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Renewable hydrogen economy outlook in Africa

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A R T I C L E I N F O

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A B S T R A C T

Hydrogen presents an opportunity for Africa to not only decarbonise its own energy use and enable clean energy access for all, but also to export renewable energy. This paper developed a framework for assessing renewable resources for hydrogen production and provides a new critical analysis as to how and what role hydrogen can play in the complex African energy landscape. The regional solar, wind, CSP, and bio hydrogen potential ranges from 366 to 1311 Gt/year, 162 to 1782 Gt/year, 463 to 2738 Gt/year, and 0.03 to 0.06 Gt/year respectively. The water availability and sensitivity results showed that the water shortages in some countries can be abated by importing water from regions with high renewable water resources. A techno-economic comparative analysis indicated that a high voltage direct current (HVDC) system presents the most cost-effective transportation system with overall costs per kg hydrogen of 0.038 $/kg, followed by water pipeline with 0.084 $/kg, seawater desalination 0.1 $/kg, liquified hydrogen tank truck 0.12 $/kg, compressed hydrogen pipeline 0.16 $/kg, liquefied ammonia pipeline 0.38 $/kg, liquefied ammonia tank truck 0.60 $/kg, and compressed hydrogen tank truck with 0.77 $/kg. The results quantified the significance of economies of scale due to cost effectiveness of systems such as compressed hydrogen pipeline and liquefied hydrogen tank truck systems when hydrogen production is scaled up. Decentralization is favorable under some constraints, e.g., compressed hydrogen and liquefied ammonia tank truck systems will be more cost effective below 800 km and 1400 km due to lower investment and operation costs.

1. Introduction

The goal to mitigate greenhouse gas emissions and maintain global warming below 2 °C to avoid catastrophic climate change after the Paris agreement [1] and more recently COP26 [2] has led to increased interest in decarbonized energy sources. Renewable energy resources are agreeably a key solution in mitigating greenhouse gas emissions.

Despite Africa's carbon footprint accounting for about 3% of the global greenhouse gasses due to current low economic activity, it heavily relies on traditional biomass as the primary source of energy to meet daily energy requirements [3]. To put this into context, it is comparable with the emissions emitted by the shipping industry which has received its fair share of attention due to its emissions. About 81% of Sub-Saharan Africa's (excluding South Africa) total primary energy demand is met by polluting biomass [4]. In addition, 75% of the global population without access to electricity live in Sub-Saharan Africa where the average access to electricity averages around 45% [5]. Around 3 billion people lack access to clean cooking and about 85% of those without access live in just 20 high impact countries in developing Asia and Sub-Saharan Africa [2,6]. An estimated 1–2.4 Gt of carbon dioxide equivalent in greenhouse gases is emitted annually in producing and using fuelwood and charcoal in Sub-Saharan Africa. Using wood fuels for daily energy needs does not only contribute to global warming but endangers people's lives by threatening people's health, reducing air quality, and reducing life expectancy.

Africa's rapid population (predicted to be 2.5 billion in 2050) and economic growth (+2.2% to +3.1% per year [7,8] though it shrunk by 2.1% in 2020 due to covid-19 [8]) will increase the continent's energy consumption and emissions, which may contribute between 5 and 20% of the global emissions in 2050 [9]. Schiffer [7] predicts Africa's emissions equivalent to around 52 billion tons in 2050 in a business as usual scenario, and the African Development Bank predicted Africa's GDP level around US$17 trillion in 2060. Sustainably meeting this rapidly growing energy demand will be key to curbing emissions and enabling Africa's growth [10]. Africa's renewable energy resources and minerals,

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Abbreviations

COP	Conference of the Parties (UN Climate Change Conference)
CSP	Concentrated Solar Power
CUF	Capacity Utilisation Factor
GHI	Global Horizontal Irradiation
GWh	Gigawatt hour
HVDC	High Voltage Direct Current
IRENA	International Renewable Energy Agency
Mt	Mega tonne
NOx	Nitrous Oxide
Nm^3	Normal cubic meters
PV	Photovoltaic
PWh	Petawatt hour
t	Tonne
TWh	Terawatt hour

which if utilised will contribute towards the global net zero transition and provide clean energy for millions of households [11].

Hydrogen can play a significant role in decarbonization of Africa's predicted greenhouse gas emissions [12]. However, most of the current global hydrogen (80%) is produced through carbon intensive methane reforming and coal gasification [13]. Hydrogen can be produced through electrolysis powered by renewable electricity (green hydrogen), and it can be used as a long-term storage medium, as a fuel for heavy-duty road and rail transportation, ships, and aircraft. It can also be used in industrial processes and as a domestic energy vector for cooking and heating [13–16]. Given the size of Africa's renewable energy resource, hydrogen presents an opportunity for Africa to not only decarbonise its own energy use and enable clean energy access for all, but also to export renewable energy. Developing a hydrogen economy in Africa can generate revenue streams while creating employment, skills, and wealth [17]. Production of green hydrogen using Africa's renewable resources offers an opportunity to propel the hydrogen economy, promote economic development through industrialization, and improve Africa's resilience [18]. Long distance hydrogen export is poised to be a huge global industry to meet the energy demands of countries or regions that have limited renewable energy resources. According to the International Energy Agency's new special report Financing Clean Energy Transitions in Emerging Markets and Developing Economies (EMDEs), investment spending in EMDEs on low carbon hydrogen, transport biofuels, biogas and biomethane supply rises from around USD 2 billion today to over USD 35 billion by 2030 in the sustainable development scenario [12].

There are several studies in literature that evaluate the potential of hydrogen shown in Table 1. According to the literature examined, no study comprehensively evaluated current and projected 2050 renewable water consumption scenarios when assessing the potential of hydrogen production in respective regions/countries. The studies that consider alternative water sources for hydrogen production such as seawater desalination did not inclusively and comparatively assess water transportation, high voltage direct current or hydrogen transportation system energy consumption and costs from regions with sufficient renewable water or energy resources. For example, Timmerberg and Kaltschmitt [19] investigated the solar PV and wind hydrogen potential in north Africa and transportation costs to Europe through blending with the existing pipelines. In addition, no developing country-based study considered the energy required to electrify the population without access to clean and affordable energy when analyzing the exploitable renewable energy resources for hydrogen production.

When considering renewable hydrogen production in developing regions such as Africa, it is imperative to consider electrification of the population without access to electricity before producing hydrogen so that the UN Sustainable Development Goal 7 of clean and affordable energy for everyone can be met. In addition, a kg of hydrogen produced by electrolysis requires 6–13 kg water, while the biomass to water ratio of supercritical water gasification is 1:10 [47]. Amid fiercely growing and acute water shortages leading to public protests [48], the amount of water required for hydrogen production is about 9000 kg water per 1000 kg hydrogen [49]. Producing hydrogen sustainably requires accounting for water consumed and available water resources so that the UN Sustainable Development Goal 6 of ensuring availability and sustainable management of water and sanitation for all can be met.

The key objectives of this paper were to develop and provide a developing country-based framework for assessing exploitable renewable resources for hydrogen production which is critical in meeting the highly interlinked UN Sustainable Development Goals, and to provide a new critical analysis as to how and what role hydrogen can play in the complex African energy landscape by: (i) considering renewable hydrogen generation options in Africa and indicating the potential energy and hydrogen production levels on offer through solar, wind, concentrated solar power, biomass, hydropower, geothermal, and tidal. (ii) Evaluating the role of renewable hydrogen and its utilisation in the complex African energy landscape. (iii) considering the debate around centralised vs decentralised, and large-scale vs small-scale in the context of hydrogen storage, distribution, and transportation, and (iv) highlighting current challenges in the context of a hydrogen economy in Africa.

The next sections of this paper are arranged as follows: section 2 presents the methodology used in assessing exploitable renewable resources for hydrogen production and techno-economic considerations. Section 3 presents the feasible renewable energy and hydrogen potential, water availability, hydrogen utilisation, storage, and distribution pathways. Section 4 presents the challenges and perspectives of the hydrogen economy in Africa and COP 26 commitments, before concluding in section 5.

2. Materials and methods

In this study, the methodology comprises of exploitable renewable energy and hydrogen potential assessment, water resource assessment, and system techno-economics analysis.

2.1. Assessment of renewable energy potential

The International Renewable Energy Agency (IRENA) estimated and quantified the geographic renewable energy potential in Africa through a GIS-based approach [50]. The report established the maximum geographically constrained potential for Solar PV (Photovoltaic), Concentrated Solar Power (CSP), Wind, and Bio (sugarcane, soybean and jatropha) energy. A complete and detailed methodology, which includes exclusion zones (cities and urban areas, protected areas, water bodies, sloped areas, agriculture land, and forest areas), inclusion zones, resource availability, solar cell and wind turbine types, efficiency, conversion and spacing factors, can be accessed in the IRENA report [50].

This study builds on the IRENA established potential to carry out a refined technical analysis aimed at establishing the technical feasibility of renewable energy and hydrogen production. References for geothermal, hydro and tidal energy potentials are [51–58].

The overall renewable energy technical potential takes into consideration the electricity consumption per capita ideal for economic development (1500 kWh) [9] for the population without access to electricity [59–61], and installed capacity which can be accessed from IRENA's query tool [62]. Equation (1) shows the feasible renewable energy technical potential.

$$FREP = CUF * (GP - IC * 8760) - ECpC * PWAE \tag{1}$$

Table 1
Hydrogen Potential and Distribution Studies (CHP-compressed hydrogen pipeline, CHT-compressed hydrogen trailer, LHT-liquefied hydrogen trailer, LHP-Liquefied hydrogen pipeline, LOHC-Liquid organic hydrogen carrier, HVDC-high voltage direct current, LNG-liquefied natural gas).

Ref	Energy Mode	Hydrogen Production Type	Location	Annual Hydrogen Potential	Water Required	Distribution	Destination
[20]	Solar PV, Wind	Electrolysis	Algeria	240 kt/km^2, 210 kt/km^2	–	–	–
[21]	Biomass	Biomass Gasification	Asia	–	–	–	–
[22]	Wind	Electrolysis	South Africa	–	–	–	–
[23]	Wind, Solar PV	Electrolysis	Global	–	–	–	
[24]	Solar PV	Electrolysis	Morocco	3.3 Gt/year	–	–	–
[19]	Solar PV, Wind	Electrolysis	North Africa	9 PWh	–	Blending compressed hydrogen with existing natural gas pipelines	Europe
[25]	Solar PV	Electrolysis	Algeria	-[a]	–	–	
[26]	Solar PV	Electrolysis	Algeria	0.1 to 0.14 Nm3/m2/d	–	–	–
[27]	Solar PV, Concentrated Solar Power	Electrolysis	Morocco, Oujda	0.302 t, 0.268 t[b]	–	–	–
[28]	Solar PV	Electrolysis	Morocco	4.5 kt	–	–	–
[29]	Wind	Electrolysis	Morocco	0.6 kt	–	–	
[30]	Solar PV	Electrolysis	Iran	5.55 kg[c]	–	–	–
[31]	Solar PV, Wind	Electrolysis with desalination	Sistan and Baluchistan, Iran	40 t[d]	–	–	–
[32]	Solar PV, wind	Electrolysis with desalination	Iran Coastal Areas	31.5 t, 7.3 kg	–	–	–
[33]	Fossil, solar PV, nuclear, low carbon energy	Electrolysis with desalination	Global	–	–	–	–
[34]	Solar PV	Electrolysis	India[e]	0.0238 TW[f]	14.54 million m^2/day	–	–
[35]	Solar PV	Electrolysis	Northeast India	1.5 to 1.9 t	–	–	–
[36]	Solar PV	Electrolysis	Islamabad, Pakistan	93.3 kt/km^2	–	–	–
[37]	Solar PV, Wind Hybrid	Electrolysis	Southwest Iran	31.68 t	–	–	–
[38]	Renewable and Fossil fuels	Electrolysis, gasification	Global	–	–	–	–
[39]	Renewable Energy Technologies	Electrolysis, gasification	Global	–	–	–	–
[40]	Renewable energy	Electrolysis	–	–	–	CHP, CHT, LHT, and LOHC	–
[41]	Renewable energy	Electrolysis	Algeria	Germany	–	Liquefied hydrogen carriers, CHP, CHT, LHT, HVDC	–
[42]	Solar PV	Electrolysis[g]	Chile	–	–	Liquified ammonia shipping	Japan
[43]	Fossil fuels	-[h]	–	–	–	LNG, ammonia, and methanol shipping	–
[44]	Fossil fuels	Steam Methane reforming	Western Canada	–	–	LNG and CHP, & shipping	Eastern Canada, Asia-Pacific, Europe, and North America
[45]	Solar PV, Wind	Electrolysis	Qinghai China	–	–	CHP	Shanghai China
[46]	Fossil fuels	Steam methane reforming, coal gasification, electrolysis	USA, China	–	–	LHP and LHT	Within

[a] 21.74% of the study area in Algeria is not suitable for hydrogen production.
[b] Equal Capacity 10 kWe.
[c] 345 W solar PV panel rated power.
[d] 2 × 400 W wind turbines.
[e] Existing petroleum and ammonia production plants hydrogen demand.
[f] Electrolyzer capacity.
[g] Ammonia is produced from electrolytic hydrogen.
[h] Liquefied natural gas, ammonia, and methanol production from fossil fuel gas.

where *FREP* is the feasible renewable electricity potential (TWh), *CUF* is the capacity utilisation factor (%), *GP* is the geographic potential (Twh) from IRENA [50], *IC* is the installed capacity (TW), *EpC* is the electricity consumption per capita (kWh), and *PWAE* is the population without access to electricity.

2.2. Assessment of hydrogen potential

The feasible renewable electricity potential determined in the previous section is used to produce hydrogen through water electrolysis. The mass of hydrogen produced through electrolysis can be calculated as shown in equation (2).

$$M_{H_2} = \frac{FREP * \eta_{Electrolysis}}{LHV_{H_2}} \quad (2)$$

where M_{H_2} is the mass of hydrogen produced (kg), *FREP* is the feasible renewable electricity for hydrogen production (TWh), $\eta_{Electrolysis}$ is the electrolysis cell efficiency (%) which is in the range of 70–85% for Proton Exchange Membrane Electrolysis Cells (PEMEC) and non-external heat addition Solid Oxide Electrolysis Cells (SOEC) [49,63]. LHV_{H_2} is the lower heating value of hydrogen (33.3 kWh/kg).

The technology considered for bio-hydrogen production is

Table 2
Renewable energy, water, and hydrogen production assumptions (CUF-capacity utilisation factor).

