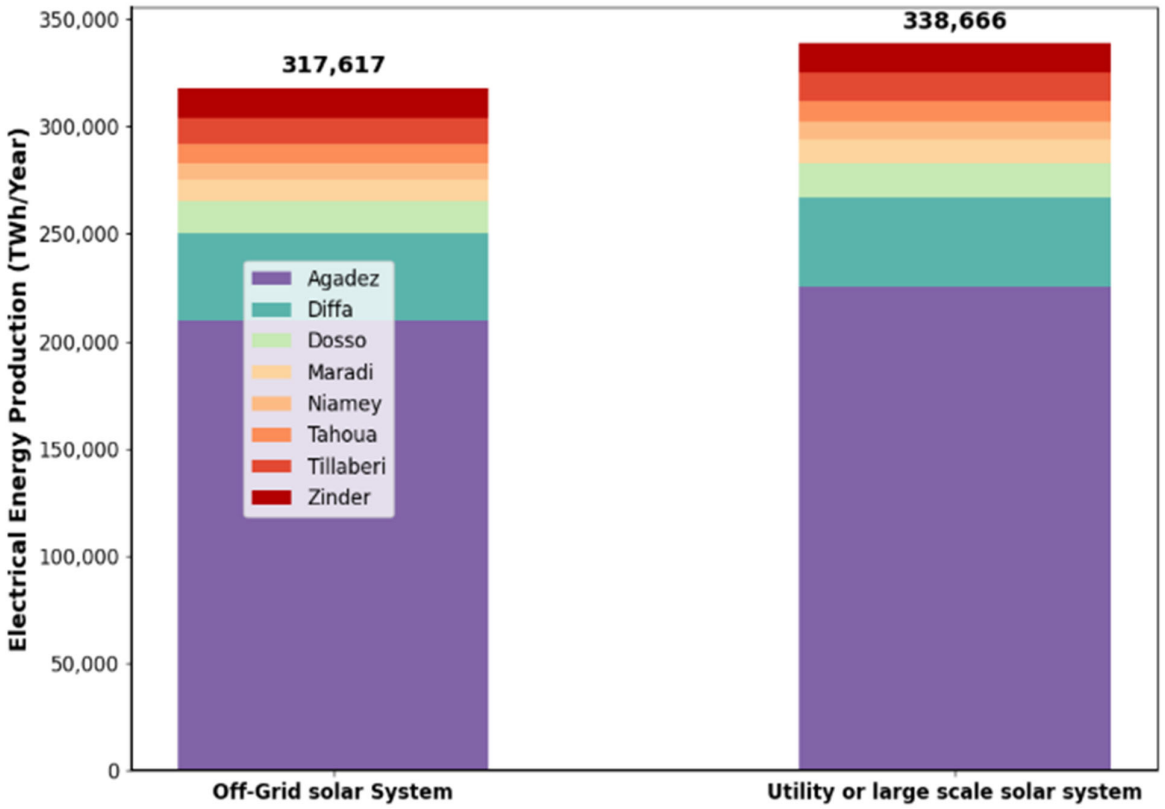

Figure 3. Electricity generation potential per type of system.

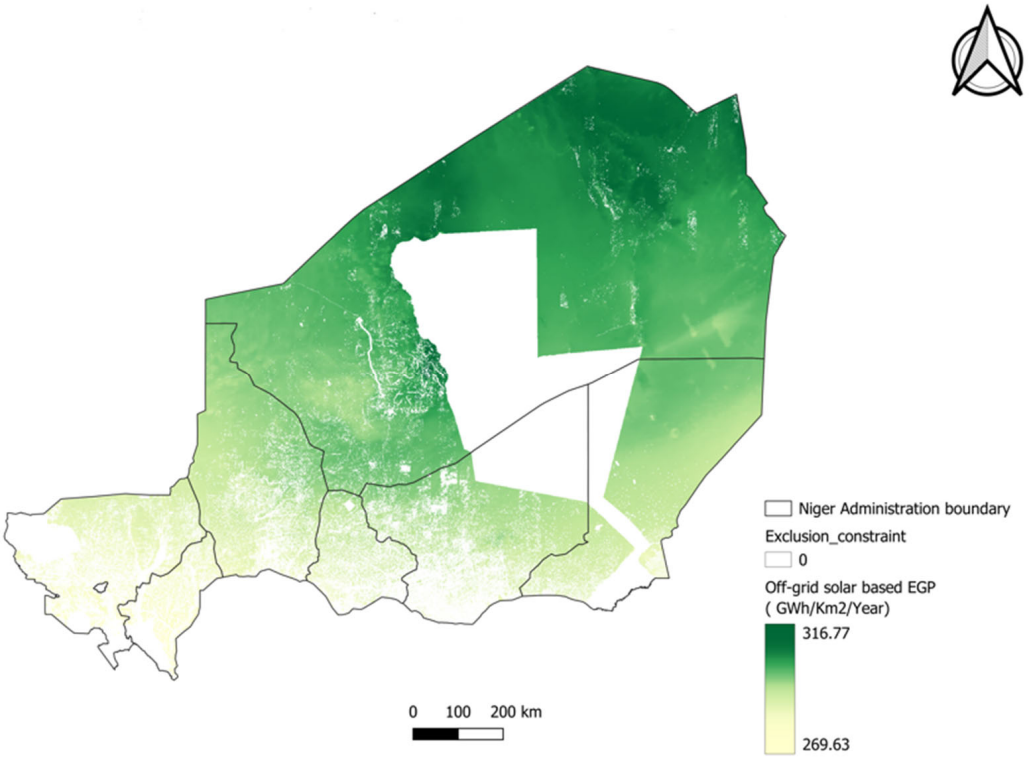

Figure 4. Off-grid solar-based electricity generation potential in Niger.

