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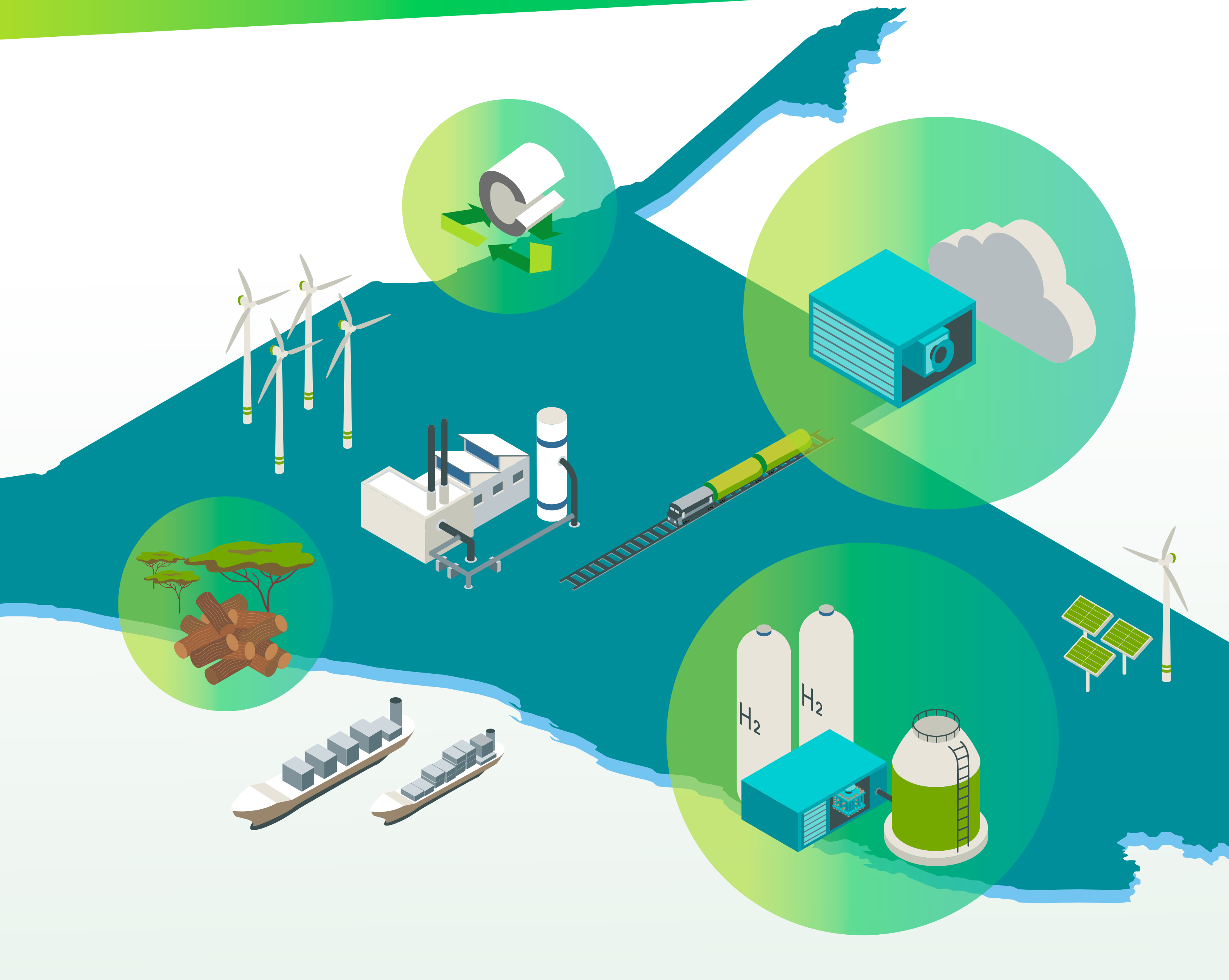
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

DEVELOPMENT OF A SUSTAINABLE CARBON CARRIER FOR PTX USE

From Namibia to a global market



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GLOSSARY

African Common Free Trade Area (AfCFTA)	AfCFTA is a free trade agreement among the African Union nations, aimed at creating a single continental market for goods and services to facilitate intra-Africa trade.
Biogenic Carbon	Biogenic carbon refers to carbon that is part of the natural carbon cycle or short cycle carbon according to the IPCC, originating from contemporary biological processes like photosynthesis, as opposed to fossil carbon, which has been sequestered for millions of years.
Bio-Hydrogen	Bio-Hydrogen is hydrogen produced through processes based on contemporary biological feedstock.
Biomass-to-X (BtX)	This term refers to technologies converting biomass into various forms of energy, chemicals, or materials, where "X" can represent products like fuel, gas, or chemicals.
Carbon Capture Utilization and Storage (CCUS)	CCUS technologies capture carbon dioxide emissions at their source and either utilize them for industrial applications or store them underground to mitigate climate change.
Direct Air Capture (DAC)	Direct Air Capture is a technology that captures carbon dioxide directly from ambient air for storage or utilization, independent of a specific emission source.
Encroaching Bush	Encroaching bush refers to the invasive or uncontrolled spread of woody plants and shrubs, a phenomenon notably prevalent in Namibia. In Namibia it is uncontrolled spread of native species. In this region, bush encroachment has substantially affected both livestock farming and natural habitats, necessitating targeted interventions for ecological restoration and land productivity improvement.
Fischer-Tropsch (FT)	The Fischer-Tropsch process is a series of chemical reactions that converts a mixture of carbon monoxide and hydrogen into liquid hydrocarbons.
Green Hydrogen	Green Hydrogen is produced using renewable energy sources apart from biomass to power the electrolysis of water, resulting in zero greenhouse gas emissions.
Methanation	Methanation is the catalytic conversion of carbon monoxide and hydrogen into methane, typically facilitated by nickel-based catalysts.
NDCs	Nationally Determined Contributions (NDCs) are commitments made by countries under the Paris Agreement to reduce greenhouse gas emissions and adapt to the impacts of climate change.
Power-to-X (PtX)	This refers to technologies that convert electricity, typically from renewable sources, into another form of energy, chemicals, or fuels (denoted by "X").
Renewable Energy Directive II (RED II)	RED II is an EU policy that sets binding renewable energy targets for EU Member States, aiming for a 32% share of renewable energy by 2030 and containing specific criteria for biomass sustainability.
Sustainable Aviation Fuel	This is a blend of conventional aviation fuel and renewable, often bio-based, fuel or 100% drop-in synthetic renewable fuel that meets specific sustainability criteria.
Sustainable Biomass	Biomass sourced from residues, wastes, or dedicated energy crops grown on land that meets defined sustainability and land-use criteria.
Synthetic Fuels	These are liquid or gaseous fuels synthesized from feedstocks other than crude oil, often involving processes like Fischer-Tropsch or methanation.
Torrefaction	Torrefaction is a thermal pre-treatment of biomass at 200-300°C, improving its chemical properties and making it more suitable for combustion or gasification.

1 EXECUTIVE SUMMARY

Namibia's Vision 2030 aims for socio-economic development, operationalized through five-year National Development Plans and accelerated by the Harambee Prosperity Plans. The second of these plans highlights the green hydrogen and Power-to-X (PtX) industry as a key growth engine, not just for Namibia but also for the broader Southern African Development Community (SADC) region. This sector is expected to significantly contribute to regional prosperity.

Given the still-developing state of Namibia's industry, the revenue prospects for PtX products like sustainable aviation fuel (SAF), methanol, and drop-in fuels largely come from industrial nations striving to defossilize their hard-to-abate sectors. Namibia's Hydrogen Strategy is in line with these international demands, adding a layer of feasibility to the endeavor. Further, with a significant number of local industries in dire need of defossilization due to international mandates set by mother companies, there is an internal market for these products as well. In this era marked by the increasing urgency to adopt cleaner, more sustainable energy systems, synthetic fuels or synfuels, chemically identical to conventional fuels, can serve as drop-in replacements in existing infrastructure, enabling a transition towards environmental sustainability and energy security.

However, the sourcing of carbon for PtX technologies for the production of synthetic hydrocarbon fuels, remains a critical consideration in terms of the sustainability outlook of the final fuel. There are three primary methods for sourcing carbon:

1. Direct Air Capture (DAC),
2. Biogenic Carbon and
3. Carbon Capture from Fossil Fuel-based Plants.

DAC captures CO_2 directly from the atmosphere. Biogenic Carbon usually refers to carbon dioxide (CO_2) captured from biomass. Carbon Capture from Fossil Fuel-based Plants, while enhancing overall resource efficiency, is not a sustainable long-term source of carbon and will not get certified as a renewable feedstock. In the urgent quest to transition away from fossil fuels and achieve climate neutrality, DAC and Biogenic Carbon present the most viable options. DAC technology is not yet commercially available and has high associated costs. The companies developing the technology cite projected costs in 2030 of 100 USD/t, while independent studies put the cost at 600 USD/t (Tollefson, 2018). While the technology has seen significant advancements, it remains uncertain when it will become cost-effective at a commercial scale. Additionally, DAC facilities require a significant amount of space, and the selection of suitable sites could pose challenges in terms of land use and impact on biodiversity. As far as biogenic carbon is concerned, two primary pathways for utilizing it exist:

1. **Capture CO_2 anywhere biomass is being used and then use that CO_2 for PtX.** These processes require substantial infrastructure, including carbon capture technology and CO_2 storage or transportation facilities. Especially for transportation, the most cost-effective way of transporting gases is through pipelines, given that biomass use typically takes place in rural areas. Pipelines have high up-front costs, and present multiple challenges in their design, implementation and use (Li et al, 2020). Currently, this is the only method of transport considered when discussing biogenic carbon use in PtX.
2. **Develop new processes that aim at maximizing the carbon carrier aspect of biomass.** This pathway involves creating innovative methods that enhance the use of biomass as a carbon carrier while simultaneously harnessing its inherent renewable energy in a productive manner. This approach involves technologies such as gasification, pyrolysis, or torrefaction, which can convert biomass into syngas, bio-oil, or biochar. These bio-based intermediates are rich in carbon and can be used as feedstocks for PtX processes to produce synthetic fuels or chemicals. The energy content of the biomass should also be utilized in these processes, creating a synergistic system of energy and resource efficiency.

In the context of advancing PtX technologies, **it's crucial to understand the implications of carbon carrier choices**. The use of CO_2 as a carbon carrier, although it is currently considered the approach of choice, poses logistical complexities due to its gaseous state, making transportation challenging and costly since pipelines need to be deployed. Carbon monoxide (CO), also a gaseous candidate, introduces additional transportation challenges owing to its toxic nature, which raises public safety concerns. The interest in developing novel carbon carriers is also on the rise.

Focusing on Namibia, there are many advantages to using its encroaching biomass resource as primary feedstock for a carbon carrier, including rangeland and habitat restoration, protecting biodiversity, increasing agricultural productivity, and stimulating rural economic development. In line with the project's mandate, this study comprehensively assessed the potential of utilizing Namibia's local residue biomass, particularly from bush encroachment, for the production of high-value PtX products, with a specific emphasis on synthetic fuels. During the initial investigative phase, it became increasingly apparent that conventional technological pathways for PtX conversion would not be sufficient to optimize the unique carbon-carrying characteristics of Namibia's encroaching bush biomass.

As a result, the study pivoted to a novel approach, centered on the development of an innovative process designed to maximize the carbon carrier aspect of the biomass. This innovative process not only supports Namibia's broader Hydrogen Strategy but also addresses the pressing issue of bush encroachment in an environmentally responsible manner. This novel process will be referred to as hybrid Biomass-PtX.

The findings indicate that by focusing on carbon optimization, Namibia can unlock a sustainable and economically viable avenue for synthetic fuel production, thereby fulfilling both local and global needs. The study proposes that this new process can be a linchpin in aligning ecological sustainability with economic viability, offering a multi-faceted solution to Namibia's bush encroachment problem while contributing to global efforts in emission reductions. There are also extended benefits to using Namibia's encroaching biomass resource, including rangeland and habitat restoration, protecting biodiversity, increasing agricultural productivity, and stimulating rural economic development.

For the design of the optimal carbon carrier based on Namibian bush biomass, the following design goals/ objectives were set:

- Ability to develop a global sustainable biogenic carbon market.
- Standardization to be possible.
- Different countries from different regions to be able to produce the standardized carbon carrier no matter the starting biomass, as long as it conforms to accepted sustainability criteria like the ones set out in RED II and in the upcoming RED III in order to be possible to develop a global market.
- Efficient transportation utilizing maritime shipping and existing logistics infrastructure.
- Preference for CO than CO_2 since the later requires energy to convert it to CO.
- Reduce technology requirements to a minimum for the processes that take place in remote areas.
- No initial preference on the end fuel product, since FT and methanation require the same inputs - COx and hydrogen.
- Commercial availability of all technologies involved.

An in-depth comparison of different alternatives took place and the proposed carbon carrier is **torrefied biomass pellets**. These are presented in the following photographs.

Torrefied bush biomass from Namibia produced by the Horizon 2020 EU funded SteamBioAfrica project (Grant Agreement No. 101036401)

Figure 1: Own photo

Example of torrefied biomass pellets

Figure 2: Shutterstock/Supachita Krerkkaiwan

Advantages of the proposed carbon carrier are presented below:

- Increased Energy Density (Niu et al, 2019).
- Enhanced Grindability of Torrefied Biomass Facilitating Pelletization (Niu et al, 2019).
- Direct pelletization is possible after grinding (Svanberg et al, 2013), (Rudolfsson et al, 2017).
- Reduced Moisture Content (Niu et al, 2019).
- Enhanced Stability (Hydrophobic, Safety Considerations, etc.) (Niu et al, 2019).
- Improved Handling (Grain Handling Equipment Can Be Used in the Logistics Chain) (García et al, 2019).
- Optimal feedstock for Gasification (Prins et al, 2006).
- Ability to Handle Residuals and Ash Management (Tripathi et al, 2019).
- Minimal process water requirements.
- Alternative market off-take opportunities de-risk the investment.
- High potential for unskilled and semi-skilled job creation.

It has to be acknowledged that there are also some challenges regarding torrefied biomass pellets:

- **Challenging resource:** Namibian encroacher bush has inherent challenges in its control and utilization. From a control perspective, it is imperative to ensure that the industry best practices are followed relating to the management, quantification, harvesting methodology, and aftercare. Additionally, legal framework still needs improvement to allow equitable industry participation from non-free hold land tenure systems. From a utilization perspective, technical challenges regarding the terrain, selectivity, relatively low yields, and the physical characteristics of the encroacher bush also need to be addressed.
- **Multistage Process:** The process of producing torrefied pellets involves multiple stages, including harvesting, chipping, aggregation, torrefaction, and pelletization. Each of these stages adds complexity and cost to the process and requires specific expertise, equipment and energy.
- **Dual Nature as both Carbon Carrier and Energy Carrier:** While being positioned primarily as a carbon carrier, the torrefied pellets are also a good energy carrier, which enhances the versatility of the torrefied pellets, but it can also increase their price, especially if demand increases from other industries looking to directly substitute fossil fuels as coal.

Furthermore, it has to be highlighted that Namibia has a substantial biomass resource in the form of encroacher bush. Namibian bush biomass is unique. Bush encroachment in Namibia is a key indicator for land degradation. The bush grows excessively due to both natural and anthropogenic causes as outlined before. The selective removal of the biomass to restore savanna ecosystems is a key target under national policies and strategies, as well as Namibian strategies to contribute to international commitments such as the UNFCCC, UNCCD and UNCBD. Studies indicate that sustainably bush controlled areas can reach almost the same above ground biomass within 3 years with less woody biomass and more grasses contributing to a higher biodiversity and a more stable ecosystem. This enhances the productivity of the land and can contribute to enhancing livelihoods and food security. It is estimated that up to 45 million hectares of land in Namibia are affected by bush encroachment.

As is clear, the use of bush biomass as a foundational element in Namibia's PtX strategy not only solves critical technological challenges but also addresses pressing environmental and socio-economic issues. Additionally, it is worth noting that this innovative hybrid Biomass-PtX approach aligns well with Namibia's NDCs and Climate Action Strategy, contributing to the nation's sustainable development while mitigating climate impact.

The value chain developed is presented in Figure 3 below.

As far as the gasification and synthesis is concerned, the optimal technological pathway which can maximize carbon efficiency is presented in Figure 4 below.

- The proposed hybrid Biomass-PtX (BtX) process introduces an innovative pathway to **significantly increase the carbon utilization efficiency in renewable synthetic drop-in fuel production.**
- Various commercial gasification technologies can be utilized.
- The H_2:CO production ratio from gasification is theoretically approximately 1:1.
- The optimum H_2:CO required for Fischer-Tropsch is roughly 2:1.
- The H_2: CO ratio required is also affected by the catalyst choice, the conversion and selectivity of the targeted products.
- **Recent research has highlighted that the roughly 30% carbon efficiency of the traditional BtX can be increased to more than 90% by complementing the process with Green Hydrogen.**

Given the complexities involved in performing even a high-level cost estimation on the proposed value chain, it was decided to focus on the carbon carrier, where enough data was available allowing the cost estimation with a degree of confidence. It is estimated that the cost for torrefied biomass pellets would be 198 EUR/ton, FOB Walvis Bay.

The cost calculation for the final drop-in fuel cost involves a large number of uncertainties for the gasification and Fischer-Tropsch synthesis steps and as such it was impossible to calculate given the constraints of this study. Based on data by IEA Bioenergy for a traditional BtX process, the final fuel cost is estimated at 75-144 EUR/MWh of synthetic fuel (IEA Bioenergy, 2020). Taking into account the Lower Heating Value of Diesel the cost of synthetic diesel is calculated to be between 0.75 – 1.44 EUR/l. The proposed hybrid Biomass-PtX process would certainly lead to a cost decrease when cheap green hydrogen is introduced to the process. There are forecasts that due to the EU Hydrogen Bank we could see in the short-term market prices of green hydrogen at 1 EUR/kg. As a reference, the current pump price of fossil diesel is 0.93 EUR/l in Namibia and 1.77 EUR/l in Germany. These figures provide the justification for a follow-up feasibility study for a plant in Namibia that could provide a more in-depth analysis for the projected cost decrease and shed more light on the actual commercial feasibility and possible returns on investment.

To provide recommendations on the way forward, initially, an in-depth analysis of Namibia was performed. Based on this analysis the following recommendations are formulated.

1. Develop and integrate Advanced Biofuels Strategy with the Green Hydrogen Strategy
2. Adopt Comprehensive Energy Policies. Currently there is no liquid renewable fuels framework in Namibia. The liquid renewable fuels framework needs to be inclusive of synthetic fuel and biofuels, as well as being aligned to the existing petroleum and renewable energy frameworks.
3. Engage in Regulatory Reforms, starting with a gap analysis of the national energy and fuels framework. Gaps include liquid renewable fuels and green hydrogen frameworks. The following step is to ensure that any missing framework is developed, aligned, made coherent to the existing frameworks.
4. Support Business Development in the Biomass and PtX Sectors
5. Conduct a Tax-Benefit Study on Renewable Fuels
6. Promote Research and Innovation
7. Develop Workforce Expertise, including skills development within the upstream biomass value chain and engineering capacity including energy and mechanical specializations.
8. Enhance critical infrastructure, especially rail for improved transport efficiency, as well as strategic inland dry ports.
9. Encourage Stakeholder Engagement
10. Establish a Phased Roadmap for Carbon Carrier and Synthetic Fuels Infrastructure

The proposed approach offers many possible commercial pathways based on five pillars:

A. Production of the torrefied biomass pellets.
B. Export of the torrefied biomass pellets.
C. Production of renewable drop-in fuels in Namibia.
D. Domestic use of renewable fuels.
E. Export of high value renewable fuels.

