Green Hydrogen Opportunities for Namibia

Phase I Report

Draft for Discussion

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Introduction

A preliminary analysis of the green hydrogen market and levelized cost of hydrogen (LCOH) shows Namibia could produce highly competitive green ammonia[1]. However, with little national demand, exports will be key to the green hydrogen strategy.

The global ammonia market today is 180 Mt driven by fertilizers and mining explosives production. The global market is expected to grow to over 500 Mt by 2050 driven by maritime shipping and power systems decarbonization especially by major developed economies with net-zero policies for 2050.

In order to position the country to compete in a global market for green ammonia, the government of Namibia must lead the development of a sector that is designed to achieve a globally competitive price and sufficient infrastructure for maritime export. The cost of ammonia is principally driven by the cost of electricity and economies of scale, and large-scale ammonia production requires large-scale, low-cost renewable energy (RE) development. A minimum initial scale of 0.5 Mt/yr of green ammonia production would require around 1000 MW of solar PV and wind investment – for comparison Namibia's domestic peak power demand is roughly 650 MW. Learning from its experience with small (<50 MW) investments in renewable energy, Namibia needs to find ways to achieve a step-change in renewable energy development if it wants to build a green hydrogen industry.

With its abundant, world-class renewable energy resources and increasing demand for green hydrogen worldwide, Namibia could be an early entrant in this new market. Countries such as Australia, Chile, Middle Eastern countries, Morocco, New Zealand and Norway are beginning to pursue GW-scale investments on the basis of national green hydrogen strategies. In these early stages of market development, the government of Namibia should focus efforts on achieving large-scale, low-cost RE development and designing models for sustainably maximizing fiscal revenue and local development in RE investments and green ammonia production. Namibia's world-class solar and wind resources give it a long-term competitive advantage in producing green hydrogen and green ammonia. Careful attention should be paid at these early stages to do proper planning and set up the proper fundamentals to ensure long-term development benefits for the country. The country should put in place a competitive, bidding process designed to maximize the national benefits and lay the foundation for long-term participation in a growing green hydrogen market.

[1] Ammonia is a carbonless derivative of green hydrogen that is more easily storable and transportable by pipeline or ship.

1. Green Hydrogen Technology 101

1.1 What is it?

Hydrogen (H_2) can be used as a fuel, an energy carrier and storage, or a feedstock. Since its use does not emit any CO_2 nor other air pollution, hydrogen is one solution to decarbonize "hard-to-abate" sectors such as transport and industrial applications, provided its own production entails zero or near zero greenhouse gas emissions. Depending on its production methods and energy sources, hydrogen is referred with various terms. **Green hydrogen** is the term used for hydrogen produced through a process called electrolysis from 100 percent renewable sources, such as hydropower, solar PV and wind, which entail zero carbon emissions directly, and very few on a cradle to grave approach. Other hydrogen production methods with low or near-zero direct carbon emissions include **blue hydrogen** and **turquoise hydrogen**. However, life-cycle analyses suggest that upstream methane slips may significantly increase the GHG footprint of these natural-gas based technologies. **Figure *1*** shows the formula describing the basic production reaction, the related direct CO_2 emissions[2], and the minimal energy required to produce each type of hydrogen. It is important to note that green hydrogen production is very energy intensive. One implication of this is that the cost of renewable energy must be very low to ensure a competitive price for green hydrogen. A second implication is that very large amounts of renewable energy capacity must be installed to drive the electrolysis.

Figure 1. The basics of gray, blue, green, and turquoise hydrogen

- **Grey** (or brown): NG steam reform., coal partial oxidation

$$CH_4 + 2H_2O \xrightarrow[heat]{} CO_2 + 4H_2$$

- **Blue**: The same with carbon capture and storage

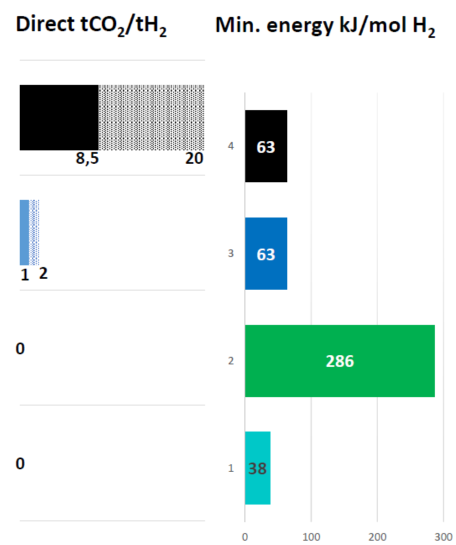
$$CH_4 + 2H_2O \xrightarrow[heat]{} CO_2 + 4H_2$$

- **Green**: water electrolysis – with green power

$$2H_2O \xrightarrow[elec]{} O_2 + 2H_2$$

- **Turquoise**: methane pyrolysis

$$CH_4 \xrightarrow[elec]{} C + 2H_2$$



Source: Original compilation.
Note: C = carbon; CH_4 = methane; CO_2 = carbon dioxide; H_2 = hydrogen; H_2O = water; kj/mol H_2 = kilojoule per molecule of hydrogen; NG = natural gas; O_2 = oxygen; tCO_2/tH_2 = tons of carbon dioxide per ton of hydrogen.

[2] Does not account for emissions associated with the production of electricity, or with the production of related machinery, or, more importantly for processes based on natural gas (blue and turquoise hydrogen) for the upstream GHG emissions from methane leaks.

Today, 96 percent of hydrogen production is based on fossil fuels, notably natural gas and coal[3]. **Figure *2*** shows the hydrogen terms by energy sources. National policies to achieve net-zero emission economies are driving a shift from grey hydrogen which dominates today toward green, turquoise and blue hydrogen.

Figure 2. Hydrogen terms by energy sources

Gray hydrogen	Nat. gas reforming
Brown hydrogen	Lignite gasification
Black hydrogen	Coal gasification
Blue hydrogen	Gray/brown/black + CCUS
Turquoise hydrogen	Nat. gas pyrolysis
Yellow hydrogen	Nuclear electricity
Green hydrogen	Renewable electricity

Source: (ESMAP, 2020)

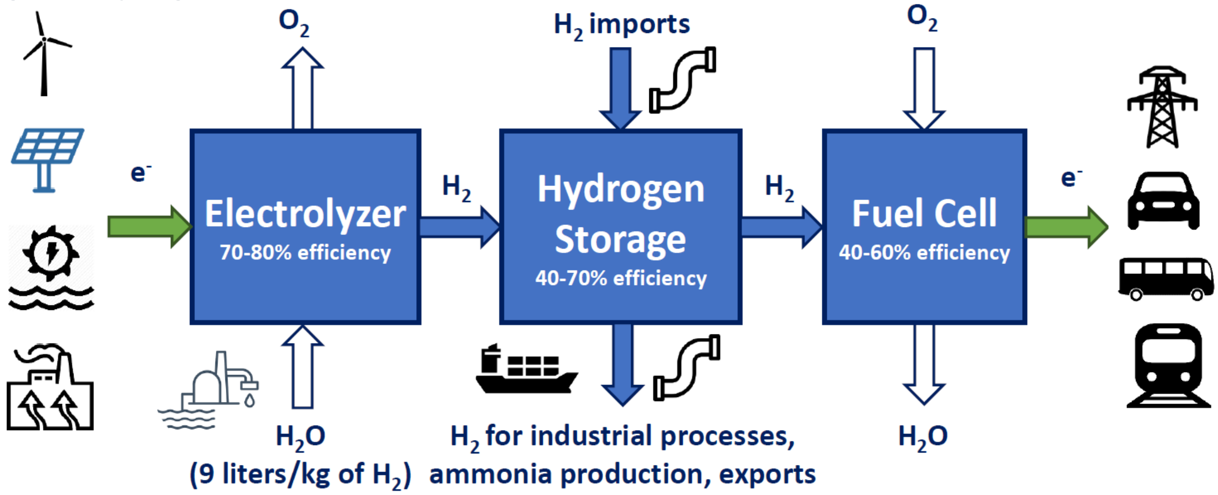
1.2 How it works?

