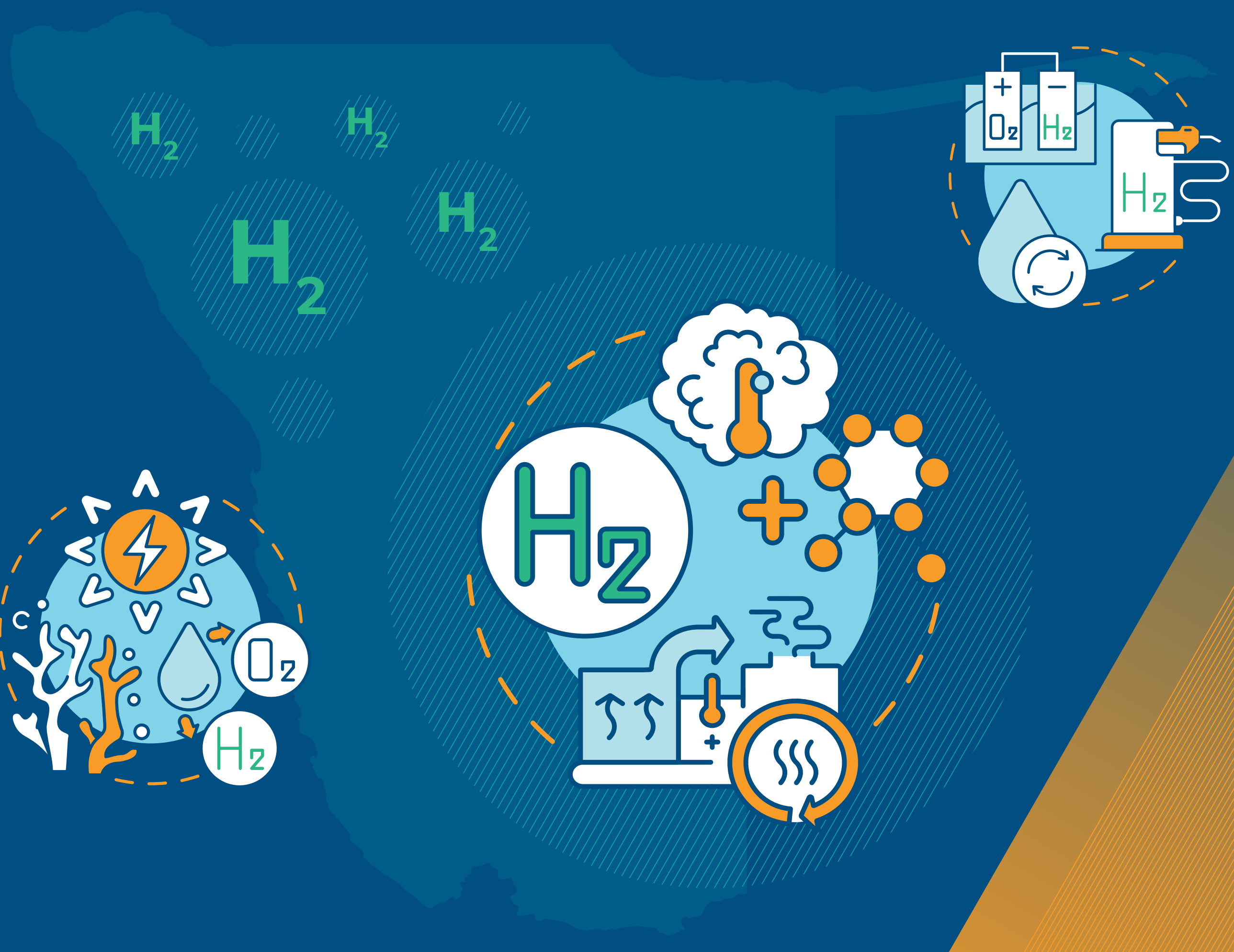
KONRAD ADENAUER STIFTUNG

Issues, Challenges and Opportunities to Develop Green Hydrogen in Namibia

Detlof von Oertzen | October 2021



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Publisher: Konrad-Adenauer-Stiftung
PO Box 1145, Windhoek, Namibia
Info.namibia@kas.de
www.kas.de/namibia

Project Coordinator: Claudia Gossow

Author: Detlof von Oertzen

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Introductory Note

With Namibia's Hydrogen generation capacity and potential economic development on the forefront of the country's National Development Agenda complimented by the recent statements made by President Hage Geingob at COP26 at the beginning of November 2021, the Konrad-Adenauer-Stiftung Namibia-Angola Country Office are excited to contribute toward this first edition of Dr Detlof von Oertzen's latest paper titled "Issues, Challenges and Opportunities to Develop Green Hydrogen in Namibia".

This informative paper could not be launched at a more ideal time as the country is gearing once more toward transforming its renewable energy arena to uplift the nation at large, with the aim to utilise and keep Namibia's natural and human resources in the loop. Therewith, to source more innovative means of renewable energy production, using a multi-sectoral approach in line with the Sustainable Development Goals, and hydrogen termed a rising enabler for a multi-sectorial transition towards a low carbon economy, we are grateful to the author for presenting the potential opportunities, challenges and issues of developing a hydrogen economy, increasingly referred to as Namibia's new "gold mine" not to mention game changer in the international community.

We believe that Dr Detlof von Oertzen in this paper has once again succeeded to link the potential of hydrogen production in addressing Namibia's high unemployment rate in particular for the youth and shine a light on the country's drastic socio-economic and environmental transformation, products of the tragic COVID-19 pandemic. We trust that the information presented herein will assist industry experts to better prepare themselves for the road ahead in successfully developing this thriving renewable energy source.

Further, we hope that Dr von Oertzen's insights captured in this publication will encourage policy makers, small and medium enterprises, the private and public sectors, as well as educational and development institutions in Namibia to join forces in tackling the country's long standing economic hardships and to embrace this beautiful country's abundant resources, not to mention its hydrogen economy potential. Our vision is that readers will feel empowered and better equipped to gradually transform Namibia to lead by example in becoming one of Africa's most independent economic drivers.

Natalie Russman
Resident Representative
Konrad-Adenauer-Stiftung e.V. Namibia-Angola Office

1. Introduction

This paper discusses how Namibia can participate and benefit from global decarbonisation efforts. It is intended to inform and contribute to rational and fact-based deliberations on the many issues, challenges, and opportunities for green hydrogen production in Namibia.

Discovered in 1766, hydrogen is once again on the lips of many [1]. Internationally, hydrogen enjoys renewed and often intense interest [2]. In Namibia too, recent pronouncements seem almost overly exuberant when hydrogen and its seemingly limitless potentials are discussed [3]. Whether many of the often-hyped expectations relating to hydrogen translate to tangible actions remains to be seen.

There is a growing realisation that manmade contributions to climate change are a serious global challenge [4]. To date, 191 countries have committed to the 2015 Paris Agreement, obligating signatories to initiate activities to limit this century's temperature rise to below 2°C above pre-industrial levels [5]. Several countries have developed action plans to reach net-zero carbon emissions by 2050, or before [6], [7], [8]. Rapid decarbonisation of all economic activities is essential if internationally agreed climate goals are to be achieved. Replacing fossil fuels by carbon-free energy sources is one of the key measures to lower carbon emissions [9].

Central to the drive towards decarbonisation is that atmospheric greenhouse gas (GHG) emissions are substantially reduced [10]. While the Covid-19 pandemic reduced global GHG emissions by some 8.8 % in the first six months of 2020, relative to the same period in 2019, long-term GHG emissions reductions require fundamental changes to how energy is produced, transported, stored, and consumed. Such a transformation is expected to affect the socio-economic realities of most countries.

From an energy perspective, global GHG emissions reductions are often technically feasible, and frequently economically viable. Decarbonising the global energy industry is most effective when carbon abatement opportunities that offer net-positive environmental and economic paybacks are undertaken first. While numerous emissions reductions opportunities exist, some are energetically and/or environmentally and/or economically less viable than others, an observation that seems to have been missed in many recent discussions, including in Namibia.

Transforming the global energy industry to reduce its emissions necessitates a dramatic shift away from producing and consuming fossil fuels such as oil, coal, natural gas and their multitude of derivative products. In the electricity industry, generation capacities based on fossil fuels will have to be replaced by those powered by renewable energy sources, especially by solar and wind resources. In addition, greater emphasis must be placed on using energy more efficiently, for example when heating or cooling buildings, transporting goods, producing food and water, and many others [11].

Switching current fuels to low- or no-carbon energy sources is often possible. For example, the electrification of some parts of the transport industry, or the heating and cooling of buildings by using clean electricity, is both possible and increasingly viable. However, producing steel, chemicals and cement, and many bulk transport activities are much more difficult to electrify than is the case in other industries. Here, reducing emissions necessitates other approaches, e.g., switching to clean fuels such as green hydrogen.

Hydrogen is an energy carrier, in other words, it is a fuel. Hydrogen must be produced, which remains costly when it is done without causing carbon emissions. But hydrogen is also a versatile feedstock, for example in the chemical and liquid fuels industries. The cost to produce clean hydrogen is steadily declining, and at the same time, the urgency to reduce global carbon emissions is dramatically increasing. International discussions increasingly consider the many uses of clean(er) hydrogen, especially in sectors where deep decarbonisation remains difficult. Such deliberations also take place in Namibia, and this paper seeks to help differentiate between ideals, lofty goals, and realities.

2. Namibia's Energy Sector

2.1 Introduction

Namibia's energy sector comprises of the regulated downstream liquid fuels and electricity sectors, and the less-structured gas, biomass, and thermal energy sectors [12]. Renewable energy sources are in use in both formal and informal settings, as well as in various sectors of the country's economy [12].

2.2 Namibia's Current Energy Mix

Namibia remains fully dependent on the import of all liquid fuels, while continuing to import more than one-half of its electricity requirements. The country's total energy mix, refer to Figure 1, is dominated by liquid fossil fuels in the form of diesel, petrol, kerosene, and heavy fuel oil. Other sizeable contributors are electricity and biomass, while coal and liquid petroleum gas (LPG) play a minor role only.

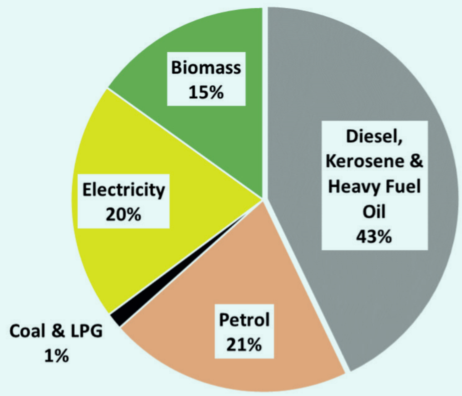

Figure 1: Composition of Namibia's total energy use by energy type [12]

2.3 Liquid Fuels

The liquid fuels sector has three subsectors, namely the upstream (i.e. exploration), midstream (i.e. storage and transportation) and downstream (i.e. distribution and supply) sectors [12].

Upstream, oil and gas exploration have resulted in significant geological insights and findings. So far, however, the only commercially exploitable fossil fuel resource is the Kudu gas field, located some 170 km north-west of Oranjemund, off the south-western coast. Midstream, Namibia remains reliant on importing all liquid fuels. Downstream, the distribution and supply of liquid fuels are dominated by multi-national entities, while state-owned Namcor gradually increases its share in the retail market [13].

2.4 Electricity

The Electricity Control Board (ECB) is Namibia's regulatory authority for the electricity industry. The electricity sector operates under well-developed legal and regulatory framework conditions [14].

The state-owned electricity utility NamPower owns and operates the country's transmission networks, which connect Namibia to southern and north-eastern markets and regional generators [15]. In 2021, NamPower owns and operates electricity generating assets with a nameplate capacity of 498.5 MW as well as 300 MW of interconnecting capacities to regional suppliers [16].

Since 2015, more than 20 Independent Power Producers (IPPs) have commenced operations. Additional IPPs are likely to join the sector as the modified single buyer market is implemented. Three regional electricity distribution companies, NamPower as well as select local and regional authorities and others distribute and supply electricity to end-users [12].

2.5 Namibia's Renewable Energy Resources

Namibia is well endowed with renewable energy resources [17]. Of special note are the solar, wind and biomass resources (the latter in the form of encroacher bush) that are available in abundance. Intermittent renewable energies, i.e. those that are only available at certain times, already contribute to power the nation [12].