Based on this, a possible roadmap for the way forward could be:

Phase A.
A1. Develop a demonstration of the complete value chain from bush biomass to renewable synthetic drop-in fuel in Namibia, acting as an enabler and stimulant for the export market.
A2. Develop infrastructure for the production of the torrefied biomass pellets in Namibia mainly for exporting. The export income can cross-finance PtX synthesis facilities in Namibia if appropriate mechanisms are put in place.
A3. Develop Hybrid Biomass-PtX infrastructure in Namibia operating as traditional BtX facilities in the short term to meet local needs first, since it is easier to ensure a domestic off-taker to facilitate commercial financing of such projects.

Phase B.
B1. As green hydrogen availability in the country rises, green hydrogen is supplied to the Biomass-PtX plants and production increases.
B2. Start developing further infrastructure to produce renewable fuels and export regionally (e.g., SADC and Africa under AfCFTA) and global markets.

In conclusion, this hybrid PtX approach serves globally as a vital short-term bridge while we await the maturity and commercial viability of DAC technologies. However, its relevance extends into the long term as well. DAC installations require significant land and infrastructure, constraints that may not be feasible to address in all locations. The bush biomass route offers a complementary alternative in such scenarios, particularly in remote or constrained areas where installing DAC plants may not be practical and where transporting gases can present logistical and cost challenges. **The hybrid approach under Hybrid Biomass-PtX of using both green and bio-hydrogen maximizes efficiencies and effectiveness, creating more new upstream job opportunities and better addresses persistent environmental challenges around bush encroachment.**

Value Chain for utilizing sustainable carbon in PtX processes

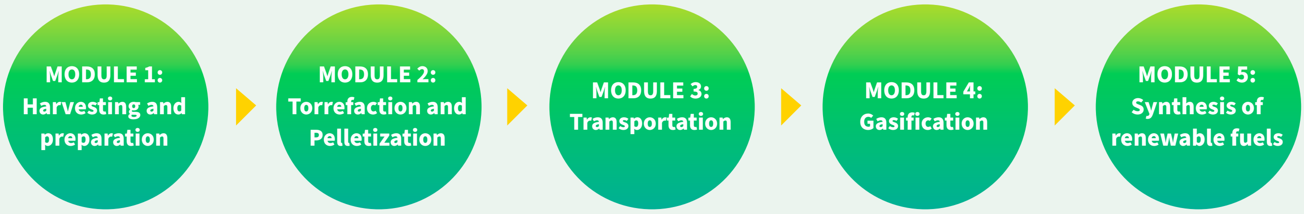

Figure 3: Own illustration

Maximization of carbon efficiency pathway

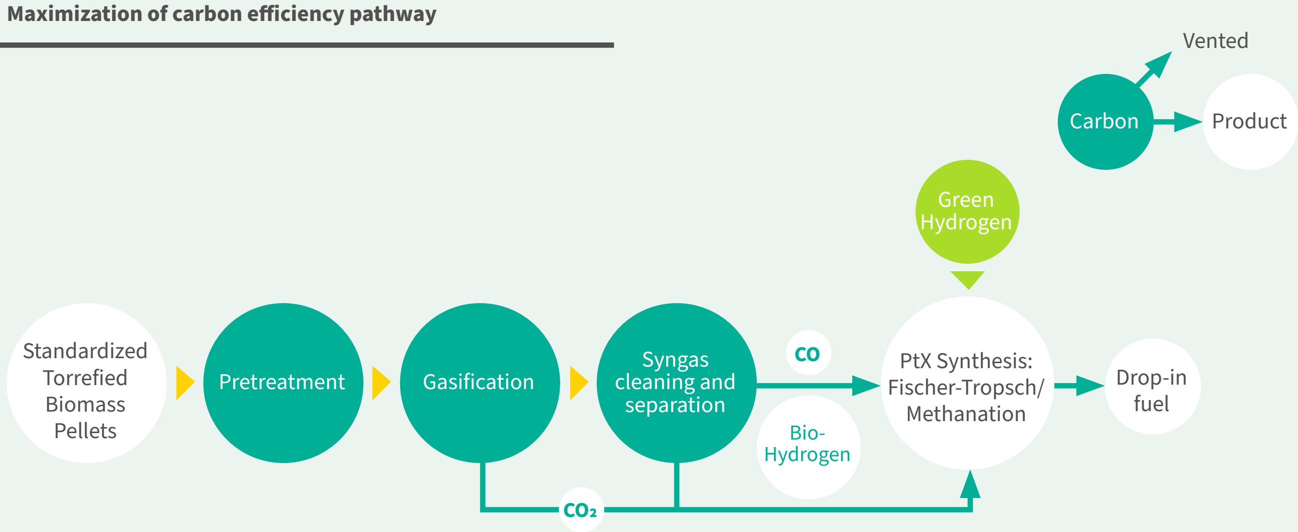

Figure 4: Own illustration

2

INTRODUCTION & BACKGROUND

Namibia is making strides in advancing its green hydrogen sector, resonating with its commitment towards sustainable development as expressed in the Vision 2030. Power-to-X technologies, leveraging Namibian green hydrogen, can provide Namibia highly desired export commodities in the form of renewable drop-in synthetic hydrocarbon fuels. With Direct Air Capture technology still in its infancy, the only viable option is to harness biogenic CO_2 from the country's abundant sustainable biomass to export as a sustainable carbon carrier or for synthesizing domestically renewable fuels, a sought after commodity in global and domestic markets.

NAMIBIA AND THE HYDROGEN ECONOMY

A Path towards a Hydrogen Economy

Guided by its Vision 2030, Namibia aspires to improve the living standards of its citizens to align with their counterparts in developed countries. To realize this vision, strategic, progressive measures have been divided into five-yearly National Development Plans (NPDs). In addition to the NPDs, the Harambee Prosperity Plans, aim to quicken the pace of these development objectives while introducing flexibility to adapt to independent intervening variables.

The second Harambee Prosperity Plan outlines three primary objectives for economic advancement, one of which underscores the necessity for cultivating complementary engines of growth. One such engine is the burgeoning green hydrogen industry, anticipated to radically transform the country and the Southern African Development Community (SADC) region. This industry promises to cultivate widespread prosperity among Namibian citizens and the SADC region in general.

In response to global calls to action from organizations such as the International Panel on Climate Change (IPCC), the International Energy Association (IEA), and the International Renewable Energy Association (IRENA), Namibia is well positioned to make a significant contribution to global defossilization efforts. This contribution is particularly commendable since the country has had very minor contribution to climate change. The country is geared up to exploit its abundant renewable resources to satisfy the soaring global demand for hydrogen and PtX products. Its geographical location and renewable potential also enable it to produce and export hydrogen products at competitive costs, thereby further boosting its economic development.

Namibia's Green Hydrogen and Derivatives Strategy, thus, holds the promise of transforming the nation into a key contributor to the global transition to net-zero emissions. The country envisages developing three hydrogen valleys located in the Southern region of Karas, the Central region including Walvis Bay port and the capital Windhoek, and the Northern region of Kunene.

This plan aligns with Namibia's aspiration to create an extensive green fuels industry, intending to produce 10-12 Mtpa hydrogen equivalent by 2050. Moreover, it intends to foster a thriving green hydrogen ecosystem across Southern Africa through synergistic infrastructure sharing, manufacturing collaboration, and power exports with neighboring nations.

According to the Green Hydrogen Strategy the green hydrogen and PtX industry is anticipated to catalyze socio-economic development in Namibia. By 2030, the sector could contribute up to US$6 billion to GDP, a 30% increase overestimates without hydrogen industry development. With a high potential job creation, the hydrogen industry stands as a promising sector for economic development and employment generation.

In the pursuit of this vision, Namibia is progressively laying down the groundwork. In alignment with Namibia's broader strategic objectives, the nation is pioneering efforts to advance the green hydrogen and PtX sector. Emphasizing the critical role of hydrogen in a sustainable energy future, the country is developing skill-building strategies, regulatory and institutional frameworks. These efforts are accompanied by the creation of dedicated concierge services. Together, these initiatives form an ecosystem designed to ensure that the process for stakeholders involved in prospective hydrogen projects is streamlined, transparent, and user-friendly.

The overall approach underscores Namibia's commitment to leverage hydrogen technology for societal benefit and to position itself as a leader in the global energy transformation. To mitigate investment risks and lower capital costs for green hydrogen and PtX projects, Namibia is setting up a facility to mobilize concessionary climate finance.

In this global race towards a sustainable future, Namibia's commitment to the green hydrogen sector demonstrates its determination to stand at the forefront of renewable energy transition. This commitment is not only a stride towards decarbonization but also a significant opportunity to enhance the socio-economic wellbeing of its people and contribute to a sustainable global future.

Overview of the Energy Sector

Namibia's energy mix is largely dominated by hydropower, which accounts for 93% of the total domestic electricity generation, according to AFREC's energy balance report for 2020. Other sources of electricity generation in Namibia include fossil thermal power and solar/wind power, accounting for 4% and 3% respectively. Namibia has one of the largest uranium resources not only in Africa but also in the world, and the government has shown interest in adding nuclear energy to its energy mix, following the example of countries like South Africa (World Nuclear Association, 2022). Until recently, Namibia did not have any indigenous sources of oil, coal, or natural gas, and as a result, all refined petroleum products are imported.

However, Namibia has recently discovered significant reserves of fossil fuel resources, estimated at 11 billion barrels of oil equivalents including light oil and natural gas. The country is still developing these resources and currently relies exclusively on imported petroleum products to meet its needs. It has to be noted that Namibia currently lacks any refining infrastructure and all refined petroleum products used currently in Namibia are imported.

Namibia is set to receive substantial oil revenues, after 2030, once the oil developers have recovered their exploration and development costs. The first crude oil production is expected in 2028. These oil finds are predicted to double the Namibian economy by 2040, with expected government earnings of up to USD 3.5 billion annually from royalties and taxes at peak oil production.

In line with the Fifth National Development Plan (NPD 5) the government is also exploring alternative energy sources, such as renewable energy, and to adopt more sustainable energy policies. The government has already made some efforts in this direction, including the development of a National Energy Policy and a Renewable Energy Policy that aim to promote the use of renewable energy sources. In full alignment, Namibia is also actively exploring the potential of hydrogen, with the aim of becoming a major player in the global hydrogen market while boosting the Namibian economy.

Green Hydrogen and PtX Export Opportunities

Namibia, situated in the southwest of Africa, has been positioning itself as a key player in the global Green Hydrogen and PtX sector. This ambition comes in spite of the fact that the Namibian industry is still relatively small and nascent. The country has recognized the enormous potential that Green Hydrogen and PtX offers, not just for its own energy independence but also as a critical solution to the global demand for clean energy.

The world's industrial nations, facing intense pressure to reduce their carbon emissions and meet international climate targets, are in desperate need of ways to reduce emissions from their hard-to-abate sectors. These include industries such as transportation, heating, and various manufacturing processes, where traditional forms of renewable energy might not be suitable or sufficient. The emissions reduction efforts are deployed in three pillars:

- Decarbonization activities, for which the main avenue is either electrification or transitioning to hydrogen use.
- Defossilization activities, for the sectors and processes that are unable to fully decarbonize.
- Activities during the transitioning period to minimize fossil carbon use through circular economy/resource efficiency, Carbon Capture Utilization and Storage (CCUS) applications and deployment of renewable fuels until either decarbonization or defossilization in all sectors/applications is achieved.

Green Hydrogen and PtX offers a clear path forward. By using renewable energy sources like wind and solar, hydrogen can be produced without emitting greenhouse gases. Through PtX green hydrogen can be transformed to a multitude of products including renewable synthetic drop-in fuels like Sustainable Aviation Fuel (SAF), Methanol, and drop-in diesel and gasoline. These fuels can serve as direct replacements for their fossil-based counterparts, allowing for a smoother transition towards a carbon-neutral world.

Industrial nations, therefore, are eyeing the potential of Green Hydrogen and synthetic fuels as vital components of their energy transition strategies. The demand for these products is not just theoretical but is becoming an urgent economic necessity.

Namibia's Hydrogen and PtX Strategy reflects the country's desire to tap into this burgeoning global market. Rich in renewable energy resources, particularly solar and wind, Namibia is well-placed to produce Green Hydrogen at a competitive cost.

Globally, activities towards securing sustainable carbon are increasing, but face major challenges. Contrary to that, Namibia has an abundant source of sustainable carbon source in the form of encroaching bush biomass. Over the past several decades, Namibia has faced a widespread issue of bush encroachment. This phenomenon, where native bush species grow unchecked and out of balance with the local ecosystem, has had significant negative impacts on agriculture, wildlife habitats, and water resources. However, this challenge also presents a unique opportunity. The encroaching bush biomass can be harvested in a sustainable and environmentally responsible manner, turning what was once considered an ecological problem into an innovative solution for the production of synthetic drop-in fuels. By utilizing the carbon in the bush biomass, Namibia can synthesize renewable fuels using Green Hydrogen. This not only aligns with global sustainability goals but also addresses a local environmental issue. The strategy of using encroaching bush biomass as a carbon source does more than merely provide raw material for synthetic fuels; it also offers an integrative solution that ties together economic growth, technological innovation, and ecological stewardship. By responsibly harvesting the bush, Namibia can restore balance to its natural landscapes, improving the viability of agriculture, and enhancing biodiversity. At the same time, it creates jobs and adds value to a sector that could become a pillar of Namibia's economy.

The government's strategic plans align with the technological, infrastructural, and regulatory requirements to make Green Hydrogen a viable and sustainable industry. But the strategy goes beyond mere production. Namibia aspires to become a hub for synthetic fuels, leveraging Green Hydrogen to produce SAF, Methanol, and drop-in fuels. This is more than a technological endeavor; it is a socio-economic vision that could transform the nation's economy.

Namibia's geographic location, close to key international shipping routes, enhances its export potential. With appropriate infrastructure development, Namibia could become a critical supply link to industrial nations seeking to transition away from fossil fuels.

The export of Green Hydrogen and synthetic fuels would also align with Namibia's diplomatic and trade goals, strengthening its relationships with key global players and international bodies. It would place Namibia firmly on the world stage as a partner in the global fight against climate change. Namibia's focus on Green Hydrogen and synthetic fuels is a forward-looking approach that aligns with both global demands and national interests. Though its industry may still be in its infancy, the strategic direction laid out in the Hydrogen and PtX Strategy places Namibia at the forefront of an emerging global trend.

By addressing the urgent needs of industrial nations to cut emissions and defossilize their hard-to-abate sectors, Namibia is not only positioning itself as a vital part of the solution but also creating an economic opportunity with significant potential for growth.

The production of synthetic fuels from Green Hydrogen, combined with the potential for export, creates a compelling narrative for Namibia. It is a story of innovation, sustainability, and global collaboration. If realized, this vision could mark a transformative moment for Namibia, placing it at the heart of the world's clean energy future.

Domestic needs for hydrogen and synthetic fuels

The big opportunity for Namibia lies in the export potential of green hydrogen and PtX. At the same time, Namibia can of course utilize these new resourced in order to minimize energy imports. An analysis of the of the current situation and future prospects of various types of fuels is presented in Annex 1.

Three of the highest contributing sectors in the GDP of Namibia are mining, agriculture (including animal farming) and fisheries. While these sectors have been pivotal in steering Namibia’s economic growth, they still heavily rely on the use of fossil fuels. Although Namibia cannot be categorized as high carbon emitter there are still commitments that need to be met by a number of private companies due to mandates set by parent companies for defossilization and also to be aligned to the aspirations of Namibia’s NDCs. Each of these sectors, given their inherent operational mechanics and logistical constraints, presents unique challenges to full electrification and the direct adoption of hydrogen as an energy source.

Thus, while the path to renewable energy is desirable and necessary, the immediate feasibility and practicality of achieving full electrification or hydrogen adoption across these sectors appear limited.

The most viable and practical way forward in the short-term seems to lie in renewable synthetic drop-in fuels. They offer a relatively seamless transition towards renewable energy, mitigating the need for significant infrastructural overhaul or technical adaptations in engines and machinery. This ensures that the transition can be economically viable and practically achievable within the given timeframe.

It is very important to highlight the full alignment of the future domestic needs of Namibia with the export opportunities presented in the previous section, ensuring that added benefits are to be harvested.

SYNTHETIC FUELS OVERVIEW

In an era marked by the compelling need for cleaner, more sustainable energy systems, synthetic fuels—also known as synfuels— most often in the form of synthetic hydrocarbons that can be used as a drop-in replacement for traditional fuels stand at the nexus of promise and innovation with their real-world applications constantly increasing. They are chemically similar to their conventional counterparts and as a result they can introduce new pathways towards environmental sustainability and energy security. For example, in August 2023, the first fully synthetic 100% drop-in SAF got standardized (ASTM D7566 Annex 8)[1]. This section outlines the specifics of synthetic fuels, their production processes, their renewable and sustainability attributes, and their potential role in the global energy landscape.

Synthetic fuels are derived through a series of conversion processes that transform a variety of feedstocks into usable fuels. The two most common processes involved in synfuel production are methanation and the Fischer-Tropsch process, which use hydrogen and carbon monoxide as primary inputs.

Methanation involves the reaction of hydrogen with carbon dioxide or carbon monoxide, generating methane, the primary component of natural gas. This process, executed at high pressures and temperatures and typically in the presence of a nickel catalyst, produces methane that can be used directly as fuel or further processed into other synthetic fuels.

The Fischer-Tropsch process, conversely, is a more sophisticated set of chemical reactions that transform a mixture of hydrogen and carbon monoxide, known as synthesis gas or syngas, into liquid hydrocarbons. This process has two main stages: the Fischer-Tropsch reaction and the product upgrading. The Fischer-Tropsch reactor uses a catalyst—typically iron or cobalt-based—to induce the formation of long-chain hydrocarbons from the syngas. The output is a mixture of hydrocarbons that is upgraded to generate various fuels, including gasoline, diesel, and jet fuel.

While synthetic fuels can be produced also by using fossil fuels (e.g., coal) the focus is in the production of renewable and sustainable fuels. Two main pathways have been identified:

- Power-to-X: These are based on the use of green hydrogen along a captured CO_2.
- Biomass-to-X: These are based on the use of biomass.

More information is presented in the following box.

The Namibian Hydrogen Strategy makes reference to derivative synthetic fuels. Moreover, there is no alternative fuels policy framework in Namibia. The Namibian Renewable Energy Policy indicates a need for an advanced biofuels policy to be developed.
As is clear, the PtX approach is more mature in terms of Strategies and Policies in Namibia as well as the under development green hydrogen projects. Given that PtX is using solely green hydrogen, the carbon source for the production of synthetic fuels is the critical component concerning the sustainability outlook of the final drop-in fuel. There are primarily three ways to source carbon for PtX technologies, each with its unique merits and challenges.