Green hydrogen is normally created from a process called electrolysis, in which electricity is channeled through a device called an electrolyzer, which splits oxygen from hydrogen in water, creating pure oxygen and pure hydrogen with zero carbon emissions[4]. In this process, **approximately 50 kilowatt-hours of electricity and 9 liters of deionized water are required to produce 1 kilogram of hydrogen using an electrolyzer of around 78 percent efficiency** (high heating value).

[3] A small percent comes from electrolysis, mostly as a by-product of the production of chlorine by electrolysis of brine ("chloralkali" process).

[4] Other green hydrogen production methods include hydrogen extraction from reformed biogas and hydrogen extraction from waste.

Figure 3. Hydrogen 101

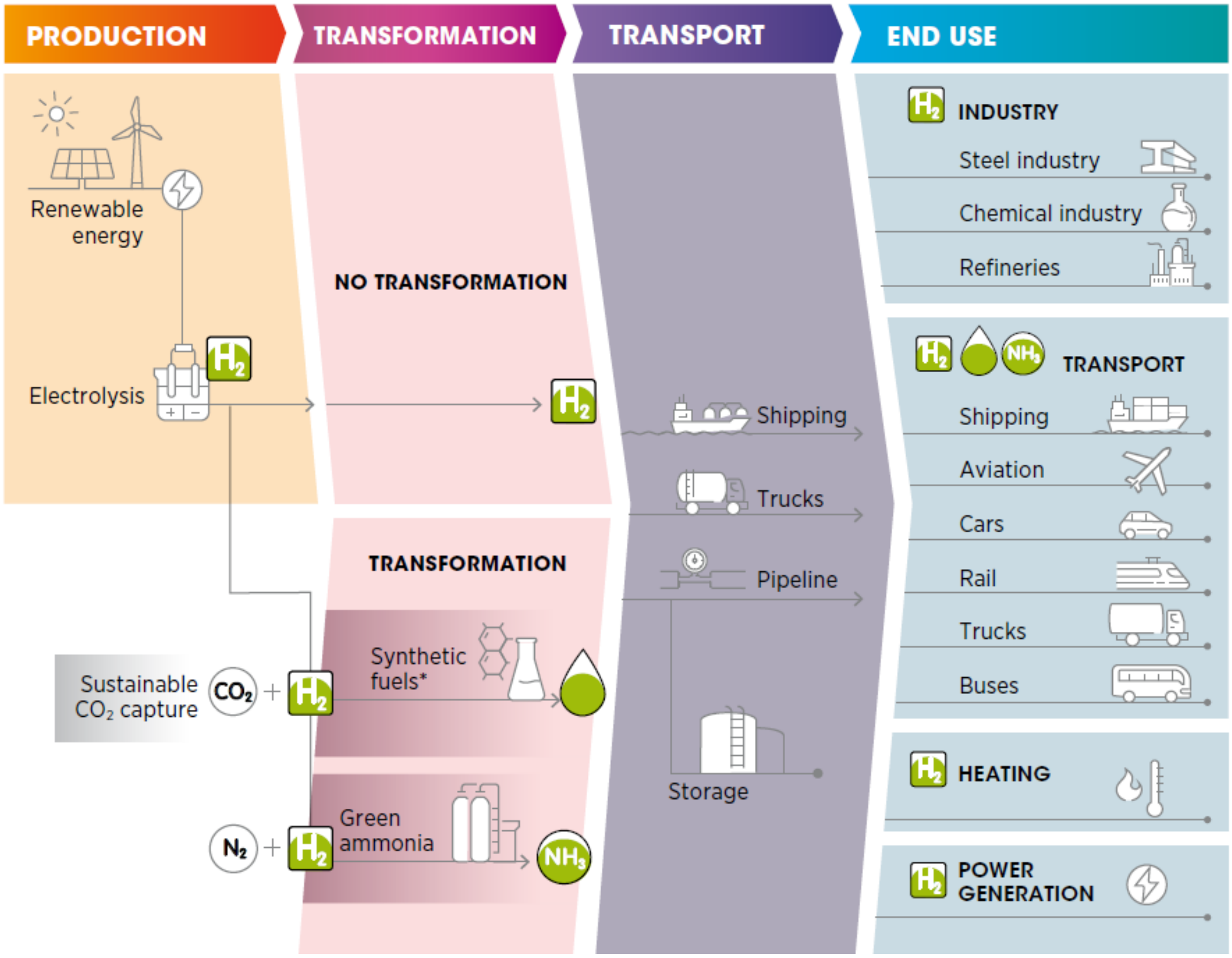


Source: (ESMAP, 2020)

1.3 Applications for hydrogen

Hydrogen can be used for a wide array of sectors including **energy** (heating, power generation), **industrial applications** (steel industry, chemical industry, refineries), and **transport** (shipping, aviation, cars, rail, truck, buses). Hydrogen can also be stored for long periods of time in various forms. **Figure *4*** summarizes the options for global hydrogen production, conversion and possible end uses across the energy system.

Figure 4. Options for global hydrogen production, conversion and possible end uses across the energy system



Source: (IRENA, 2020)

Several alternative fuels can also be created from green hydrogen for specific use cases and applications such as ammonia (NH_3) and methanol (MeOH). Most relevant areas for green hydrogen use include a) green ammonia and methanol for their industrial uses, b) refineries (to upgrade and clean fuels), c) direct iron reduction in steelmaking with hydrogen, d) hydrogen/ammonia storable/shippable fuels in power systems [5], e) ammonia as fuels (e.g. shipping, industrial furnaces, etc.), f) methanol and synthetic hydrocarbons as electro fuels/feedstocks to chemical industry and aviation, possibly co-produced with biofuels. The use of hydrogen in gas grids, terrestrial vehicles and industrial heat is often mentioned but competition with electrification is difficult. Of all these sub-segments, long-distance heavy trucks provide the best opportunity for hydrogen.

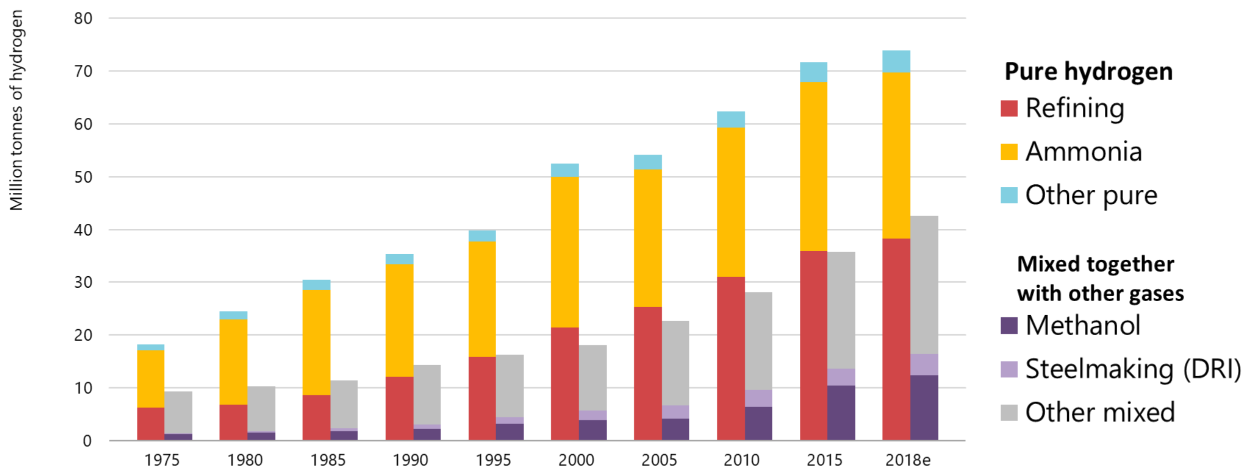
[5] Japan is seeking to import green and blue ammonia

2. Green Hydrogen Markets 101

2.1 Hydrogen Current Markets

The demand for hydrogen has been growing steadily since 1975, typically coming from the production of ammonia (for the fertilizer industry), explosives, and other chemicals, and recently switching for refining (deep conversion and desulfurization). **Figure *5*** shows the global demand for hydrogen from 1975-2018.

Figure 5. Global annual demand for hydrogen, 1975-2018



Source: (IEA, 2019)

Notes. The International Energy Agency (IEA 2019) distinguishes (i) the production of pure hydrogen from (ii) the production of hydrogen in mixtures with other gases, either (a) for a specific purpose or (b) as a by-product.

