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Review of the hydrogen supply chain and use in Africa

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ABSTRACT

The high potential in renewable energy sources (RES) and the availability of strategic minerals for green hydrogen technologies place Africa in a promising position for the development of a climate-compatible economy leveraging on hydrogen. This study reviews the potential hydrogen value chain in Africa considering production and final uses while addressing perspectives on policies, possible infrastructures, and facilities for hydrogen logistics. Through scientific studies research and searching in relevant repositories, this review features the collection, analysis of technical data and georeferenced information about key aspects of the hydrogen value chain. Detailed maps and technical data for gas transport infrastructure and liquefaction terminals in the continent are reported to inform and elaborate findings about readiness for hydrogen trading and domestic use in Africa. Specific maps and technical data have been also collected for the identification of potential hydrogen off-takers focusing on individual industrial installations to produce iron and steel, chemicals, and oil refineries. Finally, georeferenced data are presented for main road and railway corridors as well as for most important African ports as further end-use and logistic platforms.

Beyond technical information, this study collects and discusses more recent perspectives about policies and implementation initiatives specifically addressing hydrogen production, logistics, and final use also introducing potential criticalities associated with environmental and social impacts.

Abbreviations

BF:	Blast Furnace
BF-BOF:	Blast Furnace coupled with Basic Oxygen Furnace
BOF:	Basic Oxygen Furnace
CA:	Central Africa
CAPP:	Central African Power Pool
COP:	Conference Of Parties
CSP:	Concentrating Solar Power
Dii:	Desertec Industrial Initiative
DRC:	Democratic Republic of Congo
DR-EAF:	Direct Reduction coupled with Electric Arc Furnace
DRI:	Direct Reduction Iron
EA:	East Africa
EAF:	Electric Arc Furnace
EAPP:	East African Power Pool
EU:	European Union
GDP:	Gross Domestic Product
HySA:	Hydrogen South Africa
IEA:	International Energy Agency
IGU:	International Gas Union
IRENA:	International Renewable Energy Agency
LNG:	Liquified Natural Gas
MENA:	Middle East and North Africa
NA:	North Africa
NAPP:	North African Power Pool
NDC:	Nationally Determined Contributions
PV:	Photovoltaic
RES:	Renewable Energy Sources
RSA:	Republique of South Africa
SA:	Southern Africa
SAPP:	Southern African Power Pool
TEU:	Twenty-foot Equivalent Units
UNFCCC:	United Nations Framework Convention on Climate Change
USGS:	United States Geological Survey
WA:	West Africa
WAPP:	West African Power Pool

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1. Introduction

Green hydrogen emerges as a promising solution for the decarbonization of hard-to-abate sectors like iron and steel, chemical, oil refining, and other manufacturing industries (e.g., glass, ceramics, etc …) either used as a feedstock or an energy carrier for high-temperature heat production, as a fuel for mobility or power generation. Indeed, while electrification can cover substantial fuel switching in final energy demand, many studies highlight the importance of a multi-commodity energy system where renewable fuels (e.g., e-fuels produced through the use of renewable electricity often with an electrolysis step and biofuels produced from biomass conversion), and particularly hydrogen, can provide a relevant contribution for decarbonization efforts and more secure energy supply.

In the World Energy Outlook 2023, the International Energy Agency (IEA) reported the contribution of hydrogen in world final energy consumption up to 6 % by 2050 in Announced Pledges Scenario [1] with a total demand of green hydrogen of around 36 EJ compared with 11 EJ at 2022 (almost entirely produced from fossil fuels). Hydrogen consumption in Africa is today accounting for around 3 % of global demand, with Egypt being the African country with the highest hydrogen consumption, estimated at 1.4 million tons per year [2]. The share of hydrogen demand in Africa is expected to reach 5 % of world demand in 2050 in the above-mentioned Announced Pledges Scenario, corresponding to about 14 million tons of hydrogen per year, a fivefold increase from today's consumption. A study published in 2022 and supported by the African Union, the International Solar Alliance and the European Investment Bank [3] indicates a potential of hydrogen production in Africa of around 50 million tons per year by 2035 either to decarbonize domestic steel and fertilizer production and for export, leading to an estimated total 1-trillion euro investment for the whole supply chain. A study from McKinsey & Company [4] published in October 2023 reports that Africa could self-supply its domestic demand potential of between 10 and 18 million tons per year by 2050, while exports could reach around 40 million tons per year. This ramp-up of hydrogen sector in Africa could divert a significant number of projected investments in the energy sector cumulating around 800 billion dollars ($\$_{2023}$) in 2050. From these insights, it appears that although hydrogen is a nascent sector in the African continent, its high potential is recognized by several institutions and can contribute to the achievement of COP 21 resolutions, which 52 out of 54 African countries have ratified and implemented through the submission of Nationally Determined Contributions (NDCs) that address both mitigation and adaptation measures [5]. In addition, the expected economic growth of agricultural and industrial sectors in the continent with respect to the 2063 Agenda from the Africa Union [6] will lead to a potential increase in hydrogen need strengthening the resilience in key sectors such as fertilizers' production [7] and reducing the dependence on natural resource rents (e.g. high share of GDP of net export revenues) that have registered sovereign credit ratings downgraded due to the less global consumption of fossil resources linked to the pandemic outbreak [8].

There is a particular opportunity to jointly develop the hydrogen sector between Africa and the European Union whose cooperation efforts also involve the achievement of energy transition in the two continents [9]. There are also several North-South initiatives between different European and African countries that explicitly address cooperation in the field of hydrogen-like agreements between Morocco and Germany [10], Italy and Tunisia [11], Netherlands and Namibia [12], and South Africa [13]. Through the REPowerEU plan [14], the European Union aims to import up to 10 million tons per year of hydrogen by 2030 as a response to the energy crisis and climate emergencies with Africa being indicated as a potential major hydrogen supplier [2]. The role of Africa as a global hydrogen hub for trading has been addressed in the comprehensive analysis recently published by the International Renewable Energy Agency (IRENA) from a system perspective [15], logistics perspective [16], cost, and potential [17], and geopolitics implications [8]. These reports highlight Africa's significant potential in the hydrogen energy sector, emphasizing its crucial role on a global scale. Specifically, the Sub-Saharan Africa (SSA) region is projected to produce hydrogen energy equivalent to around 2.7 ZJ (zetta joules) at a cost below USD_{2018} 1.5/kg by 2050, with an additional 2 ZJ production from the Middle East and North Africa (NA). It emerges the key role of Africa, especially the Northern and Southern regions, to become a global hub for hydrogen trading. Overall, the findings reveal the diverse and complex factors underscoring hydrogen's future importance to the continent.

The role of hydrogen for domestic use in productive sectors in Africa has also been highlighted. A pioneering initiative and overview of opportunities for hydrogen in Africa has been proposed by the African Hydrogen Partnership [18] which identified 'landing zones' for initial hydrogen projects in the continent thus providing information about potential supply, demand, and infrastructure for logistics. Although some research findings outline the benefit of implementing green hydrogen systems for transportation, power, and industry sectors [10,19], the comprehensive identification and mapping of end-uses and possible hydrogen infrastructures are still poorly reported in scientific studies. Moreover, the lack of strong hydrogen policies in many African countries hinders the development of hydrogen systems in the continent [10,20] although these systems have proven to be cost-effective and capable of mitigating the rise of CO_2 emissions while promoting rural and remote electrification [21,22]. Additional studies show that hydrogen-based hybrid energy storage systems are more suitable than one technology alone, and by 2040 they will be much more competitive with price reduction of components [23,24] thus contributing even for future mini-grid configurations that can address the overall energy access challenge urgency and look at hydrogen technologies to deliver energy services at community scale.

Based on the perspectives of hydrogen for Africa and based on the state-of-art of scientific studies, this review aims to provide a comprehensive review and analysis of the green hydrogen value chain and potential domestic utilization in the continent. The goal is to provide an updated overview of the enabling factors for hydrogen in Africa, specific features at single country, and essential datasets that can be further exploited to perform quantitative investigations from other studies. After presenting the adopted methods in section 2, the study investigates the potential and readiness for hydrogen production in section 3 with a highlight of renewable electricity potential and water stress in individual country (section 3.1), the specificity at single power pool including availability of primary resources and raw materials (section 3.2), the policy in place with respect to decarbonization goals at individual country (section 3.3), the hydrogen projects under development at individual country and final sectors (section 3.4). Section 4 presents an overview of the readiness for implementing a hydrogen transport infrastructure including an assessment of regional and international natural gas pipelines (section 4.1) and liquified natural gas terminals (section 4.2) that could be retrofitted to serve as hydrogen infrastructure backbone. Section 5 investigates potential readiness for hydrogen demand in key sectors of Africa economy such as steel (section 5.1), ammonia and other chemicals (section 5.2), refining (section 5.3), and maritime logistics in African ports (section 5.4).

2. Methods

A systematic review of the scientific studies was performed following on one hand the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for peer-reviewed articles selection [25]. Nevertheless, additional reports from grey studies were selected based on their relevance to the scope of this study. The search was conducted in Google Scholar, Scopus, and Web of Science databases from January 01, 2000, until May 15th, 2024. Pertinent studies found from references of the selected articles were also manually searched. For Google Scholar, all references with the keywords "hydrogen" and

"Africa" or the names of African countries in their titles were searched, resulting in the identification of 263 publications. For Scopus and Web of Science, the same strategy was used, the search was extended to the abstract and found respectively 811 and 878 articles. As summarized in Fig. 1, after merging and removing duplicates in Mendeley, a detailed screening process for titles and abstracts was then undertaken, which excluded publications that were either off-topic or not the right document type (data set, editorial, newspapers, errata, Handbook, no peer-reviewed articles, and proceedings). The subsequent full-text screening further narrowed the selection down with additional articles being excluded for various reasons such as lack of relevance, unavailable full-text, or the study area or scope not directly linked to Africa.

Grey studies were searched in the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), United Nations Framework Convention on Climate Change (UNFCCC), Desertec Industrial Initiative (Dii), and World Bank databases. Reports related to hydrogen strategy, projects, and geopolitics in Africa or between Africa and other regions of the world, specifically the European Union were included. Finally, the acquisition of data for the assessment of potential hydrogen infrastructure and hydrogen demand within specific industrial sectors including iron and steel, ammonia production, and refineries, required gathering information from a range of authoritative sources. These sources encompassed entities such as Global Energy Monitor, BP Statistics, International Gas Union, Energy Capital and Power, Africa Fertilizer Map, and the United States Geological Survey (USGS). Complementary insights were obtained directly from corporate websites, as well as from credible freely accessible online repositories like Our World in Data.

In reviewing publications reporting hydrogen prices and other economic figures regarding cumulative investments for hydrogen systems, a thorough analysis has been performed aiming to understand the approach used to express currencies. When explicitly reported in the publications analyzed in this review, the use of the constant or current currency approach has been specified by introducing the values of inflation (in the case of a current currency approach) or the reference year of the currency (in the case of a constant currency approach). In unspecified cases, it has been assumed that the currency is expressed in constant value since this is the typical approach used for long-term

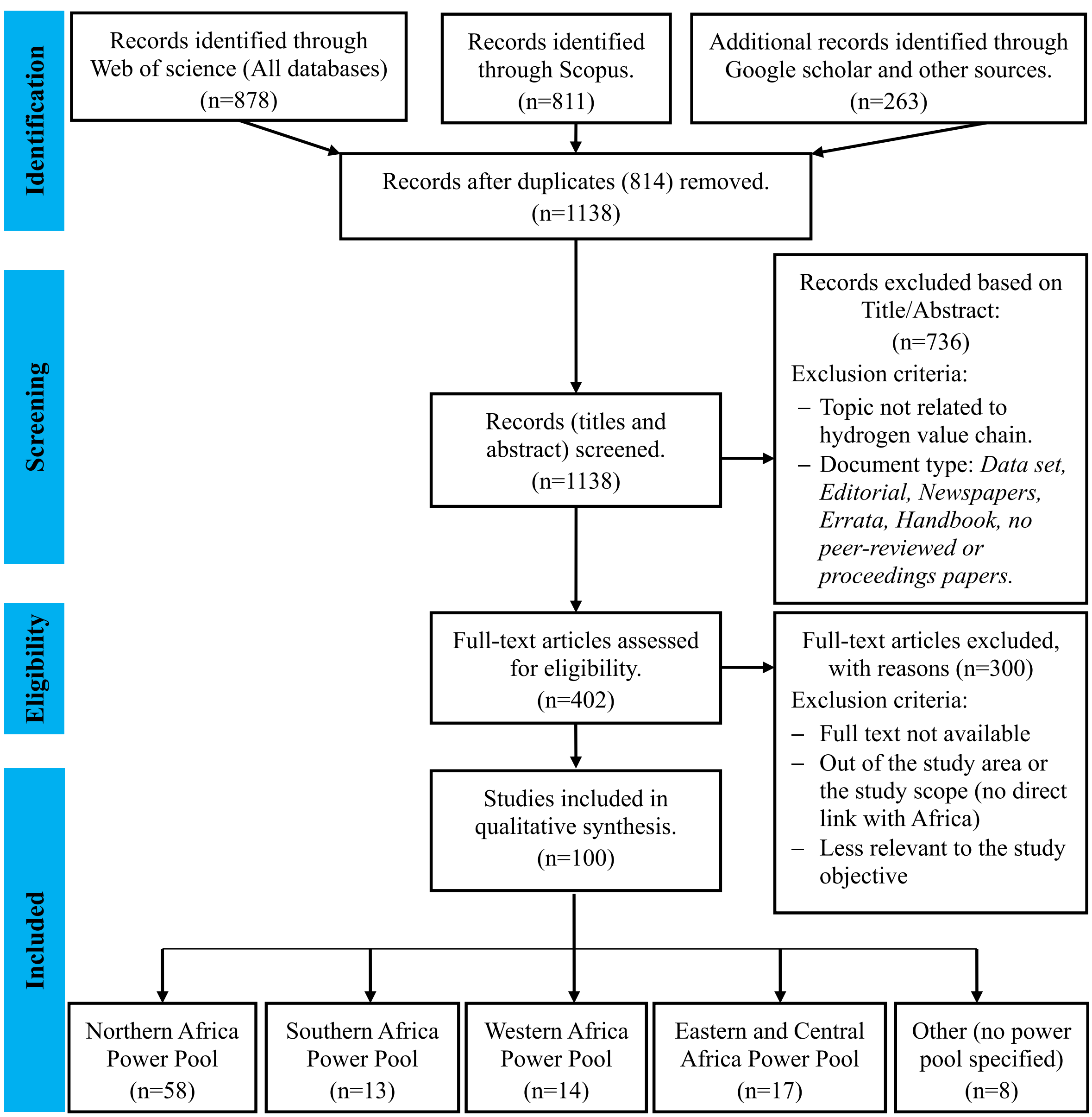

Fig. 1. Flowchart summary of the search and selection of peer-reviewed studies.

energy analyses; in these cases, the reference year for the currencies considered in this review is the year of publication of individual studies and an asterisk is used to show the assumption.