1. **Direct Air Capture (DAC):** This technology captures CO_2 directly from the atmosphere. The appeal of DAC lies in its ability to recycle carbon from the atmosphere on a global scale. However, as of now, DAC technology is not yet commercially available and has high associated costs. The companies developing the technology cite projected costs in 2030 of 100 USD/t, while independent studies put the cost at 600 USD/t (Tollefson, 2018). While the technology has seen significant advancements, it remains uncertain when it will become cost-effective at a commercial scale. Additionally, DAC facilities require a significant amount of space, and the selection of suitable sites could pose challenges in terms of land use and impact on biodiversity.

2. **Biogenic Carbon:** Biogenic carbon refers to CO_2 captured from biomass, including agricultural residues, wood waste, and other organic materials. It presents a more sustainable and economically attractive option.

Carbon Capture from Fossil Fuel-based Plants (including unavoidable carbon): This method involves capturing CO_2 from industrial processes that utilize fossil fuels, including power plants, cement factories, and steel mills. While the capture and utilization of such CO_2 could enhance the overall resource efficiency of these industries, this is not considered a sustainable source of carbon in the long term.

[1] https://renewable-carbon.eu/news/astm-decision-brings-100-saf-certification-within-reach/

Power-to-X vs Biomass-to-X

In the pursuit of sustainable and defossilized energy systems, two fundamental pathways are frequently cited: **Power-to-X (PtX) and Biomass-to-X (BtX)**. Both pathways serve to transform either electricity or biomass into a wide range of energy carriers and feedstocks, designated by the 'X'. This may include heat, power, gaseous fuels, liquid fuels, or chemicals. While each pathway carries its own set of benefits and challenges, it is the similarities, differences, and potential synergies between them that are of interest in the context of comprehensive and efficient energy transition strategies.

Power-to-X refers to a series of technologies wherein electricity—primarily derived from renewable sources such as wind or solar—is converted into heat, hydrogen (Power-to-Gas), synthetic fuels (Power-to-Liquid), or chemicals (Power-to-Chemicals). The core process in PtX is the electrolysis of water to produce hydrogen and oxygen. If the electricity used in this process is generated from renewable sources, the hydrogen produced is termed 'green hydrogen'. This green hydrogen can then be directly utilized or further processed to produce a variety of synthetic fuels and chemicals.

PtX offers a number of advantages. It provides a means of converting fluctuating renewable power into other forms of energy, thereby addressing issues related to the storage and transport of electricity. Hydrogen or synthetic fuels produced via PtX can be stored for long periods and transported over long distances, characteristics that renewable electricity lacks. PtX also offers a decarbonization pathway for sectors that are hard to electrify, such as aviation, maritime shipping, mining and agriculture. Synthetic fuels produced via PtX are often referred to as 'drop-in' fuels, as they can be used in existing infrastructures and engines without any modifications.

Despite these advantages, challenges remain for PtX. The overall efficiency of the PtX pathway is currently lower compared to direct electrification due to energy losses in electrolysis, fuel synthesis, and end-use conversion. Also, the cost of green hydrogen and synthetic fuels remains high compared to fossil-based alternatives, though costs are expected to decrease with technological advancements and economies of scale.

Biomass-to-X involves the conversion of biomass resources into a range of energy carriers and feedstocks, through processes such as combustion, gasification, pyrolysis, or biochemical conversion. Biomass, in this context, could be any organic material such as wood, agricultural residues, algae, or organic waste.

BtX technologies allow for the production of carbon-neutral fuels and feedstocks, as the CO_2 emitted during the use of the fuels can be absorbed by the subsequent growth of biomass. BtX can also offer a decarbonization pathway for sectors that are hard to electrify. Like PtX, biofuels produced via BtX are also considered 'drop-in' fuels. Moreover, biomass can provide a source of renewable carbon, which is required for the production of certain chemicals and materials. One major advantage of BtX is that it can stimulate rural economies through the cultivation and processing of biomass and create jobs.

Nevertheless, the use of biomass for energy purposes is not without controversy. Sustainability concerns are frequently raised. The availability of sustainable biomass is also limited, and it may not be sufficient to meet all demands for energy, materials, and food.

PtX and BtX should not be seen as competing technologies, but rather as complementary pathways in the transition to a sustainable energy system. Both technologies can be employed to decarbonize sectors that are hard to electrify. Moreover, both technologies can contribute to the creation of a circular economy through the recycling of CO_2. There are also potential synergies between PtX and BtX. In Power-and-Biomass-to-X (PBtX) processes, renewable electricity and biomass are jointly used to produce energy carriers or feedstocks. For example, green hydrogen produced via PtX can be combined with carbon and hydrogen from biomass in a gasification or pyrolysis process to produce synthetic fuels or chemicals. This could combine the benefits of PtX and BtX and may increase overall system efficiency and flexibility.

In conclusion, both Power-to-X and Biomass-to-X offer valuable pathways towards achieving a decarbonized and sustainable energy system. While each carries its own set of benefits and challenges, it is the complementarities and potential synergies between them that should be exploited in a holistic energy transition strategy. Future research and policy should aim to create a supportive environment for these technologies, addressing barriers and promoting synergies where possible.

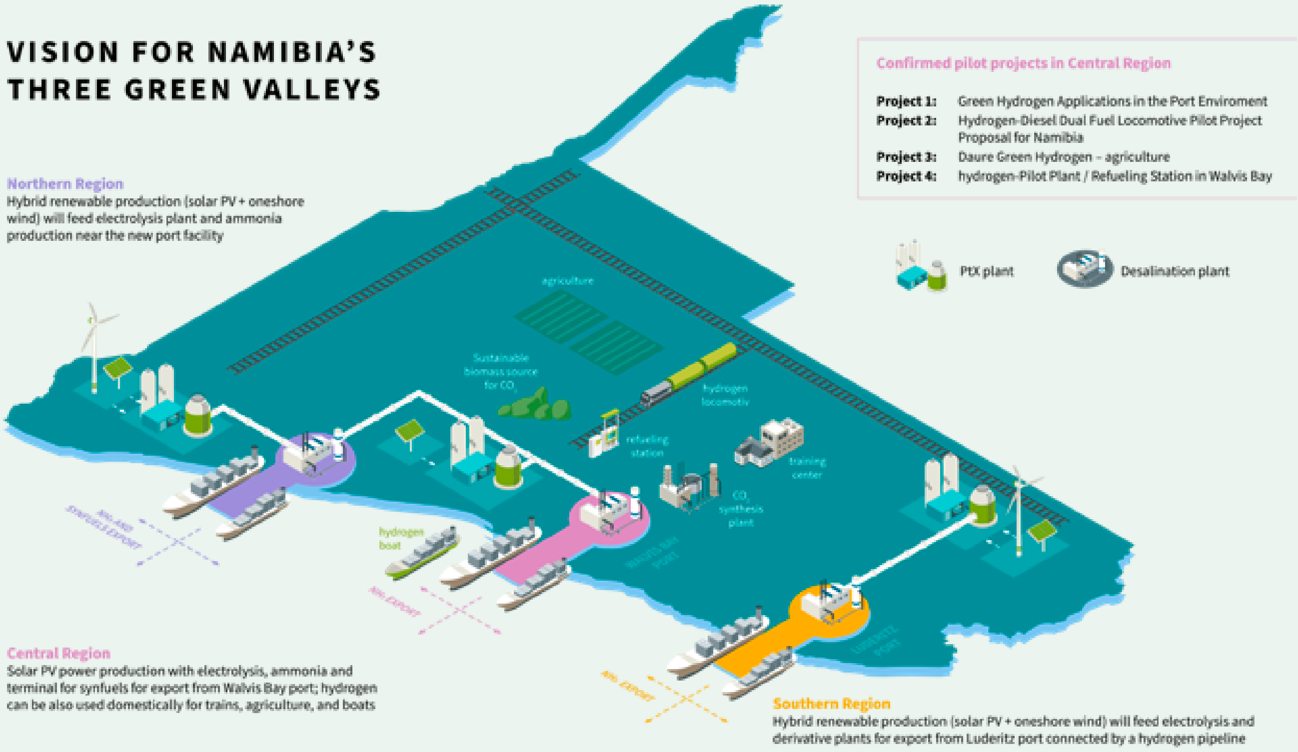

Figure 5: Hydrogen end-use demand by region in a net zero scenario
(Source: Own graphic based on: Green Hydrogen and Derivatives Strategy of Namibia)

Relying on fossil fuel-derived carbon does not align with the overall goal of decarbonizing the economy and phasing out fossil fuel use. Under the Renewable Energy Directive II of the EU, the use of captured CO_2 from fossil fuel-based processes must comply with stringent criteria, including achieving a minimum greenhouse gas emission saving threshold of 70%, to be considered as part of a renewable energy strategy.

As the global community grapples with the pressing need to transition away from fossil fuels and transition to climate neutrality, DAC and biogenic carbon are the only options in going forward. This is also reflected in the Namibian Hydrogen Strategy where it is highlighted:

> **For the resulting fuel to be climate-neutral, the CO_2 needs to come from climate-neutral sources, that is, where its 'production' has led to a net removal of CO_2 from the atmosphere – either through sustainably harvested plants (biogenic CO_2) or through technical filters (DAC).**

The sources of sustainable biomass addressed in the Hydrogen Strategy are presented in Figure 5. Biogenic Carbon is practically the only feasible option for the short-/medium-term.

Sourcing biogenic carbon

Biomass, in all its forms, can act as both an energy carrier and a source of carbon. It is renewable, widely available, and can be produced sustainably.

Two primary pathways exist for the utilization of biogenic carbon. These are:

1. **Capturing Carbon Dioxide from Biomass Usage:** This method involves capturing and storing carbon dioxide (CO_2) emissions generated during the use of biomass for energy generation or other processes. This CO_2 can then be employed in PtX applications. However, these processes require substantial infrastructure, including carbon capture technology and CO_2 storage or transportation facilities. Especially for transportation, the most cost-effective way of transporting gases is through pipelines, given that biomass use is taking place typically in rural areas. Pipelines have high up-front costs, and present multiple challenges in their design, implementation and use (Lu et al, 2020). Currently, this is the only method considered when discussing of biogenic carbon use in PtX.

2. **Developing Processes to Maximize Biomass's Carbon Carrier Aspect:** This pathway involves creating innovative methods that enhance the use of biomass as a carbon carrier while simultaneously harnessing its inherent renewable energy in a productive manner. This approach involves technologies such as gasification, pyrolysis, or torrefaction, which can convert biomass into syngas, bio-oil, or biochar. These bio-based intermediates are rich in carbon and can be used as feedstocks for PtX processes to produce synthetic fuels or chemicals. The energy content of the biomass is also utilized in these processes, creating a synergistic system of energy and resource efficiency.

In the context of advancing Power-to-X (PtX) technologies, **it is crucial to understand the implications of carbon carrier choices**. The use of carbon dioxide (CO_2) as a carbon carrier, although it is currently considered the approach of choice, poses logistical complexities due to its gaseous state, making transportation a technically challenging and costly task. Carbon monoxide (CO), also a gaseous candidate, introduces additional transportation challenges owing to its toxic nature, which raises public safety concerns.
The interest in developing novel solid or liquid carbon carriers is also on the rise.

Focusing on Namibia, there are also other advantages to using its encroaching biomass resource, including rangeland and habitat restoration, protecting biodiversity, increasing agricultural productivity, and stimulating rural economic development.

In line with the project's original mandate, this report comprehensively assesses the potential of utilizing Namibia's local residue biomass, particularly from bush encroachment, for the production of high-value Power-to-X (PtX) products, with a specific emphasis on synthetic fuels. During the initial investigative phase, it became increasingly apparent that conventional technological pathways for PtX conversion would not be sufficient to optimize the unique carbon-carrying characteristics of Namibia's encroaching bush biomass.

As a result, the study pivoted to a novel approach, centered on the development of an innovative process designed to maximize the carbon carrier aspect of the biomass. This innovative process not only supports Namibia's broader Hydrogen Strategy but also addresses the pressing issue of bush encroachment in an environmentally responsible manner.

The findings indicate that by focusing on carbon optimization, Namibia can unlock a sustainable and economically viable avenue for synthetic fuel production, thereby fulfilling both local and global needs. The project proposes that this new process can be a linchpin in aligning ecological sustainability with economic viability, offering a multi-faceted solution to Namibia's bush encroachment problem while contributing to global efforts in emission reductions.

3

BIOGENIC CARBON DERIVED FROM NAMIBIAN BUSH BIOMASS

In this chapter, the spotlight is turned on Namibia's bush biomass. The persistent issue of bush encroachment is examined, leading into a discussion on bush control and the utilization of biomass. The chapter elaborates on the vast availability of bush biomass in Namibia and delves into the sustainability aspects of this local resource. The narrative then shifts to the development of a carbon carrier for Power-to-X (PtX) applications. It outlines the design goals for this carbon carrier, aiming to maximize efficiency and sustainability in line with the country's broader decarbonization objectives. Lastly, a model for this carbon carrier is proposed, integrating the use of Namibia's bush biomass, thus presenting a solution that is not only eco-friendly but also draws on locally available resources. The potential of bush biomass as a viable and sustainable pathway for Namibia's energy transition is thus highlighted.

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BUSH BIOMASS IN NAMIBIA

Otjisewa, central Namibia: The change from the savanna landscape in 1876 (top) to 2006 (bottom), illustrating the spread of bush encroachment over time

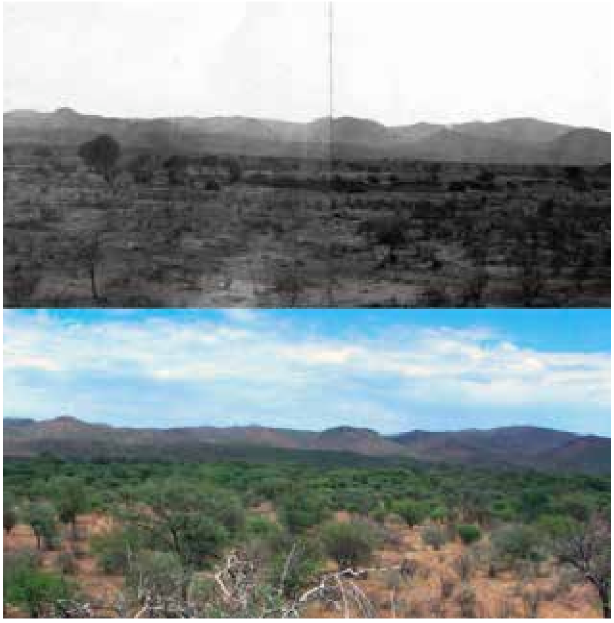


Figure 6: Böhm, Steffen & Sian Sullivan (2021)

Bush Encroachment

Namibia is increasingly being affected by a shrub thickening phenomenon, known locally as bush encroachment. Bush encroachment can be defined as the invasion and/or thickening of aggressive undesired woody species resulting in an imbalanced ecosystem (de Klerk, 2004).

However, bush encroachment is not unique to Namibia and has been occurring throughout similar savannah ecosystems across the world (Eldridge et al, 2011). In Namibia, bush encroachment is accepted as an indicator of rangeland degradation. Bush encroachment has been spreading and increasing in severity across the Namibian savannah ecosystem over the last century (Rohde & Hoffman, 2012). The impacts of bush encroachment are reaching critical levels for the Namibian economy, environment, and its people, since the majority of Namibian livelihoods are directly or indirectly linked to agriculture (Shikangalah & Mapani, 2020).

The causes of bush encroachment are multifaceted, including local land management practices and global climatic factors. The local factors include systemic fire suppression, overgrazing, changes in soil nutrient levels and changes within the species composition and diversity of herbivores. Global climatic factors include the increased atmospheric carbon dioxide (CO_2) levels, changes in rainfall patterns, and increasing average temperatures (Kgosikom & Mogotsi, 2013).

The aforementioned factors contribute towards the weakening of the grass and herbaceous layers, and as a result, have inadvertently relaxed competitive pressure on native woody species within these ecosystems. However, not all woody species tend to become encroaching. Some are better adapted to exploit the opportunity and readily fill the gap, becoming dominant over a given area. In Namibia, nine woody species have been identified as problematic encroacher species, namely Senegalia mellifera (Black Thorn Acacia), Vachellia reficiens (Red Thorn Acacia), Dichrostachys cinerea (Sickle Bush), Vachellia nilotica (Gum Arabic Tree), Vachellia luederitzii (False Umbrella Thorn Acacia), Terminalia prunioides (Purple Pod Terminalia), Terminalia sericea (Silver Cluster Leaf), Colophospermum mopane (Mopane), and Rhigozum trichotomum (Three Thorn Rizogum). These species are jointly termed "encroacher bush", however, they have geographically distinct ranges. In any given bush encroached area in Namibia, the dominant woody species are comprised by only a few of the aforementioned species.

The encroacher species are morphologically quite different from one another; however, they tend to become encroaching under similar conditions within their natural ranges, especially when specific conditions arise. Recruitment events are specific periods when the conditions for establishment of encroacher species are ideal. Recruitment events are typically related to fire, herbivory, bush density, drought, and rainfall. Areas that experience high grazing pressure and consequently low fire frequency are more prone to bush encroachment.

Areas with lower grazing pressure and more frequent fires are observed to be less prone to bush encroachment (Roques et al, 2001).

Areas are determined to be bush encroached once the density of woody species passes a certain threshold. However, there are differing accepted thresholds and they are dependent on several factors, including long-term average rainfall of the area, soil type, and the specific encroacher species.

In Namibia, Evapotranspiration Tree Equivalents (ETTE) are the units used when quantifying bush density over a given area. One ETTE is equivalent to a 1.5-meter-tall, single stemmed woody plant. Typically, at levels over 5000 ETTE per hectare, movement through the area becomes negatively impacted. Often, severely encroached areas are characterised by ETTEs of over 10,000 per hectare.

Bush encroachment can also increase or decrease in density over time due to natural events. It is observed that the density of bush tends to increase until an equilibrium is reached. Roques et al. observed the equilibrium to be equivalent to 40% canopy cover in test plots in South Africa (Roques et al, 2001). Bush density can also decrease during drought and frequent fires. However, intra-tree competition within bush encroached areas regulates the sizes of individual shrubs, keeping them smaller, and thus making them less vulnerable to drought (Kambatuku, 2011).

See also in Figure 7 the illustration of a simplified approach to the principle of stability, resilience and domain of attraction as applied to bush encroachment, highlighting the significance of savanna structure (i.e., preserving large bushes).

The extent of bush encroachment across Namibia has been estimated since the 1950's. The extent in hectares of land affected by bush encroachment has been increasing, from an estimated 4.56 million hectares in 1957 to 62 million hectares estimated in 2014. Most commonly, the estimate of 45 million hectares from SAIEA (2015) is used (See Figure 8 and Figure 9).