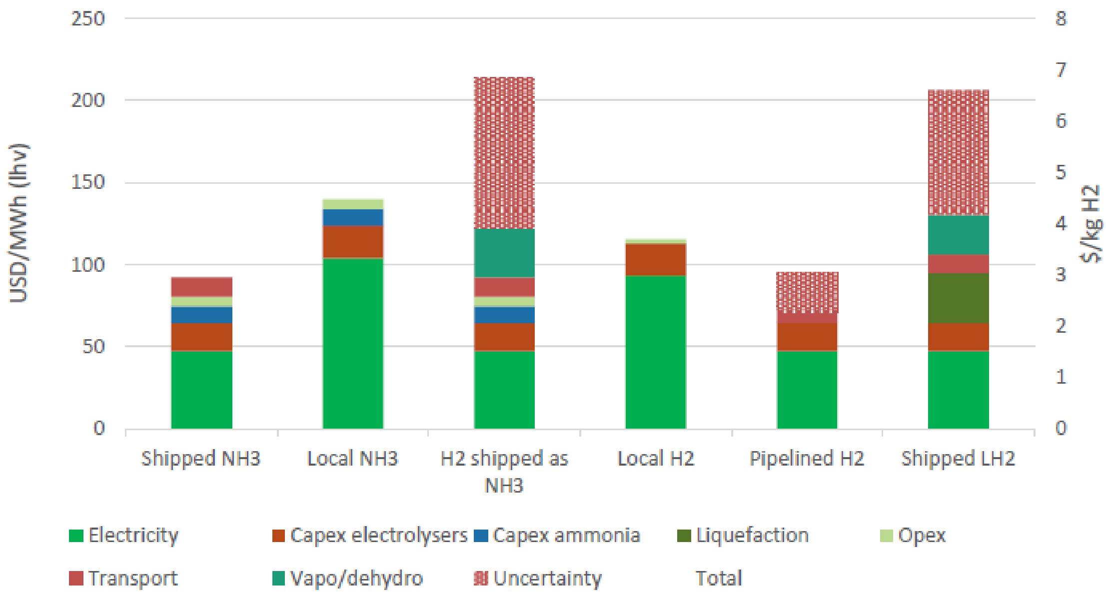
Ammonia

Ammonia represents the second-largest demand for hydrogen today after refining. Current ammonia markets include 1) nitrogen fertilizers, 2) explosives, 3) NOx reducing agents, 4) refrigerants, 5) feedstocks for polymers, and 6) cleansers. Given its higher density and, most importantly, its liquefaction at -33°C or 10 bars, ammonia can be used to store and transport hydrogen cheaply and for long periods of time, including in oceangoing tankers, barges, land-based pipelines, and trucks. Moreover, ammonia stands out among all hydrogen carriers for it can be used directly as a fuel, saving the cost of hydrogen extraction.

Figure *6* shows the difference in energy costs between imported and locally produced green hydrogen and green ammonia. Producing ammonia where hydrogen can be produced with local resources and then shipping the product in ocean-going tankers is more cost-effective than shipping hydrogen elsewhere to then be turned into ammonia and methanol, since hydrogen is very expensive to store and ship due to the need to reach very high compression, or a very low temperature for liquefaction[6].

[6] Contrary to ammonia, hydrogen can only be liquefied at -253°C and not under compression.

Figure 6. Costs of energy in Europe of different hydrogen sources



Source: Original compilation.

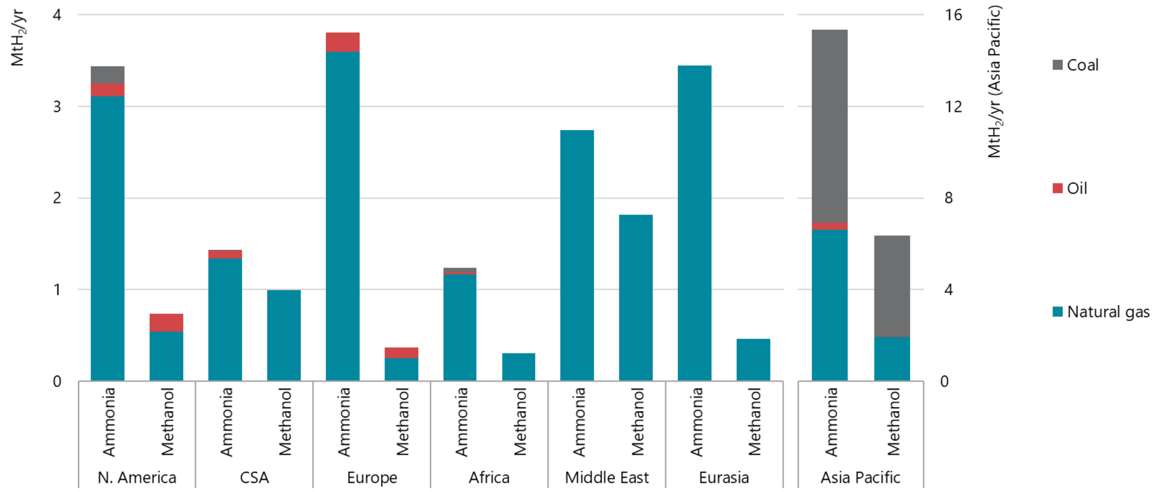
N.B. Transport assumptions: 1500 km distance, $60/t ammonia (ship or pipeline). Assumptions relative to the cost of electricity in the exporting country in e.g. North Africa is 25 €/MWh, while the electricity in the importing countries (e.g. Europe) is 55 €/MWh. Electricity would come all from renewable energy, therefore, the capacity factors of electrolyzers are estimated at 51.4% (4500 Full load hour equivalent) in North Africa, from a mix of solar and wind, and 45.7% (4000 FLHe) in Europe, from offshore wind power. Assumptions relative to the capex of electrolyzers corresponds to the best offer for large-scale electrolyzers to be build today, so the projection is for current decisions. The uncertainty in "H_2 shipped as NH_3" refers to the high cost of extraction and purification of hydrogen from ammonia. The uncertainty relative to "Pipelined H_2" expresses the large range of costs between, on the low side, the possibility to switch some existing NG pipelines to carry pure H_2 or the building of pipelines of very large diameter optimistically costed by *Hydrogen Europe*, requiring large-size compressors that do not exist, and on the high side the proven building of pure H_2 pipeline of a much smaller diameter, costed according to the literature (also retained by the IEA). The uncertainty relative to "Shipped LH_2" relates to the large range of costs between most recent, mid-scale liquefaction plants and future, large-scale liquefaction plants operating on new concepts, and to the large uncertainty relating to the capital costs of LH_2 ships, which should each be equipped with a series of LH_2 cryogenic tanks of a size that largely exceeds that of the largest LH_2 tanks that exist today (at Cap Canaveral).

Methanol

Most of the methanol today is produced from coal and gas. Current methanol markets include 1) feedstock for chemical industry and 2) fuel in the marine, automobile and electricity sectors.

Figure *7* shows hydrogen demand for ammonia and methanol production for 2018.

Figure 7. Hydrogen demand for ammonia and methanol production, 2018



Source: (IEA, 2019)
Note: CSA = Central and South America; MtH_2/yr = million tons of hydrogen per year.

2.2 Key drivers

The rapid growth of interest and demand in green hydrogen worldwide is dictated by a series of drivers. These drivers include, among others:

Global climate change commitments. Several countries around the world have already made commitments to reduce their GHG emissions, and several are pledging to reach net-zero carbon emission by 2050. Green hydrogen will play an essential role in reaching these targets, particularly in the "hard-to-abate" sectors such as some transport segments and industrial applications. Green ammonia is a key option for early decarbonization efforts with green hydrogen as it can be shipped globally in a cost-effective way, can replace gray ammonia in industrial uses and in many cases can be used directly as a carbonless fuel.