Item	Value	Unit	Ref
Solar photovoltaic farm CUF	25	%	[71,72]
Wind farm CUF	35	%	[73]
Concentrated solar power plant CUF	65	%	[74]
Supercritical water gasification plant CUF	91	%	[47]
Hydropower plant CUF	40	%	[73]
Geothermal power plant CUF	75	%	[75]
Tidal farm CUF	35	%	[73]
Soybean straw yield	72	%	[64]
Electricity consumption per capita ideal for economic development	1500	kWh	[9]
Electrolysis cell efficiency	80	%	[63,76,77]
Supercritical water gasification soybean straw to hydrogen yield ratio (tonnes/tonnes)	17/11	–	[47]
Lower heating value of hydrogen taken as its energy content	33.3	kWh/kg	[63]
Concentrated solar power plant operating water consumption	2500	m^3/GWh	[70]
Water required for population without access to safe drinking water	100	liters/person/day	[67]
2050 water demand increment	25	%	[69]
Electrolysis water consumed to hydrogen produced ratio (kg/kg)	9:1	–	[49]
Supercritical water gasification biomass-to-water ratio (kg/kg)	1:10	–	[47]

supercritical water gasification [47] with a capacity factor of 91%, and the soybean straw yield is 72% [64]. The plant is assumed to process 170 metric tons daily of soybean straw at a biomass-to-water ratio of 1:10, operating temperature of 500 °C, biomass particle size of 0.13 mm, and a reaction time of 45 min [47]. A detailed process description is found in Ref. [47]. However, it should be emphasized that bio-hydrogen can only be considered carbon negative if the carbon is captured and stored permanently.

2.3. *Assessment of renewable water resources*

The Food and Agriculture Organization (FAO) of the United Nations defines exploitable (feasible water resources which varies between

Table 5
Techno-economic transportation assumptions for truck, liquified hydrogen trailer, and compressed hydrogen trailer, and liquified ammonia tank truck.

Parameter	Truck [40,41,89,93]	Liquefied hydrogen trailer [40,41,89]	Compressed hydrogen trailer [40,41,89]	Liquefied Ammonia Tank Truck [43,94,95]
Maximum Product Load	28,500 kg	28,500 kg	28,500 kg	36,000 kg
Average Speed	50 km/h			50 km/h
Energy Consumption	0.0875 $kg_{H_2/km}$			0.0625 $kg_{H_2/km}$
Cost	203 × 10^3 \$/$unit$	1089 × 10^3 \$/$unit$	696 × 10^3 \$/$unit$	0.3 \$ t/km
Depreciation Period (yearly)	8	10	10	15
Operation and Maintenance Factor	12%	2%	2%	5%
Payload		4500 $kg/truck$	720 $kg/truck$	
Pressure		1 bar	200 bar	1 bar
Fuel Price	1.2 \$/L			
Operating Cost	35 \$/h			
Capacity Factor	50%	50%	50%	90%

Table 3
Techno-economic transportation assumptions for water pipeline transportation, sea water desalination, high voltage direct current (HVDC), hydrogen pipeline transportation, and ammonia pipeline transportation.

Parameter	Water pipeline [79–81]	Desalination [82–85]	HVDC [83,85,86]	Compressed Hydrogen Pipeline [82,87]	Liquified Ammonia Pipeline [88]
Product Quantity × 10^6 (water, HVDC, H_2, NH_3)	754 m^3	754 m^3	6974 TWh	83,800 kg	469,444 kg
Energy Consumption	0.005 kWh/m^3km^{-1}	5 kWh/m^3		0.82 kWh/kg_{H_2}	1 MWh/km
Cost	Pipe 0.00108 \$/100 $km.m^3$ Water Treatment 2.1 \$/m^3	Pipe 0.00108 \$/100 $km.m^3$ Plant 4.01 \$/m^3	0.25 $Million$ \$/km	0.291 $Million$ \$/m	0.398 $Million$ \$/km
Losses			6.6 %/1,000km	0.5%	
Depreciation Period (yearly)	75	15	50	50	50
Operation and Maintenance Factor	1%	2, \$0.24 /$m^3{}_{Var}$	4%	4%	4%
Pressure				100 bar	20 bar
Compressor/pump stage				1 per 500km	1 per128km
Capacity Factor	50%	50%	50%	50%	90%

Table 4
Techno-economic transportation assumptions for hydrogen liquefication, liquefied hydrogen release, hydrogen compression, and ammonia synthesis.

Parameter	Hydrogen Liquification [40,41,89]	Liquified Hydrogen Release [40,41,89]	Hydrogen Compression [40,41,89]	Ammonia Synthesis [63,83,90]
Energy Consumption	6.78 kWh/kg_{H_2}	0.6 kWh/kg_{H_2}	1.1 kWh/kg_{H_2}	8.21 (1.16 Haber Bosch) kWh/kg_{NH_3}
Cost	11,521 \$/$unit$	5444 \$/$unit$	8989 \$/$unit$	0.8 \$/kg_{NH_3} 400Mt
Losses	1.65%			
Depreciation Period (yearly)	20	10	7	30
Operation and Maintenance Factor	8%	4%	4%	5%
Scaling Factor	0.66	1		
Pressure	1 bar	1 bar	200 bar	112 bar
Capacity Factor	50%	50%	50%	90%

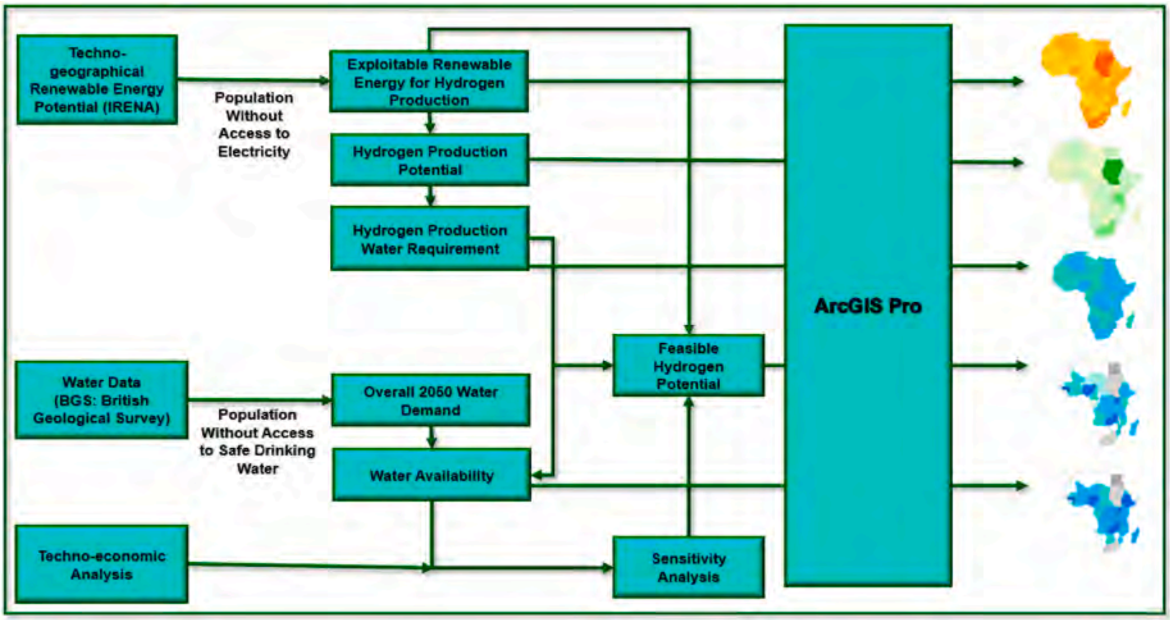

Fig. 1. Methodological flowchart for renewable hydrogen resources and hydrogen production.

Table 6
Techno-economic transportation assumptions for water, liquefied hydrogen, compressed hydrogen, and liquefied ammonia storage tanks.

Parameter	Water Storage Tank [96]	Liquified Hydrogen Storage Tank [82,97,98]	Compressed Hydrogen Storage Tank [99]	Liquified Ammonia Storage Tank [43,83,90]
Cost	79.68 $/$kg_{H_2O}$	32 $/$kg_{H_2}$	466 $/$kg_{H_2}$	0.79 $/$kg_{NH_3}$
Losses		0.2%	0%	0.024%
Depreciation Period (yearly)	30	20	20	30
Operation and Maintenance Factor	1%	4%	4%	4% $_{fixed}$, 0.001% $_{var}$
Scaling Factor		1	1	
Pressure	1 bar	1 bar	200 bar	1 bar
Capacity Factor	50%	50%	50%	90%

countries) as the water resources obtainable for growth by considering economic and environmental feasibilities of accessing groundwater, artificial storage of floodwater and water that flows to the sea, and minimum flow conditions for supporting aquatic life, navigation and environmental requirements [65]. The British Geological Survey [66] has a robust data base on water availability in Africa that considers all these mentioned factors. The water available for hydrogen production in this study takes into consideration the water required for the:

(a) population without access to safe drinking water (the UN requirement is 50–100 L/person/day [67] and upper limit was used in this study),
(b) extra growing population estimated to be 2.5 billion in 2050 [68],
(c) growing industrial, municipal, agricultural, and irrigation water demand estimated to increase by 20%–30% in 2050 [69] (25% water demand is assumed in this study),
(d) CSP operating water consumption 2500 m^3/GWh [70].

Table 2 summarises the key technological and economic assumptions used in this study to evaluate renewable energy potential, hydrogen potential, and water availability.

2.4. Techno-economic considerations

The total system costs (TSC) are calculated by equation (3) where CI is the capital investment, CRF is the capital recovery factor, OM is the fixed operation and maintenance cost, Var is the variable operation and maintenance cost, EP is the electricity price, and the hydrogen output is the system output hydrogen in kg. Interest rate and electricity price are 6% and 0.05 $/kWh.

$$TSC = \frac{\frac{CI \times CRF + OM}{Annual\ \ Operation\ \ Hours} + Var_{OM} + EP}{Hydrogen\ \ Output} \quad (3)$$

Yearly cost indices and location factors are used to give better estimates of African costs to the reference year 2022. Table 3, Table 4, Table 5, and Table 6 show the techno-economic assumptions of water transportation, high voltage direct current (HVDC), hydrogen transport, and seawater desalination. The water pipeline, seawater desalination, compressed hydrogen tank truck, liquefied hydrogen tank truck, and liquefied ammonia tank truck and pipeline systems were assumed to have two storage tanks at source and destination to stabilise the variations during production and/or consumption. The compressed hydrogen pipeline system was assumed to have one storage tank at destination because the pipeline was configured for the highest attainable mass flow rate [78]. The HVDC required only one hydrogen storage tank at destination without the need of storing the electricity at source in batteries because it is assumed to be continuously consumed at destination. Moreover, it is assumed to be connected through an HVDC super grid.

2.5. Methodological description

After modelling the hydrogen potential described in section 2.1and 2.2, the next step was to assess its feasibility through water availability assessment described in 2.3. The hydrogen potential was feasible if the water required was lower than the total exploitable renewable water resources. The data was analysed and visualised in ArcGIS Pro version 2.4.0 and the shape files were downloaded from Ref. [91]. ArcGIS Pro is a data-driven GIS application that supports data visualisation and advanced analysis [92]. To understand the effect of hydrogen production on water availability, a sensitivity analysis based on exploitable

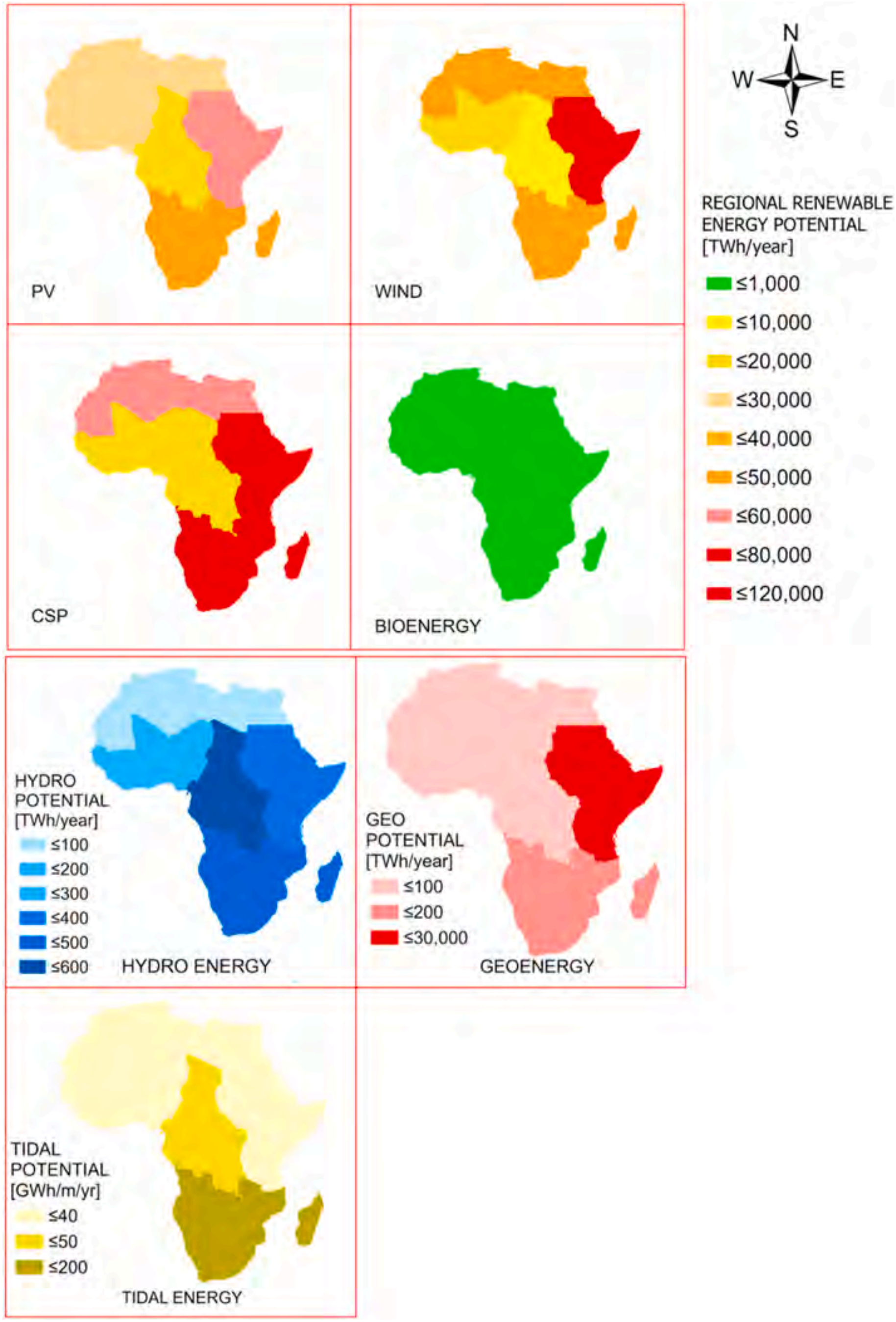

Fig. 2. Regional-level feasible renewable potential energy (PV-photovoltaic, CSP-concentrated solar power).

renewable electricity potential and overall water available after hydrogen production was carried out in section 3.4. The countries were selected based on country level water availability scenarios and water available after hydrogen production to understand the effect of renewable hydrogen production on water availability. The exploitable renewable electricity was varied from 10 to 100% hydrogen generation..