3. Results

3.1. Energy situation in Africa and readiness for hydrogen production

A first analysis for the development of green hydrogen in Africa is related with data of existing, planned, and potential renewable electricity generation in Africa. Indeed, low variable renewable energy electricity cost is a key driver for the feasibility of green hydrogen projects [26] and Africa, with its vast renewable energy potential largely untapped, is expected to play a key role in the global hydrogen arena. According to IRENA findings [15], Africa can be the fourth world region with the highest installed renewable generation capacity, up to 1 TW in 2050, specifically for hydrogen production after China, India, and the United States.

Table A1 shows the existing, planned, and potential development for hydroelectricity, solar, and wind power generation for individual countries. All African countries have considerable solar energy potential, with notable hydropower potential in the Democratic Republic of Congo, Ethiopia, and Cameroon due to their equatorial climates. However, Central Africa (CA), except Chad, has limited wind energy potential due to its dense equatorial forests. Geothermal energy, especially in the East African Rift region, presents another viable option. Ethiopia and Kenya have already implemented pilot geothermal power plants, which can be upscaled and spread to other countries [27,28].

Over 15 countries have installed more than 1 GW of renewable capacity for electricity generation, and Ethiopia, South Africa, Egypt, Angola, Nigeria, and Morocco have installed more than 5 GW so far. However, energy access remains a challenge. Only five countries (Northern African countries and Seychelles) have universal electricity access, and 12 countries out of 54 have more than 90 % of the population with access to electricity (notably around half of African countries still have less than 50 % access to electricity). While renewable capacity growth suggests potential for hydrogen production, the immediate priority should be improving electricity access [15]. Moreover, the renewable industry is not yet at the scale needed to establish a hydrogen market, especially for export. For instance, despite Morocco shows about 40 % of renewable energy sources in its electricity mix, with about 5 GW of installed capacity in 2021, it is still not on track to become a key supplier of hydrogen in Europe which will need more than 850 GW of installed renewable capacity by 2050 [15].

Using different renewable primary energy resources, all African countries have tremendous potential for hydrogen production [29]. Still, South Africa and Northern Africa countries lead the planning of hydrogen systems, having already a paved roadmap for renewable energy generation and having achieved universal energy access. However, considering water stress that could induce the high production of hydrogen, the Northern African countries are more vulnerable [8,29,30]. While recognizing the key linkages of hydrogen production within the energy-water-food nexus, the authors deem this topic deserves a more deep and dedicated research effort, beyond the scope of this review. Most studies indicate an emerging water stress potentially associated with hydrogen technologies, however, some other studies [3] indicate a potential benefit of implementing hydrogen projects in Africa with the possibility to produce up to 3800 million cubic meters of clean fresh water through desalination technologies which account 5 % of domestic needs; in addition, the availability of self-supplied green hydrogen for fertilizer production could increase the security of food supply [31].

3.2. Prospects of hydrogen systems in different African power pools

A more comprehensive understanding of hydrogen systems in Africa can be achieved under the perspective of African power pools which were established to enhance cooperation and electrical energy integration in Africa. The continent is divided into 5 power pools aligned with the African Union's economic communities:

- The North African Power Pool (NAPP) includes Algeria, Egypt, Libya, Morocco, and Tunisia. Except for Egypt, the other NAPP countries belong to the Arab Maghreb Union (UMA).
- The Southern African Power Pool (SAPP) covers 12 out of 16 countries of the Southern African Development Community (SADC).
- The West African Power Pool (WAPP) is composed mainly of countries belonging to the Economic Community of West African States (ECOWAS).
- The Central African Power Pool (CAPP) covers 10 Central African countries members of the Economic Community of Central African States (ECCA).
- The East African Power Pool (EAPP) in which the majority of the countries belong to the East African Community (EAC).

Despite numerous focused studies on the hydrogen value chain in specific regions like South Africa and Northern Africa, there is a gap in comprehensive documentation and efforts across all African power pools (see Table 1).

3.2.1. Northern African power pool

Many studies conducted on the hydrogen value chain in Africa are concentrated in the NAPP region. The general trend that emerges in almost all the studies highlights the geographical proximity of the region to Europe and its great potential to produce green hydrogen at low cost mainly from solar and wind energy to contribute to the EU green deal [32–34]. Bob van der Zwaan et al. [35] show that a hydrogen partnership between the European Union and Northern Africa countries could bring a net gain of 50 billion per year for the region. Exported hydrogen from Northern Africa to Europe is expected to be generally cheaper than locally produced in Europe [36,36,37]. However, the target of 1.5 $€_{2020}$/kg in 2030 and 1$€_{2020}$/kg in 2050 could be hardly reached [38]. The actual price remains around 3 €/kg as shown in Table 2. Nevertheless, the prospective technical potential to produce hydrogen at a cost target of 1.5 $€_{2018}$/kg in 2050 is instead huge, achieving about 2.7 ZJ [17], but this could increase significantly the water stress in the MENA region [39].

Regarding the readiness of green hydrogen value chain implementation in NAPP countries, Morocco has already defined its hydrogen roadmap in 2021 and formalized an agreement on hydrogen cooperation with the European Union, Germany, and Spain [82]. It is projected to develop a domestic market of hydrogen with a demand in 2030 of about 4 TWh and an export market equivalent of 10 TWh [8]. Given the concern about the high investment cost and water stress that derive from hydrogen system development in Morocco [83], Amrani SE et al. [84] demonstrate the feasibility of using underground water, without increasing significantly the overall cost relying on the country's high hydrogen production potential mainly from wind and solar [85,86]. Similar conclusions have also been drawn by Rawesat A. et al. [87] for the Libyan case.

The well-established gas infrastructure in Algeria connecting to Europe is an effective lever for green hydrogen development; however, the country should liberalize the access of private investors to infrastructure assets and remove stringent measures to attract more foreign investment in the hydrogen sector [88]. Furthermore, Müller VP et al. [89] recommended to invest more in energy efficiency for both local energy transition and maximizing hydrogen production for export. Boudghene S et al. [90] show that the country can export around 40 TWh of hydrogen by 2040, but this requires a tremendous investment of about 25 billion. By contrast, despite having less infrastructure compared to Algeria, Egypt is well positioned to attract more investments in the hydrogen sector thanks to its open regulations and

Table 1
Different hydrogen costs from different production technologies and in different countries in Africa.

N°	Reg.	Country	System RES sources	LCOH	Price reference year	Ref.
1	CA	Cameroon	Wind	4.4–6.3 $/kg	2022[a]	[40]
2	CA	Chad	Grid/PV/Wind	4.7$/kg	2019[a]	[41]
3	EA	Djibouti	Wind Geothermal	1.1$/kg 4.78$/kg	2021[a] 2021[a]	[42]
4	EA	Djibouti	Wind	11.5–18.3 $/kg	2023[a]	[43]
5	EA	Kenya	Hybrid (PV + Wind)	3.7–9.9€/kg	2022[a]	[44]
6	NA	Algeria	PV Geothermal	5 to 0.9 $/kg 4.7 to 3.6 $/kg	2015[a] 2015[a]	[45]
7	NA	Algeria	Wind	1.5–15.4 $/kg	2023[a]	[46]
8	NA	Algeria	Geothermal	4.7–8.7 $/kg	2015[a]	[47]
9	NA	Algeria	Wind	1.2–1.4 $/kg	2015[a]	[48]
10	NA	Algeria	PV	0.4$/Nm3	2020[a]	[49]
11	NA	Egypt	Hybrid (PV + Wind)	4.5–7.5 $/kg	2022[a]	[50]
12	NA	Egypt	Hybrid (PV + Wind)	3.9 $/kg	2022[a]	[51]
13	NA	Egypt	Hybrid (PV + Wind)	3.7–4.7 $/kg	2022[a]	[52]
14	NA	Egypt	PV Wind Hybrid (PV + Wind)	4.2–4.4 $/kg 3.7–4.1 $/kg 4.4–4.8 $/kg	2022[a] 2022[a] 2022[a]	[53]
15	NA	Egypt	Hybrid (PV + Wind)	7.2–12.3 €/kg	2023[a]	[54]
16	NA	Egypt	Hybrid (PV + Wind)	2.2–3.7 $/kg	2023[a]	[55]
17	NA	Egypt	Hybrid (PV + Wind)	1.0–3.3 $/kg	2023[a]	[56]
18	NA	Libya	Grid (2015) Grid (2030)	9.4–10 £/kg 6.2–6.5 £/kg	2017[a] 2017[a]	[57]
19	NA	Libya	Grid	3.9–9.3 $/kg	2017[a]	[58]
20	NA	Libya	Grid	2.9–6.9 £/kg H2	2017[a]	[59]
21	NA	Libya	Grid (distributed production) Grid (centralized production)	10.8–11.7 £/kg 15.0 to 19.8£/kg	2018[a] 2018[a]	[60]
22	NA	Morocco	PV	9.2–12.6 $/kg	2023[a]	[61]
23	NA	Morocco	Wind + CSP (Stirling)	21.4–23.6 €/kg	2022[a]	[62]
24	NA	Morocco	Wind	13.5$/kg	2020[a]	[63]
25	NA	Morocco	PV + CSP	4.0$/kg	2018	[64]
26	NA	Morocco	PV, Polycrystalline PV, Monocrystalline PV, Amorphous	4.9$/kg 5.5$/kg 6.3$/kg	2022[a] 2022[a] 2022[a]	[65]
27	NA	Morocco	PV	5.8$/kg	2019[a]	[66]
28	NA	Morocco	Hybrid (PV + Wind)	2.5$/kg	2022[a]	[67]
29	NA	Morocco	PV Wind Hybrid (PV + Wind)	2.3–2.5 $/kg 1.7–3.8 $/kg 2.1–3.1 $/kg	2019[a] 2019[a] 2019[a]	[68]
30	NA	Morocco	PV	4.6–5.8 $/kg	2018[a]	[69]
31	NA	Morocco	PV	21.6$/kg	2020[a]	[70]
32	NA	Morocco	PV	3.5–60 $/kg	2021[a]	[71]
33	NA	Morocco	PV	2.9 $/kg	2023[a]	[72]
34	NA	Morocco	PV CSP	5 $/kg 9.8 $/kg	2023[a] 2023[a]	[73]
35	NA	Tunisia	PV	3.3 €/kg	2021[a]	[74]
36	SA	South Africa	CSP	9.6–10.5 $/kg	2022[a]	[75]
37	SA	South Africa	Hybrid (PV + Wind)	2.5–3.0 $/kg	2018	[76]
38	SA	South Africa	Wind	1.4$/kg	2019[a]	[77]
39	SA	South Africa	Wind	6.3–9.0 $/kg	2021[a]	[78]
40	SA	South Africa	Hybrid (PV + Wind)	4.5–6.0 $/kg	2023[a]	[79]
41	WA	Ghana	PV + Hydro	4.5$/kg	2022[a]	[80]
42	WA	Ghana	PV Biogas Genset PV + Biogas Genset	5.7$/kg 31.4$/kg 9.1$/kg	2022[a] 2022[a] 2022[a]	[81]

[a] Reference year not clearly provided by the author and assumed to be the year when the study was performed.

well-established ammonia production sector [88]. Similarly to Algeria, Gritz A et al. [91] emphasized the concern about the high capital cost of hydrogen systems as one of the main barriers. Tunisia has also signed bilateral agreements with Italy and Germany for cooperation in hydrogen technology and has demonstrated the highest industrial "know-how" for hydrogen systems in all northern Africa region followed by Morocco and Egypt [92].