Decreasing cost of renewable energy. The cost of electricity is the major driver to produce green hydrogen. The cost of electricity from renewable energy, such as solar PV and wind, has decreased significantly in recent years. The lowest costs of electricity are in countries with excellent resources and adequate enabling environment that appropriately allocate public and private risks through well-designed procurement processes and those that mobilize low-cost capital. Countries with the best renewable energy resources, such as Namibia, have a long-term comparative advantage as there is the greatest potential to reach the lowest costs. A well-designed approach to renewable energy development can support a country to green the grid, produce green hydrogen for the global market, and create national and local economic benefits through foreign direct investment, fiscal revenues, and job creation.

Guarantee of origin. A crucial factor driving the demand of green hydrogen is its "Guarantee of Origin". The electricity used to produce green hydrogen must come from renewable energy sources. If a country uses grid connected electricity to produce green hydrogen, then it must green its own grid first. For green hydrogen or green ammonia that may be produced by dedicated renewable energy investments and not from the national grid, there will still be pressure by global customers to buy from suppliers with renewable energy grids. From a climate change and emissions perspective, it would be more impactful for the renewable energy in a country to push out coal-fired generation than to produce a grey hydrogen substitute. A green hydrogen exports strategy, therefore, must come alongside the pursuit of renewable energy for domestic power generation. About one-fifth of Namibia's current installed capacity is 120 MW coal-fired power station. Namibia imports much of its electricity from coal-dominated South Africa and other countries in the region. To become an attractive source of green hydrogen, therefore, Namibia will need to develop renewable energy to meet its own energy demand.

Other drivers. Other drivers include the commercial availability of technologies previously deployed in the hydrogen value chain on a small scale (ex. electrolyzers), the possibility to store hydrogen for long-term, and the supportive role hydrogen could play in integration of higher shares of variable renewable energy into the grid with a carbon free dispatchable power source.

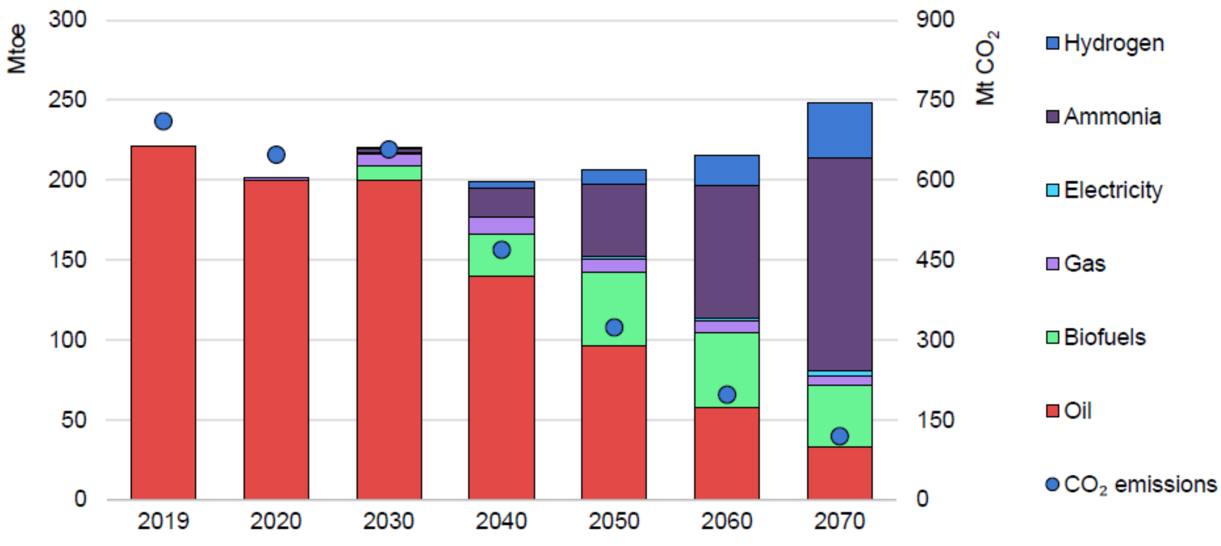
2.3 Future hydrogen markets

Beyond current hydrogen markets, new markets, driven by even more stringent global climate change commitments include the following:

- Hard-to-decarbonize hard-to electrify end-use sectors, will be the largest off-takers being chemicals, steelmaking, aviation, shipping and perhaps trucks
- The power sector will produce, store and consume hydrogen, with some trade
- Long term contracts for green hydrogen supply and its derivates

The international shipping is already shifting towards the use of ammonia. Ammonia can be used in refurbished maritime ICEs and is more conveniently handled than liquid H_2. **Figure *8*** suggests a continued trend towards ammonia in international shipping.

Figure 8. International shipping shifting towards ammonia



Source: (IEA 2020)

2.4 Barriers

Barriers exist to the development of green hydrogen. Those include, among others:

Transportation costs. Hydrogen is expensive to transport by truck or ship due to the need to reach and maintain very high compression or a very low temperature. Producing green ammonia or methanol is an alternative solution to export green hydrogen at cheaper cost.

Policy. Early government leadership is required to reach economies of scale necessary to enter the export market for ammonia. As this is a relatively new opportunity, several key stakeholders need to be involved in the process and more analytical studies need to be carried out to deeply understand the market potential and how to overcome the barriers.

Lack of infrastructure. One obstacle for the deployment of green hydrogen at scale is the lack of infrastructure, from electrolyzers to storage to transport facilities to name a few. Coordination efforts are needed to early identify the required infrastructures and not miss the opportunity to be an early market entrant.

2.5 Economies of scale

The analysis in section 3.4 shows that Namibia could produce globally competitive green hydrogen by producing green ammonia. The ammonia market today is 180 Mt driven by fertilizers and mining explosives production. The global market is expected to grow to 500 Mt driven by maritime shipping and power systems decarbonization especially by major developed economies with net-zero policies for 2050. The cost of ammonia is principally driven by the cost of electricity and economies of scale; a minimum initial scale of 0.5 Mt/yr should be considered to be globally competitive. This will have significant implications for the needed investment in renewable energy capacity. Just 0.5 Mt/yr of green ammonia production would require around 1000 MW of solar PV and wind investment – for comparison Namibia's domestic peak power demand is roughly 650 MW. Namibia will need to think big to compete against other potential green hydrogen producers. Government entities and private developers in Australia, Chile, Morocco, New Zealand, Norway, Saudi Arabia and the UAE, are considering projects, some being considerably larger than 1GW in scale.

Large industrial players are teaming up with Renewable Energy (RE) players in an effort to position themselves as early movers, identifying sweet spots well positioned worldwide to develop integrated facilities (from RE to production of green hydrogen/green hydrogen derivates) and export the green hydrogen output (often as ammonia).

However, business models are still emerging with the offtake risk being a significant risk with large projects requiring long-term commitment from green hydrogen buyers in a context where the market risk is difficult to take.

As an illustration of this driver, Saudi Arabia launched an ambitious partnership with the private sector to produce green hydrogen locally[7]. The project is structured through a joint venture equally owned by three partners:

[7] *Source: https://www.acwapower.com/news/air-products-acwa-power-and-neom-sign-agreement-for-5-billion--production-facility-in-neom-powered-by-renewable-energy-for-production-and-export-of-green-hydrogen-to-global-markets/*

- One public party: the new specific economic zone of NEOM in Saudi Arabia (through a dedicated investment vehicle), a new model for sustainable living located in the north west corner of the Kingdom of Saudi Arabia;
- Two private parties: (i) ACWA Power (leading RE player) and (ii) Air Products (EPC, owner and operator of gas facilities).

This project, scheduled to be onstream in 2025, represents a $5 billion world-scale green hydrogen-based ammonia production facility powered by renewable energy, targeting

- production of 650 tons per day of hydrogen by electrolysis using Thyssenkrupp technology;
- production of nitrogen by air separation using Air Products technology; and
- production of 1.2 million tons per year of green ammonia using Haldor Topsoe technology.

It will require integration of over four gigawatts of renewable power from solar, wind and storage. Air Products will be the exclusive off-taker of the green ammonia and intends to transport it around the world to be dissociated to produce green hydrogen for the transportation market.

2.6 Infrastructure required for export

The presence of the existing deep-sea port at Walvis Bay makes Namibia strategically located and well placed to export. However, the development of green hydrogen at scale will need a series of infrastructure that would allow for efficiencies and strategic decisions. Important questions include:

- What is the best optimal location to produce green ammonia for export? Close to port, or close to renewable energy resources?
- What type of infrastructure are needed? Would it be cost efficient to pipe ammonia to Walvis Bay or to upgrade the port at Luderitz?
- Does Namibia have salt caverns to store hydrogen? How would the cost of production change if production were to be near these storage locations?

