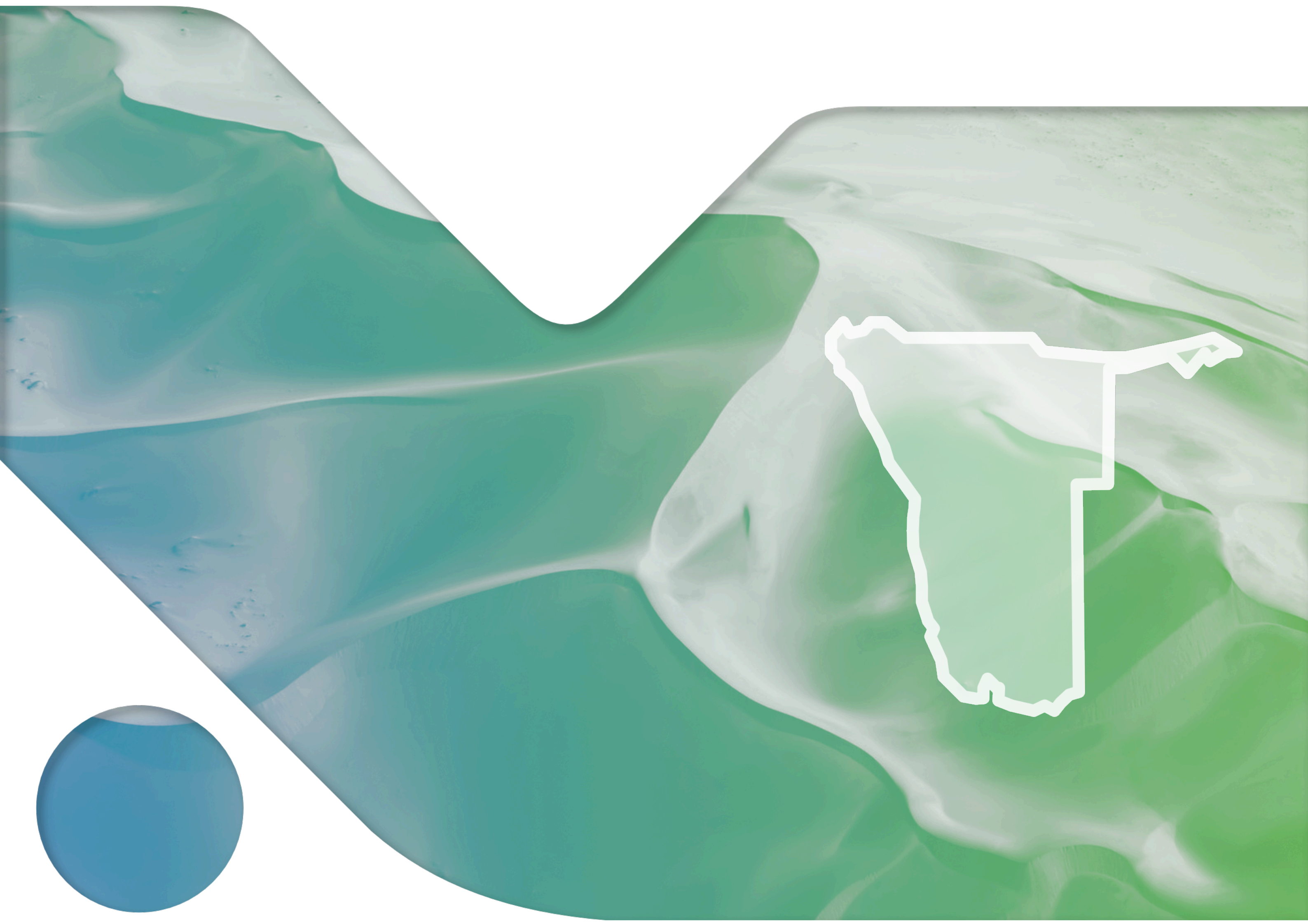
GreeN-H2 Namibia

Green Hydrogen Production in Namibia

Report



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Authors
Anusha Roshini Alagu
Chokri Boumrifak
Luisa Fernanda López González

Editor
DECHEMA Gesellschaftfür Chemische Technik und Biotechnologie e.V.

Responsible for content under the terms of press legislations
Chokri Boumrifak

DECHEMA e.V.
Theodor-Heuss-Allee 25
60486 Frankfurt am Main
Germany

Email: chokri.boumrifak@dechema.de

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Graphics and typesetting
Chokri Boumrifak

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Namib Desert, yfxrqWar-88 by @joshuakettle, Joshua Kettle

Rails, su3FE5qTEjw by @imedianamibia, Alan J. Hendry

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DECHEMA
Gesellschaft für Chemische Technik
und Biotechnologie e.V.
Theodor-Heuss Allee 25
60486 Frankfurt am Main
Germany
Phone: +49 (0)69 7564-0
Fax: +49 (0)69 7564-117
E-Mail: info@dechema.de

Project Partner

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Introduction

Global warming, caused by the increased concentration of greenhouse gases (GHG) in the atmosphere, is increasingly becoming a major concern around the world. The consumption of fossil fuels is one of the major factors contributing to the emission of GHG. In recent years, efforts for replacing fossil fuels with renewable energy resources are advancing. Green hydrogen from renewable energy resources is gaining importance as a key component to defossilize hard to abate sectors and to reduce GHG.

One of the world's highest potentials to harvest renewable energy is Namibia. This potential can be leveraged to produce green hydrogen in large quantities for low costs. It is estimated that in 2030 the production of green hydrogen in Namibia can be economically competitive, only second to Chile [1]. Due to this advantage, the Government of Namibia identified green hydrogen and its derivatives as an emerging export opportunity for the country.

In 2021, the National Green Hydrogen Council was established by the Government, to oversee the development of green hydrogen in the country. It is composed of a Green Hydrogen Commissioner and members of the National Planning Commission, the Central Bank, Namibia Investment Promotion and Development Board (NIPDB) and four Ministries (Finance; Mines and Energy; Environment, Forestry and Tourism; Agriculture, Water and Land Reform) [2].

In this context, the Green Hydrogen Council launched the Namibian Green Hydrogen Strategy at COP27 in 2022 (see section 2.1).