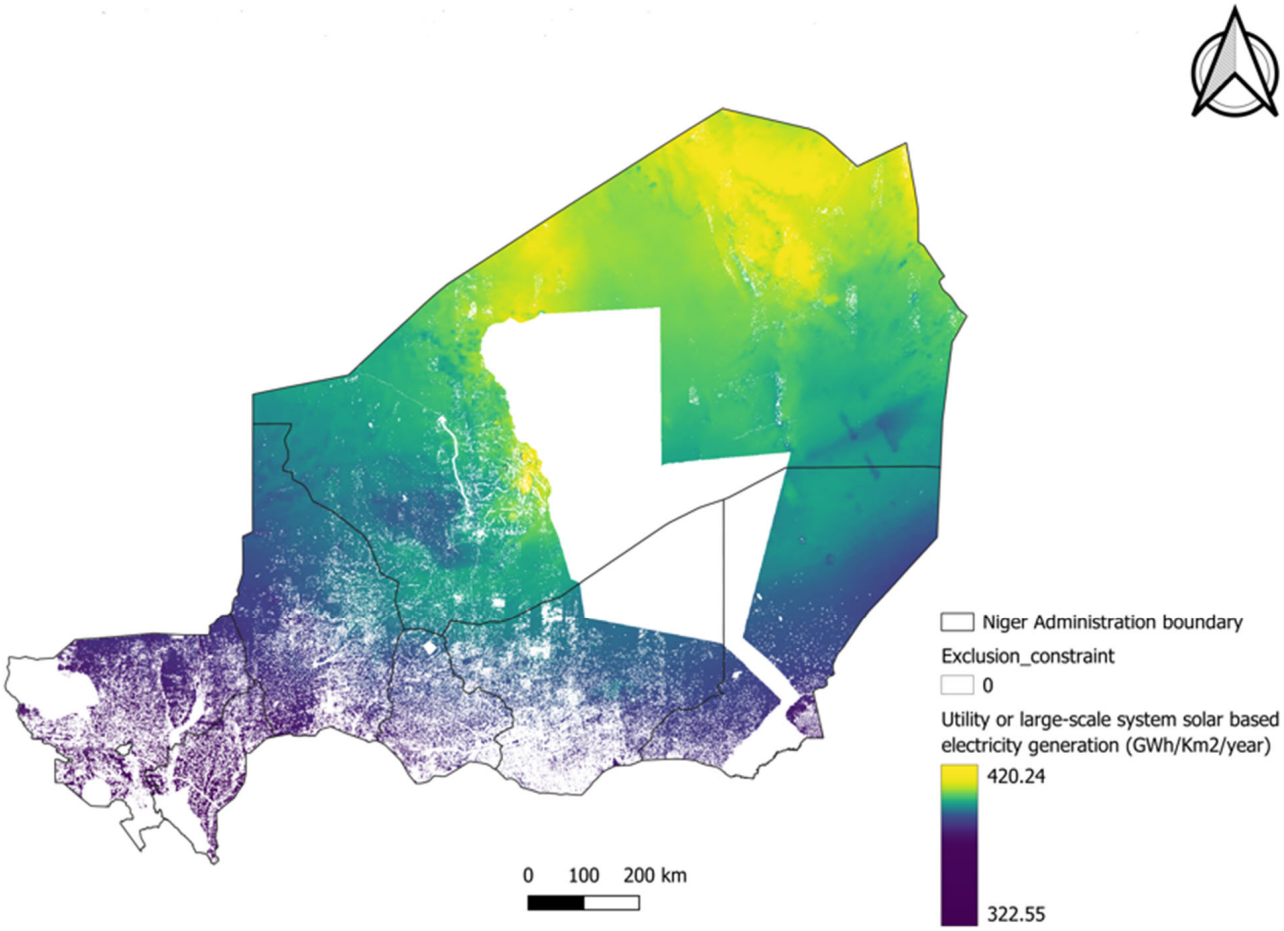

Figure 5. Utility-scale solar-based electricity generation potential in Niger.

The electricity generation potential, as depicted in Figure 4, for off-grid solar systems varies from 268 to 374 GWh/km^2/year, averaging roughly 333 GWh/km^2/year (Table A1 of Appendix A). As a result, the Agadez region emerges with the highest potential, which corresponds to 196,401 TWh/year, followed by the Diffa region, with 39,326 TWh/year, and Tahoua, with 30,247 TWh/year. Regions such as Agadez and Diffa offer the highest potential due to the expansive eligible land and high irradiance values. The overall electricity yield over Niger's territory ranges from 1320 to 1841 kWh/kWp. Notably, the major energy specific yield is concentrated in the northern, eastern, southeast, and northwestern parts of Niger, corresponding to 1625 kWh/KWp. The lowest yield is attributed to potential shading caused by the high mountains in some locations.

Similarly, the electricity generation for utility-scale systems is estimated from 322 to 420 GWh/km^2/year (see Figure 5), with a specific yield ranging between 1480 kWh/kWp/year and 2064 kWh/kWp/year (Table A2, Appendix A). The Agadez region contributes the largest share of electricity generation potential, estimated at 22,588 TWh/year, owing to its expansive land area and high solar irradiance. This estimate significantly exceeds the values reported for comparable regions in Africa, such as the Dakha-Ouest Ed-Dahab region in southern Morocco [60] and urban zones like Khartoum, Sudan [61], where the estimated generation potentials remain well below 100,000 TWh/year. These comparisons highlight Niger's strategic advantage for large-scale solar deployment and green hydrogen production.

It is evident that the electricity generation potential of utility-scale power plants is significantly higher than that of off-grid power systems. This disparity can be attributed primarily to the lower efficiency of off-grid systems, which is largely influenced by the

complexity and limitations of balance-of-system (BoS) components [36]. The estimated difference in the electricity generation potential between the two system types amounts to approximately 41,549 TWh/year. Furthermore, these findings are consistent with previous studies conducted in the North African region, which employed similar methodological approaches [27,28]. This study demonstrates that the orographic constraints affect some locations due to the mountain shading of sun radiation.

3.2. Technical Potential for Solar-Based Green Hydrogen Production

In this section, the result of the green hydrogen production potential using PEM and alkaline water electrolyzers is presented for both off-grid and utility-scale systems. The results illustrate that the green hydrogen potential density for the PEM electrolyzer using the off-grid solar system averages 6238 tons/km^2/year, fluctuating from 5417 to 7058 tons/km^2/year according to the location, as presented in the map of Figure 6 (Table A3, Appendix B).