Other studies were focused on the feasibility and performances of hydrogen production systems through small-scale on-site experimental setups using solar PV systems [93–96]. Under the Algerian climate, C.A. Menad et al. [93] analyzed the experimental performance of an alkaline electrolyzer, while both N. Khelfui et al. [94], and A. Gougui et al. [95] investigated the performance of a PEM electrolyzer. In Morocco, Ourya I. and Abderafi S [97]. recommended alkaline water electrolyzer for industrial green hydrogen production. Sens, L. et al. [38] showed that large hydrogen storage could decrease the hydrogen export price by 50 %, and even if it has been proven that the existing gas pipeline between Northern Africa and Europe can transport hydrogen up to 20 % of blending [98,99], storage is still essential and would promote the handling of the system, and enhance the local use of hydrogen [58,74]. In Egypt, a study by Youssef A et al. [100] proposed hydrogen storage as a way of improving power grid frequency stability for high renewable electricity penetration, while Seleem et al. [101] discussed that relying on the freshwater from the Nil river, the excess electricity production can be used for hydrogen production in periods with low electricity demand without increasing the water stress in the country.

3.2.2. *Southern African power pool*

Among all African countries in general and the SAPP, the Republique of South Africa (RSA) is the most well-prepared to implement hydrogen-based energy systems. This country has been the subject of a large number of studies to assess the potential of local production and use of hydrogen but also export [102–104]. Since 2008, a strong and ambitious national hydrogen program branded Hydrogen South Africa (HySA) was launched [105,106]. The RSA wants to be a world reference in providing fuel cells and electrolyzer platinum-based catalysts. HySA aims to cover 25 % of the global demand for fuel cell catalysts by 2020 thereby leveraging the value of more than 80 % of the platinum world reserve

Table 2
Mitigation targets and hydrogen policies in African countries with respect to last submitted Nationally Determined Contributions (NDCs).

	Country	Paris Agreement	Mitigation Target (reduction of GHGs emissions in %)			RES Electricity Target	H_2 in NDC	Observation
			Cond.	No Cond	Total			
1	Algeria	20/10/16	15	7	22	27 % 2030	No	
2	Angola	16/11/20	10	14 by 2025	24	>70 % 2015	No	
3	Benin	31/10/16	8.8	12.5	21.3	Not available	No	Forestry not included
4	Botswana	11/11/16			15	Not available	No	
5	Burkina Faso	11/11/16	9.82	19.6	29.42	Not available	No	
6	Burundi	17/1/18	20	3	23	NA > 90 %	No	
7	Cabo Verde	21/9/17	6	18	24	54 % 2030 & 100 % 2040	No	
8	Cameroon	29/7/16	23	12	35	25 % 2035 without Hydro		
9	Central African Rep	11/10/16	12.46	11.82	24.28	Not available	No	
10	Chad	12/1/17	18.8	0.5	19.3	Not available	No	
11	Comoros	23/11/16	22 %	0.0115	23 %	Not available	No	47 % sink
12	Congo	21/4/17	32.19	21.46	53.65	NA	No	
13	Côte d'Ivoire	25/10/16	68.54	30.41	98.95	45 %	No	
14	DR Congo	13/12/17	19	2	21	Not available	No	
15	Djibouti	11/11/16	20	40	60	Not available	No	
16	Egypt	29/6/17			33 %	42 % 2030	Yes	Electricity sector
17	Equatorial Guinea	30/10/18			20 %2030 &50 %2050	Not available	No	
18	Eritrea	Not ratified	26.5	12	38.5	Not available	No	
19	Eswatini	21/9/16	9	5	14	50 % 2030	No	
20	Ethiopia	9/3/17	54.8	14	68.8	Not available >90 %	No	
21	Gabon	2/11/16			8.2	>80 % 2025	No	Forestry not included
22	Gambia	7/11/16			49.7	Not available	No	
23	Ghana	21/9/16	39.4	24.6	64MtCO_2	Not available	No	
24	Guinea	21/9/16	7.3	9.7	17	80 % 2030	No	excluding UTCAFT
25	Guinea-Bissau	22/10/18	20	10	30	58 % 2030	No	
26	Kenya	28/12/16	25.28	6.72	32	Not available	No	
27	Lesotho	20/1/17	25	10	35	50 % 2030	No	access to clean energy
28	Liberia	27/8/18	54	10	64	≥30 % 2030	No	
29	Libya	Not ratified						
30	Madagascar	21/9/16			14	79 %	No	sink 32 %
31	Malawi	29/6/17	45	6	51 % 2040	Not available	No	
32	Mali	23/9/16			40 %	Not available	No	
33	Mauritania	27/2/17	81	11	92	48 % 2021 & 50.34 2030	Yes	
34	Mauritius	22/4/16	26	14	40	60 % 2030	No	
35	Morocco	21/9/16	27.2	18.3	45.5	52 % 2030	No	
36	Mozambique	4/6/18			40MtCO_2e	Not available >90 %	No	
37	Namibia	21/9/16	14	77	91	100 % 2030	Yes	
38	Niger	21/9/16	34.4	10.6	45	Not available	No	Energy sector
39	Nigeria	16/3/17	27	20	47	30 % 2030	No	
40	Rwanda	6/10/16	22	16	38	Not available		
41	Sao Tome & Principe	5/11/16			27 %		No	
42	Senegal	21/9/16	22	7	29	40.7 % 2035	No	
43	Seychelles	29/4/16			27.30 %	15 %	No	Energy sector
44	Sierra Leone	1/11/16			10 % 2030 & 25 % 2050	Not available	No	
45	Somalia	22/4/16			30	Not available	No	
46	South Africa	1/11/16			17 % 2025 & 32 % 2030	Not available	Yes	77 % of coal-based electricity production
47	South Sudan	23/2/21			92 %	92 % with hydro & 3 % w/o hydro	No	Electricity sector
48	Sudan	2/8/17			33.18MtCO_2eq		No	Energy Sector
49	Togo	28/7/17	30.06	20.51	50.57	50 % 2025	No	
50	Tunisia	10/2/17	17	28	45	12 % 2030	Yes	
51	Uganda	21/9/16	18.8	5.9	24.7	Not available	No	
52	Tanzania	18/5/18			30–35 % 2030	100 % 2050		
53	Zambia	9/12/16			25–47	Not available	No	
54	Zimbabwe	7/8/17			40	Not available	No	

that contains the country [20,107]. The same importance is for other materials used for electrolyzer catalysts such as iridium that again South Africa and Zimbabwe own in large amounts. However, a social life cycle assessment study by Akhtar MS et al. [108] shows a risk of many social issues including child labor in the case of South Africa. To avoid social inequalities associated with the hydrogen system development, Kalt T et al. [109] recommended public ownership of hydrogen projects to ensure equitable distribution of wealth generated by the sector.

Wind and solar energy sources are the most promising technologies for green hydrogen production in SAPP [110,111]. To promote the local use of hydrogen, HySA infrastructure competence center developed both lab-scale and commercial-scale solar hydrogen production systems capable of producing respectively 0.5 kg H_2/day and 2.5 kg H_2/day [5]. To date, more than 4000 hydrogen hybrid underground locomotives are working in the South African mining sector [106]. Nevertheless, the target market goes beyond national and regional boundaries. The European Union and Japan particularly have expressed interest in the hydrogen produced in the SAPP which could be exported to Japan for instance at 2.5 to 3$\$_{2018}$/kg by 2030 [76]. Bilateral agreements have been signed between Namibia and EU countries such as Germany [112], Belgium [113], and the Netherlands [12]; South Africa has signed agreements with the Netherlands and specifically with the port of Amsterdam [8]. The Namibian hydrogen project [112], with the potential of producing around 0.3 million tons of H_2 per year, is also part of joint regional efforts that are making the SAPP a competitive hub for a carbon-free and cost-effective hydrogen supply chain. In its final configuration, the hydrogen project in Namibia will have a renewable generation capacity of 5 GW with 3 GW of installed electrolyzer capacity [8].

3.2.3. Western African power pool

The world's first natural hydrogen deposit discovery in Mali in 1987 paved the way for the prospecting of natural hydrogen across the world [114]. Since 2012, the Bourakebougou village in Mali has been electrified thanks to the electricity production from natural hydrogen genset [115,116]. The success of the industrialization phase of natural hydrogen exploitation, can contribute to the development of energy systems by diversifying the different sources of hydrogen production. Mali can thus become a regional leader in the production of natural hydrogen. Prinzhofer, A. et al. [117] demonstrated that the natural hydrogen production price is approximately 2–10 times smaller than the cost of conventional hydrogen production. Other studies investigated the potential of green hydrogen production and utilization in different Western African countries [80,118,119]. In Ghana, Ampah JD. et al. [120] demonstrated that power-to-hydrogen coupled with pumped hydro and electric vehicles have a great potential to increase the penetration of renewable energy resources in the Ghanaian energy mix. Asare-Addo M [121]. also reported a green hydrogen maximum potential of 14.2 Gt/y from solar and 1.5 Gt/y from wind. Additionally, studies conducted by Agyekum et al. [80] emphasize the substantial advantages the Ghanaian agricultural sector could gain from local hydrogen production and utilization in processing fertilizers. This would significantly improve the empowerment of the region's food sector, which depends more on the import of fertilizers, especially from Russia [7].

Moreover, considering the Nigerian case study, beyond the effect on the local oil product market that could induce the development of hydrogen systems, the market growth of hydrogen would positively affect other sectors such as fuel cell technologies and even the biofuel production sector [119]. Indeed, the experiment conducted by Jaikumar, S. et al. [122] proved that the co-firing of hydrogen and biodiesel in internal combustion engines increases the overall thermal efficiency of the engine. Additional studies are still needed to assess the impact of hydrogen systems on the water-energy and food nexus considering local specifications while addressing detailed economic aspects. Indeed, Faydi et al. [123] shows that the high capital cost of hydrogen technologies still makes them less competitive vis a vis to other alternatives technologies in Nigeria. To date the projected green hydrogen production cost price is around 4.5$\$_{2022*}$/kg H_2 [75,112].

3.2.4. Central and Eastern African power pools

In the CAPP and EAPP, hydrogen systems are not yet well documented. Nevertheless, while assessing the potential of green hydrogen production in Djibouti mainly from wind [43], studies by Pasquet G. et al. [124] highlighted the possibility of natural hydrogen deposits in the country. Additional studies emphasize the contribution that the geographic positioning of the country could bring to the establishment of a new hydrogen corridor linking Eastern African countries to the rest of the world, particularly MENA and Europe [42,125]. In Kenya, Palacios, A. and Bradley, D. [126], presented the benefits of clean fuel access such as hydrogen in the cooking sector by highlighting the detrimental impacts that the traditional use of biomass for cooking is producing. It has been argued by Schöne N. et al. [24] that both hydrogen combustion and power-to-hydrogen-to-power e-cooking technologies will evolve in the future and be economically competitive compared to fossil fuel-based cooking by 2040. From a study performed in 2022, the current green hydrogen production cost achievable in the country ranges from 3.7 to 9.9€/kgH_2 [44].

Finally, some studies focused on Cameron underline the high potential of green hydrogen production from wind [40] or hybrid systems [127,128] with current price averaging 4.3 to 6.3 $\$_{2022}$/kg$H_2$ [127]. As for the other countries, in Cameron, the high investment cost concerns have been raised by Sapnken F et al. et al. [129] even if hydrogen can significantly contribute to the decarbonization of the transport sector with a projected demand of 1.75–2.5 Mt H_2 per year. It is important to note the role that the Democratic Republic of Congo (DRC) would play in the regional implementation of hydrogen systems. Being part of both the EAC [130] and the SADEC [20], while geographically located in the CAPP, DRC constitutes the bridge to connect different regions. Moreover, it has a huge potential for renewable primary energy and the highest hydropower potential of the continent [131] that are needed for green hydrogen production. Through multilateral partnerships with Germany, China, and other African countries [132,133], the development of the Grand Inga hydropower project could significantly contribute to both the electrification of the continent and green hydrogen production [134,135].

3.3. Policy in place for hydrogen in Africa

Previous paragraphs have highlighted primary renewable energy potential in different African countries as a preliminary requirement to produce green hydrogen. Energy access levels and other specific features at different power pools have been introduced including existing infrastructure, availability of raw materials, potential domestic demand for productive use and transport, and linkages with water/food. There are however other levers that need to be considered and relate with the policy framework. Table 2 reports the current trend of mitigation policies in different African countries with respect to last submitted Nationally Determined Contributions (NDCs) [136]. Except for Eritrea and Libya, all African countries ratified the Paris Agreement and committed to take both mitigation and adaptation actions. However, despite the willingness of African countries to reduce emissions, increase carbon sink, and develop adaptation measures, many governments must deal with the climate issue in relation with other priorities such as food security, poverty eradication, and access to energy. Therefore, a considerable part of the climate mitigation target is conditioned by international financial assistance being the Green Climate fund [137], one of the international mechanisms intended to financially support the climate-compatible efforts of developing countries.

Interestingly, 5 African countries have included hydrogen in their NCDs as an effective way to achieve mitigation targets often coupled with high RES targets in electricity production. Besides to policies, there will be the need to develop hydrogen codes and standards that are missing for using hydrogen-based technologies in different sectors [20].

Among the countries that included hydrogen in NDCs, Mauritania has committed to developing a green hydrogen roadmap. The roadmap will cover the potential for blue/green hydrogen production and potential domestic uses in industry and transport [138]. The Tunisian government is also committed to integrating hydrogen in the decarbonization process of the industrial sector and supporting research on the development of green hydrogen [139]. Egypt, which produces 8 % of global fertilizer production [136], has the main target of green hydrogen for ammonia production [140]. Tunisia and Egypt also belong to the MENA hydrogen alliance which has been working actively for the development of the hydrogen value chain in the MENA region since 2020 [141].

