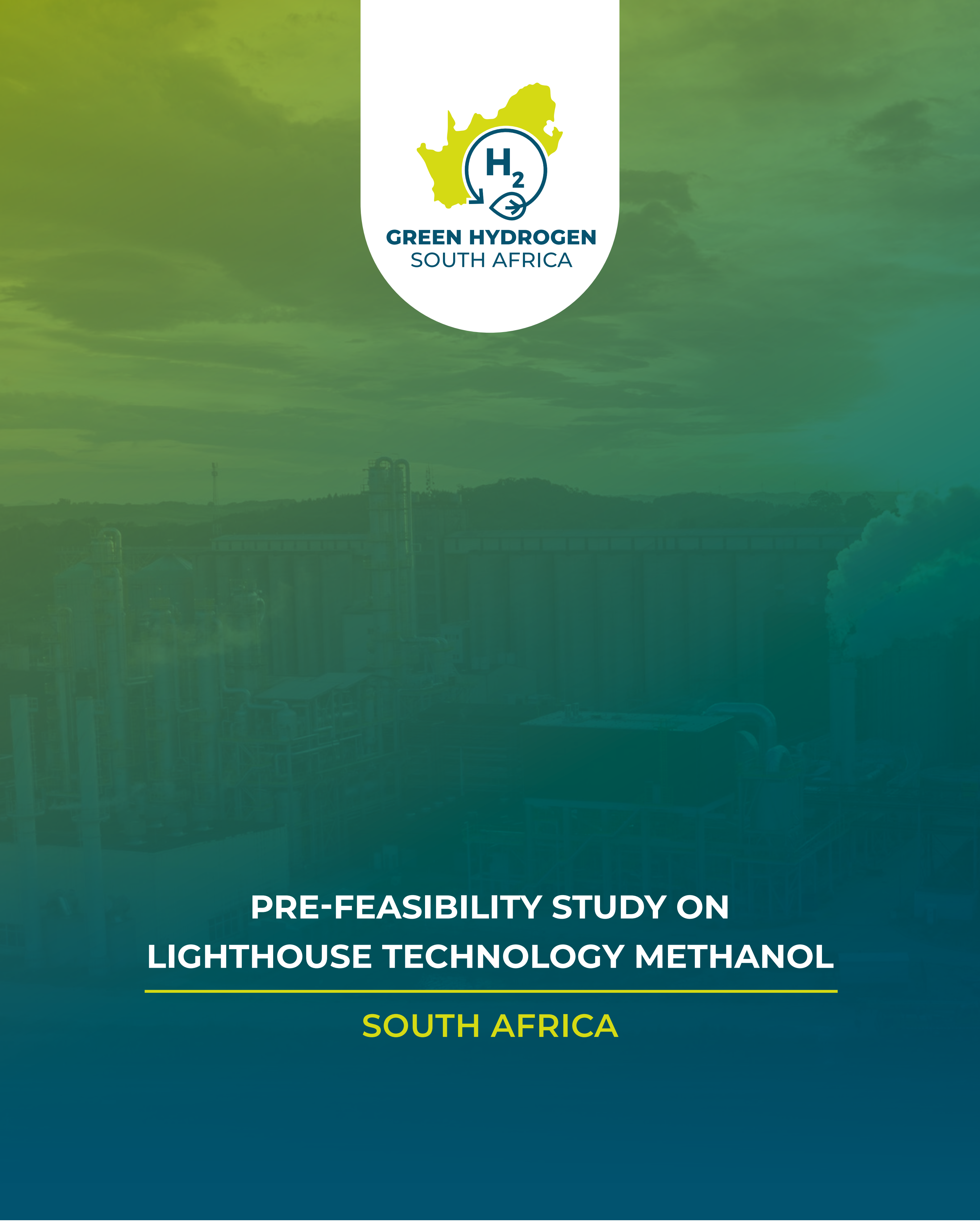

GREEN HYDROGEN
SOUTH AFRICA

PRE-FEASIBILITY STUDY ON LIGHTHOUSE TECHNOLOGY METHANOL

SOUTH AFRICA

german
cooperation
DEUTSCHE ZUSAMMENARBEIT

Implemented by:
giz Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

GFA
CONSULTING GROUP

CSIR
Touching lives through innovation

PRE-FEASIBILITY STUDY ON LIGHTHOUSE TECHNOLOGY METHANOL

SOUTH AFRICA

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ACRONYMS

AEC	Alkaline Electrolyser Cells
AEL	Air Emissions Licence
BA	Basic Assessment
B-BBEE	Broad-Based Black Economic Empowerment
BEIS	United Kingdom Department for Business, Energy and Industrial Strategy
°C	Degree Celsius
CA	Competent Authority
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CfD	Contract for Difference
CMB	Compagnie Maritime Belge
CMS	Conventional Methanol Synthesis
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRF	Capital Recovery Factor
CSIR	Council for Scientific and Industrial Research
CSP	Concentrating Solar Power
CWDP	Coastal Waters Discharge Permit
CZA	Copper, zinc and aluminium oxides
DALRRD	Department of Agriculture, Land Reform and Rural Development
DFFE	Department of Forestry, Fisheries and the Environment
DFI	Development Financial Institution
EA	Environmental Authorisation
EAP	Environmental Assessment Practitioner
EC	European Commission
EIA	Environmental Impact Assessment

EMPr	Environmental Management Programme
EPC	Engineering, Procurement and Construction
ES	Environmental and Social
ESS	Environmental Screening Study
ETS	Emission Trading System
EU	European Union
EUR	Euro
FDI	Foreign Direct Investment
FGD	Flue Gas Desulphurisation
FLH	Full Load Hours
FSC	Forest Stewardship Council
FTZ	Free Trade Zone
GFA	GFA Consulting Group GmbH
GH$_2$	Green Hydrogen
GHCS	Green Hydrogen Commercialisation Strategy for South Africa
GHG	Green House Gas
GIS	Geographic Information System
GIZ	Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GMeOH	Green Methanol
GNH$_3$	Green Ammonia
GoO	Guarantee of Origin
GW	Giga Watt
H$_2$	Hydrogen
H2.SA	Promoting a South African Green Hydrogen Economy (H2.SA)
HIA	Heritage Impact Assessment
HSRM	Hydrogen Society Roadmap for South Africa
IAS	Invasive Alien Species
ICCE	International Code of the Construction and Equipment
IDZ	Industrial Development Zone
IGCC	Integrated Gasification Combined Cycle
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change

IRR	Internal Rate of Return
JET IP	Just Energy Transition Investment Plan
KOH	Potassium Hydroxide
KTPA	Kilotonnes per Annum
KWH	Kilowatt Hour
LCOE	Levelised Cost of Electricity
LCOH	Levelised Cost of Hydrogen
LCOM	Levelised Cost of Methanol
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
MEPC	Marine Environment Protection Committee
MHI	Major Hazardous Installation
MKTPA	Million Tonnes Per Annum
Mt	Million Tonnes
MW	Mega Watt
NEM:AQA	National Environmental Management: Air Quality Act
NEM:ICMA	National Environmental Management: Integrated Coastal Management Act
NEMA	National Environmental Management Act
NHRA	National Heritage Resources Act
Nox	Nitrogen Oxides
NPM	Net Present Methanol
NPV	Net Present Value
NREL	United Kingdom Department of Energy’s National Renewable Energy Laboratory
NWA	National Water Act
O2	Oxygen
OHSA	Occupational Health and Safety Act
OPEX	Operational Expenditures
PEM	Per Annum
PFS	Pre-Feasibility Study
PPA	Power Purchase Agreement
PPP	Public Participation Process

PtX	Power-to-X
PV	Solar Photovoltaic
RE	Renewable Energy
RED II	Renewable Energy Directive
REDZ	Renewable Energy Development Zones
ROE	Return on Equity
RO	Reverse Osmosis
SAF	Sustainable Aviation Fuel
SAHRA	South African Heritage Resources Agency
SALA	Subdivision of Agricultural Land Act
SAMSA	South African Maritime Safety Authority
SANBI	South African National Biodiversity Institute
SAT	Single Axis Tracking
SBP	Sustainable Biomass Program
SEC	Specific Energy Consumption
SEZ	Special Economic Zone
SIP	Strategic Infrastructure Project
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cells
SURE	Sustainable Resources Verification Scheme
TAME	Tertiary Amyl Methyl Ether
TFA	Tilted Fixed-Axis
TNPA	Transnet National Ports Authority
TPD	Tonnes Per Day
TPFS	Techno-Economic Pre-Feasibility Study
UN	United Nations
US	United States
USD	United States Dollar
Vt	Variable Transport Cost
WACC	Weighted Average Cost of Capital
WUL	Water Use Licence
ZAR	South African Rand

Introduction

This study was carried out by GFA-CSIR as part of the project 'Promoting a South African Green Hydrogen Economy (H2.SA)' implemented by the *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH*. H2.SA supports the South African public and private sectors in realising the potential of a sustainable green hydrogen (GH_2) economy for the country.

The study is intended to serve as a model for a pre-feasibility study (PFS). It contains all critical elements of a preliminary systematic assessment of a project idea. In this case of a green methanol (GMeOH) project in South Africa.

In a nascent market environment, it also serves as an orientation for different stakeholders, regardless of whether they want to approach the development of a green methanol project from a technical, financial, environmental or social perspective. Additionally, it can encourage project developers to customise the study to suit their specific needs. In this way, the utility of the study can enable a wider set of stakeholders to participate in the future implementation of GH2/Power-to-X (PtX) investment projects, thus making a broad and sustainable contribution to a future GH2 economy in the country.

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The study is organised into three parts:

Part 1: Identifies potential project designs and highlights the key considerations when ideating a project concept at pre-feasibility stage.

Part 2: Presents a detailed GMeOH techno-economic pre-feasibility study (TPFS) example.

Part 3: Carries out a brief financial pre-feasibility assessment of the exemplary project.

The introductory section briefly sets the local context and explains why the production of GMeOH in South Africa holds significant export potential.

Although this study covers all relevant aspects of the initial evaluation of a project idea, it does not claim to provide all encompassing knowledge. As it is the case at pre-feasibility level, it offers guidance and focuses on essentials, especially in the context of South Africa, within the study's defined scope.

1.1 What is a Pre-feasibility study about & how to use it to guide your project development?

A PFS is an initial assessment tool used to vet potential development ideas, pinpointing the most promising avenues and eliminating less favourable options. It delves into the technical, economic, regulatory, and financial dimensions, primarily aiming to address questions like:

- Is the idea economically and financially worthwhile to evaluate in more detail (move to feasibility study phase) and ultimately pursue?
- What are the regulatory aspects that may facilitate or hinder moving forward with the idea?
- What expected social and environmental impacts would result from implementing the project idea?
- What are the main risks and uncertainties of the idea?

The essence of the PFS is to equip project developers with the knowledge they need to offer a convincing, technologically and economically sound project strategy. This should be presented in a manner that convinces potential investors of the project's viability and potential for financing. The overarching goal is to ascertain if the project concept is feasible from **both business and technical standpoints,** and **to secure funding** for the subsequent phases of the project's evolution.

To achieve this, a PFS concisely captures vital **technical, economic, and financial** details pertinent to the project idea. Central to a PFS is the project's design, which is the primary determinant of its economic viability and overall feasibility. Alongside the technical and economic design, special emphasis must be placed on ensuring the project's **environmental and social alignment.** These considerations are intertwined with assessing the **prospective market context,** which encompasses political, regulatory, and legal frameworks.

1.2 Methodology of the present study

This study aims to outline the essential aspects to consider when conceptualising a GMeOH project in South Africa at pre-feasibility (study) stage. The study is divided into three main parts:

i) **Part 1A:** An overview, introducing the local landscape and elements that favourably influence GMeOH production in South Africa. This part also briefly explains why we focus on the production of GMeOH and not on other PtX products.

ii) **Part 1B:** GMeOH pre-feasibility study guidance – a comprehensive guide detailing key considerations for early-stage GMeOH production facilities. This part includes the exemplary project design, process inputs (like carbon capture and storage, renewable energy, water, hydrogen, and GMeOH production, storage, and transport), site selection, environmental and societal implications, and financial analysis. A range of project implementation strategies is also explored.

iii) **Part 2:** A GMeOH techno-economic pre-feasibility study example, derived from the guidance in Part 1B, exploring a hypothetical GMeOH project. This section includes calculations for the levelised cost of electricity (LCOE), levelised cost of hydrogen (LCOH), and levelised cost of methanol (LCOM) using a specific calculation tool presented in an Excel spreadsheet, which is available at H2.SA.

iv) **Part 3:** A financial pre-feasibility assessment, which delves into the financial intricacies of the GMeOH project, as proposed by Part 2.

Part 1 adheres to the traditional structure of a PFS and can be tailored to any GH_2/PtX project concept. The project can be contextualised and multiple design options can be discussed as illustrated in Part 1B. Thus, Part 1 serves as a standard template detailing the structure and content typically addressed during the project's ideation and preliminary assessment phases. Part 2 examines a concrete project idea with a focus on its techno-economic viability while Part 3 explores potential funding avenues and discusses the composition/blend of various finance options and solutions.

The following chapter summarises the framework conditions for GMeOH production in South Africa. A similar market analysis should precede the techno-economic design of a project idea in any PFS.

PART 1 A:

Brief assessment of local context

PART 1 A:

Brief assessment of local context

Project developers usually have some sense of the market when they first consider a project idea. They are constantly following trends and looking for new developments to fill in the market. The market for GH_2/PtX is only just emerging, while many aspects are new and there are a number of unknowns, especially in the global interplay. The initial project idea might make intuitive sense to the developer, but only a preliminary systematic assessment of all critical elements during the ideating phase of a project provides a sound basis to move the project idea forward.

A market analysis and assessment of the local context investigates the intersection of demand and supply that will create a market for a product at a given price and places the analysis in the overall market context. Part 1A is intentionally detailed to shed light on the market environment. In a known and established market, the analysis may be less extensive, depending on the project idea. A PFS should always include a market valuation to underpin the intuitive entrepreneurial market expectation with facts.

The following section shall give project developers an insight into the current market dynamics in South Africa for the development of a GMeOH project. Moreover, the analysis serves as an orientation aid for a project developer's own assessment of the market environment when ideating their own project.

South Africa has numerous GH_2/PtX market opportunities, ranging from the potential export to international markets, to the use of GH_2 to promote the decarbonisation of the domestic economy, to facilitating maritime transport at its borders and meeting aviation refuelling needs. While green ammonia (GNH_3) emerges as a promising vector for GH_2 export, GMeOH represents another potent pathway worth exploring.

Recent studies, including those by IRENA (2022), have highlighted the cost-effectiveness of GMeOH as a GH2 vector, making it a viable alternative to GNH3 in certain contexts. Furthermore, GMeOH is gaining traction as a sustainable fuel for various maritime and transportation applications. This presents a dual opportunity for both domestic utilisation and international trade (Machaj, 2022) (Roos T. H., 2021), positioning South Africa as a potential global leader in GMeOH trade. Parallel to this, there is a burgeoning potential for GMeOH to revolutionise South African industries, especially those reliant on traditional methanol such as the plastics, resins, and solvents sectors.

In light of these developments, the exploration of GMeOH in South Africa underscores the country's potential strategic positioning for emerging green technologies and markets.

1.3 Why green methanol – market view

1.3.1 International market

Methanol is a versatile chemical compound with multiple applications, ranging from being a feedstock for various derivatives to its usage in transportation and power generation. With the global energy paradigm shifting towards sustainable sources, methanol, especially when derived from renewable sources, has gained significant attention from industry stakeholders and policymakers alike. Some of methanol's derivative chemicals include:

- **Acetic acid** (used in e.g., fleece, adhesives, paints),
- **Methyl methacrylate (MMA)** (used in e.g., PMMA-LCD screens, automotive manufacturing),
- **Silicone** (used in e.g., sealants, lubricants, medical equipment, insulation),
- **Olefins** (used in e.g., plastics, ethyl propylene, polypropylene),
- **Formaldehyde** (used in e.g., medium-density fibreboards, plywood).

As a fuel, it can be used directly (e.g., marine fuels), as a substitute, or in blends with gasoline and diesel, as well as in biodiesel methyl tert-butyl ether (MTBE) and Dimethyl-ether production. Traditionally, methanol production has been reliant on natural gas or coal. However, the advent of renewable sources, such as biomass, biogas, and electrolysis of water using renewable electricity, heralds a transformative phase for methanol production.

In 2022, the global methanol market stood at an estimated 111.2 million metric tonnes[1](Mt), with projections indicating a compound annual growth rate (CAGR) of 4.3% from 2022 to 2032[2]. This growth trajectory is propelled primarily by the demand for methanol-based fuels and chemicals, especially in the Asia-Pacific region, which contributes to over half of the global methanol consumption. The expanding petrochemical sector in countries like China and India further solidifies the market's upward trend. Of the 53 Mt of hydrogen used in industry in 2022, about 30% was for methanol production (IEA, 2023).

Despite the promising outlook, the methanol market is not without challenges. The fluctuating nature of natural gas prices, coupled with the environmental and health repercussions of methanol production, presents significant challenges. Additionally, competition from other fuels and chemicals further intensifies the market dynamics. The COVID-19 pandemic has also cast a shadow, disrupting supply chains, curtailing industrial activities, and dampening demand in 2020 and 2021[3].

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[1] https://www.statista.com/statistics/1323406/methanol-production-worldwide/

[2] https://www.chemanalyst.com/industry-report/methanol-market-219

[3] https://www.fortunebusinessinsights.com/industry-reports/methanol-market-101552

Segmentation of the methanol market reveals a wide array of categories based on derivatives, applications, end-users, and geographical regions. The competitive landscape is equally diverse, with major players like Methanex Corporation, SABIC, PETRONAS, Mitsubishi Gas Chemical Company, and Mitsui & Co., among others, steering the market's direction.

The future of the methanol market appears promising, particularly with technological advancements and emerging applications. GMeOH, produced from renewable sources, is gaining traction as a means to curtail greenhouse gas (GHG) emissions and stride towards carbon neutrality. This form of methanol finds usage both as a low-carbon fuel and as a feedstock for green chemicals. Another domain is methanol fuel cells, presenting a cleaner and more efficient power alternative for a large number of applications.

The global market, valued at USD 3.3 billion in 2019, is expected to swell to USD 5.3 billion by 2027, underpinned by a CAGR of 5.8%[4]. The mounting demand for renewable methanol across chemicals, fuels, transportation, and power generation segments bolsters this growth. Regulatory measures aimed at reducing GHG emissions and the global pivot towards low-carbon energy sources further augment the market's potential.