To support the development of a green hydrogen economy in the country, the Government of Namibia signed four notable international agreements [3]:

- A Joint Communique of Intent (JCoI) was signed with the German Government to cooperate in research and development, conduct feasibility studies and support the development of joint pilot plants [4].
- An agreement on cooperation in the field of hydrogen economy was concluded between the German Federal Ministry for Economic Affairs and Climate Action and the Namibian Energy Ministry [5].
- Namport, the Namibian Ports Authority, signed a Memorandum of Understanding (MoU) with the Port of Rotterdam (Netherlands), to build the necessary infrastructure to supply green hydrogen from Lüderitz to Rotterdam [6].
- A MoU for cooperation in the field of Green Hydrogen was signed between the Ministry of Mines and Energy of Namibia with the Ministry of Energy of Belgium [7].
- The EU and Namibia agreed on a strategic partnership on sustainable raw materials and green hydrogen [8]

This report provides an overview of current developments of Namibia's green hydrogen endeavors and the potential for its production capacities and future exports.

Hydrogen Production and Namibia's potential

Hydrogen Production and Namibia's potential

Green Hydrogen and Derivatives Strategy

The Government of the Republic of Namibia (GRN) published the Namibia Green Hydrogen and Derivatives Strategy in November 2022, implemented by the Southern African Science Service Center for Climate Change and Adaptive Land Management (SASSCAL) and sponsored by the German Federal Ministry of Education and Research (BMBF) [9]. This section summarizes the most important points discussed in the strategy.

The strategy prognosticates Levelized Cost of Hydrogen (LCOH)[1] in Namibia of 1.2 – 1.6 USD per kg hydrogen in 2030 and 0.8 – 0.9 USD per kg hydrogen in 2050.

The focus of the hydrogen strategy is the export of green hydrogen derivatives including ammonia, methanol, synthetic kerosene and iron. However, despite the potentials for low green hydrogen production costs in Namibia, the costs of transporting green hydrogen and its derivatives could be high depending on distances and type of transport which also needs to be considered for the derivatives.

Ramp-up targets for green hydrogen production (hydrogen equivalents) are 1-2 Mt/a in 2030, 5-7 Mt/a in 2040 and 10-15 Mt/a in 2050. This production in 2050 requires about 750 TWh/a of renewable electricity. For this purpose, three hydrogen valleys (Figure 1) will be developed to harvest their high renewable energy potentials:

1. The southern region (ǁKaras) has the advantage of having the port of Lüderitz. In this region, the government created the Tsau ǁKhaeb National Park Southern Corridor Development Initiative (SCDI) which foresees the development of production sites and infrastructure for wind and solar renewable energy production, desalination, green hydrogen and ammonia production, a deep-water port in Lüderitz and green steel production. Hyphen Hydrogen Energy is currently developing the first project under this initiative (see section 0). This region has a potential to produce 5 Mt/a of green hydrogen equivalent by 2050 [9].
2. The central region (including Khomas, Otjozondjupa and Erongo) is well developed and has the opportunity to develop an export infrastructure at the Walvis Bay Port. Nevertheless, the wind potential in the central region is limited compared to the southern region; this could delay production at large scale until costs for solar and electrolysers decrease. Production capacity of 3 Mt/a of green hydrogen equivalent by 2050 [9] could be expected in this region. Cleanergy Namibia and HDF Energy are two larger projects planned in this region (for more details see section 0).
3. The northern region (Kunene) still requires a port infrastructure for the export of green hydrogen and derivatives. Green hydrogen equivalent production potential by 2050 is estimated to be 5 Mt/a [9].

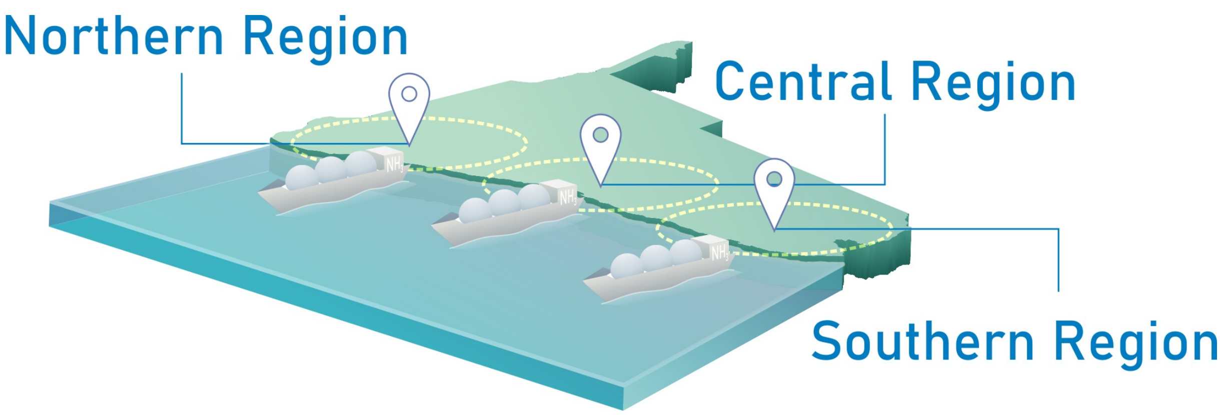

Figure 1 Namibia's three green valleys based on Namibian Green Hydrogen and Derivatives Strategy [9].

1 The Levelized Cost of Hydrogen (LCOH) accounts the investment and operating costs of producing 1 kg of hydrogen. It is a useful methodology to compare different production routes and sites.

Hydrogen Production and Namibia's potential

Hydrogen development in Namibia will not only defossilize internal energy consumption but could besides accelerate the country's economic growth. In 2030 and 2040 the GDP could grow by 32%, compared to an economy with no hydrogen industry. This industry could also generate 600,000 jobs by 2040 [9].

The strategy estimates a domestic hydrogen equivalent demand of 0.095 Mt/a in 2040. Possible applications include the use for hydrogen-fueled and fuel-cell trucks, in tugboats, regional trains and for ammonia production.

In order to unlock Namibia's hydrogen potential, the country will introduce a fit-for-purpose regulatory and institutional framework. The Synthetic Fuels Act will define standards and regulations for the production of green hydrogen and its derivatives. The Namibian Green Hydrogen Program will support private stakeholders in the development, financing, and maintenance of hydrogen projects on state-owned land[9].

Demand and Production Costs

Today, hydrogen is less of an energy carrier and vastly applied as feedstock for refineries, ammonia, and methanol production. The global demand in 2021 was about 94 Mt of hydrogen [10], [11], [12]. Besides its application in the chemical and petrochemical sector, hydrogen is also used in the production of steel. The so called direct reduced iron is gained through the reaction of hydrogen with iron ore. These are today's major applications of hydrogen, as can be seen in Figure 2. Nearly two thirds of hydrogen (62%) is produced mostly from natural gas (methane) via steam reforming and 19% is being produced from coal. Another 18% originate from refineries (naphtha reforming) [12]. Hydrogen from fossil fuels with captured carbon only accounts to 0.7% and hydrogen from electrolysis takes roughly 0.04%.