Namibia conditionally committed to reducing 42 % of transport emissions by replacing conventional fuels with hydrogen, which represents 3.59 % of the total reduction [142]. Furthermore, Namibia plans to decarbonize the electric mix by 2030 while producing green hydrogen. Small stationary fuel cell systems have already started to be piloted across the country for tourism and residential consumers. The Republic of South Africa, for its part, has committed to using a green hydrogen system to support public transport and the development of fuel-cell electric vehicles in the country [143].

Policy efforts should consider not only decarbonization goals but overall sustainability of hydrogen systems. Beyond the economic and environmental dimensions that have been introduced throughout this review, there is a social dimension to consider. For example, it is needed to address the establishment of high value-added chains based on the processing of raw materials for hydrogen technologies largely available in different Africa countries [144]. Similar attention should be addressed at the end of the hydrogen technology lifecycle for an effective waste management (these considerations are clearly valid and relevant for other clean technologies paths relevant at global and African scale) and avoid/mitigate an emerging global decarbonization divide [145].

3.4. Hydrogen projects under development in Africa

South Africa and Morocco account for more than half of announced hydrogen projects in the continent. Ammonia is the main product of these projects given the high fertilizer demand in the continent. The other targeted end-uses of current hydrogen projects are the mobility, power, and iron and steel sectors. Details on announced hydrogen projects are reported in Table A2, which has been elaborated from the International Energy Agency - Hydrogen Production and Infrastructure Projects Database – in its last release in October 2023 [146].

Depending on each country's hydrogen strategy, project goals vary. In South Africa, the focus is on transitioning the transport sector with hydrogen systems [143]. Many projects planned in the country target methanol, synthetic fuels, or pure hydrogen for the transport sector. Currently, the only operational green hydrogen project in Africa is in South Africa and produces 600 tons annually with a 3.5 MW electrolysis capacity. Together with the other projects that target the production of ammonia, all these projects align with the country's hydrogen roadmap, aiming for inclusive, net-zero carbon economic growth by 2050 [147]. The main priorities include decarbonizing heavy transport and energy-intensive industries, strengthening the green energy sector while creating an export market for the country's green hydrogen and hydrogen-based products including fuel cell components [147].

Egypt focuses on ammonia production for nitrogenous fertilizers, crucial for its agriculture sector. Most of planned hydrogen projects should start before 2030 [140]. It should be noted that the agricultural sector represents 28 % of employment in Egypt and uses 60 % of the local production of fertilizers.

Morocco has already drawn up its "Green Hydrogen" roadmap and is continuing to develop the power-to-X sector within the framework of a partnership agreement signed with Germany on behalf of PAREMA (Moroccan-German Energy Partnership). This agreement aims to develop the green hydrogen production sector and to set up research and investment projects in the use of this energy carrier [148]. The Moroccan government set up a National Green Hydrogen and Power-to-x Commission [149], and created a national research and development platform branded "Green H2A" center. The center is intended as a test platform comprising pilots of small powers (1–5 MW) of electrolysis, green ammonia, green methanol, and synthetic fuels [149]. Furthermore, Morocco's flagship project, boasting a 100 MW electrolyzer capacity, epitomizes the nation's ambition to lead in the global hydrogen market [149]. This project, as indicated in Table 4, should start in 2025 (see Table 5).

Mauritania is very active in the power-to-desert project supported by the African Development Bank Group (AfDB). The 3 billion USD project aims to make the Sahel the world's largest solar energy production region with up to 10 GW installed capacity [150] with availability to produce also green hydrogen. Furthermore, the AMAN project, a fruit of the partnership between the Mauritanian government and the American firm CWP Global, with an estimated total budget of 40 billion USD aims to implement a 30 GW power-to-X project from solar and wind energy in the Northern part of the country [151], producing hydrogen and hydrogen-based products. Finally, the HYPEN project in Namibia comes to strengthen efforts started by South Africa in the establishment of the Southern green hydrogen corridor. The 10 billion USD project aims to produce up to 0.3 million tons of green ammonia for both local use and export. The production is projected to reach 1 million tons of ammonia per year by 2027 [152].

4. Mapping of potential logistic infrastructure for hydrogen in Africa

4.1. Pipelines

Following the same rationale of [153], to assess the potential development of a hydrogen transport system for Africa, it is possible to refer to the already existent and proposed natural gas infrastructure as hydrogen blending or infrastructure repurposing for pure hydrogen transport may be a feasible option. Furthermore, the previous existence of natural gas pipelines and other natural gas infrastructure may speed up the uptake of an industrial hydrogen ecosystem as reported by IRENA [8].

The map in Fig. 2 shows the overall natural gas transport infrastructure currently existing, under construction, planned, and proposed in Africa. The map was created using data from Global Energy Monitor [154] and the International Gas Union [155] for LNG, and canceled, under construction, mothballed, operating, proposed, and shelved pipelines. The potential pipelines map is based on current multilateral discussions among different African countries as reported by the International Gas Union [155]. Currently, the Northern Africa region leads in pipeline infrastructure, boasting about 23,733 km or 77.4 % of the continent's total operational gas pipeline length. This is followed by Western Africa with 4347 km (14.16 %) and Southern Africa with 1565 km (5.1 %). These regions have transportation capacities of 460 bcm/y for Northern Africa, 141 bcm/y for Western Africa, and 6.5 bcm/y for Southern Africa, respectively. The genesis of natural gas infrastructure in Northern Africa traces back to the 1960s with the development of the Hassi R'Mel gas field in Algeria's Saharan desert sector, primarily to meet European natural gas import demands. Consequently, the infrastructure mainly consists of pipelines that carry natural gas from this field to the coast (where also the most relevant domestic consumption is located) and onwards to Europe via four major offshore pipelines.

Much more recent is the development of the infrastructure in Western Africa (coastline of Gulf of Guinea), Central Africa, and Southern Africa (mainly Mozambique) with most developments being offshore pipelines designed to transport gas from offshore fields to feed the LNG terminals. In the near term, it is planned the establishment of an offshore pipeline loop from Nigeria to Spain. For the long term, five key projects stand out: First, South Africa anticipated the largest expansion with an onshore pipeline connecting the Republic of South Africa to Mozambique. Second, another significant project is the proposed trans-Saharan gas pipeline, intending to link the Nigerian and Algerian gas networks through Niger, spanning 4128 km with a capacity of 30 bcm/y.

Table 3
Top 20 operating, under construction, and mothballed pipelines by length.

Countries	Pipeline Name	Status	Capacity [bcm/y]	Length [km]	Diameter [inch]
Algeria, Tunisia, Italy, Slovenia	Trans-Mediterranean Gas Pipeline	Operating	33.5	2,475	48
Algeria, Morocco, Spain, Portugal	Maghreb-Europe Gas Pipeline	Operating	12	1,350	
Nigeria	Trans Nigeria Gas Pipeline	Construction	36.2	1,300	
Egypt, Jordan, Syria, Lebanon	Arab Gas Pipeline	Operating	10	1,200	
Libya	Libya Coastal Gas Pipeline	Operating	6.25	1,164	34
Egypt	South Valley Gas Pipeline	Operating	12	930	36, 32, 30
Mozambique, South Africa	Mozambique-South Africa Gas Pipeline	Operating	5.59	865	
Algeria	In Salah Gas Pipeline	Operating	9	830	
Algeria	Hassi R'Mel-Skikda-El Kala Gas Pipeline	Operating	9	784	48
Algeria	GR-5 Gas Pipeline	Operating	8.8	770	56
Algeria, Spain	Medgaz Gas Pipeline	Operating	8	757	24, 48
Nigeria, Ghana, Togo, Benin	West African Gas Pipeline	Operating	2.07	678	
Libya	Brega-Khoms Gas Pipeline	Operating	11.61	645	34
South Africa	Secunda–Durban Lilly Gas Pipeline	Operating	0.61	600	18
Algeria	Hassi R'Mel-Skikda Gas Pipeline	Operating	20.47	575	40
Algeria	Hassi R'Mel-Skikda II Gas Pipeline	Operating	20.47	575	42
Algeria	Rhourd Ennous-Hassi R'Mel I Gas Pipeline	Operating	12	535	48
Tanzania	Mtwara–Dar es Salaam Gas Pipeline	Operating	8.1	533	36
Algeria	GR-4 Gas Pipeline	Operating	12	531	48
Algeria	Tidikelt-Tamenrasset Gas Pipeline	Operating	7.24	530	16

Table 4
Selected planned/proposed gas pipelines.

Countries	Pipeline Name	Status	Capacity [bcm/y]	Length [km]	Diameter [inch]
Nigeria, Benin, Togo, Ghana, Côte d'Ivoire, Liberia, Sierra Leone, Guinea, Guinea-Bissau, The Gambia, Senegal, Mauritania, Morocco, Spain	Nigeria-Morocco Gas Pipeline	Proposed	30	5660	
Nigeria, Niger, Algeria	Trans-Saharan Gas Pipeline	Proposed	30	4128	48, 56
Mozambique, South Africa	African Renaissance Gas Pipeline	Proposed	–	2600	
Mozambique, South Africa	GasNosu North-South Gas Pipeline	Proposed	–	2600	
Djibouti, Ethiopia	Ethiopia–Djibouti Gas Pipeline	Proposed	12	767	
Tanzania, Kenya	Tanzania–Kenya Gas Pipeline	Proposed	–	600	
Israel, Egypt	Israel–Egypt Offshore Gas Pipeline	Proposed	10	592.62	
South Africa, Namibia	Phased Gas Pipeline Network	Proposed	–	289.17	
Israel, Egypt	Israel–Egypt Onshore Gas Pipeline	Proposed	5	79.35	

The third, fourth, and fifth planned projects include pipelines aiming to connect Ethiopia to Djibouti, Kenya to Tanzania, and South Africa to Namibia.

Further details of gas pipeline infrastructure are reported in Table 3 and Table 4. Notably, Table 3 summarizes the most relevant gas infrastructure in Africa by length including international pipeline corridors with Europe and the Middle East (international corridors are indicated with grey-colored rows in Table 3).

Some of these international pipeline infrastructures are key for hydrogen trading from Africa to abroad, especially with Europe. In particular, according to the European Hydrogen Backbone initiative, involving thirty-three gas transmission system operators and aiming at assessing the future shape of hydrogen backbone in Europe and nearby areas, the European Union will need 32,616 km and 57,662 km of hydrogen gas networks in 2030 and 2040 respectively, whose more than 50 % and 60 % will be natural gas-repurposed infrastructure respectively [153].

The European Hydrogen Backbone has identified the Northern Africa and Southern Europe corridor as strategic for supplying hydrogen to final users (industry, mobility, power, and feedstock), especially in Italy

Table 5
Top 20 operating and under-construction LNG facilities.

Country	Terminal Name	Status	Import/Export	Capacity [Mtpa]	Location	Floating
Nigeria	Nigeria LNG Terminal	Construction	Export	8	Bonny Island	
Egypt	Sumed BW FSRU	Operating	Import	5.7	Port of Ain Sokhna	yes
Angola	Angola LNG Terminal	Operating	Export	5.2	Soyo	
Egypt	Damietta SEGAS LNG Terminal	Operating	Export	5	Damiette Port	
Algeria	Arzew-Bethioua LNG Terminal	Operating	Export	4.7	Bethioua	
Algeria	Skikda LNG Terminal	Operating	Export	4.5	Skikda	
Nigeria	Nigeria LNG Terminal	Operating	Export	4.1	Bonny Island	
Nigeria	Nigeria LNG Terminal	Operating	Export	4.1	Bonny Island	
Nigeria	Nigeria LNG Terminal	Operating	Export	4.1	Bonny Island	
Algeria	Gassi Touil LNG Terminal	Operating	Export	4	Arzew	
Equatorial Guinea	Punta Europa LNG Terminal	Operating	Export	3.7	Malabo	
Egypt	Egyptian LNG Terminal	Operating	Export	3.6	Idku	
Egypt	Egyptian LNG Terminal	Operating	Export	3.6	Idku	
Mozambique	Coral South FLNG Terminal	Construction	Export	3.4	Coral Gas Field	yes
Nigeria	Nigeria LNG Terminal	Operating	Export	3.3	Bonny Island	
Nigeria	Nigeria LNG Terminal	Operating	Export	3.3	Bonny Island	
Nigeria	Nigeria LNG Terminal	Operating	Export	3.3	Bonny Island	
Ghana	Tema FSRU	Construction	Import	1.7	Tema	yes
Algeria	Arzew-Bethioua LNG Terminal	Operating	Export	1.37	Bethioua	
Algeria	Arzew-Bethioua LNG Terminal	Operating	Export	1.37	Bethioua	