Examples include the country's most substantive solar resources, the good wind resources, as well as the hydropower resources from highly variable perennial rivers. Namibia's renewable energy resources will play an increasingly important role in future, specifically in the further development of the country's electricity sector, thereby further enhancing the security of supplies.

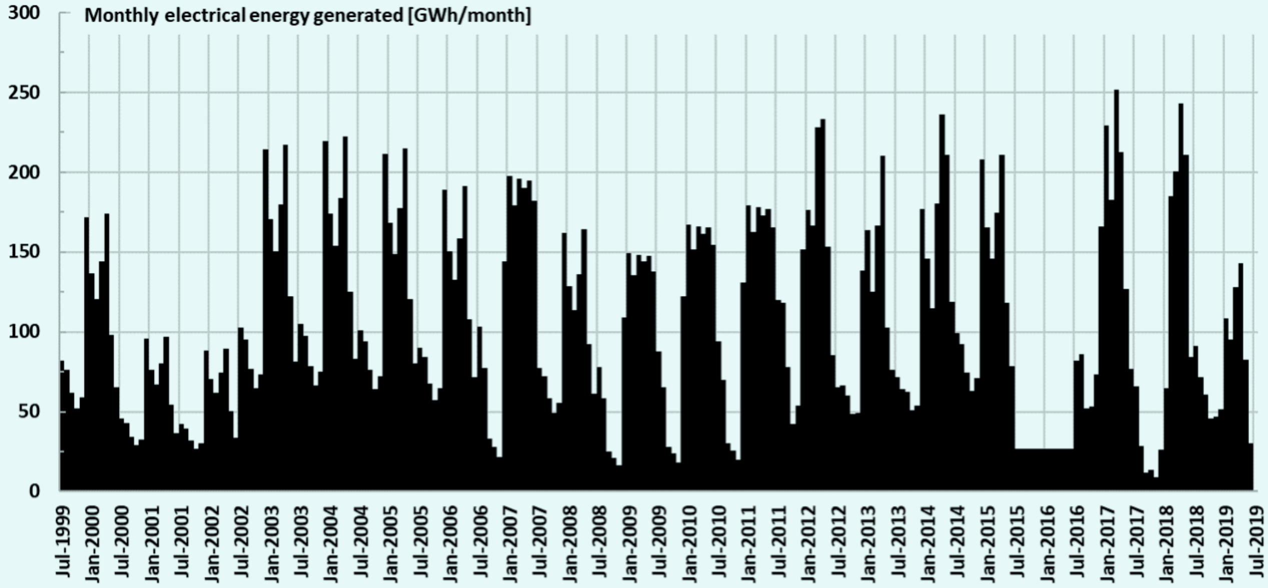

Figure 2: Ruacana's monthly electricity output between 1999 and 2019, in GWh/month [12]

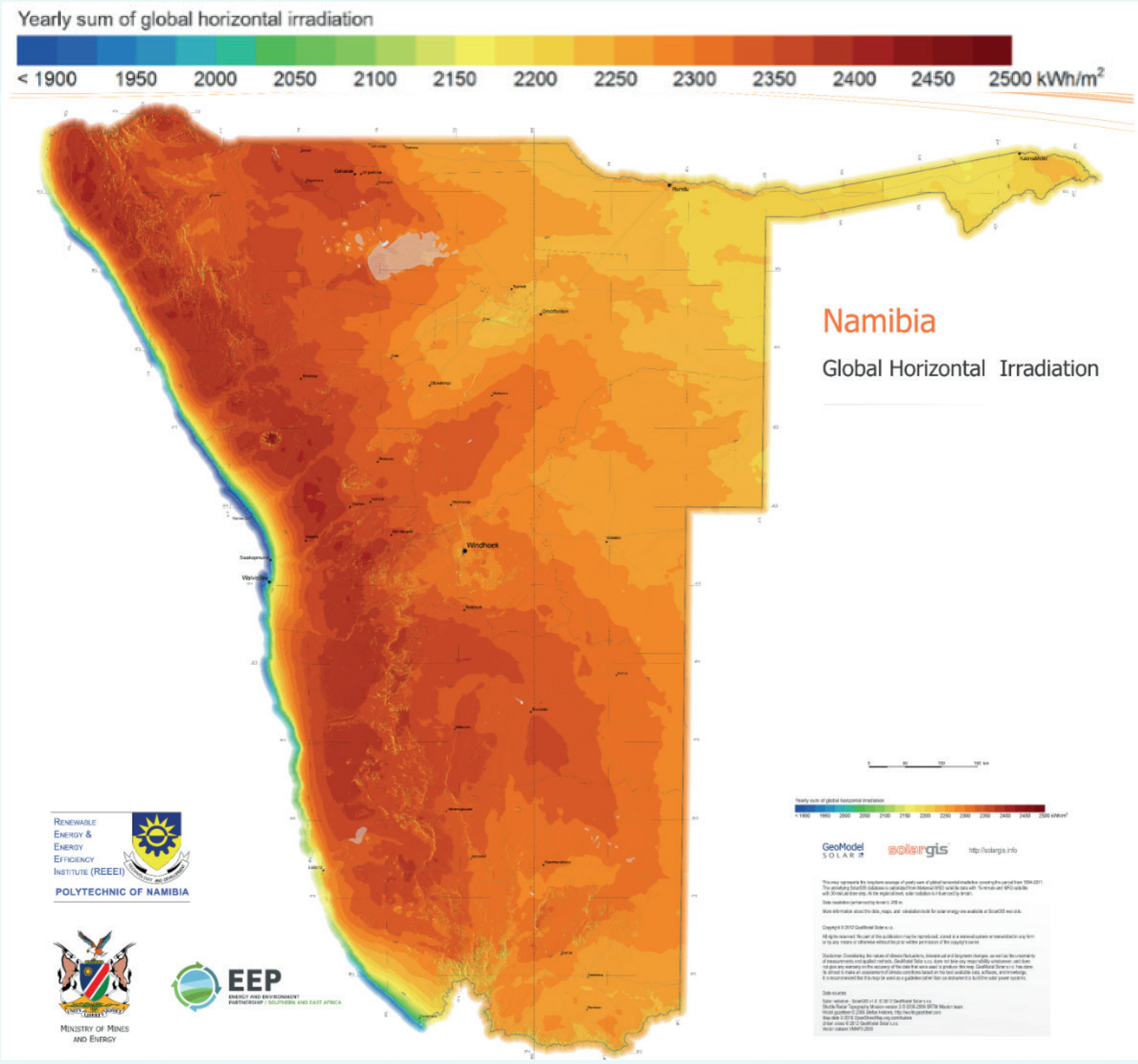

Figure 3: Namibia's world-class solar global horizontal irradiation potential, in kWh/m²/a [18]

- **Hydropower potentials** exist in the Kunene River, and to a lesser degree, in the Okavango and Orange rivers [12]. Figure 2 shows the electricity output of the Ruacana hydroelectric power station, in giga-Watthour (GWh) per month, between July 1999 and July 2019. Evidently, this run-of-river power plant's output is highly variable and remains dependent on rainfall as well as the multiple large-scale uses of water in the upper basin of the Kunene River in south-western Angola.

  Changes in regional climate are expected to further increase the variability of flows at Ruacana. In addition, the many new agricultural projects and industrial developments initiated in southern Angola will negatively affect the reliability and availability of water in the Kunene River and will substantially influence the future output of Ruacana as a generation asset of national importance.

- **Solar resource:** Namibia's world-class solar resources are shown in Figure 3 [18]. This renewable resource is most suitable for solar electricity generation, e.g., by way of solar photovoltaic or concentrated solar plants and for thermal applications. In recent years, solar electricity generation is increasingly contributing to both grid and off-grid electricity supplies, and solar thermal technologies, specifically to replace electric water heaters, are becoming more popular too [12].

- **Wind energy resource:** Namibia's wind potentials, especially along the southern coast and at select inland locations, are good to excellent, yet they remain an almost untapped energy resource. Figure 4 shows average wind power densities at 100 metres above ground level [19].

- **Biomass:** more than one-half of all Namibian households continue to use wood for cooking and/or space heating. Biomass also serves as a primary feedstock of the charcoal industry. It is also used as animal fodder, and as a fuel to displace coal or liquid fossil fuels in both thermal and electrical applications. The local use of biomass for charcoal production, household consumption, as animal fodder and to replace fossil fuels, has rapidly increased, particularly in recent years [12].

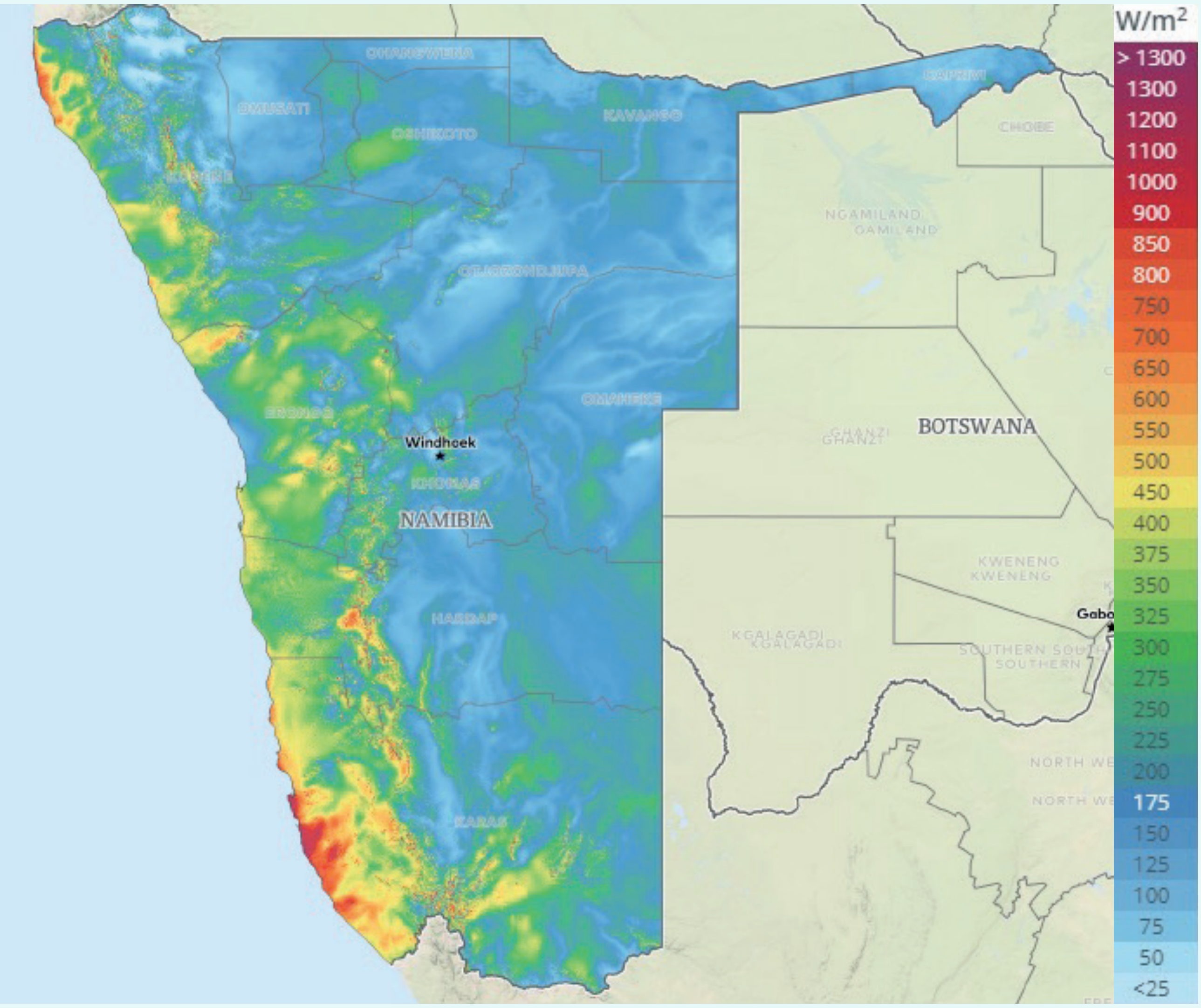

Figure 4: Namibia's wind power potentials at 100 m above ground level, in W/m² [19]

- **Geothermal potentials** exist, albeit in select locations only. However, their capacities remain unclear, implying that these resources are not yet ready for commercial development [12].