An extract from the illustrating the stable states within a savannah system

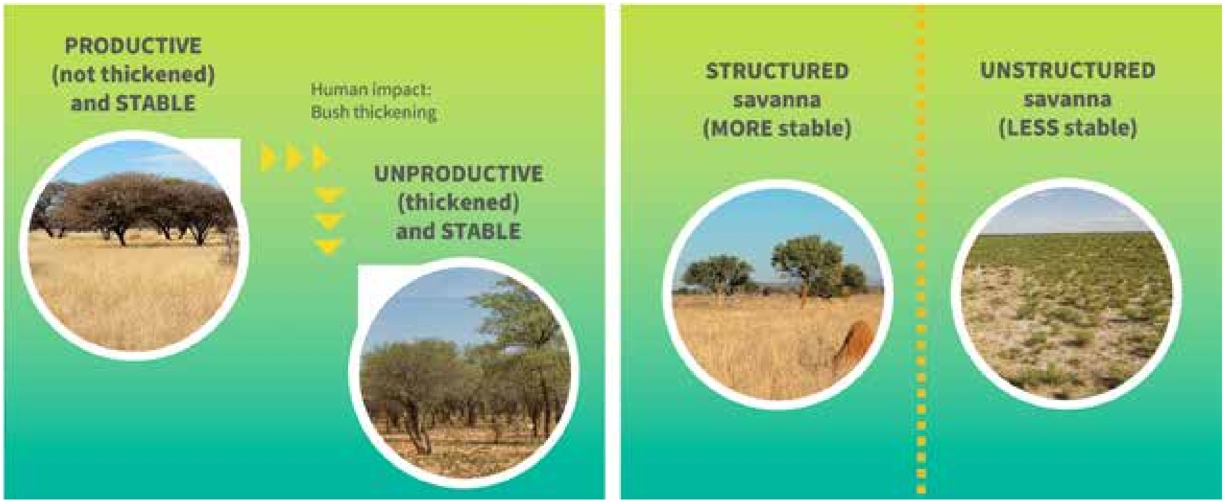


Figure 7: An extract from the illustrating the stable states within a savannah system. (Adapted from: Smit, de Klerk, Schneider, & van Eck, 2015)

Historic estimates of total areas affected by bush encroachment across Namibia, in hectares

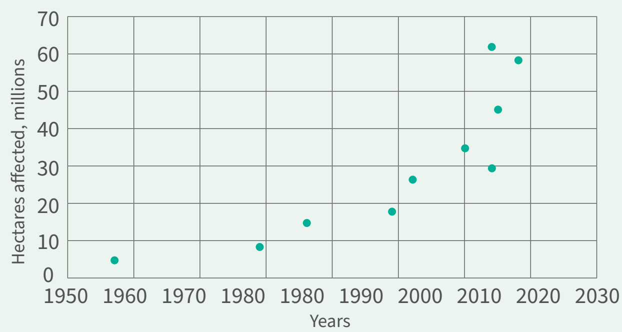


Figure 8: Rawlinson (1994); National Reclamation Strategy (1988); Lubbe & Slater (1985); Bester (1999); Zimmermann & Joubert (2002); Christian, van der Merwe, Bockmühl , Mostert , & de Klerk 2010); Honsbein (2014); Rothauge (2014); SAIEA (2015); Government of Namibia (2018)

Bush encroachment in Namibia indicating and estimated 45 million hectares of affected land

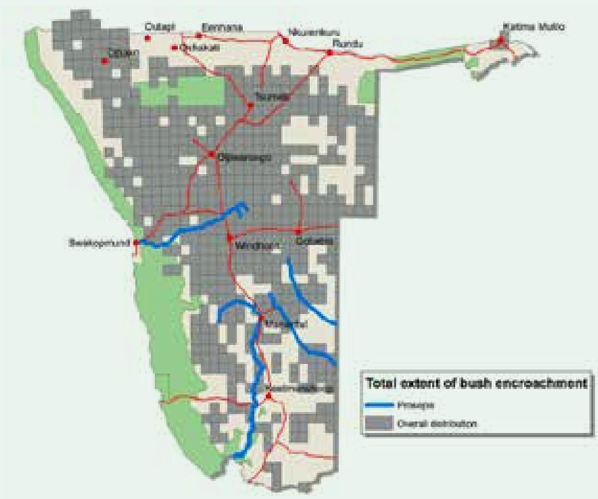


Figure 9: SAIEA (2015)

Bush Control and Biomass Utilisation

Bush control is recognised as one of the initial steps towards the restoration of bush encroached areas. Bush control takes different forms, from use of arboricides to the use of heavy equipment to kill and/or remove the excess bush from the land. Bush control is still largely seen as a means to restore rangeland productivity of affected land. However, standalone bush control is no longer economically viable for many landowners. This has necessitated the need to add value to the resulting biomass residues stemming from bush control to help offset the costs of the bush control.

Availability of the Bush-Biomass resource

In 2015, a quantification study was conducted in the Otjiwarongo area, which indicates that a 30-35% reduction of standing biomass is equivalent to 10.811-12.652 tonnes of woody biomass (dry matter) per hectare. This suggests that the available bush encroachment resource for harvest in Namibia can be as high as 486-569 million tonnes at first-time harvest. This biomass resource is equivalent to:

- 7.3 million terajoules of thermal energy, or
- 174 million tonnes of oil, or
- 249 million tonnes of coal.

Such a significant quantity of biomass is sufficient to meet the national power requirements for more than 140 years.

The current biomass industry in Namibia comprises of:

- Approximately 1.2 million tonnes of biomass per annum for charcoal (export)
- Approximately 600,000 tonnes of biomass per annum for firewood use (domestic & export)
- Approximately 250,000 tonnes of biomass per annum for fencepoles (domestic)
- Approximately 40,000 tonnes per annum of biomass for industrial energy (domestic)

The total **current utilization** is estimated at 2.1 million tonnes per annum.

Studies have found that without concerted post-harvest aftercare, areas that have been harvested will tend to re-encroach to original encroached levels within 14-26 years, depending on several factors such as rainfall, species, and soil type.

However, even if aftercare is applied, the tendency of the land will still be to become re-encroached due to the aforementioned local and global factors, such as erratic rainfall, fire suppression, fewer frost incidences, and increased atmospheric CO_2 levels.

Bush biomass potential

Standing resource
45 million Ha x 36.222 tonnes per Ha
1.63 billion tonnes (dry matter)

Extractable resource
45 million Ha x 10.811 tonnes per Ha
486 million tonnes (dry matter)

Sustainable extraction
486 million tonnes / 26 years
18.7 million tonnes (dry matter) per annum

Potential
18.7 mil.t – 2.1 mil.t (actual)
16.6 million tonnes (dry matter) per annum

Figure 10: Own illustration

Based on currently available data, it is estimated that, the resource can be utilized at a quantum of between 18.7 - 40.6 million tonnes per annum. This range of utilization takes into account the factors that influence bush encroachment, including the availability of resources, the level of aftercare applied, and external factors beyond local level management. By utilizing the resource sustainably, it is possible to maintain a consistent level of production over an extended period. See also the graph in Figure 10.

However, it is important to note that the supply radii may increase with higher value end products. The main limiting factor in sustaining the biomass processing centers is the upstream logistic costs that involve the transport of biomass from the field to the processing plant.

Assuming that the biomass is dried and densified in the field, which is considered to be a good practice, and only road transport is used, since the case for rail for upstream transport is limited, a harvesting area of up to 3 million hectares can be considered. This area has at a maximum 100 km radius, can supply a central processing plant with 650,000 tons per annum for 25 years, assuming no regrowth and that only 50% of the land is harvestable.

Transporting encroacher bush biomass is best suited in hog fuel form, such as P100 or similar, which allows legal transport limits to be maximized and in field processing to be minimized. Based on analytical testing done by the Namibia Biomass Industry Group the moisture content of the biomass, as received, varies between 3-21%, averaging at 8.5%, while the average ash content, as received, is 3-8% (unscreened), averaging at 4.5%. The average calorific value, as received, ranges between 11-17 Mj/kg, averaging at 15 Mj/kg, making it an ideal energy feedstock.

Sustainability of Namibian Bush-Biomass and Standardization

In 2021, GIZ Namibia commissioned the study "International Biomass Fuel Certification for Namibian Encroacher Bush" under the GIZ Bush Control and Biomass Utilization Project (BCBU). The study reported that Namibia, with its abundant resources of encroacher bush biomass, has the potential to contribute significantly to the global energy market in the context of renewable and sustainable energy sources. This potential lies in the alignment of the Namibian bush biomass with the European Union's Renewable Energy Directive (RED II) standards, as well as the sustainability certifications that enforce RED II, including Sustainable Biomass Program (SBP), SURE and others.

Namibian encroacher bush biomass is an undefined resource under RED II. A recent due diligence study undertaken by an international project developer assessing encroacher bush biomass under RED II, indicates that bush biomass is best classified as "waste and residues, other than agricultural, aquaculture, fisheries and forestry residues". It is not considered an agricultural biomass, as it is not a direct result of agricultural activity, nor is it considered a forestry biomass, as it is not a biomass produced from forestry activities.

In conclusion, the study finds encroacher bush to be RED II compliant when classified as waste from agricultural land, assuming that it meets the other RED II requirements, including the minimum carbon savings target of 70%, which is inherently project specific.

With that in mind, either SBP, SURE, or any other RED II compliant certification schemes can be used to ensure RED II compliance of Namibian encroacher bush derived products and projects. The widely adopted Forest Stewardship Council (FSC) certification scheme in Namibia is not in itself compliant to RED II, however, it has many compliant areas and is therefore seen as an additive certification scheme that can be used in conjunction with other RED II compliant schemes, reducing the need for duplication of efforts in some areas.

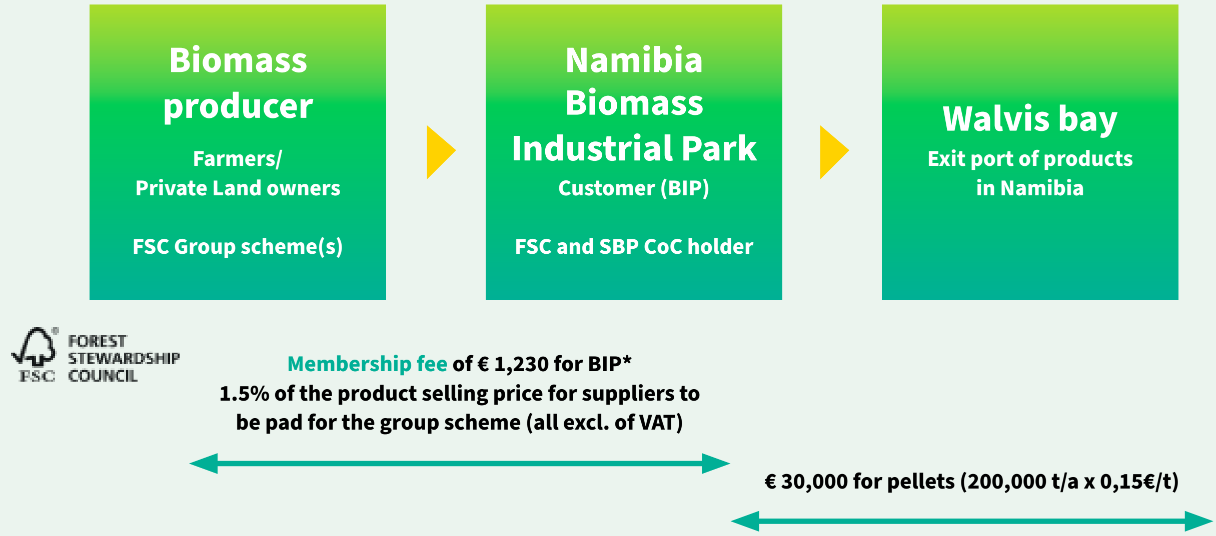
While the certification process is of critical importance, it is also necessary to understand the feasibility and cost structure of such certification schemes. To ensure the sustainability of the certification systems, members are responsible for covering the related costs. However, in many certification systems, these costs are shared between multiple members. Figure 11 represents the costs of FSC for a biomass project in Namibia. In Namibia, more than 1.6 million hectares of land is currently FSC certified.

Biomass certification schemes are especially important for processing plants since the certification applies to organizations that produce, trade, or use woody biomass.

Furthermore, certification goes beyond only enabling access into international markets. Certification schemes such as FSC also include social welfare indicators to be met regarding workers' rights and employment conditions as per the International Labor Organization (ILO) conventions. This provides an added benefit of certification: enhancing the quality of life, job security, education, training, and several key social and ecological measures, hence promoting all three pillars of sustainability.

Namibian bush biomass presents a significant opportunity in terms of sustainable carbon, particularly within the context of the European Union's renewable energy standards. With the correct certification and implementation of sustainable management practices, Namibian bush biomass has the potential to make substantial contributions towards global renewable energy efforts, while also enhancing the socio-economic standards. Voluntary adherence to recognized certification schemes reflects the country's commitment to adhere to the principles of sustainable development and its compatibility with the EU's sustainability requirements concerning biomass.

Annual certification related fees



* Fee for Membership can be waived out depending the arrangement of FSC certificate

Figure 11: Based on IfaS, International Biomass Fuel Certification for Namibian Encroacher Bush & GIZ (2021)

Biomass sustainability challenges

The utilization of biomass, although considered renewable, involves an intricate web of sustainability issues that warrant careful evaluation. Biomass, encompassing a broad range of organic materials from plants, trees, and agricultural waste, indeed regenerates over time, yet its use as an energy source involves a variety of implications and trade-offs. The principle of carbon neutrality constitutes one of the main points of debate in the discourse on biomass sustainability. When organic matter is burned for energy, it releases carbon dioxide into the atmosphere. This carbon dioxide, in theory, is reabsorbed when new plants grow, thereby creating a 'carbon cycle'. However, the speed of this cycle varies and it can take years, even decades, for new trees to absorb the quantity of carbon dioxide released by the combustion of their mature counterparts. In the short to medium term, this could contribute to higher atmospheric CO_2 levels, although the Intergovernmental Panel on Climate Change (IPCC) categorizes biomass energy within the fast domain of the carbon cycle.

Land use change is another significant issue that arises from biomass utilization. The conversion of forests into plantations or agricultural land, either directly or indirectly through displacement of other land uses, can lead to substantial CO_2 emissions, biodiversity loss, and ecological imbalance. This change not only disrupts existing ecosystems but also diminishes the land's ability to act as a carbon sink.The question of sustainable sourcing and deforestation becomes more critical with rising demand for biomass. In the face of increasing biomass consumption, there is a legitimate concern that such pressure might give rise to unsustainable management practices or, in extreme cases, deforestation, threatening biodiversity, ecosystem services, and our decreasing the earth's ability to absorb CO_2 from the atmosphere. Moreover, biomass resources, although renewable, are not unlimited. Using biomass for energy can instigate competition with other applications of these resources, including food and feed production or the preservation of natural habitats. This competition can lead to adverse social implications, such as food insecurity, and exacerbate ecological concerns like habitat destruction. Lastly, the matter of air pollution is a significant factor in the discussion of biomass energy. Combustion of biomass, particularly in inefficient systems, contributes towards air pollution by emitting particulate matter, nitrogen oxides, and other pollutants. These substances degrade air quality and pose risks to human health, adding another layer of complexity to the biomass energy debate.

In conclusion, the sustainability of biomass is multifaceted and context-dependent. It hinges on several critical factors, including carbon neutrality, land use change, sustainable sourcing, competition with other biomass uses, and impacts on air quality. Therefore, careful management, stringent policy measures, and continual monitoring are essential to ensure that biomass energy use aligns with the overarching objectives of environmental sustainability and climate change mitigation.

DEVELOPING A CARBON CARRIER FOR PTX

As is clear, Namibia has an abundant sustainable resource in the form of encroaching bush-biomass. As was highlighted in the previous chapter, the focus of this project is to develop a new process that aims to maximize the carbon carrier aspect of biomass. It has to be highlighted though that biomass is always an energy carrier in all its forms and this energy content, being inherently renewable, needs to be utilized.

Design goals for the Carbon Carrier

The following design goals/ objectives were set:

- **Ability to Develop a Global Market:** The proposed process should not only cater to local or regional demands but also be scalable and flexible enough to penetrate and develop a global market. This encompasses considering factors such as cost-effectiveness, scalability, compatibility with different types of biomass, and adaptability to various geographical, climatic, and logistical conditions. Furthermore, the process must be efficient and sustainable to gain acceptance in a market increasingly sensitive to environmental and sustainability concerns.
- **Standardization to be Possible:** Standardization plays a crucial role in ensuring the quality and compatibility of the carbon carrier and also for developing a global market. A standardized process ensures uniformity in the output irrespective of where the process is carried out. It also allows for streamlined operations, easy comparison of performance metrics, and aids in setting regulatory guidelines. Therefore, it is a primary objective that the developed process should be adaptable to a standardized protocol, which will guide its execution and output evaluation.
- **Different Countries from Different Regions to be Able to Produce the Standardized Carbon Carrier:** The process should be designed in such a way that it allows different countries across the globe to produce the standardized carbon carrier using their local biomass, provided it meets the sustainability criteria defined under the Renewable Energy Directive (RED) II, and eventually under the stricter regulations of the forthcoming RED III. This promotes the inclusivity and adaptability of the process, opening it up to a global supply chain and allowing for regional self-sufficiency.
- **Efficient Transportation Utilizing Maritime Shipping and Existing Logistics Infrastructure:** Given the global nature of the biomass market, the process should yield a carbon carrier that is easy to transport over long distances. This implies that the carbon carrier's physical and chemical properties should be such that it can be conveniently transported using maritime shipping or other existing logistics infrastructure, without necessitating significant infrastructural modifications.
- **Preference for CO over CO_2 for improved energy efficiency:** The process should aim to yield carbon monoxide (CO) rather than carbon dioxide (CO_2). This is because the conversion of CO_2 to CO requires additional energy inputs. By targeting CO production, the process would conserve energy, thereby improving its overall efficiency.
- **Try to Keep Technology Requirements to a Minimum for the upstream Processing typically Taking Place in Remote Areas:** The process should be designed such that the technology requirements are minimized, especially for processes carried out in remote areas. This will ensure that the process is accessible and can be carried out even in regions with limited access to advanced technology or technical expertise. Simplicity and robustness should be core principles guiding the design of the process.
- **No Initial Focus on End Fuel, Since Fischer-Tropsch and Methanation Require the Same Inputs - COx and Hydrogen:** At the initial stages, the focus should not be on the end fuel but on the efficient and sustainable production of the carbon carrier. Both Fischer-Tropsch synthesis and methanation processes require the same inputs, COx, and hydrogen. Therefore, the produced carbon carrier should be able to cater to both these processes. The choice of end fuel can be made at a later stage based on market demand, logistical considerations, and environmental impact.
- **Commercial availability of all technologies involved.** Since the solution needs to be deployable in the short term, only commercial technologies are considered.

Proposed Carbon Carrier

Initially an investigation took place concerning possibilities to use elemental forms of carbon often referred as allotropes as carbon carriers. All of these had a number of characteristics that made their use as carbon carriers for PtX use impractical:

1. **Synthetic (lab) Diamonds:** The extreme hardness of diamond makes it impractical for use as a carbon carrier, particularly when factoring in the complexities and costs of synthesizing diamond from biomass.
2. **Graphite:** Although it has various industrial applications, graphite is not ideal for transportation because of its soft and slippery nature. The potential for contamination during long, overland, and sea transportation routes could be a concern.