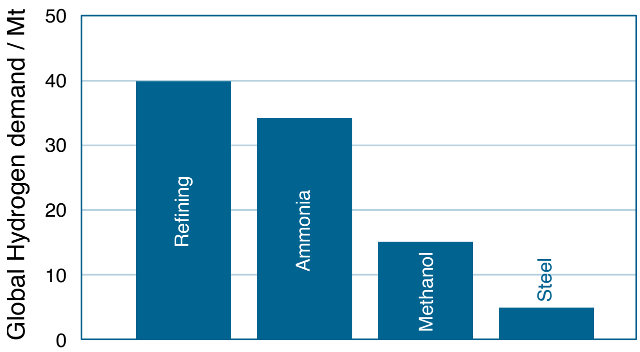

Figure 2 The global hydrogen demand is mainly driven by refineries and the production of ammonia, methanol and steel. [12]

Thus, the current contribution of so-called clean hydrogen to the total hydrogen production is still neglectable [12].

Hydrogen produced from fossil resources is labeled as grey. If the emitted CO_2 is being captured, the hydrogen is labeled as blue [11]. However, in 2021 about 900 Mt of CO_2 were released globally for hydrogen production [10], [11], [12]. Therefore, sustainable pathways for hydrogen production are needed to provide an alternative for hard to electrify sectors and supply hydrogen as a feedstock for the chemical industry.

Another method to generate hydrogen is the splitting of water with electricity. This method is called electrolysis and its carbon emissions depend on the origin of the electricity. Thus, the operation with renewable electricity serves as a climate friendly alternative for producing hydrogen that is labeled as green. Another electricity source, which is considered to be carbon-free, stems from nuclear power [11].

Currently, the global production of green hydrogen is comparatively low. A major hurdle is the high production cost leading to high prices for green hydrogen (high investment and electricity cost). [11]. The production cost of grey hydrogen can range from 1 - 2.5 USD per kg hydrogen and is highly dependent on the fluctuating natural gas prices. Blue hydrogen increases in cost to 1.5 – 3 USD per kg hydrogen due to the extra cost for the carbon capturing process. The current average cost for green hydrogen production globally is about 4 – 9 USD per kg hydrogen and is expected to decrease with growing production scale [11]. Therefore, cost reduction is a crucial task and requires lower electricity costs, optimization in efficiency of the hydrogen generation but also improvements for the infrastructure to transport, store and further process hydrogen [11].

The future demand for green hydrogen is expected to increase since new applications for defossilization undertakings will grow. Most hydrogen production targets for 2030 (see Table 1) of leading industrial countries give an idea of the production scale that could increase by about 22-38%. According to the IEA the hydrogen demand could account to 115-130 Mt per year for 2030[10].

Table 1 Production targets of Namibia and leading industrial countries for 2030s [9], [12]

Country	Canada	China	EU[1]	Japan	Namibia	UK	US
Mt / year	4	0.1-0.2	20	3	1-2	2.85	10

1 Imports and domestic production

Globally, there are numerous projects that have the potential to provide over 3 Mt low-emission or green hydrogen per year. Most of the projects that reached final investment decision (FID) are situated in North America, EU, China, and Japan [13]. Whereas green hydrogen production is currently expensive, costs are expected to drop significantly for 2030 and 2050 with the expansion of the production in regions with high potential for renewable energies. Especially in Africa, the potential for solar and wind energy is so high that there is a noticeable impact on the levelized production cost of hydrogen. For Namibia, it is expected that it reaches around 2 USD per kg hydrogen until 2030 while the Namibian hydrogen strategy aims for even lower values. Moreover, some studies expect that economy of scale effects further reduce production costs below 1 USD per kg hydrogen until 2050. However, this does not include transportation costs and the cost of liquification [13]. Therefore, costs for end-use hydrogen for exports will still be higher compared to the before mentioned optimistic studies. Namibia positioned itself early on as a major green hydrogen producer, being one of few large-scale project frontrunners world-wide. With its large hydrogen production potential and competitive production cost, it can be a significant contributor to the global market.

Transport Costs

The ambition by various industrialized countries to defossilize is expected to significantly increase global demand for green hydrogen. For this growing demand the preparation of large industrial-scale hydrogen networks and transport infrastructure becomes prerequisite [11]. For the worldwide trade of hydrogen to be feasible, technologies for transportation need to be improved for efficiency and reduced in costs. According to the IEA, in 2030 pipelines are only cost efficient for distances up to 2,500 km and 600 kt per year. In the context of Namibia, this means that hydrogen exports to other continents will require shipping [14]. Studies show that large-scale imports of hydrogen results in high costs for long distances [11]. Transport via pipeline is usually most cost-effective which could apply to targets on the African continent such as Namibia's neighboring countries.

Public international agreements give a glimpse of future hydrogen hubs beyond the African continent. The port of Rotterdam (NL) is to this day one of Europe's largest trade ports that stepped forward to become a transport center for green hydrogen and derivatives. A MoU with Namibia already set the ground for future exports to this hub. Long distance transport of green hydrogen is one of the major challenges in terms of cost efficiency in infrastructure expansion. Consequently, the identification of a suitable medium or derivative is essential, due to the low volumetric energy density of hydrogen [11]. For such long transcontinental distances, hydrogen is best transported in liquid form to increase the volumetric energy density. However, liquifying hydrogen or converting it to ammonia, methanol or other derivatives comes with increased energy consumption for the transformation process of the gaseous form (cooling, compression, reaction energy etc.). These effects can be reduced moderately with increasing production scale [11].