- **Ocean and wave energy potentials** await to be further assessed and properly quantified [12].

2.6 Namibia's Non-Renewable Energy Resources

- **Uranium:** since 1976, uranium-bearing minerals are mined in Namibia, to produce uranium concentrate for export, see Figure 5. The country is amongst the four largest uranium producers, contributing more than 10% of global supplies in 2018. Expressing Namibia's uranium exports in terms of their potential to generate electricity renders the country a net energy exporter [20].

- **Natural gas:** discovered in 1974, the Kudu gas field holds proven reserves of at least 37 billion cubic meters. However, despite extensive exploration work and 3-dimensional seismic surveys costing hundreds of millions of Namibian dollars, its commercial development and use remains elusive [17].

- **Waste:** several waste disposal facilities, e.g. near Windhoek, Walvis Bay and Swakopmund, as well as other sources of waste could potentially be developed to produce both heat and electricity.

- **Oil:** indications of the existence of potentially exploitable resources exist. However, no discoveries of commercially viable and exploitable oil resources have been recorded to date.

- **Coal:** some deposits exist, e.g. near Aranos, but these are unsuitable for commercial exploitation.

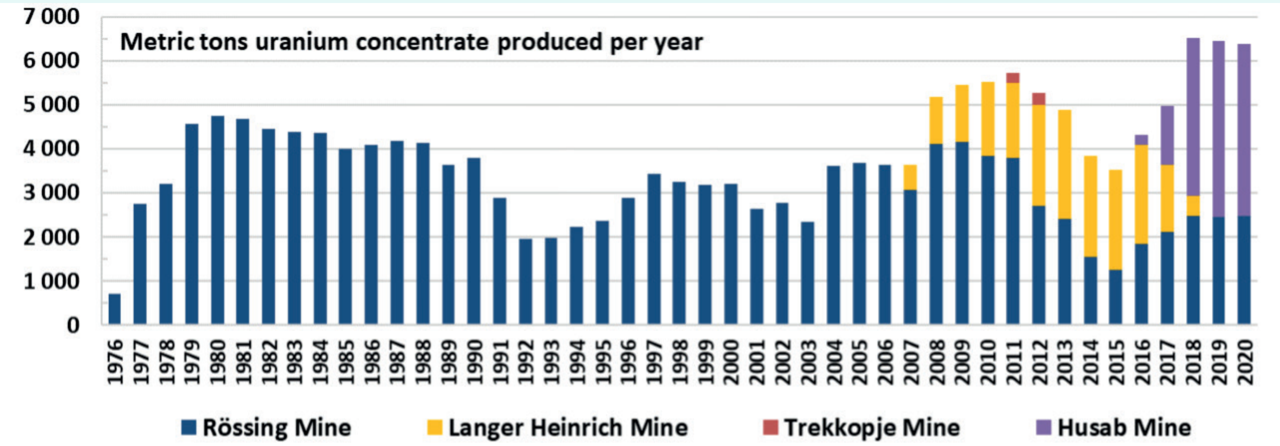

Figure 5: Namibian uranium concentrate production since 1976, in metric tons per year [20]

3. Climate Change, Greenhouse Gas Emissions and Decarbonisation

3.1 The Paris Agreement

Today, 191 out of 197 parties to the United Nations Framework Convention on Climate Change (UNFCCC) are signatories of the Paris Agreement of 2015, thereby committing to actively limit man-made global warming and initiate actions to adapt to the impacts associated with climate change [21]. The Agreement is an internationally binding treaty that charts a course of actions to address global climate change by accelerating efforts towards a sustainable low-carbon future [22]. This has far-reaching implications, including for Namibia, despite the country remaining a net carbon sink [23].

The Paris Agreement's central aim is to strengthen the global response to the threat of climate change by limiting average global surface temperature rises to below 2°C (degrees Celsius) compared to pre-industrial levels [24]. To enable countries to initiate the economic transformations deemed necessary to achieve the Agreement's goals, access to new sources of finance, technologies and capacity building support are essential, to effectively implement greenhouse gas emissions reductions and initiate climate-resilient development pathways [24]. Individual countries describe their plan of climate mitigation and adaptation actions in their nationally determined contributions (NDC) documents, noting that Namibia submitted its updated NDC to the UNFCCC in July 2021 [25].

3.2 Greenhouse Gas (GHG) Emissions

As part of their efforts to implement the Paris Agreement, many countries have embarked on efforts to reduce their atmospheric greenhouse gas (GHG) emissions. Some countries have already announced plans to reach climate-neutrality. Substantial reductions of GHG emissions necessitate that processes that emit GHGs are limited, or phased out completely. The most common GHGs include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) [26].

Fossil fuels are significant contributors to man-made GHG emissions. Such emissions are most readily reduced by fuel switching, i.e. by replacing those fuels that emit carbon compounds when being combusted by low- or no-carbon emitting fuels, or by using carbon-free electricity, and the adoption and use of energy efficient technologies [27], [28].

3.3 Decarbonisation

Decarbonisation is the new mantra for the systematic reduction of atmospheric carbon emissions [29]. A global phase-out of fossil fuels would see their replacement by low-carbon fuels and shifting towards the use of carbon-free electricity, where this is possible and economically viable. Some energy end-uses are better suited for increased electrification than others are, e.g., replacing fossil fuelled vehicles by electric vehicles that are charged using low- or no-carbon electricity, which is particularly effective in the passenger and light vehicle segments [30].

Other applications dependant on the use of fossil fuels, however, are considerably more challenging to decarbonise. Industrial sectors that are challenging to wean off their fossil fuel needs are, amongst others, the chemical industry, shipping, heavy transport, and the aviation industries. In select cases, GHG emissions from these hard-to-abate industries could be lowered by switching to low(er)-carbon synthetic fuels, i.e. liquid or gaseous fuels made from natural gas, coal, oil shale, tar sands and biomass feedstock, including methane, methanol, ethanol, to name a few. In the context of this paper, the use of hydrogen instead of fossil fuels, specifically green hydrogen and its derivatives, is of interest [31].

4. Hydrogen

4.1 Introduction

Hydrogen is the most abundant element in the known universe [32]. Yet despite its cosmic abundance, molecular hydrogen (H_2) on earth is rare. However, hydrogen can be produced from compounds containing bound hydrogen, e.g., by splitting the constituents of water (H_2O), or from hydrocarbons such as methane (CH_4), and others.

Hydrogen is a fuel. This means that hydrogen is a chemical energy carrier, similar to fossil fuels, which are chemical energy carriers as well. Important similarities between hydrogen and fossil fuels include, that fossil fuels such as oil, coal, and natural gas, can be readily stored, transported, and used to generate heat and electricity. The same can be achieved with hydrogen. However, upon combustion, hydrogen emissions are limited to water vapour, while burning fossil fuels results in carbon emissions, including in the form of carbon dioxide (CO_2).

In 2018, the worldwide hydrogen consumption amounted to some 70 Mt (million metric tons) [33]. Hydrogen is a versatile feedstock and has a range of important uses: of special importance is its use in the production of ammonia and synthetic hydrocarbons, which is mainly taking place in industrialised nations. Ammonia is a pre-requisite in the production of fertilisers used in agriculture, as well as for explosives used in the mining industry. Synthetic fuels are used in the chemical industries of many industrialised nations, and they are also of interest as maritime and air transport fuels [34].

Hydrogen's many derivative products, i.e., the products that can be made from hydrogen, range from hydrogen-based synthetic fuels, chemicals, direct fuels for internal combustion engines, and as a fuel that powers fuel cells, which are used to generate electricity. Increasingly, hydrogen is also becoming of greater interest as a reducing agent in the steel industry, as a fuel for high-temperature industrial processes, and as a temporary energy carrier, e.g., serving as medium- and long-term or seasonal energy store, and to generate electricity. As a fuel, the use of hydrogen in the transport sector necessitates storage, distribution and refuelling networks and facilities, which should preferably be close-by to where the fuel is produced, to minimise losses and substantial infrastructure investments.

Given the need to decarbonise economies, hydrogen's potential as the new fuel that powers nations has captured the attention of scientists, politicians and many a fortune seeker too. Historically, visions of a global hydrogen economy have caused exuberance and gravity-defying enthusiasm, the same elements as are evident in many a contemporary deliberation on hydrogen today. It is both instructive and sobering to recognise that a transformation to a hydrogen economy has remained a dream.

4.2 Producing Hydrogen

Today, most hydrogen is produced from fossil fuels, such as natural gas and oil [35]. These conversion processes lead to emissions amounting to some 830 million tons of carbon dioxide (CO_2) per year, which is equivalent to about 2% of global CO_2 emissions from fossil fuels [33]. Hydrogen that is produced with low- or no-carbon emissions is a prime candidate to fully displace fossil fuels, which is seen to be an essential step to create climate-neutral economies.

The most common approaches to produce hydrogen are by way of steam methane reforming and autothermal reforming [36]. In steam reforming, the hydrocarbons contained in natural gas (mainly methane) are broken down into hydrogen and CO_2 in the presence of water vapor, under high temperatures and pressures. Usually, the heat required for the process is from burning a fraction of the fossil fuel feedstock, resulting in additional CO_2 emissions.

Autothermal reforming entails combining the process of steam reforming with an additional oxidation step, e.g., the high-temperature gasification of coal, to synthesise hydrogen from a fossil fuel feedstock, such as methane [36].

4.2.1 The "Colours" of Hydrogen

Hydrogen produced using steam or autothermal reforming is known as *grey hydrogen,* meaning that the production process causes CO_2 emissions. Hydrogen production from natural gas emits around 0.3 kg_{CO2}/

kWh_{H2} (kilogram CO_2 per kilowatt-hour of hydrogen produced). In contrast, hydrogen production from crude oil leads to emissions of 0.36 kg_{CO2}/kWh_{H2}, while the use of coal to produce hydrogen emits 0.57 kg_{CO2}/kWh_{H2} [33]. These emissions exclude those from the production process, transport, and storage of the precursor feedstock as well as the construction of the production plant.

Hydrogen known as *turquoise hydrogen* is produced when natural gas or methane is thermally split using the process of pyrolysis, producing hydrogen, solid carbon, and some CO_2 [33]. *Blue hydrogen* is produced by reforming natural gas whilst collecting, storing, and re-using the resulting CO_2 [33].

Green hydrogen is produced when water is split into its constituents, i.e., into hydrogen and oxygen, without leading to carbon emissions. Such clean splitting is achieved when the input energy required to split water is derived from carbon-free energy sources. Several processes are used to produce *green hydrogen*, including electrolysis, the use of high-temperature heat of solar thermal origin, and the direct use of solar radiation in a process known as photolysis [37].

4.2.2 Hydrogen from the Electrolysis of Water

In 2021, electrolysis is the most technologically advanced process used to produce hydrogen. Three main types of electrolysis, namely *alkaline electrolysis*, *proton exchange membrane electrolysis* (PEM electrolysis) and *high-temperature (HT) electrolysis* are used [36].

Alkaline electrolysis is a mature process to produce hydrogen on industrial scales and has been applied for many decades. *PEM electrolysis* has niche applications, while the maturity of *HT electrolysis* remains to be demonstrated. It is noted, however, that *HT electrolysis* appears to be well-suited for variable operating conditions, as would be the case when powering electrolysis using intermittent renewable energy sources [36].

Further development is needed to enhance the durability and cost-effectiveness of contemporary electrolysers [35]. To date, the world-wide production capacities of electrolysers remain limited, and require significant upscaling if the global green hydrogen production ambitions – as are seen to be part of the international drive to decarbonise economies – are to be achieved [36].

Producing hydrogen by way of the electrolysis of water using electricity from renewable energies is not entirely GHG-neutral, but causes considerably lower emissions than those emitted in processes that involve the use of fossil fuels. Generally, if electricity is used to split water, it is important that this input energy does not lead to substantive additional GHG emissions. In this context it is important to note that most conventional electricity supplies are based on a mix of different energy sources, and therefore result in net-positive GHG emissions. Provided that the GHG emissions associated with the electricity mix are low, or close to zero, hydrogen produced from such a mix is termed *green hydrogen*. Namibia's current electricity mix is associated with CO_2 emissions ranging between 0.69 kg_{CO2}/kWh and 0.83 kg_{CO2}/kWh [12].