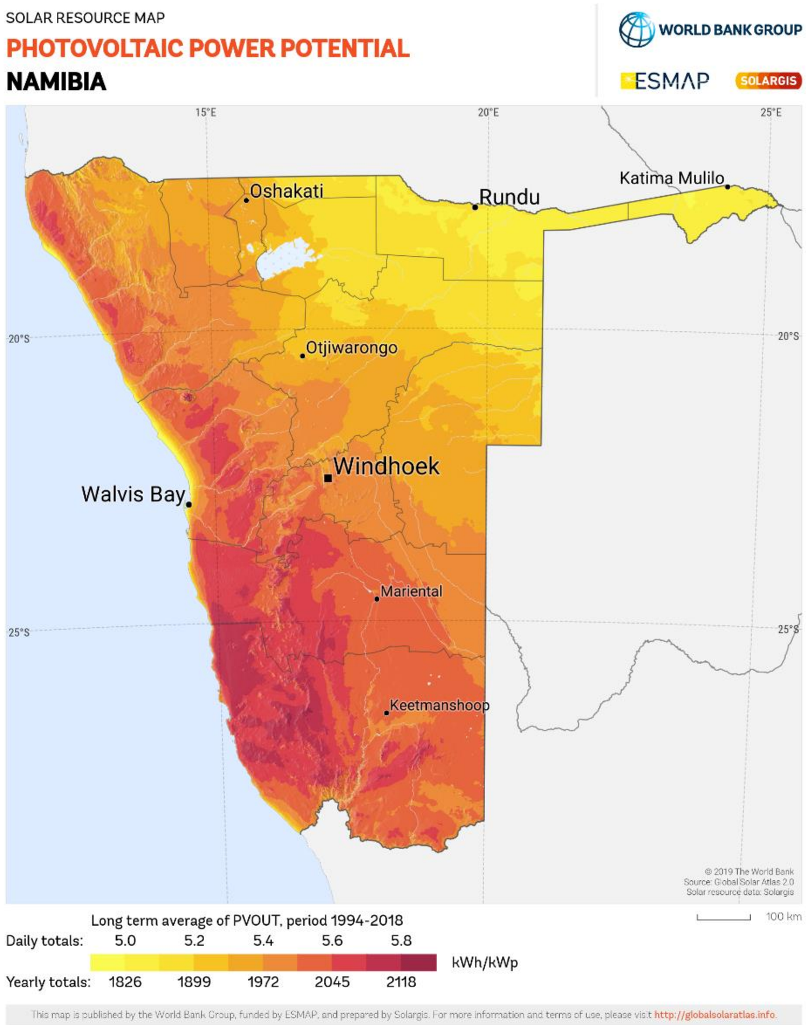
Future studies for optimization are needed, along with the analysis for cost of pipeline, salt caverns for storage, and solar and wind resources.

3. Production of green hydrogen in Namibia

3.1 Key advantages

The potential for green electricity production in Namibia is many times the country's domestic electricity consumption. This is due to Namibia's excellent renewable energy resources. Solar resource is one of the world's best, particularly in the southern part of the country, and wind resource is also excellent, as provided in **Figure *9*** and **Figure *10***.

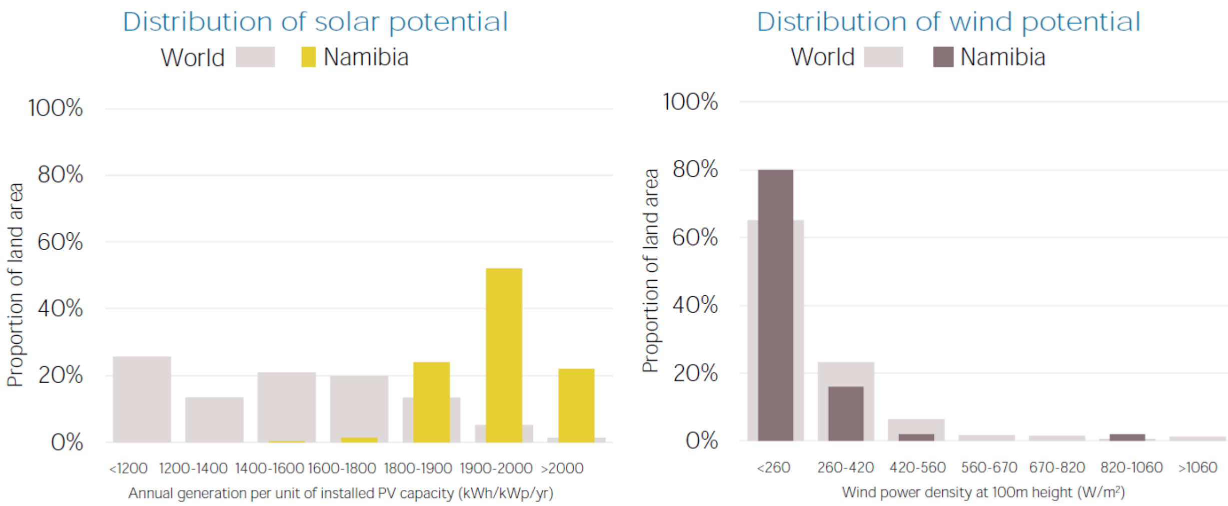
Figure 9. Photovoltaic power potential in Namibia



Source: ESMAP

Figure 10 shows the distribution of solar and wind potential in Namibia compared to the world.

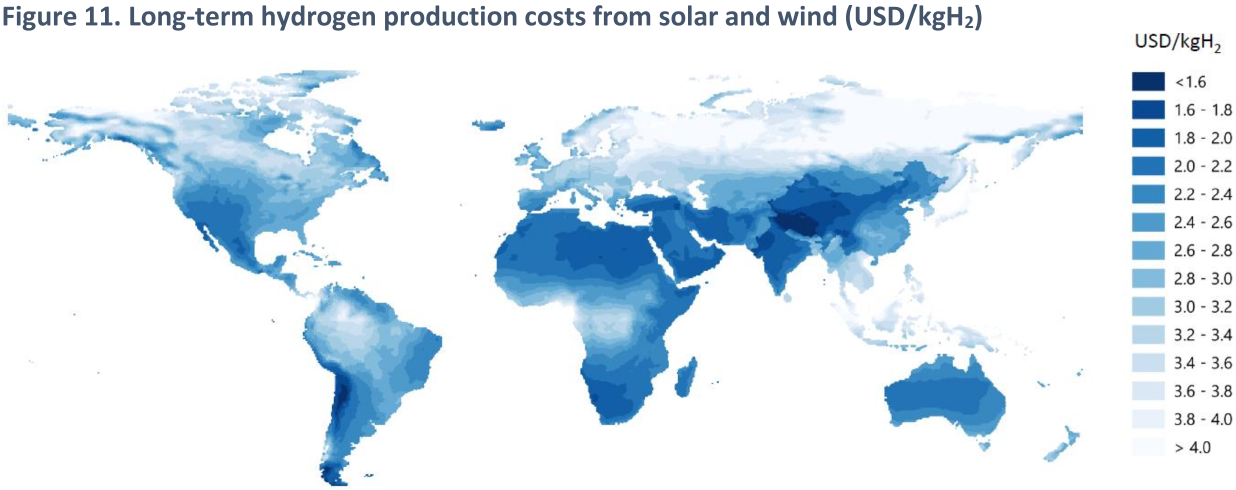
Figure 10. Solar and wind potential in Namibia compared to the World



Source: (IRENA, 2020)[8]

Globally, regions with most favourable renewable resources will likely export hydrogen-rich chemicals and fuels to consumption centres. The following figure shows the long-term hydrogen production costs from solar and wind (USD/kgH_2).

Figure 11. Long-term hydrogen production costs from solar and wind (USD/kgH_2)



[8] Solar PV: Solar resource potential has been divided into seven classes, each representing a range of annual PV output per unit of capacity (kWh/kWp/yr). The bar chart shows the proportion of a country's land area in each of these classes and the global distribution of land area across the classes (for comparison). Onshore wind: Potential wind power density (W/m2) is shown in the seven classes used by NREL, measured at a height of 100m. The bar chart shows the distribution of the country's land area in each of these classes compared to the global distribution of wind resources. Areas in the third class or above are considered to be a good wind resource.