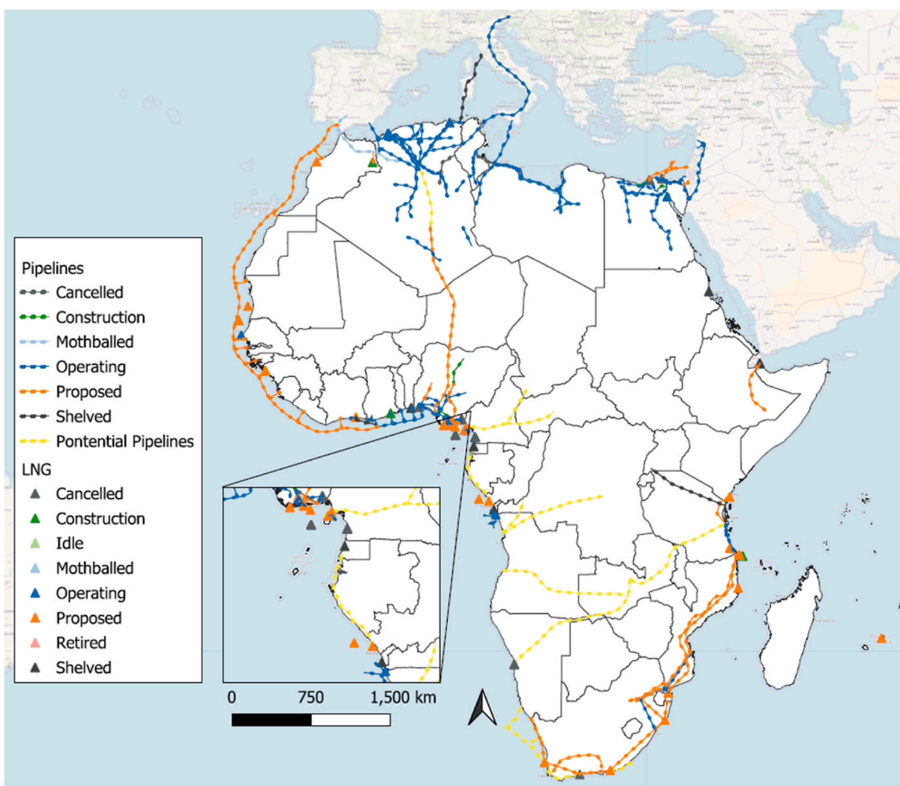

Fig. 2. African gas pipelines and LNG facilities map. Notes: The figure is based on data from the *Global Energy Monitor* and *the International Gas Union* [155].

and Germany, enabling a hydrogen supply potential of ~100 TWh by 2030, increasing to roughly 340 TWh by 2040, entirely produced in Algeria and Tunisia with a supply cost ranging 2.1–3.8 $€_{2022*}$/kg at 2030 and 1.4–2.8 $€_{2022*}$/kg at 2040 [156]. This corridor has the potential to provide up to 25 % of all EU hydrogen imports in 2030. The European Hydrogen Backbone identifies at 2030 the Trans-Mediterranean Gas Pipeline (TRANSMED) as the key infrastructure to import hydrogen from Northern Africa and Southern Europe corridor with its capacity of up to 33.5 bcm/y of natural gas and overall, 52 % share of the total throughput pipeline interconnection capacity between EU and NA [157].

The Southwest Europe & Northern Africa [153] corridor is another potential hydrogen supply route for Europe, enabling a hydrogen supply potential of ~160 TWh by 2030 (potential of 40 % of total imports of the RePowerEU plan), increasing to roughly 570 TWh by 2040, entirely produced in Morocco and Algeria, with a supply cost ranging 2–3.8 $€_{2022*}$/kg at 2030 and 1.4–2.7 $€_{2022*}$/kg at 2040 [156]. The European Hydrogen Backbone [153] considers at 2040 the Maghreb-Europe Gas Pipeline (MEG) as the most important import infrastructure of the Southwest Europe & Northern Africa corridor with its capacity of up to 12 bcm/y of natural gas and overall, 19 % of share of the total throughput pipeline interconnection capacity between EU and Northern Africa [157].

Looking more closely at Fig. 2 and Table 3, an important international pipeline could be the Arab Gas Pipeline, connecting Egypt, Jordan, Syria, Lebanon and with potential to connect with the TANAP-TAP pipeline and provide a further supply to Europe through the East and South-East Europe corridor. In addition, there is the proposed Israel–Egypt Offshore and Onshore Gas Pipeline, as indicated in Table 4 and represented in Fig. 2, that could offer further connection with the planned EastMed-Poseidon project [158]. There is also potential to connect the Western Africa region to Northern Africa - European gas pipeline corridors considering the proposed Trans-Saharan gas pipeline, the Western Africa Gas Pipeline, and the Nigeria-Morocco Gas Pipeline indicated in Tables 3 and 4.

Interestingly, looking at Tables 3 and 4, there is an inter-Africa opportunity for hydrogen transport via existing (with the need of repurposing) and proposed/planned (with the need to be hydrogen-ready) gas infrastructure either in Northern Africa, Southern Africa, and Western Africa which are the most advanced in terms of hydrogen projects and policies and contain many potential users for domestic hydrogen consumption.

4.2. Liquified natural gas terminals

The development of LNG terminals in Africa has been progressing at a varied pace across the continent. Both onshore and offshore terminals are being developed for natural gas export and import. Algeria, Egypt, and Nigeria are major players in LNG exports, with significant installed capacities of respectively 29.34, 12.2, and 23.02 Mtpa of operational LNG facilities. Together, they contain 92 % of the total operational LNG facilities in Africa.

Mozambique and Mauritania are also emerging in the LNG sector with several projects expected to come into operation within the coming years. Mozambique has heavily invested in building LNG facilities in the Rovuma Basin, where more than 19.1 Mtpa capacity of LNG facilities is expected in the short term. Some African countries including Morocco and South Africa are considering LNG import terminals to meet their growing energy demands, with announced LNG terminal projects totaling 5.15 Mtpa and 4 Mtpa, respectively.

Further details of LNG terminal installations and projects in Africa are reported in Table 7 and Table 6.

Similarly for the gas pipelines, existing LNG terminals can ensure a proper ecosystem for the development of the hydrogen supply chain, especially for export purposes via liquefaction routes and other hydrogen-based liquid carriers. It is reported that modification of existing LNG infrastructure could accommodate the hydrogen supply chain by reducing costs by about 50–60 % than building new infrastructure, this is relevant for retrofitting cryogenic liquefaction cycles and LNG storage tanks. Savings have been also mentioned in the case of terminals with either LNG or liquid hydrogen shipping for the possibility of sharing common equipment and auxiliary utilities [16].

Existing LNG facilities also encompass trading relations among countries that could be of high interest and again accelerate the establishment of hydrogen corridors. As reported by BP Statistics 2022, around 60 % (or about 9.1 billion cubic meters) of exported LNG from Algeria reaches Europe (France, Spain, and Italy ranking as top importer countries). Most LNG exports (about 75 %) from Angola reach the Asia Pacific region. Two-thirds of exported LNG from Egypt is again supplied to the Asia Pacific region (China and India) while slightly less than 15 % is imported in Europe. More than half of Nigeria's exports of LNG reach Europe, especially France and Spain. Other African exports, around 70 % of the total exports, again are supplied to the Asia-Pacific region [159].

5. Mapping potential domestic industrial off-takers of hydrogen

Hydrogen is among the possible alternatives for the decarbonization of hard-to-abate sectors acting as a fuel for high-temperature heat generation in industry or heavy-duty road and rail transport and as feedstock in industrial sectors such as ammonia and methanol synthesis. With its tremendous land dimensions and limited countries with access to the sea, the logistics of goods within the African continent rely mostly on heavy-duty road transportation systems and unelectrified railways. This constitutes one of the potential areas of green hydrogen use in the continent. Furthermore, in Africa, many industrial sectors including the iron and steel industry, ammonia and methanol processing industry, and refineries, are well established and constitute potential future off-takers of green hydrogen.

Fig. 3 illustrates selected industrial installations including iron and steel plants, ammonia plants, and refineries. Northern Africa is the region with most of these installations followed by Western Africa and Southern Africa. The map in Fig. 3 was built based on the actual physical address of each plant. The geographical coordinates were found either on each company website or by searching on Google Maps except for the iron and steel industries for which all data were collected from Global Energy Monitor [160]. Regarding the main trading corridors in sub-Saharan Africa reported in Fig. 3, both roads and railways were georeferenced based on the map provided by the Africa Fertilizer Map initiative [161].

Africa produces slightly more than 1 % of global raw steel with about 22.2 million tons per year in 2021 (world production of raw steel in 2021 was 1950 million tons). Half of the raw steel production in Africa takes place in Egypt (around 10 million tons of raw steel) followed by South Africa and Algeria (with around 5 and 4 million tons of raw steel respectively). Other producing countries are Kenya, Libya, Mauritania, Morocco, Nigeria, Rwanda, Tanzania, Tunisia, Uganda, and Zambia [162].

Table 6
Selected planned/proposed LNG terminals.

Country	Terminal Name	Status	Start Year	Import/Export	Capacity [Mtpa]	Location	Floating
Cameroon	Etinde FLNG Terminal	Proposed	2023	Export	1.3		yes
Guinea	Guinea LNG Terminal	Proposed	2023	Import	–	Kamsar	
Guinea	Guinea LNG Terminal	Proposed	2023	Export	–	Kamsar	
Mauritania	New Fortress Banda LNG Terminal	Proposed	2024	Export	–	Banda gas field	
Morocco	Morocco FSRU	Proposed	2022	Import	–		yes
Morocco	Jorf Lasfar LNG Terminal	Proposed	2025	Import	5.15	Jorf Lasfar	
Mozambique	Rovuma LNG Terminal	Proposed	2025	Export	7.6	Afungi peninsula	
Mozambique	Rovuma LNG Terminal	Proposed	2025	Export	7.6	Afungi peninsula	
Mozambique	Matola FSRU	Proposed	2025	Import	0.5	Matola	yes
Nigeria	Nigeria LNG Terminal	Proposed	2026	Export	3.4	Bonny Island	
Nigeria	UTM Offshore FLNG Terminal	Proposed	2026	Export	1.52	Yoho field	yes
Congo Rep	Congo FLNG Terminal	Proposed	2023	Export	1.4		yes
South Africa	Richards Bay FSRU	Proposed	2026	Import	1	Richards Bay	yes
South Africa	Saldanha Bay FSRU	Proposed	2022	Import	1	Saldanha Bay	yes
Tanzania	Tanzania LNG Terminal	Proposed	2027	Export	5	Lindi	
Tanzania	Tanzania LNG Terminal	Proposed	2027	Export	5	Lindi	

Table 7
Operating iron and steel plants with potential H_2 utilization.

Plant name	Country	Status	Start year	Nominal crude steel capacity (ttpa)	Nominal DRI capacity (ttpa)	Detailed production equipment	Hydrogen Consumption Range, H2 [kt/y]	
Algerian Qatari Steel Jijel plant	Algeria	operating	2013	2200	2500	1 Midrex DRI plant (2.5 MTPA); 2 EAF	68	129
Sider El Hadjar Annaba steel plant DRI expansion	Algeria	proposed	2021	N/A	2500	1 DRI	68	129
Tosyali Algerie Oran steel plant	Algeria	operating	2008	3700	2500	1 Midrex DRI plant (2.5 MTPA); EAF	68	129
Tosyali Algerie Oran steel plant DRI expansion	Algeria	proposed	unknown	N/A	2500	1 DRI plant (Midrex and Paul Wurth)	68	129
Egyptian Sponge Iron and Steel Company Sadat City plant	Egypt	operating	2008	3000	2000	1 Midrex DRI plant (1.76 MTPA); 2 EAF	55	104
Al-Ezz Dekheila Steel Alexandria plant	Egypt	operating	1986	3200	3100	3 Midrex DRI plants (Midrex 1 (0.72 MTPA), Midrex 2 (0.8 MTPA), Midrex 3 (0.8 MTPA)); 4 EAF	85	160
Ezz Flat Steel Ain Sokhna plant	Egypt	operating	1993	2300	1900	1 DRI plant; 1 EAF (185-tonne)	52	98
Suez Steel Solb Misr Attaka plant	Egypt	operating	2000	2050	1950	DRI plant; 2 EAF	53	101
Libyan Iron and Steel Misrata plant	Libya	operating	1979	1750	1750	2 Midrex DRI plants (1.1 MTPA total), Midrex 3 (0.65 MTPA); 6 EAF (3 × 90-tonne, 3 × 90-tonne)	48	91
Delta Steel Company Warri plant	Nigeria	operating	1982	1300	1020	1 Midrex DRI plant (1.02 MTPA); EAF	28	53
ArcelorMittal Newcastle Steel Works	South Africa	operating	1971	1900	250	coking plant; sinter plant; Corex BF-DRI plant (C-1000, 0.5 MPTA); 3 BOF	7	13
ArcelorMittal Vanderbijlpark Steel Works	South Africa	operating	1947	4500	950	coking plant; sinter plant; DRI plant; 2 BF; 3 BOF	26	49
ArcelorMittal Saldanha Steel Works	South Africa	mothballed	1998	1200	800	2 Corex BF-DRI plants (2 C-2000 + Midrex DRI, 1.6 MTPA total); EAF (# unknown)	22	41
African Natural Resources & Mines Kaduna steel plant	Nigeria	operating	2020	1000	1000	pellet plant; DRI plant; EAF	27	52
						Total	**677**	**1279**