When compared to conventional fuels, GMeOH offers significant environmental benefits, slashing carbon dioxide emissions by up to 95% and virtually eliminating sulphur oxide and particulate matter emissions. The Methanol Institute has noted over 80 GMeOH projects worldwide, with projections hinting at a production of over eight million metric tonnes of e-methanol and bio-methanol by 2027[5]. These figures, combined with the anticipated surge in the production scale of bio-methanol and e-methanol facilities, underscore the significant potential of the GMeOH market. The projected GMeOH production capacity is presented in Figure 1.

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[4] https://www.alliedmarketresearch.com/renewable-methanol-market

[5] https://www.methanol.org/renewable/

Box 1. Renewable methanol versus green methanol

Understanding the nuances between renewable methanol and green methanol involves delving into the complexities of sustainable fuel production, reflecting a spectrum of opinions within the industry, regulatory bodies, and environmental advocacy groups. The debate centres on the criteria for production processes and the sources of both hydrogen and carbon dioxide used in methanol synthesis.

Renewable methanol: Broadly, renewable methanol refers to methanol produced from renewable resources, which can include biomass, biogas, and municipal waste. The renewable designation emphasises the feedstock's origin, focusing on the sustainability and renewability of the primary material inputs. Regulatory frameworks like the European Union (EU) define renewability by setting a threshold for emissions reduction (currently 70%) to classify fuels as renewable, highlighting the importance of GHG savings in defining renewability.

Green methanol: Green methanol narrows the focus further. Specifically, green methanol is produced using GH_2 - hydrogen generated through the electrolysis of water using renewable energy sources, excluding biomass. Moreover, the carbon dioxide utilised in green methanol production is ideally sourced from the atmosphere (direct air capture) or from biogenic sources, ensuring that the methanol production contributes to a circular carbon economy and achieves net-zero or negative carbon emissions. However, opinions diverge on the strictness of criteria for green methanol, especially regarding the source of carbon dioxide (CO_2). Some stakeholders argue that green methanol should exclusively use CO_2 from renewable energy-powered direct air capture or biogenic sources, ensuring the process's carbon neutrality. Others adopt a more flexible stance, accepting long-cycle CO_2 from various sources, including industrial emissions, as long as the hydrogen used is green. This flexibility aims to increase the scalability of green methanol production by utilising available CO_2 streams, even if they originate from non-renewable sources, under the premise that the overall process still contributes to reducing carbon emissions.

These differing opinions reflect broader debates on how best to achieve decarbonisation goals within the energy sector. While the ideal scenario combines renewable energy sources for hydrogen production with sustainably sourced carbon, practical considerations, and current technological capabilities often necessitate compromises and transitional strategies. In conclusion, the distinction between renewable and green methanol hinges on both the sustainability of feedstock and the carbon intensity of the production process. As the industry evolves, so too will these definitions, driven by advances in technology, regulatory changes, and the imperative to address climate change. The ongoing dialogue among various stakeholders underscores the complexity of achieving truly sustainable energy solutions and the importance of clear, transparent definitions to guide policy and practice.

In this study, the terms green methanol and renewable methanol can be used interchangeably and both imply the use of green hydrogen.

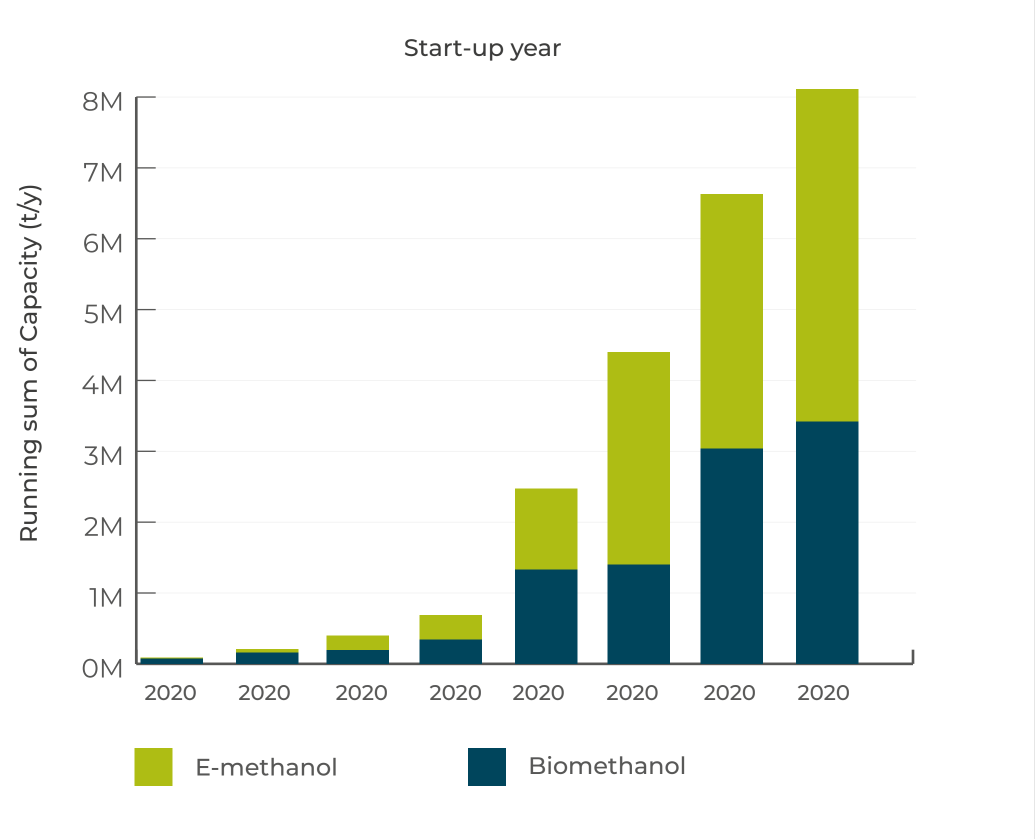

Figure 1: Projected renewable methanol production capacity (Source: https://www.methanol.org/renewable/)

Source: Methanol Institute Renewable Methanol database of current/announced projects

In conclusion, the international methanol market is a dynamic ecosystem, teeming with opportunities and challenges in equal measure. While its foundational significance as an essential chemical building block remains unaltered, the market's evolution, influenced by technological innovations, regulatory landscapes, and global sustainability goals, promises a future replete with possibilities and transformative shifts. The exploration of GMeOH in the South African context accentuates the region's strategic potential in the global energy and chemical landscape.

South Africa can become a pivotal force in the growing global GMeOH market, fortified by its unique competitive advantages. These encompass abundant land resources and a rich repository of renewable energy (RE) sources with high availability factors, both of which can significantly reduce the cost of GMeOH production, making it a lucrative investment prospect for potential financiers.

1.3.2 Local market

The methanol industry in South Africa has observed considerable fluctuations over the past decade. With a Compound Annual Growth Rate (CAGR) of +3.8% from 2012 to 2022, the market has been resilient[6]. The South African methanol market demand stood at 3566.4 thousand metric tonnes in 2020 and is forecast to reach 5207.03 thousand metric tonnes by 2030, growing at a healthy CAGR of 3.37% until 2030[7].

In 2022, the South African methanol market expanded by 2.3%. This growth marks a recovery, following a two-year decline, and signifies the market's second consecutive year of growth. The peak in market value was observed in the period leading up to 2019, after which a slight dip was noted, with the market regaining momentum by 2022. Despite the global challenges, the production of methanol in South Africa has been steady, with the total output value reflecting an average annual growth of +2.5% from 2012 to 2022.[8]

South Africa's methanol exports experienced a sharp downturn in 2022, plummeting by 68.8%. Historically, exports peaked in 2012, but have since faced a persistent decline. The primary importer of South African methanol is Nigeria, accounting for a 66% share of total exports. Other significant destinations include China and Ghana. Over the decade, exports to Nigeria have been dwindling at an average rate of -8.2%. Similarly, exports to China have decreased at an average of -2.5%. In contrast, Ghana has seen a remarkable surge, with an average growth rate of +30.9% over the same period. The most significant price hike was observed in 2021, with a 204% surge. Over the years, export prices have been volatile, with the highest prices being for exports to China and the lowest for Tanzania[9].

The methanol imports into South Africa witnessed robust growth in 2022, surging by 204%. This growth signifies a positive trend, especially after a period of stagnation in the market. The Netherlands emerged as the dominant supplier, contributing to the bulk of methanol imports into South Africa. Following closely are Qatar and Saudi Arabia. Over the past decade, imports from The Netherlands have grown exponentially, with a CAGR of +220.1%. Over the years, import prices have witnessed significant fluctuations. Among the main foreign suppliers of methanol to South Africa, Trinidad and Tobago offered the highest price, while Saudi Arabia provided one of the lowest[10].

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[6] https://www.indexbox.io/store/south-africa-methanol-methyl-alcohol-market-analysis-forecast-size-trends-and-insights/

[7] https://www.chemanalyst.com/industry-report/south-africa-methanol-market-211

[8] https://www.indexbox.io/store/south-africa-methanol-methyl-alcohol-market-analysis-forecast-size-trends-and-insights/

[9] *Ibid.*

[10] https://www.indexbox.io/store/south-africa-methanol-methyl-alcohol-market-analysis-forecast-size-trends-and-insights/

The EU's Carbon Border Adjustment Mechanism (CBAM) presents both a threat and an opportunity for South African methanol exports to the EU. As a policy tool designed to ensure that carbon-intensive goods entering the EU bear a carbon cost akin to domestic production, the CBAM can significantly influence the competitiveness of South African methanol in the European market. At present, the CBAM does not explicitly cover methanol, as its focus is on certain goods and selected precursors categories (cement, iron and steel, aluminium, fertilisers, electricity, and hydrogen).

However, the expected expansion of the CBAM to cover chemicals and alternative fuels is likely to increase the import costs of fossil-derived methanol entering the EU. This shift in regulation poses significant challenges for South Africa's traditional methanol sector, while, at the same time, improving the market prospects for locally produced GMeOH for export since it significantly increases the economic rationale for investing in GMeOH production.

1.3.3 Border market

Maritime shipping remains a significant challenge in the quest to reduce global GHG emissions. PtX products present a promising solution for this hard-to-abate sector. At the International Maritime Organisation (IMO) Marine Environment Protection Committee gathering in July 2023, member states pledged to a set of ambitious GHG targets (IMO, 2023):

1. A commitment to slash the CO_2 emissions intensity of international shipping by 40% by 2030, benchmarked against 2008 levels,
2. Embrace zero or near-zero GHG emission technologies, fuels, or energy sources, aiming for them to constitute at least 5%, with an aspiration towards 10%, of the energy consumed by international shipping by 2030,
3. Endeavour to achieve net-zero GHG emissions from international shipping around 2050.

Being an integral part of the United Nations (UN), the IMO's resolutions are obligatory for member states. This commitment thus paves the way for a growing market for sustainable bunker fuels. Among the leading contenders in the realm of sustainable bunker fuels are GNH_3 and GMeOH, both of which offer distinct advantages:

1. Ammonia stands out as a sustainable fuel option as it emits zero CO_2 upon combustion. While there are concerns regarding the emission of nitrogen oxides (NOx), these can be mitigated through controlled combustion temperatures and exhaust gas treatments. Given its potential impact on marine life, ammonia's toxicity must not be overlooked. Companies like Wärtsila and MAN are already venturing into the development of GNH_3-compatible marine engines. Notably, the Belgian Compagnie Maritime Belge (CMB) has championed GNH_3 as their preferred

sustainable marine bunker fuel. An added advantage of GNH_3 as a marine fuel is its potential role as a primary transport vector for GH_2, indicating its likely availability wherever export initiatives are present. However, at the time of writing the IMO is yet to finalise regulations for maritime shipping utilising GNH_3.

2. GMeOH has a number of strengths. The strength of methanol lies in its closed carbon loop when produced sustainably through GH_2 and with sustainably sourced CO_2 positioning it as an eco-friendly and efficient fuel option for the maritime industry. Unlike conventional marine fuels, which are high in sulphur and carbon content, GMeOH combusts to produce mainly water and CO_2. This process makes it a near-carbon-neutral fuel when considering the lifecycle emissions. Additionally, GMeOH can be used in internal combustion engines with minor modifications, providing a feasible transition option for existing fleets alongside new builds. Advancements in technology further bolster the case for GMeOH. Companies such as Wärtsilä and MAN are developing marine engines specifically designed to run on methanol, offering more efficient combustion processes and designs optimised to handle GMeOH's lower energy density compared to traditional fuels. These developments are critical as they address one of the primary challenges of adopting new fuels – the retrofit of existing infrastructure – which is a significant barrier in the maritime industry.
3. GMeOH also offers distinct advantages as a maritime fuel, particularly in terms of safety and existing infrastructure compatibility. GMeOH is less toxic and easier to handle than ammonia, reducing risks associated with storage and bunkering operations. Moreover, methanol can be integrated more seamlessly into current fuel infrastructure and requires fewer modifications for use in existing engine designs compared to GNH_3, which necessitates significant adaptations due to its corrosive properties and higher ignition energy. This makes GMeOH a more immediately viable option for widespread adoption in the maritime industry.

1.4 Methanol as GH_2 vector

Methanol, a versatile and well-established chemical compound, is emerging as a prominent vector for GH_2. Its liquid state at ambient conditions offers significant advantages for transportation and storage. Methanol can be transported and stored using existing infrastructure, reducing capital costs.

South Africa's rich RE resources, especially solar and wind, present a potential for producing GH_2 through water electrolysis. This GH2 can then be combined with a carbon source to synthesise GMeOH, offering a more energy-dense and easily transportable form of RE.

The complexity of GMeOH as a hydrogen vector is intricately linked with its carbon component. Synthesising methanol from GH_2 requires a carbon source, and preserving methanol's renewable character typically veers towards biogenic carbon. This approach, derived from biomass or Direct Air Capturedirect air capture (DAC), brings its suite of challenges. Biomass sources grapple with issues like land competition, water requirements, and potential clashes with food production. DAC is a technology still evolving which remains energy-intensive.

For applications where methanol's carbon component plays a crucial role, such as specific chemical processes, its production is justifiable. Conversely, for endeavours solely hinging on elemental hydrogen, transitioning from GH_2 to GMeOH and back might not be the optimal route.

In essence, GMeOH shines brightest when applications can harness both its hydrogen and carbon attributes efficiently. Additionally, methanol is a primary feedstock for a wide range of chemical products. This means that once transported to its destination, GMeOH can be sold directly to end users without the need for further conversion. This is a significant advantage over other carriers like GNH_3, which would typically need to be cracked back into GH_2 to be usable in many applications.

In conclusion, while methanol is a promising hydrogen vector, its potential is maximised in specific applications that benefit from its dual attributes. As the global push for sustainable energy solutions intensifies, the role of GMeOH in the energy transition landscape will likely become (even) more significant.

1.5 Why South Africa?

The potential for large-scale production of GMeOH in South Africa is significantly bolstered by geographical, regulatory, and policy factors. South Africa's unique geographical positioning, combined with a conducive regulatory environment and forward-thinking energy policies, positions it at the forefront of GMeOH production. The subsequent sections explore these distinct advantages, explaining why South Africa can be considered a prime location for GMeOH production catering for both the international market and the domestic demand.

1.5.1 Domestic methanol production and use

Currently, Sasol is the largest producer of methanol in South Africa, based on their coal-to-liquid processes. A large portion of the produced methanol (up to 60%) is used internally for Sasol's TAME (tertiary amyl methyl ether) process as well as a CO_2 capturing solvent in their Rectisol process.

A large proportion of the remainder methanol is distributed through local supply agreements to producers of formaldehyde. Data (2019) given in Table 1 below were drawn from multiple market reports and interviews conducted by CSIR in 2019 indicate production levels and consumers.

Table 1: 2019 Methanol usage data in South Africa

User	Area	Consumption of methanol (Metric tonnes per annum) 2019
Formaldehyde producers	-	**44,000**
Wood Chemicals	Piet Retief	40,500
Resinkem	Umbogintwini	3,500
TAME producer	-	**80,000**
Sasol	Sasolburg	80,000
Captive as process chemical	-	**4,000**
Sasol	Secunda	4,000
Methylamine producer	-	**8,000**
African Amines	Newcastle	8,000
Other identified users (including paint strippers, fuel & heating)		**4,000**
Total		**140,000**

South Africa also imports methanol, with the Netherlands and Qatar being the largest trade suppliers over the last two years (SARS data)[11].

1.5.2 Renewable energy resources

Solar photovoltaic (PV) and wind energy stand out as the primary RE sources best suited to drive the generation of GH_2 and subsequently GMeOH in South Africa. The vast landscapes of South Africa, blessed with consistent sunlight and steady winds, are conducive to harnessing these energy forms efficiently. A solar and wind atlas are presented in Figure 2.

While concentrating solar power (CSP) equipped with thermal storage presents a viable option, especially for supplying dispatchable renewable electricity during night-time, its cost competitiveness lags behind PV and wind. The expense associated with CSP makes it a less preferred choice.

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[11] https://tools.sars.gov.za/tradestatsportal/ (accessed 05/02/2024). Methanol tariff code is 29051100

Preliminary studies have revealed South Africa's enormous potential in pioneering an offshore wind industry. The country's expansive coastline, combined with its offshore wind capabilities, culminates in a technical potential of an estimated 49 giga watt (GW) for fixed platform and 852 GW for floating platform offshore wind energy production (World Bank, 2021).

While solar PV and wind energy are pivotal to South Africa's green energy landscape, the potential of biomass-derived energy should not be underestimated (Figure 2). Biomass power plants offer a viable source of biogenic CO_2 and can provide a steady stream of renewable electricity. This electricity can act as a base load complementary to the intermittent nature of solar or wind (as it will be shown in Part 2), thus serving as a reliable backbone to the energy mix.