Whether or not the production of hydrogen from electrolysis is ultimately viable depends on technical as well as economic factors. Upfront investment requirements, cost of capital, process conversion efficiencies, production hours per year, cost of electricity and prevailing market prices are the main drivers determining whether it is viable to create national green hydrogen production capacities [35].

4.2.3 Hydrogen from Woody Biomass

A large variety of woody biomass raw materials are suitable for hydrogen production. The gasification of biomass, e.g., in the form of wood, wood chips or agricultural residues, results in syngas, which is a mix of gases consisting of hydrogen, carbon monoxide, and CO_2 [37]. Other biomass-related production processes entail the use of biogas in steam reforming, and using of bacteria to induce the fermentation of feedstock and splitting water by way of photo-biological approaches. While of interest, most of the latter processes must be further developed to reach full commercial maturity, and their viability in large-scale applications remains to be demonstrated.

As most forms of biomass feedstock regrows in time, using biomass is often viewed as being carbon-neutral, as similar amounts of CO_2 are emitted during the decomposition of the biomass resource as are absorbed during its growth phase. However, using naturally occurring biomass resources, such as the Namibian encroacher bush resource, is generally not entirely GHG-neutral. This is because the harvesting, processing, and transporting of such biomass results in GHG emissions, over and above those from soil disturbances caused during such activities. While it would be premature to conclude that Namibia's biomass resource is not suitable to produce hydrogen, numerous challenges remain to be addressed before this indigenous energy resource can feed local industrial-scale hydrogen production facilities [17].

4.2.4 Hydrogen from Photo-related Processes

For a sun-drenched country, such as Namibia, concentrating solar thermal plants could eventually be used to split water into its constituents. In addition, processes such as photo-electrochemical and photo-catalytic splitting allow the direct use of solar radiation to generate hydrogen. However, these approaches have not yet reached the technical maturity that is necessary for their large-scale commercial application [37].

In photo-biological water splitting processes, solar radiation is used to produce hydrogen from water. This is a special type of photosynthesis, resulting in hydrogen as a by-product from the metabolic processes of microorganisms used in the process. However, to date, the process efficiencies remain low, thus necessitating considerable additional research and development before their large-scale roll-out [37].

4.3 Economics of Hydrogen Production

The economics of producing hydrogen from intermittent renewables, such as the sun or the wind, is improved as the number of full production hours per year are increased. It is for this reason that solar and wind resources that complement each other, for example with the sun being available when the wind does not blow and vice versa, are important pre-requisites in the design of efficient green hydrogen production facilities powered from renewable energy resources.

Generally, producing, converting, transporting, and using fuels leads to energy losses. Such losses can be expensive, and sometimes render a fuel non-viable. To minimise losses, energy supply systems deliberately minimise the number of conversions required, from production to its end-use.

In the case of hydrogen production from electrolysis, present day electrolysers are about 67% efficient. This means that about one-third of the input energy required to produce hydrogen is lost during the electrolysis process alone. In other words, more than 1.5 units of energy are needed to produce one energy unit of hydrogen. To illustrate: it takes some 50 kWh of electrical energy to electrolytically produce one kilogram of hydrogen, the latter having an energy content of some 33.3 kWh. This underlines that the production of hydrogen is energetically expensive. In 2021, producing green hydrogen remains commercially non-viable [38], especially because the majority of electricity generation plants in operation today produce electrical energy at prices that remain too high to cost-competitively produce green hydrogen [39].

Today, producing hydrogen without causing carbon emissions remains, in most cases, expensive [40]. Commercially, it is only viable to produce green hydrogen if the associated costs of production, including the cost of energy required to do so, is very low in comparison with present-day electricity prices [41]. It is important to note that additional processing, liquefaction, transport, storage and further conversion of hydrogen, for example into a fuel such as ammonia, adds to the energy bill associated with hydrogen's production chain. Unless all production steps, from cradle to grave, are exceptionally optimised, green hydrogen remains energetically and financially expensive [39], [40], thus mostly remaining a non-competitive alternative amongst the range of fuels that are available.

Today, producing hydrogen from natural gas costs between N$ 0.53/kWh_{H2} (€ 0.03/kWh_{H2}, using an exchange rate of N$ 17.50 = € 1.00) and N$ 1.05/kWh_{H2} (€ 0.06/kWh_{H2}). In contrast, producing green hydrogen by electrolysis costs between N$ 1.75/kWh_{H2} (€ 0.1/kWh_{H2}) and N$ 2.63/kWh_{H2} (€ 0.15/kWh_{H2}) [40], [41]. Further cost reduction potentials exist and are estimated to range between 50% and 60% [41], [42]. As the scale of hydrogen production increases, and individual component costs decrease, green hydrogen costs are expected to decrease. The Hydrogen Council estimates that costs between N$ 0.3/kWh_{H2} (€ 0.017/kWh_{H2}) and N$ 0.88/kWh_{H2} (€ 0.05/kWh_{H2}) will be achievable by 2050 [42].

5. Green Hydrogen Production in Namibia?

5.1 Introduction

This section assesses whether Namibia meets the pre-requisites to produce green hydrogen on a medium to large scale.

Producing green hydrogen by electrolysis of water, on viable scales, necessitates ready access to large tracts of low- or no-cost land, an abundance of cheap electricity, and one or several low-cost clean water sources. Essential processing facilities include low-cost electrolysis plants, water desalination plants if seawater is used as source, as well as hydrogen processing, storage, and transport facilities. If the synthesised product is to be further converted, for example to ammonia or synfuels, additional production facilities are required as well. If products are to be exported, adequate pipeline and/or port infrastructure is a requirement too.

5.2 Large Tracts of Available Land

Namibia is a vast country with a very low population density. Southern Namibia, in particular, also boasts amongst the best solar resources in the world. Its coastal and near-coastal areas are desert and semi-desert areas, with good to excellent wind resources.

Namibia's near-costal desert areas all form part of national conservation areas which are particularly sensitive to disturbances. Creating large-scale hydrogen production and processing facilities in this brittle environment will be associated with multiple negative impacts on the environment. Amongst others, these are likely to include impacts on existing water resources, land- and ecosystem degradation, soil degradation and its likely contamination by process chemicals. In addition, pollutants from the desalination of seawater, which is necessary to undertake electrolysis and produce hydrogen derivatives, are most likely to occur on a significant scale and therefore necessitate stringent and continuous environmental management efforts [43].

A sharp increase in the demand for land that is to be used for large-scale hydrogen and derivative production will increase the demand and competition between resources. This competition also introduces difficult trade-offs between the conservation goals of hyper-sensitive areas and the prospects of creating much-needed jobs, new income opportunities and new long-term development prospects.

5.3 Abundance of Low-cost Electricity

Hydrogen must be produced as it cannot be sourced directly in nature. Its production necessitates an abundance of low-cost input energy, either in the form of fossil fuels or electricity. To produce green hydrogen by electrolysis, significant renewable energy resources must be available, to convert these to low-cost electricity. If such electricity generation capacities are not in place, they must be newly built. To date, Namibia imports more than one-half of its annual electricity requirements from southern African countries [44]. Evidently, Namibia does not have spare electricity generation capacities, let alone generation plants using renewables, to be used to produce hydrogen, other than to power a pilot plant [12].

Whether, and in what period, additional renewable generation capacities are to be brought online is the topic of Namibia's National Integrated Resource Plan (NIRP) [45]. In 2021, the NIRP of 2016 was updated, describing the timing and roll-out of additional electrical generation capacities to meet the country's electricity demand over the next 20-years. The updated NIRP does not include the requirements associated with the production of green hydrogen, which is a shortcoming.

Whether it is more important to decrease Namibia's long-standing electricity dependencies before creating the infrastructure to produce green hydrogen, or *vice versa,* is a conundrum that has yet to form part of public policy deliberations. An argument in favour of fast-tracking the development of Namibia's renewable energy potentials, to create green hydrogen production capacities, is that these may offer an opportunity to re-energise Namibia's economy. An argument recently attributed to Namibia's President relating to green hydrogen ambitions expresses that *"… we are talking about serious matters that would pull our country out of the morass"*, and illustrates the importance that something other than a business-as-usual approach is required to revive the country's economy [46].

Namibia's embrace of larger-scale renewable energy technologies – in the form of commercial solar and wind capacities – started in earnest in 2015 [12]. However, many potential projects remain on the drawing boards, often for years, with little progress being made. If new electricity generation capacity is to be brought online quickly, a reset of mindsets and elimination of red tape will be essential. Such a change of how business is currently done is particularly important in areas relating to how plant, equipment and services are procured, how land is made available, and how legal and regulatory provisions support the unfettered implementation of projects, rather than delay them.

5.3.1 Hydrogen from Wind Energy Converters

Worldwide, wind power is amongst the favoured renewable energy sources to produce green hydrogen and its derivatives. As shown in Figure 4, Namibia is well-endowed with wind energy resources, particularly along the coastal areas along the western, southern, and south-western parts of the country. On land, some 3,500 km^2 (square kilometres) along the south-western onshore coastal areas has wind resources that warrant the use of conventional wind energy converters, offering a combined electricity generation potential of approx. 15 GW (gigawatt) [47]. Of note are the considerable off-shore wind energy potentials, specifically in south-western Namibia, which could provide further scope to benefit from these sustainable natural endowments.

It is noted that large tracts of the onshore land along the south-western coast continue to be used for diamond mining, which complicates the access to land and its use for other purposes. Electricity transmission capacities, serving the southern coastal areas are limited to low-capacity transmission connections to the towns of Lüderitz and Oranjemund. Most substantial power evacuation infrastructure would have to be built unless all electricity from future wind power plants is to be dedicated for consumption by future hydrogen production and processing facilities.

5.3.2 Hydrogen from Solar Photovoltaic Power Plant

The magnitude of the worldwide solar energy potential is staggering. This implies that solar resources are key for future green hydrogen production [48]. As concentrated solar power plants have not reached the same technical maturity as solar photovoltaic (PV) power generation, and cost considerably more than solar PV capacity, the latter is the likely solar power choice to be considered for green hydrogen production [37].

The solar irradiation in the form of the global horizontal irradiance, as depicted in Figure 3, is testimony to Namibia's exceptional solar resource potentials [18]. The solar resource in south-central Namibia in particular, is massive, and offers potential yields from solar PV plants that are well-above those in most other countries of the world [50]. Using conventional solar PV technologies, this world-class resource offers electricity generation potentials ranging between 2,200 kWh/m^2/a and 2,500 kWh/m^2/a [50]. In view of southern Namibia's sparse population densities, ample land area could potentially be made available to construct solar PV plants on gigawatt scales.

A pre-requisite for such developments, however, is that adequate transmission infrastructure would have to be established, to evacuate power from where it is generated and deliver it to where it will be used. A modern 1-axis controlled solar PV plant produces some 70 GWh/km^2/a [51]. Namibia's //Kharas Region alone has a surface area of some 161,500 km^2, which is vast. The scale of the potential solar resource can be appreciated when noting that an area of only 48 km^2 of solar PV plant would suffice to generate the country's total electricity consumption of 3,362 GWh in 2019/20 [44]. Again, this illustrates the enormous potential that Namibia's solar resource holds in store [17].

5.4 Water

Water is an essential input for hydrogen production by electrolysis. Namibia is a water-scarce country, having an overall water risk classification of *'extreme'* [52]. This implies that both feedwater and process water are not available in any significant quantities, certainly not in quantities that would be adequate to meet production requirements for green hydrogen and the processing of its derivatives.

One option that could provide input water is the desalination of sea water drawn from the Atlantic Ocean. There are no major technical obstacles to desalination to deliver potable and process water. Present-day improvements and refinements centre on reducing the overall energy requirements and cost of individual process elements and enhancing the plant longevity. However, desalinated water remains considerably more costly than traditional water supplies for industrial and chemical uses [53].

Separating salt and dissolved solids from seawater is energy intensive. Contemporary desal plants use between 3 and 8 kWh of electrical energy per cubic meter of desalinated water. The cost of input energy has a significant impact on the operational costs of desalination plants, further underlining that low-cost electricity is a pre-requisite for the commercial production of green hydrogen.