3. **Carbon Black:** The fine, powdered form of carbon black would make it problematic to transport, particularly when considering the possibility of airborne contamination and loss of material during transit.
4. **Carbon Nanotubes:** The specialized production methods and high costs associated with carbon nanotubes make them an impractical choice for a carbon carrier in remote, less developed regions.
5. **Graphene:** The delicate nature of graphene sheets, combined with the complexity of producing them, render this form of carbon impractical for bulk transport and use in less developed areas.
6. **Fullerenes:** The highly specialized synthesis process and unclear bulk properties make fullerenes a less ideal option for use as a carbon carrier produced in remote areas.
7. **Carbon Fibers:** Although strong, the cost of producing carbon fibers and their specific application in high-performance materials limit their utility as general-purpose carbon carriers.
8. **Carbon Nanofibers:** Similar to carbon fibers, the specialized production and high costs make this form impractical for use as a general-purpose carbon carrier.
9. **Amorphous Carbon:** Its lack of crystalline structure could lead to material inconsistencies, making it a less reliable form of carbon for transportation and application purposes.
10. **Glassy Carbon:** The production of glassy carbon usually requires specialized equipment and high temperatures, making it challenging to produce in remote areas.
11. **Pyrolytic Carbon:** Generally used in highly specialized applications like biomedical implants, the complex production and specific uses make it a poor choice for a carbon carrier.

Then more traditional biomass forms were considered including wood chips, wood pellets, torrefied wood and charcoal, it was determined that a torrefied biomass was a compromise between carbon content and carbon efficiency, as well as having other downstream processing advantages.

Wood chips are relatively low in carbon content (45-50%), but more importantly, they are low in bulk density, ensuring that if they are subjected to any meaningful transport distances, the transport costs and related carbon emissions would erode their carbon efficiency. Secondly, raw wood chips are difficult to standardize and their qualities are impacted by many factors, including season, species, harvesting and chipping methodologies, storage duration and conditions, relative humidity, etc.

In order to improve some of the characteristics of wood chips, **wood pellets** were also considered. Wood pellets are widely traded as an energy feedstock and can be more easily standardized. They have greatly improved transport and handling characteristics over wood chips, and as such, their carbon efficiency is higher considering transport. However, wood pellets still retain some undesirable qualities, such as their carbon content still being the same as wood chips, their sensitivity to moisture during transport and storage, and their high volatile matter content, which causes downstream processing challenges during gasification and fuel synthesis.

Charcoal was also considered as a possible carbon carrier. Namibia is one of the largest exporters of charcoal globally, and so leveraging an existing industry would come with notable advantages. Locally produced charcoal is high in carbon content (70-80%). However, it is produced in a carbon inefficient pyrolysis process, whereby over half of the carbon in the wood used to produce charcoal is lost in emissions. Additionally, charcoal's bulk density is still relatively low, adding cost and emissions against transport. Charcoal is still susceptible to moisture during transport and storage, but it does not risk biological degradation like wood chips/pellets. However, it also has an inherent risk of self-ignition, especially when handled in bulk and raw forms. This self-ignition risk has increased safety measures and associated costs when exporting charcoal, and all but prevents it from being shipped in bulk or breakbulk formats.

Higher purity forms of charcoal were also considered, such as activated carbon, due to its even higher carbon content (85-95%), but in order to activate charcoal, it requires energy intensive processes involving additional thermal and/or chemical treatments, which further decreases the carbon efficiency of the product, as well as having a significant impact on the cost of the finished product .Furthermore, its porous nature makes it highly absorbent, which could pose a problem if it were to absorb other materials during transportation, particularly by sea.

Charcoal can also be briquetted, which helps to increase bulk density and reduce the self-ignition risk, however, it does not bind together without a binding agent. Typically, the binding agent used in Namibia is a gelatinized plant-based starch produced from maize, which needs to be imported from South Africa. The binding agent is both costly and directly competes with food crops. It also further worsens the carbon efficiency as a carbon carrier, as up to 10% of its mass is attributed to imported agricultural produce.

A compromise between wood chips and charcoal is torrefied or "toasted" wood. The torrefaction process is a light pyrolysis treatment which not only strips the biomass of its moisture, but also of some of its volatile matter. This results in an increased carbon content (55-60%), and also gives it some desirable processing characteristics. Furthermore, the torrefaction process retains most of the carbon content from the original feedstock, with minimal emissions, of which, can also be largely captured as by-products. However, torrefied wood in chip form is very low in density, and as such, suffers from longer transport distances.

Pelleting torrefied biomass is similar to pelleting raw wood chips, in that it does not require a binding agent and it significantly increases bulk density. However, torrefied biomass is more friable or "brittle", making them easier to grind down for pelleting. Torrefied pellets are also inherently more stable during transport than both raw biomass and charcoal. In combination with also having a relatively high carbon content, the proposed carbon carrier is **torrefied biomass pellets**. These are presented in the following photographs.

The proposed carbon carrier is **torrefied biomass pellets**. These are presented in Figure 12 and Figure 13.

Advantages of the proposed carbon carrier are presented below:

- **Increased Energy Density:** Torrefied pellets exhibit a high energy density due to the partial removal of moisture and volatile components during the torrefaction process. This increased energy density improves the fuel efficiency of the pellets, which could lead to significant cost and energy savings in transport, handling, and storage (Niu et al, 2019).
- **Enhanced Grindability of Torrefied Biomass Facilitating Pelletization:** The torrefaction process changes the physical properties of biomass, enhancing its grindability. This enhanced grindability facilitates the pelletization process, resulting in higher quality and more consistent pellets (Niu et al, 2019).
- **Direct pelletization is possible after grinding:** Recent research has shown that there is no need to add a binder and that pellets can be prepared using standard white pellet equipment (Svanberg et al, 2013),(Rudolfsson et al, 2017).
- **Reduced Moisture Content:** The torrefaction process significantly reduces the moisture content of the biomass, improving the energy value of the pellets and reducing susceptibility to biological degradation (Niu et al, 2019).
- **Enhanced Stability (Hydrophobic, Safety Considerations, etc.):** Torrefied pellets are hydrophobic, meaning they resist water absorption. This property, coupled with their increased stability, reduces the risk of degradation during storage and transport, and improves the safety profile by reducing the likelihood of spontaneous combustion (Niu et al, 2019).

Torrefied bush biomass from Namibia produced by the Horizon 2020 EU funded SteamBioAfrica project (Grant Agreement No. 101036401)

Figure 12: Own photo

Example of torrefied biomass pellets

Figure 13: Figure 2: Shutterstock/Supachita Krerkkaiwan

- **Improved Handling (Seed Handling Equipment Can Be Used in the Logistics Chain):** The similar physical properties of seeds and torrefied pellets allow for the use of existing seed handling equipment in the logistics chain, thereby reducing the capital expenditure required for new infrastructure (García et al,2019).
- **Optimal Fuel for Gasification:** Given their higher carbon content and reduced moisture, torrefied pellets can be more readily gasified than other forms of biomass, making them an optimal fuel for gasification processes (Prins et al, 2006).
- **Ability to Handle Residuals and Ash Management:** The use of torrefied pellets can also simplify ash management, as the ash produced during combustion or gasification can be more readily collected and utilized compared to other biomass fuels (Tripathi et al, 2019).
- **No High Water Needs:** Unlike some biofuel production processes, the torrefaction and pelletization processes do not require significant quantities of water, making these pellets more environmentally friendly and suitable for areas with water scarcity.
- **Inherently a De-risked Investment:** Torrefied pellets are a versatile fuel source that can replace many existing solid biomass fuels. This versatility de-risks the investment as the market for these pellets can be more stable and less susceptible to fluctuations in demand for a specific fuel.
- **High potential for unskilled and semi-skilled job creation:** The harvesting of the biomass can be accomplished manually, semi-mechanized, or fully mechanized. For developing economies, harvesting approaches chosen tend to be less mechanized, which reduces the barriers of entry for the workforce. This is a great advantage that many governments would potentially be interested in realizing.

It has to be acknowledged that there are also some challenges regarding torrefied biomass pellets:

- **Challenging resource:** Namibian encroacher bush has inherent challenges in its control and utilization. From a control perspective, it is imperative to ensure that the industry best practices are followed relating to the management, quantification, harvesting methodology, and aftercare.

Additionally, legal framework still needs improvement to allow equitable industry participation from non-free hold land tenure systems. From a utilization perspective, technical challenges regarding the terrain, selectivity, relatively low yields, and the physical characteristics of the encroacher bush also need to be addressed.

- **Multistage Process:** The process of producing torrefied pellets involves multiple stages, including harvesting, collection in a hub, chipping, torrefaction, and pelletization. Each of these stages adds complexity and cost to the process and requires specific expertise and equipment.
- **Dual Nature as Carbon Carrier and Energy Carrier:** While being a carbon carrier and an energy carrier enhances the versatility of torrefied pellets, it can also increase their price, especially if demand increases from other industries looking to replace.

The overall outlook looks very promising, and the challenges can essentially be mitigated. The most significant challenge of the multistage process is mitigated by the fact that the processes to be deployed in rural and probably remote areas do not require high technology or complex engineering solutions for each of the stages.

Torrefaction

Torrefaction is a thermochemical process that transforms biomass into a high-energy-density product, often compared to coal, suitable for utilization in various energy conversion systems. The process typically occurs at temperatures between 200 and 300 degrees Celsius in an oxygen-deprived environment. The choice of temperature and duration can significantly influence the resulting product's properties.

The process begins with the removal of moisture, followed by the partial decomposition of the biomass' hemicellulosic fraction, leaving a product rich in cellulose and lignin. This leads to an increase in the material's carbon content and calorific value. The process also volatilizes some of the biomass's oxygenated compounds, reducing the oxygen content of the material, which further increases the energy density.

The torrefaction process makes the biomass hydrophobic, significantly reducing the risk of moisture uptake during storage and transport, enhancing the transport efficiency. The torrefied biomass also becomes more friable or brittle, which improves its grindability, an essential process prior to pelletization and specific applications such as co-firing in coal power plants. Torrefaction can be performed using different types of reactors, including rotary kilns, moving beds, and fluidized beds. The choice of reactor can influence the uniformity of the torrefaction process and the quality of the end product. Control over parameters such as residence time, temperature, and the heating rate is critical in achieving a product with desirable characteristics.

Torrefaction approached can be broadly categorized in 3 categories; dry torrefaction, wet torrefaction and steam torrefaction. Dry torrefaction is the most common method and involves heating biomass in an oxygen-depleted environment at temperatures typically ranging from 200 to 300 degrees Celsius. The process starts by driving off the moisture, followed by thermal decomposition of the hemicellulosic fraction. This method results in a product with increased energy density, improved grindability, and hydrophobic characteristics. In contrast, wet torrefaction, also known as hydrothermal carbonization, is conducted in the presence of water at relatively lower temperatures, typically between 180 to 260 degrees Celsius, and higher pressure to maintain the water in a liquid state. This method can handle wet biomass, reducing the need for initial drying. Wet torrefaction leads to a higher yield of solid product than dry torrefaction, but the resulting product has lower energy density and higher oxygen content. It also generates a liquid by-product, referred to as "process water," which contains a significant fraction of the biomass carbon and requires further treatment or utilization. Steam torrefaction is another variant where superheated steam is used as the heating medium instead of inert gases, commonly applied in dry torrefaction. The steam environment can offer better heat transfer, more uniform heating, and a higher heating rate. This method has the potential to lower the torrefaction process's energy consumption and increase the overall energy efficiency. Furthermore, steam torrefaction can achieve a higher torrefaction degree at a lower temperature compared to dry torrefaction due to steam's reactive nature. However, the application of steam torrefaction is less common since it is a newer technology. Dry torrefaction and steam torrefaction are best suited to the proposed application.

The energy required for torrefaction can be supplied by the combustion of the volatile gases released during the process, improving the overall energy efficiency. Torrefaction's net energy yield is dependent on various factors, including the type and initial moisture content of the biomass, the torrefaction conditions, and the efficiency of the energy recovery systems.

The EU-funded SteamBio Africa project in Namibia is demonstrating a novel super-heated steam torrefaction process. The novelty is that the process conditions can be operated at atmospheric pressures, negating the need for high pressures, which do not allow for continuous processing and serve to increase capital and energy costs. SteamBio Africa’s demonstration plant is the final pre-commercialization step towards rolling out the technology more widely.

The process of pelletizing the torrefied biomass is generally more straightforward than pelletizing untreated biomass. The torrefaction process changes the biomass's physical and chemical properties, allowing the pellets to be denser and more durable, with higher energy content per unit of volume. In conclusion, biomass torrefaction is a promising pretreatment technology that can enhance biomass's fuel properties and facilitate its use in various energy applications.

4

FROM THE CARBON CARRIER TO A GLOBAL MARKET

This chapter provides an encompassing exploration of the journey from the carbon carrier to renewable synthetic drop-in fuels. It scrutinizes the entire value chain, beginning with the harvesting and preparation of biomass, the critical first steps in biomass conversion. Following this, it delves into the transportation aspect, detailing how torrefied pellets are moved from rural locations to processing facilities using existing infrastructures. The centerpiece of the chapter is a detailed exposition of the proposed hybrid Biomass Power-to-X process. The chapter emphasizes the necessity of each phase in the value chain and underlines the potential of this approach for sustainable and renewable fuel production globally powering the Energy Transition.

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FROM THE CARBON CARRIER TO RENEWABLE SYNTHETIC DROP-IN FUELS

Value Chain for utilizing sustainable carbon in PtX processes

Figure 14: Own illustration

Overview of the Value Chain

The value chain consists of 5 batches of activities:

1. **Harvesting and Preparation:** This is the first step in the value chain, where sustainable biomass is harvested. Following harvest, the biomass can either be chipped into smaller pieces to facilitate handling and transport or transported in larger pieces. The harvested biomass must adhere to the local harvesting framework, industry best practices and sustainability criteria comparable to the ones set by the Renewable Energy Directive II (RED II) and Land-Use Change and Forestry (LULUCF) Directive, ensuring that the biomass has been sourced responsibly and without causing significant harm to the environment. The biomass is then collected to a facility serving a specified area. Previous experience suggests a maximum harvesting radius of 100 km (Lindeque, 2020), (Petrick, 2020).
2. **Torrefaction and Pelletization:** Once the biomass is collected, it undergoes torrefaction, a thermochemical treatment at temperatures typically ranging between 200 and 300°C in a low-oxygen environment. Torrefaction removes moisture and volatile components, enriching the carbon content and increasing the carbon and energy density of the biomass. Following torrefaction, the biomass is densified into pellets. Pelletization provides the biomass with uniform shape and size, improving handling, reducing transport costs, and enhancing combustion or gasification characteristics.
3. **Transportation:** With increased carbon and energy density and enhanced physical properties, torrefied pellets can be transported more efficiently compared to raw biomass. Due to their physical resilience, they can be transported using existing logistics infrastructure, significantly reducing the need for specialized equipment. They can be shipped globally using any combination or road, railway and maritime freight, allowing production and consumption locations to be geographically disconnected. Traditional grain handling equipment can be utilized in the logistics chain.
4. **Gasification:** Upon reaching their destination, the torrefied pellets undergo gasification, a process that converts the carbon-rich biomass into a mixture of carbon monoxide and hydrogen, known as syngas. The gasification process is performed at high temperatures and pressures, often in the presence of steam or oxygen. Following gasification, the syngas is cleaned to remove any impurities. It can be used as is, separated into its constituent gases or complemented by green hydrogen.
5. **Synthesis of Renewable Fuels:** The final step in the value chain is the synthesis of renewable fuels from the syngas. This can be accomplished with mainly two methods, the Fischer-Tropsch process for any hydrocarbon or methanation for methane production, depending on the desired end fuel. In both processes, the syngas reacts with a catalyst to produce a hydrocarbon fuel. The resulting fuel is a drop-in ready, renewable substitute for conventional fossil-based fuels, closing the loop of the carbon cycle and contributing to the reduction of greenhouse gas emissions.

Essentially the value chain can be divided in activities taking place where the biomass is sourced and activities taking place where the production of renewable synthetic drop-in fuels are manufactured. Box 3 presents more information concerning torrefaction. The following section will focus on gasification and synthesis, since the actual processes chosen have also to do with legislation apart from technical/ technological considerations.

The previous chapter focused on the second step; the following sections provide more details for the rest of the steps.

Harvesting and preparation

The harvesting and preparation step has been investigated extensively in the past and there are existing examples in Namibia as Ohorongo Cement use of chipped biomass. The topic has been extensively investigated in a study published under the "Support to De-bushing project"(de Wet, 2015). The harvesting of bush-biomass process can be broken down in the following steps:

Bush and Tree Felling Tools and Equipment

Bush and tree felling is accomplished using different types of equipment based on the scale and requirements of the operation. For manual labor-based operations, the widely-used bush-pick, an axe-pick combination, is usually employed. This tool is efficient in felling trees and bushes with minimal investment. In contrast, mechanized tree felling utilizes a range of equipment, starting from a push trolley equipped with a belt-driven circular saw, up to large excavators equipped with a hydraulic cutter/shear and grab or buncher. These robust machines can fell bush at a high rate, covering up to four hectares of medium-density (± 15 t/ha wet) encroached area in an eight-hour shift.

Infield Drying

Following the felling process, the cut bush is typically left infield for drying for a number of weeks. This process is crucial to reducing the moisture content of the biomass, which is facilitated by the dry climate of Namibia. Encroacher bush are easier to chip when dry, using less energy and causing fewer blockages through a horizontal infeed grinders and chippers. The aim is to achieve moisture contents as low as 10-14 % before further processing.

Feeding the Chipping/Grinding Operation

After drying, the whole bush are fed into the chipper or grinder. The feeding is performed either manually or mechanically, depending on the size of the chipper or grinder. For smaller operations, manual feeding is usually sufficient. A mechanical feeder, such as an excavator with grapple or three-wheel logger, grabs the dry bush from the field and feeds the bush onto the infeed tables of the chipper or grinder.

The Chipping/Grinding Operation

Chipping or grinding is a critical and often challenging stage of the processing, often where the majority of downtime occurs. The selection of the chipper or grinder is crucial and must align with the throughput requirements and the type of tree/bush to be harvested. Small gravity-feed wet wood chippers are generally fed by hand, and the wood is cut with blades bolted to a high inertia drum, which also acts as a flywheel and pneumatic blower to blow the chips out and into a correctly positioned container. Larger operations require machines with a horizontal infeed system equipped with hydraulically operated reversible rollers to control the infeed tempo to the chipper or grinder. These machines can blow out the final product or use an out-loading conveyor for larger operations.

Shuttling

Once chipped, the biomass needs to be moved from the field to a staging area. Due to the low bulk density of wood chips (between 240 to 300 kg/m3), high volume trailer-type containers are required. It is generally more advantageous to perform infield chipping and shuttle the chips out of field, rather than carting whole bush or logs out to a central chipping station.

Transferring Chips onto On-road Trailers

From the staging area, the chips are transferred onto 100 to 110 m3 on-road trailers. Harvesting operations located close to the point of use (<25 km) can be loaded into off/on-road shuttle cars to eliminate double handling. Only a change of tractor type, from off-road to on-road, is required at the transfer station.

Transporting

The final product is transported on public roads to the point of use. This stage typically involves high volume (up to 110 m3) three-axle walking floor or tipper trailers due to the low bulk density (240 – 300 kg/m3) of the dry wood chips.