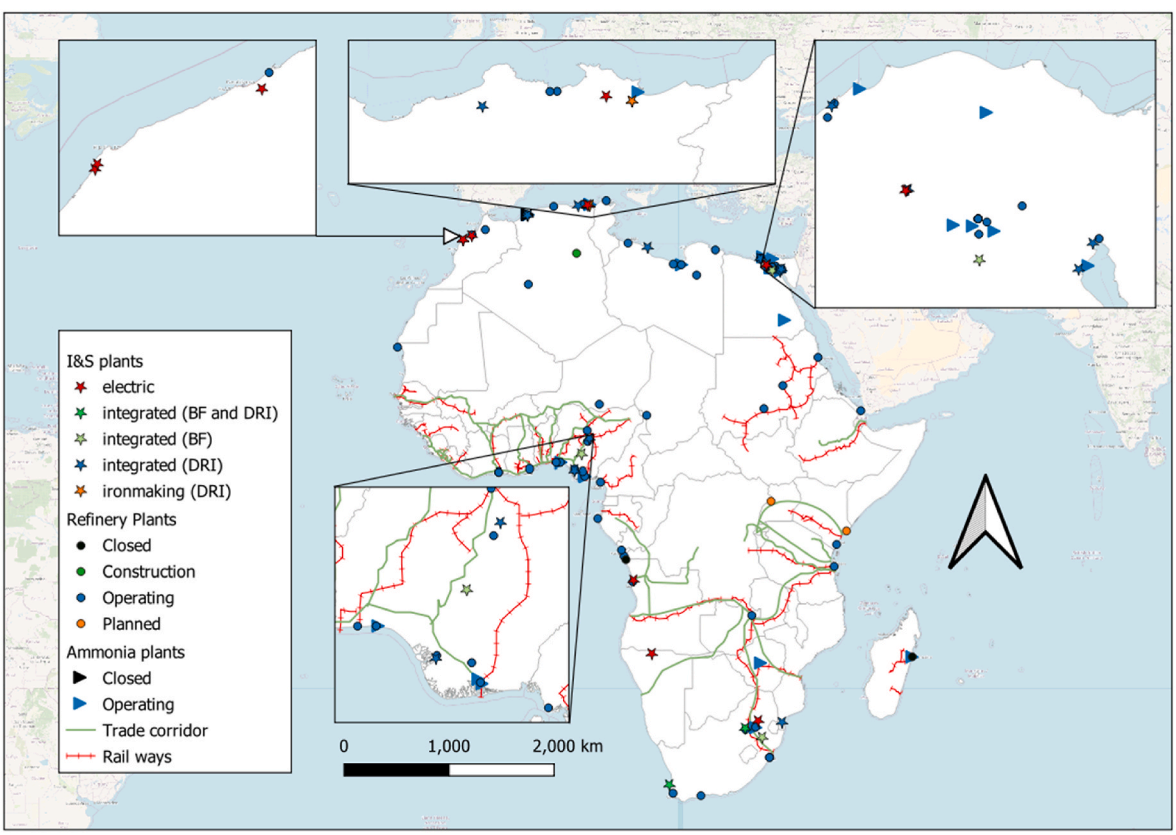

Fig. 3. Map of selected African industry plants and main sub-Saharan trade corridor and railways. Notes: *The figure is based on data from Global Energy Monitor* [154], *Energy Capital and Power, Africa Fertilizer Map, and the United States Geological Survey (USGS). The plants were georeferenced based on their physical addresses.*

Africa is also an ammonia producer sharing 5 % of global production with around 9.9 million tons per year (global production in 2021 was around 182 million tons). Egypt is again sharing almost half of African production (around 5 million tons per year) followed by Algeria and Nigeria. Libya and South Africa also have facilities for ammonia production [163]. Ammonia deserves special attention since it is considered a major hydrogen carrier for future global hydrogen trading. Indeed, according to IRENA outlook, ammonia could share most of the hydrogen trading through shipping (accounting for 45 % of total global trading in 2050) [15].

Finally, refineries throughout Africa in 2021 were around 1,800,000 barrels per day sharing 2.3 % of global production (around 80,000,000 barrels per day). Around half of this production is located in Egypt, Algeria, and South Africa. Nigeria is also a key player [159].

Fig. 3 also illustrates the main sub-Saharan railways and trade corridors via road. 36 of 54 African countries have railway infrastructure extending over a total length of nearly 85,000 km, of which approximately 70 % is fully operational [164,165]. Almost all these infrastructures were built during the colonial era and are still not electrified; the few electrified railways are located in Northern Africa and the Republic of South Africa [10]. The railway that connects Adis Ababa and Djibouti, 756 km long, is the only transnational fully electrified railway, the remaining transnational sub-Saharan railways are unelectrified [166,167]. This offers a possibility of migrating from diesel traction currently used to traction based on hydrogen. On the other hand, road transportation still represents 80 % of freight transport [164]. The development of hydrogen systems could therefore contribute to decarbonizing heavy-duty transportation.

Subsections 5.1 to 5.4 examine the potential readiness for hydrogen demand in selected hard-to-abate sectors of Africa's economy, including iron and steel, ammonia and methanol production, oil refineries, and maritime logistics in African ports. However, the authors do not claim to have covered all the issues linked to the hydrogen value chain in Africa. Especially the potential hydrogen demand is based on existing industrial capacity without including expansion correlated with population increase or economic development. Furthermore, all data used are secondary data, which, despite cross-checking, can still lead to some not accurate estimation.

5.1. Iron and steel industry

According to the World Steel Association, in 2022 the total steel production in the African continent was 21.1 million tons slightly decreased compared to 2021 (22.3 million tons) but increased compared to 2020 (19.1 million tons) and the previous years. Only 13.3 % of the total steel was produced with the Basic Oxygen Furnace (BF-BOF) and 86.7 % with electric arc furnace (EAF); 52.5 % of the iron produced in South Africa in 2022 was produced with BOF, hence excluding South Africa only 7.3 % of the steel produced in Africa is produced with the traditional route. Iron and steel industries use three main different routes for manufacturing including the traditional Integrated Blast Furnace coupled with Basic Oxygen Furnace (BF-BOF)), the integrated Direct Reduction coupled with Electric Arc Furnace (DR-EAF), and the scrap-EAF routes [168] that are fully electrified and use recycled steel as the main input. Direct Reduction Iron (DRI)-based plants use hydrogen from natural gas or syngas to directly reduce iron oxide into DRI. The DRI is then used in an EAF to complete the steel-making process. Most of the time the DRI is combined with recycled steel (scrap) at a variable ratio. Finally, the traditional steel-making process uses a BF to produce liquid pig iron that is then refined in BOF to complete the steel production. Despite the lowest cost of production, BF-based plants are the most polluting plants in the iron and steel industry. However, the usage of alternative fuels such as biochar, methane, or hydrogen to replace partially or completely coke that is currently used can significantly improve the environmental impact of the process [169].

To estimate the potential of hydrogen consumption in the African iron and steel industry, the authors considered only the existing DR-EAF plants and hybrid plants that include both BF and DR modules. According to IEA, the specific hydrogen consumption per ton of direct reduced iron produced lies in the range of 47–68 kg/t of DRI [170].

An average value of 57.5 kg/t of DRI was considered in the calculation. The capacity factor of the DR plants in Africa in 2021 was calculated according to Midrex statistics [171] to be 48 % which is a very low number for the optimal economics of these plants. Table 7 shows the potential needs of hydrogen in the case of 100 % fuel switching for the analyzed plants considering both the actual capacity factor and a capacity factor of 90 % that would guarantee the optimal economics for the production. Results are presented in Table 7 for the different plants located in African countries. From the findings, it is highlighted that the iron and steel sector in Africa could consume up to 1.28 million tons of hydrogen per year considering the existing and near-term proposed DR-EAF plants. Egypt and Algeria would require around 75 % of the total assessed hydrogen consumption.

5.2. Ammonia and methanol production

Historically, many African countries have been relying on ammonia imports to meet their agricultural needs. However, some African countries, mainly Egypt, Algeria, and Nigeria, have started developing domestic ammonia production facilities. The current hydrogen need in the operating ammonia plants on the continent has been estimated considering the stoichiometric reaction for ammonia formation from molecular nitrogen and hydrogen which leads to around 176.5 kg of hydrogen per ton of ammonia [172]. Following the result reported in Table 8, the current hydrogen needs to meet the total installed ammonia production capacity in Africa is around 2.1 million tons per year.

Egypt and Algeria have a big share of African ammonia industries with respectively 0.706, and 0.386 million tons of hydrogen needed per year. Given the potential benefits of ammonia in agriculture and its

Table 8
Top 10 operating ammonia plants.

Country	Name	Location	Status	Capacity [kt/y] NH_3	H_2 need [kt/y]
Nigeria	Dangote fertiliser	Lagos	Operating	2800	494.1
Egypt	Egyptian Fertilizer Company - EFC	Suez	Operating	1550	273.5
Nigeria	indorama eleme fertilizer & chemicals limited	Port Harcourt	Operating	1500	264.7
Algerie	El Sharika El Djazairia El Omania lil Asmida SpA" (AOA SpA)	Mers El Hadjadj	Operating	1460	257.6
Egypt	Misr Fertilizers Production Company (MOPCO)	Cairo	Operating	1276	225.2
Lybia	Lifeco Urea Plant	Marsa al Brega	Operating	803	141.7
Algerie	Arzew-Fertial	Arzew	Operating	730	128.8
Egypt	Egypt Basic Industries Corporation (EBIC)	Cairo	Operating	730	128.8
South Africa	SASOL	Secunda	Operating	600	105.9
Egypt	Abu Qir Fertilizers Company (AFC)	Alexandria	Operating	449	79.2
			Total	**11,898.0**	**2099.6**

emerging role in the energy sector, it is likely that the interest and developments in ammonia production in Africa will continue to evolve in the coming years.

Methanol production is much smaller compared to the production capacity of ammonia. At present, there are few dedicated methanol production plants in Africa. To synthesize methanol, various feedstocks can be used, including natural gas, coal, biomass, and municipal waste, depending on the availability of resources in specific regions. The main feedstock is natural gas that can be substituted with green hydrogen when it is available. The amount of hydrogen required for methanol production can be estimated considering different processing routes that lead to 125–188 kg of hydrogen per ton of methanol [173].

Given the installed capacity of methanol plants (not reported on the map of Fig. 3), the estimated hydrogen needs in the sector range from 0.9 million tons per year to 1.3 million tons per year. The details of each plant are summarized in Table 9.

5.3. Refineries

Countries with well-developed refining industries include Algeria, Egypt, South Africa, Nigeria, Libya, and Morocco. The oil refining sector is one of the biggest producers and consumers of hydrogen which is used mainly for the removal of sulfur from crude oil and upgrading heavier crude via hydrocracking. In particular, the hydrogen consumption in the hydrocracking process varies, depending on the feed composition, from 1000 to 2000 standard cubic feet (SCF) per barrel of crude oil [174,175]. Hydrotreating, or catalytic hydrogen treating is a process that involves the use of hydrogen to remove materials, mainly sulfur from the stream feed [176]. Depending on the sulphury content, at least 500 SCF of hydrogen is needed per barrel of crude for sulphury removal through hydrofining. To estimate the present hydrogen need in the refinery sector of the continent, an average value of 2000 SCF hydrogen per barrel of crude oil was used [175]. The top 20 refineries in Africa by capacity and their estimated hydrogen need are reported in Table 10 with a total consumption for the continent estimated at 8.63 million tons of hydrogen per year.

5.4. Mapping African ports as potential hydrogen off-takers

Ports are key infrastructures for the development of the hydrogen value chain either as hubs for trading or as potential hydrogen off-takers for achieving decarbonization targets. Africa contributed to global maritime trading with 35,806,550 TEU (Twenty-foot Equivalent Units) in 2022, corresponding to about 4 % of global maritime container transport. Fig. 4 depicts major African countries for maritime container transport with data updated at 2022 according to the United Nations Conference on Trade and Development - UNCTAD [177]. In addition, Africa has an important role for liquids maritime trading. According to UNCTAD data in 2019, crude oil loading in Africa accounted for 13 % (equivalent to 226 million metric tons) of global crude oil loading with Northern Africa sharing 27 %, Central Africa sharing 39 % and Western Africa sharing 34 % of total crude oil loading in Africa. Notably, other tanker trade loaded (e.g., ammonia) in Africa accounted for 100 million metric tons in 2019, and around 8 % of global tanker trade loaded. Northern Africa, Central Africa, and Western Africa shared respectively 45 %, 14 %, and 31 % of the total other tanker trade loaded in the continent. According to Statista [178] elaborations, exports of ammonia were 1346 thousand metric tons in 2022 from Algeria and 675 thousand metric tons in 2022 from Egypt.

Africa shows therefore an articulated port infrastructure that could benefit from hydrogen production for the decarbonization of port operations and maritime transport and offer also valuable opportunity for maritime trading of hydrogen in liquid form or through ammonia carriers. Therefore, ports could be a further off-taker for domestic hydrogen consumption especially if sector coupling with industry and logistic hubs are considered as multiple-use consumption clusters. According to IEA, in 2022, international shipping contributed approximately 2 % of global energy-related CO_2 emissions, underscoring its significant role in climate change dynamics [179]. The International Maritime Organization (IMO) has updated its emissions reduction targets, aligning them with the Paris Agreement's objectives and indicating a nearly 15 % reduction in emissions from 2022 levels by 2030. A key international initiative for green ports is the C40 Ports & Shipping Program [180]. Some African cities join this network including Dakar, Freetown, Abidjan, Accra, Lagos, Nairobi, and Addis Ababa. The C40 Ports & Shipping Program aims to create a proactive community through partnerships involving cities, ports, and the industry sector to boost the necessary transformations for a carbon-neutral future. When dealing with energy consumption in ports, three main services can be considered including ship logistics, port logistics, and electricity-based services. The most relevant source of consumption and greenhouse gas emissions is represented by ships' operation in the port, which includes consumption for maneuvering and berth operation (stationary operation), the latter accounting for around 85–95 % of the total fuel consumption [181]. Several technologies have been indicated for decarbonizing logistics of ships in ports especially for berth operations like cold ironing and the use of alternative and clean fuels including hydrogen and ammonia that could be also used as maritime fuels. Indeed, electrification through cold ironing, while effective, is limited by the substantial investments required and the dependency on shore-based infrastructure. In contrast, hydrogen and ammonia offer onboard solutions that can reduce the port's overall emissions, especially during berthing operations [181]. In Ref. [181], it is shown how hydrogen can decarbonize berth operations in ports, fast and at a lower cost if the synergy with industrial decarbonization pathways takes place. Indeed, ports could benefit from low prices for hydrogen and its utilization in multiple typologies of users following a cluster-oriented decarbonization policy.