3.2 Synergies with RE

Renewable energy is already part of the energy dialogue for a sustainable development of Namibia paving the way for livelihood development. Green hydrogen offers a unique opportunity to both increase the development of renewable energy in the country while looking into new market opportunities that would economically benefit Namibia. Adding large PV and wind power capacity for flexible electrolysers loads will reduce the volume of firm electricity generation required to ensure domestic electricity security. Another synergy may lie in developing large-scale pumped-storage hydropower to increase energy security, progressively eliminate the need for thermal power plants, and deliver firm electricity to hydrogen production.

3.3 Initial scale required in Namibia

Size matters and articulation between green hydrogen development and renewable deployment is critical. Cost competitiveness in the global ammonia market is associated with economies of scale of large production facilities. Namibia minimum size to have competitive price to enter the ammonia export market is 0.5 Mt of ammonia production per annum (commercial-scale ammonia plant), which would require power supply in excess of a 1 GW investment in solar and wind. Indeed, 1 GW electrolyzer capacity with 50% capacity factor would deliver 87,600 t of hydrogen, enough to make 496,400 t of ammonia. With 100% capacity factor firm electricity, ~1 Mt of ammonia could be produced.

3.4 Cost competitive production potential (cost simulation)

Preliminary estimates of prodution costs of green hydrogen and ammonia in near term in three locations in Namibia show that the country could produce both hydrogen and ammonia at highly competitive prices.

Levelized renewable electricity costs in theses locations resulted in 28.7 USD/MWh for solar PV, and ranges from 28.8-46.6 USD/MWh for wind. With assumptions targeting large scale projects in the near term, the preliminary analysis finds H_2 production costs of 1.94-2.27 USD/kg. Desalination of wáter at 1 USD/m^3 adds 0.01 USD/kg H_2, which represents 0.5% to H_2 production cost. Oxygen sale may add small value.

For the produciton of ammonia, also assuming commercial scale plants in the near term, the analysis finds production costs in the range of 437-548 USD/t NH_3, depending mostly on the assumption for flexiblity of the Haber-Bosch reactor (40%, 80%), and the type of hydrogen storage available (steel tanks or underground), where the possibility to use underground cavern storage of hydrogen could further reduce the cost of producing green ammonia.

Production cost of solar and wind

Levelized Cost of Electricity, LCOE (USD/MWh) was calculated for four locations in Namibia: Karas spot for solar, Luderitz South and Luderitz area 1 and Swakopmund for wind. ***Figure 12*** shows the data locations for modeling RE production costs.

Figure 12. Solar and wind data locations for modeling RE production costs

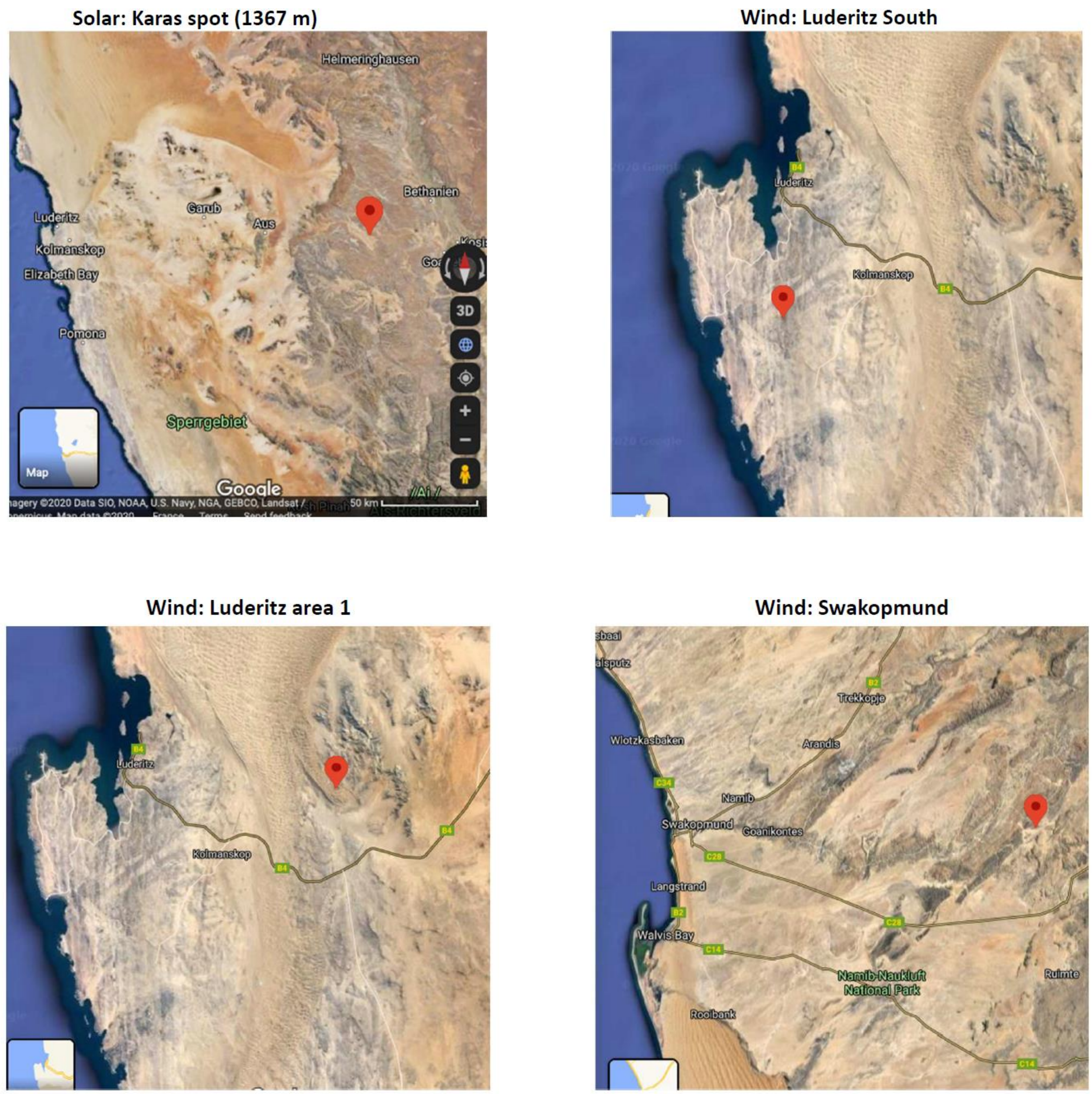


Figure 13 shows the LCOE calculations for wind and PV sites in USD/MWh)

Figure 13. LCOE calculations for wind and PV sites (USD/MWh)

Wind

Area	South of Luderitz	Luderitz 1	Swakopmund	Keetmanshoop area (not modeled)
Latitude (º)	-26,734888	-26,658833	-22,657236	-26,238225
Longitude (º)	15,156191	15,322185	15,636119	18,029674
Turbine class	1	1	2	3
Capacity factor	63,3%	50,1%	45,3%	44,4%
CF net	56,9%	45,1%	40,8%	40,0%
CAPEX (USD/kW)	1513	1513	1600	1716
WACC	6,0%	6,0%	6,0%	6,0%
lifetime (y)	25	25	25	25
Capital Recovery Factor	7,8%	7,8%	7,8%	7,8%
OPEX (%/y)	1,69%	1,69%	1,69%	1,69%
technical losses	10%	10%	10%	10%
$LCOE_w$ (USD/MWh)	28,8	36,4	42,6	46,6

PV

Area	Karas
Latitude	-26,67305
Longitude	16,82534
Elevation	1367 m

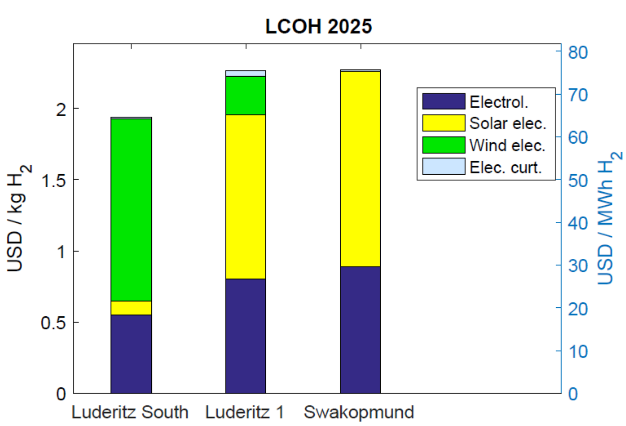
CAPEX (USD/kW)	800
OPEX (%/y)	1,73%
tech loss	10%
CF net	30,4%
LCOE (USD/MWh)	28.7

Source: authors own calculations.