Transportation

Namibia, with its abundance of bush biomass, is uniquely poised to benefit from the production and export of torrefied pellets. However, the success of this initiative is closely tied to the efficiency and reliability of the transportation system that conveys this carbon carrier from their production sites to various end-use locations. The broad spectrum of transportation means available today – road, rail, and maritime – each with their unique benefits, have the potential to be utilized for this purpose.

In the realm of road transportation, torrefied pellets have a distinct advantage. Given their standardized size and shape, they can be transported in bulk using existing road transport vehicles, such as trucks and trailers. This is a substantial advantage, particularly in rural Namibia, where road transport infrastructure is well-developed and trucks remain the primary mode of freight transport. Utilizing existing equipment minimizes capital investment and enables a quick and efficient start to pellet distribution.

The ease of handling and storing torrefied pellets, compared to raw biomass, further enhances their suitability for road transport. Given their hydrophobic nature, these pellets can withstand outdoor storage conditions, reducing the need for expensive indoor storage facilities. This property allows for flexibility in transportation schedules, contributing to overall logistical efficiency.

The significance of rail transport in the logistics chain cannot be underestimated, especially for long-haul bulk shipments or from locations in rural Namibia served by rail. Torrefied pellets can be transported using standard rail cars, thereby benefiting from the high loading capacities of rail freight. This mode of transportation can be particularly relevant when the pellets need to be transported from central production sites to coastal ports for international export or to neighboring countries connected via rail.

Maritime transport, given its unparalleled capacity for transporting large volumes over long distances, will undoubtedly play a pivotal role in the global distribution of Namibian torrefied pellets. Shipping can accommodate vast quantities of torrefied pellets in either bulk carriers or shipping containers, the latter offering benefits in terms of flexibility and compatibility with intermodal transport systems.

Specifically, containerized shipping of pellets can offer several advantages. Standardized shipping containers are designed for easy transfer between different modes of transport – trucks, trains, and ships – making them a linchpin of modern logistics. Torrefied pellets can be readily loaded into these containers at the production site, then seamlessly transferred onto trucks, trains, or ships, thereby simplifying the transportation process and reducing handling requirements.

The relative density and stability of torrefied pellets make them well-suited for long sea voyages, reducing the risk of degradation and subsequent loss of product during transit. Additionally, the global ubiquity of containerized shipping means these pellets can potentially reach any corner of the globe from Namibian shores, underscoring the international reach of this carbon carrier.

Overall, the use of existing transportation methods and equipment offers a pragmatic and efficient solution for conveying torrefied pellets from rural Namibia to global markets. By aligning the production and export torrefied biomass pellets with the established logistics chain, the process can achieve both economic viability and logistical efficiency. However, it is essential to recognize that successful implementation will require careful planning, strategic infrastructure development, and broad stakeholder engagement to overcome logistical hurdles and ensure a smooth and efficient flow of these pellets from production to end-use sites.

Gasification and Synthesis: A Hybrid Biomass Power-to-X process

Gasification and synthesis processes need to take place in the same location to minimize the distance the gases need to be transported. Moreover, these two processes can and need to be cross-optimized since at the end of the day the maximum amount of synthetic fuel with minimum cost needs to be obtained, while the maximum carbon use is achieved.

The most traditional approach utilized today is presented in Figure 15 below and is a BtX process. Essentially biomass is first gasified and then the syngas is utilized for the synthesis of drop-in fuels utilizing the Fischer – Tropsch process. As is depicted, most of the carbon is vented in the atmosphere. This happens because biomass gasification usually produces a syngas with a ratio of $CO:H_2$ roughly 1:1, while Fischer – Tropsch requires a ratio of $CO:H_2$ roughly 1:2. Since this process is optimized in minimizing the cost of the final drop-in fuel, carbon efficiency is not prioritized.

Due to the financial incentives put in place by many governments to collect and store CO_2 the above process has been evolved as depicted in Figure 16. Here as much as possible of the CO_2 is captured and then moved to storage. Given that this BtX process is carbon neutral, the capturing and storage of CO_2 essentially makes this process carbon negative. One of the key highlights of this approach is the fact that vented carbon is minimized.

A new and innovative technological approach has been conceived having the ability to maximize carbon use is presented in Figure 17.

The proposed hybrid Biomass Power-to-X (B-PtX) process introduces an innovative pathway to significantly increase the carbon utilization efficiency in renewable synthetic drop-in fuel production. At the core of this system, we find gasification and a supplementary green hydrogen feed that drastically alters the traditional BtX approach.

Entrained flow gasification is particularly suited for the supplied fuel in this case - the torrefied biomass pellets. These pellets, having been subjected to torrefaction, exhibit enhanced properties such as increased energy density and improved grindability, making them ideal candidates for this high-temperature, oxygen-starved gasification process. The entrained flow gasification technology, renowned for its high carbon conversion rates and its ability to process fuels with low ash fusion temperatures, is hence an excellent fit.

In the conventional gasification process, the stoichiometric ratio between hydrogen (H_2) and carbon monoxide (CO) is roughly 1:1. This ratio, however, is not ideal for processes such as the Fischer-Tropsch synthesis, which requires a $H_2:CO$ ratio closer to 2:1 for optimal operation.

This ratio requirement in Fischer-Tropsch synthesis is influenced by various factors including the catalyst choice, the conversion rate, and product selectivity. For instance, cobalt-based catalysts, known for their high activity and selectivity towards long-chain hydrocarbons, prefer a H_2-rich environment, thus necessitating a higher H_2:CO ratio.

To rectify this mismatch and improve overall carbon efficiency, the hybrid Biomass PtX process incorporates the use of green hydrogen. Recent research has underlined that the traditional BtX process's carbon efficiency of approximately 30% can be augmented to over 90% by supplementing the process with green hydrogen (Ostadi et al, 2019). This additional hydrogen serves two crucial functions - it adjusts the H_2:CO ratio to meet the Fischer-Tropsch synthesis requirements and participates in the conversion of captured CO_2 to CO through the inverse water-gas shift reaction, maximizing carbon usage.

Cost considerations

Given the complexities involved in performing even a high-level cost estimation on the proposed value chain, it was decided to focus on the carbon carrier, where enough data was available allowing the cost estimation with a degree of confidence.

A previous study developed in 2020 by Carbon Capital for the benefit of the Namibia Biomass Industry Group Calculated a FOB price at Walvis Bay, Namibia of 118.10 EUR/t.

Based on current figures and analysis performed by the consultants' team, it is estimated that the local value chain costs would have increased by 26.5% compared to the figures used in the 2020 study. As such, the FOB cost of a white pellet at FOB Walvis Bay incoterms would be around EUR 142/tonne at today's rates, as opposed to EUR 117/tonne.

Based on current information from SteamBioAfrica Horizon2020 project (Grant Agreement No. 101036401) it is estimated that **the cost for torrefied biomass pellets would increase to EUR 198/tonne, FOB Walvis Bay.**

The cost calculation for the final drop-in fuel involves a large number of uncertainties for the gasification and Fischer-Tropsch synthesis steps and as such it was impossible to calculate given the constraints of this study.

A 2020 IEA Bioenergy report stated that the overall conversion efficiency from biomass to FT products ranges between 40-55%, depending on multiple factors, while the final fuel cost is estimated at 75-144 EUR/MWh of synthetic fuel. This applies for a traditional BtX process. Taking into account the Lower Heating Value of Diesel the cost of synthetic diesel is calculated to be between 0.75 – 1.44 EUR/l.

The proposed hybrid Biomass-PtX process would certainly lead to a cost decrease when cheap green hydrogen is introduced to the process. There are forecasts that due to the EU Hydrogen Bank we could see in the short-term market prices of green hydrogen at 1 EUR/kg. As a reference the current pump price of fossil diesel is 0.93 EUR/l in Namibia and 1.77 EUR/l in Germany. These figures provide the justification for a follow-up feasibility study for a plant in Namibia that could provide more in depth analysis for the projected cost decrease and shed more light in the actual commercial feasibility and possible profits projections.

BtX process to produce synthetic fuels

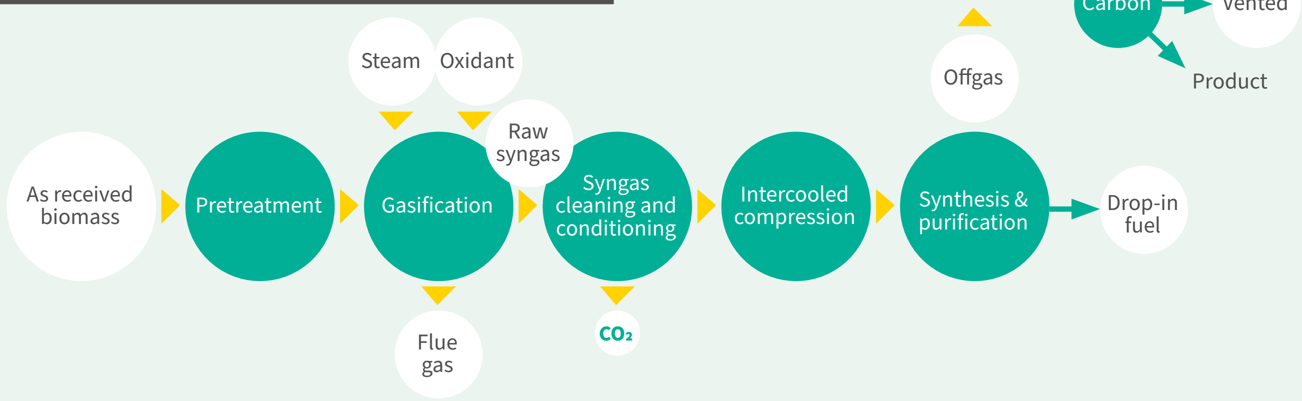

Figure 15: Based on Poluzzi, Guandalini, d'Amore & Romano (2021)

BtX process to produce synthetic fuels coupled with carbon capture and storage

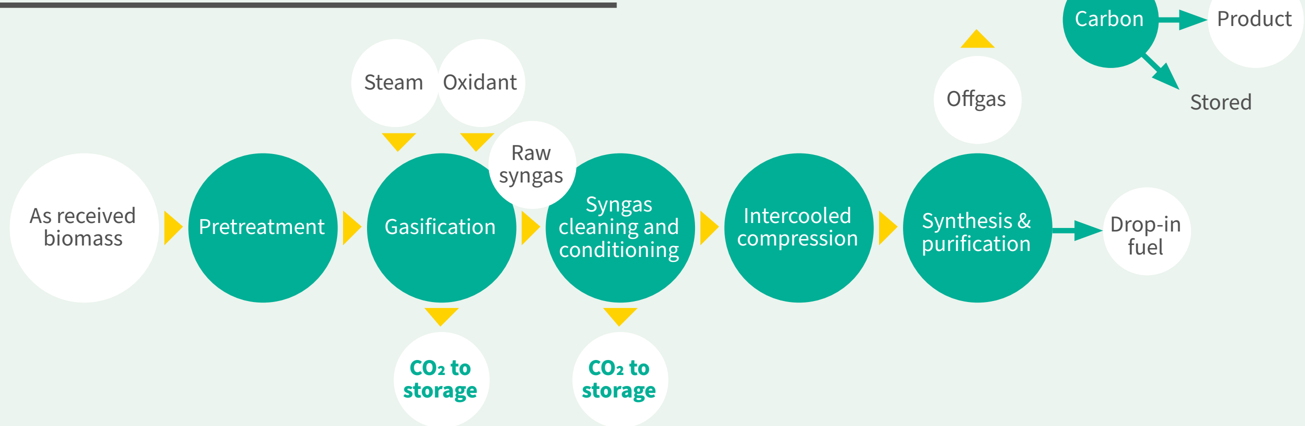

Figure 16: Based on Poluzzi, Guandalini, d'Amore & Romano (2021)

Maximization of carbon use process

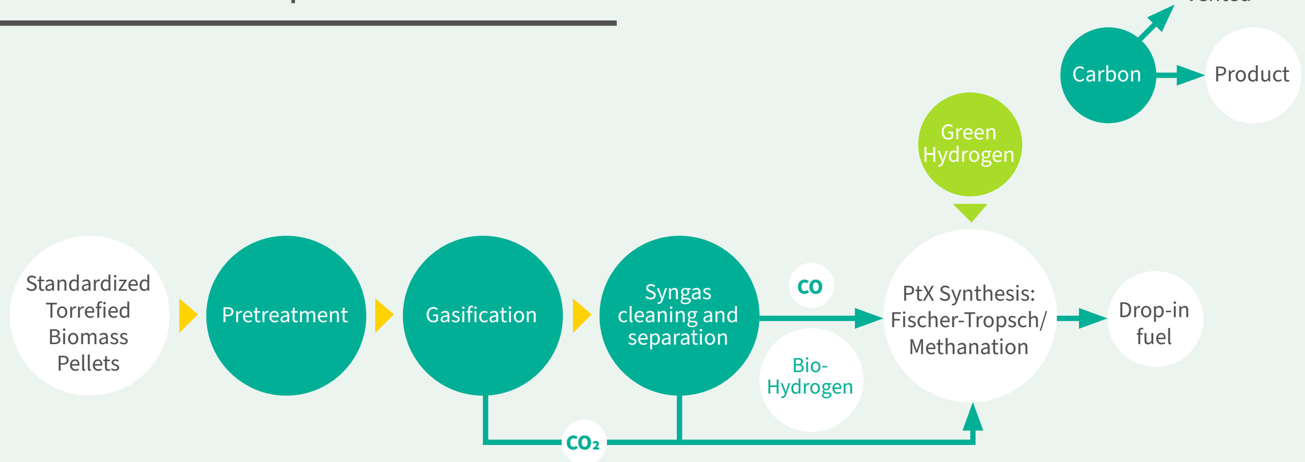

Figure 17: Own illustration

5 RECOMMENDATIONS

The recommendations emphasize the need for a comprehensive, multi-faceted approach to integrate torrefied biomass and Power-to-X technologies into Namibia's energy strategy. Key guidelines include the adoption of a phased roadmap for infrastructure development, focusing initially on the biomass sector and its potential for job creation in rural areas. Concurrent efforts to enhance research, education, and training will support the transition to more technically demanding endeavors linked to synthetic fuels production. Policy and regulatory reforms will facilitate investment in the sector, and the establishment of quality control, certification, and standardization systems will ensure the global competitiveness of Namibia's biomass products. Additionally, the government is advised to commission a comprehensive tax-benefit study to inform decisions on fuel taxation and develop mechanisms for risk mitigation.

RECOMMENDATIONS

An in-depth analysis of Namibia was performed in line with the findings presented in the previous chapter. This analysis was performed utilizing three main tools:

- PESTEL Analysis
- SWOT analysis
- Consultations with Namibian stakeholders

The results of the analysis are presented in Annex 2.

Based on this analysis the following recommendations are formulated. Each recommendation emphasizes a critical aspect of the energy transition aspects relevant to renewable synthetic hydrocarbons production. While each has its own merits, their true potential lies in their synergistic implementation, creating a comprehensive and effective approach to advancing Namibia's energy transition.

1. **Integrate Advanced Biofuels Strategy with the Green Hydrogen Strategy:** To fully leverage the potential of the hybrid Biomass PtX pathway, an integrated strategy for advanced biofuels and green hydrogen should be developed. This strategy should articulate how the two pathways can complement each other, detailing the technological, logistical, and policy synergies. This approach aligns with the broader vision of developing a diverse and resilient renewable energy sector, providing multiple pathways to energy security and sustainability.
2. **Adopt Comprehensive Energy Policies:** Currently there is no liquid renewable fuels framework in Namibia. The liquid renewable fuels framework needs to be inclusive of synthetic fuel and biofuels, as well as being aligned to the existing petroleum and renewable energy frameworks. The government ought to develop and implement a comprehensive energy policy that recognizes the potential of biomass and Power-to-X technologies. This policy ought to articulate a clear vision for the integration of these technologies into the country's energy mix and outline strategies for harnessing their synergies. To ensure the longevity of these initiatives, consistency and transparency in energy and environmental policies are key, serving to build private sector confidence and encourage long-term investment.
3. **Engage in Regulatory Reforms:** Effective regulation is crucial for the development and growth of the power-to-X sector. This entails the update of existing energy regulations regarding bush biomass use and renewable fuels. This process can start with a gap analysis of the national energy and fuels framework. Gaps include liquid renewable fuels and green hydrogen frameworks. The following step is to ensure that any missing framework is developed, aligned, made coherent to the existing frameworks. Further, regulatory sandboxes could be created to allow for the testing of new technologies and business models under a temporary relaxation of regulations. This creates a safe space for innovation, reducing risks and providing valuable insights for the refinement of regulatory frameworks.
4. **Support Business Development in the Biomass and PtX Sectors:** In addition to fostering a conducive business environment through policy and regulatory measures, the government ought to actively support the development of start-ups and small enterprises in the biomass and PtX sectors. This could take the form of business incubation and acceleration programs that provide mentorship, funding, and networking opportunities. Simultaneously, a package of incentives, such as tax breaks, low-interest loans, or guaranteed purchase agreements, should be developed to attract private sector investment in PtX projects.
5. **Conduct a Tax-Benefit Study on Renewable Fuels:** When considering the domestic use of the renewable drop-in fuels, the transition will have significant implications for government revenues, particularly those derived from fuel taxes. As such, a comprehensive tax-benefit study should be conducted to assess these fiscal impacts. The study has to evaluate the potential environmental benefits, impacts on foreign currency reserves, viability of the domestic renewable fuels industry, and potential socio-economic benefits such as job creation. The findings will provide an evidence base for policy decisions on the taxation of renewable fuels.
6. **Promote Research and Innovation:** Namibia should prioritize the fostering of research and innovation as crucial drivers of the transition towards a sustainable energy future. The focus should be on overcoming technological challenges and optimizing the hybrid Biomass PtX pathway. This will involve establishing an inclusive innovation ecosystem where academic institutions, research centers, industry, and government collaboratively push the boundaries of knowledge and technology. The establishment of research grants and the development of collaborative research programs with international institutions could be instrumental in this endeavor. A culture of continuous improvement should be inculcated, keeping abreast with global advancements in renewable energy technologies and ensuring their timely assimilation into local practices.
7. **Develop Workforce Expertise:** A comprehensive approach to workforce development is pivotal for the successful deployment of biomass and power-to-X technologies. This includes skills development within the upstream biomass value chain and engineering capacity including energy and mechanical specializations. This is realized curating targeted education and training programs, facilitating knowledge transfer from international experts, and promoting advanced education and research in this field. Such initiatives will equip the Namibian workforce with the

necessary skills and expertise to competently manage and innovate within the biomass power-to-X sectors. Attracting and retaining top talent should be a key part of this strategy, underpinned by a strong emphasis on career development and lifelong learning.