A techno-economic comparative analysis between water pipeline transportation, seawater desalination, HVDC transmission, liquefied and compressed hydrogen truck, and compressed hydrogen pipeline transportation, liquefied ammonia truck and pipeline system energy consumption and costs was carried out using the techno-economic assumptions in Table 3, Table 4, Table 5, and Table 6. Hydrogen is assumed to be produced at the same price ($/kg) between Tamanrasset in Algeria and Abuja in Nigeria due to similar location factors between north and west Africa. The amount of water transported or desalinated is equivalent to the required electricity for hydrogen production for HVDC, and equal to the hydrogen or ammonia transported for a given renewable electricity exploitable potential and 1500 km equal and straight-line distances between Tamanrasset and the Mediterranean Sea, and Tamanrasset and Abuja. The effect of varying renewable exploitable electricity generation and distance on system costs and energy consumption was assessed through a sensitivity analysis in section 3.5.3.2. The methodology is summarised in Fig. 1.

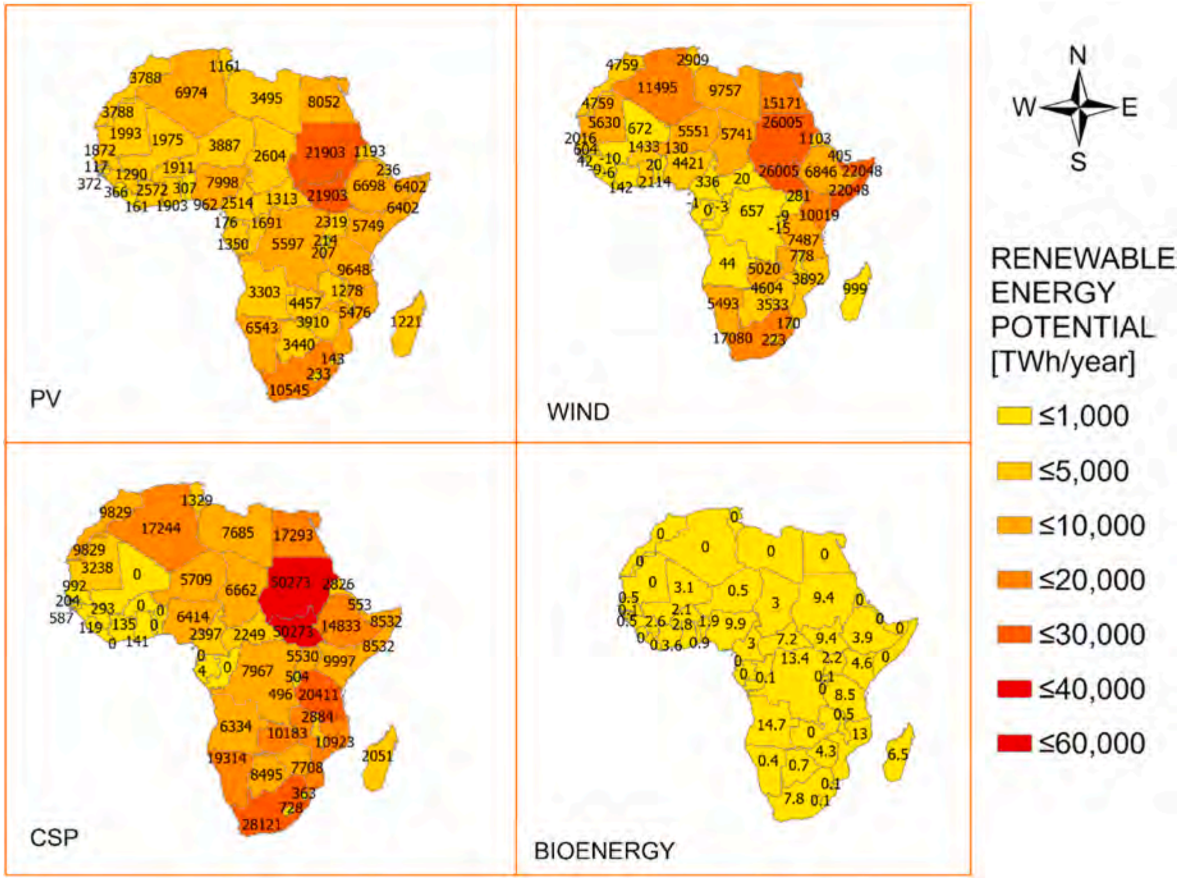

Fig. 3. Country-level feasible renewable potential energy (PV-photovoltaic, CSP-concentrated solar power).

3. Results and discussion

3.1. Feasible renewable energy potential

Fig. 2 shows the regional-level renewable energy potentials for solar photovoltaic, concentrated solar power (CSP), wind, bio energy, hydropower, geothermal, and tidal energy. East Africa has higher regional cumulative solar PV potential with 54,870 TWh/year followed by south with 40,705 TWh/year, comparable north and west Africa from 25,473 to 25,938 TWh/year potentials, and central Africa has the lowest potential with 15,411 TWh/year. Interestingly, south and east Africa have comparable CSP potentials from 112,209 to 114,254 TWh/year followed by north Africa which is significantly lower with 56,627 TWh/year, and comparable west and central Africa with 17,060 to 19,440 TWh/year potentials. East Africa has significantly higher wind potential with 74,740 TWh/year, followed by comparable south and north Africa from 41,984 to 49,735 TWh/year potentials, west Africa with 17,362 TWh/year, and central Africa with 6914 TWh/year.

Hydro, geothermal and tidal energy cumulative potentials shown in Fig. 2 do not account for energy required to electrify the population without access to electricity and are not considered in hydrogen production due to their lower potentials compared to solar PV, CSP and wind energy potentials. These renewable energy technologies are also highly suitable for base load power generation. Central Africa has higher hydro energy potential with 570 TWh/year followed by south with 416 TWh/year, east with 335 TWh/year, west with 101 TWh/year, and north Africa with 60 TWh/year. East Africa has higher geothermal energy potential with 27,150 TWh/year followed by south with 120 TWh/year, and comparable central, west and north Africa potentials. The regional tidal energy potentials are for countries that are bordered by oceans, and for these, south ocean-bordered countries have higher potential with 107 GWh/m/year followed by central with 46 GWh/m/year, and comparable lower potentials for north, east, and west ocean-bordered with 31 GWh/m/year.

Fig. 3 shows the country-level renewable energy potentials for solar photovoltaic, concentrated solar power (CSP), wind, and bio energy. The results outline that Africa has solar PV, Wind, and CSP exploitable potential for hydrogen production ranging from 100 TWh/year to 22,000 TWh/year, 20 TWh/year to 26,000 TWh/year, and 4 TWh/year to 50,300 TWh/year respectively. This potential accounts for the capacity utilisation factor, geographic potential, installed capacity, energy consumption per capita, and energy required to electrify the population without access to electricity. Sudan has the highest technically feasible solar PV potential with 21,903 TWh/year followed by South Africa with 10,545 TWh/year while Gambia has the lowest technically-feasible potential with 117 TWh/year. The potential of most countries lies between 1000 TWh/year and 11,000 TWh/year with very few countries below 1000 TWh/year due to their lower exploitable areas.

Sudan has the highest wind energy potential with 26,005 TWh/year followed by Somalia with 22,048 TWh/year, while Togo has the lowest potential with 20 TWh/year. Gambia does not have the technical feasibility to produce wind electricity, and this is indicated by 0. Countries that do not have sufficient wind energy potential to meet the energy demands of the population without access to electricity are indicated by negative values and these include Guinea, Sierra Leone, Liberia, Equatorial Guinea, Republic of the Congo, Rwanda, and Burundi. Besides these countries and a few ranging below 1000 TWh/year, most countries have wind energy potentials ranging above 1000 TWh/year to 26,005 TWh/year. The data in Fig. 3 and subsequent figures is provided in the supplementary file.

Under CSP, the exploitable potential for hydrogen production is highest for Sudan with 50,273 TWh/year followed by South Africa with

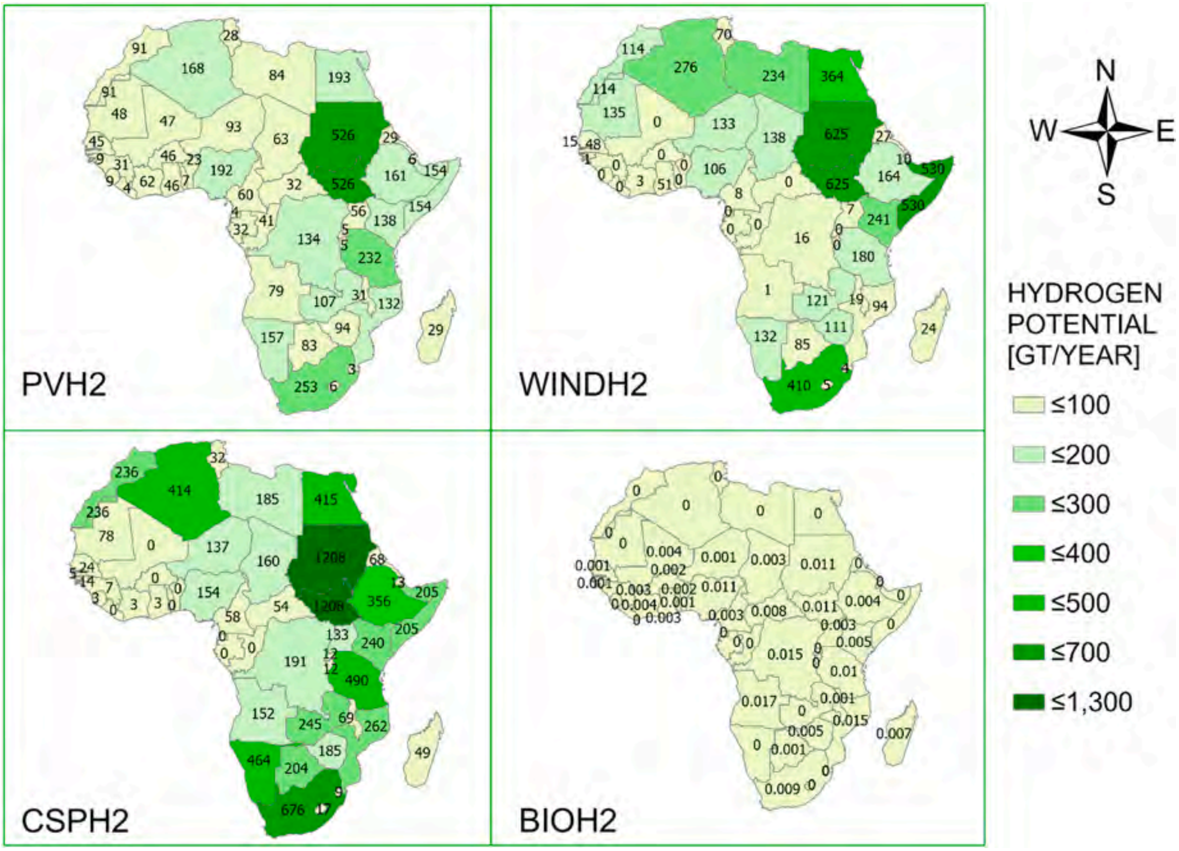

Fig. 4. Country-level feasible renewable hydrogen potential (PVH2-solar photovoltaic hydrogen, CSPH2-concentrated solar power hydrogen, WINDH2-wind hydrogen, BIOH2-biohydrogen).

28,121 TWh/year, while Gabon has lowest potential with 4 TWh/year. Mali, Burkina Faso, Liberia, Togo, Benin, Equatorial Guinea, and Republic of the Congo do not have the technical feasibility to produce CSP electricity. The potential of most countries lies above 2000 TWh/year with very few countries below 500 TWh/year due to their lower exploitable areas.

The bioenergy potential for rainfed soybean straw in Africa is generally very low compared to solar PV, CSP and wind energy with the highest potential being only 14.7 TWh/year. It is 0 in northern African countries due to the inherent dry conditions, and it is also 0 for a few countries such as Zambia and this is largely due to the type of rainfed crop in this study. Only rainfed soybean bioenergy is considered in this study and its potential did not account for energy required to electrify the population without access to electricity due to its low yield. Other crop residues and wastes such as maize, rice, sorghum, and millet straws were not considered in this study. However, IRENA [50] gives a comprehensive outlook of rainfed and irrigated sugarcane, and rainfed jatropha which can be converted to hydrogen through sugarcane-based ethanol steam reforming [100,101] or jatropha hydrothermal gasification [102] but these are not considered in this study due to lack of information and uncertainties of hydrogen conversion processes. Nonetheless, the total African potential of sugarcane-based bioethanol and jatropha yield is over 2.5 mega tonnes [50].

3.2. Feasible renewable hydrogen potential

Fig. 4 shows the country level technically feasible renewable hydrogen potentials in Africa produced through water electrolysis from exploitable solar PV, wind, CSP electricity, and soybean straw gasification with maximum values of 526 Gt/year, 625 Gt/year 1208 Gt/year, and 0.01 Gt/year respectively. Sudan has the highest solar PV hydrogen potential of 526 Gt/year followed by Tanzania and South Africa with comparable 232 to 253 Gt/year 11 countries scattered across the continent have similar hydrogen potentials ranging from 107 to 193 Gt/year while the rest have hydrogen potentials ranging from 3 to 94 Gt/year. Under wind hydrogen, Sudan stands out with 625 Gt/year followed by Somalia with 530 Gt/year, South Africa with 410, and the lowest potentials in Angola and Guinea Bissau with 1 Gt/year. Unlike solar PV hydrogen potential that is evenly distributed across the continent, wind hydrogen potential is concentrated in northern, eastern, and southern African regions ranging from 114 Gt/year, 364 Gt/year, 625 Gt/year and 410 Gt/year respectively. Most countries have CSP hydrogen potentials ranging from 137 to 1208 Gt/year while significantly few countries range from 3 to 78 Gt/year with most of these countries located in West and Central Africa. Hydrogen produced through rainfed soybean straw gasification has the lowest potential with Angola having the greatest potential of 0.017 Gt/year.

Fig. 5 shows the cumulative regional-level feasible renewable hydrogen produced through solar photovoltaic, concentrated solar, and wind electricity, and soybean straw gasification. East Africa tops solar PV hydrogen with 1311 Gt/year followed by south with 974 Gt/year, north and west with similar potentials from 612 to 617 Gt/year, and central Africa with significantly lower hydrogen potential of 366 Gt/year. Wind hydrogen potential is highest in east Africa with 1782 Gt/year followed by south and north with comparable potentials of 1005 to 1194 Gt/year, and notably lower wind hydrogen potentials in west and central of 357 Gt/year and 162 Gt/year respectively. CSP hydrogen potential is comparable in south and east Africa from 2333 to 2738 Gt/year followed by north with 1360 Gt/year, and remarkably lower west and central Africa with 351–463 Gt/year. Apart from north Africa where rainfed soybean straw is not feasible, the rest of the regions have similar cumulative bio hydrogen potentials ranging from 0.03 to 0.06 Gt/year.