Contemporary electrolysers need between 10 to 20 litres of water to produce one kilogram of hydrogen [54]. While desalination technologies are mature, producing potable and process water remains costly, both in terms of capital expenditure requirements as well as their continuous operation. To illustrate: a desalination plant with an output capacity of 20 Mm^3/a (million cubic meters per year), i.e. similar to the Erongo desalination plant at Wlotzkasbaken, has an electrical energy requirement of between 120 and 150 GWh/a. If its full output capacity is dedicated to produce hydrogen, up to 2 Mt_{H2} (million tons of hydrogen) could be produced per year, consuming some 0.1 kWh/kg_{H2}.

The European Union's Hydrogen Strategy has a hydrogen production target of 10 Mt_{H2} by 2030 [6]. Therefore, to meet this target using demineralised sea water necessitates up to 10 desalination plants of the capacity of the Erongo plant. This, amongst other arguments, illustrates that pronouncements that Namibia is becoming *"a green hydrogen hub for Africa"*, seem overly optimistic [55].

Desalination plants often affect both coastal and marine ecosystems. The release of brine and the chemicals used in the desalination process has adverse impacts on the diversity of marine life [56]. A new generation of electrolysers is currently being developed, for direct use with salt water, but these remain technically immature and are not deemed ready for industrial scale uses yet [57], [58].

5.5 Storage and Transport

Transporting hydrogen by ship remains far from being carbon neutral. The upscaling of conventional transport capacities for hydrogen would therefore likely significantly increase transport-related GHG emissions. Cost-effective and climate-neutral storage, transport and shipment approaches for hydrogen must be further developed before they become a realistic option to convey large quantities of hydrogen around the world. Also, many contemporary compounds serving as carrier media in the transport of hydrogen are known to be highly hazardous, which complicates their use [37].

In future, short- and medium-distance transport of hydrogen and its derivatives is likely to be achieved by pipeline, as well as by cargo ships. However, the low density of gaseous hydrogen renders it inefficient for transport and necessitates mechanical compression to increase its volumetric density. The liquefaction of hydrogen almost doubles its volumetric density and is achieved by its repeated compression and cooling. This is an energy-intensive process, consuming between 36% and 45% of the energy content of hydrogen [59]. The International Energy Agency expects that further improvements in liquefaction will reduce losses to about 22.5 % [33].

The boiling point of hydrogen is minus 253 °C, meaning that liquefied hydrogen must be transported in special-purpose heat-insulating cryo-tanks. Contemporary tanks used to transport hydrogen are prone to losses, mainly due to the gradual boil-off of hydrogen. This implies that some 0.2 % (0.06 %) of a total hydrogen load evaporates per day when using a tank of 100 m^3 (20,000 m^3) [59]. For this reason, the large-scale conveyance of liquefied hydrogen is not yet considered fully mature, and purpose-built tanks for large(er)-scale maritime transport are in various stages of their further development.

To decarbonise the shipping industry, the use of low-carbon synfuels is entirely possible, thereby reducing the considerable emissions burden associated with both the global shipping and transport industries. An example of the displacement of heavy fuel oils is the switching to green ammonia, which can be readily liquefied by compression, and does not require special carrier media for its transport.

Transport of hydrogen by pipeline over short- to medium distances is most economical when volumes are high. To date, considerable discrepancies and uncertainties remain, regarding the minimum distance from which point onward the transport of liquefied hydrogen by ship is cheaper than its transfer by pipeline. By 2030, it is estimated that transport distances exceeding 1,500 km are most economically undertaken by ship [33]; others suggest that this distance must be greater than 6,000 km [61]. Cost differences between pipeline and ship transport also critically depend on whether existing infrastructure can be repurposed, or whether it must be newly built.

Trucks equipped with special-purpose tanks conveying compressed or liquefied hydrogen are used for the last-mile distribution and supply of hydrogen. In most parts of the world, hydrogen distribution networks and storage facilities at distribution points still remain non-existent. It will be a considerable challenge to roll out hydrogen distribution infrastructure, especially in sparsely populated countries such as Namibia, noting that its potential uses in local industry and for heating purposes remain limited.

5.6 Human Capacities

Despite Namibia's renewable energy resource abundance, the country's attractiveness to become a future exporter of green hydrogen and related products depends on many other aspects too. These include, amongst others, that the human, technical and financial resources to create industrial production capacities are available when needed.

In August 2021, the German government signed a Memorandum of Agreement with Namibian counterparts to support human resource development, mainly at the University of Namibia and the Namibian University of Science and Technology [62].

5.7 Funding Requirements

Regarding the requirement for funding associated with the creation of hydrogen production and processing infrastructure, it is evident that considerable funding challenges exist in 2021, even those required to continue the execution of the Government's primary functions and responsibilities.

This implies that approaches other than those reliant on Namibia's small tax-payer base are needed to fund ambitious infrastructure projects. Any reliance on budgetary allocations from state coffers is considered unrealistic. It is therefore essential that international funding opportunities are tapped into.

5.8 Attracting International Developers

In June 2021, the Government of Namibia launched an international and local call for investors and interested parties to submit proposals to assess, develop and operate green hydrogen production facilities in the country [63], [64]. The call resulted in nine submissions, which were adjudicated prior to the COP26 Conference that took place in Glasgow, Scotland, in the United Kingdom, between 31 October and 12 November 2021 [65].

At COP26, the Namibian delegation announced that HYPHEN Hydrogen Energy (Pty) Ltd was the preferred bidder to develop the country's first large-scale vertically integrated green hydrogen project, in the Tsau //Khaeb National Park south of Lüderitz. The project, which is suggested to be worth some US$ 9.4 billion, seeks to ultimately produce 300 kt_{H2} of green hydrogen per year, both for regional and global markets, either in the form of pure green hydrogen or green ammonia [66].

6. Opportunities for Green Hydrogen Developments in Namibia

6.1 Introduction

In 2021, green hydrogen constitutes a tiny fraction of the total global hydrogen that is produced. A dramatic increase in green hydrogen production capacities necessitates enormous financial investments and would only be considered if markets are created that are willing and able to successively displace common fossil energy carriers. These global challenges are similar to the daunting requirements that Namibia faces in establishing an even modest green hydrogen economy.

As a country without a manufacturing base, with minimal industrial capacities, a tiny local market, and an ailing economy, creating a green hydrogen economy may seem utopian. Irrespective of whether a green hydrogen economy is an achievable near-term aspiration, as is suggested by some, or remains a distant hope, this section describes some of the opportunities that could be unlocked by creating local green hydrogen production capacities.

6.2 Local Demand for Hydrogen

In 2021, local requirements for hydrogen for commercial and industrial uses are non-existent. While potentials exist, these have not been developed, as alternatives to hydrogen remain plentiful, and the delivery and use of hydrogen necessitates an infrastructure that does not exist. A demand for industrial uses of hydrogen could, in time, be developed, provided that the cost to switch fuels is justifiable. Initial pre-feasibility assessments undertaken for several medium and large-scale industrial and mining operations in Namibia have shown that the absence of a reliable and cost-competitive hydrogen distribution, storage and supply infrastructure presently renders fuel switching non-viable [66]. This may change in time, provided that the scale and cost at which hydrogen is produced and delivered can become more competitive.

In the absence of large-scale local hydrogen consumers, the establishment of a local distribution infrastructure is considered unlikely. The same applies for hydrogen uses in the local electricity sector, which would require the establishment of reliable and cost-effective delivery approaches to power fuel cells or conventional internal combustion engines to generate electricity. Given the near-continuous decline of solar PV prices, and the rapid decline of medium- to large-scale energy storage infrastructure in the past years, it seems unlikely that hydrogen-powered electricity is likely to establish a local foothold in Namibia's internal market in the near future, except possibly where use options are located directly at and around the production sites and excess hydrogen is available as a fuel.

6.3 Hydrogen for Export

The Namibian Government's Southern Corridor Development Initiative envisions the establishment of industrial-scale export-oriented capacities to produce green hydrogen and ammonia in the south of the country [68]. The initiative seeks to identify international actors to establish green hydrogen and ammonia production facilities powered by wind and solar energy, with demineralised water being supplied from local desalination plants. These efforts are to be realised around the small town of Lüderitz, which are to additionally benefit from a to-be-developed wind blade manufacturing plant, a green steel processing plant as well as a fertiliser plant. Hydrogen export capacities are to enable the shipment of green hydrogen to markets, in what some already pronounce to become a green hydrogen export hub to the world.

Generating capacities of 1 GW wind power and 0.5 GW solar PV would produce some 0.1Mt_{H2} per year. Exporting 0.05 Mt_{H2} and converting the other half to produce ammonia yields some 0.2 Mt_{NH3} per year. How such quantities of hydrogen and ammonia could be handled, stored, and transported, and eventually exported via the small port of Lüderitz remains entirely unclear [69].

The Southern Corridor Development Initiative envisages the creation of some 30 GW of generating capacities, assumed to be powered by renewable energy sources [68]. Establishing such generation capacities would be staggering by Namibian standards, noting that the country's wind power capacity installed to date stands at 5 MW, and a solar PV capacity of approx. 200 MW in late 2021.

6.4 Ammonia

In 2018, the worldwide ammonia production capacities amounted to some 235 Mt [70]. Today, actual ammonia (NH_3) production ranges between 180 Mt_{NH3}/a and 230 Mt_{NH3}/a, consuming between 30 Mt_{H2}/a and 40 Mt_{H2}/a [71]. Some 80 % of this ammonia is used in the form of industrial fertiliser, noting that an estimated 45 % of the world's food production depends on the use of such fertilisers. Whilst China remains the world's largest nitrogen producer, with an output amounting to about 1/3rd of the current global production, while an estimated 20 Mt_{NH3}/a are produced in Europe [54].

Almost the entire industrial production of ammonia is derived using the Haber-Bosch process, using atmospheric nitrogen as well as synthesised hydrogen [54]. Mostly, the hydrogen used for ammonia production is derived from fossil fuels. Replacing such hydrogen by its low-carbon equivalent could be a positive step toward decarbonising agriculture and reducing the GHG footprint of the world's vast food production system.

Future-oriented applications of ammonia could significantly reshape the large-scale transport sector, especially in the marine environment: heating ammonia in the presence of a catalyst enables the recovery of hydrogen. This process, once it has reached industrial maturity, would enable the transport of hydrogen in the form of ammonia. Using ammonia as a carrier medium of hydrogen holds several advantages: gaseous ammonia is readily liquefied by compression under ambient conditions, whereas most technical requirements to transport large quantities of ammonia are already in place, including the infrastructure required for use in the shipping industry. However, the transportation of hydrogen in the form of ammonia is associated with conversion losses of some 40% [72].

Ammonia offers several desirable characteristics that suggests its use to store hydrogen. It has an energy density of 22.5 MJ/kg and physical properties like those of propane, which implies that it can be readily stored in inexpensive pressure vessels [71]. In the transport sector, using ammonia instead of hydrogen overcomes the need for large storage tanks necessary to transport hydrogen, as well as the infrastructure limitations associated with the storage, handling, and transport of hydrogen [72]. However, ammonia is a flammable, highly corrosive and toxic gas associated with several significant health and safety risks. Also, ammonia is toxic to aquatic and marine organisms, and its emissions lead to the formation of atmospheric particulates known to contribute to the acidification of soils [73].

6.5 Green Iron

The global steel-making industry produces some 1.8 billion tons of steel per year, responsible for almost 8 % of manmade greenhouse gas emissions [74]. Iron and steel are pre-requisites for many industrial activities, ranging from construction, transport, the energy industry, and countless other endeavours. Decarbonising the making of steel is therefore important to reduce worldwide GHG emissions [75].

Traditional steel production uses coke (an almost pure source of carbon made by heating coal in the absence of air) to generate heat and supply the carbon required to strip oxygen from native iron ore, thereby producing pure metallic iron, i.e. 'reducing iron oxide to iron' [76]: $Fe_3O_4 + CO \rightarrow 3\ FeO + CO_2$ and $FeO + CO \rightarrow Fe + CO_2$. This process, used for some 70 % of global iron ore production, takes place in blast furnaces and results in pig iron as well as considerable emissions, including some 1.8 tons of CO_2 per ton of pure iron. Alternatives are sought, including the direct reduction of iron ore using hydrogen and carbon monoxide and its further processing to steel in electric arc furnaces [76]. It is recorded that transporting elemental iron instead of iron ore reduces conveyance requirements by about one third.