8. **Enhance Infrastructure:** The large-scale harvesting and processing of biomass necessitates significant improvements in the transport and processing infrastructure. From the construction of new roads and railway lines to the upgrading of existing ones and enhancing the ports which can serve as export hubs, these measures will provide a crucial foundation for operational efficiency and commercial success. Equally important is the development of systems for quality control and certification, ensuring that the torrefied biomass pellets meet international standards and are thus competitive on the global market.
9. **Encourage Stakeholder Engagement:** For the successful transition to a sustainable energy future, the active participation and support of all stakeholders are essential. Namibia ought to, therefore, engage with local communities, biomass producers, potential investors, and other stakeholders, providing them with opportunities to contribute to decision-making processes. Public-private partnerships can serve as a powerful tool in this regard, sharing risks and benefits and fostering collaborative problem-solving.
10. **Establish a Phased Roadmap for Carbon Carrier and Synthetic Fuels Infrastructure:** The development of a phased roadmap is essential to balance the immediate socio-economic needs with the long-term energy objectives of Namibia. In the first phase, the focus should be on harnessing the country's abundant biomass resources, which presents an immediate opportunity for large-scale job creation, especially among unskilled workers in rural areas. Activities in this phase should include promoting sustainable bush thinning activities and the establishment of biomass collection, torrefaction, and pelletization hubs. This would not only provide valuable employment opportunities but also produce a standardized carbon carrier that can be exported to international markets.
In the second phase, as the green hydrogen infrastructure starts maturing, the roadmap should shift focus towards ramping up the production of synthetic fuels domestically using the hybrid Biomass PtX pathway. This involves integrating the green hydrogen production with biomass gasification processes. By combining the strengths of both technologies, this hybrid process can produce synthetic fuels that are both environmentally sustainable and economically competitive.
The phased approach allows for the realization of immediate benefits through job creation and revenue generation from biomass export while laying the foundation for the establishment of a cutting-edge synthetic fuels industry. By aligning the roadmap with the country's socio-economic realities and energy objectives, Namibia can forge a unique path towards a sustainable energy future.

FOCUS ON A ROADMAP

The proposed approach offers many possible commercial pathways based on five pillars:

A. Production of the torrefied biomass pellets.
B. Export of the torrefied biomass pellets.
C. Production of renewable drop-in fuels in Namibia.
D. Domestic use of renewable fuels.
E. Export of high value renewable fuels.

As was presented before, evolution in stages is possible for each of the pillars. The first step is clear, to develop a demonstration of the complete value chain in Namibia, which will act also as an enabler and stimulant for the export of the torrefied biomass pellets. Setting production facilities for the torrefied biomass pellets is less capital intensive and essentially be place in the and starting in the short-term with BtX processes able to be hybridized when green hydrogen quantities become available in Namibia can offer an effective pathway in bridging biomass use and its benefits like new jobs creation and mitigation of the encroaching bush challenge with the long-term vision of the Green Hydrogen Strategy.

A possible roadmap could be:

Phase A.
A1. Develop a demonstration of the complete value chain in Namibia, acting as an enabler and stimulant for the export market.
A2. Develop infrastructure for the production of the torrefied biomass pellets in Namibia mainly for exporting. The export income can cross-finance PtX synthesis facilities in Namibia if appropriate mechanisms are put in place.
A3. Develop Hybrid Biomass-PtX infrastructure in Namibia operating as traditional BtX facilities in the short term to meet local needs first, since it is easier to ensure a domestic off-taker to facilitate commercial financing of such projects.

Phase B.
B1. As green hydrogen availability in the country rises, green hydrogen is supplied to the Biomass-PtX plants and production increases.
B2. Start developing further infrastructure to produce renewable fuels and export in regional (e.g., SADC and Africa under AfCFTA) and global markets.

6 CONCLUSIONS

The novel carbon carrier coupled with a hybrid Biomass Power to X approach can optimize carbon use from these torrefied biomass pellets and be supplemented with green hydrogen for higher efficiency. This pathway promises to serve as a crucial bridging solution, particularly until Direct Air Capture (DAC) technologies become commercial and cost-effective both for Namibia and globally. Namibia can develop an integrated strategy for renewable fuels encompassing both advanced bio-fuels and green hydrogen. Evolution in stages is possible and starting in the short-term with BtX processes able to be hybridized when green hydrogen quantities become available in Namibia can offer an effective pathway in bridging biomass use and its benefits like new jobs creation and mitigation of the encroaching bush challenge with the long-term vision of the Green Hydrogen Strategy.

International PtX Hub
Supported by: Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag
Implemented by giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GFA CONSULTING GROUP

CONCLUSIONS

Namibia's Vision 2030 aims for socio-economic development, operationalized through five-year National Development Plans and accelerated by the Harambee Prosperity Plans. The second of these plans highlights the green hydrogen and PtX industry as a key growth engine, not just for Namibia but also for the broader SADC region. This sector is expected to significantly contribute to regional prosperity.

Given the still-developing state of Namibia's industry, the revenue prospects for green hydrogen derivative products like synthetic aviation fuel (SAF), methanol, and drop-in fuels largely come from industrial nations striving to defossilize their hard-to-abate sectors. Namibia's Hydrogen Strategy is in line with these international demands, adding a layer of feasibility to the endeavor. Further, with a significant number of local industries in dire need of defossilization due to international mandates set by mother companies, there is an internal market for these products as well.

Biomass-to-X (BtX) processes offer a sustainable way to generate renewable fuels by converting biomass resources. However, they often face limitations in terms of carbon utilization efficiency. On the other hand, Power-to-X (PtX) technologies propose an alternative route, leveraging carbon sources, though often unsustainable, coupled with renewable energy to produce fuels.

As a resolution to these shortcomings, a novel carbon carrier is proposed in the form of torrefied biomass pellets. This innovative approach optimizes carbon usage and can be further enhanced with green hydrogen for more efficient and cost-effective fuel production. More importantly, this approach aligns perfectly with Namibia's environmental goals. Namibia faces the issue of bush encroachment, a phenomenon where native vegetation is overwhelmed by encroaching bush species, resulting in biodiversity loss and soil degradation. Employing this biomass for fuel production provides an economic incentive for bush thinning, offering a win-win situation by simultaneously mitigating an environmental problem and adding value to an otherwise problematic natural resource.

As is clear, the use of bush biomass as a foundational element in Namibia's Power-to-X (PtX) strategy not only solves critical technological challenges but also addresses pressing environmental and socio-economic issues. Additionally, it's worth noting that this innovative hybrid PtX-BtX approach aligns well with Namibia's NDCs and Climate Action Strategy, contributing to the nation's sustainable development while mitigating climate impact.

This hybrid PtX approach serves globally as a vital short-term bridge while we await the maturity and commercial viability of Direct Air Capture (DAC) technologies. However, its relevance extends into the long term as well. DAC installations require significant land and infrastructure, constraints that may not be feasible in all locations. The bush biomass route offers a complementary alternative in such scenarios, particularly in remote or constrained areas where installing DAC plants may not be practical and where transporting gases can present logistical challenges.

In sum, the use of torrefied bush biomass pellets not only fills an immediate technological need but also aligns with Namibia's ecological goals and land management strategies. This approach offers a comprehensive solution that promises to be viable in both the short and long term, making it an attractive option for Namibia's sustainable PtX future.

While the individual processes in the proposed pathway are all commercially available, this proposal is innovative in its combination of these processes to achieve a common objective - maximizing the supply of sustainable carbon to PtX hubs in Namibia and around the world. This integration presents a unique set of challenges, primarily revolving around the need for overall process optimization. As each process has traditionally been optimized individually, this holistic perspective demands a fresh approach, ensuring optimal interaction and compatibility between the integrated stages. In this light, **the next step is to embark on a pre-feasibility study.** This study should seek to evaluate the operational and economic feasibility of the proposed pathway, identifying potential bottlenecks and optimization opportunities. Crucially, the involvement of market actors is essential in this phase, particularly for the gasification and Fischer-Tropsch (FT) synthesis stages. These processes are intimately linked, with the output of the gasification process directly feeding into the FT synthesis. As such, there is a need for cross-optimization, ensuring that these processes are mutually compatible and efficient. By incorporating the inputs and expertise of market actors, this pre-feasibility study would not only provide valuable insights into the practical aspects of implementing the proposed pathway but also facilitate stakeholder buy-in, fostering a collaborative approach towards the advancement of this promising hybrid Biomass PtX solution.

Concluding, we need to remind that biomass in all its forms including the torrefied biomass pellets has an energy content which is renewable. This energy content needs to be utilized along with green hydrogen. The legislative framework in Namibia does not currently acknowledge advanced biofuels in general and bio-hydrogen in particular. The hybrid technical approach utilizing both green hydrogen and bio-hydrogen maximizes efficiencies and overall effectiveness.

The proposed approach offers many possible commercial pathways based on five pillars:

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Evolution in stages is possible for each of the pillars. The first step is clear, to develop a demonstration of the complete value chain in Namibia, which will act also as an enabler and stimulant for the export of the torrefied biomass pellets. Setting production facilities for the torrefied biomass pellets is less capital intensive and essentially be place in the and starting in the short-term with BtX processes able to be hybridized when green hydrogen quantities become available in Namibia can offer an effective pathway in bridging biomass use and its benefits like new jobs creation and mitigation of the encroaching bush challenge with the long-term vision of the Green Hydrogen Strategy.

8 ANNEXES

ANNEX 1. CURRENT USE AND FUTURE PROSPECTS OF VARIOUS FUELS IN NAMIBIA

Hydrogen consumption

As of 2023, Namibia aligns with the international trend where the need for hydrogen within commercial and industrial sectors remains largely dormant. Though potentials for the development of hydrogen exist, they are yet to be actualized, primarily because alternatives to hydrogen are abundant, and the required infrastructure for the delivery and utilization of hydrogen is undeveloped and needs to be constructed (Von Oertzen, 2021).

The prospects for domestic industrial uses of hydrogen may gradually surface, contingent on an economically justifiable transition in fuel sources. Several initial pre-feasibility studies conducted for medium and large-scale industrial and mining operations in Namibia have identified that the current absence of reliable and cost-competitive infrastructure for hydrogen distribution, storage, and supply hinders the feasibility of fuel switching at present. However, future changes in the scale and cost of hydrogen production and delivery could increase competitiveness and render fuel-switching a viable option.

Given the lack of large-scale local hydrogen consumers in Namibia's industry sector, the likelihood of establishing a local distribution infrastructure is deemed minimal. This assessment also extends to hydrogen applications within the local electricity sector, where the establishment of reliable and cost-effective delivery methods would be necessary to power fuel cells or conventional internal combustion engines for electricity generation.

In light of the continuous decrease in solar PV prices, and the rapid decline in the costs of medium- to large-scale energy storage infrastructure in recent years, the probability of hydrogen-powered electricity establishing a local foothold in Namibia's internal market appears remote in the near term. Exceptions may occur in specific circumstances, such as at production sites with excess hydrogen or in locations necessitating particular grid services, including base load provision, reactive power balancing, and ancillary services.

Finally, it's noteworthy to mention the green hydrogen pilot project underway in Namibia. Upon completion, this project will mark a significant milestone as the first case to utilize green hydrogen for applications in locomotive, port equipment, and agriculture, thereby potentially signaling a shift in the nation's energy landscape.

Ammonia

Ammonia, a crucial chemical compound, serves various essential functions across different sectors, with its applications spanning agriculture, industry, and beyond. Its role as a vital ingredient in various agricultural and industrial processes cannot be overstated, particularly in the context of Namibia.

In the agricultural sector of Namibia, ammonia is predominantly utilized as a fertilizer to enhance crop growth and increase yields, especially in regions plagued by poor soil fertility. Namibia's arid climate and the country's heavy reliance on agriculture for sustenance and economic livelihood necessitate innovative solutions to improve soil productivity. The application of ammonia-based fertilizers has proven to be an effective strategy in combating the challenges of poor soil quality and aridity, providing the nutrients needed for crops to thrive.

Furthermore, ammonia's significance extends into the mining industry, where it plays a vital role in the extraction of valuable minerals such as copper, gold, and uranium. The mining sector is a significant contributor to Namibia's economy, and the utilization of ammonia in various extraction processes ensures efficiency and profitability. Its unique properties enable the efficient separation and recovery of these minerals, underscoring its indispensability in the mining industry.

Despite ammonia's critical importance in both agriculture and mining in Namibia, the country lacks a domestic industry dedicated to the production of ammonia and its derivatives. Currently, Namibia relies heavily on imports from other sources to meet its demand for this vital compound. This dependence on external suppliers presents both challenges and opportunities. The reliance on imports might lead to increased costs and potential supply chain vulnerabilities, which could impact both the agricultural and mining sectors adversely.

Considering the growing demand and multifaceted applications of ammonia in Namibia, there is a burgeoning opportunity to explore the establishment of a local ammonia production industry. Developing domestic production capabilities could lead to increased self-reliance, reduced costs, and potentially open up new industrial avenues related to ammonia's derivatives. The Hyphen project is expected to realize this potential at an extent aiming at achieving production equal to 1,000,000 tons of ammonia per annum for Phase 1 and doubling this capacity in Phase 2[2].

Methanol

Methanol has been recognized as a versatile chemical with various industrial applications, including as a fuel, solvent, and feedstock for chemical synthesis and is specifically referenced in the Hydrogen Strategy. In Namibia, it has primarily been used as a fuel for cooking and heating, particularly in rural areas where access to electricity and other energy sources is limited. This has been advantageous due to the relatively low cost of methanol and its ability to be produced from renewable sources such as biomass and waste materials. Namibia, like many other countries, has been exploring the potential of methanol beyond cooking and heating. The government has expressed interest in using methanol as a fuel for transportation, particularly in remote areas where traditional gasoline or diesel fuel may be expensive or unavailable. This could be particularly beneficial in Namibia, where there are abundant natural resources but traditional fossil hydrocarbon fuels are imported. Methanol can also be used as a feedstock for chemical synthesis, such as in the production of formaldehyde, which has various industrial applications in the manufacture of plastics, resins, and textiles.

Expanding the use of methanol in Namibia could have several advantages. It could help reduce the country's dependence on imported fossil fuels, promote sustainable development, and create opportunities for local production and utilization of renewable resources. Methanol has a relatively low environmental impact compared to other fossil fuels, as it produces lower emissions of harmful pollutants when burned. Additionally, Namibia has significant potential for producing methanol from renewable sources, such as agricultural waste and biomass, which could contribute to the country's efforts to transition to a more sustainable and resilient energy system.

However, it's important to consider potential challenges and risks associated with the expanded use of methanol in Namibia. These may include issues related to production, storage, transportation, and distribution of methanol, as well as ensuring proper safety measures are in place to handle this flammable liquid. Proper regulations and guidelines should be in place to ensure safe production, storage, transportation, and usage of methanol.

In conclusion, methanol has shown promise as a versatile and sustainable chemical with various industrial applications in Namibia, particularly as a fuel for cooking, heating, transportation, and as a feedstock for chemical synthesis. While there are potential benefits to expanding its use, careful planning, regulation, and safety measures should be in place to ensure its safe and sustainable utilization in Namibia's energy and industrial sectors.

Transportation Fuels: Road, Rail and Shipping

Currently, the main transportation fuels used in Namibia are gasoline and diesel, which are imported primarily from South Africa. New significant oil discoveries were made in recent time and are currently being developed. Namibia also imports liquefied petroleum gas (LPG) and aviation fuel. In recent years, the Namibian government has taken steps to encourage the use of renewable energy sources for transportation. For example, the National Renewable Energy Policy makes specific reference to the potential of producing and using ethanol and biodiesel. There are also several private sector initiatives to produce biofuels in Namibia, including from used cooking oil, jatropha and other crops. In addition to biofuels, there is also growing interest in electric vehicles (EVs) in Namibia . However, the lack of charging infrastructure and the high cost of EVs remains a challenge to widespread adoption.

Apart from road transportation, vehicles used in agriculture and mining face certain challenges in being converted to electricity or hydrogen at least in the short to medium term. These challenges are not Namibia specific and the one of the most prominent solutions is the use of drop-in renewable fuels.

The Namibian railways are mainly powered by diesel locomotives. The Namibian railways have a total network length of about ~2,687 km. No tracks are currently electrified. The pilot hydrogen project also envisages the use of green hydrogen in dual fuel locomotives. However, due to the generally poor state

[2] https://hyphenafrica.com/projects/

of the rail infrastructure and historically poor management of the state-owned rail operator, the majority of freight is moved by truck across the country, including commodities transiting from neighboring countries to the port of Walvis Bay.

As far as shipping is concerned, Namibia's primary port, Walvis Bay, serves as a logistics hub for both Namibia and neighboring countries including Botswana and Zambia. It currently handles approximately 5 million tonnes of cargo and receives around 3000 vessels annually. Walvis Bay is also home to a large fishing industry, of which, many have their own vessels and jetties.

Walvis Bay port has recently developed a new container terminal with a maximum capacity of at least 750,000 containers per annum. Walvis Bay port also hosts two bulk terminals as well as a fuel terminal.

There are three fuel providers to the ships who berth in Walvis Bay, including NamPort, the state-owned operator, and two private sector suppliers. Most of the fuel being provided is said to be marine diesel and heavy fuel oil.

While there may be limited pressure on local fishing companies to switch to renewable fuels, the internationally operated container and cruise liners may be under more pressure from their home territories to lower emissions.

Additionally, an ocean mining operator in the diamond sector is also under pressure from its international shareholders, having committed to decarbonizing by 2030. An almost insurmountable challenge, unless they can source readily available drop-in synthetic fuels. The pilot green hydrogen project envisions one dual fuel vessel to be employed by Namport. During the consultations held Debmarine expressed their strategy to defossilize by 2030, which would require either the use of renewable drop-in diesel or the modification of their vessels to dual fuel.

Sustainable Aviation Fuel

Namibia has a comparatively small aviation sector. However, its neighbor, South Africa hosts the largest aviation hub in sub-Saharan Africa. Namibia, like many other countries, recognizes the importance of reducing greenhouse gas emissions in the aviation sector and transitioning towards more sustainable practices. Sustainable aviation fuel (SAF) offers a potential solution to address this challenge, while at the same time Namibia has the opportunity to produce SAF for the region, including South Africa, which is frequented by most of the large airline operators. However, the development and adoption of SAF depend on various factors, including feedstock availability, production technology, and policy support.. Common feedstocks for SAF include non-edible plant oils, agricultural residues, and municipal waste. Namibia has diverse ecosystems, including arid regions, where certain plants and agricultural by-products could potentially serve as feedstock sources. In August 2023, ASTM D7566 Annex 8 was announced, which is the first fully synthetic 100% drop-in SAF getting standardized. This opens up the possibilities for synthetic SAF production as envisioned in the hydrogen strategy mainly for export purposes.

Collaboration with international partners or organizations experienced in SAF production could support the development of such capabilities. Policy support plays a crucial role in promoting the production and use of sustainable aviation fuel. Governments can incentivize investments in SAF production facilities, implement regulations concerning SAF, and support research and development initiatives in the field. Encouraging partnerships between the government, industry stakeholders, and research institutions can help drive progress in this area. Sunfire which is German company that specializes in the development of solid oxide electrolysis cell (SOEC) technology for the production of green hydrogen and synthetic fuels had cooperation with the Namibian airline to produce sustainable aviation fuels but Air Namibia has now been liquidated to date. There is limited information on the collaboration regarding the sustainable aviation fuel with other industry player in Namibia although green hydrogen and other synthetic fuel have attracted much attention.