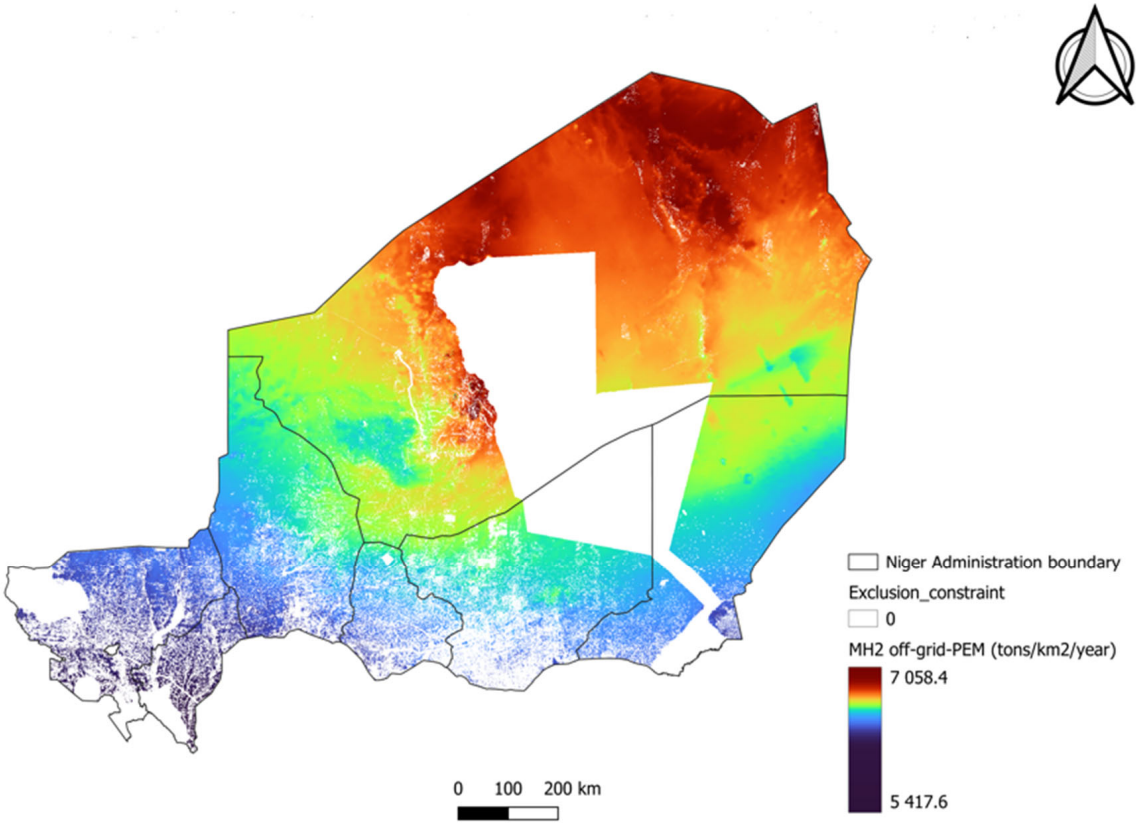

Figure 6. Off-grid system solar-based green hydrogen potential using the PEM water electrolyzer.

Moreover, the hydrogen potential using the alkaline water electrolyzer for the off-grid system is estimated at 5988 tons/km^2/year, ranging from 5201 to 6776 tons/km^2/year (see Figure 7). The larger potential is located in the northwest and northeast parts of Niger, due to the important solar radiation and eligible land for solar plant installation. The study finds that the total hydrogen potential for the PEM water electrolyzer is higher compared to the alkaline water electrolyzer, corresponding to 5931 Mt/year and 5694 Mt/year (Figure 8), respectively, explained by the higher efficiency of the PEM water electrolyzer.

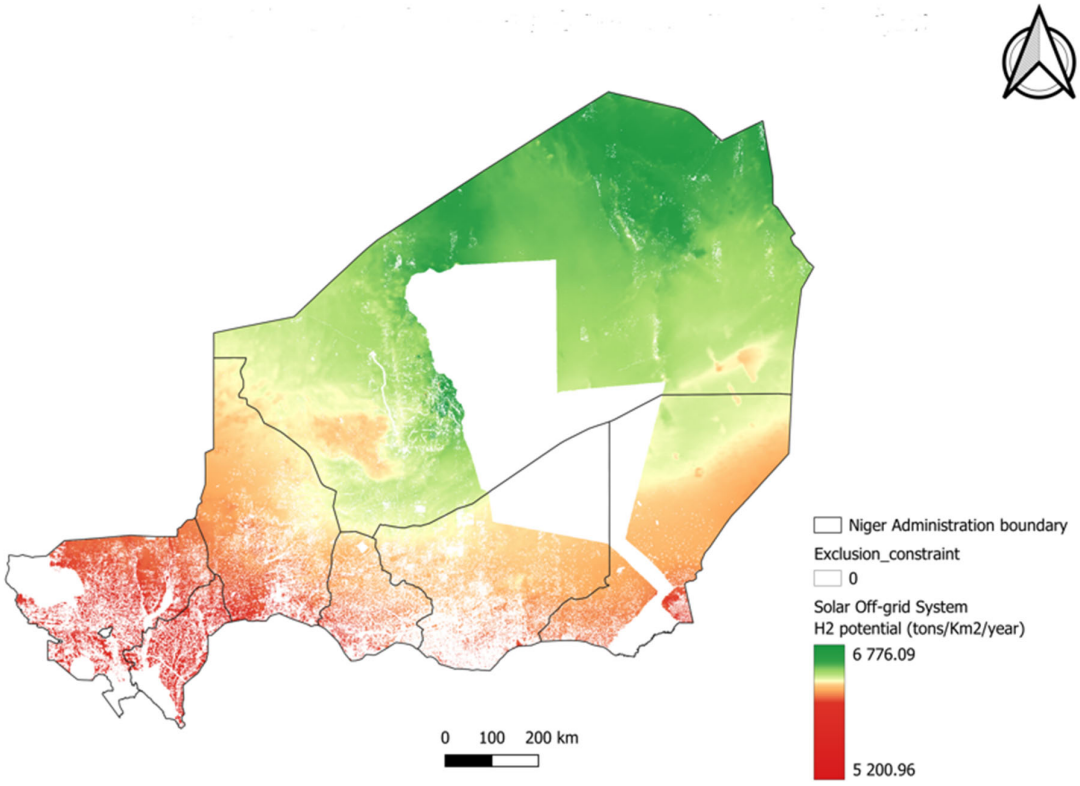

Figure 7. Off-grid system solar-based green hydrogen potential using the alkaline water electrolyzer.