If green hydrogen is used, the total emissions footprint of making steel can be dramatically reduced: $Fe_3O_4 + H_2 \rightarrow 3\ FeO + H_2O$ and $FeO + H_2 \rightarrow Fe + H_2O$, consuming about 540 m^3 of hydrogen per ton of iron. Various companies are developing green steel capabilities, including the Swedish SSAB [77], the German Thyssen Krupp [78], multinational ArcelorMittal [79] to list a few.

Country-specific climate and emissions targets, as well as carbon taxes, are among the main drivers today, spurring steel producers into finding more environmentally benign production methods. The greening of the steel industry requires dramatic changes in terms of the status quo production approaches used for this critically important commodity [80].

Opportunities include the addition of green electricity generation capacities, noting that about one quarter of the world's current electricity generation capacity would be required to generate sufficient green hydrogen to enable the transition to green steel production. This scale-up necessitates vast additional investments in revamping the entire steel industry, including massive green hydrogen production and substantial additions to transport capacities. Such a transition hinges on electricity prices that are considerably lower than they currently are, and higher carbon prices (presently at € 60/t_{CO2} in the European Union) [81].

Most steel producers in the northern hemisphere would not readily meet their hydrogen requirements from local sources. To date, the demand for green hydrogen far exceeds the supply. In time, export facilities will be created, particularly in the global south, possibly including Namibia as well.

The Namibian company *HyIron Green Technologies* [82], in collaboration with European partners such as CO2Grab [83], plans to introduce green iron production in the country. Local iron ore, for example originating at the iron ore mine near Dordabis [84] or the to-be-developed Shiyela iron deposits in the western Namib [85], and green hydrogen produced in the Erongo Region, would be used. Such new capabilities would introduce future-oriented clean production approaches to mining and its value-addition in Namibia, and create local jobs whilst adding value to locally produced export products.

6.6 Synthetic Fuels

Synthetic hydrocarbons are produced using hydrogen and a source of carbon. End-products include liquid fuels and gases. Synthetic fuels, or synfuels for short, are readily transportable, including the use of infrastructure established to convey liquid petroleum products or natural gas. This implies that investments in new infrastructure in general are considerably smaller than would be the case if hydrogen were to be transported [86].

Emissions from synfuels usually include CO_2. To reduce their carbon footprint, direct air capture powered by carbon-free energy is used which entails the removal of atmospheric CO_2. However, most such technologies are not yet available for deployment on industrial scales and further development is needed to enhance their economy in industrial settings [86].

To produce low-carbon synfuels, green hydrogen is required. A power-to-liquid (PtL) process entails the use of electricity to generate hydrogen and convert it to a liquid fuel. An example is the production of synfuels, and related liquid raw materials used in the chemical industry. In contrast, power-to-gas (PtG) processes convert electrolysed hydrogen to gaseous end-products, for example methane or methanol, the latter is used as fuel additive and feedstock for petrochemical products. With expanded synfuel production, methanol could assume a more dominant role as a liquid fuel, for example in internal combustion engines or to feed purpose-built fuel cells in vehicles [86]. In October 2021, Belgian investors were reported to be *"... interested in investing N$ 860 million to start a synthetic fuel pilot plant in the Erongo Region*" [87].

7. Challenges and Risks for Green Hydrogen Developments in Namibia

7.1 Contemporary Hydrogen Production

To date, producing hydrogen from low-carbon energy sources remains costly and non-competitive when compared to hydrogen made from fossil fuels. Green hydrogen depends on a raft of incentives and deliberate government interventions to compete with grey hydrogen and fossil fuels [88].

The International Energy Agency suggests that the cost of producing hydrogen from electricity generated from renewable energy resources could fall by 30% by 2030 [33]. Such reductions may materialise when international efforts to upscale the elements needed for green hydrogen production could be focused. Given the inertia of markets, new developments need tangible incentives, as well as the further decline of renewable electricity prices, cost reductions for electrolysers and innovative approaches to transport massive amounts of hydrogen cost-effectively. This is a most ambitious set of pre-conditions.

7.2 Policy and Regulatory Frameworks

Presently, there are no specific policies or regulations that guide the development of hydrogen-related activities in Namibia. Few investors would rely on word-of-mouth assurances and promises alone. Enhancing investment certainty necessitates pragmatic, low-barrier approaches to conducting business. While it can be assumed that most interested parties would eagerly accept the award of 40-year concessions, as indicated in Namibia's call under the Southern Corridor Development Initiative, few tangible developments are likely to materialise without solid legal and regulatory frameworks on which hydrogen-related investments can be executed [68].

Hydrogen-related quality standards are an essential element in to-be-developed legal provisions and regulations. These must address both upstream and downstream requirements, including those required for the safe handling, storage, transport and further processing of hydrogen, product purity requirements, GHG emissions accounting across the full production process, and ways in which the origin of hydrogen for exports can be certified, to name but a few [54].

7.3 Markets and Market Readiness

Solid supporting peripheral infrastructure and reliable value chain elements are necessary for the establishment of medium- to large-scale industrial processes. Without a local market, the absence of distribution capacities for hydrogen, and few realistic prospects for wide-scale fuel switching in the short- and medium-term, local demand for green hydrogen will not drive local hydrogen production.

Without an established gas transport infrastructure in Namibia, and severely limited electricity transmission capabilities, such infrastructure would have to be newly built. Relating to export capacities, the Lüderitz harbour's freight handling capacities remain most limited, without relevant handling, storage or piping infrastructure. Reliable high-volume import and export capacities are critical if the Government's Southern Corridor Development Initiative is to be realised [68].

7.4 Namibia as Price Taker

As a non-industrialised country with no technical manufacturing base, Namibia remains a price taker in all technology-related undertakings. We pay what others ask us to. This has significant repercussions, and creates numerous dependencies. International exchange rates, commodity prices, prices for hydrogen production technologies, expert know-how and many other input requirements determine whether and how the design, implementation, and operation of complex production processes for green hydrogen is likely to evolve. Such dependencies will not rapidly disappear, and Namibia will remain a dwarf in the league of giants determining the know-how, finance and technology that shape the adoption and use criteria of global green hydrogen and its derivatives.

The viability of establishing green hydrogen capacities in Namibia depends on forces of supply, as well as those underpinning demand. Both depend on the development of trade volumes, production and trading conditions, pricing developments, and many other factors. Most such aspects are determined by international markets and actors, in response to demand, supply and specific government incentives. These forces and developments are beyond Namibia's reach, and do not consider the country's actual needs and wants.

7.5 International Drivers

International actions to address global climate change are expected to drive the establishment of green hydrogen production and its markets. Massive flows of finance committed to restart economies following the Covid-19 pandemic, as well as gradually increasing carbon taxes are already making their presence felt in global energy markets. Carbon taxes are expected to play an important role in incentivising future low-carbon developments.

International commitments have set global imperatives that shape markets, influence finance flows, innovation, and commodity prices. Decisive actions relating to global GHG emissions are key drivers that determine the speed and depth of the energy transition towards clean(er) fuels. However, tangible actions towards establishing low-carbon economies remain slow, and the commitments of most countries are still considered insufficient to remain within the +1.5^{0}C above pre-industrial levels climate goal. Possibly, more concerted international efforts will be agreed on during COP26 [65].

8. Conclusions

Today, Namibia produces what it does not need, while procuring what it requires. Producing green hydrogen, in the absence of a local market, could be seen as doing more of the same. This, however, would be too one-sided a view. Indeed, developing Namibia's renewable energy riches can, if done with circumspection, create a growth engine to power national development in all its facets [11].

In the endeavours to create climate-neutral growth and development opportunities, Namibia must avoid making available its resources merely to enable industrialised nations to meet their clean energy needs. Local green hydrogen ventures must allow Namibia to meet its own development aspirations too. Engaging others to drive local development, rather than setting our own agenda, direction and pace of development is a cardinal risk. Expressed in different terms, this cautionary sentiment was recently attributed to the chairperson of the Parliamentary Standing Committee on Natural Resources and relate to activities of a foreign oil exploration company undertaking exploration work in Namibia: "*How did you let a guest dictate to you? They have the money and technology, but we have the resources. How can you not be allowed entry into your own house? That should not happen.*" [89].

Outsourcing the planning, development, and implementation of Namibia's pathway to the future, for example to entities from industrial nations, cannot possibly be a credible option for a country that has just recently gained its independence from foreign domination. At the same time, for a developing nation, such as Namibia, fast-tracking the roll-out of infrastructure to produce hydrogen holds many risks.

Committing to infrastructure developments that are several orders of magnitude larger than any similar developments made in the past is a strategy that bets the country's future on one specific development trajectory, with little or no leverage to guide their direction and viability [90], [91].

Giga-scale power production and associated transmission capacities do not exist in Namibia. They will, however, be essential to provide ultra-cheap electricity that is a pre-requisite to desalinate water, and from it, produce green hydrogen and its derivatives.

None of the multitude of legal and regulatory provisions needed to become "*a green hydrogen hub*" are in place yet. And suitable processing facilities for green hydrogen, as well as storage, transport, and export facilities, to name but a few, will have to be newly built as well, as none of the existing facilities are even closely adequate to enable Namibia to enter the arena where global energy players are active.

Once investments in power generation and hydrogen production infrastructure are made, they must yield returns. Whether such returns are likely to be generated, or will be much higher/lower than expected, depends on factors that are, once again, beyond Namibia's influence. Factors such as the development of commodity prices and exchange rates, the pace, scope, and volume of production undertaken by other parties, and the competitive actions of players with deep pockets, excellent technical capacities and resource endowments that are similar to Namibia's renewable energy riches will remain beyond the country's abilities to influence their outcomes. Countries with considerable experiences in the large-scale export of commodities, e.g., Australia and Chile, and those close to potential off-takers, e.g., Morocco with its proximity to European markets, are examples of those actors that find themselves in the competitive space for green hydrogen that Namibia may join in future.

Despite recent exuberant pronouncements, celebrations that green hydrogen is set to transform Namibia's economy remain premature. Realism is needed to change Namibia's notoriously slow delivery on promises that are essential for expansionary programs. Unshackling bureaucratic hurdles, fast-tracking the delivery of suitable land for development, creating access to water and many others are examples of issues that must be urgently addressed. Unbridled optimism needs copious able heads, hearts, and hands to bring real progress, one step at a time. The time has come that grand fabulations about green hydrogen's miraculous impacts on Namibia, while possibly enjoyable, are replaced by realism and a fact-based commitent to actions to shape our common future.

9. Recommendations

This paper concludes with recommendations to strengthen rational deliberations and enhance decision-making to enable Namibia to benefit from global green hydrogen needs, while at the same time meeting its own development requirements.

It is recommended that

1. **a National Hydrogen Policy** is developed, informed by southern African and international trends, focusing on the creation of transparent institutional, governance and regulatory provisions to guide the further development of green hydrogen initiatives and their synchronisation with the multitude of Namibia's other development needs;
2. **a National Hydrogen Strategy and Action Plan** is developed in tandem with the above-mentioned Policy, to map out realistic goals and establish objectives to guide the country's actions relating to green hydrogen developments, to inform and align the expectations of key public and private stakeholders, including a strategic assessment to identify and rank approaches to be taken to maximally benefit from international, regional and local hydrogen production, processing, storage, transport and market opportunities;
3. **a cost-benefit assessment** is undertaken on the main approaches and actions as identified in the above-mentioned Strategy, to quantify the implications of Namibia's entry into green hydrogen initiatives, including a macro- and micro-economic assessment of the overall risks, gains and losses towards the establishment of local green hydrogen capacities;
4. **incentive packages to reduce the investment risks faced by early adopters** are assembled, which are likely to include a mix of financial incentives, assistance in meeting or exceeding legal and regulatory provisions, fast-tracking access to land, utility connections and related matters of immediate relevance to lower the barriers to targeted investments;
5. **pragmatic regulations and standards** be developed to guide hydrogen-related initiatives, while ensuring that such efforts are maximally integrated with provisions governing related sectors in Namibia's economy, and informed by best international practice;
6. **an assessment of local supply chain requirements** be undertaken to enhance their ability to support and benefit from emerging hydrogen-related activities, specifically those relating to the supply of goods and services for green hydrogen production and processing of its derivatives, as well as those related to transport, storage and the export of such products;
7. **a national infrastructure master plan** is devised to ensure that the country's water, electricity, communications and information technology, road, rail as well as port infrastructure is consistently and systematically developed to meet national requirements while specifically enabling and benefitting from internationally funded climate-neutral developments;
8. **a suite of support activities be crafted to enable Namibia's water, electricity, agricultural and mining sectors** to support and benefit from local hydrogen-related activities and outputs;
9. **local research, development and tertiary education efforts be strengthened** to improve Namibia's overall education and training outcomes by creating and deepening linkages between the country's productive sectors, including those emerging because of hydrogen-related developments in Namibia and elsewhere; and
10. **international and regional co-operation agreements be focused on funding investments that** enable Namibia to maximally benefit from climate-neutral developments including those in the field of green hydrogen and derivatives production, in accordance with best legal and regulatory provisions, practices and standards.