Fig. 5 summarizes the most important ports in Africa with an indication of size in terms of TEU. The map was built starting from data available in Ref. [182] and complementing with information available from individual port authorities. It is evident from Figs. 3 and 5 how ports can be either a booster and a hub for the hydrogen industry in Africa enabling supply (e.g., production, trading, bunkering) and demand side value chains in a cluster-oriented perspective. For demand-side value chains, opportunities arise from road freight closely connected with ports logistics and trading, cargo handling at ports and ship operations, synergies with industrial users and urban areas, and hydrogen for shipping (bunkering and domestic transport) either in pure form or in other liquid carriers. The different shares of these final uses will depend on ports archetypes as described in Ref. [183] encompassing

Table 9
Existing and under-construction methanol plants.

Country	Name	Location	Status	Capacity	H_2 need [kt/y]
Egypt	Methanex Egipt	Cairo	Operating	1300 kt/y	162.5–243.8
Libya	Thyssenkrupp Industrial Solutions	Brega	Operating	2 × 1.25 kt/d	114.1–171.1
Nigeria	Brass Fertilizer and Petrochemical Company Limited (BFPCL)	Odioma	Construction (2024)	10 kt/d	456.3–684.4
South Africa	Sasol	Johannesburg	Operating	–	–
Equatorial Guinea	Atlantic Methanol Production Company LLC ("AMPCO")	Bioko Island	Operating	1 Mt/y (2001)	125.0–187.5
Algeria	Sonatrach Arzew Methanol Plant	Oran	Construction (2026)	80 kt/y	10.0–15.0
			Total	**6942.5 kt/y**	**867.8–1301.7**

Table 10
Top 20 operating refineries plants by capacity.

Country	Name	Location	Status	Capacity [kbbl/d]	H_2 [kt/y]
Nigeria	Dangote Refinery (Dangote Group of companies)	Lagos	Operating	650	1125.3
Algeria	Skikda Refinery (Sonatrach)	Skikda	Operating	350	605.9
Libya	Ra's Lanuf Refinery (National Oil Corporation)	Ras Lanuf	Operating	220	380.9
Nigeria	Port Harcourt Refinery (NNPC)	Rivers	Operating	210	363.6
South Africa	Sapref Refinery (a joint venture of Royal Dutch Shell and BP) (Sapref)	Sapref	Operating	180	311.6
South Africa	Sasol Refinery (Secunda CTL) (Sasol)	Secunda	Operating	150	259.7
Egypt	Cairo Mostorod Refinery (EGPC)	Cairo	Operating	142	245.8
South Africa	Engen Refinery (Enref) (Petronas)	Wentworth	Operating	135	233.7
Egypt	El Nasr Refinery (EGPC)	Suez	Operating	132	228.5
Morocco	Mohammedia Refinery (SAMIR)	Mohammedia	Operating	127	219.9
Nigeria	Warri Refinery (NNPC)	Delta	Operating	125	216.4
Libya	Zawiya Refinery (National Oil Corporation)	Az-Zāwiyah	Operating	120	207.7
Egypt	Alexandria El Mex Refinery (EGPC)	Alexandria	Operating	117	202.6
Nigeria	Kaduna Refinery (NNPC)	Kaduna	Operating	110	190.4
South Africa	Natref Refinery (a joint venture between Sasol and Total South Africa)	Sasolburg	Operating	108	187.0
Algeria	Skikda condensate Refinery (Sonatrach)	Cité bouloudani	Operating	100	173.1
Egypt	Alexandria MIDOR Refinery (EGPC)	Alexandria	Operating	100	173.1
South Africa	Cape Town Refinery (Chevref) (Chevron South Africa)	Milnerton Industrial	Operating	100	173.1
Soudan	Khartoum Refinery (Sudan Khartoum Refinery Company)	Hillat ed Dareisa	Operating	100	173.1
Egypt	Alexandria Ameriya Refinery (EGPC)	Cairo	Operating	81	140.2
			Total	**3357.0**	**5811.7**

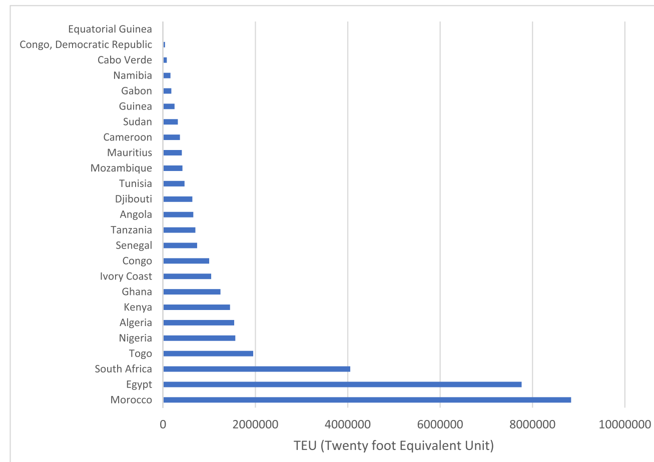

Fig. 4. Ports capacity aggregated for different African countries. Data from United Nations Conference on Trade and Development - UNCTAD at 2022 with the exception of Congo, Democratic Republic (2019) Algeria, Cameroon, Guinea, Gabon, Equatorial Guinea (2020), and Ivory Coast (2021).

industrial archetype, logistics and transport archetype, bunkering archetype, and urban archetype.

6. Conclusion

The African continent has enormous potential for establishing a sustainable green hydrogen system. This study reviews the potential for hydrogen value chain in the continent considering perspectives for global trading as well as domestic utilization. The study highlights the potential for green hydrogen production, infrastructure for its handling, and applications in final uses. Furthermore, existing policies and projects are reviewed with respect to energy and climate medium and long-term plans of individual African countries. While considering the entire regional African perspective, this review also highlights some specific sub-regional and individual-country features investigating main pathways undertaken by African power pools.

A main feature of this review is also the sharing of detailed georeferenced maps and technical data of key infrastructure for hydrogen consumption including individual industrial installations, the most important road and railway corridors in Africa. Specific maps are also presented showing location of key infrastructure and technical data for the required hydrogen logistics including gas transport pipelines, liquefication facilities, most important ports in the continent.

The tremendous untapped solar, wind, and hydro energy are among the best options for hydrogen production in the continent with a great potential of reaching a production cost of less than or equal to 1.5 $€_{2018}$/kg by 2050. Firstly, self-produced green hydrogen could contribute to decarbonizing hard-to-abate industrial sectors in the continent. The study reviews potential industrial off-takers of hydrogen resulting in an estimated hydrogen need for the decarbonization of selected industrial sectors which ranges from 667 to 1279 kt/y for the iron and steel industries; 2099.6 kt/y for the ammonia industry, 867.8 to 1301.7 kt/y for methanol, and 8670 kt/y for refineries. Therefore, the total estimated

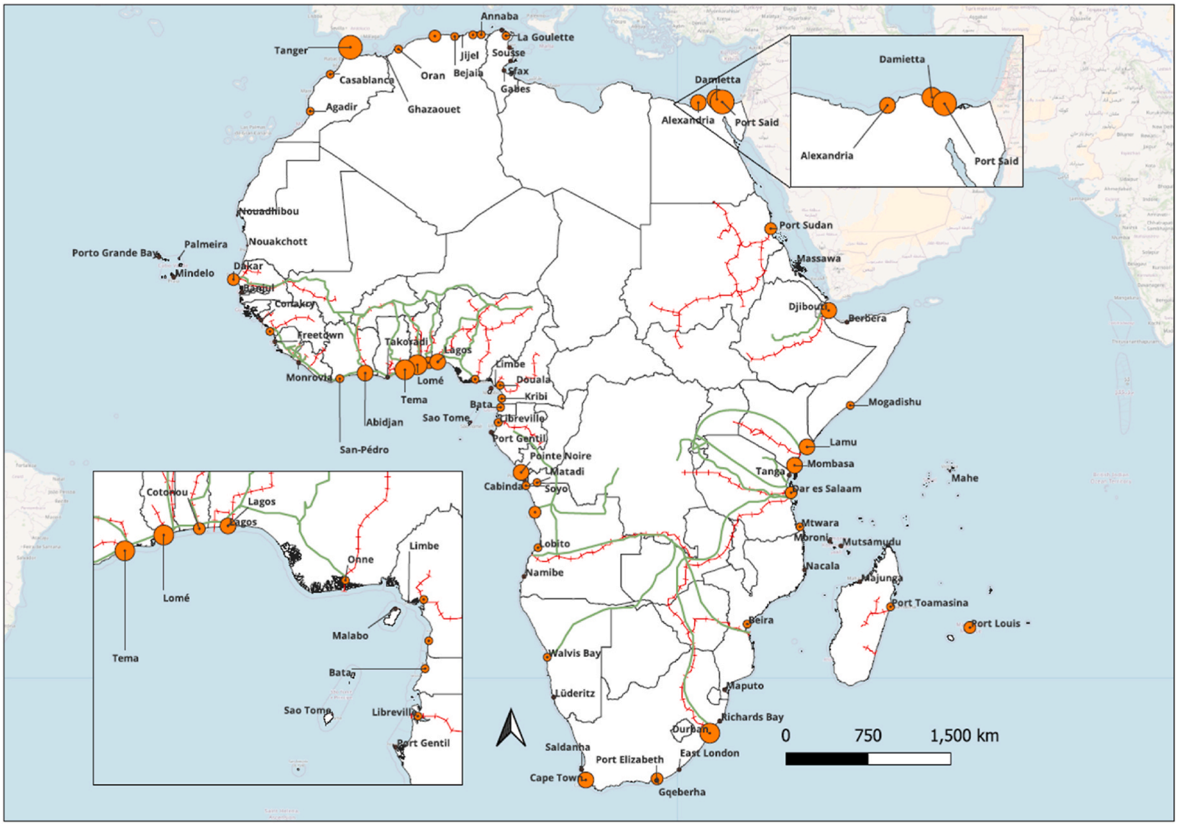

Fig. 5. Map of African ports and main sub-Saharan trade corridor and railways. Notes: This figure has been elaborated based on data available on PwC [182] and at the individual port authority.

low-hanging fruit green hydrogen need (still with not competitive cost) is around 13 million tons per year meaning focusing in those sector that already use hydrogen from fossil fuel production and that rely on it mostly as a feedstock.

However, the lack of strong and clear regulations and policies in many African countries still hinders the development of hydrogen systems in the continent. The review shows how Morocco and South Africa have established clear hydrogen roadmaps and, through an analysis of NDCs submitted by African countries, it highlights that five African countries have indicated hydrogen technologies as a possible mitigation solution. In addition, dedicated hydrogen infrastructures are also needed. The study presents a detailed overview of the well-established gas infrastructure in the continent that could be repurposed or used for both gas and hydrogen transportation.

Many hydrogen projects are announced on the continent, the majority of which target the production of ammonia for fertilizer production followed by methanol and synfuels for mobility applications. Among the numerous announced hydrogen projects, few of them have reached the construction and operating phase. Therefore, there is still room for investments in the sector to capitalize on the massive renewable energy resources of the continent for green hydrogen production and to make Afrique a key player in fast fast-growing hydrogen market both for domestic use and export.

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.2024.115004.

Appendix B. Supplementary data

Table A1
Existing, planned, and potential of RES-based power plants in Africa.