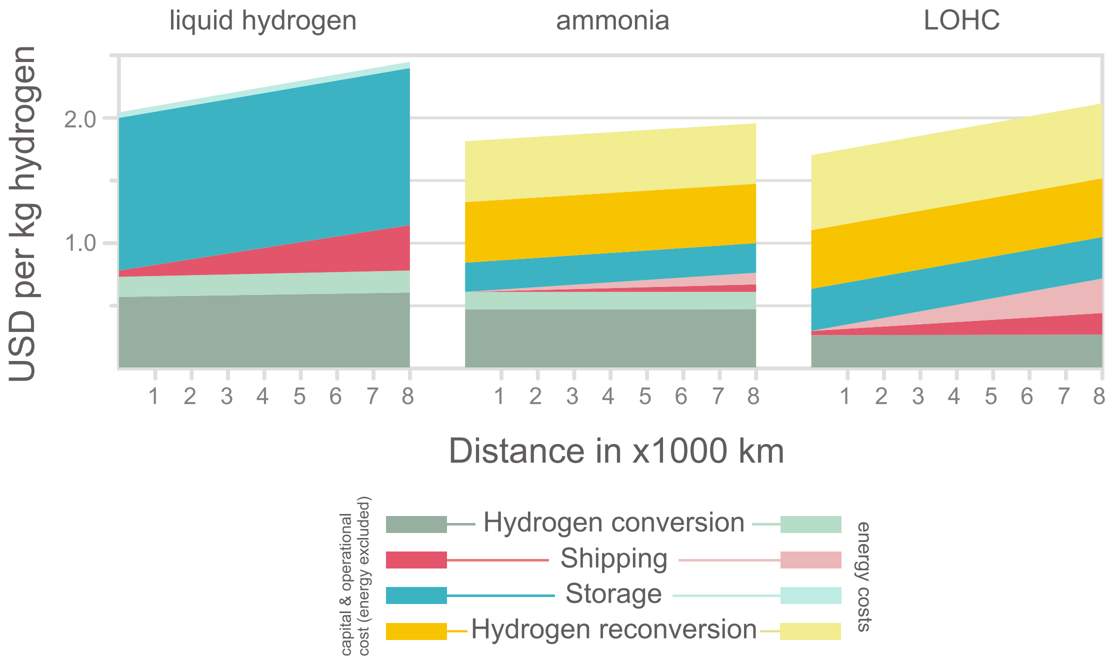

Figure 3 Maritime transport costs depend on the transport method (LH2, ammonia or LOHC) and the energy consumption for conversions; based on IEA [14].

Whereas maritime transport costs from Namibia to Rotterdam are hard to estimate, there are studies for similar distances e.g. export from the Arabian gulf to Rotterdam for products like LH2 (liquid hydrogen), ammonia, LOHC (liquid organic hydrogen carrier, methylcyclohexane) [11]. For these similar distances costs of 2.1-5.2 USD per kg hydrogen need to be considered additionally to the production costs [11].

It is expected that by 2030, liquid hydrogen can be shipped over large distances with average transportation cost of about 2.5 USD per kg hydrogen (Figure 3) that can range widely between 2.0 - 3.7 USD per kg hydrogen. The main cost factor for liquid hydrogen handling is the storage capacities that are energy intensive for cryogenic conditions. For shipping of ammonia or LOHC the main cost factor is the energy intensive recovery of hydrogen with about 1.9 – 2.2 USD per kg hydrogen (NH_3) and 2.0 – 2.5 USD per kg hydrogen (LOHC) [14]. Since the energy on the import side is even more expensive, conversion to hydrogen is very costly and requires measures to increase energy efficiency (Figure 3). Compared to the current LNG transport, hydrogen transport would be several multitudes more expensive [14].

Extra costs can be saved with production paths that do not require the recovery of the hydrogen. Base chemicals such as ammonia or methanol are a good use of these pathways, since they can serve as precursors for chemicals with added value or directly be used as fuels. For regaining hydrogen from ammonia so called ammonia crackers could be applied. However, ammonia crackers are not yet fully mature. To circumvent the use of such ammonia crackers, ammonia could be also applied directly and reduce production costs significantly. For example, ammonia could be used for the production of fertilizers, polymers, explosives or as a fuel [11].

Hydrogen Carriers

Transporting pure hydrogen implies some challenges due to its low volumetric energy content at ambient conditions. It can be either transported in gaseous form at high pressures or as a liquid at low temperatures. The choice of transport depends on the distance and the available infrastructure.

Another option consists in chemically bonding the hydrogen in other molecules which are easier to transport. A reverse reaction can be carried out to release and utilize the hydrogen at the final destination, or the transport molecule can be directly used or further converted into more valuable products. Suitable options for the second case include ammonia and methanol, since their current production is already based on (fossil) hydrogen for which an infrastructure for transportation is available.

Liquid hydrogen (LH2)

Hydrogen is liquified by compressing and cooling the gas to -253°C. The cryogenic requirements add extra cost to infrastructure measures for storage and piping. [10], [11]

Liquid organic hydrogen carrier (LOHC)

Hydrogen can be bound to organic solvents called liquid organic hydrogen carriers (LOHC). Methylcyclohexane (MCH) is such a carrier that contains hydrogen which is chemically bound and can be transported in liquid form. The hydrogenation of LOHCs is a reversible process and hydrogen can be released at the import destination. In this way hydrogen is liquified at moderate temperature and is safer to handle. However, only 6% of the weight of MCH is hydrogen. [10], [11]

Ammonia (NH_3)

Ammonia is a well-established chemical that has been used for fertilizer production for about 100 years. Therefore, the handling of transport and storage is already advanced, and ammonia can be shipped as a liquid at moderate temperatures and pressures. Today about 20 Mt per year of ammonia are shipped. As a hydrogen carrier, shipping could drastically increase and measures need to be taken to ensure safety with the handling of such a toxic and aggressive compound. Regaining the hydrogen from ammonia through so called crackers is still under development and not yet a mature technology. Therefore, applications without hydrogen recovery could be favorable for the use of ammonia as a fuel or base chemical. [10], [11]

This option seems to be favored by Namibian stakeholders. There are MoUs and production targets to produce at least 300,000 tonnes of ammonia for shipping from Lüderitz to Europe. Also, small scale projects e.g. Daures Green Hydrogen Village aim to produce ammonia which should serve domestic fertilizer production.[10], [11]


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Electrolysers

Namibia's ambitious plan to become a leading country for green hydrogen production depends highly on the availability and installment of its key technology: electrolysers. A challenge to this day is the expensive production and limited capacities of electrolysers. Moreover, there are various types of electrolysers which need to be selected for their suitability. The most important electrolysis methods can be divided into three groups: alkaline water electrolysis (AEL), solid oxide electrolysis (SOE) and proton exchange membrane electrolysis (PEM).