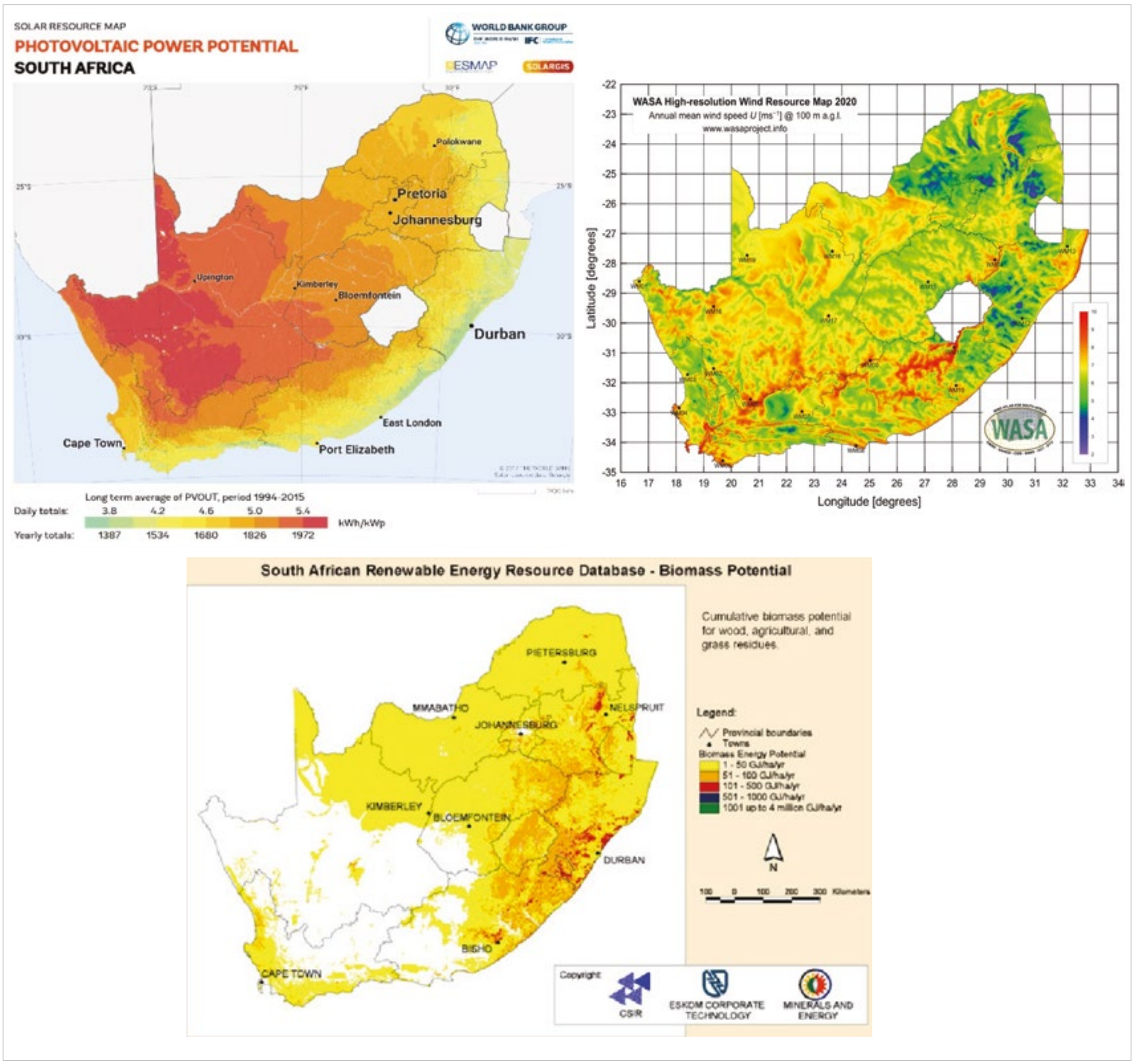

Figure 2: South African solar (left), wind (right) and biomass (bottom left) resource (https://solargis.com/; http://wasadata.csir.co.za/wasa1/WASAData; (Banks, 2005))

However, the absence of a detailed framework for renewable synthetic fuels and energy carriers poses a challenge and offers an opportunity at the same time. It is imperative for policymakers to consider the inclusion of biomass-derived electricity, especially in hybrid configurations with PV or wind. Such an approach would not only optimise energy provision costs but also reduce the reliance on battery storage solutions on project development level. As South Africa charts its path in renewable fuels'/energy carriers' regulations, it is crucial to ensure flexibility, inclusivity, and foresight in the policies, ensuring that they are adaptable to the evolving energy landscape.

1.5.3 (Ex)Port infrastructure

GMeOH is emerging as a promising vector for the export of GH_2 from South Africa. The factors driving this viability include South Africa's rich RE resources, ample land apt for RE installations, and the strategic advantage of having a local carbon source, thereby reducing the intricacies and costs associated with transporting gases. The prime locations for GMeOH production should either be adjacent to a port, minimising overland transport expenses, or at locations connected by a railway network. The main relevant ports to serve the export are presented in Figure 3.

Figure 3: Southern African ports (Maritime Studies South Africa, 2015)

However, exporting GMeOH from ports situated in urban areas demands meticulous planning and heightened safety protocols. Methanol's low flash point signifies its flammability, and its combustion yields a barely visible blue flame, making it difficult to detect in case of fires.

Several of South Africa's commercial ports present challenges for the bulk export of GMeOH due to their urban settings. However, in each case a less constrained "sister" port exists nearby:

- **Durban,** with its bustling activities, is shifting its liquid fuel operations to the **Port of Richards Bay**, approximately 170 kilometres (km) to the northeast, a decision taken by the Transnet National Ports Authority (TNPA).
- **The more spacious Port of Saldanha Bay, located 110 km to the north, overshadows Cape Town port, constrained by limited land.**
- **Gqeberha** (formerly Port Elizabeth) might be in close proximity to urban centres, but the more expansive **Port of Ngqura (Coega)** is a mere 20 km away.
- Certain ports like Mossel Bay, Lüderitz, and East London, due to their shallow draughts, might not be optimal for GMeOH export. Nonetheless, they can still participate in the GMeOH supply chain, especially by leveraging bunker barges for the provision of sustainable bunker fuel.

The following ports stand out for GMeOH export:

- **Saldanha Bay** is South Africa's deepest port, accommodating vessels with draughts up to 20.5m.
- **Coega/Ngqura** is designed for a variety of vessels, boasting berths with draughts reaching 16.5m.
- **Richards Bay,** the country's primary exporting port, offers a plethora of berths with depths extending up to 19 metres (m).
- **Boegoebaai,** an upcoming deep-water port near the Namibian border, is poised to introduce two berths, bolstered by an extensive railway system and supplementary infrastructure.

Furthermore, the **Port of Maputo** in Mozambique presents potential as an export hub for GMeOH. Its proximity to South Africa and its berths with average draughts of 10-11m make it a contender. While it lies 60 km from the South African border, accessing prime solar and wind resources would require a journey of at least 200 km decreasing its attractiveness for the purpose at hand.

In light of the considerations outlined, the ports of Saldanha Bay, Coega/Ngqura, Richards Bay, and Boegoebaai emerge as primary contenders for the export of GMeOH from South Africa. The final selection among these ports will be intricately tied to their proximity and connectivity to essential feedstock resources, particularly biomass plants, vital for GMeOH production. In the subsequent sections, we will delve deeper into this interrelation, evaluating the synergies between port infrastructure and the availability of feedstock to determine the most strategic location(s) for GMeOH production and export in Part 2 of this study.

1.5.4 Special Economic Zones

Special Economic Zones (SEZs) are strategically designated regions crafted to stimulate economic activities, drive exports, and foster a conducive environment for business operations. They serve as key pillars for South Africa's economic strategy, offering a blend of incentives, infrastructure, and strategic location to attract both domestic and international investments. In accordance with the SEZ Act No 10 of 2014, South Africa has demarcated four distinct categories of SEZs:

- **Free Port:** Located adjacent to entry ports, these zones facilitate duty-free unloading of imported goods. Within these areas, goods can undergo various value-adding activities such as storage, processing, or repackaging, all while being subject to customs regulations.
- **Free Trade Zones (FTZs):** Predominantly duty-free, FTZs offer advanced storage and distribution amenities. They cater to value-adding activities within the SEZ, primarily targeting subsequent export markets.
- **Industrial Development Zones (IDZs):** Specifically designed industrial estates, IDZs are magnets for both domestic and foreign direct investments. Their primary focus is on nurturing value-added, export-oriented manufacturing sectors and services.
- **Sector Development Zones (SDZs):** These zones concentrate on the growth of specific industries or sectors. Through a combination of tailored industrial infrastructure, incentives, and technical services, they cater predominantly to the export market.

At present, South Africa has 11 SEZs, strategically dispersed across various provinces, each offering unique advantages and facilities as depicted in Figure 4.

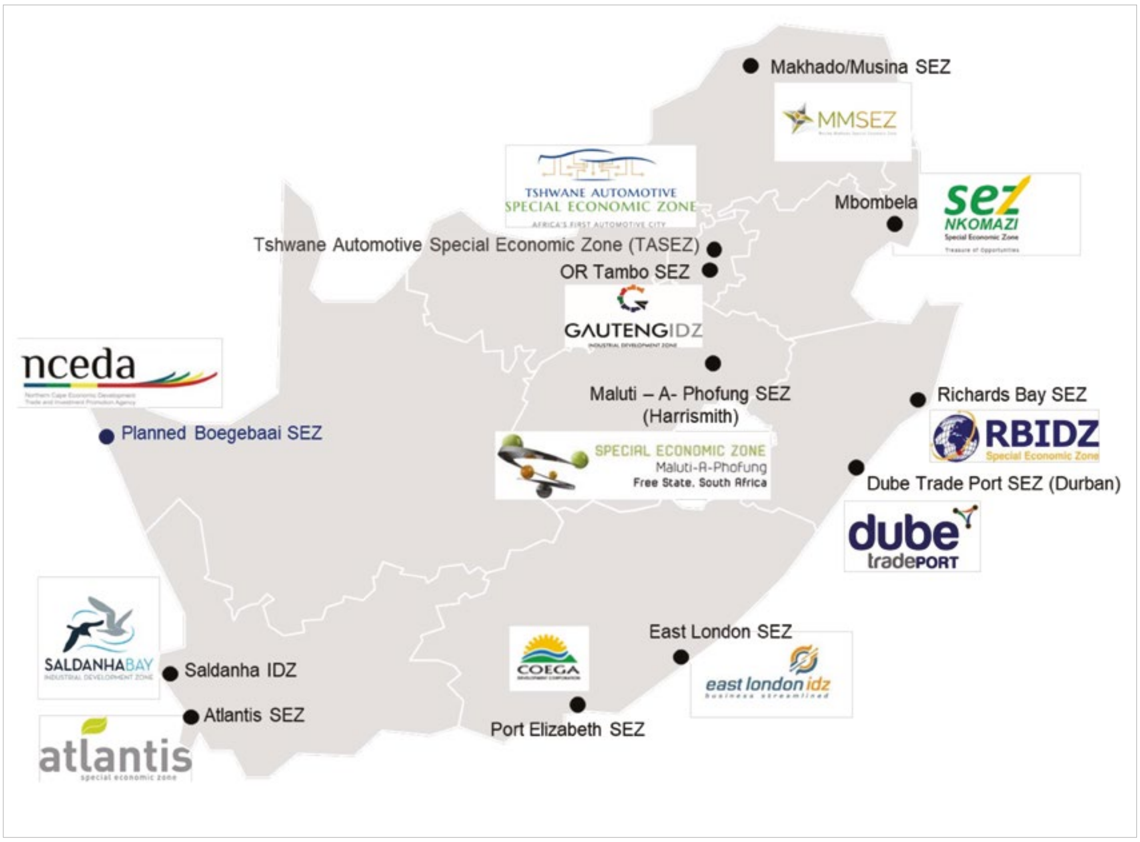

Figure 4: Location of South Africa's 11 existing SEZ's and the planned Boegoebaai SEZ (CSIR, 2023)

SEZs play a pivotal role in bolstering South Africa's economic trajectory. They not only lure foreign direct investments (FDI) but also enhance the nation's export competitiveness, amplify employment avenues, and pave the way for technological advancements. In the context of GH_2/PtX projects, certain SEZs offer competitive advantages, such as:

- Good wind and solar resources potential,
- Proximity to port infrastructure,
- Enabling ease of access to the export markets, which are key enablers to support the development of the GH_2 economy.

Further sweetening the proposition for businesses, SEZs roll out a plethora of incentive schemes:

- A preferential corporate tax rate of 15% for eligible entities,
- An accelerated 10% depreciation allowance on infrastructure,
- Exemptions from customs duties and value added tax (VAT) on imported raw materials and production-related goods,

- Employment tax incentives for companies hiring low-income employees (with annual salaries below ZAR 60,000)[12],
- Tax allowances for both new industrial initiatives and enhancements to existing projects.

Historically, SEZs have successfully enticed a broad spectrum of industries, ranging from RE developers and gas solution providers to steel producers, cement plants, and manufacturers of fuel cell electric vehicle (FCEV) components. This record underpins their potential as catalysts to spearhead the GH_2 economy in South Africa.

1.5.5 Political framework

South Africa has shown considerable foresight in its approach to the GH_2 economy, as evidenced by the development and implementation of key national policies and strategies. The prominent guiding documents in this realm are the Hydrogen Society Roadmap for South Africa (HSRM) (Innovation, 2021) and the Green Hydrogen Commercialisation Strategy for South Africa (GHCS) (Department of Trade, 2022).

The core objectives outlined in both the HSRM and GHCS revolve around establishing robust GH_2 export markets and spearheading the decarbonisation efforts across diverse economic sectors. The HSRM stands out as a cornerstone document in this context. Its overarching goal is to stimulate the country's economic growth, catalyse sustainable green employment opportunities, advance national competitiveness, and transition towards a secure, affordable, and sustainable energy future (DSI, 2022).

To achieve this, the HSRM has delineated six strategic priority actions for cultivating the GH_2 economy in South Africa:

- Development and optimisation of hydrogen production, storage, and distribution processes,
- Establishment and expansion of an export market for GH_2 products,
- Decarbonisation initiatives targeting the transport sector,
- Greening the energy-intensive industrial domain,
- Enhancing the power sector with sustainable green energy solutions,
- Positioning South Africa as a global hub or 'centre of excellence' for manufacturing in the hydrogen sector.

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[12] *Approximately EUR 3000 (October 2023).*

Supplementing these actions, the HSRM also highlights several catalytic projects. These include the establishment of the Boegoebaai SEZ with a focus on GNH3 production; the Platinum Valley Initiative aimed at decarbonising the heavy-duty transportation sector; and initiatives for sustainable aviation fuels (SAF) that leverage existing Fischer-Tropsch infrastructures.

On the other hand, the GHCS identifies the vast commercial prospects that South Africa holds in pioneering a green energy sector. Specific avenues include:

- Production and international export of GH_2 to cater to emerging global green energy markets,
- Domestic GH_2 production to reach South Africa's decarbonisation goals,
- Fostering industrial competencies in manufacturing and supplying equipment pivotal to the global GH_2 value chains.

Furthermore, the GHCS envisions the immediate trajectory of the South African GH_2 economy to emphasise compression and fuel cells for diverse mobility needs, alternative fuels for transport, shipping and aviation, ammonia and methanol production, and industrial applications, particularly concerning chemicals and metal furnaces (see Figure 5).

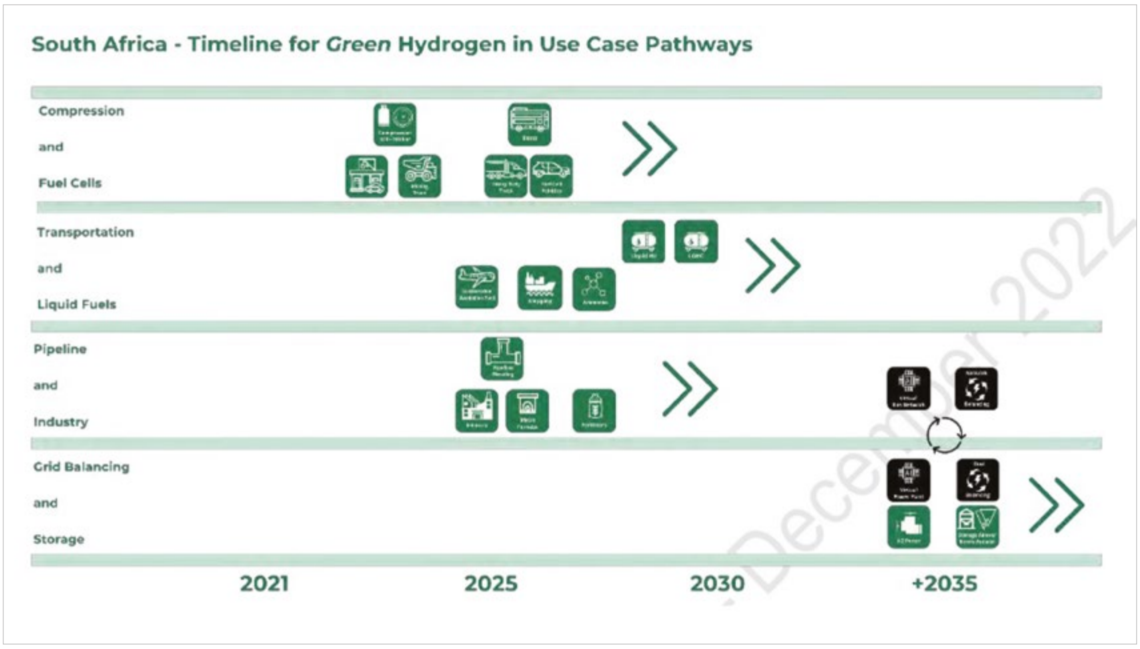

Figure 5: Indicative GH_2 commercialisation roadmap (DTIC, 2022:21)

In view of this study, a key initiative is the methanol production project by a consortium, including Earth and Wire, ENERTRAG South Africa, and 24Solutions to establish a pioneering facility in Humansdorp, Eastern Cape. This facility aims to produce zero-carbon e-methanol for both domestic consumption and export. The production process will integrate GH_2 with carbon sourced from a blend of local biomass and non-recyclable municipal waste.

In addition to the HSRM and GHCS, South Africa's Just Energy Transition Investment Plan (JET IP) underscores the nation's commitment to a low-emission, climate-resilient future. It identifies the GH_2 sector as pivotal in achieving a just energy transition, positioning South Africa as a global leader in GH_2 export. The proposed investments between 2023-2027 for the GH_2 and GMeOH subsectors amount to ZAR 319.01 billion, which includes ZAR 0.12 billion for project feasibility and ZAR 12 billion for capital cost investments.

However, for South Africa's hydrogen economy to flourish, regulatory and policy enablers are indispensable. While the country possesses several policies conducive to nurturing the GH_2 economy, there exist challenges. These barriers encompass electricity grid reliability, clarity in sector-specific strategies, and a lack of regulations for hydrogen transport and storage. Potential catalysts that demand urgent attention include financial incentives, clear sector planning, technology standardisation, and strengthened safety specifications.

In essence, South Africa's GH_2 policy framework reflects a holistic vision, encompassing both immediate actions and long-term strategies. The nation's commitment to fostering a sustainable hydrogen economy is evident, with the promise of significant economic, environmental, and societal benefits on the horizon (Innovation, 2021).