Production cost of green hydrogen

Levelized Cost of Hydrogen, LCOH (USD/kg) was calculated to find the optimal sizing of wind and solar. Optimal shares of wind and solar depend on resource quality/costs and variability. ***Figure 14*** shows the optimal sizing of wind and solar (as=Ps/PH2, aw=Pw/PH2) found for lowest LCOH (without H_2 storage).

Figure 14. LCOH with optimal hybrid wind-PV plants (USD/kg)



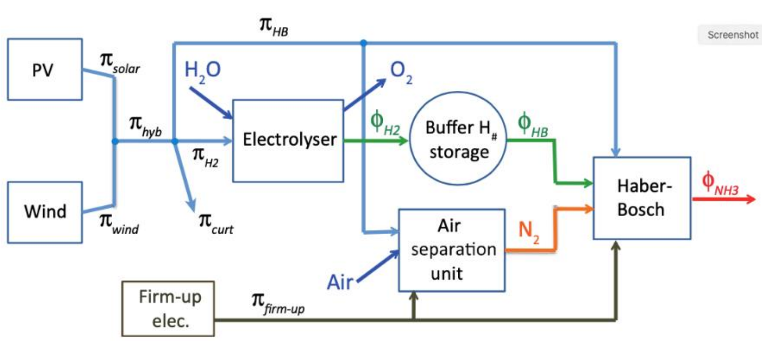
	Lud. S.	Lud. 1	Swak.
CF solar (%)	30,4	30,4	30,4
CF wind (%)	56,9	45,1	40,8
LCOE solar (USD/MWh)	28,7	28,7	28,7
LCOE wind (USD/MWh)	28,8	36,4	42,6
a_s^*	0,145	1,16	1,21
a_w^*	1,02	0,145	0
CF_electrolyser (%)	61,8	40,9	36,4
curtailment* (%)	0,89	2,5	0,93
Hibridz. Gain (%)	1,1	0,81	0
LCOH (USD/kg)	**1,94**	**2,26**	**2,27**

Source: authors own calculations
Note: desalination of water at 1 USD/m3 adds 0.01 USD/kg H2 = 0.5% to H2 production cost. Oxygen sale may add small value

Production cost of green ammonia

Levelized Cost of Ammonia, LCOA (USD/tNH3) was calculated for the timeframe 2025 for three flexibility cases, a) steel tanks, flex 40%, b) flex 80%, c) cavern, flex 40%. ***Figure 15*** shows the modeling of partially flexible NH_3 production. Haber-Bosch combines H_2 and N_2 from air. Synthesis reactor not fully flexible needs H_2 storage, either steel tanks or underground.

Figure 15. Modeling of partially flexible NH3 production

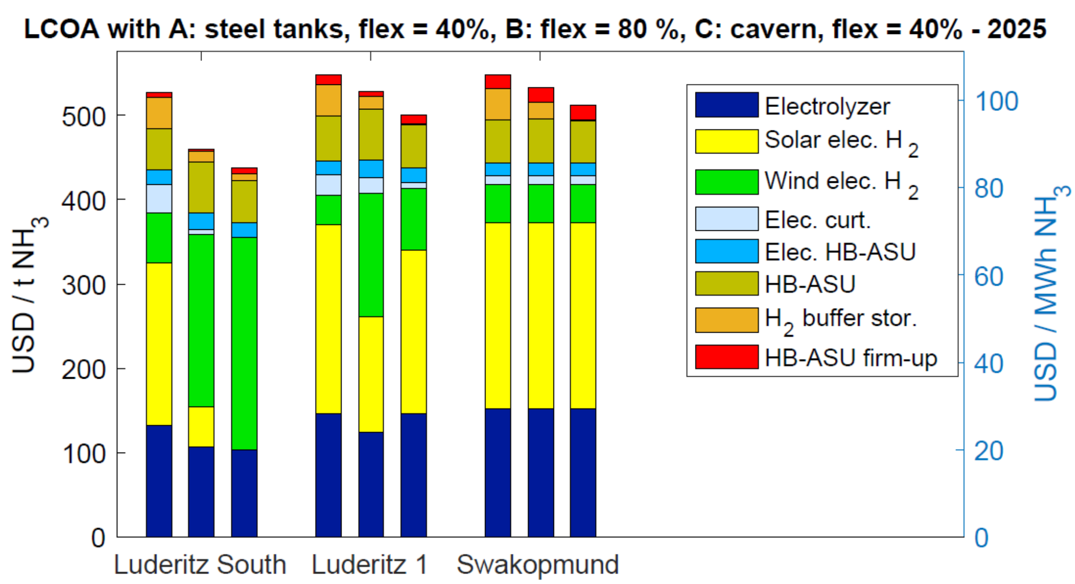


Haber-Bosch parameters	
$CAPEX_{syn}$ (USD/tpy)	333
$OPEX_{syn}$ (% CAPEX/y)	4
lifetime (y)	30
Elec. cons. (MWh/t fuel)	0.64
conversion efficiency (%)	99
Flexibility down (% max load)	40 / 80
max ramp (+/- % load/ h)	20
cold stop min. duration (h)	48
$CAPEX_{stor}$ cylinders (USD/kWh) (LHV)	12
$CAPEX_{stor}$ cavern (USD/kWh) (LHV)	0.6
$OPEX_{stor}$ storage (% CAPEX/y)	1

Source: authors own calculations
Note: parameters for commercial scale plant

Figure 16 shows the production costs of green NH3 for three flexibility cases. H_2 Storage can be very costly for synthesis unit of low flexibility (esp. for wind)

Figure 16. LCOA for three flexibility cases (USD/t)



Source: authors own calculations

Figure 17 illustrates the optimal NH3 plant parameters. Implicit LCOH is higher than previously found LCOH with fully flexible offtake assumed (without storage).

Figure 17. Optimal NH3 plant parameters

	Luderitz South			Luderitz 1			Swakopmund		
	flex 40% (steel tanks)	flex 80% (steel tanks)	flex 40% (cavern)	flex 40% (steel tanks)	flex 80% (steel tanks)	flex 40% (cavern)	flex 40% (steel tanks)	flex 80% (steel tanks)	flex 40% (cavern)
LCOH implicit (USD/kg)	2,26	1,98	1,94	2,33	2,3	2,26	2,32	2,32	2,32
a_s^*	1,4	0,4	0	1,4	1	1,14	1,26	1,26	1,26
a_w^*	0,23	0,91	1,14	0,11	0,57	0,2	0,13	0,13	0,13
HB oversizing	1,16	1,43	1,18	1,25	1,43	1,18	1,2	1,23	1,18
CF_electrolyser (%)	46,2	58,4	60,9	41,2	49,2	40,2	39,6	39,6	39,6
curtailment* (%)	11,1	1,9	0,0	8,1	5,9	2,1	3,5	3,5	3,6
H_2 storage (days)	3,3	0,9	19,4	3,7	1,3	8,4	3,9	2,1	4,0
firm-up (%)	8,41	3,42	9,54	16,7	7,79	14	22,8	23,3	22,8
Hibridzation Gain (%)	7,7	2,2	0	3,5	4,1	3,2	2,7	2,4	0,9
LCOA (USD/t)	**527**	**460**	**437**	**548**	**528**	**501**	**548**	**533**	**512**

Source: authors own calculations

Figure 18 shows a commercial scaled example of 1,000 tpd green NH3 plant in Luderitz 1. Economies of scale are important.