Alkaline electrolysis is a widespread and established electrolysis method, which therefore has a high technological maturity. Its name already reveals the alkaline operation with a highly concentrated solution of KOH/NaOH. However, this method is operated at low current densities of up to 400 mA/cm^2 (for large-scale hydrogen production, more than 1 A/cm^2 would be desirable) and an energy efficiency of up to 80%. A new variant of alkaline electrolysis (anion exchange membrane, AEM) uses a polymer membrane instead of an asbestos diaphragm. However, AEM electrolysis is still in an earlier development phase.[15], [16], [17], [18]

SOE is characterized by very high energy efficiencies of over 90%. At high temperatures (up to 850°C), this method electrolytically splits water steam into hydrogen. The decisive disadvantage of SOE is that the electrolytic cell is not yet sufficiently durable for continuous operation, as the high temperatures lead to faster wear.

PEM water electrolysis is considered the preferred option in hydrogen production due to the high purity of the hydrogen, high energy efficiency (80-90%), higher current densities (2-3 A/cm^2), ease of use and higher flexibility in handling fluctuating currents compared to other electrolyser types. The major disadvantage of PEM electrolysis is the high cost and high vulnerability of the catalyst [15], [16], [17], [18].

Both alkaline and PEM electrolysis are commercially available, while SOE and AEM electrolysis continue to be developed. But unlike AEM electrolysis (still on a kW scale), SOE is now approaching industrial scale.

Global electrolyser production capacity has increased significantly in recent years, reaching 11 GW per year in 2022, mostly produced in Europe and China. By 2030, a capacity of up to 365 GW could be built through the implementation of upcoming global projects. Europe and Australia together cover almost half of the planned electrolyser production capacities. This would represent a significant increase, but would still fall short of the 550-560 GW of installed electrolyser capacity needed to achieve climate neutrality by 2050 (Table 2).[19]

Table 2 Required electrolysis capacities until 2050 according to net zero scenario [19], [20]

Year	Alkaline (MW)	PEM (MW)	Other (MW)	Total (MW)
2019	164	80	13	257
2020	197	108	14	319
2021	354	147	58	559
2022	404	217	66	687
2023 (estimated)	1152	921	811	2,884
2030 (net zero emissions)				560,000

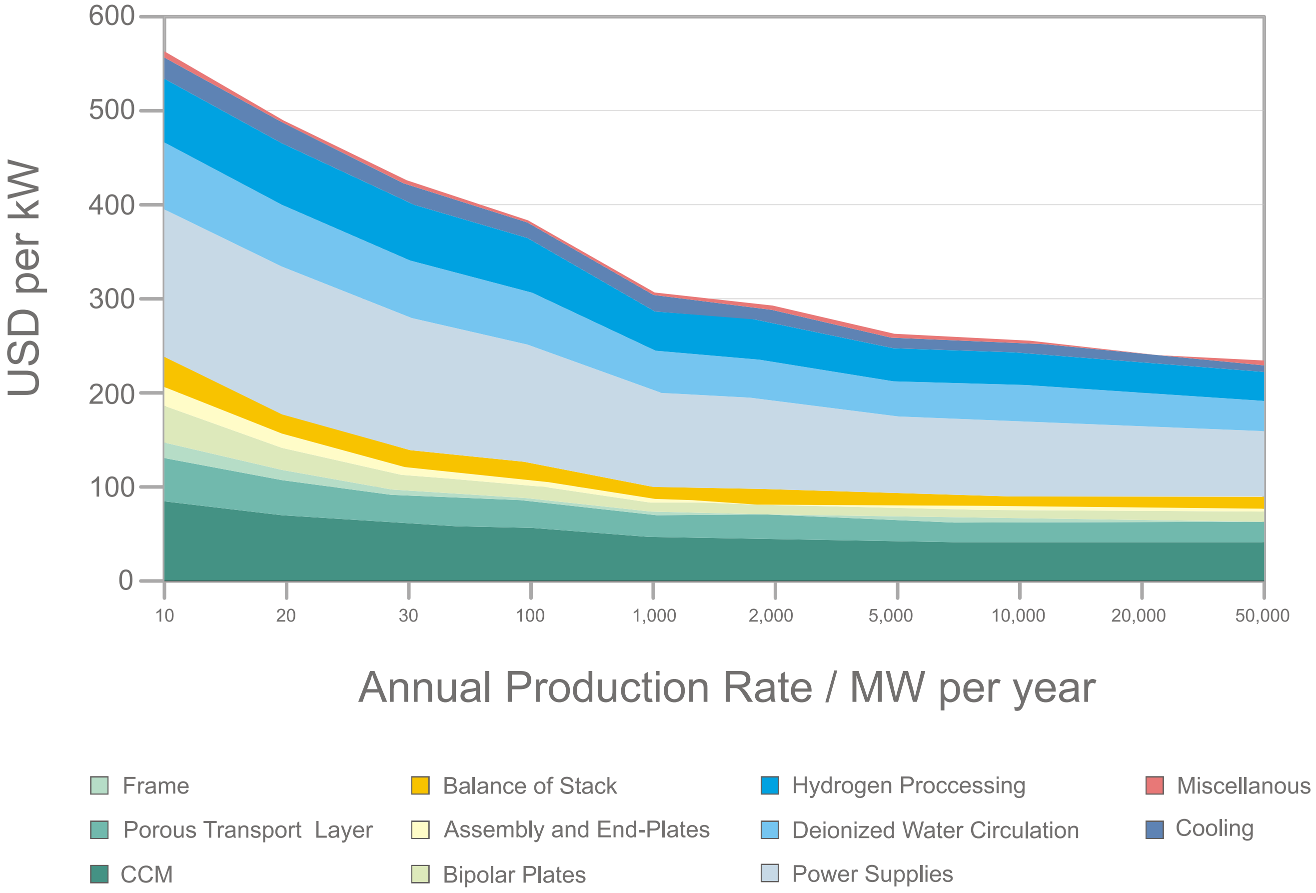

Figure 4 Correlation of production scale with electrolyser cost; based on [21]

PEM and alkaline water electrolysers are currently perceived as being considerably more expensive in terms of both capital and operating costs when compared to hydrogen production based on fossil fuels. Specifically, PEM water electrolysers are estimated to be 50% - 60% more costly than their alkaline counterparts, creating an additional barrier to their widespread adoption.[21]

However, it is important to note that both PEM and alkaline electrolysers still hold potential for cost reduction. This potential reduction can be achieved through economies of scale (Figure 4), increased automation, greater availability of components, lower material costs, the growing market demand, and deployment for energy storage applications (such as coupling electrolysers with underground storage or tanks).[21] At the moment most PEM electrolysers can be expected to cost about 1 million USD per MW.