PART 1 B:

Pre-Feasibility Study Guidance

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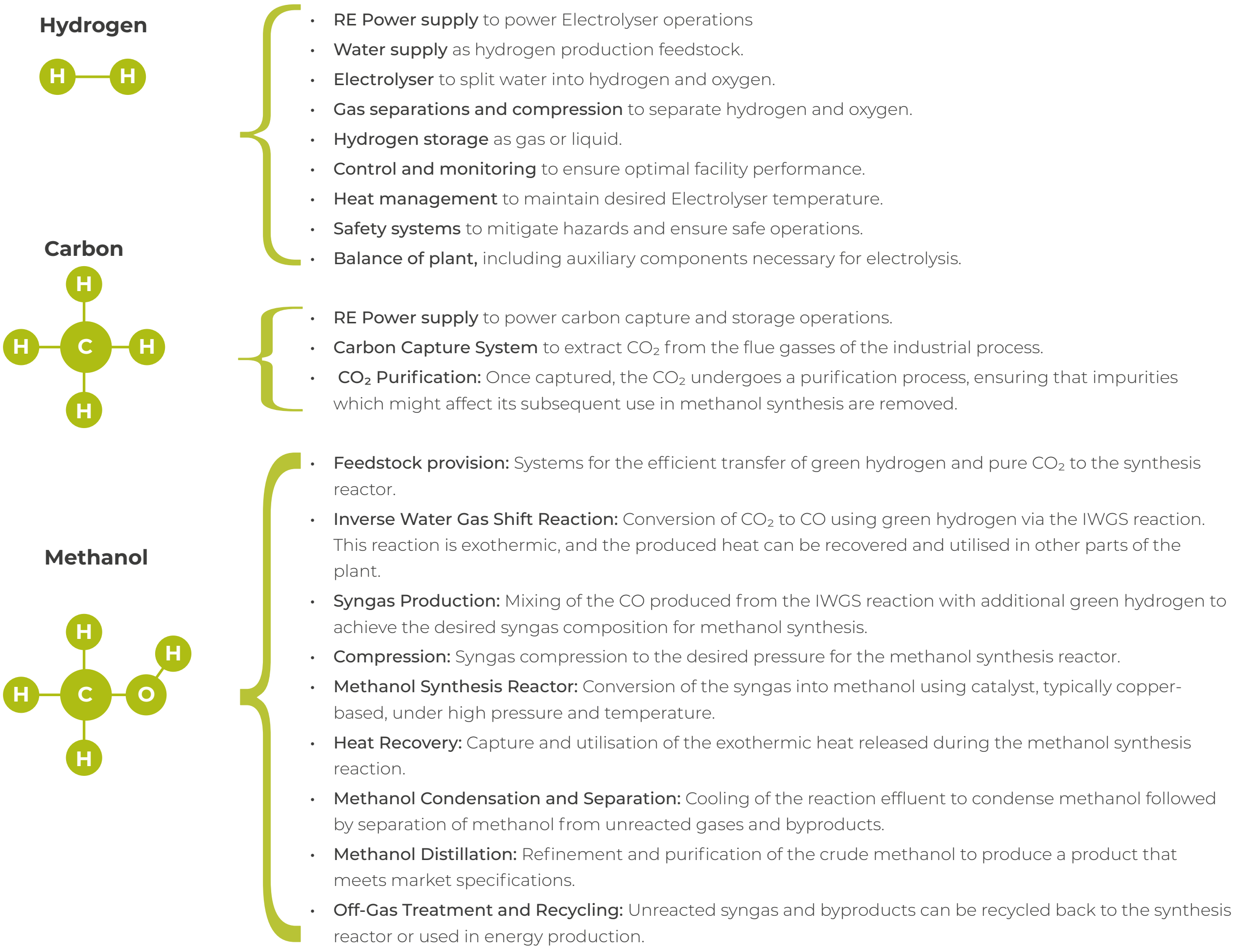
Pre-Feasibility Study Guidance

Once the analysis of the framework and market conditions is complete, the PFS should turn to the centrepiece; the exploration of the possible project design(s). This following chapter is dedicated to the techno-economic design of a GMeOH project and explores relevant options.

GMeOH production involves three main components: 1) GH_2 production, 2) the provision of a carbon source, and 3) GMeOH production (Figure 6). It should be noted that this figure assumes the use of point carbon sources.



Hydrogen

- **RE Power supply** to power Electrolyser operations
- **Water supply** as hydrogen production feedstock.
- **Electrolyser** to split water into hydrogen and oxygen.
- **Gas separations and compression** to separate hydrogen and oxygen.
- **Hydrogen storage** as gas or liquid.
- **Control and monitoring** to ensure optimal facility performance.
- **Heat management** to maintain desired Electrolyser temperature.
- **Safety systems** to mitigate hazards and ensure safe operations.
- **Balance of plant,** including auxiliary components necessary for electrolysis.

Carbon

- **RE Power supply** to power carbon capture and storage operations.
- **Carbon Capture System** to extract CO_2 from the flue gasses of the industrial process.
- **CO_2 Purification:** Once captured, the CO_2 undergoes a purification process, ensuring that impurities which might affect its subsequent use in methanol synthesis are removed.

Methanol

- **Feedstock provision:** Systems for the efficient transfer of green hydrogen and pure CO_2 to the synthesis reactor.
- **Inverse Water Gas Shift Reaction:** Conversion of CO_2 to CO using green hydrogen via the IWGS reaction. This reaction is exothermic, and the produced heat can be recovered and utilised in other parts of the plant.
- **Syngas Production:** Mixing of the CO produced from the IWGS reaction with additional green hydrogen to achieve the desired syngas composition for methanol synthesis.
- **Compression:** Syngas compression to the desired pressure for the methanol synthesis reactor.
- **Methanol Synthesis Reactor:** Conversion of the syngas into methanol using catalyst, typically copper-based, under high pressure and temperature.
- **Heat Recovery:** Capture and utilisation of the exothermic heat released during the methanol synthesis reaction.
- **Methanol Condensation and Separation:** Cooling of the reaction effluent to condense methanol followed by separation of methanol from unreacted gases and byproducts.
- **Methanol Distillation:** Refinement and purification of the crude methanol to produce a product that meets market specifications.
- **Off-Gas Treatment and Recycling:** Unreacted syngas and byproducts can be recycled back to the synthesis reactor or used in energy production.

Figure 6: The main components constituting the production of GMeOH

To withstand scrutiny by a potential investor, a project design idea of a GMeOH project should consider the following mains elements:

- **Project design:**
    - Establishing an appropriate technical design scenario,
    - Selecting a site/s,
    - Sizing the methanol production plant,
    - Determining costs,
    - Considering any engineering, procurement and construction (EPC) requirements,
    - Establishing potential ownership structures.
- **Environmental and social aspects:**
    - Early consideration of environmental and social constraints to select suitable site options,
    - Understanding the impact drivers and ultimate environmental and social impacts.
    - Authorisations, approvals and permits:
    - Identification of any approvals required in terms of the applicable regulatory frameworks.
- **Stakeholders:**
    - Identify stakeholders that will play a role during the project development and implementation.
- **Typical development phases and schedule:**
    - Outline the development steps and timeframes, taking into account any timeframes associated with approvals,
    - Identify potential long-lead or time-sensitive steps.
- **Financial assessment:**
    - Determine the potential business case of the project idea, including estimate weighted average cost of capital (WACC), capital expenditures (CAPEX) and operational expenditures (OPEX).

2. Project design

Traditionally, methanol production has relied on the conventional methanol synthesis (CMS) process, wherein carbon monoxide (CO) and hydrogen (H_2) react to form methanol, described by the chemical reaction: $CO + 2H_2 \rightarrow CH_3OH$. This approach predominantly uses natural gas as a feedstock, but can be adapted to utilise CO_2 and GH_2 as feedstock. To align with the CMS process, the initial step involves converting the captured CO_2 to CO using the inverse water gas shift reaction. Once CO is produced, it is combined with GH_2 in a reactor. In the presence of a catalyst, these substances react to produce methanol and water. After the reaction, the resultant mixture is subjected to a purification process to yield high-purity methanol. This environmentally conscious approach, leveraging captured CO_2 and GH_2, exemplifies the industry's progression towards sustainable methanol production.

In this section, we delve into the design principles and prerequisites for a GMeOH project. We consider the challenges associated with GMeOH production, including the fluctuating nature of RE sources, the necessity for consistent operation of the methanol synthesis reactor, and the associated capital (CAPEX) and operational (OPEX) expenses.

One of the critical elements of the GMeOH production is the carbon source. For this reason, it is important to explore and evaluate the prevailing current (and future) sources of carbon at PFS stage. The aim must be to identify a sustainable carbon source at the outset of the ideation process. In addition to the technical feasibility and sustainability of the production, the identification and fixture of a reliable carbon source is also a key component of the financial pre-feasibility assessment in view of the bankability of a project.

For this reason, the following snapshot on carbon sourcing precedes the technical design of the operations.

2.1 Carbon source - snapshot

The production of GMeOH requires GH_2 and carbon/CO_2, with the latter playing a pivotal role in the synthesis process. The origin and type of carbon used for GMeOH production can significantly affect the sustainability, environmental and emission footprint of the methanol production. Carbon sources for methanol synthesis can be broadly categorised into two main groups based on their carbon cycle length and in full alignment with the Intergovernmental Panel on Climate Change (IPCC):

Group 1 - Long-cycle carbon sources: Long-cycle carbon sources are those that release carbon into the atmosphere that has not been in circulation for millions of years. These sources primarily involve carbon stored in geological formations.

1. **Oil-derived sources:** These are traditional fossil fuel-based sources where carbon is extracted from underground reserves in the form of oil, coal, or natural gas. When this carbon is burned or processed, it releases CO_2 that has been sequestered for millions of years, adding to the atmospheric CO_2 concentration.
2. **Unavoidable carbon:** Certain industrial processes release CO_2 as a by-product, even though carbon might not be the primary raw material. An example is the cement industry for which limestone ($CaCO_3$) is a key raw material. When heated to produce lime (CaO), CO_2 is released. This CO_2 is ancient carbon being reintroduced into the atmosphere.

Group 2 - Short-cycle carbon sources: Short-cycle carbon sources are those that have a relatively quick turnover in the environment, typically within a span of a few years to a decade. These sources primarily involve carbon that is actively circulating in the atmosphere and biosphere.

1. **Direct air capture:** DAC is a technology that captures CO_2 directly from ambient air. Since the atmospheric CO_2 concentration is a mix of both recent and ancient emissions, DAC can be considered a short-cycle source, especially when the captured CO_2 is used and then released within a short timeframe.
2. **Biogenic CO_2:** This carbon source originates from biological processes. For instance, when plants grow, they absorb CO_2 from the atmosphere. When these plants decompose or are processed, they release this CO_2 back into the atmosphere. Capturing this CO_2 for methanol synthesis essentially borrows carbon that was recently in the atmosphere, making it a short-cycle source.

The distinction between short-cycle and long-cycle carbon sources is crucial, especially in the context of climate change and methanol production. Short-cycle sources are considered more sustainable as they do not release ‘new’ carbon to the atmosphere. Instead, they operate within a closed loop, recycling the same carbon molecules. On the other hand, long-cycle sources add to the net atmospheric CO_2 levels, exacerbating global warming.

The choice of carbon source also affects the ‘green’ credentials of the methanol produced. Methanol derived from short-cycle sources can be termed “green” or “renewable” methanol as it does not contribute to the net increase in atmospheric CO_2 over its lifecycle. In contrast, methanol produced using long-cycle sources does not qualify as ‘green’.

However, it is important to note that while the source of carbon is a significant factor, other considerations, such as energy used in the production process, transportation, and overall lifecycle analysis, also play a role in determining the sustainability of the methanol production.

There is a growing emphasis on leveraging short-cycle carbon sources to reduce GHG emissions and achieving net-zero. For the exploration of GMeOH production, the choice of the carbon source will be a critical factor, influencing both the environmental impact and the market acceptance.

2.1.1 Group 1 - Long-cycle carbon sources

The utilisation of fossil-derived carbon, particularly in the synthesis of methanol, is a critical point for discussion in view of any methanol production. Long-cycle carbon sources can be captured from industrial facilities using fossil fuels like coal and oil or constitute so-called unavoidable carbon emissions, such as those from lime in cement production.

Harnessing fossil-derived carbon to produce methanol epitomises resource efficiency by repurposing carbon emissions into a valuable and useable product, which would otherwise be released to the atmosphere. Moreover, capturing CO_2 from existing fossil-fuel based plants can, in some instances, prove more cost-effective than other CO_2 sources. This financial advantage can catalyse early adoption and scaling of carbon capture and utilisation (CCU) technologies. Industries that currently rely heavily on fossil fuels can embark on a phased transition towards more sustainable energy sources. This not only reduces their GHG emissions but, in conjunction with CCU technologies, also creates point sources of biogenic carbon. Such a transition ensures that industries remain resilient and adaptable in a rapidly changing energy landscape.

While capturing and using fossil-derived carbon emissions for methanol synthesis offers immediate benefits, it is crucial to recognise the long-term implications. Utilising these emissions in products merely delays their release into the atmosphere, as most products have a finite lifecycle. From an environmental perspective, storing these emissions (carbon capture and storage, CCS) might offer a more sustainable solution, especially for unavoidable carbon emissions. It is interesting to see novel concepts researched like mineralisation in the cement industry in order to store the unavoidable emissions in the product of the plant[13]. This approach ensures that long-cycle carbon remains sequestered, mitigating its climatic impact.

Investments in CCS technologies demand significant capital and have a long-time horizon, often extending beyond 2050. For any investment in CCS, it appears imperative to strategise with a forward-looking lens, ensuring that investments today align with the sustainability imperatives of tomorrow. While the utilisation of fossil-derived carbon in methanol synthesis in particular and synthetic fuels in general offers tangible benefits, it is essential to approach it with a holistic and long-term perspective. In view of the methanol production, the focus must be on the product and its properties, especially when it comes to export or use in shipping, because, as shown, there are established rules for when a product is considered green.

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[13] *https://www.nature.com/articles/s43247-022-00390-0*

2.1.2 Group 2 - Short-cycle carbon sources: DAC

DAC seeks to actively removing CO_2 directly from the ambient air. The technology operates on a principle of chemically binding CO_2 from the atmosphere to a medium, often a liquid solvent or solid sorbent. Once captured, the CO_2 can be concentrated, purified, and then either stored or used as a raw material in various applications, including methanol synthesis.

Advantages

1. **Flexibility:** Unlike other carbon capture techniques that need to be co-located with emission sources, DAC systems can be installed virtually anywhere. This flexibility ensures that they can be strategically placed closer to storage or utilisation sites, reducing transportation needs.
2. **Scalability**: DAC technology has the potential to be scaled up to capture significant amounts of CO_2, making it a viable option in the global effort to combat climate change.
3. **Global impact:** Since DAC draws CO_2 directly from the atmosphere, every tonne captured has a direct, global impact on atmospheric CO_2 levels.

Challenges and other considerations

Economic viability: While the technology holds immense promise, to date its economic feasibility remains a significant hurdle. Estimates of the cost of capturing CO_2 using DAC vary widely. A running pilot plant by Climeworks in the United States of America has a cost of around USD 600/tonne of CO_2. Cost of capturing CO_2 from the air is estimated to drop to USD 250-300/tonne of CO_2 by 2030. There is potential to further decrease these costs down to USD 100/tonne of CO_2 by 2050, but so far, projections have not been achieved[14,15.]

Energy requirements: DAC systems are energy-intensive. To become a viable solution in the green and just energy transition, the energy required to power the DAC should ideally come from RE sources. This necessity further complicates the economic calculations, as it ties the feasibility of DAC to the availability and price of RE.

Land and infrastructure: Establishing DAC facilities requires significant land, which can raise concerns related to land use, ecosystem disruption, and biodiversity impacts. All the more so as space requirements are huge when coupled with RE facilities[16], e.g.

- 34.7 km2 for a 1 Mt/year plant when powered by PV
- 66 km2 for a 1 Mt/year plant when power by wind energy

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[14] https://www.nature.com/articles/d41586-018-05357-w

[15] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/042222-cost-of-capturing-co2-from-air-to-drop-to-250-300mtco2e-end-decade-climeworks

[16] https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal

4. **Technological maturity:** While advancements are rapid, DAC technology is still in its developmental stages. The leap from pilot projects to commercial-scale operations requires further technological refinement and optimisation.

DAC represents a very promising technology and is a critical piece of the multifaceted approach to address global CO_2 emissions. However, the path to mainstream adoption will require a concerted effort from researchers, policymakers, industry stakeholders, and investors. For the purpose of this study, we thus do not consider DAC for the technical design of the GMeOH production.

2.1.3 Group 2 - Short-cycle carbon sources: Biogenic carbon

Biogenic carbon is categorised as short-cycle due to its rapid exchange between the atmosphere and biological entities, primarily through photosynthesis. This cyclical interaction, wherein carbon is released and recaptured, serves as a temporary carbon reservoir, potentially counteracting emissions when managed judiciously. Its inherent renewability makes biogenic carbon a promising alternative to fossil-based sources, offering sustainable pathways for various industries, from biofuels to bioplastics.

2.1.4 Biomass & sustainability

As organic matter, biomass is a valuable renewable resource. However, its utilisation must consider sustainability aspects that require comprehensive analysis and evaluation. One of the prominent discourses surrounding biomass sustainability is the principle of **carbon neutrality**. Combusting organic matter releases CO_2, which is theoretically reabsorbed during the regrowth of plants, creating a carbon cycle. However, the speed of this carbon reabsorption varies. It may take prolonged periods for newly planted trees to absorb the CO_2 emitted by their older counterparts. This interim period could potentially elevate atmospheric CO_2 levels. The IPCC does recognise biomass energy within the rapid domain of the carbon cycle.

Land utilisation, particularly when forests are converted into plantations or agricultural zones, can lead to extensive CO_2 emissions, biodiversity loss, and ecological imbalances. Such land-use changes disturb established ecosystems and reduce the land's efficiency as a carbon sink. As demand for biomass swells, concerns about unsustainable practices or even deforestation become pressing. Furthermore, **biomass resources**, while renewable, **are not infinite**. The growing appetite for biomass can spark competition with other resource applications, like food production or habitat preservation. This rivalry can introduce adverse societal effects, such as food scarcity and habitat destruction.

Air pollution is another facet of the biomass debate. Combustion, especially in non-optimised systems, emits pollutants like particulate matter and nitrogen oxides. These emissions can deteriorate air quality and pose significant health hazards.