Abbreviations

bn	billion
€	Euro; official currency of 19 of the 27 member states of the European Union
ECB	Electricity Control Board
GW	gigawatt; unit of electrical generation capacity; 1,000 MW = 1 GW
GWh	gigawatt-hour; energy unit; 1 GWh = 1 thousand MWh = 1 million kWh
IPP	independent power producer
kW	kilowatt; unit of electrical generation capacity
kWh	kilowatt-hour; energy unit
LPG	liquid petroleum gas
MME	Ministry of Mines and Energy
MW	megawatt; unit of electrical generation capacity
MWh	megawatt-hour; energy unit, 1 MWh = 1 thousand kWh
Mt	megatons; one million metric tons
Mt/a	megatons per annum
N$	Namibian dollar
NamPower	Namibia Power Corporation (Pty) Ltd
PV	photovoltaic; solar PV technology converts sunlight to electricity
SADC	Southern African Development Community
TWh	terawatt-hour; energy unit, 1 TWh = 1 000 GWh = 1 billion kWh
US$	United States dollar

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The Author

Dr Detlof von Oertzen is the Director of VO Consulting, which is an independent specialist consulting firm active in the energy, environment, and radiation sectors.

Born in Windhoek in 1962, Detlof holds a PhD in high-energy nuclear physics from the University of Cape Town, and an MBA (Finance) from the Australian AGSB.

Detlof is a member of various international, regional, and national multi-disciplinary specialist teams, serves on several energy, electricity, and radiation protection expert groups, and is a member of NamPower's Board of Directors since 2017.

References

[1] https://www.washingtonpost.com/business/energy/why-hydrogen-is-the-hottest-thing-in-green-energy/2021/06/19/4c116f1e-d0bb-11eb-a224-bd59bd22197c_story.html?variant=116ae929826d1fd3; last accessed on 20 October 2021.

[2] Hydrogen Council, *Hydrogen Insights, A perspective on hydrogen investment, market development and cost competitiveness*, February 2021, https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021-Report.pdf; last accessed on 20 October 2021.

[3] New Era, 4 August 2021, *Namibia: Geingob Banks On Green Hydrogen,* https://allafrica.com/stories/202108040605.html; accessed on 23 October 2021.

[4] International Panel on Climate Change, https://www.ipcc.ch/sr15/; last accessed on 20 October 2021.

[5] United Nations Framework Convention on Climate Change, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement; last accessed on 20 October 2021.

[6] European Commission, 2020, *A Hydrogen Strategy for a Climate-Neutral Europe*, www.ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf; last accessed on 20 October 2021.

[7] United States Department of Energy, 2002, *National Hydrogen Energy Roadmap*, https://www.hydrogen.energy.gov/pdfs/national_h2_roadmap.pdf; last accessed on 20 October 2021.

[8] Council of Australian Governments, COAG, 2019, *Australia's National Hydrogen Strategy*, https://www.industry.gov.au/sites/default/files/2019-11/australias-national-hydrogen-strategy.pdf; last accessed on 20 October 2021.

[9] Final Report of the High-Level Panel of the European Decarbonisation Pathways Initiative, November 2018, https://ec.europa.eu/info/sites/default/files/research_and_innovation/research_by_area/documents/ec_rtd_decarbonisation-report_112018.pdf; last accessed on 20 October 2021.

[10] https://www.visualcapitalist.com/a-global-breakdown-of-greenhouse-gas-emissions-by-sector/; accessed on 20 October 2021.

[11] von Oertzen, Detlof, *REEE-powering Namibia*, https://voconsulting.net/wp-content/uploads/2020/03/REEE-powering-Namibia.pdf; accessed on 20 October 2021.

[12] von Oertzen, Detlof, 2019, *State of the Namibian Electricity Sector - 2019*, www.voconsulting.net

[13] National Petroleum Corporation of Namibia, Namcor, https://www.namcor.com.na/; accessed on 20 October 2021.

[14] Electricity Control Board, https://www.ecb.org.na/; accessed on 20 October 2021.

[15] NamPower, https://www.nampower.com.na/; accessed on 20 October 2021.

[16] NamPower, https://www.nampower.com.na/About.aspx; accessed on 20 October 2021.

[17] von Oertzen, Detlof, 2012, *Namibia's Energy Future – A Case for Renewables*, https://voconsulting.net/wp-content/uploads/2020/03/NamEnergyFuture.pdf; last accessed on 20 October 2021.

[18] Kindly provided by the Namibia Energy Institute (formerly the Renewable Energy and Energy Efficiency Institute) at the Namibia University of Science and Technology; GeoModel Solar; http://nei.nust.na/.

[19] Global Wind Atlas, https://globalwindatlas.info/report/download/Namibia/?layer=legend.filter.powerDensity&index=2&h=100&sl=null&buffer=0&scaling=standard&title=Namibia; last accessed on 20 October 2021.

[20] VO Consulting, www.voconsulting.net. The author gratefully acknowledges the contribution of select data by the Namibian Uranium Institute, www.namibianuranium.org/; last accessed on 20 October 2021.

[21] Status of ratification of the Paris Agreement of 2015, United Nations Framework Convention on Climate Change, https://unfccc.int/process/the-paris-agreement/status-of-ratification; last accessed on 20 October 2021.

[22] Paris Agreement of 2015, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement; last accessed on 20 October 2021.

[23] https://cop23.unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement; last accessed on 20 October 2021.

[24] Key aspects of the Paris Agreement, https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement; last accessed on 20 October 2021.

[25] Government of the Republic of Namibia, *Namibia's Updated Nationally Determined Contribution, 2021,* https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Namibia%20First/Namibia's%20Updated%20NDC_%20FINAL%2025%20July%202021.pdf; last accessed on 23 October 2021.

[26] United States Environmental Protection Agency, *Overview of Greenhouse Gases,* https://www.epa.gov/ghgemissions/overview-greenhouse-gases; last accessed on 15 October 2021.

[27] United States Environmental Protection Agency, *Sources of Greenhouse Gas Emissions*, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions; last accessed on 15 October 2021.

[28] World Nuclear News, *Nuclear part of UK's strategy for reaching net-zero,* 19 October 2021, https://www.world-nuclear-news.org/Articles/Nuclear-part-of-UK-s-strategy-for-reaching-net-zer; last accessed on 23 October 2021.

[29] The UNFCCC defines "decarbonisation" as follows: 'Decarbonisation: The process by which countries or other entities aim to achieve a low-carbon economy, or by which individuals aim to reduce their carbon consumption.', https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-i.pdf; last accessed on 20 October 2021.

[30] McKinsey, *Why the automotive future is electric*, 7 September 2021, https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/why-the-automotive-future-is-electric; last accessed on 23 October 2021.

[31] Hydrogen Council, Hydrogen Decarbonization Pathways, https://hydrogencouncil.com/en/hydrogen-decarbonization-pathways/; last accessed on 20 October 2021.

[32] The Science Times, *Hydrogen Is The Most Common Element: Here's The Reason Why,* 3 April 2017, https://www.sciencetimes.com/articles/11524/20170403/hydrogen-is-the-most-common-element-heres-the-reason-why.htm; last accessed on 20 October 2021.

[33] International Energy Agency (IEA), 2019, *The Future of Hydrogen,* https://www.iea.org/reports/the-future-of-hydrogen; last accessed on 20 October 2021.

[34] Hydrogen Council, 2020, *Path to Hydrogen Competitiveness A Cost Perspective*, www.hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf; last accessed on 20 October 2021.

[35] International Renewable Energy Agency (IRENA), 2018: *Hydrogen from renewable power: Technology outlook for the energy transition*, https://www.irena.org/-/media/files/irena/agency/publication/2018/sep/irena_hydrogen_from_renewable_power_2018.pdf; last accessed on 20 October 2021.

[36] Hebling, C. et al., 2019, *Eine Wasserstoff-Roadmap für Deutschland*, Fraunhofer Institut für System- und Innovationsforschung ISI, Fraunhofer-Institut für Solare Energiesysteme ISE, https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/2019-10_Fraunhofer_Wasserstoff-Roadmap_fuer_Deutschland.pdf; last accessed on 22 October 2021.

[37] Roeb, M. et al., 2020, *Wasserstoff als ein Fundament der Energiewende. Teil 1: Technologien und Perspektiven für eine nachhaltige und ökonomische Wasserstoffversorgung*, Deutsches Zentrum für Luft- und Raumfahrt, https://www.researchgate.net/publication/346300856_Wasserstoff_als_ein_Fundament_der_Energiewende_Teil_1_Technologien_und_Perspektiven_fur_eine_nachhaltige_und_okonomische_Wasserstoffversorgung; last accessed on 22 October 2021.

[38] International Renewable Energy Agency, IRENA, 2020, *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5 °C climate goal*, https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction#:~:text=Scaling%20up%20electrolysers%20to%20meet%20the%201.5oC%20climate%20goal&text=Green%20hydrogen%20can%20help%20to,haul%20transport%2C%20shipping%20and%20aviation; last accessed on 22 October 2021.

[39] Bloomberg New Energy Finance, 2020, *Hydrogen Economy Outlook*, https://data.bloomberglp.com/professional/sites/24/BNEF-Hydrogen-Economy-Outlook-Key-Messages-30-Mar-2020.pdf; last accessed on 22 October 2021.

[40] International Renewable Energy Agency, IRENA, 2019, *Global energy transformation: A roadmap to 2050*, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_
2019.pdf; last accessed on 15 October 2021

[41] Prognos AG, 2020, *Kosten und Transformationspfade für strombasierte Energieträger*, https://www.bmwi.de/Redaktion/DE/Downloads/Studien/transformationspfade-fuer-strombasierte-energietraeger.pdf?__blob=publicationFile; last accessed on 15 October 2021

[42] Hydrogen Council, 2020, *Path to hydrogen competitiveness. A cost perspective.* https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf; last accessed on 15 October 2021

[43] Matthes, F.C. et al., 2020, *Wasserstoff sowie wasserstoffbasierte Energieträger und Rohstoffe. Eine Überblicksuntersuchung*, Öko-Institut e.V., https://www.oeko.de/fileadmin/oekodoc/Wasserstoff-und-wasserstoffbasierte-Brennstoffe.pdf; last accessed on 22 October 2021.

[44] NamPower Annual Report 2020, https://www.nampower.com.na/public/docs/annual-reports/NamPower%20Annual%20Report%202020.pdf; last accessed on 22 October 2021.

[45] Ministry of Mines and Energy, *National Integrated Resource Plan 2016*, http://www.mme.gov.na/files/publications/2b7_ELECTRICITY%20SECTOR%20NATIONAL%20INTEGRATED%20RESOURCE%20PLAN%20(NIRP)%202016%20REPORT.PDF; last accessed on 22 October 2021.

[46] The Namibian, 7 October 2021, *Geingob shies away from rapist's appointment to Swapo think tank*, https://www.namibian.com.na/106050/read/Geingob-shies-away-from-rapists-appointment-to--Swapo-think-tank; accessed on 22 October 2021.

[47] Using Google Earth overlain by the Global Wind Atlas for south-western Namibia, refer to reference [19], at 4 MW/km^2.