	Country	Hydro			Solar			Wind			Population 2021	GDP per capita 2021	with access to elec. 2020	Water stress
		Existing [131]	**Proposed** [131]	**Potential** [184]	**Existing** [131]	**Proposed** [131]	**Potential** [184]	**Existing** [131]	**Proposed** [131]	**Potential** [184]	[185]	[186]	[187]	[8]
		MW	**MW**	**MW**	**MW**	**MW**	**TWh/y**	**MW**	**MW**	**TWh/y**				
1	Cameroon	1382.0	9092.4	23,970.0	0.1	231.8	13,811		155.4	994.9	27,198,628	1666.9	64.7	Low
2	Central Afriacan Rep	20.2	554.4	2041.0	25.9		8755			79.0	5,457,154	461.1	15.5	Low
3	Chad				149.5	447.5	20,790			11,262.7	17,179,740	685.7	11.1	High
4	Congo Rep	235.5	6455.3	2565.0			6780				5,835,806	2290.4	49.5	Low
5	DR Congo	2741.7	35,786.5	100,000.0	12.5	864.0	35,301			2214.4	95,894,118	577.2	19.1	Low
6	Equatorial Guinea	313.2		2607.5	4.8		706				1,634,466	7506.7	66.7	Low
7	Gabon	441.2	621.4	6007.8			5408				2,341,179	8635.3	91.6	Low
	Total CA	**5133.8**	**52,510.0**	**137,191.3**	**192.8**	**1543.3**	**91,551**	**0.0**	**155.4**	**14,551.0**	**155,541,091**			
8	Burundi	63.3	467.1	1761.0	7.5	14.4	1674				12,551,213	221.5	11.7	Low
9	Djibouti				27.8	310.5	1799	86.3	115.8	1160.4	1,105,557	3150.4	42.3	High
10	Eritrea				6.9		9124		26.6	3695.5	3,620,312	643.8	52.2	High
11	Ethiopia	10,192.1	10,790.9	46,500.0	481.4	864.0	50,113	675.8	1216.5	19,821.0	120,283,026	925.1	51.1	Low
12	Kenya	737.5	1463.2	9000.0	334.0	746.5	38,445	842.4	627.9	28,941.7	53,005,614	2081.8	71.4	Low
13	Rwanda	112.1	71.0	524.8	15.5	40.1	1681				13,461,888	822.3	46.6	Low
14	Seychelles				6.9	4.2		6.6			99,258	14,653.3	100.0	Low
15	Somalia	4.3		4.6	27.8	0.1	38,843			63,048.7	17,065,581	447.0	49.7	Low
16	South Sudan		2060.9	2951.7	1.2	20.8	55,079			24,814.0	10,748,272	1071.8	7.2	Low
17	Sudan	2060.9	2060.9	4923.2			110,158		324.1	50,606.1	45,657,202	751.8	55.4	Medium
18	Tanzania	2445.8	2310.1	4280.0		334.0	70,286	2.4	975.8	21,540.4	63,588,334	1099.3	39.9	Low
19	Uganda	1549.1	2310.1	4700.0	103.7	160.8	18,052		30.9	939.5	45,853,778	883.9	42.1	Low
	Total EA	**17,165.1**	**21,534.2**	**74,645.3**	**1012.7**	**2495.4**	**395,254**	**1613.5**	**3317.6**	**214,567.3**	**387,040,035**			
20	Algeria	235.5			644.9	268.3	54,434	11.0	21.4	32,844.3	44,177,969	3690.6	99.8	High
21	Egypt	2741.7	4088.6	3715.7	2234.6	1075.8	58,823	2356.9	2034.7	43,358.9	109,262,178	3698.8	100.0	High
22	Libya				96.4	288.6	25,802	26.6	167.3	27,878.0	6,735,277	6357.2	69.7	High
23	Morocco	1946.5	826.7	54.0	803.1	1794.6	30,282	2189.9	842.4	13,606.8	37,076,584	3795.4	100.0	Low
24	Tunisia	59.8		56.0	34.6	4993.6	6690	279.8	782.7	8312.5	12,262,946	3807.1	100.0	High
	Total NA	**4983.5**	**4915.3**	**3825.7**	**3813.6**	**8420.9**	**176,031**	**4864.2**	**3848.5**	**126,000.5**	**209,514,954**			
25	Angola	6097.1	5137.4	7809.0	96.4	693.9	23,105		675.8	202.0	34,503,774	1953.5	46.9	Low
26	Botswana				53.7	77.4	26,834			10,096.0	2,588,423	6805.2	72.0	High
27	Comoros				2.9	37.3					821,625	1577.5	86.7	Low
28	Eswatini	56.5	118.7	78.2	10.0	103.7	1131			485.7	1,192,271	3978.4	79.7	Low
29	Lesotho	177.0	1164.4	301.2		96.4	2060		51.6	642.8	2,281,454	1094.1	47.4	Medium
30	Madagascar	235.5	2589.5		103.7	89.6			21.4		28,915,653	500.5	33.7	Low
31	Malawi	371.7	1463.2	1042.0	160.8	53.7	9684		260.0	2290.5	19,889,742	634.8	14.9	Low
32	Mauritius	56.5			77.4	25.9		41.4	48.0		1,266,060	9106.2	99.7	Low
33	Mozambique	2310.1	3445.0	6269.0	72.0	310.5	38,875	124.7	241.5	11,206.1	32,077,072	491.8	30.6	Low
34	Namibia	313.2	657.9	720.0	186.1	359.4	55,899	5.3	86.3	15,697.9	2,530,151	4865.6	56.3	High
35	South Africa	3253.8	1382.0	902.0	2993.6	20,025.7	85,518	3942.3	7096.8	48,830.4	59,392,255	7055.0	84.4	Medium
36	Zambia	2902.8	3647.4	6113.0	120.1	1930.7	33,585		434.8	14,389.6	19,473,125	1137.3	44.5	Low
37	Zimbabwe	1038.8	1736.5	1970.0	120.1	3220.6	27,738			13,184.6	15,993,524	1773.9	52.7	Low
	Total SA	**16,813.0**	**21,342.0**	**25,204.4**	**3996.8**	**27,024.8**	**304,429**	**4113.7**	**8916.2**	**117,025.6**	**220,925,129**			
38	Benin	140.9	621.4	505.9	25.9	49.9	3898			405.0	12,996,895	1319.2	41.4	Low
39	Burkina Faso	45.0	79.6	150.0	249.4	215.4	7742			4161.5	22,100,683	893.1	19.0	High
40	Cape Verde		26.9		14.4	22.3		26.6	12.8		587,925	3293.2	94.2	Low
41	Gambia			12.0		215.4	790		3.9	174.3	2,639,916	772.2	62.3	Low
42	Ghana	1549.1	696.6	1904.4	288.6	644.9	7873	241.5	1216.5	608.4	32,833,031	2363.3	85.9	Low
43	Guinea	1164.4	3647.4	5713.0		288.6	5671			2.0	13,531,906	1189.2	44.7	Low
44	Guinea-Bissau		19.1	184.0		24.0	2399			124.0	2,060,721	795.1	33.3	Low
45	Ivory Coast	926.7	1305.3	1809.7		334.0	10,546			430.0	27,478,249	2549.0	69.7	Low
46	Liberia	94.5	737.5	1027.4		40.1	667			971.0	5,193,416	675.7	27.5	Low
47	Mali	416.7	279.4	517.4	186.1	447.5	7906		11.0	1923.0	21,904,983	873.8	50.6	Low
48	Mauritania				83.3	5.2	12,978	144.4		16,100.3	4,614,974	2166.0	47.3	Medium
49	Niger	118.7	133.0	367.0	11.6	268.3	24,498		260.0	15,945.8	25,252,722	590.6	19.3	Low
50	Nigeria	5137.4	6455.3	6385.0	215.4	12,005.1	32,456	10.2	100.0	10,140.3	213,401,323	2065.7	55.4	Low
51	Sao Tome & Principe	5.8	25.4			2.0					223,107	2360.5	76.6	Low
52	Senegal		112.1	1400.0	268.3	96.4	9056	155.4	107.6	5770.6	16,876,720	1636.9	70.4	Low
53	Sierra Leone	56.5	554.4	817.9	32.2	25.9	1696				8,420,641	480.0	26.2	Low
54	Togo	59.8	149.1	252.0	49.9	149.5	1257		26.6	79.0	8,644,829	973.2	54.0	Low
	Total WA	**9715.5**	**14,842.5**	**21,045.7**	**1425.1**	**14,834.5**	**129,433**	**578.1**	**1738.4**	**56,835.2**	**418,762,041**			
	Total Africa	**53,810.9**	**115,144.0**	**261,912.4**	**10,441.0**	**54,318.9**	**1,096,698**	**11,169.5**	**17,976.1**	**528,979.6**	**1,391,783,250**			

Table A2
Hydrogen projects in Africa compiled from Ref. [146].

N°	Project name	Country	Date	Status	Prod	End-use	Announced Size	Normalized capacity	
								MWel	kt H_2/y
1	Sonangol	Angola	2024	C	NH_3	NH_3	280 kt	291.0	50.4
2	Lesedi Power Project	Botswana	2023	FS	H_2				
3	Grand Inga hydroelectric power project	DR Congo		C	H_2				
4	MoU Fortescue Future Industries-Djibouti	Djibouti		C	H_2				
5	Egypt Ministry of Electricity and Renewable Energy	Egypt		FS	H_2				
6	KIMA - Aswan electrolyser	Egypt	2000 to 2019	D	NH_3	NH_3	165 MW	165.0	28.0
7	Cairo Green Hydrogen	Egypt		C	H_2				
8	EBIC - Ammonia plant	Egypt	2024	FS	NH_3	NH_3	100 MW	100.0	15.0
9	EEHC - Siemens MoU	Egypt		C	H_2		100–200 MW	150.0	26.0
10	Ain Sokhna plant, Suez Canal Economic Zone (SCZone), phase 1	Egypt	2026	FS	NH_3	HN_3, Mob	140 kt NH_3/y using 25 kt H_2/y	144.3	25.0
11	Ain Sokhna plant, Suez Canal Economic Zone (SCZone), phase 2	Egypt		C	NH_3	HN_3, Mob	350 kt NH_3/y	216.4	37.5
12	Ain Sokhna ammonia project	Egypt	2025	FS	NH_3	HN_3, Mob	390 kt NH_3/y	405.3	70.2
13	Masdar Hassan Allam green hydrogen, phase 1	Egypt	2026	FS	MeOH	MeOH, Mob	100 kt MeOH/y	110.4	19.1
14	Masdar Hassan Allam green hydrogen, phase 2	Egypt	2030	C	NH_3	NH_3	4 GW electrolysis, 2.3 Mt NH_3/y	3889.6	673.9
15	Total Eren, Enara green ammonia, phase 1	Egypt		C	NH_3	NH_3	300 kt NH_3/y	311.8	54.0
16	Total Eren, Enara green ammonia, phase 2	Egypt	2030	C	NH_3	NH_3	1.5 Mt NH_3/y	1247.2	216.1
17	Scatec Green Ammonia	Egypt	2025	C	NH_3	NH_3	1 Mt NH_3/y	1039.4	180.1
18	ReNew Power - Egypt MoU, Hydrogen, phase 1	Egypt	2025	C	H_2		20 t H_2/y	115.4	20.0
19	ReNew Power - Egypt MoU, Hydrogen, phase 2	Egypt	2029	C	H_2		200 kt H_2/y	1038.9	180.0
20	ReNew Power - Egypt MoU, Ammonia phase 1	Egypt	2025	C	NH_3	NH_3	100 kt NH_3/y	103.9	18.0
21	ReNew Power - Egypt MoU, Ammonia phase 2	Egypt	2029	C	NH_3	NH_3	1.1 Mt NH_3/y	1039.4	180.1
22	Kenya Private Sector Alliance - FFI MoU	Kenya		C	NH_3	NH_3			
23	Saipem and Alboran Hydrogen (1 plant)	Morocco		C	H_2				
24	OCP Group demo project	Morocco	2022	UC	NH_3	NH_3	4t NH_3/day	1.5	0.3
25	HEVO-Morocco	Morocco	2026	FS	NH_3	NH_3	31 kt H_2/y	206.8	31.0
26	Masen - KfW	Morocco	2025	FS	H_2		100 MW	100.0	17.3
27	Amun	Morocco		C	H_2	NH_3			
28	Aman - Green Hydrogen Project	Mauritania	2030	FS	H_2	NH_3, I&S	10 Mt NH_3	10,393.6	1800.7
29	Project Nour	Mauritania		FS	H2		10 GW	10,000.0	1732.5
30	Hyphen Hydrogen Energy - phase I	Namibia	2026	FS	NH_3	NH_3	120 kt H_2/y - 1 GW	1.0	0.2
31	Hyphen Hydrogen Energy - phase II	Namibia		C	NH_3	NH_3	350 kt H_2/y - 3 GW	3.0	0.5
32	O&L group - CMB.TECH hydrogen hub	Namibia	2023	FID	H_2	Mob	4 MW	4.0	0.7
33	Renewstable Swakopmund	Namibia	2025	FS	H_2	Power	24 MW	24.0	4.2
34	MoU EEC-Niger	Niger		C	H_2				
35	Anglo-American Mogalakwena mine	South Africa	2022	O	H_2	Mob	3.5 MW	3.5	0.6
36	Boegoebaai green hydrogen	South Africa		FS	H_2		400 kt H_2/y	2308.8	400.0
37	Nelson Mandela Bay green ammonia plant, phase 1	South Africa	2025	FS	NH_3	NH_3	156 kt NH_3/y	162.1	28.1
38	Nelson Mandela Bay green ammonia plant, phase 2	South Africa	2026	FS	NH_3	NH_3	780 kt NH_3/y	648.6	112.4
39	Sasolburg green hydrogen project	South Africa	2023	FS	H_2	MeOH, P, I&S, Mob	6 t H_2/d	12.6	2.2
40	Secunda SAF Project - Phase I	South Africa		FS	SF	SF	15 kt synfuels/y	44.5	7.7
41	Secunda SAF Project - Phase II	South Africa	2040	C	SF	SF	2.5 Mt synfuels/y	7412.5	1284.2
42	Prieska ammonia project, phase 1	South Africa	2025	FS	NH_3	NH_3	72 kt NH_3/y - 12.9 kt H_2/y	74.5	12.9
43	Prieska ammonia project, phase 2	South Africa	2030	C	H_2		500 kt H_2/y	2811.5	487.1
44	Zimbabwe NH_3 plant	Zimbabwe	1975 to 2015	D	NH_3	NH_3	100 MW	100.0	16.9

Data availability

The link to the full dataset has been shared.

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