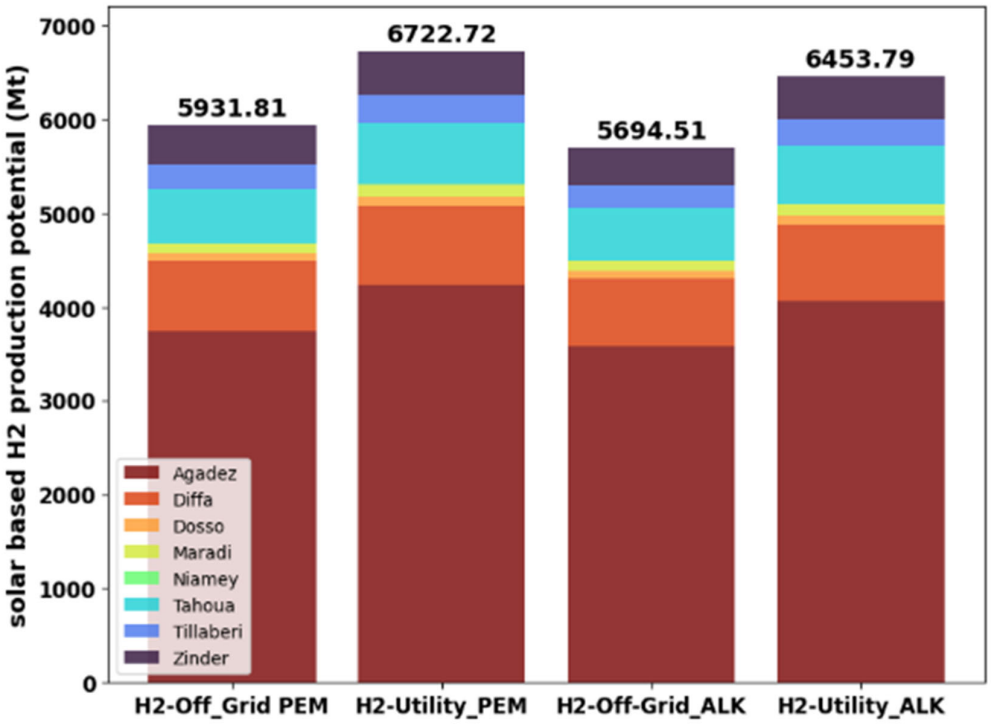

Figure 8. Green hydrogen production potential for PEM and alkaline water electrolyzers.

The analysis provided by Figure 8 shows that the total annual green hydrogen potential is estimated at 6723 Mt/year and 6454 Mt/year, respectively, using the PEM and alkaline water electrolyzers for the utility-scale system. The geospatial average densities of the green hydrogen potential for the PEM and alkaline electrolyzers range from 7999 to 6140 tons/km^2/year and from 7069 to 6787 tons/km^2/year, respectively, as shown in

Figures 9 and 10 (see Appendix B, Table A4). Generally, the green hydrogen potential for the utility-scale solar power plants is higher in less densely populated areas with significant solar radiation.

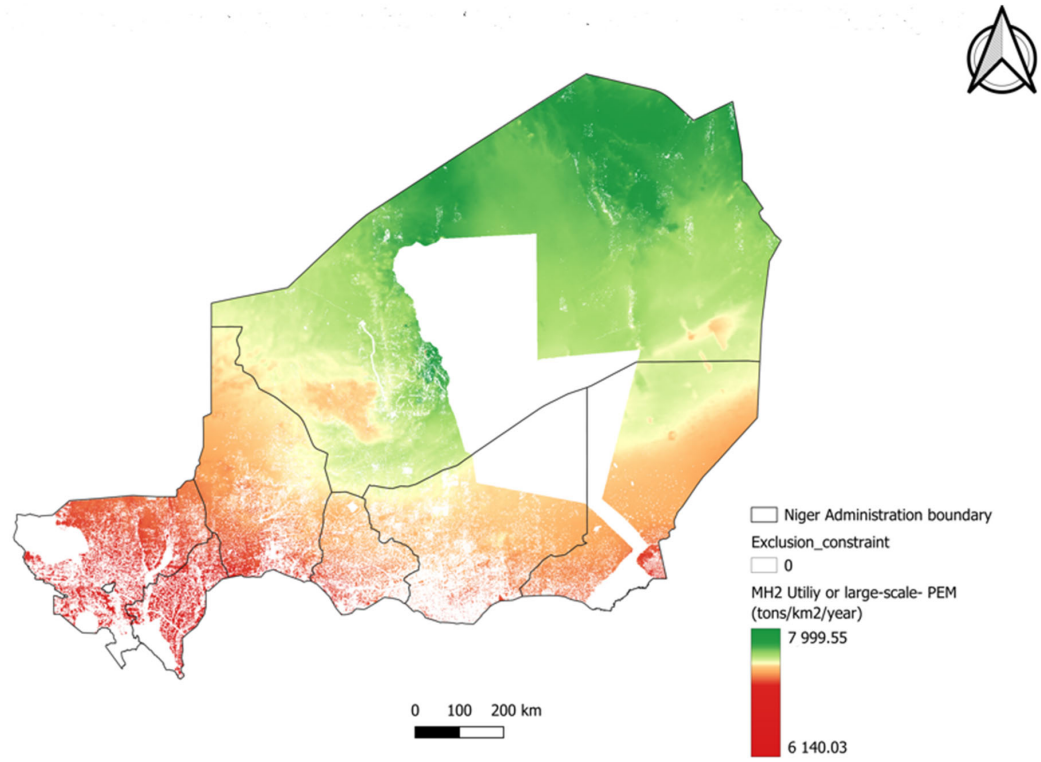

Figure 9. Utility-scale system solar-based green hydrogen potential using the PEM water electrolyzer.