In contrast, the cost considerations for AEM and solid oxide electrolysers are a more significant challenge. These technologies are primarily commercialized by only a few companies, and many of their components remain at the laboratory scale. Additionally, AEM is limited with system sizes typically ranging only up to a few kilowatts. While AEM and solid oxide electrolysers still have the potential to contribute to achieving low production costs for green hydrogen, they require more development compared to conventional alkaline or PEM technologies.[21]

However, it is worth noting that AEM, in particular, benefits from the use of less expensive materials, such as titanium, which can represent a substantial portion of the stack cost in PEM electrolysers. As a result, AEM technology has a competitive advantage when it comes to potential cost reduction.[21]

Hydrogen Production and Namibia's potential

Green Hydrogen Potential Overview

The most influential factor on green hydrogen potential is the renewable energy potential of the country. Estimated average photovoltaic theoretical potential for Namibia ranges between 2,150 and 2,450 kWh/m²/a [8] while the wind potential for Walvis Bay and Lüderitz are estimated to be 3,047 kWh/m²/a and 4,936 kWh/m²/a, respectively [9]. Mukelabai et al. estimated a total energy potential for the country as follows: 6,543 TWh/a for PV, 19,314 TWh/a for Concentrated Solar Power (CSP) and 5,493 TWh/a for wind energy [22]. This is due to high full load hours in the country, as high as around 2,800 h for PV and 3,700 h for wind [23].

A site-specific renewable energy potential for ground-mounted PV, CSP and onshore wind energy in 2050 was estimated by Thomann et al. Without excluding protected areas, the potentials were estimated to be 8,490 TWh, 11,180 TWh and 1,870 TWh, respectively. If protected areas are subtracted, the potentials of PV and CSP are reduced by 22% and the one of wind by 17% [24], as seen in Figure 5.

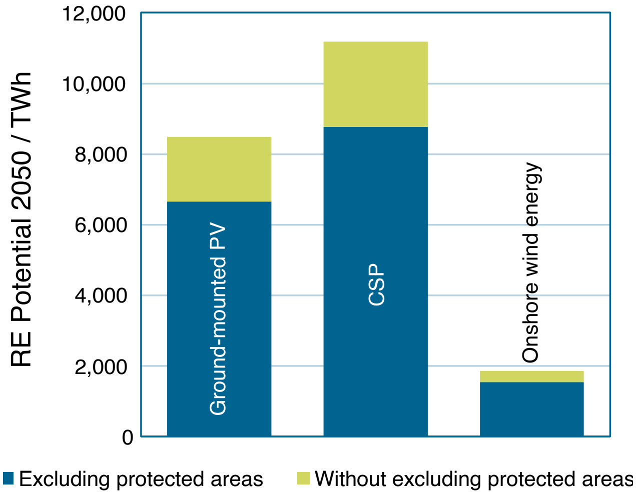

Figure 5 Renewable potentials in Namibia in 2050 [24]

Hank et al. analyzed technical feasibility and production costs for green hydrogen and derivatives production in different countries for the year 2030. Production for local consumption and export was considered. Three regions of Namibia were included in the analysis: Omaruru, Walvis Bay and Lüderitz. Some areas were excluded for the analysis of wind and photovoltaic power potentials, including nature reserves, forests, wetlands and urban and agricultural areas [25].

The lowest costs of production and export of liquified green hydrogen are seen in Lüderitz with an estimation of 8.55 USD per kg[1] of liquified hydrogen (ammonia or other derivative might have reduced costs). Renewable energy production (wind and photovoltaic) accounts for the largest share of these costs, about half. Electrolysis, liquefaction and transport also play an important role [25]. The same authors estimated that in 2030, a total of 227.2 kt of green hydrogen can be produced in these three regions [25].

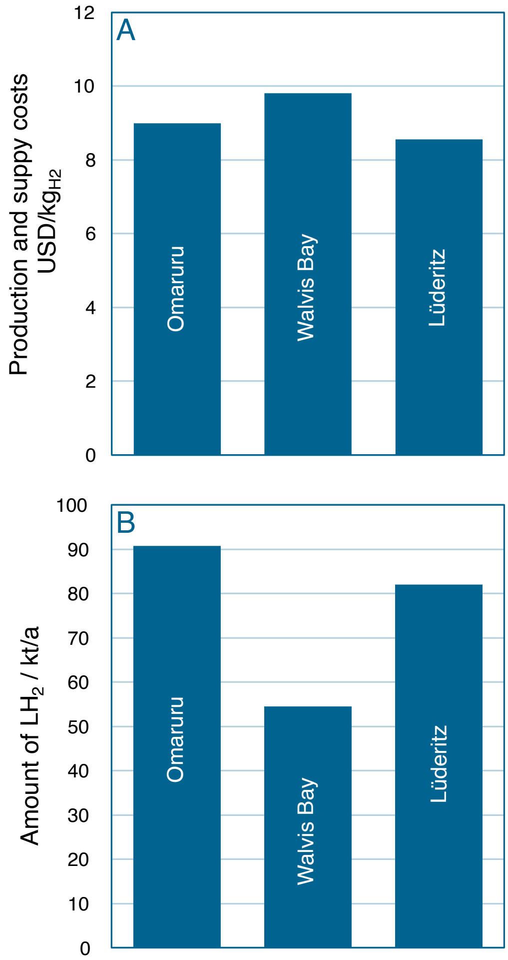

Figure 6 Prognosed production and supply costs (A) and potential production (B) of green hydrogen in 2030 for the regions Omaruru, Walvis Bay and Lüderitz [25]

Further relevant factors affecting the potential of green hydrogen are discussed below.

1 Converted to USD with the factor 0.9221 EUR/USD

Availability of clean water or desalination systems

The production of green hydrogen via electrolysis needs fresh water as a feedstock. Namibia, a mostly arid country, presents water stress and recurrent drought periods. Around 65% of the water supply in the country comes from ground water resources, whose recharge through rainfall is only limited [26]. As a consequence, ground water resources should be handled carefully and should not be considered an optional feedstock for the hydrogen industry. The most common studied alternative is the desalinization of sea water to produce ultra-pure water for the electrolysis. The environmental impacts of this process are currently investigated and should be minimized as far as possible. More information about this topic can be found in the desalination report carried out by the team of GreeN-H2 Namibia [27].

Available infrastructure for hydrogen transport and storage

Infrastructure development of green hydrogen is crucial for its distribution from the production site to the final use site and includes adequation, transportation and storage. Currently, a local demand of hydrogen for industrial applications does not exist in the country since there are no oil refining or fertilizers production facilities. Therefore, infrastructure for hydrogen and its derivatives must be built hand in hand with the production sites.