Certification schemes like the Sustainable Biomass Program (SBP) and the Sustainable Resources Verification Scheme (SURE) play crucial roles in ensuring the sustainability of products and projects. Although schemes like the Forest Stewardship Council (FSC) offer a foundation, they might not be entirely compliant with stricter frameworks like the EU's Renewable Energy Directive (RED) II. Such certifications also underscore social welfare. They advocate for improved worker rights, job security, education, training, and other pivotal socio-ecological factors, promoting a holistic approach to sustainability.

2.1.5 Sourcing biogenic carbon

Biomass serves dual purposes: an energy carrier and a carbon source. The two primary pathways for biogenic carbon utilisation include:

1. **Capturing carbon dioxide from biomass usage:** This approach focuses on harnessing CO_2 emissions from biomass energy generation or other processes. The captured CO_2 then becomes a candidate for PtX applications. Challenges arise from the infrastructure needs of carbon capture technology and CO_2 transportation facilities, especially in rural settings where biomass use is prevalent. Pipeline transportation, although effective, incurs high upfront costs and poses design and usage challenges. On the other hand, if biomass is used in a location which allows for co-location of PtX production, it becomes a 'low-hanging fruit' for project development.
2. **Maximising biomass as a carbon carrier:** This strategy seeks to innovate biomass conversion methods to optimise its role as a carbon carrier. Techniques like gasification, pyrolysis, or torrefaction transform biomass into carbon-rich intermediates such as syngas, bio-oil, or biochar. These intermediates can then serve as PtX process feedstock for synthetic fuel or chemical production. In this holistic approach, both the biomass's energy and carbon content are harnessed efficiently.

2.1.6 Sustainable biomass availability in South Africa

South Africa, with its diverse ecosystems and vast landscapes, is currently grappling with two prominent environmental challenges; the proliferation of invasive alien species and bush encroachment. Both present threats to the country's biodiversity, water resources, and agricultural productivity. However, they also provide an untapped potential for sustainable biomass, which can be harnessed for energy production and carbon capture. In this section, we briefly explore the two sources, associated challenges, and potential benefits.

Invasive alien species in South Africa

South Africa is home to over 2033 alien species, out of which 771 have been identified as invasive. These invasive species exert considerable pressure on native ecosystems, and 107 of them cause significant impacts, with 80 being plant species (Van Wilgen, 2021).

- **Overconsumption of water:** Invasive alien species (IAS) often consume more water than native plants, leading to water scarcity.
- **Decreased agricultural productivity:** IAS compete with native vegetation and agricultural crops, reducing yields and affecting food security.
- **Increased wildfire risks:** Certain IAS are flammable, increasing the frequency and intensity of wildfires.
- **Ecosystem service disruption:** The proliferation of IAS affects the ecosystem's natural balance, affecting services like soil fertility and water purification.
- **Land value reduction:** Large-scale infestations can devalue land, affecting both agricultural and real estate sectors.
- **Climate change and biodiversity loss:** IAS can alter the carbon storage capacity of ecosystems and contribute to the loss of native species.

The economic ramifications of IAS are stark. The **overuse of water resources** by these plants is estimated to result in **losses worth USD 773 million annually.** Additionally, there is a reduction in rangeland productivity valued at USD 45 million per year, and **biodiversity losses** estimated at a **minimum of USD 57 million annually** (WWF, 2021).

Bush encroachment in South Africa

Bush encroachment is a widespread phenomenon affecting 10-20 million hectares, primarily within South Africa's grasslands and savannas. In severely encroached areas, a single bush species can dominate up to 75% of the landscape.

- **Loss of carrying capacity:** Dense bush cover hampers the movement and feeding of livestock and cattle, affecting the livelihoods of commercial and communal ranchers.
- **Reduced biodiversity:** The dominance of a single bush species can lead to reduced plant diversity, affecting the overall health of the ecosystem.
- **Water resource strain:** Bush encroachment can result in increased water consumption, leading to resource scarcity.

The primary drivers of bush encroachment include:

- Overgrasing, which weakens the grass cover and gives bushes an opportunity to spread,
- Suppression of bushfires, which allows bush species to grow unchecked,
- Exclusion of specific browsing game species, which would naturally control bush growth,
- Elevated atmospheric CO_2 levels, which favour the proliferation of woody biomass.

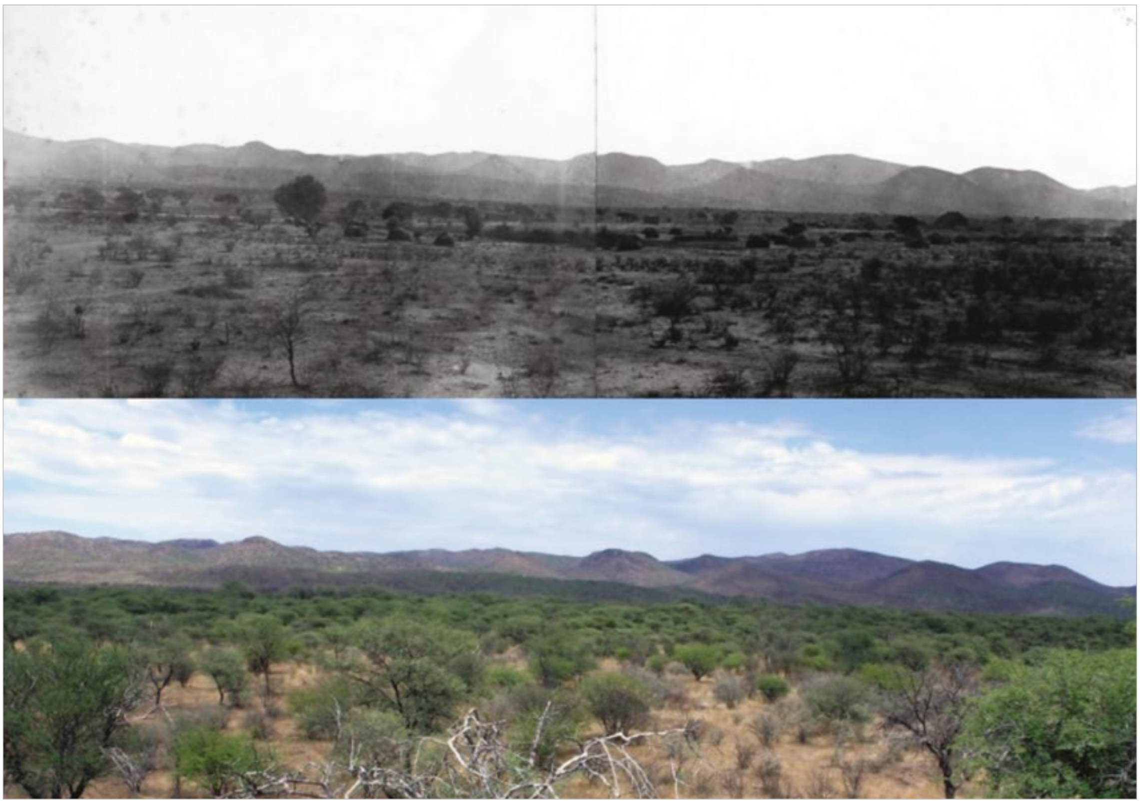

Figure 7: The change from the savanna landscape in 1876 (top) to 2006 (bottom), illustrating the spread of bush encroachment over time in Otjisewa, central Namibia (Source: Böhm, Steffen & Sian Sullivan (2021)

For the production of GMeOH, both IAS and bush encroachment offer an opportunity since it can be utilised for energy production and as a source of biogenic carbon (Kyriakarakos, 2023). This would aid in mitigating the adverse effects of these phenomena and contribute to South Africa's sustainable energy goals alike. However, a measured, scientific approach, coupled with stringent regulations and community involvement and a detailed market analysis would be required to further assessment the market potential, production routes and volumes, all of which go beyond the scope of this study.

For the purpose of this study and the GMeOH production using a sustainable carbon source, the biggest opportunity lies with sourcing biogenic carbon from existing plants, which currently utilise biomass as an energy resource. This approach presents a readily accessible strategy to capture and repurpose carbon, providing immediate benefits both environmentally and economically. Tapping into this existing infrastructure and resource offers a pragmatic solution, which may lay the foundation for a more comprehensive and long-term biomass strategy, both on project as well as on regional and national governmental level. The following figure presents existing biomass power plants in South Africa that can be considered as point-sources of biogenic carbon.

Figure 8: Biomass power plants in South Africa (green circles) (EC DG JRC, Clean Access Tool[17])

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[17] https://africa-knowledge-platform.ec.europa.eu/energy_tool

2.2 Approaches to technical design

2.2.1 Overview

The production of GMeOH requires three inputs:

- Carbon for the synthesis of GMeOH,
- Electricity for water electrolysis to produce hydrogen and GMeOH synthesis. This in turn requires land with adequate potential to produce renewable electricity,
- Water for the production of hydrogen.

The availability of each of the above resources will determine the production volume of GMeOH.

The main assumption made in this study is that water supply is not constrained, whereas the carbon supply by a point source may be considered constrained. Finally, the availability of land with sufficient potential for RE production is heavily reliant on the chosen location.

Therefore, the **first step is to estimate the maximum GMeOH capacity production potential of the given carbon point source.** This determines the maximum size of the methanol production (plant) **under the assumption that RE supply is unconstrained** (unconstrained power scenario). In case the **RE supply would be constrained, then the power supply could become the determining factor for the maximum methanol production** (plant) capacity (constrained power scenario).

2.2.2 Carbon availability

As pointed out earlier, this study assumes a CO_2 point source captured from a biomass combustion plant. By doing so, the produced methanol can indeed be considered renewable.

Based on available literature, the following assumptions can be made for the carbon point source:

- Emissions from biomass plant: 1,204 g CO_2/kilowatt hour (kWh) (Pamela L. Spath, 2006),
- Carbon capture efficiency: 90% (Jiang, Achieving zero/negative-emissions coal-fired power plants using amine-based postcombustion CO_2 capture technology and biomass cocombustion, 2020). Higher efficiency would lead to increased cost for carbon capture,
- Average uptime of the biomass plant: 8500 hours (Yang, 2021),
- CO_2 needs: 1.37 tonne of CO_2 to produce 1 tonne of methanol (Ravikumar, 2020),

- Typical methanol plant carbon efficiencies can range from 89-95%[18],
- For each 1 MW of biomass combustion plant installed capacity, 9,210.6 tonnes of CO_2/year can be captured,
- 1 tonne of GMeOH production needs roughly 1.5 tonnes of CO_2 and 200 kg of GH_2[19],
- Each 1 MW of biomass combustion plant installed capacity can provide 6,723 tonnes of GMeOH.

Considering an added safety buffer, a rule of thumb can be formulated as **'1 MW of biomass combustion plant production capacity can provide carbon for 6,500 tonnes of GMeOH on an annual basis'.**

It must be emphasised that this rule of thumb provides a basis only for initial preliminary calculations at PFS stage. The actual characteristics of the carbon point source to be utilised need to be further analysed for each project in depth in the forthcoming steps of project development.

2.2.3 Unconstrained power scenario – start with methanol plant size

In case that the available power is not constrained by any factor including land availability or transmission line capacity, the design process begins with the sizing of the GMeOH plant which is followed by the hydrogen production subsystem and concluding with the RE subsystem. Two main factors affect the decision of the production capacity of the methanol synthesis:

1. Carbon point sources are pre-existing in practically all cases. This means that there is already a plant emitting CO_2[20]. These emissions are either left in the atmosphere or captured and transported for sequestration. The size of the plant and the process used essentially determine the availability of CO_2 in terms of quantity. This means that the methanol synthesis plant can have a maximum capacity equal to the capacity that is utilising the total available CO_2 of the point source.
2. Commercial competitiveness factors. **Renewable methanol will not be a direct competitor in terms of cost with e.g., natural gas derived methanol at least in the short to medium term**. At the same time, the market already needs low emission fuels for transporting goods into markets like the EU in accordance with the CBAM[21].

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[18] https://www.digitalrefining.com/article/1002891/methanol-from-co2-a-technology-and-outlook-overview

[19] https://www.globalmaritimeforum.org/news/methanol-as-a-scalable-zero-emission-fuel

[20] *In cases where big industrial integrated projects are developed under circular economy paradigms, both the process producing CO_2 and the methanol synthesis process could be developed at the same time and the developer can set design criteria for optimal integration based on the target production capacities of all products.*

[21] *The EU's CBAM is the landmark tool to put a fair price on the carbon emitted during the production of carbon intensive goods that are entering the EU, and to encourage cleaner industrial production in non-EU countries. The gradual introduction of the CBAM is aligned with the phase-out of the allocation of free allowances under the EU EmissionsETS to support the decarbonisation of EU industry.*

The methanol synthesis process consumes a very low fraction of the electricity of the system, with some 2% of the overall process (Van Antwerpen, 2023). This means that there is no reason to actively investigate part load or on/off operation. However, it must be emphasised that plant operations can be interrupted for up to 24 hours using a method that involves closed-loop recirculation and supplemental heating of the synthesis loop. This industry-standard technique enables brief production interruptions without a complete shutdown and subsequent restart of the facility[22].

This is based on the assumption that the synthesis plant is constantly supplied by hydrogen and CO_2. While for the CO_2 supply only a buffer of a few hours up to one day can ensure optimal operations, the hydrogen production subsystem, which consumes most of the RE, must be carefully designed. Another assumption is that a constant water supply to the Electrolyser is ensured.

In reality, the objective of providing a constant stream of hydrogen to the continuously running methanol synthesis reactor can be met by optimally designing the following sub-systems:

- RE generation:
  - PVs
  - Wind turbines
  - Biomass plant produced power,
- Electricity storage in the form of batteries,
- Variable load operation of the water electrolysis process,
- Hydrogen storage,
- Electricity storage in the form of hydrogen, which requires the presence of a hydrogen fuel cell,
- Electricity storage in the form of methanol, which requires the presence of a methanol fuel cell or gas turbine,
- Supervisory energy management system to ensure optimal operation.

Typically, the RE plant's capacity exceeds that of the Electrolyser. Increasing RE capacity enhances the Electrolyser's capacity factor, thereby lowering hydrogen production costs. Similarly, as RE capacity grows, the capacity factors for both the Electrolyser and the methanol plant improve. However, this also leads to periods where electricity production surpasses the joint demand of the Electrolyser and methanol synthesis plant. In scenarios where this surplus electricity cannot be sold externally, it must be curtailed, leading to waste and loss of potential revenue. Under these circumstances, a lower (optimal) RE capacity is preferable to prevent higher methanol costs compared

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[22] *GBH Enterprises Ltd., Methanol Loop Start Up and Shut Down, Slideshare Presentation, https://www.slideshare.net/GerardBHawkins/methanol-loop-start-up-and-shut-down.*

to scenarios where excess electricity can be sold. Nevertheless, efforts must be made to ensure that the methanol plant remains operational even when instant RE is limited. The overarching goal is to optimise the process to produce GMeOH at the minimum possible cost per tonne.

2.2.4 Constrained power scenario – start with power supply size

In certain instances, the available RE at a specific site might be limited. This limitation could be due to two reasons:

1. The scarcity of appropriate land for establishing solar and wind infrastructure necessary for generating renewable electricity, or
2. Constraints in the transmission line's capacity, especially if the methanol plant and/or Electrolyser are not located adjacent to the RE infrastructure.

In such scenarios, the design approach is initiated with the determination of the power supply's capacity, followed by sizing the Electrolyser, and concluding with the design of the methanol plant. As it was explained earlier, the Electrolyser typically has a larger capacity compared to the methanol plant, and the RE capacity exceeds that of the Electrolyser.

However, when the power supply is the restricting factor, both the capacities of the Electrolyser and the methanol plant must be downscaled and fine-tuned to achieve the most cost-effective methanol production.

2.2.5 Site selection for a GMeOH project

The **most important variable when selecting a site for a GMeOH project is the secure supply of carbon**. Given that CO_2 is a gas, the only cost-effective way of transporting it is through pipelines. These pipelines are difficult and costly to develop and operate. Therefore, when siting the GMeOH project, the co-location of the methanol synthesis plant with the CO_2 source should be given higher priority than the provision and use of a pipeline. At present, **RE contributes to approximately 50% of the overall per-unit cost of GMeOH** (Van Antwerpen, 2023). Hence, it is crucial for GMeOH projects to be located in regions that offer optimal solar and wind resources, ensuring the lowest possible costs in electricity generation.

Since GMeOH is a liquid, it makes sense to co-locate all processes and transport the final liquid only for end use. Transporting gases (hydrogen, CO_2) can be cost-prohibitive.

Deciding between different cases hinges on the potential to achieve economies of scale. At project ideation stage, the key considerations in selecting an appropriate site should include:

- **Availability and readiness of infrastructure,** such as transmission lines and pipelines (refer to Table 2),
- **Proximity to various markets,** including local, border, and export markets,
- **Political backing** and potential incentives,
- Access to a **skilled labour force,**
- **Opportunities for future expansion** of the project,
- **Environmental and physical limitations.**

Table 2: Infrastructure requirements of the different methanol supply case options ([+] means that the infrastructure is required, [–] means that the infrastructure in not relevant to the case)

Case / Infrastructure	ColocatED RE, Electrolyser, MEOH Synthesis and MeOH demand	Wheel RE and ColocatED Electrolyser, MEOH Synthesis and MeOH demand	Transport GH_2 and colocatED MEOH Synthesis and MeOH demand	ColocatED RE, Electrolyser, MEOH Synthesis and transport Meoh
RE plant	+	+	+	+
Power lines	-	+	-	-
Electrolyser	+	+	+	+
Water supply	+	+	+	+
Gas pipeline	-	-	+	-
Truck/ship	-	-	+	+
CO_2 capture	+	+	+	+
GH_2 storage	+	+	+	+
Balancing technology	+	+	+	+
GMeOH synthesis plant	+	+	+	+
GMeOH storage	+	+	+	+

Access to and the presence of shared infrastructure, like power transmission lines, along with large-scale transport facilities for moving GH_2 and GMeOH from production sites to usage points, are critical for the effective implementation of PtX technologies. Conducting a geospatial analysis to evaluate current and planned shared infrastructures and their impact on the project in question is essential. For further details on site selection and its connection to environmental and social prefeasibility, see section 3.

The site selection phase's ideal outcome in project design should be identifying one or several locations, precisely marked with latitude-longitude coordinates or represented in a spatial data format (e.g., KMZ/Google Earth or shapefile).

2.3 Sizing a carbon capture and utilisation system

2.3.1 Brief background and overview

As industries worldwide grapple with the challenges of decarbonisation, CCSU has emerged as a viable solution, especially for sectors where direct emission reductions are difficult to achieve. CCSU encompasses a set of technologies aimed at capturing CO_2 emissions from large point sources, such as industrial plants and power stations. Once captured, the CO_2 can either be stored or utilised.