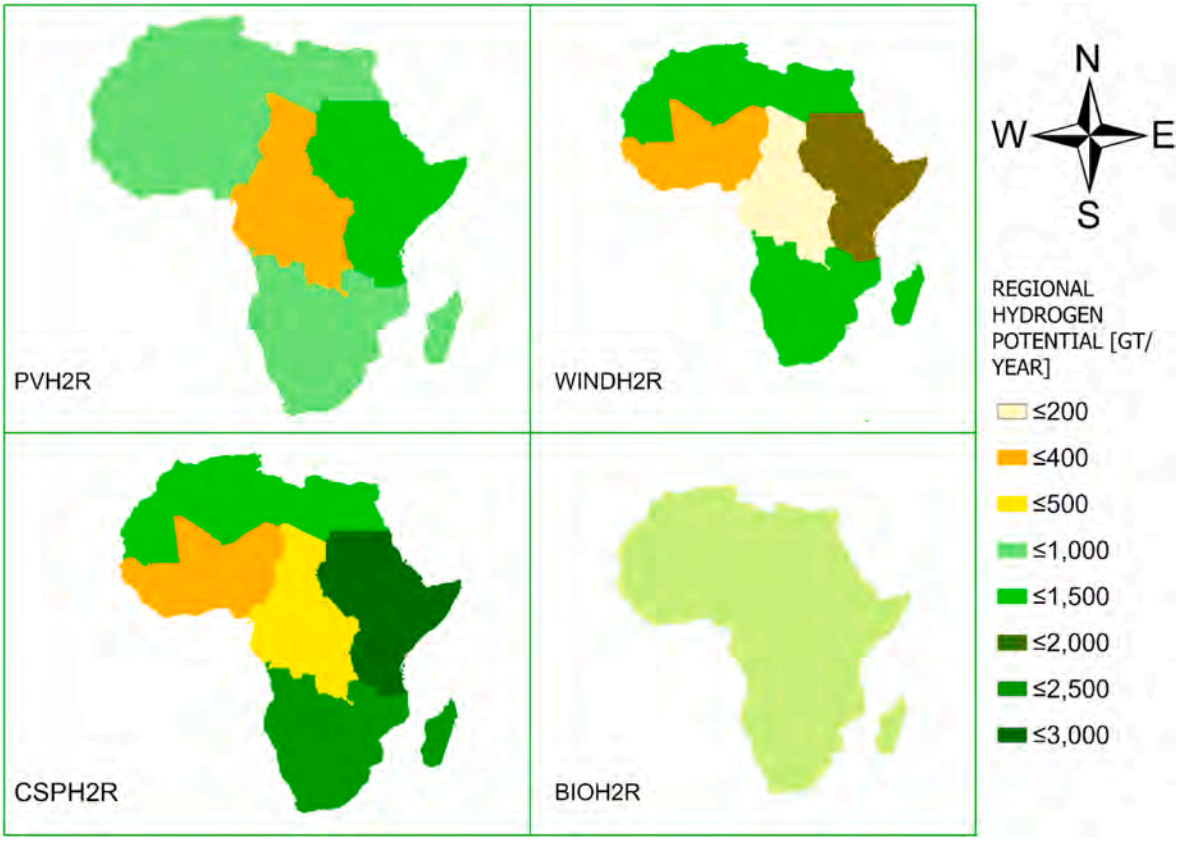

Fig. 5. Regional-level feasible renewable hydrogen potential (PVH2-regional solar photovoltaic hydrogen, CSPH2-regional concentrated solar power hydrogen, WINDH2-regional wind hydrogen, BIOH2-regional biohydrogen).

Country-level feasible renewable hydrogen per exploitable/available land area is shown in Fig. 6. Hydrogen produced per available land area shows substantial normalisation for solar PV hydrogen ranging from 0.21 to 0.27 Mt/km^2/year but these low numbers mean that more available/exploitable area is used per Gt hydrogen or TWh electricity produced. Algeria has solar PV hydrogen potential per exploitable area of 0.22 Mt/km^2/year which is similar to the results of Rahmouni et al. [20], with a slightly higher total annual production of 0.24 Mt/km^2/year. Contrastingly, the total annual solar PV potential for Algeria ranged from 259 to 369 GWh/km^2/year while it is smaller in this study, 9 GWh/km^2/year, because it considers the entire cumulative exploitable area. The annual wind hydrogen potential of Rahmouni et al. [20], is 0.21 Mt/km^2/year while it is 0.4 Mt/km^2/year in this study which might be due to the different wind energy methodologies applied. This study applied the detailed IRENA [50] methodology of calculating capacity factors relative to wind speed categories using the standard Rayleigh distribution method. Touili et al. [24] estimated the total potential of hydrogen production in Morocco to be around 3.3 Gt/year while this study potential is 91 Gt/year due to the limiting average Moroccan Global Horizontal Irradiation (GHI) used in the former study, whereas this study uses a cumulative and comprehensive area specific GHI coupled with the total exploitable area and spacing factors [50]. This is also observed through the difference between hydrogen production per available area between the two studies i.e., 0.25 Mt/km^2/year (this study) and 2.4 kt/km^2/year ([24]). Gambia and Ghana have the highest hydrogen potential per available area of 3.34 and 3.32 Mt/km^2/year which means that less exploitable area is used per Gt hydrogen produced. CSP hydrogen poses significant land uptake in West Africa with values as low as 0.01 Mt/km^2/year. However, the rest of the countries have higher values compared to solar PV from 0.23 to 0.84 Mt/km^2/year in Cameroon and Lesotho respectively. Wind hydrogen has better overall available area utilisation with values as high as 0.89, 3.32 and 3.34 Mt/km^2/year for Somalia, Ghana, and Senegal respectively. Bio hydrogen produced per available area is uniform at 0.05 Mt/kmˆ2/year across all countries with the exception of North Africa countries.

3.3. Hydrogen production and water availability

Water required for hydrogen production is directly proportional to the feasible exploitable renewable energy and subsequent hydrogen produced. The water required for CSP hydrogen is significantly higher due to the extra CSP operation water and this is depicted in Fig. 7 where CSP hydrogen production in Sudan requires 136,553 million m^3/year. The highest water requirements for solar PV, wind and bio hydrogen production are 4736 million m^3/year, 5623 million m^3/year, and 0.15 million m^3/year respectively. Overall water requirement for wind hydrogen is fractionally higher than solar PV hydrogen, and significantly higher than bio hydrogen as per hydrogen potential.

Fig. 8 shows the sustainable and business-as-usual 2050 water scenarios against the exploitable renewable water resources. The business-as-usual scenario only considers the total industrial, municipal, agricultural and irrigation water demand in 2050 while the sustainable scenario considers the former plus water required for the population without access to safe drinking water and water required for the forecasted extra population in 2050. All North African countries as well as Mauritania, Sierra Leone, Sudan, Somalia, Zimbabwe, Eswatini, and South Africa have a renewable water deficit in a business-as-usual 2050 scenario with Egypt having the highest magnitude of −104,188 million m^3/year which increases to −111,516 million m^3/year in sustainable 2050 scenario. Namibia, Senegal, and Guinea Bissau fall into a renewable water deficit under a sustainable 2050 water scenario.

The country level water available after hydrogen production under the assumption that all the solar PV, wind, CSP and bio exploitable

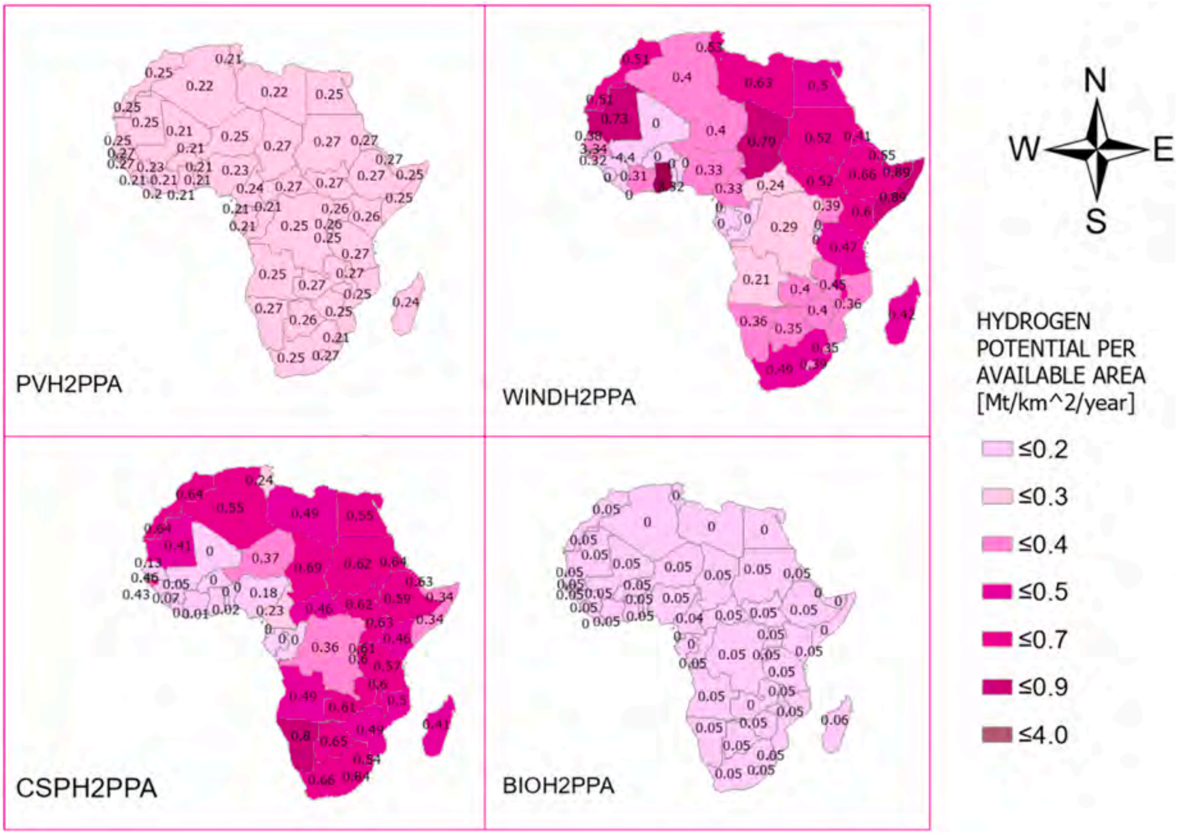

Fig. 6. Country-level feasible renewable hydrogen per available area (PVH2PPA-solar photovoltaic hydrogen per available area, CSPH2PPA-concentrated solar power hydrogen per available area, WINDH2PPA-wind hydrogen per available area).

potential energy is used for hydrogen production is shown in Fig. 9. In addition to the countries that have renewable water deficits, Malawi, Zimbabwe, and Botswana have deficits under solar PV and wind hydrogen sustainable 2050 scenarios. Gabon only has a deficit of −175 million m^3/year under the solar PV hydrogen sustainable scenario. The wind hydrogen potential of Chad is substantially higher than its solar PV potential and this is observed through the water deficit under wind hydrogen sustainable 2050 scenario. Intriguingly, most West African countries as well as Equatorial Guinea, Gabon, Republic of the Congo, Burundi, Rwanda, Uganda, Zambia, and Madagascar, and excluding Niger and countries that already have deficits would sustainably produce CSP hydrogen. Bio hydrogen has negligible impact on renewable water availability due to its lower production scale.

The cumulative renewable water available after maximum feasible hydrogen production is shown in Fig. 10. Only north Africa has a renewable water deficit for solar PV, wind, and bio hydrogen production. Under CSP hydrogen production, only west Africa has renewable water available due to the region's significantly lower CSP electricity and hydrogen potential. These regional water availability results after hydrogen production offer potential solutions to the renewable water deficit problems faced by some countries. For example, renewable freshwater trade could be one of the potential solutions from the west, central and east Africa to north Africa. Similarly countries such as Zambia which have enormous exploitable water resources could export it to other southern African countries. Renewable freshwater trade is poised to be a lucrative business in this regard due to the growing hydrogen economy coupled with unsustainably high freshwater abstraction rates in some countries. A comparative analysis of renewable water export and other possible solutions for this renewable water deficit crisis will be discussed in the next section 3.5.3.

3.4. Renewable energy, hydrogen and water availability sensitivity analysis

A sensitivity analysis based on exploitable renewable electricity potential and overall water available after hydrogen production is shown in Fig. 11. These countries (Botswana, Chad, Gabon, Malawi, and Namibia) were selected because they indicated water shortages at 100% renewable hydrogen production. The water available after solar PV and wind hydrogen production in Botswana reduces steadily from 450 million cubic meters/year at 10% renewable hydrogen production to −250 million cubic meters/year at 100% (maximum) renewable hydrogen potential. The cross over to a deficit in water availability occurs around 70% renewable electricity generation implying that hydrogen can be sustainably produced below 70% renewable electricity potential. Similarly, Gabon, Chad, and Malawi can sustainably produce solar PV and wind hydrogen below 40%, 75% and 10% respectively.

Fig. 12 shows how the water available after hydrogen production varies for countries such as Algeria that already have water deficits in the sustainable 2050 water scenario, and countries such as Kenya, Ethiopia, Nigeria, and Democratic Republic of Congo with enormous renewable water. The sensitivity results also show the direction countries can make in their hydrogen and renewable energy strategies in terms of exploitable renewable energy potential and water availability. For example, countries such as Kenya, Ethiopia, Democratic Republic of Congo, Angola, Lesotho, Mozambique, Tanzania, Eritrea, Central African Republic, Chad, Niger, Senegal, Gabon, and Sierra Leone cannot sustainably produce hydrogen through their exploitable CSP electricity from 10 to 100% thus should focus on solar PV and wind hydrogen production. Nigeria, Guinea, Ghana, Zambia, Burundi, Rwanda, Uganda, Madagascar, Gabon, Equatorial Guinea, and Ivory Coast can sustainably produce hydrogen at any percentage of CSP electricity generation. Utilising the trade-off between renewable electricity

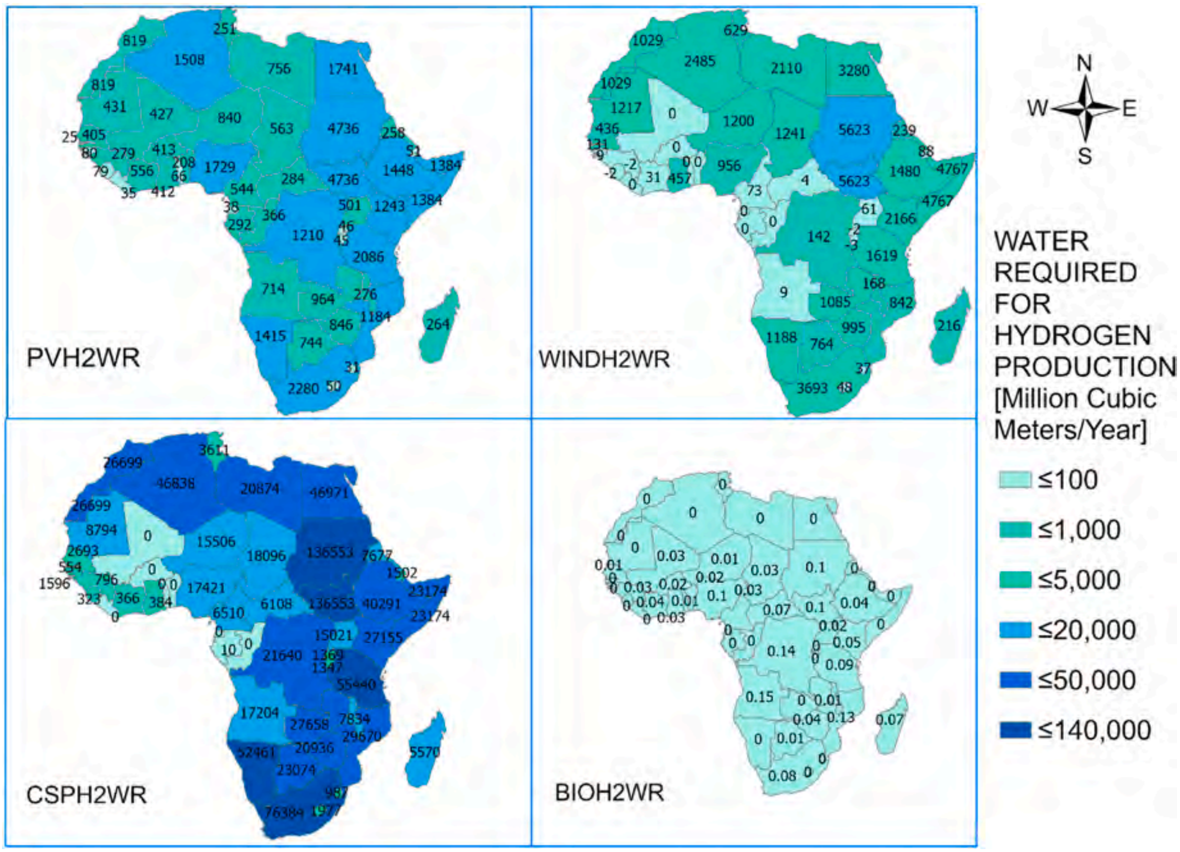

Fig. 7. Country-level water required for hydrogen production (PV2WR-solar photovoltaic hydrogen water required, CSP2WR-concentrated solar power hydrogen water required, WINDH2WR-wind hydrogen water required, BIOH2WR-biohydrogen water required).

generation, hydrogen production and renewable water resource availability will play an important role by providing stakeholders with key information during development of country specific renewable hydrogen strategies and targets.