Natural gas

While Namibia has significant reserves of natural gas, its use and infrastructure for this energy source are currently limited. Namibia has an estimated 11 trillion cubic feet of natural gas reserves, primarily located offshore along the country's western coast. However, to date, very little of this resource has been developed or utilized due to various factors, including the high capital costs associated with exploration and production, a lack of infrastructure, and limited domestic demand. Currently, the country relies on imported electricity, primarily from South Africa, to meet its energy needs. However, Namibia is actively exploring ways to develop its natural gas resources to diversify its energy mix and reduce its reliance on imported electricity. In recent years, there have been efforts to encourage investment in Namibia's natural gas sector. In 2019, Namibia's Ministry of Mines and Energy launched a licensing round for offshore exploration blocks, and several international companies have expressed interest in exploring these areas. As for infrastructure, Namibia currently lacks the necessary pipelines, liquefied natural gas (LNG) terminals, and other facilities needed to develop and transport natural gas. However, there are plans are underway to construct a 400-kilometer gas pipeline from the Kudu gas field offshore to the coastal town of Walvis Bay, which could help unlock the country's natural gas resources and provide a reliable source of energy.

ANNEX 2: COUNTRY ANALYSIS

In order to develop a robust and optimized roadmap, it was decided to perform an analysis of the country utilizing two methods:

- PESTEL analysis
- SWOT analysis

PESTEL analysis is a framework used to assess and analyze the external macro-environmental factors that can impact a specific project. It examines various dimensions that can influence business operations and decision-making. The acronym PESTEL stands for:

1. Political: Examines political factors such as government stability, regulations, taxation policies, trade policies, and political risks.
2. Economic: Considers economic factors like economic growth, inflation rates, exchange rates, interest rates, and industry-specific trends.
3. Sociocultural: Focuses on social and cultural aspects including demographic trends, consumer attitudes, lifestyle preferences, social norms, and cultural shifts.
4. Technological: Looks at technological factors such as emerging technologies, research and development activities, technological disruptions, and the overall technological landscape.
5. Environmental: Considers environmental factors like climate change, sustainability practices, environmental regulations, and the impact on the organization's operations.
6. Legal: Examines legal factors such as laws, regulations, compliance requirements, intellectual property protection, and labor laws.

PESTEL analysis helps gain a comprehensive understanding of the external factors that may influence strategies, operations, and decision-making processes.

SWOT analysis is a framework used to evaluate the internal strengths and weaknesses of a project, as well as the external opportunities and threats it faces. It provides insights into the current status and helps identify areas of competitive advantage and areas that need improvement. The acronym SWOT stands for:

1. Strengths: Internal factors that provide a competitive advantage or unique capabilities. These can include, skilled workforce, innovative products/services, efficient processes, or financial stability.
2. Weaknesses: Internal factors that place at a disadvantage or hinder the performance of the project. These can include lack of resources, outdated technology, weak market presence, inefficient operations, or inadequate skills.
3. Opportunities: External factors that present potential avenues for growth, new markets, emerging trends, or favorable circumstances that can be used to capitalize on.
4. Threats: External factors that pose risks and challenges to the success. These can include competitive pressures, changing consumer preferences, economic downturns, regulatory changes, or technological disruptions.

By analyzing a project's internal strengths and weaknesses in relation to the external opportunities and threats, a SWOT can helps identify strategic priorities, make informed decisions, and develop roadmaps to leverage their strengths and address challenges.

PESTEL Analysis

Political factors

Political factors include government policy, political stability, restrictive trade policies, tax policies, and labour laws, among others.

Table 1: The Political Factors of the PESTEL Analysis

POLITICAL FACTORS	Likelihood H or L	Impact + or -	Opportunities to be maximised OR threats to be minimised
1. Government policy towards PtX and use of biogenic CO from bush biomass	High	+	**Opportunity** Advocate for favorable PtX and biomass policies and participate in policy-making processes.
2. Regulatory framework for renewable fuels production	High	+	**Threat** Engage with regulators to understand the new needs and develop if needed new relevant regulations
3. Political stability and support for PtX and biogenic CO from bush biomass projects	High	+	**Opportunity** Build strong relationships with government stakeholders to ensure ongoing support
4. International relations and agreements on climate change	Low	+	**Opportunity** Leverage international climate commitments to garner support for power-to-X projects.
5. Policy on land use and bush encroachment management	High	+	**Threat** Work closely with land managers to ensure practices align with policies and aim to influence such policies in favor of sustainable bush biomass harvesting.

Economic Factors

Economic factors influence the implementation of PtX/biomass activities. They include economic policies, economic activities, economic growth, interest rates, inflation, disposable incomes, unemployment rates, natural resource endowments, etc.

Table 2: The Economic Factors of the PESTEL Analysis

ECONOMIC FACTORS	Likelihood H or L	Impact + or -	Opportunities to be maximised OR threats to be minimised
1. Funding and investment availability for power-to-X projects utilizing biomass carbon source.	High	+	**Opportunity** Develop compelling business cases to attract investment and explore various funding options.
2. Economic feasibility of power-to-X compared to other energy sources	High	-	**Threat** Improve efficiency and cost-effectiveness through technological innovation and operational optimization.
3. Job creation and economic growth potential	High	+	**Opportunity** Invest in local hiring and training to maximize job creation.
4. Market demand for power-to-X products	High	+	**Opportunity** Understand and anticipate market trends, and develop products that meet market needs.
5. Economic implications of infrastructure development	High	-	**Threat** Economic implications of infrastructure development.

Sociocultural Factors

Sociocultural factors include demographic characteristics including population, population growth rates, household sizes, fertility rates, age distribution, geographic distribution, cultural barriers, lifestyle attitudes, career attitudes, etc.

Table 3: The Social Factors of the PESTEL Analysis

SOCIAL FACTORS	Likelihood H or L	Impact + or -	Opportunities to be maximised OR threats to be minimised
1. Public perception and acceptance of power-to-X	Low	+	**Opportunity** Communicate the benefits of power-to-X and engage with communities to gain acceptance.
2. Potential for improving energy access in rural areas	Low	+	**Opportunity** Develop strategies for extending power-to-X applications to rural areas.
3. Job creation and social development potential	High	+	**Opportunity** Leverage power-to-X projects for local job creation and social development.
4. Impact on communities involved in biomass harvesting	High	+	**Threat** Implement fair labor practices and ensure that local communities benefit from biomass harvesting operations.
5. Gender disparities in access to energy services/fuels and decision-making.	High	-	**Threat** Address gender disparities through targeted interventions and promote gender equality in energy efficiency initiatives.

Technological Factors

Technological factors include technological incentives, level of innovation, automation and R&D policies, technological awareness, technological changes, trends, etc.

Table 4: The Technological Factors of the PESTEL Analysis

TECHNOLOGICAL FACTORS	Likelihood H or L	Impact + or -	Opportunities to be maximised OR threats to be minimised
1. Advances in power-to-X and biomass technologies	High	+	**Opportunity** Invest in research and development to capitalize on technological advances.
2. Availability of necessary technology and expertise locally.	High	-	**Threat** Develop local expertise through training and capacity building.
3. Potential for technological innovation in biomass processing	High	+	**Opportunity** Foster an environment conducive to innovation and continuous improvement.
4. Technological challenges in implementing power-to-X applications.	High	-	**Threat** Identify and address technological challenges through research and development.
5. Adaptation of technology to local biomass characteristics and conditions	High	+	**Threat** Customize technology to suit local conditions for optimal performance.

Environmental Factors

Environmental factors include environmental policies, climate change issues, global warming and Greenhouse Gas (GHG) emissions, level of awareness about environmental issues, pressure from environmental Civil Society Organisation (CSO) / Non-Governmental Organisation (NGO) lobby groups, etc.

Table 5: The Environmental Factors of the PESTEL Analysis

ENVIRONMENTAL FACTORS	Likelihood H or L	Impact + or -	Opportunities to be maximised OR threats to be minimised
1. Contribution to climate change mitigation	High	+	**Opportunity** Leverage power-to-X's potential for reducing emissions to gain support from environmentally conscious stakeholders.
2. Environmental impact of large-scale biomass harvesting	Low	-	**Threat** Implement sustainable harvesting practices to minimize environmental impacts.
3. Sustainability of biomass resource over time	High	-	**Threat** Manage biomass resources sustainably to ensure long-term availability.
4. Potential impacts on biodiversity and ecosystem health.	High	-	**Threat** Conduct environmental impact assessments and implement mitigation measures to protect biodiversity.
5. Role of power-to-X sustainable fuels in diversifying the energy mix	High	+	**Opportunity** Highlight the role of power-to-X in enhancing energy security through diversification.

Legal Factors

Legal factors are closely related to political factors; however, they are focused more on the legal and regulatory framework conditions that enable the effective implementation of PtX/Biomass activities including anti-discrimination laws, anti-trust laws, copyright, patents and intellectual property laws, health and safety laws, etc.

Table 6: The Legal Factors of the PESTEL Analysis

LEGAL FACTORS	Likelihood H or L	Impact + or -	Opportunities to be maximised OR threats to be minimised
1. Compliance with renewable fuel production laws and regulations	High	-	**Threat** Ensure full compliance with all legal requirements related to fuel production.
2. Regulations pertaining to biomass harvesting	High	-	**Threat** Understand and comply with all laws regulating biomass harvesting.
3. Legal implications of land use for PtX/Biomass projects	High	-	**Threat** Ensure all land use for PtX/Biomass projects complies with legal requirements and best practices.
4. Regulations pertaining to carbon emissions and climate change	High	+	**Opportunity** Utilize regulations as an opportunity to highlight the climate benefits of PtX/Biomass technologies.
5. Legal framework for the commercialization and trade of PtX/Biomass produced renewable fuels	High	+	**Opportunity** Understand and leverage the legal framework to facilitate the trade and commercialization of PtX/Biomass produced renewable fuels.

SWOT Analysis

The SWOT analysis is undertaken to identify this project's internal strengths and weaknesses, as well as its external opportunities and threats. Ultimately, this is a framework for leveraging strengths, improving on weaknesses, minimising threats, and taking advantage of opportunities.

Strengths

The internal strengths and strategies to leverage them are presented in the table below.

Table 7: The Strengths of the SWOT Analysis

STRENGTHS	Strategies to leverage strengths
1. **Abundant Biomass Resource:** With bush encroachment affecting 45 million hectares, Namibia has an abundant biomass resource that can be converted into energy.	Engage in mass sustainable bush thinning operations to retrieve the biomass and employ it in power-to-X pathways.
2. **Energy Potential:** The energy potential of Namibia's biomass is vast, reportedly enough to provide for national electrical requirements for over 140 years.	Develop robust methods to convert biomass into fuels, leveraging the energy potential for power-to-X applications.
3. **Existing Biomass Industry:** Namibia's existing biomass industry demonstrates an established value chain for biomass processing especially in the form of charcoal.	Expand the industry's focus to include power-to-X applications towards supplying CO and invest in the necessary technological advancements.
4. **Regrowth Capability:** The bush biomass resource regrows over time, providing a sustainable feedstock for power-to-X applications.	Develop a sustainable harvesting strategy that takes regrowth rates into account to ensure a consistent biomass supply.
5. **Biomass Characteristics:** The biomass has favorable characteristics for energy production, including relatively low moisture content and high calorific value.	Optimize power-to-X processes to capitalize on these biomass characteristics.

Weaknesses

The internal weaknesses and strategies to minimise them are presented in the table below.

Table 8: The Weaknesses of the SWOT Analysis

WEAKNESSESS	Strategies to minimize weaknesses
1. **Limited Infrastructure:** Namibia's current infrastructure might not be sufficient for large-scale power-to-X applications, particularly in terms of transportation.	Invest in infrastructure development, including roads, railroads and biomass processing facilities.
2. **Logistical Challenges:** The biomass is spread out across a large area, increasing logistical complexity and cost.	Develop decentralized power-to-X facilities to minimize transport distances or break-down the processes in multiple steps to optimize the logistic chains.
3. **Re-encroachment:** Biomass re-encroachment can make it challenging to maintain a consistent biomass supply.	Implement effective land management strategies to control re-encroachment.
4. **Limited Expertise:** The power-to-X field requires advanced expertise, which might be lacking locally.	Invest in education and training to develop local expertise in power-to-X technologies.
5. **High Upfront Costs:** The initial costs of establishing power-to-X facilities can be high.	Seek domestic and international funding, potentially leveraging the environmental benefits of power-to-X to attract investment.

Opportunities

The internal opportunities and strategies to exploit them are presented in the table below.

Table 9: The Opportunities of the SWOT Analysis

OPPORTUNITIES	Strategies to exploit opportunities
1. **Renewable fuels Production:** PtX/Biomass applications offer an opportunity for renewable fuels production from local resources.	Promote the environmental benefits of PtX/Biomass to gain public support and attract investment.
2. **Climate change mitigation:** Renewable fuels produced through PtX utilizing biogenic CO_2 support climate action.	Invest in PtX/Biomass technologies and seek funding and support from climate-focused entities.
3. **Job Creation:** The development of a PtX/Biomass industry could create jobs and stimulate economic growth.	Highlight the economic benefits of power-to-X to gain public and government support.
4. **Energy Security:** PtX/Biomass applications can contribute to energy security by reducing dependence on imported fuels.	Advocate for PtX/Biomass as a strategy for energy security at the national level.
5. **Diversification of Energy Mix:** PtX/Biomass applications can help diversify Namibia's energy mix, reducing reliance on any single energy source.	Include PtX/Biomass in national energy policy and planning to encourage a diverse energy mix.

Threats

The internal threats and strategies to counter them are presented in the table below.

Table 10: The Threats of the SWOT Analysis

THREATS	Strategies to counter threats
1. **Regulatory Barriers:** Existing regulations may not be conducive to the development of PtX/Biomass applications.	Engage with policymakers to advocate for favorable regulations.
2. **Market Uncertainty:** The market for power-to-X products is still emerging and may be unpredictable.	Develop flexible business models that can adapt to changing market conditions.
3. **Technological Challenges:** PtX/Biomass technologies are complex and may face technical challenges in implementation.	Invest in research and development to overcome technical barriers.
4. **Environmental Impacts:** Large-scale biomass harvesting could have negative environmental impacts, such as loss of biodiversity.	Implement sustainable harvesting practices and conduct environmental impact assessments.
5. **Competition for Biomass:** There may be competition for biomass resources from other sectors, such as charcoal and firewood production.	Develop a strategic plan for biomass use that balances the needs of different sectors and engage existing producers in diversifying their portfolio.

7

REFERENCES

- Böhm, Steffen, et Sian Sullivan, ed. Negotiating Climate Change in Crisis. Cambridge: Open Book Publishers, 2021
- Carbon Capital (2020), Availability, Quality and Suitability of Bush Biomass from Namibia for the Purpose of Substituting Fossil Fuels in Energy Generation in Hamburg, Namibia Biomass Industry Group.
- de Klerk, J. (2004). Bush Encroachment in Namibia. Windhoek: Ministry of Environment and Tourism, Directorate of Environmental Affairs.
- de Wet M.J. (2015), Harvesting of Encroacher Bush Compendium of harvesting technologies for encroacher bush in Namibia, GIZ "Support to De-bushing project"
- Eldridge, D., Bowker, M., Maestre, F., Roger, E., Reynolds, J., & Whitford, W. (2011). Impacts of shrub encroachment on ecosystem structure and functioning: towards a global synthesis. Ecology Letters 14, 709-722
- García, R., Gil, M. V., González-Vázquez, M. P., Rubiera, F., & Pevida, C. (2019). Biomass pelletization: contribution to renewable power generation scenarios. Production of materials from sustainable biomass resources, 269-294.
- IfaS (2021), International Biomass Fuel Certification for Namibian Encroacher Bush, GIZ.
- Kambatuku, J., Cramer, M., & Ward, D. (2011). Intraspecific competition between shrubs in a semi-arid savanna. Plant Ecology
- Kgosikoma, O. E., & Mogotsi, K. (2013). Understanding the Causes of Bush Encroachment in Africa: The Key to Effective Management of Savanna Grasslands. The 22nd International Grassland Congress (pp. 1569-1572). Sydney: New South Wales Department of Primary Industry.
- Lindeque, C. (2020). Availability, Quality and Suitability of Bush Biomass from Namibia for the Purpose of Substituting Fossil Fuels in Energy Generation in Hamburg. Windhoek: Namibia Biomass Industry Group.
- Lu, H., Ma, X., Huang, K., Fu, L., & Azimi, M. (2020). Carbon dioxide transport via pipelines: A systematic review. Journal of Cleaner Production, 266, 121994.
- Niu, Y., Lv, Y., Lei, Y., Liu, S., Liang, Y., & Wang, D. (2019). Biomass torrefaction: properties, applications, challenges, and economy. Renewable and Sustainable Energy Reviews, 115, 109395.
- Nunes LJR. A Case Study about Biomass Torrefaction on an Industrial Scale: Solutions to Problems Related to Self-Heating, Difficulties in Pelletizing, and Excessive Wear of Production Equipment. Applied Sciences. 2020; 10(7):2546
- Ostadi, M., Rytter, E., & Hillestad, M. (2019). Boosting carbon efficiency of the biomass to liquid process with hydrogen from power: The effect of H_2/CO ratio to the Fischer-Tropsch reactors on the production and power consumption. Biomass and Bioenergy, 127, 105282.
- Poluzzi, A., Guandalini, G., d'Amore, F., & Romano, M. C. (2021). The potential of power and biomass-to-X systems in the decarbonization challenge: a critical review. Current Sustainable/Renewable Energy Reports, 1-11.
- Rohde, R., & Hoffman, M. (2012). The historical ecology of Namibian rangelands: Vegetation change since 1876 in response to local and global drivers. Science of The Total Environment, 276-288.
- Roques, K. G., O'Connor , T. G., & Watkinson, A. R. (2001). Dynamics of shrub encroachment in an African savanna: relative influences of fire, herbivory, rainfall and density dependence. Journal of Applied Ecology, 268-280
- Rudolfsson, M., Borén, E., Pommer, L., Nordin, A., & Lestander, T. A. (2017). Combined effects of torrefaction and pelletization parameters on the quality of pellets produced from torrefied biomass. Applied Energy, 191, 414-424.
- Petrick, W. (2020). Environmental Impact Assessment (EIA) for the proposed Encroacher Bush. Windhoek: SLR.
- Prins, M. J., Ptasinski, K. J., & Janssen, F. J. (2006). More efficient biomass gasification via torrefaction. Energy, 31(15), 3458-3470.
- Shikangalah, R., & Mapani, B. (2020). A review on bush encroachment in Namibia: From a problem to an opportunity? Journal of Rangeland Science, 256-266.
- Svanberg, M., Olofsson, I., Flodén, J., & Nordin, A. (2013). Analysing biomass torrefaction supply chain costs. Bioresource technology, 142, 287-296.
- Tollefson, J. (2018). Sucking carbon dioxide from air is cheaper than scientists thought. Nature, 558(7709), 173-174.
- Tripathi, N., Hills, C. D., Singh, R. S., & Atkinson, C. J. (2019). Biomass waste utilisation in low-carbon products: harnessing a major potential resource. NPJ climate and atmospheric science, 2(1), 35.
- Von Oertzen, Detlof. Issues, Challenges and Opportunities to Develop Green Hydrogen in Namibia. Konrad-Adenauer-Stiftung, 2021.
- World Nuclear Association (2022). Uranium in Namibia. https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/namibia.aspx

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