- **Storage (CCS):** CCS refers to the process of capturing CO_2 emissions, transporting them, and then storing them deep underground to prevent their release into the atmosphere. The storage typically occurs in geological formations, where CO_2 can be trapped in porous rock layers for thousands of years.
- **Utilisation (CCU):** Instead of storing the captured CO_2, it can be repurposed for various applications. This includes producing synthetic fuels, chemicals, building materials, or even enhanced oil recovery processes. The advantage of utilisation is that it provides an economic incentive to capture CO_2, turning a waste product into a valuable resource. However, it is important to note that not all utilisation processes result in permanent removal of CO_2 from the atmosphere. Some applications, such as synthetic fuels including methanol, will release the CO_2 back when the fuel is burned. Hence, a balance between storage and utilisation strategies is essential for effective carbon management based on the source of CO_2.

CCSU offers multiple advantages and has the potential to bring about significant cost reductions[23].

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[23] https://doi.org/10.1016/j.ijggc.2015.04.018

CCSU involves three stages relevant for the carbon sourcing for the methanol synthesis:

- **1) Capture:** CO_2 is separated from other gases resulting from combustion or industrial processes. Multiple technologies can achieve this, including:
    - **Liquid solvents:** Employing chemical or physical solvents, such as amines or proprietary solvents, to absorb CO_2,
    - **Solid adsorbents:** Utilising materials that attract and hold CO_2 molecules on their surface,
    - **Membranes**: Serving as filters to separate CO_2 from other gases,
    - **Solid-looping:** Involving metal oxides or other compounds that can transfer CO_2 or oxygen between reactors,
    - **Inherent CO_2 capture:** These are breakthrough technologies, which incorporate CO_2 capture into their fundamental design, eliminating the need for additional capture equipment.
- **2) Transport:** Once captured, CO_2 is usually compressed and transported to the storage or utilisation site. This can be achieved through pipelines or ships, depending on the distance and geographic challenges.
- **3) Storage or utilisation:** For storage, the compressed CO_2 is injected deep underground into geological formations. Over time, it gets trapped and permanently stored, ensuring it does not return to the atmosphere.
- Alternatively, as it is the case for the purpose of the methanol production at hand, the captured CO_2 can be put to use for the production of synthetic fuels, chemicals and plastics production, greenhouse use, and algae growth.

2.3.2 Typical carbon capture system of a power plant

A typical carbon capture system of a power plant is a complex arrangement of interconnected processes and equipment as it will be shown in the following.

1. **Source of emissions:** A power plant, typically fuelled by coal, natural gas, or biomass, produces flue gas containing CO_2 along with other emissions such as nitrogen oxides (NOx), sulphur oxides (SOx), particulates, and water vapor.
2. **Flue gas treatment:** Before the flue gas can be processed for carbon capture, it usually undergoes a series of treatments:
    - **DeNOx systems** are often selective catalytic or non-catalytic reduction units that reduce nitrogen oxide emissions.
    - **Electrostatic precipitators or fabric filters** are used to remove particulate matter.
    - **Flue gas desulphurisation:** This process removes sulphur dioxide, typically using a limestone or lime slurry.

3. **The CO_2 capture system** is at the heart of the carbon capture process. Depending on the technology applied, there are three types of capture systems:

   1) **Post-combustion capture:** This is the most common method for retrofitting existing power plants. In this method:

   - Flue gas is cooled down and directed to an absorber tower,
   - A solvent, typically an amine-based solution, is sprayed from the top of the absorber. As the flue gas rises, the solvent binds with the CO_2,
   - The CO_2-rich solvent is then directed to a stripper or regenerator, where it is heated. This releases the pure CO_2 gas, which is then compressed and ready for transport or storage,
   - The solvent is recycled back to the absorber.

   2) **Pre-combustion capture:** Common in integrated gasification combined cycle (IGCC) plants.

   - Coal or biomass is gasified to produce syngas (a mixture of CO and H_2),
   - The syngas undergoes a shift reaction, converting CO to CO_2. While capturing CO directly is of higher value, since most downstream applications require CO, it is a more challenging process,
   - Afterwards, the CO_2 is captured using physical solvents like Selexol or Rectisol. The remaining hydrogen-rich gas is combusted to produce electricity. To directly capture CO, you would need to apply pressure swing absorption, membrane separation, chemical looping, or a comparable technology.

   3) **Oxy-fuel combustion:** This involves burning the fuel in nearly pure oxygen instead of air.

   - This results in a flue gas that is primarily CO_2 and water vapor. After cooling and condensation of the water vapor, almost pure CO_2 is obtained.

4. **CO_2 compression and dehydration:** Once captured, the CO_2 is either locally stored or compressed to a supercritical state, making it easier to transport. Before compression, the CO_2 is dehydrated to remove any remaining water, preventing corrosion in transport equipment.
5. **Transportation:** The compressed CO_2 is transported, often via pipelines, to a storage or utilisation site.

The carbon capture process, especially post-combustion, requires significant amounts of heat. Heat integration systems can recover waste heat from the power plant to improve overall efficiency. The choice of technology and equipment often depends on the specific characteristics of the power plant, the fuel used, and the intended application of the captured CO_2. A typical system that is generally used for retrofitting in existing plants is the post-combustion capture technology presented in Figure 9.

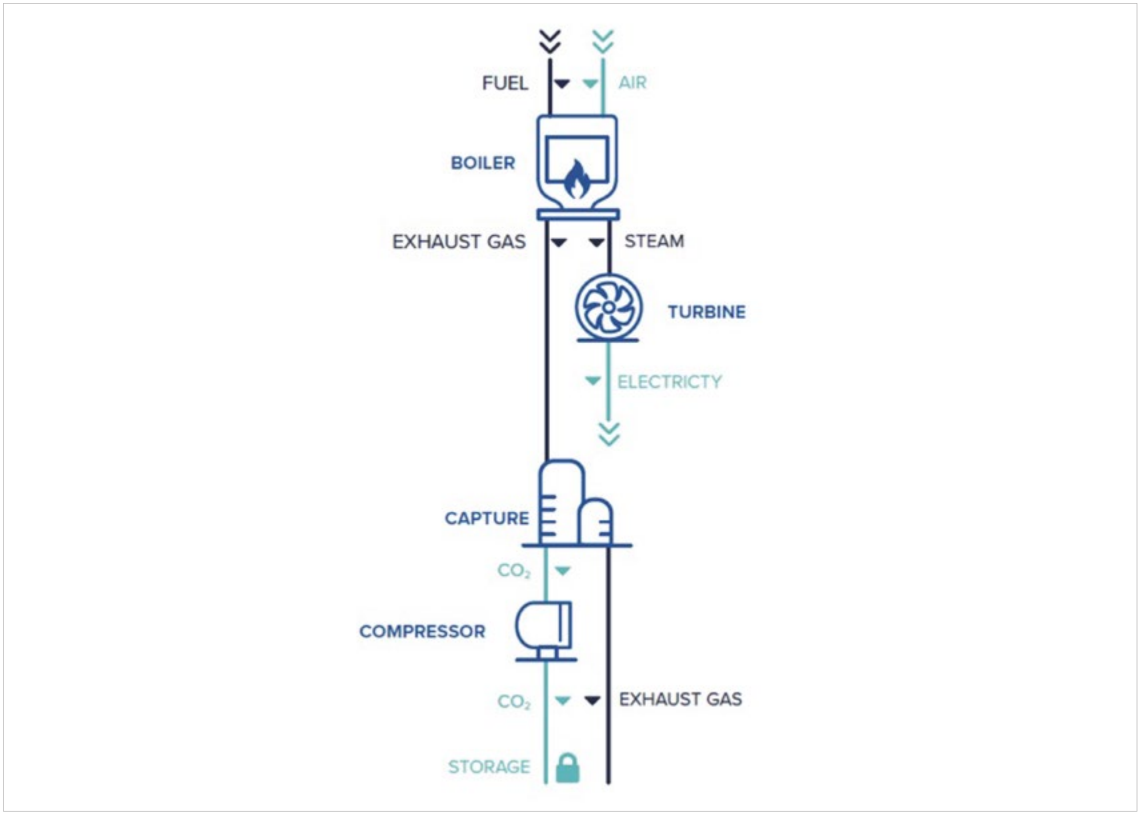

Figure 9: Post-combustion CO_2 capture (Source: https://www.globalccsinstitute.com/wp-content/uploads/2022/06/Capture-diagram.png)

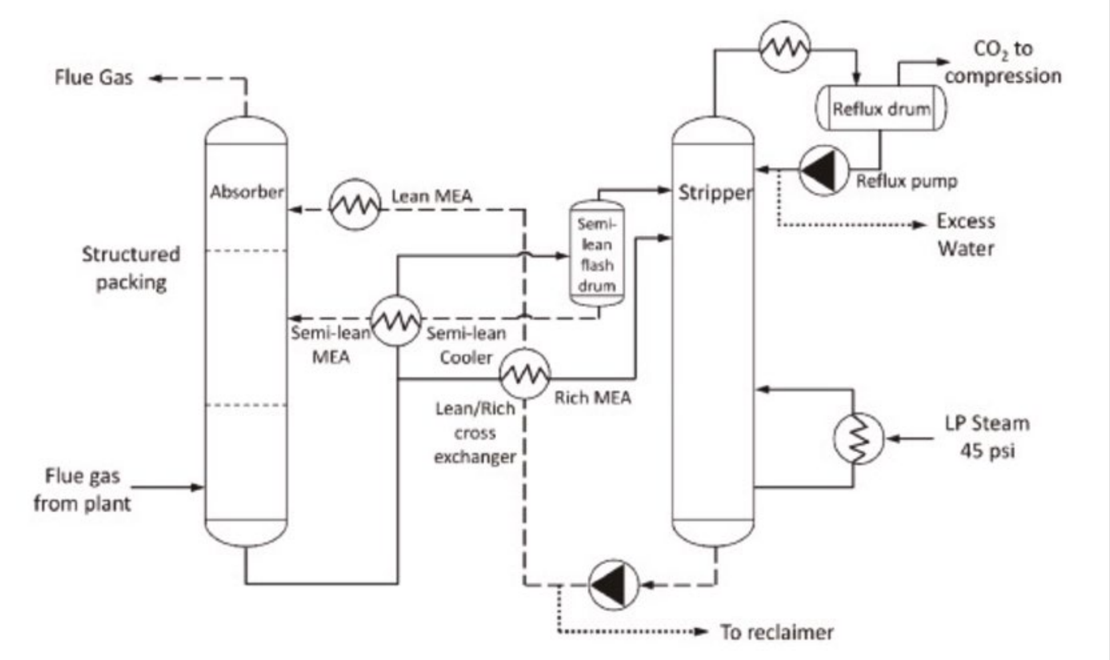

Figure 10: A typical CO_2 absorption process with absorber and stripper or desorber column (Source: (Chao, 2021))

It should be noted that there is an efficiency loss of approximately 10 % of the power production plant due to the post-combustion CO_2 capture. Roughly, two-thirds of this loss can be attributed to the CO_2 capture. Although the latest steam cycles for power generation boast high efficiency, no significant advantage can be observed in terms of reduced energy requirements for carbon capture across sub-critical, supercritical, or ultra-supercritical steam cycles. Furthermore, the efficiency loss has been found to remain consistent across different coal types, including lignite and bituminous coal. The role of CO_2 capture technology in mitigating this loss is paramount. Existing research suggests that for every 1 GJ/tonne of CO_2 reduction in the regeneration energy of the scrubbing solvent, there is a potential for a 2% efficiency improvement. Solid sorbents and membranes can assist in this direction (Goto, 2013) but post-combustion capture technology is the most widely used mature technology nowadays using appropriate solvents like amines (Chao, 2021).

2.3.3 Typical methanol synthesis plant

Excluding the production process for syngas, the production for methanol from syngas can be explained using the block flow diagram below. For methanol production, there are a few distinct steps that are important in the overall process. These include compression, catalytic synthesis, purification/distillation and storage. All of these components must be considered when designing a methanol production plant. As configurations may vary from plant to plant, for the purposes of this study it was decided to consult the literature to propose a process simulation, as various optimisation studies based on newer optimisation techniques under development are still being carried out. The following figure (Nguyen Van Duy, 2020) presents a detailed process overview, including most auxiliary equipment.

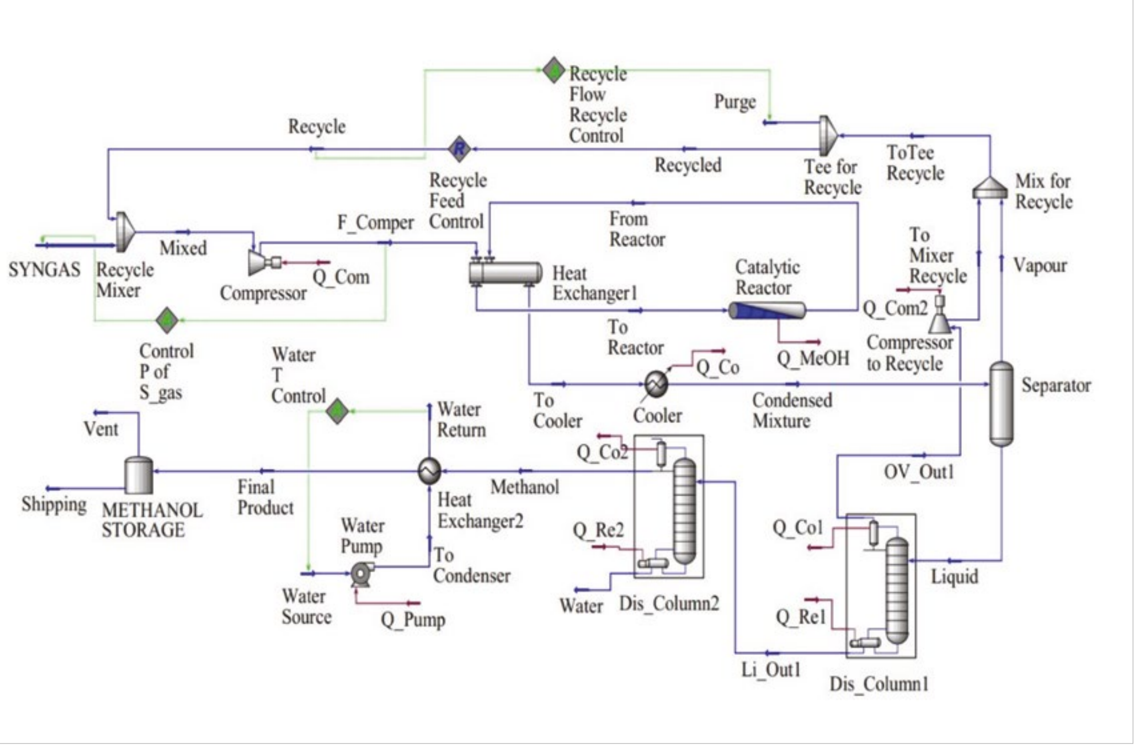

Figure 11: Typical methanol production process from syngas ((Nguyen Van Duy, 2020)

While the above process is largely indicative of the current production process for methanol, it is suggested as the preferred option due to the commercial maturity of the technology as well as the catalyst development. For GMeOH production to follow this route, syngas production would have to be achieved in a sustainable manner with the CO_2 derived from non-fossil-based sources.

For the direct hydrogenation of CO_2, a similar model was developed including all of the compression steps, as well as the reaction and distillation steps. It has to be highlighted that the model was developed in DWSIM, a CAPE-OPEN compliant chemical process simulator, and it was also utilised to calculate the financial details of developing such a plant (i.e., CAPEX and OPEX). A similar approach can be applied for any PFS.

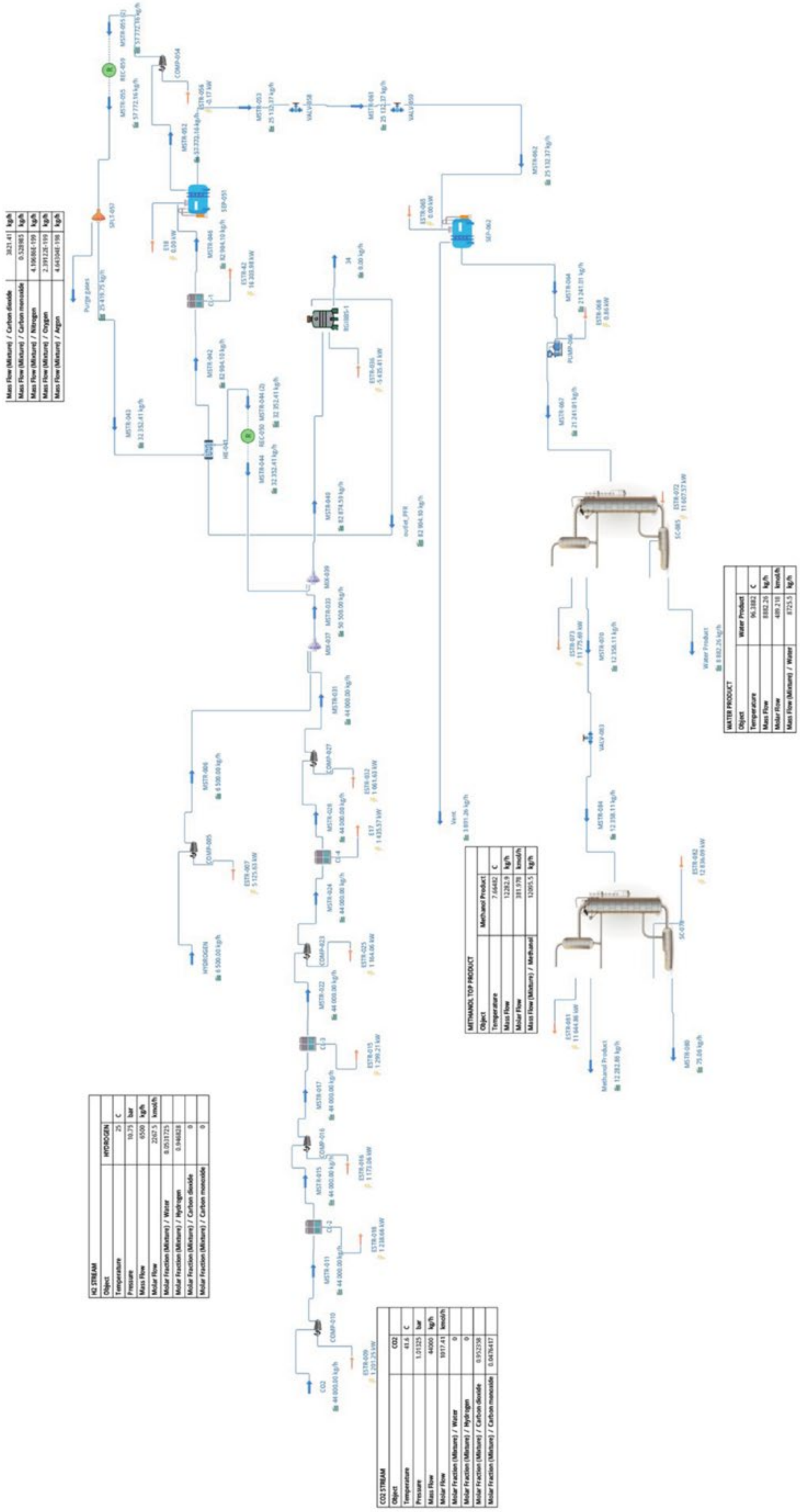

Figure 12: Direct hydrogenation route for methanol production

While the processes are similar, the direct hydrogenation route poses some challenges in terms of catalyst development and commercial scale deployment. Table 3 provides a comparison between the two different routes.