3.5. Hydrogen utilisation, storage, and distribution

The role of renewable hydrogen and its utilisation in the complex African energy landscape is evaluated in this section, and the debate around centralised vs decentralised, and large-scale vs small-scale in the context of hydrogen, storage, distribution pathways, and transportation is considered using techno-economic and sensitivity analysis.

3.5.1. Hydrogen utilisation

Short and long-term export of renewable energy through green hydrogen to regions that do not have sufficient renewable energy resources will be indispensable in propelling Africa's hydrogen economy, and the global hydrogen economy intrinsically. Highly advanced economies such as Germany set hydrogen importing targets as high as 96 TWh and the European Union approved a €900 million German scheme to support investments in renewable hydrogen production [103]. Developed countries such as Australia and New Zealand are already positioning themselves towards tapping this potential hydrogen market by exporting to these renewable resource-limited countries such as Japan. But countries that will be able to produce renewable hydrogen competitively will exploit this market more than other countries that will not have a competitive advantage, and African countries are distinctly positioned in this regard.

The ammonia market is poised to be one of the earliest and large-scale international and local markets for renewable hydrogen adoption. Green hydrogen can be converted into ammonia using the Haber Bosch process [104,105], a century old commercial technology. This ammonia can be used to produce fertilizer and ammonia nitrate fuels used in mining, a core industry in African countries [106]. Large-scale local fertilizer production will be key in meeting the food demands of Africa's fastest growing population. Specifically, a continental nitrogen consumption of 181 kg nitrogen/ha/year from the current 35 kg nitrogen/ha/year should be met by 2050 to have a self-supporting food environment [106–110]. Currently, only few African countries including Algeria, Morocco, Nigeria, Tunisia, Egypt, South Africa, and Nigeria produce fertilizers on a large scale [106]. Regional fertilizer production backed by renewable hydrogen potential and water availability is very promising due to the existing and growing local fertilizer market that remains untapped. Hydrogen partnerships will have to be backed by regional and international partnerships to unleash the maximum potential.

Aviation and road transport sectors will also be impactful as they will consequentially transition to renewable hydrogen and a percent of electric vehicles through Africa's passive user technology status. For instance, hydrogen-based airplanes and vehicles will eventually be utilised in Africa when advanced economies such as the UK stop manufacturing combustion engines [111]. Hydrogen storage for grid load balancing can also play a role in hydrogen utilisation. The existing local markets such as mining, cement, and steel industries can also facilitate internal uptake of renewable hydrogen through the replacement of fossil fuels in their processes with green hydrogen.

Renewable hydrogen for domestic cooking can also play a crucial role in decarbonizing the heavily carbonized African traditional cooking system. The market for clean cooking is already present [112], but penetration will require the development of the right hydrogen business, social and techno-economic models. To put this into perspective, the average African (Zambian) domestic monthly expenditure on charcoal

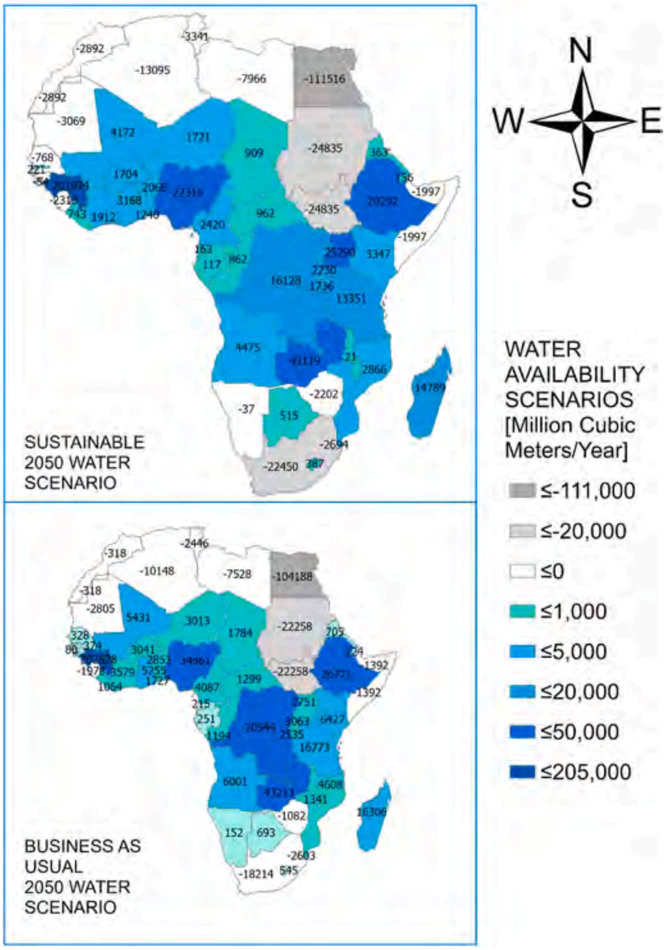

Fig. 8. Country-level water availability scenarios (renewable water minus business-as-usual and sustainable 2050 water demand).

for cooking (average of 4 bags) is £44 per month [113,114], which is comparable with the average UK domestic monthly expenditure on gas for heating and cooking, £46.42 per month in 2020 and £47.92 per month in 2021 [115].

3.5.2. Hydrogen storage

Hydrogen storage technologies are highly dependent on associated energy consumption and economic costs. Ammonia as a hydrogen carrier can be suitable for long distance hydrogen transport due to its low energy consumption and system costs. But it may have to be decomposed into hydrogen and nitrogen depending on the end usage. In addition, ammonia is attractive as a hydrogen carrier because it can help to meet local African fertilizer production needs and energy needs while producing ammonia for export.

Internal hydrogen consumption in industries such as the transportation and domestic energy sectors dictate the hydrogen storage through the purity required in proton exchange membranes or domestic cooking applications. Hydrogen could be transported as compressed or liquified hydrogen via pipelines, high pressure tank trucks or liquified tank trucks. However, most African countries do not have pipeline infrastructure that can be integrated and repurposed for compressed hydrogen pipeline transport thus initial costs for pipeline transport will be considerably higher than other technologies. However, pressurized natural gas cylinders are currently widely used for cooking and this could be leveraged.

3.5.3. Hydrogen distribution pathways, techno-economics, and sensitivity analysis

3.5.3.1. Distribution pathways and techno-economic analysis. Exploitable renewable water resources are crucial towards development of a feasible hydrogen economy. Section 3.3 revealed that some African countries are facing severe water stress due to unsustainable water utilisation levels, and other countries will have similar water crises in business-as-usual and sustainable 2050 water scenarios. The water crisis currently faced by some countries will be exacerbated by hydrogen production unless regional and interregional water transportation systems are developed. Another possible solution could be transmitting renewable electricity through high voltage direct current (HVDC) from regions and/or countries without exploitable renewable water to regions with sufficient exploitable renewable water resources for hydrogen production through partnerships. Such partnerships would also lead to creation of an African super grid which is critical in integration of intermittent renewable energy resources by reducing electricity generation costs and improving grid reliability, availability, and flexibility.

A further alternative solution would be importation of hydrogen by countries that cannot produce hydrogen due to limited renewable hydrogen resources, but this solution would place a recipient country in a disadvantaged position in terms of economic development unless synergistic and strategic partnerships are agreed such as sole ammonia production in respective hydrogen importing countries and/or regions and exported to hydrogen producing regions and/or countries, and vice versa. These transportation pathways and scenarios are sketched in Fig. 13 and Fig. 14 respectively. A detailed description of the scenarios can be obtained in Appendix. A consideration for countries with renewable water deficits such as Algeria, Egypt, Libya, and Sudan [116], but with vast natural gas reserves could consider blue hydrogen i.e., steam methane reforming or methane cracking with carbon capture and sequestration. These could be utilised as transition technologies towards full abatement with the added advantage of monetizing natural gas resources [117]. However, this option would have to be thoroughly examined because the assets could suffer from premature write-downs due to green hydrogen cost reduction, tight global environmental policies and hydrogen certifications [117], and lack of funding for new oil and gas projects [91].

Table 7 and Table 8 show the results of a techno-economic comparison between water pipeline transportation, seawater desalination, HVDC transmission, liquified and compressed hydrogen truck, and compressed hydrogen pipeline transportation, liquified ammonia truck and pipeline system energy consumption and costs at 50% solar PV exploitable potential. To put this into context, 50% of Algeria's exploitable solar PV electricity generation is 15 times the size of China's current solar PV electricity generation.

Interestingly, electricity transmission for hydrogen production via HVDC offers the most energetically effective and lowest overall energy consumption with 93 TWh followed by compressed hydrogen truck, water pipeline, desalination, compressed hydrogen pipeline, liquefied ammonia tank truck, liquefied ammonia pipeline, and liquefied hydrogen with 619 TWh. To put this into perspective, HVDC is more energetically efficient than water pipeline transportation which consumes 6 TWh compared to just 0.7 TWh for HVDC. Hydrogen compression energy consumption is similar for HVDC, water pipeline transportation, seawater desalination, compressed hydrogen pipeline and truck systems, and it is the highest energy consumption element in these systems e.g., compressed hydrogen tank truck system energy consumption is comprised of truck energy consumption with 2 TWh and hydrogen compression with 92 TWh.

The energy consumption of these systems can be significantly higher if the hydrogen is liquefied and not compressed. Compressed hydrogen pipeline transportation energy consumption is substantially higher in these systems with 206 TWh (which is higher than liquified ammonia

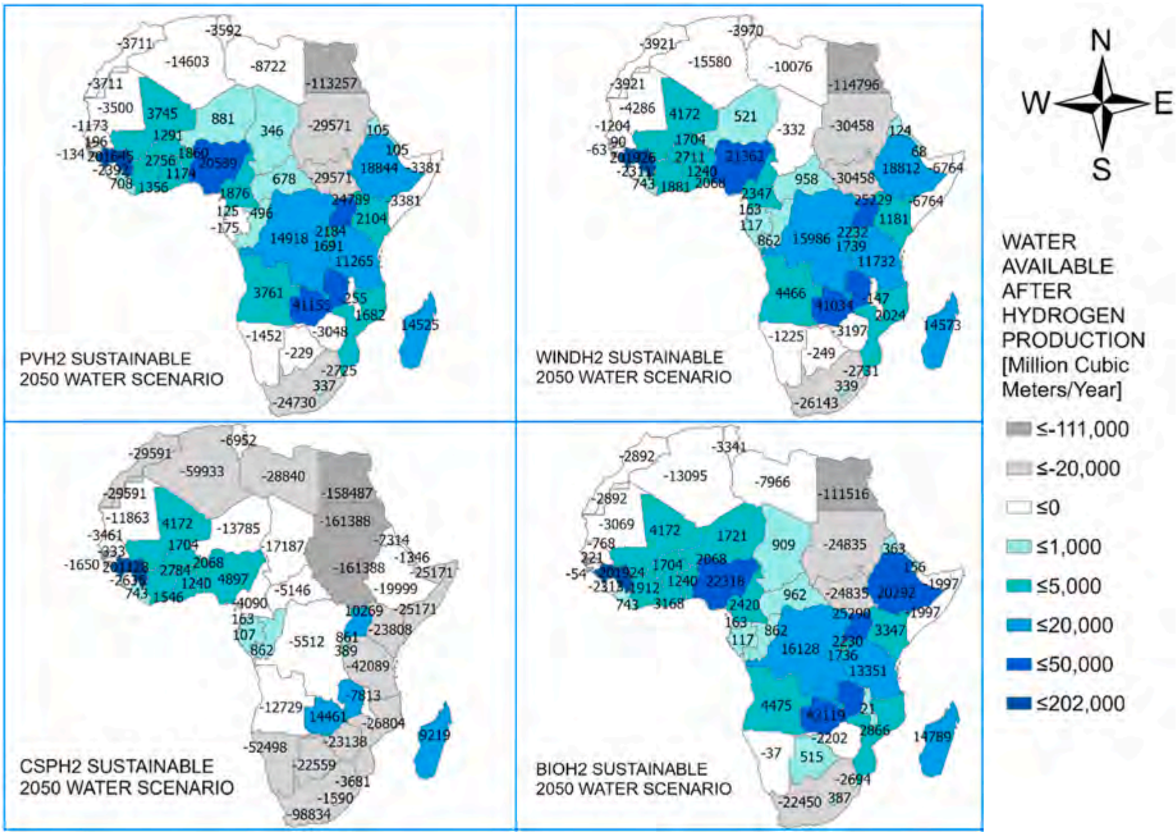

Fig. 9. Country-level water available after hydrogen production (PVH2-solar photovoltaic hydrogen, CSPH2-concentrated solar power hydrogen, WINDH2-wind hydrogen, BIOH2-biohydrogen).