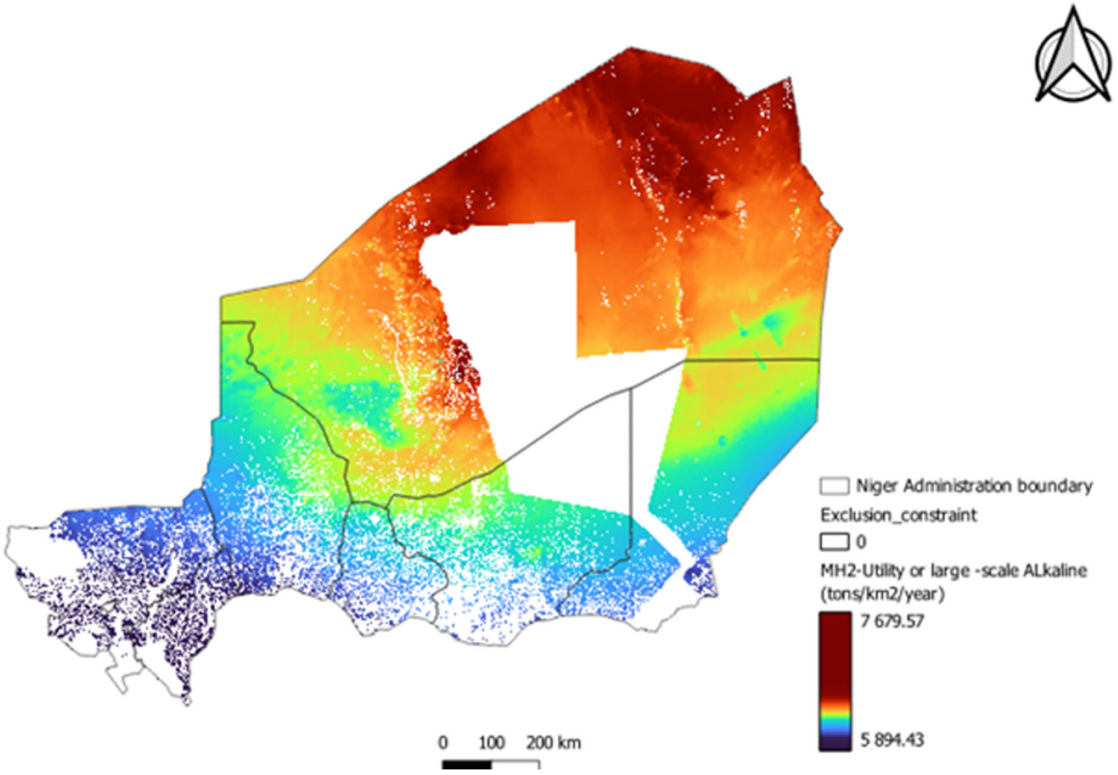

Figure 10. Utility-scale system solar-based green hydrogen potential using the alkaline water electrolyzer.

Further, the Agadez region alone accounts for over 60% of the national potential, making it a strategic region for export-oriented hydrogen projects to northern Africa. The results demonstrate that green hydrogen production using PEM electrolysis is notably higher than that of alkaline systems. This is particularly evident for both the utility-scale and off-grid scenarios. The advantage is primarily due to the higher efficiency of PEM electrolyzers, combined with the strong solar-based electricity generation potential across eligible regions (see Figure 8).

These findings are consistent with the Africa Energy Outlook 2022, published by the International Energy Agency, which highlight Niger's substantial solar-based green hydrogen potential [62]. The projected world hydrogen demand in 2050 is estimated between 200 and 600 Mt/year according to the World Energy Council's insights, considering the low- and high-ambition trajectories, respectively [63]. Remarkably, the estimated hydrogen potential in Niger could cover at least nine times the world's hydrogen demand. Additionally, the estimated hydrogen production values in this study significantly exceeded those reported in Togo [29] and Ghana [30], highlighting Niger's competitive position due to the vast eligible land and high solar irradiance levels.

3.3. Economic Analysis of Electricity Generation from Solar PV Technology

The economic analysis of electricity generation reveals that that the levelized cost of electricity ranges from 0.061 to 0.079 EUR/kWh for off-grid systems, and from 0.054 to 0.07 EUR/kWh for utility-scale systems, by 2030. It has been found that the LCOE in this study is quite higher compared to the IRENA 2022 renewable energy technology cost report [64] which can be attributed to the equipment transport cost being under-estimated in the IRENA model, which is particularly significant in landlocked countries like Niger. Additionally, the declining cost of electricity by 2030 is attributed to the maturity of the PV technology. Meanwhile, the cost disparity between off-grid and utility-scale systems may be rationalized by economies of scale, with later lacking balance-of-system (BoS) equipment and batteries, which affects the efficiency and increases the investment cost of the system.

3.4. Economic Analysis of Green Hydrogen Production Using PEM Water Electrolyzer

The result of the LCOH analysis using the PEM water electrolyzer result for the off-grid system by 2030 is between 4.72 and 5.99 EUR/kgH_2 according to the solar potential in Niger. The result demonstrates a reduction from 0.21 to 0.32 EUR/kgH_2 compared to the LCOH in 2020 (4.93 to 6.31 EUR/kgH_2) (see Figure 11). Similarly, the cost of hydrogen for the utility-scale system presents a decrease from 0.16 to 0.27 EUR/kgH_2, and from 4.255.48 EUR/kgH_2 (2020) to 4.09–5.21 EUR/kgH_2 (2030). In contrast, the levelized cost of the hydrogen potential for the utility-scale system, utilizing desalinated water, is projected to range from 4.10 to 5.22 EUR/kgH_2 in 2030. This illustrates a similar trend for the hydrogen cost reduction compared to domestic water use.