Table 3: Comparisons between two different routes for methanol production

Aspect	Steam methane reforming (SMR)	Direct hydrogenation
Feedstock	Natural gas (primarily methane)	CO_2 and H_2
Reaction process	$CH_4 + H_2O \rightarrow CO + 3H_2$ (reaction 1) $4CO + 2H_2 \rightarrow CH_3OH$ (reaction 2)	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$
Catalyst	Copper-based catalyst	Copper-zinc oxide-based with alumina or other promoters
Temperature & pressure	High temperatures (800-1,000°C) and pressures (20-30 bar)	Elevated temperatures (around 200-300°C) and pressures (50-80 bar)
Source of CO_2/H_2	Not directly used; by-product from natural gas	Directly utilises captured CO_2 and generated hydrogen (often from renewable sources)
Carbon utilisation	Indirect (from methane)	Direct utilisation of CO_2, aiding in carbon utilisation
Emission reduction	Less direct impact on emissions	Reduces emissions by using captured CO_2
Energy intensity	Energy-intensive process	Requires less energy input compared to SMR
Catalyst stability	Relatively stable catalysts developed	Catalyst development for stability remains a challenge
Environmental impact	Moderate greenhouse gas emissions, potential air pollutants	Lower emissions, reduced direct impact on air quality
Advantages	Commonly used, established process	Utilises CO_2, potential for emission reduction
Challenges	Greenhouse gas emissions, energy-intensive	Catalyst development, efficiency at industrial scales

Catalyst optimisation

As for any conversion process, the most important component sits with the catalysts. The literature on direct hydrogenation to date has focused on the development of an optimised catalyst to improve conversion and selectivity to methanol. The catalyst is usually based on copper, zinc and aluminium oxides and while they have a number of advantages, they there also some drawbacks. A few of these must be investigated when designing the methanol plan including:

- **Deactivation:** Catalysts can lose their activity over time for a variety of reasons, including sintering (particles clumping together and decreasing surface area), fouling by impurities in the feedstock, or chemical processes that alter the catalyst's structure. This increases OPEX due to catalyst replacement or renewal on a regular basis.
- **Selectivity and yield:** Although the catalyst help produce methanol, it may also encourage the synthesis of by-products or other processes that reduce the methanol selectivity and yield. Maintaining selectivity to maximise methanol production and reduce by-products is a challenge for plant operations.
- **Operating conditions:** Pressure, temperature, and the H_2/CO ratio needed for optimal catalyst performance may not always be the best for the overall efficiency of the process. It is important to strike a balance between the energy expenses associated with catalyst activity and advantageous operating conditions.
- **Poisoning of catalysts:** Certain impurities or contaminants in the feedstock have the ability to stick to the catalyst surface and lower its activity. For example, sulphur can contaminate the catalyst frequently used for methanol production.
- **Energy consumption:** The process of producing methanol requires a lot of energy. High temperatures and pressures may be necessary for the catalyst to work properly, which increase both the energy consumption and OPEX.
- **Challenges with scale-up:** The performance of a catalyst demonstrated in laboratories may not always be congruent with large-scale industrial processes. Catalyst performance can vary at different scales depending on factors including overall system dynamics, heat and mass distribution in larger reactors, and constraints on mass transfer.
- **Cost of catalyst development:** The investigation and creation of novel, highly effective catalysts can be costly and time-consuming. Even though catalyst technology is constantly developing, it can require a lot of work and money to put these new catalysts into use in commercial production.

Plant operation impacts

Methanol catalysts' capacity to withstand load cycling, which entails changes in production rates or operating conditions, is contingent upon the type of cycling, reactor architecture, and particular catalyst formulation. In the process of producing methanol, load cycling might involve adjustments to feedstock composition, flow rates, temperature, and pressure swings.

The catalysts used in the production of methanol are made to withstand some operating state variations. However, catalyst longevity and performance may be impacted by sudden or drastic changes in environmental factors. Among the things to think about when using load cycling and catalysts are:

- **Thermal stability:** During load cycling, catalysts must be able to tolerate temperature changes without suffering appreciable deterioration. Thermal shock can be brought on by abrupt temperature fluctuations, which can alter the structure of the catalyst and lower its activity.
- **Pressure fluctuations:** Ideally, catalysts should remain stable in the face of changing pressure levels. The performance of the catalyst may be impacted by excessive pressure changes that alter its porosity or create mechanical stress.
- **Sensitivity to feedstock changes:** Performance of the catalyst may be impacted by modifications in the feedstock's composition, such as shifts in the H_2/CO ratio or the presence of contaminants. The sensitivity of certain catalysts to these alterations may affect their capacity to withstand load cycling.
- **Catalyst regeneration:** Catalysts which are readily re-generable or reactive after load cycling are advantageous. Upon contact with different environments, catalysts may be partially reactivated, although some may require more frequent replacement or regeneration.
- **Sustained durability:** Regular load cycling may contribute to the deterioration of the catalyst over time, limiting its overall lifespan. Catalysts displaying higher durability under fluctuating operating conditions should thus be favoured.

Although catalysts are designed to withstand certain operating fluctuations, rapid or regular load changes can lead to accelerated degradation. This can lead to reduced efficiency and higher OPEX, as the catalyst has to be replaced or renewed more frequently.

2.3.4 Balancing technology

To optimise continuous operation, the GMeOH production facility should integrate a balancing power source. This source is crucial for maintaining consistent energy supply during low RE generation periods. During ideation of the project, a detailed analysis of potential solutions should include:

- **Battery storage:** Batteries offer a mainstream solution for energy balancing. The plant should incorporate a battery storage system capable of storing excess energy generated during peak RE periods. This stored energy can be utilised during low RE availability. Key considerations include battery capacity, charge-discharge rates, lifespan, and the efficiency of the energy storage system, and costs.
- **Hydrogen fuel cells:** These convert stored hydrogen back into electricity. Hydrogen produced during high RE periods can be stored and used in fuel cells to generate electricity when RE generation is insufficient. The design must consider the efficiency of hydrogen production, storage pressures, and fuel cell conversion efficiencies.
- **Methanol fuel cells:** Similar to hydrogen fuel cells, these convert methanol into electricity. If the plant produces excess GMeOH, it can be utilised as a fuel source in these cells. Factors like methanol storage, fuel cell efficiency, and by-product management should be assessed.
- **Electricity from the grid:** If the grid can supply 100% RE-sourced electricity, it can be a balancing source. This requires an in-depth evaluation of grid reliability, the proportion of RE in the grid mix, and potential agreements with utility providers.

Considering the need for energy balance, if alternative technologies (other than grid power) are used, the RE plant must be upsised. This ensures sufficient energy generation for the GMeOH production and charging the energy storage system or producing surplus hydrogen.

Furthermore, by capturing the CO_2 from a biomass plant, this plant can also contribute to system balance since it is producing renewable electricity. It can provide a base-load power supply, supplementing energy during periods of low RE availability subject to the agreement with the plant operator. This integration can enhance overall system efficiency and reliability, ensuring consistent operation of the GMeOH production facility.

2.3.5 Water electrolysis

Electrolysers are pivotal in GH_2 production, transforming water into GH2 and oxygen. Their selection is crucial for project design, considering three prevalent technologies (IEA, 2019): Alkaline electrolyser cells (AEC), proton exchange membrane (PEM) electrolysers, and solid oxide electrolyser cells (SOECs).

1. **AEC technology:** This method uses liquid water for electrolysis at temperatures up to 80°C. Established since the 1920s, AEC is a mature, commercialised technology. Notably utilised in fertiliser and chlorine industries, AEC units are available in large capacities, with some models reaching up to 165 MWe. They offer lower capital costs, primarily due to the non-use of precious metals. However, AEC technology requires the use of a potassium hydroxide (KOH) electrolyte solution, necessitating its recovery and recycling.
2. **PEM systems:** These systems also electrolyse liquid water but eliminate the need for KOH recovery and recycling. Operating at temperatures similar to AEC, PEM Electrolysers are generally smaller in scale. A key advantage is their capability to produce hydrogen at higher pressures, making them suitable for mobility applications where less compression is needed for hydrogen storage. However, they incur higher costs due to the use of expensive membrane materials and electrode catalysts like platinum and iridium. Currently, PEM systems have a shorter lifespan compared to AEC technologies.
3. **SOECs:** While not yet commercially widespread, SOECs are in the demonstration phase. They operate at higher temperatures, electrolyzing steam (not liquid water) with high electrical efficiency and using ceramic materials as the electrolyte. Their operation requires an external heat source for steam generation. Unique to SOECs is their reversible operation as a fuel cell, allowing the conversion of stored hydrogen back into electricity, potentially providing grid-balancing services. Additionally, SOECs can co-electrolyse steam and CO_2, producing synthesis gas (a mixture of carbon monoxide and hydrogen), thereby eliminating the need for a separate water-gas shift process.

Each Electrolyser technology offers distinct advantages and considerations, making them suitable for different applications within GH_2 production projects.

2.3.6 Water supply and quality

In addition to evaluating the techno-economic aspects of water availability and purity, it is crucial to consider environmental and social implications. Ensuring access to sustainable water sources and responsible water management is vital in the project's final assessment and pre-feasibility study, especially in view of the water constraints in South Africa.

Hydrogen production through water electrolysis requires approximately nine litres of water for every kilogram of H_2 and eight kilograms of oxygen (O_2) produced (IEA, 2019). This is the stoichiometric minimum, but additional water is needed for other purposes:

- The water fed to the electrolyser contains trace impurities. Additional purge water is required to remove these contaminants, which could accumulate on the electrolyser surfaces, necessitating an extra 10-25% water usage.
- Regular cleaning of PV panels with water is essential for optimal power generation.
- Water is also necessary for cooling the electrolyser system.

South Africa faces significant water stress due to climate variability, ranking as the 30th driest country globally. By 2030, regions like Gauteng, Mpumalanga, KwaZulu-Natal, and the Western Cape are expected to experience severe water shortages (GreenCape, 2019). Therefore, hydrogen production must not compromise water availability for local communities, agriculture, and other economic sectors (Roos T. H., 2021). The German National Hydrogen Strategy emphasises sustainable water supply in hydrogen-producing countries, ensuring that water scarcity is not exacerbated by hydrogen production. Over-dimensioning the water supply system for desalinated seawater projects can offer surplus potable and irrigation water, benefiting local communities without affecting the project's economics.

Desalinating seawater for coastal GH_2 facilities is an efficient alternative, consuming a negligible fraction of the hydrogen production's energy and financial cost. The specific energy consumption (SEC) for electrolysis is around 50 kWh/kgH2, while for desalination, it is about 3-5 kWh per 1,000 kg of water. This results in an energy ratio of desalination to electrolysis of approximately 0.0009, making it a minor component of overall GH_2 production costs.

Japan's cost targets for hydrogen are indicative of the minimal impact of desalination on hydrogen production costs. With desalination costs ranging between USD 0.005 – USD 0.020 per kg of hydrogen, this represents less than 1% of the projected hydrogen cost by 2025 (Roos T., 2020). Therefore, GH_2 production can contribute to water resilience, bearing desalination costs more readily than communities or agriculture.

For coastal GH_2 production, sustainable water sources such as desalinated seawater, mine water, or acid mine drainage are preferable. Municipal wastewater should be considered only after exhausting these sources. Inland GH_2 production should prioritise desalination of contaminated sources like mine water or industrial wastewater, reserving municipal wastewater for future industrial needs.

Water quality is crucial in GH_2 production as impurities can affect Electrolyser performance, hydrogen quality, and lifespan. Most manufacturers recommend a water resistivity value of 1 MΩ. Seawater purification methods include electric dialysis reversal, multistage desalination, and reverse osmosis (RO). Table 3 provides an overview of the methods used for seawater desalination, including electric dialysis reversal, multistage desalination and RO.

Table 4: Main techniques for seawater desalination

Technology	Description	Advantages	Disadvantages
Multistage desalination	In this method, seawater is vaporised in several stages, producing steam on one side and concentrated brine on the other. The vapour is recovered and condensed to form fresh water, while the brine is rejected to the environment (once-through configurations) or mixed with saline water feed (brine recirculation configurations)	· Well suited for areas with abundant thermal energy · High concentration values	· High CAPEX · High energy consumption · Higher ecological impact
Reverse osmosis	RO uses membrane that selectively prohibit the passage of certain particles but allow others by exerting pressure on the membrane systems	· Proven technology · Low energy consumption · Low cost	· Lower recovery rate · Lower purified water quality · Less suitable for unmanned operations
Electric dialysis reversal	The method uses direct voltage to split fed water into water types: (1) water that has low conductivity (i.e., product water), (2) water that contains dirt ions (i.e., concentrated or brine water) and (3) water that produces electric potential difference (electrode water)	· Higher recovery rate · Simple integration in renewable network	· Less mature technology · Energy consumption dependent on feed water salinity

Source: (Assad, 2022)

2.3.7 Renewable energy power plant

In the GMeOH production process, renewable electricity plays a pivotal role in powering various subsystems:

- Desalination of water (if applicable),
- Charging of battery storage systems (if applicable),
- Electrolysis for GH_2 production,
- CO_2 capture processes (while notably power from the power plant itself is typically utilised),
- Operation of the methanol synthesis plant.

Given this framework, exploring different renewable power plant configurations is critical to determine the optimal capacity for a GMeOH plant. Viable RE sources include PV and wind power. CSP with thermal storage, while technically feasible, currently incurs higher costs compared to PV or wind energy solutions.

The efficiency of infrastructure utilisation can be assessed through full load hours (FLH). Given the substantial capital costs of Electrolysers, economical production of GH_2 and GMeOH necessitates high FLH values[24]. Attaining these high FLH values can be facilitated by addressing several key requirements (Roos T. H., 2021):

1. **Optimal placement of RE infrastructure:** Solar PV and wind installations should be situated in regions with optimal solar and wind resources. These installations need not be co-located with the electrolysis plant, allowing for flexibility in site selection.
2. **Dedicated RE infrastructure:** Utilising only surplus RE from the grid is insufficient due to the resultant low FLH of the Electrolysers and the consequent high hydrogen costs. Therefore, dedicated RE infrastructure, where all generated electricity is exclusively supplied to the Electrolyser plant, is essential for enhancing Electrolyser FLH.
3. **Utilisation of cutting-edge RE technology:**
   a. **Solar PV with tracking systems:** Single-axis tracking PV (SAT PV) systems, which track the sun's movement, offer about 25-30% higher annual FLH values than stationary installations. Despite a 10-15% higher capital expenditure (CAPEX), SAT PV should be preferred unless specific environmental factors, such as wind-blown sand, significantly increase operational expenses (OPEX) (Agora Verkehrswende, Agora Energiewende and Frontier Economics, 2018).
   b. **High-capacity factor wind turbines:** Wind turbine design should maximise the capacity factor, with large rotor diameters and the tallest feasible hub heights, as FLH increase with hub height (Lantz, et al., 2019). The benefits of higher FLH outweigh any potential increase in wind electricity costs.

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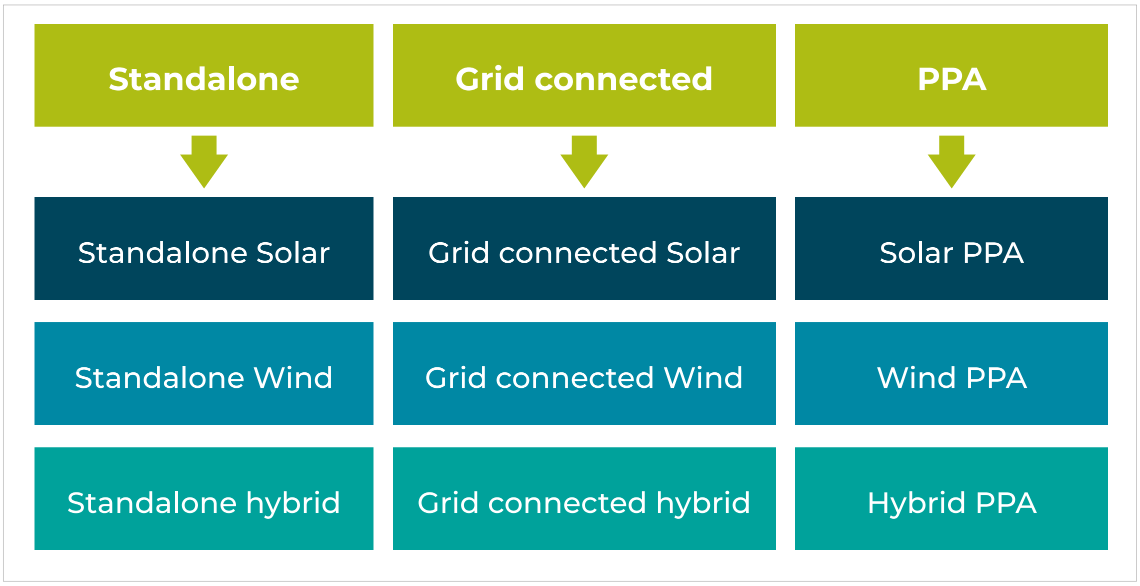
[24] *FLH values of at least 3,000 to 4,000 are recommended (Agora Verkehrswende, Agora Energiewende and Frontier Economics, 2018)*

4. **Hybrid RE systems:** Utilising a combination of PV and wind energy can further increase Electrolyser FLH. Wind energy can power the Electrolyser at night, while a combined supply of wind and solar PV can be used during the day.
5. **Oversizing the RE plant:** Oversizing the RE infrastructure relative to the Electrolyser can improve its FLH. Surplus power generation, especially during peak RE production periods, can either be sold (contributing to regional/national energy security and reducing hydrogen costs) or curtailed if not utilised.