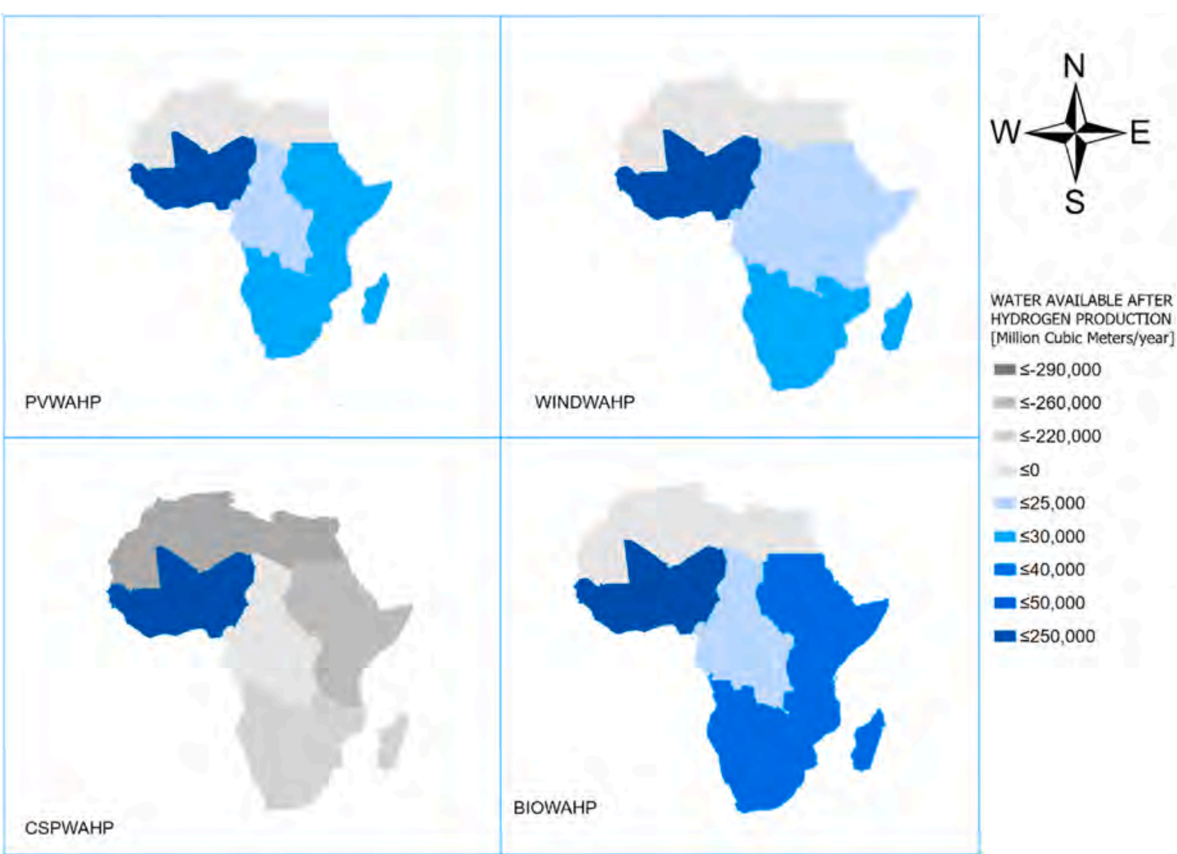

Fig. 10. Regional water available after hydrogen production (PVWAHP-solar photovoltaic water available after hydrogen production, CSPWAHP-concentrated solar power water available after hydrogen production, WINDWAHP-wind water available after hydrogen production, BIOWAHP-biohydrogen water available after hydrogen production).

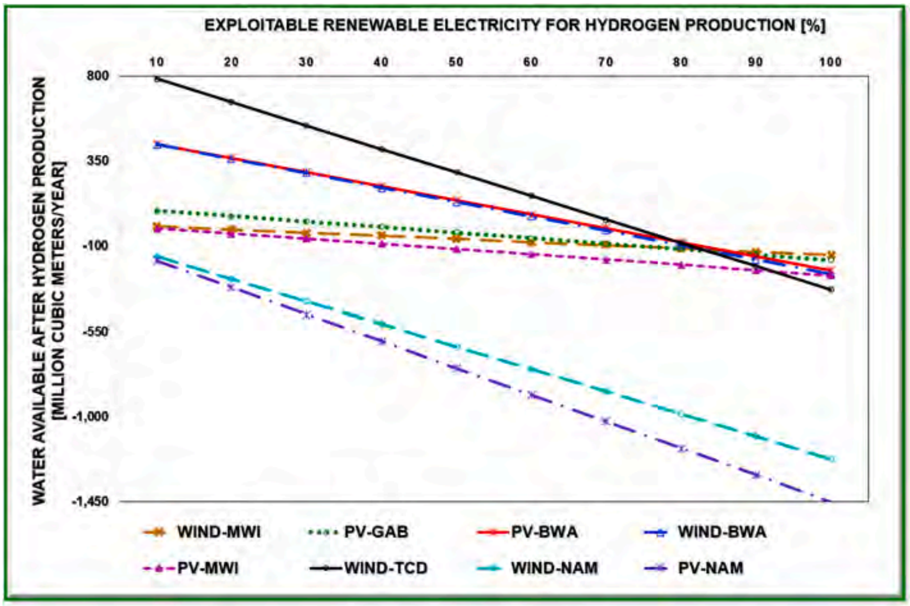

Fig. 11. Sensitivity analysis of exploitable renewable electricity for hydrogen production and water available after hydrogen production (BWA-Botswana, TCD-Chad, GAB-Gabon, MWI-Malawi, NAM-Namibia, PV-solar photovoltaic, CSP-concentrated solar power).

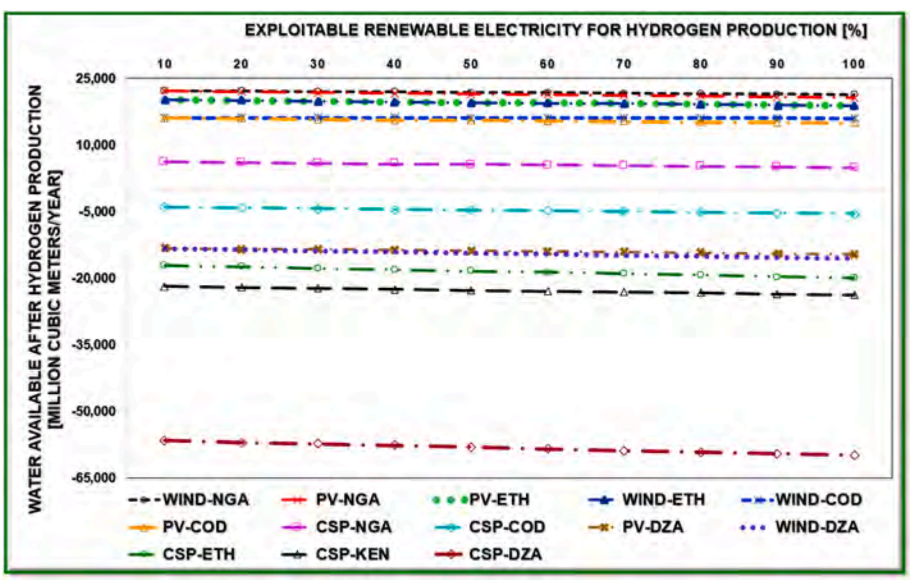

Fig. 12. Sensitivity analysis of exploitable renewable electricity for hydrogen production and water available after hydrogen production (KEN-Kenya, ETH-Ethiopia, NGA-Nigeria, DZA-Algeria, COD-Democratic Republic of Congo, PV-solar photovoltaic, CSP-concentrated solar power).

pipeline transport with 12 TWh), and hydrogen liquefaction with 568 TWh. Liquefied ammonia pipeline and truck have similar overall energy consumption with 556 TWh and 544 TWh respectively, and ammonia synthesis consumes over 70% of the overall energy consumption. Ammonia tank truck, liquefied hydrogen tank truck, HVDC, and water treatment systems have significantly lower energy consumption per system ranging from 0.008 to 0.8%.

In Table 8 showing the system costs, the HVDC system presents the most cost-effective transportation system with overall costs per kg hydrogen of 0.038 $/kg, followed by water pipeline with 0.084 $/kg, seawater desalination 0.1 $/kg, liquefied hydrogen tank truck 0.12 $/kg, compressed hydrogen pipeline 0.16 $/kg, liquefied ammonia pipeline 0.38 $/kg, liquefied ammonia tank truck 0.60 $/kg, and compressed hydrogen tank truck with 0.77 $/kg. The HVDC, water pipeline and seawater desalination system costs including compressed pipeline transportation are 0.18 $/kg, 0.22 $/kg, and 0.23 $/kg respectively. HVDC system costs are the most cost effective due to higher efficiency compared to other systems with energetic losses as low as 7 ten thousandths over a thousand-kilometer distance. In other words, HVDC transmission costs only 0.02 $/kg hydrogen than a water pipeline system which consumes 0.07 $/kg hydrogen. If the hydrogen produced by HVDC, water pipeline or seawater desalination is liquified instead of compression, then the system costs including transportation are 0.14 $/kg, 0.19 $/kg, and 0.20 $/kg respectively. Liquified hydrogen tank truck system is significantly cheaper than the compressed hydrogen tank truck, compressed hydrogen pipeline (comparable), liquified ammonia tank truck and pipeline systems despite its massively higher energy consumption during liquefaction. This is due to its high hydrogen

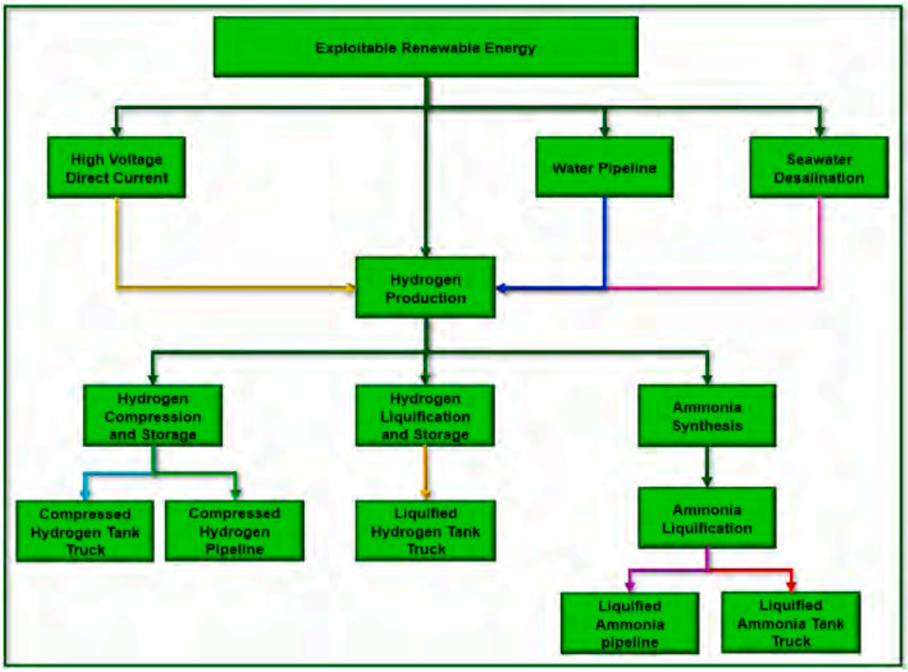

Fig. 13. Transportation pathways.

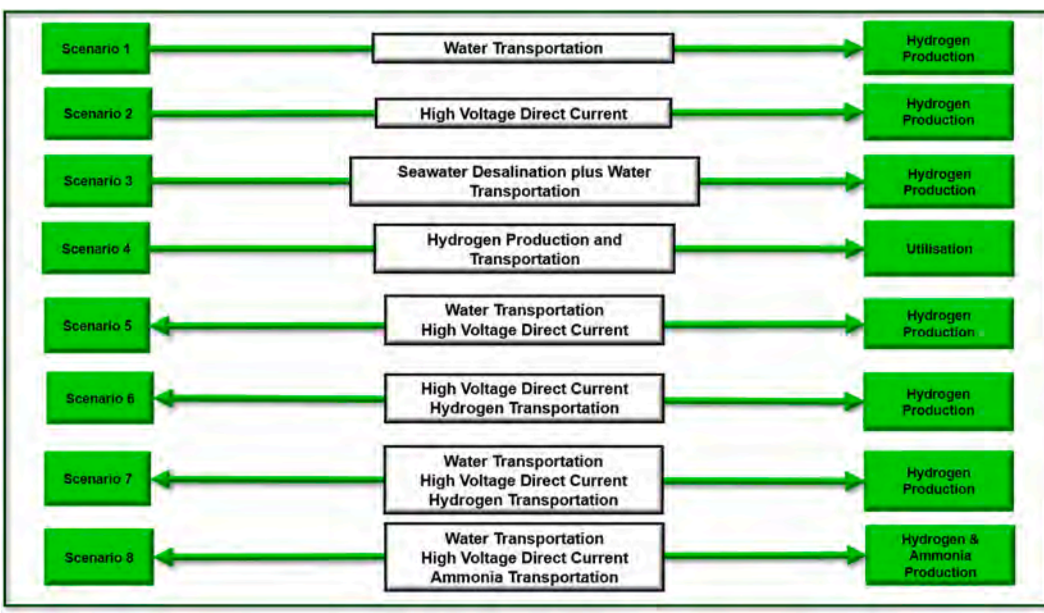

Fig. 14. Transportation pathway scenarios.

carrying capacity in comparison with these systems. The major costs in liquefied ammonia pipeline (0.384 $/kg) and tank truck systems are pipeline and tank truck (0.44 $/kg) costs which are 69%–73% higher than compressed hydrogen pipeline (0.124 $/kg) and liquified hydrogen tank truck (0.118 $/kg) costs respectively. A sensitivity analysis is presented in the following section using scaled Tornado graphs to allow for comparison of the variables being analysed.

3.5.3.2. Distribution pathways techno-economic sensitivity analysis. Fig. 15 shows the system energy consumption sensitivity analysis with varying exploitable solar PV electricity generation from 10% (bottom) to 50% on the left side, and 60% (bottom) to 100% on the right side at a fixed transportation distance of 1500 km. Exploitable renewable electricity generated for hydrogen production is directly proportional to water required for hydrogen production. A liquefied hydrogen tank truck system has the biggest energy consumption over the generation range followed by a liquefied ammonia tank truck and pipeline with comparable energy consumption. The overall system energy consumption of compressed hydrogen tank truck system is lower than HVDC which has the lowest overall energy consumption up to 50% electricity generation.

Fig. 16 shows the system energy consumption sensitivity analysis with varying transportation distance from 200 km (bottom) to 5600 km on the left side, and 6200 km (bottom) to 11,600 km on the right side in intervals of 600 km at a fixed exploitable solar PV electricity generation of 50%. Compressed hydrogen pipeline energy consumption is lower

Table 7
System energy consumption of water pipeline transportation, seawater desalination, high voltage direct current transmission (HVDC), liquefied hydrogen truck, compressed hydrogen truck, compressed hydrogen pipeline, liquefied ammonia pipeline, and liquefied ammonia tank truck transportation system.