Generally, we can notice an average levelized cost of green hydrogen reduction between 0.26 and 0.21 EUR/kgH_2, respectively, for off-grid and utility-scale systems. A steady cost reduction of 0.01 EUR/kgH_2 for the green hydrogen potential has been observed for the utility-scale solar system using a domestic water source compared to desalinated water for the PEM water electrolyzer. The projected reduction in the hydrogen production costs by 2030 is primarily driven by declining investment and operational expenditures, along with the rapid expansion of green hydrogen markets. However, green hydrogen must still overcome economic barriers to compete effectively with fossil fuel-based hydrogen, particularly in regions where conventional production remains subsidized [11].

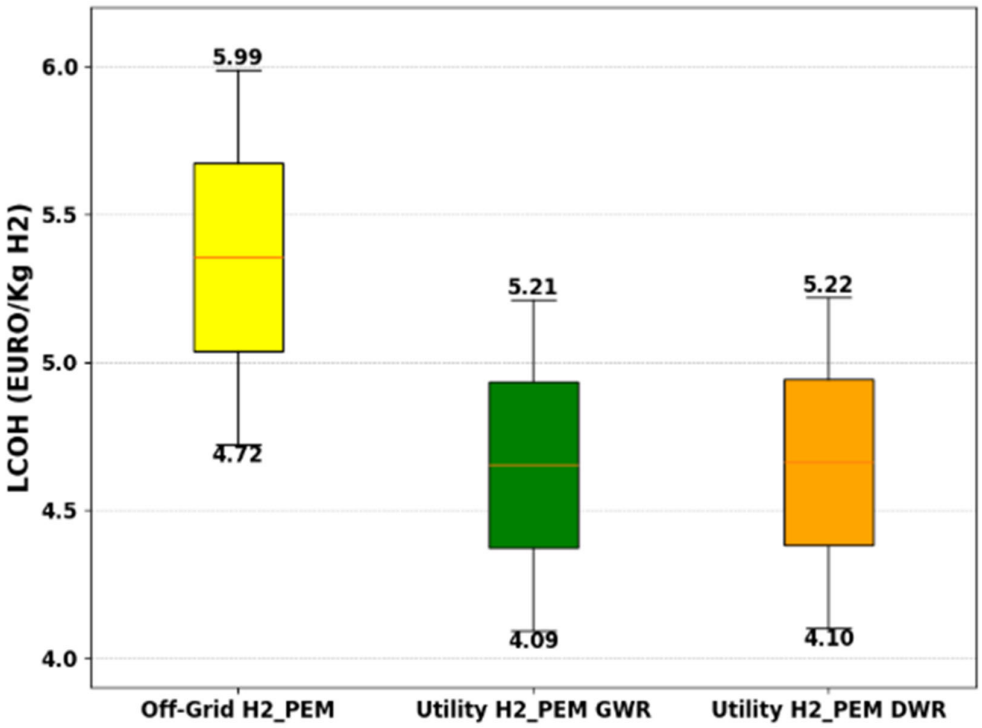

Figure 11. Levelized cost of green hydrogen for different types of solar systems.

The investment and operation cost decreases, as well as the growing markets of green hydrogen technology, by 2030 are the main reasons for the cost reduction, although they still need to be competitive with fossil fuel-based hydrogen production. For instance, Ramachandra's study on the green hydrogen production potential using a PEM water electrolyzer for an off-grid solar system in Germany found that the levelized cost of hydrogen (LCOH) decreased from 4.89 EUR/kgH_2 to 7.02 EUR/kgH_2 [24]. Thus, this demonstrates the cost competitiveness of the green hydrogen potential in Niger for the regional hydrogen economy. Additionally, Samir carried out a geospatial evaluation of the green hydrogen potential using a PEM electrolyzer. The author considered the cost of the electrolyzer, the operation and maintenance, and the stack replacement cost without including the water cost, resulting in a cost of green hydrogen varying between 4.54 and 5.35 EUR/kgH_2 [28]. The green hydrogen production cost in Niger still shows potential for competitiveness compared to those found in Morocco, which is likely driven by the region's abundant solar resources. Another study carried out by Ahmadi in Afghanistan's Helmand province has shown an LCOH production potential using solar PV varying from 2.09 to 2.18 USD/kg over the regions [65]. The low LCOH value may be attributed to the author's omission of stack replacement costs and water costs in the analysis. Overall, the LCOH projections for Niger show a steady decrease by 2030, aligning with the findings from the Fraunhofer Institute for Solar Energy Systems, which emphasized the long-term cost competitiveness through technological improvement and scale-up [46].

3.5. Economic Analysis of Hydrogen Production Using Alkaline Water Electrolyzer

In this section, similarly, a hydrogen cost analysis is conducted using alkaline water electrolyzers, as presented in Figure 12. The results show a decrease in the levelized cost of hydrogen (LCOH) for off-grid systems. In 2020, the LCOH ranged from 5.27 to 6.7 EUR/kgH_2, while, by 2030, it is projected to range from 5.05 to 6.37 EUR/kgH_2. This reflects a cost reduction of approximately 0.22 to 0.3 EUR/kgH_2, which is equivalent to a 4.5% decrease compared to 2020 levels. Furthermore, the cost analysis for the

utility-scale system using domestic water sources demonstrates a cost variation from 4.38–5.67 EUR/kgH_2 (2020) to 4.22–5.40 EUR/kgH_2 (2030), indicating a decrease in the green hydrogen cost of 0.16–0.17 EUR/kgH_2. Similarly, the same trends of green hydrogen cost reduction are observed using desalinated water for the utility-scale solar system, varying from 4.39–5.68 EUR/kgH_2 in 2020 to 4.23–5.41 EUR/kgH_2 in 2030. Particularly, the cost variation observed using the two water sources for the utility-scale system is marginal at 0.01 EUR/kgH_2. Comparing the utility-scale systems with the off-grid ones, there is an average levelized cost of green hydrogen difference of 0.93 EUR/kgH_2.