Availability of land

Land available for the construction of renewable energy facilities and green hydrogen and derivatives production plants is a decisive factor in the green hydrogen economy. Land use for these purposes is in direct competition with land use for agriculture, housing and biodiversification. If the land use for green hydrogen is not correctly managed, biodiversity can be affected and intensification of food insecurity can occur [28].

Regulations and legislation for green hydrogen development

There is no specific legislation or policy in Namibia which regulates the production and export of green hydrogen in place yet. A green hydrogen legislation in the country should include aspects such as licensing, health and safety, standardization of processes and equipment, distribution and use of green hydrogen and its derivatives and certification [29].

A fiscal regime should also be introduced in order to increase the competitiveness of Namibian green hydrogen derivatives. Fiscal incentives such as carbon taxes are some options to develop such a fiscal regime [29].

The Government of Namibia is planning to develop a “fit-for-purpose regulatory and institutional framework” for green hydrogen as stated in Green Hydrogen and Derivatives Strategy [9]. In this context, the Synthetic Fuels Act will define standards, define clear oversight activities and advance development with private and public sector [9].

Publicly known projects

With the aim of becoming a hub to produce and export green hydrogen globally, the Namibian Government is currently pushing foward a considerable number of projects across the country, in close cooperation with the private sector and other governments, such as the German.

An overview of the locations of announced green hydrogen projects are represented in Figure 7 and described below.

Figure 7 Map with planned green hydrogen and derivatives projects in Namibia

Cleanergy Solutions Namibia / Refueling Station

Cleanergy Solutions Namibia is a joint venture between the Ohlthaver & List (O&L) Group and CMB.TECH, which aims to build a demonstration hub in Walvis Bay comprised of hydrogen production, a hydrogen refueling station for heavy duty vehicles and a training center. At the demonstration phase, a solar facility will power a 5 MW PEM water electrolysis, complemented by an additional 5 MW battery energy storage system [30], [31]. This facility will produce 200 t/a of green hydrogen [32] and also offers a training and education opportunity for future professionals in the field of green hydrogen.

The fueling station should provide hydrogen fuel for 10 vehicles per day with an average fill per vehicle of 20 kg of hydrogen at 350 bar [31].

Daures Green Hydrogen Village

The Daures Green Hydrogen Consortium is developing the Daures Green Hydrogen Village, a facility for ammonia production located in the Daures Constituency in the Erongo region of Namibia.

The development of this facility starts in a first phase with a demonstration plant producing around 100 t/a of green ammonia, for which 0.25 MW electrolyser capacity will be installed. After full demonstration, the production should be scaled-up progressively in different phases, until a full scale-up after 2032, reaching 700,000 t/a of ammonia production, suitable for international export [33].

Besides the green hydrogen and ammonia production plants, a greenhouse for the production of carbon free “green” tomatoes and carrots powered by fuel cells is also planned.

Hydrogen-Diesel Dual Fuel Locomotive

The project aims to create a local off-take for green hydrogen in Namibia, which will be used to fuel two H_2-Diesel dual fuel locomotives: one retrofitted to use the existing engine and the other re-powered with a new hydrogen-ready engine [34]. This also offers an opportunity to reduce carbon emssions of the rail transport in Namibia, which is mainly fueled with diesel.

The building and assembly of the locomotives will take place in South Africa, while the actual operation will be between Walvis Bay and Kranzberg by TransNamib. Besides system engineering, planning, testing and operation, the project includes staff training and maintenance of the developed equipment [35].

Table 4 summarizes key data about the projects described above. In total, all projects are planning a production of about 530 kt/a of green hydrogen at their advanced stages. This represents 27% to 53% of the targeted production for 2030 in the Namibia Green Hydrogen and Derivatives Strategy.

HyIron

The current demand for iron globally is expected to rise significantly from its current level of 1.9 billion t/a to 2.2 billion t/a by 2030 [36]. Currently, iron production emits large amounts of CO_2, mostly due to the use of coal as a reducing agent and of the combustion of fossil fuels to achieve high temperatures. It is therefore crucial that new production capacities consider a transition into carbon-free technologies. Hydrogen Direct Reduction (HDR) facilitates this transition, due to a considerable emissions reduction if low-emission or green hydrogen is used.

The Oshivela project (HyIron), anounced an annual production of 1 million tonnes of iron [36]. This project in Namibia is set to pioneer the first industrial production of iron with net-zero emissions, utilizing HDR. The initial phase of the project, equipped with a 20 MW solar photovoltaic system, aims to achieve an annual output of 15,000 tonnes of Direct Reduced Iron (DRI) and is scheduled to commence in late 2024. According to HyIron a feasibility study is being conducted to investigate capacity expansion for the production of 1 million tonnes of DRI per year [36]. As the production scales up, there are plans to incorporate an additional 18 MW of wind energy and 140 MW of solar energy [36]. These power plants will supply energy for the water electrolysis process, to produce green hydrogen, which reacts with the oxygen in the iron ore to form water. This water is recycled within the production process. To produce 1 tonne of DRI, 58 kg of hydrogen are needed [37]. Based on this, it was estimated that for the production of 1 million tonnes of DRI, approximately 58,000 tonnes of green hydrogen are required.

Hyphen Hydrogen Energy

Hyphen is a joint venture by the German company Enertrag and the British company Nicholas Holdings. It envisions to implement one of the largest green hydrogen projects in the Sub-Saharan Africa and the first GW scale green hydrogen project in Namibia. This project, located within the Tsau Khaeb National Park in the ||Karas region (near Lüderitz), takes place as part of the Southern Corridor Development Initiative (SCDI), the first step in the development of a large-scale hydrogen production in the country.

In May 2023, the Government of Namibia and Hyphen signed a Feasibility and Implementation Agreement. It states the responsibility of Hyphen to the technical, financial, environmental, social and commercial delivery of the project. The government, on the other side, will develop and implement the necessary legal, fiscal and regulatory framework and will provide the land on which the project will be established. Hyphen contracted an external consultant (SRL Environmental Consulting) to carry out the future Environmental Impact Assessment of the project, which is expected to start in the first quarter of 2024 [38].

The initiative started in 2023 and the full-scale development is anticipated to be achieved before the end of the decade, reaching 350,000 metric tonnes per year of green hydrogen, which will be further converted into green ammonia. For this purpose, around 7 GW of renewable energy generation and 3 GW of electrolysis capacity should be installed [39].

Furthermore, three MoUs were signed with potential off-takers. In total the MoUs promise exports with more than 1 milllion tonnes of ammonia starting 2027 (Table 3) [40].