Figure 18. Scaled example: 1,000 tpd green NH3 plant in Luderitz 1

flex=40%	**Electrolyser**	**Solar**	**Wind**	**Haber-Bosch**	**H_2 storage**	**Total**
Capacity (MW)	815	1140	93,1	306	8600	0
CAPEX (MUSD)	489	913	141	228	129	1900
flex=80%						
Capacity (MW)	673	673	385	349	3470	0
CAPEX (MUSD)	404	538	582	252	52,1	1830

Source: authors own calculations

4. High-Level Opportunities for Namibia

4.1 Global player

Large industrial players are teaming up with renewable energy players in an effort to position themselves as early movers, identifying sweet spots well positioned worldwide to develop integrated facilities (from renewable energy to production of green hydrogen and its derivatives) and export the green hydrogen output such as ammonia. Namibia is well positioned to become a global player in green hydrogen export in the form of green ammonia. As shown in the preliminary analysis on costs, the country could have one of the lowest hydrogen production costs in the world produced on a large scale. Namibia would be competing with Australia, Chile, Middle East countries, Morocco, New Zealand, Norway and others as these countries are pursuing GW-scale investment.

4.2 Driving RES development, attract new investments

Namibia has excellent solar and wind energy potential and is well placed to produce renewable hydrogen at a cost-competitive price. Green hydrogen will further drive investments of large-scale renewable energy, including solar and wind, thus offering significant opportunity to economic growth and stimulate investment and jobs in the country. Close integration with the rest of the power system is critical to optimize costs, increase energy security and maximize synergies to increase fiscal revenues, strengthen marketability ammonia from green electricity, and more affordable electricity for all.

4.3 Socio-economic benefits (local development, job creation, skills development)

Preliminary evaluation of the socio-economic benefits of the renewable energy program contemplated under this green hydrogen scenario (1,140MW solar and 93.1MW wind, **Figure *18***) not considering at this stage the socio-economic impacts triggered by the green hydrogen deployment include:

- **Local added value** (measured as the difference between output and intermediate consumption, contributing to national GDP):
  - including direct, indirect and induced added value
  - 250 to 300 MUSD of local added value during the years of development and construction of the plants
  - 300 to 350 MUSD of local added value during the phase of operation and maintenance of the Plants
- **Employment** (including direct, indirect and induced jobs):
  - 3,500 to 4,500 local jobs supported in average during the years of development and construction of the plants
  - 500 to 600 local jobs supported in average during the phase of operation and maintenance of the plants

4.4 Others potential opportunities

Mining could be a national market for hydrogen, haul trucks could be propelled by green electricity via batteries and/or catenaries and/or hydrogen fuel cells, ammonia is at the core of mining explosives, desalination requirements for green hydrogen could be oversized for local water consumption, supply diversification will increase energy security and less exposure to expensive, volatile, imported liquid fuels. Green hydrogen would contribute to greenhouse gas emissions reduction target of 89 percent by 2030, as in Namibia's Nationally Determined Contribution under the Paris Agreement commitments.

5. Conclusion and recommendations

5.1 Summary of opportunities

Preliminary analysis of green hydrogen market and LCOH shows Namibia could produce highly competitive green hydrogen in the form of green ammonia, but with little national demand, exports will be key to the green hydrogen strategy. Exporting green ammonia at competitive price requires large scale RE development with a minimum of 1000 MW to start compared to the 650MW domestic power sector. The country would benefit from the economies of scale to position itself to compete in a global current and future market for green ammonia (hydrogen). With its abundant amount of renewable energy sources and an increasing demand in green hydrogen and its derivates worldwide, Namibia could become an important global player competing with several countries as they are pursuing GW-scale investments. In these early stages of market development, the government of Namibia should focus efforts on achieving large-scale, low-cost RE development and designing models for sustainably maximizing fiscal revenue and local development in RE investments and green ammonia production. Namibia's world-class solar and wind resources give it a long-term competitive advantage in producing green hydrogen and green ammonia. Careful attention should be paid at these early stages to do proper planning and set up the proper fundamentals to ensure long-term development benefits for the country. The country should put in place a competitive bidding process designed to maximize the national benefits and lay the foundation for long-term participation in a growing green hydrogen market.

5.2 Stakeholders to engage

The following is a list of stakeholders that would be important to engage with early in the discussion to better define the opportunities and government priorities:

- Office of the President
- Ministry of Finance
- National Planning Commission
- Ministry of Mines and Energy
- Minister of Public Enterprises
- Ministry of Industrialization and Trade
- Ministry of Environment, Forestry, and Tourism
- Ministry of Labour, Industrial Relations, and Employment Creation
- Ministry of Agriculture, Water, and Land Reform
- Ministry of Higher Education, Training, and Innovation
- Ministry of Gender Equality, Poverty Eradication and Social Welfare
- Ministry of Gender Equality and Child Welfare
- Electricity Control Board
- NamPower
- Industry and financial sector representatives
- Academia and research organizations

The creation of a national commission on hydrogen or a technical roundtable could be envisioned to serve as a platform to exchange information to build consensus, advance technological progress, and co-ordinate strategic activities.

5.3 Phase 2 Technical Assistance

The objective of a potential technical assistance (TA) in Phase 2 is to support Namibia to develop and implement its national strategy for green hydrogen.

The structure, tasks, and outputs below are intended to guide discussions with the Government of Namibia on the design of the proposed TA.

1. Conduct strategic analysis to optimize position of Namibia in future global market for GH

TASKS

A. Analyze markets for green hydrogen (GH): trends, opportunities, domestic and international
B. Assess local costs of supply and other key characteristics: gauge Namibia's competitiveness
C. Market sounding: potential customers for GH and its derivatives, key stakeholders on the GH value chain
D. Identify potential roles for the public party: seize opportunities, mitigate risks, mobilize private investment

OUTPUTS

→ *Prioritize medium- and long-term markets/applications for GH*
→ *Position Namibia's public and private stakeholders on GH value chain*
→ *Identify feasible business models*

2. Identify prerequisites to develop GH at scale

TASKS

A. Specify optimum RE deployment to meet demand for GH and its derivatives: ammonia, methanol, etc.
B. Identify synergies between GH development and desalination/water supply
C. Assess logistics needs: storage of GH and derivatives, transport, domestic and international
D. Evaluate legal, regulatory, institutional and financing framework (including the "green" certification of GH

OUTPUTS

→ *Select RE sites to serve GH production alongside those to generate electricity for grid*
→ *Set targets and timeline for RE expansion (size, location, technology) to meet local/ international market demand for GH*
→ *Recommend adjustments to legal, regulatory, institutional and financial arrangements as needed*

3. Maximize socio-economic and environmental benefits

TASKS

A. Analyze GH value chain: components, jobs, skills, competitive advantages
B. Map local players on GH value chain, including RE value chain
C. Specify key steps and associated entry points to maximize socio-economic and environmental benefits
    i. Maximize local industrialization where competitive to create jobs, enhance skills, transfer knowledge
    ii. Support community development at sites of GH value chain investments to enhance resilience, livelihoods

OUTPUTS

→ *Quantify potential contributions to economic, social and environmental goals*
→ *Action plan to deploy GH as a catalyst for the socio-economic development of the country*

4. Deploy cross-sector, medium- and long-term roadmap for GH development

TASKS

A. Prepare action plan for prerequisites in each sector/application identified
B. Prepare action plan to maximize socio-economic benefits and bridge gaps identified
C. Optimize links between GH development and deployment of renewable energy
D. Prepare risk allocation matrix to optimize the roles of the public and private sectors
E. Select business model(s), structure GH program to leverage private capital and maximize socio-economic benefits

OUTPUT

→ *Identify pipeline of investment projects along GH value chain and its derivates*
→ *Define catalytic roles of public parties, implementing roles of private parties*
→ *Map out financing required to support pipeline of investments*

References

ESMAP. (2020). *Green Hydrogen in Developing Countries.* Washington, DC: World Bank.

European Commission. (2020). *Communication COM/2020/301: A hydrogen strategy for a climate-neutral Europe.* European Commission.

IEA. (2019). *The Future of Hydrogen.* Paris: IEA.

IRENA. (2020). *Green Hydrogen: A guide to policy making.* International Renewable Energy Agency, Abu Dhabi.

IRENA. (2020). *Namibia Energy Profile.* Masdar City: IRENA International.