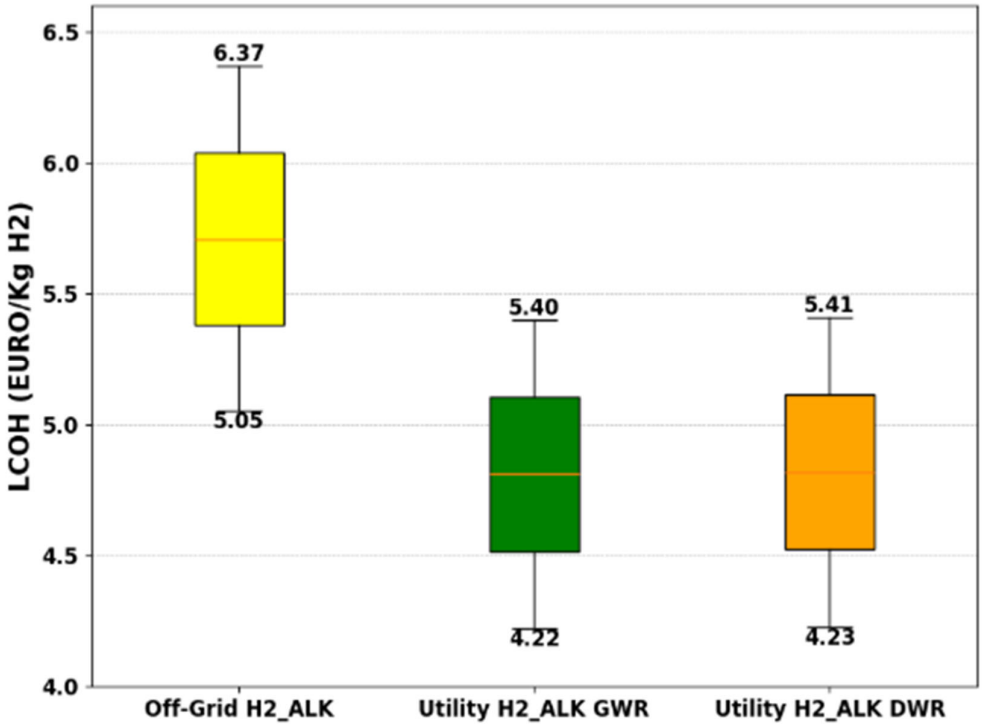

Figure 12. Levelized cost of green hydrogen for various solar systems by 2030 using the alkaline water electrolyzer.

In comparison to a study conducted in the Sultanate of Oman [66] focusing on the solar-to-hydrogen potential and economic analysis for site suitability, the economic analysis showed an LCOH of 6.31 USD/kgH_2–7.32 USD/kgH_2. Notably, the cost of hydrogen production in Oman appears to be higher compared to the LCOH in the current study, possibly due to the higher electricity cost generated from solar PV technology in Oman relative to Niger. Furthermore, the study encompassed the hydrogen storage cost, resulting an increase in the levelized cost of green hydrogen.

Meanwhile, the H2 Atlas project, implemented by Forschungszentrum Jülich, provides an online geographical information platform focused on West Africa's hydrogen potential (ECOWAS H2 Atlas). However, it primarily concentrates on supply-side constraints, neglecting considerations of geographical aspects regarding accessibility to water resources in the cost analysis [67]. To address this gap, the current study factored in water transport and deionization costs, contributing to a more inclusive analysis of the levelized cost of hydrogen.

Comparatively, the levelized cost of hydrogen between the H2 Atlas project and the current study for the year 2020 show general alignment, with slightly higher LCOH values in some regions, mainly due to the consideration of water constraints. It is important to note that the green hydrogen cost analysis presented in the ECOWAS H2 Atlas does not currently include projections for the year 2030. Consequently, these findings can assist

decisionmakers in formulating hydrogen strategic plans that are aligned with ECOWAS hydrogen targets [13].

3.6. Sensitivity Analysis Results

In this study, a ±10% change in the electrolyzer efficiency significantly impacted the levelized cost of hydrogen (LCOH). For the PEM electrolyzers (with a 75% baseline efficiency), this translates to a shift in the energy demand from 52.5 kWh/kgH_2 to between 47.7 and 58.3 kWh/kgH_2, causing an LCOH change of ±0.47–0.54 EUR/kgH_2. Similarly, for the alkaline electrolyzers (with a 72% efficiency), the energy demand varies between 49.3 and 60.2 kWh/kgH_2, shifting the LCOH by ±0.40–0.48 EUR/kgH_2. On average, both systems show a combined sensitivity of ±0.43–0.51 EUR/kgH_2. These results highlight the critical role of the electrolyzer performance in reducing the green hydrogen costs

This research strengthens the existing academic perspective that electrolyzer improvements combined with declining costs will boost the green hydrogen operational sustainability primarily in solar-rich developing nations.

4. Conclusions

This study provided a comprehensive techno-economic analysis of solar-based green hydrogen potential, focusing on both off-grid and utility-scale systems, utilizing a geospatial approach for alkaline and PEM water electrolyzers. The GLAES tool was employed to assess eligible areas for solar system installation by considering environmental and socio-technical constraints. The findings indicate a substantial electricity generation potential in Niger by using solar PV systems, with estimates at 311,617 TWh/year for off-grid and 353,166 TWh/year for utility-scale systems. The potential of hydrogen production using PEM water electrolyzers is estimated at 5932 Mt/year for off-grid systems and 6723 Mt/year for utility-scale systems. Similarly, the potential for hydrogen production using alkaline water electrolyzers is estimated at 5694 Mt/year for off-grid systems and 6454 Mt/year for utility-scale systems. The LCOH production potential decrease for PEM and alkaline water electrolyzers by 2030 ranges between 4.72–5.99 EUR/kgH_2 and 5.05–6.37 EUR/kgH_2 for off-grid and 4.09–5.21 EUR/kgH_2 and 4.22–5.4 EUR/kgH_2 for utility-scale systems. This study indicates that the levelized cost of hydrogen (LCOH) for alkaline water electrolyzers is lower compared to proton exchange membrane (PEM) electrolyzers. This is primarily due to the higher investment costs associated with PEM systems. Furthermore, the analysis revealed that using desalinated water leads to a higher levelized cost of hydrogen (LCOH) compared to using domestic water sources. This underscores the importance of effective water resource management in green hydrogen production. These findings offer valuable insights to support decisionmakers in developing strategic plans for integrating and deploying green hydrogen technologies. Such strategies are vital for advancing the transition toward sustainable and low-carbon energy systems. However, one of the main limitations of this research is the lack of consideration of the cost implication on the overall hydrogen supply chain for various end-users.