Table 3 MoUs signed with Hyphen [40]

Agreements with HYPHEN	tonnes
Approtium, South Korea	250,000
RWE, Germany	300,000
Not named	500,000

Renewstable Swakopmund

Hydrogene de France (HDF) Energy Namibia initiated the Renewstable® Swakopmund project, a non-intermittent renewable electricity power plant, which integrates intermittent renewable energy sources and the on-site green hydrogen energy storage [41].

The technologies implemented in this project encompass solar panels, green hydrogen production and storage, high-power fuel cells, and lithium-ion batteries. While these technologies are individually established, their innovative integration results in a dependable, adaptable, and readily deployable power solution. This process uses fuel cells to generate electricity from hydrogen to achieve sustainable power generation.

During daylight hours, the solar power plant generates carbon-free electricity, serving as the primary energy source for the Renewstable® Power Plant. To address end-of-day peak power demands and ensure electricity service stability, the battery storage system, in conjunction with hydrogen storage, comes into play.

The long-term H_2 storage system plays a crucial role by converting electricity from the photovoltaic park into hydrogen through an electrolyser system during the day and further storing the gaseous hydrogen generated in horizontal metallic tanks. During the night, the hydrogen fuel cell produces electricity from the stored hydrogen.

The production of baseload electricity will be fed into the national grid (see Table 4).

Table 4 Summary of all projects

Project	Start and duration	Location	Green hydrogen production after final scale-up	Final product	Consortium
Cleanergy / Refueling Station	2022-2027	Walvis Bay, Erongo	200 t/a [1]	Hydrogen	Cleanergy Solutions Namibia: Ohlthaver & List (O&L) Group and CMB.TECH
Daures Green Hydrogen Village	2022-2023	Daures Constituency, Erongo	240,000 t/a	Ammonia / fertilizers	Enersense Energy Namibia, UNAM (NGHRI), University of Stuttgart, Windwise
HyRail - Hydrogen-Diesel Dual Fuel Locomotive	2024-2026	Walvis Bay to Kranzberg corridor	-	Green Hydrogen off-take for dual locomotive	CMB.TECH, UNAM Hyphen Technical, TransNamib, NGHRI, Nicholas Holding
HyIron / Oshivela project	2024 -	District Grootfontain,Otjozondjupa	58,000 t/a [2]	Direct Reduced Iron (DRI)	HyIron, Elino/TS Group, CO2GRAB, LSF Energy
HYPHEN	2023 -	Tsau/Khaeb National Park, Kharas	350,000 t/a	Ammonia	Government of Namibia, Enertrag, Nicholas Holdings
Renewstable Swakopmund	2024 -	Swakopmund, Erongo	1,400 t/a	Electricity (from green hydrogen power plant)	HDF Energy

1 Communicated value for the first phase of the project. Value for final scale-up is not known.
2 Estimated value for the production of 1 million tonnes of DRI

Conclusions

Currently, global green hydrogen production is rather marginal compared to the conventional hydrogen production. Due to the increasing demand in the future for defossilization endeavors, there is a need to scale-up green hydrogen production. This applies especially to countries like Namibia with its abundant renewable energy resources. Namibia is taking the opportunity to become a major exporter of green hydrogen products and plans to use the momentum to benefit its own economy.

A major undertaking to become competitive on the global market is the reduction of production and transportation costs. At the moment, green hydrogen production is about 2-3 times more expensive compared to grey and blue hydrogen. However, electrolyser costs are expected to decrease and owing to Namibia's high renewable potentials and economy of scale effects, it can be expected that production cost will reach a reasonable level. A potential bottleneck could be the production capacities of electrolysers, leading to considerable procurement delays.

Even more challenging are transportation costs. Since most of the potential off-takers of green hydrogen products are located overseas, long-distance transport needs to be taken into account. To transport large quantities of hydrogen, liquefaction into various forms (LH2, LOHC or NH_3) is required. Consequently, recovery of the hydrogen at the import location is necessary and the energy for this process cannot be neglected which can make the hydrogen twice as expensive compared to its production cost. Improvements in efficiency might only lead to moderate cost reductions. Therefore, products that can be further used and don't require the recovery of hydrogen are more favorable cost-wise (e.g., green ammonia used as fuel, base chemical, for fertilizers production, etc.).

Namibia's Green Hydrogen and Derivative Strategy also mentions to export excess energy to neighboring countries, namely South Africa, Botswana, and Zambia. However, in context of green hydrogen as an energy carrier, projects with countries like South Africa have not been an important focus point so far [40]. There are hypothetical talks about a green hydrogen pipeline connecting Namibia and South Africa but uncertainties about South Africa's future hydrogen demand of its domestic industry put such endeavors into question [40]. Therefore, Namibia's first exports will probably be distributed to other continents and will require shipping as a transport method.

The Green Hydrogen and Derivative Strategy assumes comparatively low production costs below 2 USD per kg hydrogen in 2030 and even below 1 USD per kg hydrogen in 2050. Such low production costs might compensate additional transportation costs, but it needs to be mentioned that, since the publication of the strategy, investment costs have increased and will also impact the production costs.

The Strategy also sets production targets of 1-2 Mt per year in 2030 and 10-15 Mt per year in 2050. After completion of the three hydrogen villages in 2050 a demand of about 750 TWh per year is expected. Most of the projects still need to come to fruition. Namibia has six confirmed green hydrogen projects that differ in scale and realization approaches but mostly focus on the production of green hydrogen or ammonia. Amongst these projects the Hyphen project is by far the largest one.

Cost reductions can be achieved through efficiency improvements of production and transport and strategic orientation for products that can be further processed. At the moment ammonia is a suitable candidate as an export product which not necessarily needs to be reconverted into green hydrogen, due to its various established applications. Further options including methanol and synthetic fuels should be explored but need to identify an additional sustainable carbon source, required for the production.

Despite Namibia's high potentials, there needs to be awareness of hurdles that will increase the cost for green hydrogen such as challenging transport costs. Moreover, Namibia is not largely industrialized and the emerging green hydrogen industry is confronted with a greenfield environment. This becomes noticeable in the lack of skilled working force and industrial and basic infrastructure. These are challenges that the early pilot projects are already confronted with and need to demonstrate how to overcome these difficulties. Nevertheless, Namibia can leverage from its developments in the growing renewable energy sector and its high potential for low-cost green hydrogen production in this country. This sets the ground for Namibia to become major global producer for green hydrogen and its derivatives and could also benefit the country economically from new emerging industrial sectors.

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