[48] RenewEconomy, 18 October 2021, *Easiest first step to net zero is to build massive amounts of solar*, https://reneweconomy.com.au/easiest-first-step-to-net-zero-is-to-build-massive-amounts-of-solar/?fbclid=IwAR0AXIVDi8o8ADlJDaEDosDgyQJ1rgE4jedopC2U4Tqs1MfcMQFdt8DIt7A; accessed on 22 October 2021.

[49] RenewEconomy, 18 October 2021, *Stunningly cheap solar to power China's pivot away from coal*, https://reneweconomy.com.au/stunningly-cheap-solar-to-power-chinas-pivot-away-from-coal/?fbclid=IwAR0u-KPbuptkK5Rn5aWWioKio45SJf25_-C4bWTx5WdQShsU8AmqfeZiJTE; last accessed on 22 October 2021.

[50] International Renewable Energy Agency, IRENA, 2014, Estimating the Renewable Energy Potential in Africa: A GIS-based approach, https://www.irena.org/publications/2014/Aug/Estimating-the-Renewable-Energy-Potential-in-Africa-A-GIS-based-approach; last accessed on 22 October 2021.

[51] National Renewable Energy Laboratory, 2013, *Land-Use Requirements for Solar Power Plants in the United States, https://www.nrel.gov/docs/fy13osti/56290.pdf*; last accessed on 26 October 2021.

[52] AQUEDUCT, https://www.wri.org/aqueduct; last accessed on 19 October 2021.

[53] von Oertzen, Detlof and Braby, Justine, 04 July 2019, *Industrial Corridors as a Backbone of Namibia's Development, http://www.progress-namibia.com/main/post/industrial-corridors-as-a-backbone-of-namibias-development-by-detlof-von-oertzen-and-justine-braby/*; last accessed on 19 October 2021.

[54] Kasten, P., Heinemann, C., 2019, *Kein Selbstläufer: Klimaschutz und Nachhaltigkeit durch PtX. Diskussion der Anforderungen und erste Ansätze für Nachweiskriterien für eine klimafreundliche und nachhaltige Produktion von PtX-Stoffen*. Öko-Institut e.V., https://www.oeko.de/fileadmin/oekodoc/Impulspapier-soz-oek-Kriterien-e-fuels.pdf; last accessed on 22 October 2021.

[55] Atlantic Council, 24 September 2021, *Namibia: A green hydrogen hub for Africa*, https://www.atlanticcouncil.org/event/a-green-hydrogen-hub-for-africa/; last accessed on 19 October 2021.

[56] Koj, J. C., Wulf, C., Zapp, P., 2019, *Environmental impacts of power-to-X systems - A review of technological and methodological choices in life cycle assessments*, https://www.sciencedirect.com/science/article/abs/pii/S1364032119304228; last accessed on 19 October 2021.

[57] Malins, C., 2017, *What role is there for electrofuel technologies in European transport's low carbon future?*, https://www.researchgate.net/publication/343098853_What_role_is_there_for_electrofuel_technologies_in_European_transport's_low_carbon_future; last accessed on 19 October 2021.

[58] Fasihi, M., Efimova, O., Breyer, C., 2019, *Techno-economic assessment of CO2 direct air capture plants*, https://www.sciencedirect.com/science/article/pii/S0959652619307772; last accessed on 22 October 2021.

[59] Moradi, R., Groth, K. M., 2019, *Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis*, https://www.researchgate.net/publication/332042449_Hydrogen_storage_and_delivery_Review_of_the_state_of_the_art_technologies_and_risk_and_reliability_analysis; last accessed on 22 October 2021.
[60] Nikolaidis, P., Poullikkas, A. (2017): A comparative overview of hydrogen production processes, https://www.sciencedirect.com/science/article/abs/pii/S1364032116305366; last accessed on 22 October 2021.
[61] Brändle, G., Schönfisch, M., Schulte, S., 2020, *Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen*, https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2021/03/EWI_WP_20-04_Estimating_long-term_global_supply_costs_for_low-carbon_Schoenfisch_Braendle_Schulte-1.pdf; accessed on 22 October 2021.
[62] Bundesministerium für Bildung und Forschung, Press Release, 25/08/2021 | No. 172/2021, https://www.bmbf.de/bmbf/shareddocs/pressemitteilungen/de/2021/08/172_namibia_eng.pdf?__blob=publicationFile&v=1; last accessed on 22 October 2021.
[63] Namibia Investment Promotion and Development Board, Express Interest | Southern Corridor Development Initiative (Green Hydrogen), https://nipdb.com/express-interest-southern-corridor-development-initiative/; last accessed on 19 October 2021.
[64] Namibia Investment Promotion and Development Board, Express Interest | Green Hydrogen Opportunities, https://nipdb.com/express-interest-green-hydro-opportunities/; last accessed on 19 October 2021.
[65] United Nations Climate Change Conference UK2021, COP26, https://ukcop26.org/; accessed on 19 October 2021.
[66] HYPHEN Hydrogen Energy press release, 4 November 2021, www.hyphenafrica.com; accessed on 12 November 2021.
[67] VO Consulting, Internal Report - *Pre-feasibility assessment of the demand for hydrogen in select Namibian industries*, https://voconsulting.net
[68] Namibia Investment Promotion and Development Board, NIPD, Southern Corridor Development Initiative, Market Sounding for Request for Proposals, 10 June 2021, https://namibiapppconference.com/wp-content/uploads/2021/06/GHN-RFP-rev-2.pdf; accessed on 19 October 2021.
[69] Namibia Ports Authority, Port of Lüderitz, https://www.namport.com.na/galleries/port-of-luderitz/27/; accessed on 22 October 2021.
[70] Statista, *Production capacity of ammonia worldwide from 2018 to 2030*, https://www.statista.com/statistics/1065865/ammonia-production-capacity-globally/; accessed on 22 October 2021.
[71] PubChem – Ammonia, https://pubchem.ncbi.nlm.nih.gov/compound/Ammonia; accessed on 22 October 2021.
[72] Giddey, S., Badwal, S. P. S., Munnings, C., Dolan, M., 2017, *Ammonia as a Renewable Energy Transportation Media*, https://www.semanticscholar.org/paper/Ammonia-as-a-Renewable-Energy-Transportation-Media-Giddey-Badwal/fdf5f2f1c90123ae7478691bc93d8df85d030583; accessed on 22 October 2021.
[73] Markiewicz, M. et al., 2019, *Hazard assessment of quinaldine-, alkylcarbazole-, benzene- and toluene-based liquid organic hydrogen carrier systems*, Energy and Environmental Science (2019) 12 (1), 366-383, dx.doi.org/10.1039/c8ee01696h.
[74] World Steel Association, https://www.worldsteel.org/; accessed on 22 October 2021.
[75] World Steel Association, https://www.worldsteel.org/steel-by-topic/statistics/steel-statistical-yearbook.html; accessed on 22 October 2021.
[76] Fuel Cell and Hydrogen Energy Association, *Hydrogen as a Clean Alternative in the Iron and Steel Industry*, https://www.fchea.org/in-transition/2019/11/25/hydrogen-in-the-iron-and-steel-industry; last accessed on 13 October 2021.
[77] HYBRIT Fossil Free Steel, https://www.hybritdevelopment.se/; last accessed on 22 October 2021.
[78] Thyssen Krupp Steel, https://www.thyssenkrupp-steel.com/en/company/sustainability/climate-strategy; last accessed on 22 October 2021.
[79] ArcelorMittal, https://corporate.arcelormittal.com/about-us/making-steel; last accessed on 22 October 2021.
[80] United States Department of Energy, H2@Scale Workshop, 2018, https://www.energy.gov/sites/prod/files/2018/08/f54/fcto-h2-scale-kickoff-2018-19-green.pdf; accessed on 22 October 2021.

[81] European Union Emissions Trading System, https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets_en; accessed on 22 October 2021.

[82] The author gratefully acknowledges fruitful discussions with Johannes Michels of HyIron Green Technologies, johannes.michels@hyiron.com.

[83] The author gratefully acknowledges fruitful discussions with Dr Stephan Koehne of CO2Grab, https://www.co2grab.com/; last accessed on 22 October 2021.

[84] Loadstone Namibia, Dordabis Mining Project, http://lodestonepty.com/lodestones-dordabis-mining-project/; accessed on 22 October 2021.

[85] Deep Yellow Limited, News Release 22 October 2021, Sale of Non-Core Shiyela Iron Ore Project (ML176); https://deepyellow.com.au/wp-content/uploads/SaleOfNonCoreShiyelaIronOreProjectML17622Oct21.pdf; accessed on 22 October 2021.

[86] Heinemann, C. et al., 2019, *Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland. Zusammenfassung und Einordnung des Wissenstands zur Herstellung und Nutzung strombasierter Energieträger und Grundstoffe.* Öko-Institut e.V., https://www.oeko.de/fileadmin/oekodoc/PtX-Hintergrundpapier.pdf; last accessed on 22 October 2021.

[87] Namibian Sun, 8 October 2021, https://www.namibiansun.com/news/belgians-look-to-invest-n860m-in-fuel-plant2021-10-08; accessed on 22 October 2021.

[88] RECHARGE, 21 October 2021, *There is no commercial case for green hydrogen — unless government incentives or quotas are put in place', say CEOs,* https://www.rechargenews.com/energy-transition/there-is-no-commercial-case-for-green-hydrogen-unless-government-incentives-or-quotas-are-put-in-place-say-ceos/2-1-1086100; accessed on 22 October 2021.

[89] The Namibian, 20 October 2021, *Tweya blasts officials for failing to police,* https://www.namibian.com.na/106495/read/Tweya-blasts-officials-for-failing-to-police-ReconAfrica; accessed on 22 October 2021.

[90] Port of Rotterdam, 9 November 2021, *Several Rotterdam terminals to be ready for hydrogen imports by 2025*, https://www.portofrotterdam.com/en/news-and-press-releases/several-rotterdam-terminals-to-be-ready-for-hydrogen-imports-by-2025?fbclid=IwAR1ZnFNp9Y6CF2MxialULP0O52s90UFJTvF7gOD2AbktdbRoe9_uC2k8jA0; accessed on 12 November 2021.

[91] New Era, 11 November 2021, *Namport prepares to become Green Hydrogen export hub…positions local ports to export hydrogen, by-products, https://neweralive.na/posts/namport-prepares-to-become-green-hydrogen-export-hub?fbclid=IwAR0zVerB_kI7mzW41QmzPIomwk7iI8H8ToYoru4Q_SZpLzf2dEM9kbZdexQ; accessed on 12 November 2021.*

Freedom, justice and solidarity are the basic principles underlying the work of the Konrad-Adenauer-Stiftung (KAS). The KAS is a political foundation, closely associated with the Christian Democratic Union of Germany (CDU). As co-founder of the CDU and the first Chancellor of the Federal Republic of Germany, Konrad Adenauer (1876-1967) united Christian-social, conservative and liberal traditions. His name is synonymous with the democratic reconstruction of Germany, the firm alignment of foreign policy with the trans-Atlantic community of values, the vision of a unified Europe and an orientation towards the social market economy. His intellectual heritage continues to serve both as our aim as well as our obligation today.

In our European and international cooperation efforts we work for people to be able to live self-determined lives in freedom and dignity. We make a contribution underpinned by values to helping Germany meet its growing responsibilities throughout the world.

In order to achieve its socio-political goals, the Windhoek office of the Konrad Adenauer Foundation works together with a partner organization Women's Action for Development (WAD) as well as with various co-organisers in so called 'self-initiated measures'.

The self-initiated measures of the KAS offices play an increasingly important role. Through such instruments, pressing problems and questions can be immediately addressed. KAS in Namibia cooperates closely with the Parliament, Office of the Ombudsman, Office of the Judiciary, educational and other developmental institutions such as TUCSIN to name only a few, in order to focus on measures dealing with good governance, youth empowerment, capacitating civil society, SME development, promotion of renewable energies and the rule of law as well as enhanced democratic structures and support of political parties.

KONRAD ADENAUER STIFTUNG

info.namibia@kas.de
+264 61 225-568
+264 61 225-678
http://www.kas.de/web/namibia

Namibia Office
P.O. Box 1145
7th Floor Mutual Tower
223 Independence Avenue
Windhoek, Namibia

www.kas.de