Author Contributions: Conceptualization, B.D.B., R.B., M.M.S., A.L.B. and R.A.; Methodology, B.D.B., R.B., M.M.S., A.L.B. and R.A.; Software, B.D.B., R.B., M.M.S. and A.L.B.; Formal analysis, B.D.B.; Investigation, B.D.B., R.B., M.M.S. and R.A.; Writing—original draft, B.D.B., R.B., M.M.S., A.L.B. and R.A.; Writing—review & editing, B.D.B., R.B., M.M.S., A.L.B. and R.A.; Funding acquisition, R.B. and R.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Technical potential of electricity generation for off-grid solar systems.

Region	Available Land	Geographical	Solar Off-Grid EGP	Solar Off-Grid EGP	Solar Off-Grid Yield	Solar Off-Grid Yield	Solar Off-Grid EGP_{Total}
	(km^2)	Potential (%)	(GWh/km^2/Year) Min	(GWh/km^2/Year) Max	(kWh/kWp/Year) Min	(kWh/kWp/Year) Max	(TWh/Year)
Agadez	706,037.56	78.43%	269.63	374.30	1320.36	1841.18	196,401.50
Diffa	156,906	71.61%	330.98	353.34	1628.09	1738.05	39,326.14
Dosso	31,002	39.01%	316.02	337.65	1554.51	1660.92	4298.67
Maradi	35,100	41.93%	331.82	347.94	1632.20	1711.52	6015.76
Niamey	425.63	5.12%	322.20	331.70	1584.87	1631.65	6.6
Tahoua	106,677	76.16%	329.31	349.94	1619.89	1721.37	30,247.40
Tillabéri	89,623	41.69%	318.14	340.21	1564.90	1673.50	13,550.22
Zinder	145,430	67.89%	334.32	351.45	1644.50	1728.75	21,770.84
Total							**311,617.17**

Table A2. Technical potential of electricity generation for utility-scale systems.

Region	Available Land	Geographical	Solar Utility-Scale Yield	Solar Utility-Scale Yield	Solar Utility-Scale EGP	Solar Off-Grid EGP	Solar Off-Grid EGP_{Total}
	(km^2)	Potential (%)	(kWh/kWp/Year) Min	(kWh/kWp/Year) Max	(GWh/km^2/Year) Min	(GWh/km^2/Year) Max	(TWh/Year)
Agadez	706,037.56	78.43%	1479.97	2063.74	322.55	420.24	222,588.37
Diffa	156,906	71.61%	1824.89	1948.15	375.11	400.45	44,569.62
Dosso	31,002	39.01%	1742.42	1861.69	358.16	382.68	4871.83
Maradi	35,100	41.93%	1829.49	1918.41	376.06	394.34	6817.86
Niamey	425.63	5.12%	1776.45	1828.88	365.16	375.93	7.51
Tahoua	106,677	76.16%	1815.7	1929.45	373.22	396.60	34,280.39
Tillabéri	89,623	41.69%	1754.07	1875.79	360.55	385.58	15,356.91
Zinder	145,430	67.89%	1843.29	1937.72	378.89	398.31	24,673.62
Total							**353,166.15**

Appendix B

Table A3. Technical potential of hydrogen production for off-grid solar systems.

Region	Available Land	Geographical	Solar Off-Grid EGP	ALK_Based H2 Potential	PEM_Based H2 Potential	ALK_Based H2 Total	PEM_Based H2 Total
	(km^2)	Potential (%)	(TWh/Year) Total	(Tons/km^2) Mean	(Tons/km^2) Mean	Potential (Mt/Year)	Potential (Mt/Year)
Agadez	706,037.56	78.43%	196,401.50	5084.50	5296.36	3589.06	3738.61
Diffa	156,906	71.61%	39,326.14	4521.49	4709.89	718.65	748.59
Dosso	31,002	39.01%	4298.67	2354.45	2452.55	78.55	81.82
Maradi	35,100	41.93%	6015.76	2614.23	2723.16	109.93	114.51
Niamey	425.63	5.12%	6.6	285.19	297.07	0.121	0.126
Tahoua	106,677	76.16%	30,247.40	4783.72	4983.04	552.74	575.77
Tillabéri	89,623	41.69%	13,550.22	2554.32	2660.75	247.61	257.93
Zinder	145,430	67.89%	21,770.84	2532.11	2637.62	397.84	414.42
Total			**311,617**			**5694.53**	**5931.81**

Table A4. Technical potential of hydrogen production for utility-scale systems.

Region	Available Land	Geographical	Solar Utility-Scale EGP	ALK_Based H2 Potential	PEM_Based H2 Potential	ALK_Based H2 Total	PEM_Based H2 Total
	(km^2)	Potential (%)	(TWh/Year) Total	(Tons/km^2) Mean	(Tons/km^2) Mean	Potential (Mt/Year)	Potential (Mt/Year)
Agadez	706,037.56	78.43%	222,588.37	5762.44	6002.54	4067.6	4237.09
Diffa	156,906	71.61%	44,569.62	5124.36	5337.88	814.47	848.40
Dosso	31,002	39.01%	4871.83	2668.38	2779.56	89.02	92.73
Maradi	35,100	41.93%	4871.83	2962.38	3086.25	124.59	129.78
Niamey	425.63	5.12%	7.51	323.21	336.68	0.137	0.143
Tahoua	106,677	76.16%	34,280.39	5421.55	5647.44	626.44	652.54
Tillabéri	89,623	41.69%	15,356.91	2894.90	3015.52	280.63	292.32
Zinder	145,430	67.89%	24,673.62	2869.73	2989.30	450.88	469.67
Total			**353,166**			**6453.8**	**6722.7**

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