		Distribution Systems							
		Water Pipeline [TWh]	Seawater Desalination [TWh]	High Voltage Direct Current [TWh]	Compressed Hydrogen Pipeline [TWh]	Compressed Hydrogen Tank Truck [TWh]	Liquefied Hydrogen Tank Truck [TWh]	Liquefied Ammonia Tank Truck [TWh]	Liquefied Ammonia Pipeline [TWh]
System components	Water Pipe	6	6						
	Water Treatment	0.008							
	Desalination		4						
	HVDC			0.7					
	Hydrogen Compression	92	92	92	92	92			
	Compressed Hydrogen Pipeline				206				
	Hydrogen Liquefaction						568		
	Liquefied Hydrogen Release						50		
	Hydrogen Truck					2	0.3		
	Ammonia Synthesis							392	392
	Ammonia Storage							152	152
	Ammonia Truck							0.2	
	Liquefied Ammonia Pipeline								12
	Total	**98**	**102**	**93**	**298**	**94**	**618**	**544**	**556**

than liquefied hydrogen tank truck, liquefied ammonia tank truck and pipeline until 3800 km–4400 km, and lower than HVDC, water transportation and seawater desalination below 800 km. Similarly, a compressed hydrogen tank truck system has lower energy consumption than HVDC, seawater desalination and water pipeline systems below 200 km. Liquefied ammonia pipeline energy consumption is higher than liquefied ammonia tank truck along the distance range and higher than liquified hydrogen tank truck above 11,600 km.

Fig. 17 shows the system cost sensitivity analysis with varying exploitable solar PV electricity generation and transportation distance. A liquefied ammonia tank truck, liquefied ammonia pipeline, and HVDC overall system costs increased gradually from 0.45 $/kg to 0.6 $/kg, 0.43 $/kg to 0.54 $/kg, and 0.019 $/kg to 0.062 $/kg hydrogen respectively. Water pipeline transportation, seawater desalination, liquefied hydrogen tank truck, and compressed hydrogen pipeline transportation overall system costs are inelastic when the electricity generation increases because the mass of hydrogen produced in these systems increases linearly, dissimilar to the former systems. Nevertheless, all these systems will have varying levels of nonlinearity, however negligible it may be, in practical applications.

In Fig. 18, compressed hydrogen and liquefied ammonia tank truck systems experience the sharpest and largest increment in cost from 0.12 $/kg to 5.8 $/kg and 0.14 $/kg to 3.5 $/kg hydrogen respectively while the distance increases from the 200 km–11,600 km due to significantly higher fuel consumption costs. Compressed hydrogen tank truck is higher because of its lower carrying capacity over the distance range. Overall cost increment in water transportation and seawater desalination are moderately low at 30% compared to HVDC, compressed hydrogen pipeline, water pipeline, and liquified ammonia pipeline. Nonetheless, HVDC system overall costs are the lowest over the distance range. Compressed hydrogen and liquified ammonia tank truck systems have lower and competitive costs against liquified ammonia pipeline below 800 km and 1400 km respectively. Similarly, compressed hydrogen pipeline and liquified hydrogen tank truck have lower costs than seawater desalination and water transportation up to 1400 km, competitively lower costs against liquified ammonia pipeline up to 9200 km and 10,400 km respectively. The next section 4 highlights the current challenges in the context of a hydrogen economy in Africa.

These sensitivity analysis results show that centralised and decentralised hydrogen production will both have pivotal roles in Africa's hydrogen economy. This will largely depend on the hydrogen usage e.g., local consumption, ammonia production for fertilizer production, or export. The results also quantify the significance of economies of scale due to cost effectiveness of certain systems over other systems such as compressed hydrogen pipeline and liquified hydrogen tank truck systems when hydrogen production is scaled up. While centralised hydrogen production is favorable in short and long-term to drive down costs and export huge hydrogen and/or ammonia quantities for these technologies, decentralization in the short term is generally favorable under some constraints, though it has potential for meeting off grid community energy needs. For example, compressed hydrogen and liquefied ammonia tank truck systems will be more cost effective below 800 km and 1400 km transportation distances because they have lower costs against liquefied ammonia pipeline, seawater desalination, and water transportation. On the other hand, it will be cost-effective to develop compressed hydrogen pipeline and liquified hydrogen tank truck systems over a liquified ammonia pipeline below 10,400 km transportation distance.

4. Challenges and perspectives of african hydrogen economy

This study has highlighted the critical water challenges on the African continent which will be worsened with hydrogen production. But it has also provided possible solutions to overcome this exacerbating water crisis towards the attainment of a sustainable hydrogen and African economy.

Table 8
System costs of water pipeline transportation, seawater desalination, high voltage direct current transmission (HVDC), liquified hydrogen truck, compressed hydrogen truck, compressed hydrogen pipeline, liquified ammonia pipeline, and liquified ammonia tank truck transportation system.

		Distribution Systems							
		Water Pipeline [$/kgH_2$]	Seawater Desalination [$/kgH_2$]	High Voltage Direct Current [$/kgH_2$]	Compressed Hydrogen Pipeline [$/kgH_2$]	Compressed Hydrogen Tank Truck [$/kgH_2$]	Liquefied Hydrogen Tank Truck [$/kgH_2$]	Liquefied Ammonia Tank Truck [$/kgH_2$]	Liquefied Ammonia Pipeline [$/kgH_2$]
System components	Water Pipe	0.07	0.07						
	Water Treatment	0.000001							
	Water Storage	0.000028	0.000014						
	Desalination		0.0174						
	HVDC			0.024					
	Hydrogen Compression	0.00002	0.00002	0.00002	0.00002	0.00002			
	Hydrogen Compressed Storage	0.0135	0.0135	0.0135	0.0135	0.0135			
	Compressed Hydrogen Pipeline				0.12406				
	Hydrogen Liquefaction						0.00000004		
	Liquefied Hydrogen Release						0.00000002		
	Hydrogen Storage				0.027	0.027	0.0028		
	Hydrogen Truck					0.7318	0.1171		
	Ammonia Synthesis							0.0817	0.0002
	Ammonia Storage							0.0817	0.0002
	Ammonia Truck							0.43632	
	Liquefied Ammonia Pipeline								0.38406
	Total	**0.0844**	**0.101**	**0.038**	**0.165**	**0.772**	**0.120**	**0.600**	**0.3885**

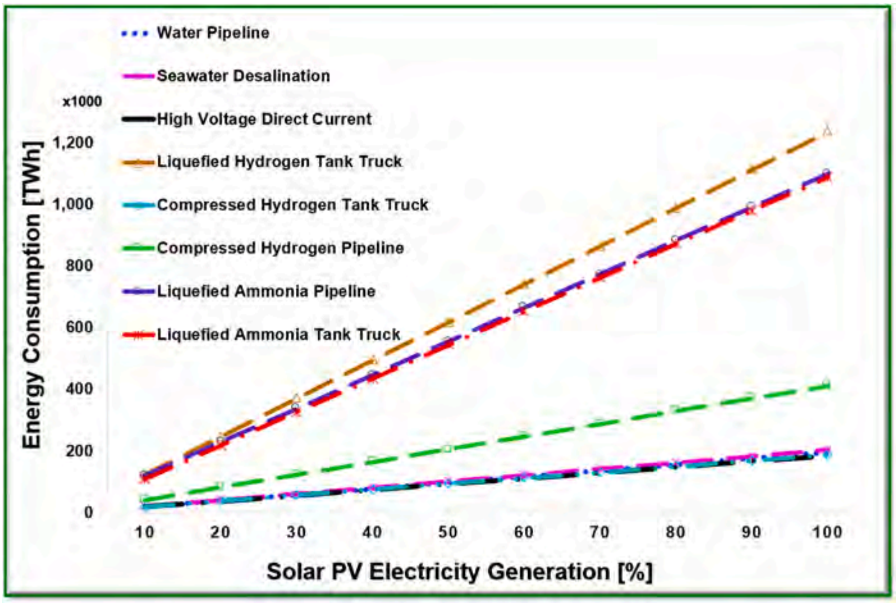

Fig. 15. Sensitivity analysis of energy consumption with varying exploitable solar photovoltaic (PV) electricity generation at a fixed distance of 1500 km for high voltage direct current, water pipeline, seawater desalination, liquefied hydrogen tank truck, compressed hydrogen pipeline, liquefied ammonia pipeline, liquefied ammonia tank truck, and compressed hydrogen tank truck systems.

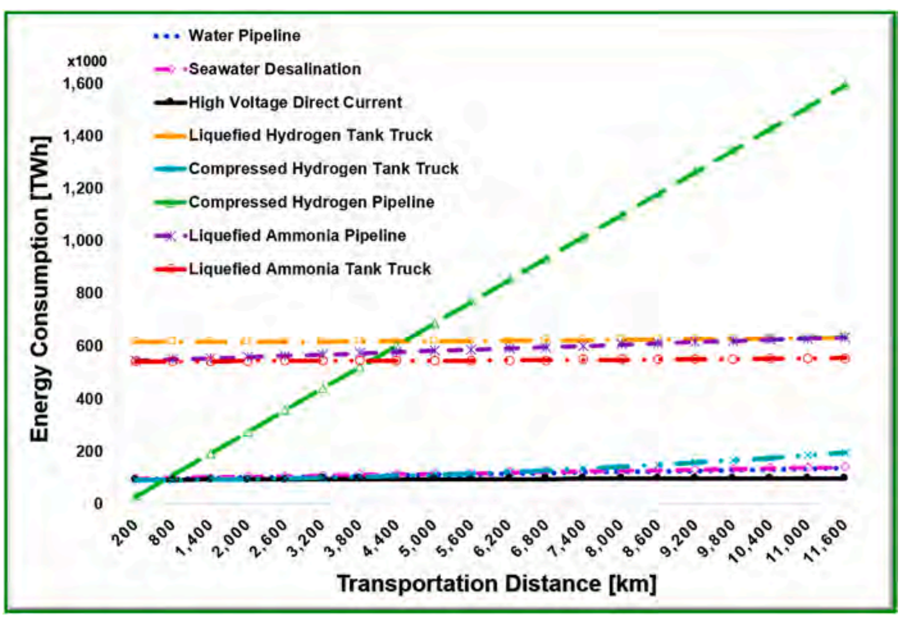

Fig. 16. Sensitivity analysis of energy consumption with varying transportation distance at a fixed exploitable solar PV electricity generation of 50% for high voltage direct current, water pipeline, seawater desalination, and liquefied hydrogen tank truck, compressed hydrogen pipeline, liquefied ammonia pipeline, liquefied ammonia tank truck, and compressed hydrogen tank truck systems.

4.1. Added value of regional collaboration

Local, regional and international partnerships [118–120] will be instrumental in driving down costs and risks through accelerated large scale hydrogen technology development. Working together will be important as it is a win-win situation for all African countries. These partnerships will also enable accessibility of ready markets that would have been otherwise hard to penetrate without the support of local markets. In addition, building state of the art ports for global hydrogen exports should not be left as a sole responsibility of the countries that are bordered by oceans, but it can be done and financed collectively so that Africa's competitive hydrogen environment can be cemented further. Hydrogen conversations and communications between countries should be deliberately and hastily done to expedite the hydrogen economy.

Optimisation of risk diversification needs to be taken into account and utilised in renewable African bond issuances [121]. The African Hydrogen Partnership demonstrated this in Fig. 19 which illustrates the comprehensive, integrated and strategy by addressing supply and demand concurrently while distributing capital to several sectors, issuers, and countries in a diversified way [121]. Fig. 19(a) shows a breakdown of the sample financial instrument by hydrogen fuel cell and related power-to-gas renewable energy sectors required for a functioning renewable hydrogen transportation and hydrogen production energy system [121]. Fig. 19(b) shows risk diversification across various

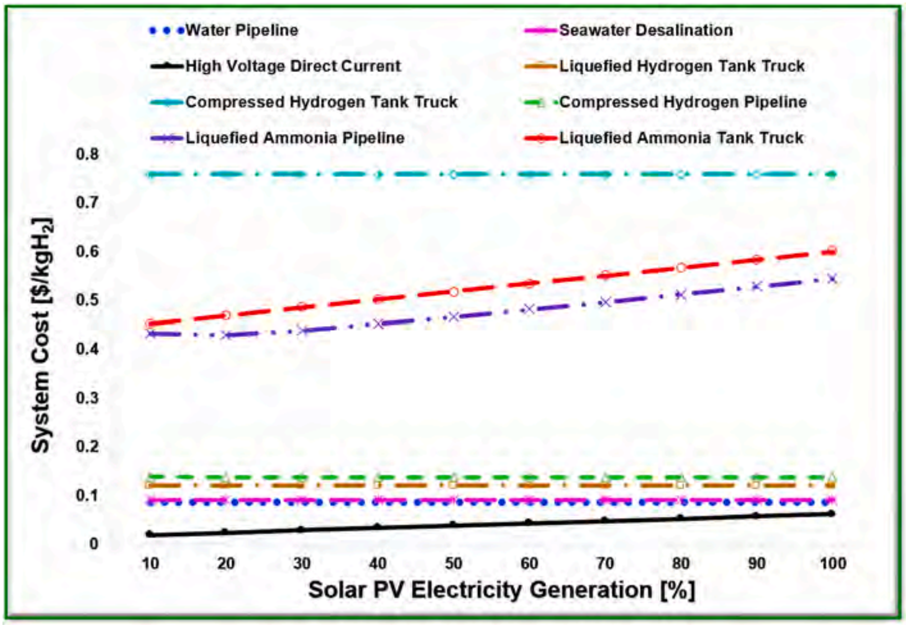

Fig. 17. Sensitivity analysis of cost with varying exploitable solar photovoltaic (PV) electricity generation at a fixed transportation distance of 1500 km for high voltage direct current, water pipeline, seawater desalination, and liquefied hydrogen tank truck, compressed hydrogen pipeline, liquefied ammonia pipeline, liquefied hydrogen pipeline, and compressed hydrogen tank truck systems.

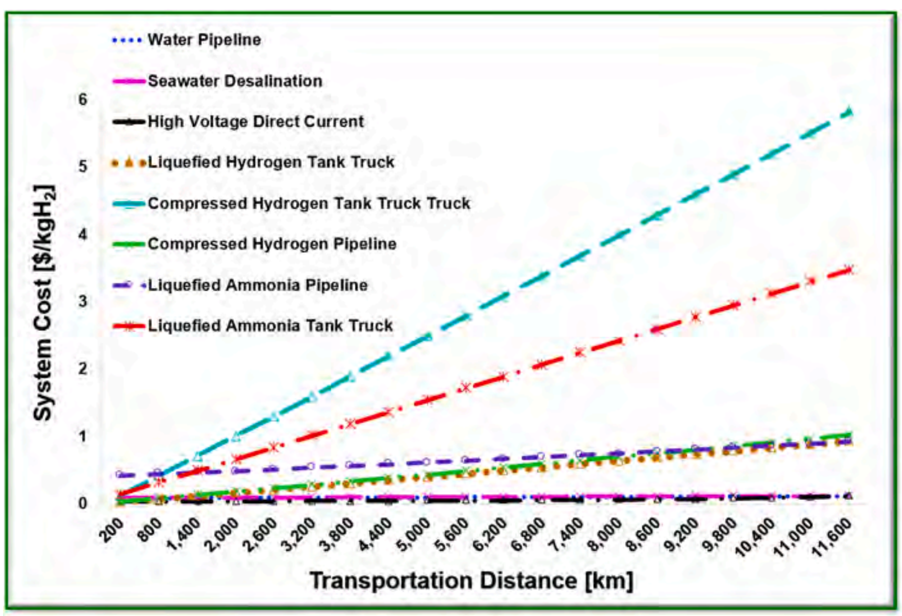

Fig. 18. Sensitivity analysis of cost with varying transportation distance at a fixed exploitable solar PV electricity generation of 50% for high voltage direct current, water pipeline, seawater desalination, and liquefied hydrogen tank, compressed hydrogen pipeline, liquefied ammonia pipeline, liquefied ammonia tank truck, and compressed hydrogen tank truck systems.

countries. The country breakdown of renewable hydrogen securitized bond includes six countries as an example and a lot more countries can be included as well [121]. Regional stability (economic and political), not just on a country level, will be crucial in boosting investor confidence by attracting external funds onto the African continent due to regional synergistic effects that are appealing to investors such as renewable hydrogen resources, reduced investment risks, and human resource.

4.2. Conference of the parties (COP) 26 UN climate change conference commitments

The COP26 [2] country commitments underscored yet again the key role individual African countries will play in the net zero transition, and more specifically the African hydrogen economy. Fig. 20 shows the African country level COP26 commitments towards the net zero target, coal phasing out, methane emission reduction, and deforestation COP26 commitments. 45% and 43% of African countries have committed to net zero targets and cutting methane emissions respectively. Most countries without net zero and methane reduction targets stem from north,

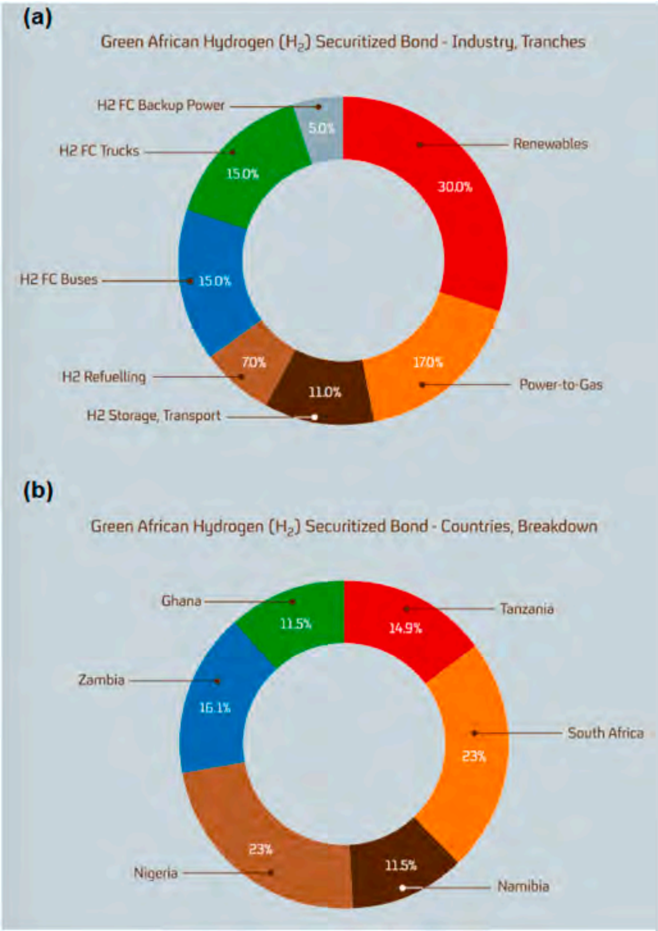

Fig. 19. An example of diversification of hydrogen economy risk (H2-hydrogen, FC-fuel cell) (source [121]).

central, and west Africa, and south, east, and north Africa respectively. Contrastingly, only 17% African countries pledged to phasing out coal comprising of only Botswana, Zambia, Somalia, Egypt, Ivory Coast, Senegal, Mauritania, and Morocco. Impressively, 64% of African countries pledged to end deforestation paving way for clean cooking fuels such as hydrogen.

4.3. Public awareness and policies

Public awareness [119] of hydrogen will have important ramifications on its large-scale adoption in Africa and around the world. Public awareness varies significantly per community due to several influential factors such as education levels and access to information through the internet, and the latter depends on the former since an uneducated person cannot use the internet to gain knowledge. It will be crucial to provide sufficient comparative energy technologies and cost-related information before convincing locals [118]. Renewable hydrogen developers should have robust sales and marketing structures that will sell the hydrogen product to consumers through grass root informative campaigns and sociological research-based solutions.

Last but not the least, the role of effective and deliberate policies [118–120] cannot be emphasized enough towards the development of a global and African hydrogen economy. African governments should start drafting their hydrogen strategies using studies such as this one and reaching out to other African countries. They should do this now, and extremely swiftly so that they can make the most of Africa's renewable hydrogen potential outlined in this study.

5. Conclusions

This study developed and provided a developing country-based framework for assessing exploitable renewable resources for hydrogen production in Africa, and to provide a new critical analysis as to how and what role hydrogen can play in the complex African energy landscape. Renewable hydrogen production options in Africa have been assessed and the potential hydrogen production country and regional levels on offer through solar, wind, concentrated solar power, biomass have been evaluated. The role of renewable hydrogen and its utilisation in the complex African energy landscape has been presented, the debate around centralised vs decentralised, and large-scale vs small-scale in the context of hydrogen, storage, distribution pathways, and transportation has been investigated through techno-economic and sensitivity analysis, and the current challenges in the context of a hydrogen economy in Africa have been highlighted.

Africa has solar photovoltaic (PV), wind, and concentrated solar power (CSP) exploitable potential for hydrogen production ranging from 100 TWh/year to 22,000 TWh/year, 20 TWh/year to 26,000 TWh/year, and 4 TWh/year to 50,300 TWh/year respectively. Bioenergy potential for rainfed soybean straw in Africa is generally low compared to solar PV, CSP and wind energy. Regionally, east Africa tops solar PV hydrogen with 1311 Gt/year followed by south with 974 Gt/year, north and west with similar potentials from 612 to 617 Gt/year, and central Africa with significantly lower hydrogen potential of 366 Gt/year. Wind hydrogen potential is highest in east Africa with 1782 Gt/year followed by south and north with comparable potentials of 1005 to 1194 Gt/year, and notably lower wind hydrogen potentials in west and central of 357 Gt/year and 162 Gt/year respectively. CSP hydrogen potential is comparable in south and east Africa from 2333 to 2738 Gt/year followed by north with 1360 Gt/year, and remarkably lower west and central Africa with 351–463 Gt/year.

Regionally, only north Africa has a renewable water deficit for solar PV, CSP, wind, and bio hydrogen production. The sensitivity results show that Botswana's crosses over to a water deficit occurs at 70% renewable electricity generation implying that hydrogen can be sustainably produced below 70% renewable electricity potential. Similarly, Gabon, Chad, and Malawi can sustainably produce solar PV and wind hydrogen below 40%, 75% and 10% respectively. The sensitivity results depict country level specific hydrogen and renewable energy strategies i.e., countries such as Kenya, Ethiopia, and Congo cannot sustainably produce hydrogen through their exploitable CSP energy thus should focus on solar PV and wind hydrogen production whereas as countries such as Nigeria, Guinea, Ghana, and Zambia can sustainably produce hydrogen at any percentage of CSP electricity generation. The results also show that the acute water shortages in some countries can be abated by water pipeline transportation e.g., the overall water deficit in Algeria (14,000 million m^3/year) during solar PV and wind hydrogen production can be met by the surplus renewable water in Nigeria (22,000 m^3/year).

Short and long-term long-distance export of renewable hydrogen to regions that do not have sufficient renewable energy resources will be indispensable in propelling Africa's hydrogen economy, and the global hydrogen economy intrinsically. The ammonia industry is poised to be one of the earliest and large-scale international and local markets for renewable hydrogen adoption. Additionally, the existing local markets such as mining, cement, and steel industries, and transportation sectors can also facilitate internal uptake of hydrogen due to Africa's passive user technology status. Furthermore, renewable hydrogen for domestic cooking can also play a crucial role in decarbonising the heavily carbonized African traditional cooking system because the market for clean cooking is already present. However, its penetration will require the development of the right hydrogen business, social, technical, and economic models.

The results of a techno-economic comparison between Tamanrasset in Algeria and Abuja in Nigeria indicate that electricity transmission for

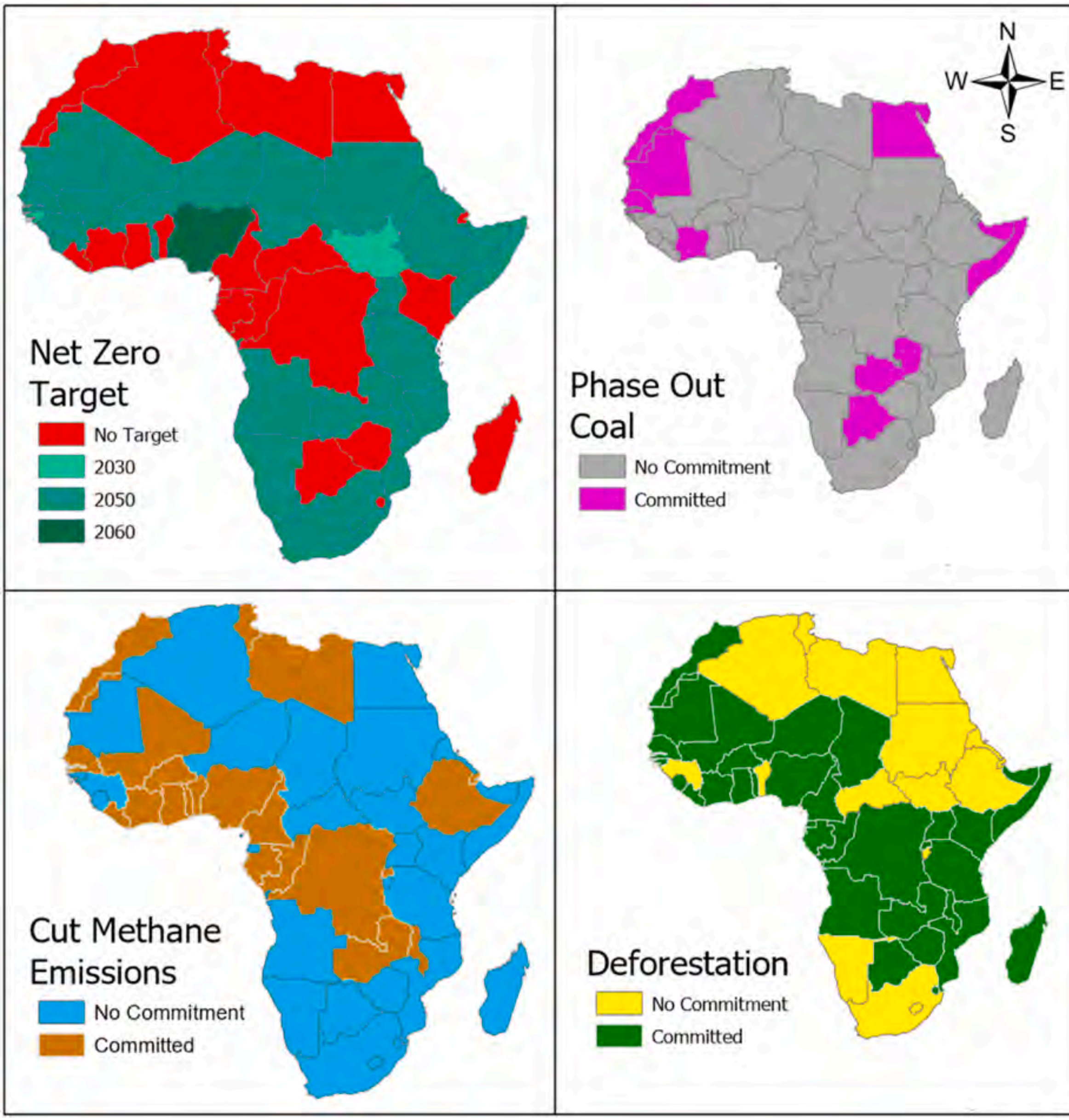

Fig. 20. COP26 Africa country level commitments.

hydrogen production via high voltage direct current (HVDC) offers the most energetically effective and lowest overall energy consumption distribution system followed by compressed hydrogen truck, water pipeline, desalination, compressed hydrogen pipeline, liquified ammonia tank truck, liquefied ammonia pipeline, and liquified hydrogen tank truck systems. HVDC system presents the most cost-effective transportation system with overall costs per kg hydrogen of 0.038 $/kg, followed by water pipeline with 0.084 $/kg, seawater desalination 0.1 $/kg, liquified hydrogen tank truck 0.12 $/kg, compressed hydrogen pipeline 0.16 $/kg, liquefied ammonia pipeline 0.38 $/kg, liquefied ammonia tank truck 0.60 $/kg, and compressed hydrogen tank truck with 0.77 $/kg. Furthermore, the sensitivity analysis results show that centralised and decentralised hydrogen production will both have pivotal roles in Africa's hydrogen economy. For instance, compressed hydrogen and liquefied ammonia tank truck systems will be more cost effective below 800 km and 1400 km transportation distances. On the other hand, it will be cost-effective to develop compressed hydrogen pipeline and liquified hydrogen tank truck systems over a liquified ammonia pipeline below 10,400 km transportation distance.

Finally, renewable energy access, water availability, regional and international hydrogen partnerships will be instrumental in driving down costs and risks through accelerated large scale hydrogen technology development. Working together will be important as it is a win-win situation for all countries. Furthermore, public awareness, regional peace and stability, skill development and advancement, and deliberate hydrogen policies are some of the key challenges that should be overcome hastily to make the most of Africa's attractive renewable hydrogen potential outlined in this study and to meet the highly interlinked UN Sustainable Development Goals.

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Credit author statement

Mulako Dean Mukelabai: Conceptualisation, Methodology, Formal analysis, Writing – Original draft preparation. Writing – Reviewing and Editing, Visualisation, Preparation.: Upul Wijayantha: Conceptualisation, Supervision, Writing-Reviewing and Editing.: Richard Blanchard: Conceptualisation, Supervision, Writing-Reviewing and Editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112705.

Appendix

Table A1
Description of transportation pathway scenarios

Scenario	Description
1	Water pipeline transportation from a country/region with exploitable renewable water resources to a country/region without exploitable renewable water resources for hydrogen production.
2	Renewable electricity transmission via high voltage direct transmission from a country/region with exploitable renewable electricity to a country/region without exploitable renewable electricity for hydrogen production.
3	Seawater desalination plus water pipeline transportation from the sea into a country/region without exploitable renewable water resources for hydrogen production.
4	Hydrogen production and transportation from a country/region with exploitable renewable electricity and water to a country without exploitable renewable electricity and/or water.
5	Water pipeline transportation and renewable electricity transmission via high voltage direct current from a country/region with exploitable renewable water and/or electricity to a country/region without exploitable renewable water or electricity for hydrogen production.
6	Renewable electricity transmission via high voltage direct current from a country/region with exploitable renewable electricity for hydrogen production, and subsequent hydrogen transportation.
7	Water pipeline transportation and renewable electricity transmission via high voltage direct current transmission from a country/region with exploitable renewable water and/or electricity for hydrogen production and subsequent transportation.
8	Water pipeline transportation and renewable electricity transmission via high voltage direct current from a country/region with exploitable renewable water and/or electricity for hydrogen and ammonia production, and subsequent transportation.

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