For powering the methanol plant and Electrolyser, three electricity supply configurations are possible: standalone systems, connection via a transmission grid, and power purchase agreements (PPA). While for the standalone systems, the use of renewable electricity is self-evident, this is not the case for the transmission grid and PPAs. As such, incorporating guarantees of origin (GoOs) for green electricity is a crucial aspect of ensuring the sustainability and credibility of the GMeOH production process. GoOs are certificates that provide transparent and verifiable information about the source of electricity, specifically confirming that a given amount of electricity was generated from RE sources. They are instrumental in tracking and validating the renewable nature of the electricity used in GMeOH production, from water desalination to powering the Electrolyser and methanol synthesis plant.

The integration of GoOs in the GMeOH production value chain serves several key purposes. Firstly, it ensures adherence to global sustainability standards and compliance with environmental regulations, which is increasingly important for market acceptance and consumer trust. Secondly, GoOs enable producers to substantiate their claims of using 100% RE, which is pivotal in maintaining the ‘green’ label of the methanol produced. This is particularly pertinent when the electricity is sourced from the grid or through PPAs, where the renewable origin of the electricity might not be immediately apparent. Furthermore, GoOs play a strategic role in market differentiation, allowing GMeOH producers to position their product as genuinely sustainable, which can command a premium in the market. This system also facilitates the tracking of RE use, offering transparency and accountability in reporting and marketing, thus enhancing the credibility of the GMeOH project and industry alike.

The three electricity supply configurations lead to nine different power supply scenarios (Figure 13):



Standalone	Grid connected	PPA
Standalone Solar	Grid connected Solar	Solar PPA
Standalone Wind	Grid connected Wind	Wind PPA
Standalone hybrid	Grid connected hybrid	Hybrid PPA

Figure 13: Potential configurations of the RE plant to supply electricity to the Electrolyser and GNH$_3$ production plant

Standalone system configuration: The methanol production setup, comprising the Electrolyser, and methanol synthesis facility, is directly linked to an autonomous off-grid RE installation[25]. This system operates independently from the conventional transmission and distribution grid. The RE-generated electricity is primarily allocated for GH$_2$ production via via electrolysis, GMeOH synthesis, and potentially for water desalination operations. Any excess electricity generated is either directed towards charging battery storage systems or is considered as surplus energy and curtailed.

Grid-connected configuration: In this arrangement, the methanol production system is interconnected with a dedicated RE power plant through either a public electricity grid (via wheeling) or a dedicated transmission line. The electricity produced serves similar purposes as in the standalone configuration: it powers GH$_2$ production (electrolysis), GMeOH production, and possibly water desalination. This setup incurs additional costs, including grid connection fees and service charges (for systems connected through a public grid), along with the initial capital and ongoing operational expenses. Surplus power, in this case, can either be utilised for battery charging or sold to external entities through the public power grid (subject to regulatory permissions) or is considered surplus and curtailed.

PPA system: Here, the methanol production system is powered using RE electricity procured from an external provider under a PPA. The RE electricity within this framework may be delivered through a public power grid (when the RE installation's location differs from the methanol plant's location) or via an on-site generation facility owned by an independent developer. The PPA might cover additional power requirements for battery charging systems if implemented.

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[25] *As noted before, the energy needed for CO$_2$ capture used in practically all cases is provided by the power plant.*

The aggregated RE power requirement (RE_{power}) *for a given methanol production system equals the sum of the power demands of various electricity-consuming components: the Electrolyser (* H_{2_power}*), and the methanol synthesis process (* MS_{power}*),* as indicated in Equation 1.

$$RE_{power} = H_{2\_power} + MS_{power}$$

Equation 1

The capacity of the RE power plant must properly be determined to ensure that the system operates within allowable limits, especially for the methanol synthesis plant. The operation of a methanol synthesis plant within its allowable limits is crucial for maintaining its efficiency, ensuring product quality, and prolonging the life of the catalyst and process units. Operating outside these limits can have several adverse effects:

1. **Catalyst degradation:** Methanol synthesis typically involves a catalyst, which facilitates the chemical reaction under specific conditions of temperature and pressure. Operating outside the optimal range can lead to faster degradation of the catalyst, reducing its effectiveness and lifespan. This degradation not only affects the catalyst itself but can also lead to the formation of unwanted by-products, affecting the purity of the methanol produced.
2. **Thermal and mechanical stress:** Deviating from the designed operating parameters can impose additional thermal and mechanical stress on the equipment. This can lead to accelerated wear and tear, increasing maintenance requirements and potentially causing unplanned downtime.
3. **Energy and mass transfer imbalance:** The methanol synthesis process relies on a delicate balance of mass and energy transfer. Operating outside the allowable limits can disrupt this balance, leading to inefficiencies in the process. This imbalance can result in lower conversion rates of feedstock to methanol, thus decreasing overall process efficiency and increasing operating costs.
4. **Safety risks:** Methanol synthesis involves handling of flammable and potentially hazardous materials under high pressure and temperature. Operating beyond safe limits increases the risk of leaks, fires, or explosions, posing a threat to plant safety and the surrounding environment.
5. **Quality of end product:** The quality of the produced methanol is highly dependent on consistent process conditions. Variations beyond the acceptable limits can lead to inconsistencies in the product quality, which might not meet the required standards for certain applications.

Adjusting the operation dynamically to match the fluctuating power supply can disrupt the equilibrium of the synthesis process and adversely affect the catalyst and equipment. However, it is noted that temporary suspension of operations for up to 24 hours is feasible through closed-loop recirculation and assisted heating of the synthesis loop. This approach allows the plant to pause production without necessitating a full shutdown and subsequent start-up, which can be resource-intensive and potentially harmful to the equipment and catalyst. This method offers a compromise between operational flexibility and maintaining the integrity of the synthesis process (Van Antwerpen, 2023). Finally, it has to be mentioned that the methanol synthesis plant consumes a very small fraction of the total energy consumed in the system (~2%) (Van Antwerpen, 2023). As such, the impact of dynamic operation is marginal and is not considered in the study.

2.4 Cost dimensions and – estimations

Similar to electricity generation and hydrogen production, the common metric for economic analysis of methanol production is the Levelised cost of methanol (LCOM), which is the average cost per kg of building a methanol production system[26] and operating it over the project lifetime.

2.4.1 Cost elements of a methanol plant

The LCOM encompasses the comprehensive range of costs associated with a methanol production project. This includes CAPEX, ongoing OPEX, and costs associated with financing. The LCOM calculation considers the performance metrics of the system, ensuring a holistic financial assessment. Figure 14 illustrates the various cost components integral to a methanol production system, highlighting the key factors that affect the overall LCOM.

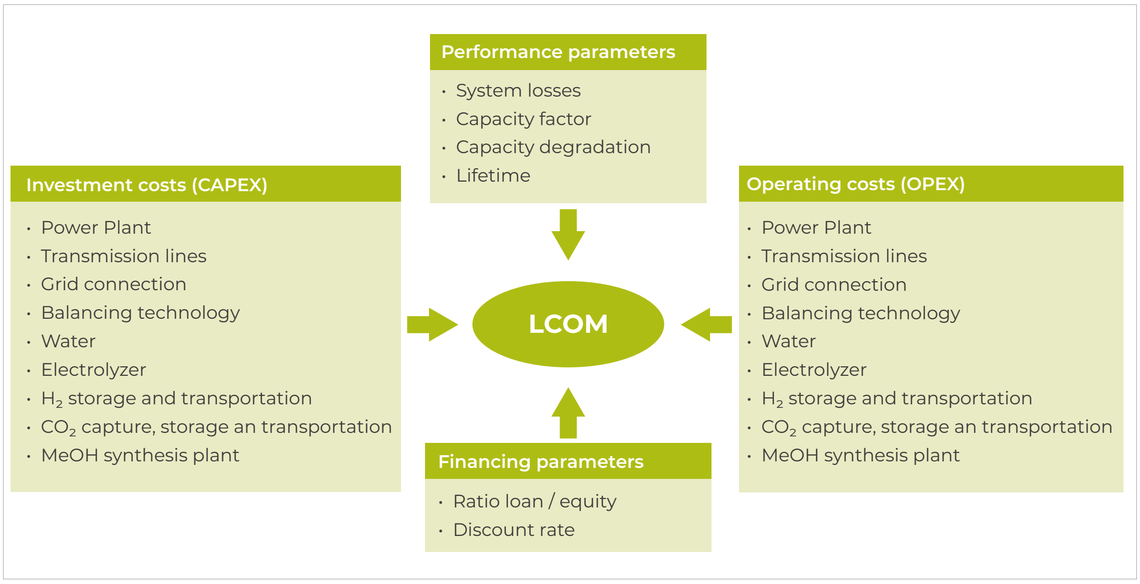

Figure 14: Cost components for a methanol production system

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[26] In this report, "methanol production system" refers to all assets associated with MeOH production including power plant, transmission lines and pipelines, water supply, electrolyser and H2 storage, balancing technology, CO_2 capture and MeOH synthesis plant.

CAPEX encompasses the costs associated with constructing a methanol plant. This includes expenses for building, purchasing equipment/components, and their installation. In contrast, OPEX includes costs incurred during the plant's operation. Fixed OPEX includes expenses necessary to maintain plant operations irrespective of production levels. Variable OPEX, however, fluctuates based on the plant's output, ranging from zero during non-operational periods to peak levels when the plant operates at full capacity.

Performance parameters of a methanol production system are closely tied to the capacity factor, which is influenced by the RE plant's capacity factor and the scale of the balancing technology. Equipment degradation, another crucial performance parameter, affects plant output and varies based on technology, plant location, operational conditions, and equipment age. System longevity and subsystem efficiencies, which dictate system losses, are also integral performance aspects.

Key financing parameters include loan conditions (interest rates and repayment periods) and the equity-to-loan ratio, leading to the determination of the WACC once the return on equity is known. Central to the financial-economic analysis, particularly for net present value (NPV) and the LCOH and LCOM, is the discount rate. This rate should reflect the capital's opportunity cost and is typically estimated based on average returns from similarly risky investments.

It is important to note that not all methanol systems include every cost element illustrated in Figure 14. Cost considerations largely depend on the RE plant's configuration and the chosen balancing technology. For example, CAPEX and OPEX associated with pipelines will vary depending on whether dedicated or public grids are used for electricity transmission to the Electrolyser / methanol plant. Additionally, the cost implications of CO_2 supply (capture and transportation) are significant factors in the overall economic feasibility of the methanol production system.

2.4.2 Computation of LCOM

The calculation of the LCOM currently utilises two distinct methodologies originally developed for determining the Levelised Cost of Energy (LCOE). These methods have been put forward by two separate entities: the United Kingdom Department for Business, Energy, and Industrial Strategy (BEIS) and the United Kingdom Department of Energy's National Renewable Energy Laboratory (NREL) (Aldersey-Williamsa & Rubertb, 2018).

According to the approach recommended by BEIS (BEIS, 2016), the LCOM (expressed in EUR/kgMeOH) is calculated by dividing the discounted total of all incurred costs, or the NPV, by the discounted total of methanol produced, referred to as the net present methanol (NPM) (as per Equation 2).

$LCOM_{BEIS} = \frac{NPV_{Costs}}{NPM} = \frac{\sum_{t=1}^{n} \frac{C_t + O_t + V_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{A_t}{(1+d)^t}}$	Equation 2

In Equation 2:

- t is the period ranging from year 1 to year n,
- C_t the capital cost in period t (including decommissioning),
- O_t the fixed OPEX in period t,
- V_t is the variable OPEX in period t,
- A_t is the methanol generated in period t,
- d is the discount rate,
- n is the final year of operation.

In an integrated GMeOH system that includes power generation, hydrogen production, CO_2 capture, and water supply, the variable transport cost (Vt) is negligible. However, when any of these essential inputs — such as electricity, hydrogen, CO_2 or water — are externally procured, the Vt becomes a significant factor in the overall cost analysis.

In contrast to the approach adopted by the BEIS, the method proposed by the NREL incorporates the Capital Recovery Factor (CRF) (NREL, 2018). This factor is utilised to convert upfront CAPEX into a sequence of annual costs, reflecting the impact of the discount rate. This method provides a nuanced approach to financial assessments by accounting for the time value of money over the lifecycle of the project (see Equation 3).

$\mathbf{LCOM_{NREL}} = \frac{C_o * \frac{i.(1+i)^n}{(1+i)^n - 1} + O}{8760 * C_f} + V = \frac{C_o * CRF + O}{8760 * C_f} + V$	Equation 3

In Equation 3:

- C_o is the overnight capital cost,
- i is the interest/discount,
- O is the fixed OPEX,
- C_f is the capacity factor,
- V is the variable operation.

$C.(1+i)^n$ expresses the future cost of the plant based on an assumed discount rate, while $\frac{i}{(1+i)^n - 1}$ subdivides the future cost into equal annual costs over the lifetime of the plant.

Both the BEIS and NREL methods typically generate comparable LCOM outcomes. However, this alignment largely holds true under specific conditions and for simpler, singular technology scenarios. Aldersey-Williams and Rubert's (2018) analysis titled "Levelised cost of energy – A theoretical justification and critical assessment" revealed that congruence between the NPV and CRF methods is contingent upon several simplifying assumptions. These include a consistent annual output and cost, all capital expenditures occurring in the first year with immediate initiation of capital recovery, the financing term mirroring the project's operational lifespan, and the absence of decommissioning expenses.

For traditional discounted cash flow-based investment evaluations, which necessitate the application of discount factors to all revenues and costs, the authors advocate the NPV method (Equation 2). This approach inherently accommodates the application of these discount factors, thereby offering a more nuanced and comprehensive financial analysis for complex projects.

2.5 Ownership structure

The development of large-scale GH_2 and GMeOH projects is still in its early stages, and as such, a universally applicable ownership model has yet to be established. In formulating ownership structures at the PFS stage, it is beneficial to draw parallels with similar large-scale energy projects, such as liquified natural gas (LNG) initiatives. While each project has its unique aspects, various models and considerations are useful for conceptualising the ownership structure. However, the final structure will evolve through the project development process, influenced by factors such as project sponsors and the allocation of financial risks. Many other options are conceivable and should be explored during the project ideation process at PFS stage, some of which are highlighted in the following.

An integrated model involves the project developer owning all the facilities, including RE sources, the GH_2 unit, and the methanol production plant. Developing a GMeOH project assumes that a point source of CO_2 has been identified. A procurement agreement will be realised for the CO_2 and a parallel project needs to be realised for installing CO_2 capture system able to supply the contracted quantities to the GMeOH facility in case one does not exist. The GMeOH is then sold under a purchase agreement, with project financing handled by project sponsors. On the demand side, this model usually envisages the off-taker owning or leasing import facilities, which allows for control over this critical asset and facilitates the import of GMeOH from various suppliers (Dentonnes, 2017).

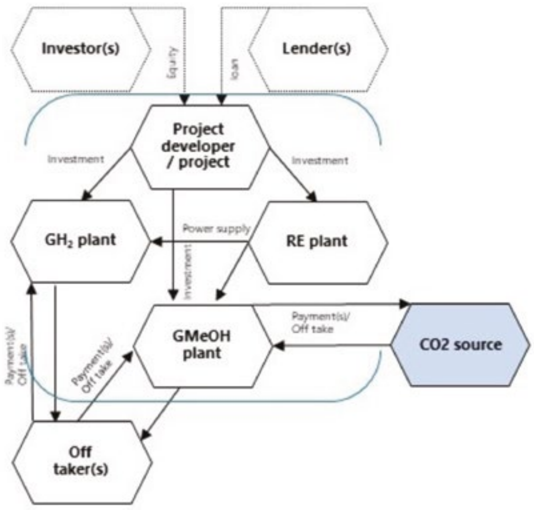


Figure 15: Integrated model with off taker(s)

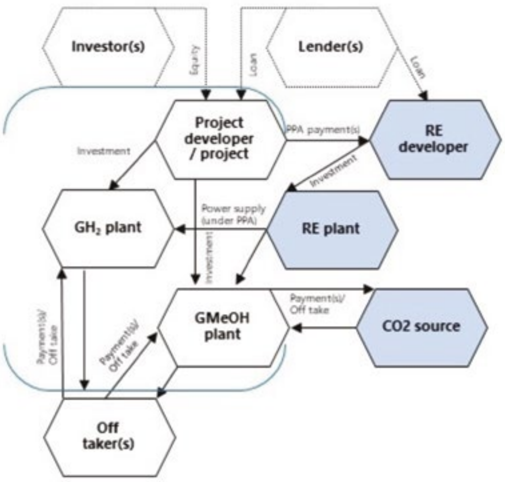


Figure 16: Segregated model with off taker(s)

Alternatively, a segregated model might involve third-party involvement for specific aspects, such as RE provision through a PPA and CO_2 supply. Given the complexity of GMeOH projects, which require diverse expertise across different production stages, it is plausible that various entities might operate different segments of the production chain, with the project owner purchasing the intermediate products. These models are also viable when the project proponent is producing GH_2 or GMeOH primarily for self-consumption rather than market sale.

Under a tolling agreement, the GMeOH off-taker pays a fee to process GH_2 through the methanol plant. The toller retains the flexibility to sell the produced GMeOH entirely, or alternatively, sell excess power (in grid-connected scenarios) or GH_2 domestically. This model necessitates a higher degree of flexibility in GMeOH off-take and is typically more suited to entities operating in multiple markets.

In the context of South Africa, where GMeOH production is expected to be largely for export, it is imperative to consider maritime transport in the ownership structure analysis. Specialist companies, with existing vessel fleets and operational expertise, are likely to manage the cargo capacity. Project owners or tollers would typically enter into long-term charter agreements to ensure control over shipping, a strategic move particularly crucial in mitigating supply chain disruptions (Coordinator, 2013).

Besides these ownership models and agreements, the Broad-Based Black Economic Empowerment (B-BBEE) Act (53/2013) sets out codes of best practice specifically for South Africa. B-BBEE is mandatory if a company is undertaking a project with the South African government and is sometimes mandatory if the project is working with a large South African company. B-BBEE must be assessed on a case-by-case basis for each project. The Generic B-BBEE Codes of Good Practice (2019) are a set of guidelines used by South African entities not covered by specific sector codes to measure their compliance with B-BBEE requirements. The goal is to assess their contribution to economic inclusivity and transformation. These codes assess five elements, each contributing to an overall B-BBEE score:

- Ownership: Black ownership of shares and voting rights,
- Management Control: Black representation in senior management and decision-making,
- Skills Development: Investment in training and development for black employees,
- Enterprise and Supplier Development: Supporting development of black-owned businesses and procurement from black suppliers,
- Socio-Economic Development: Initiatives improving the living standards of black communities.

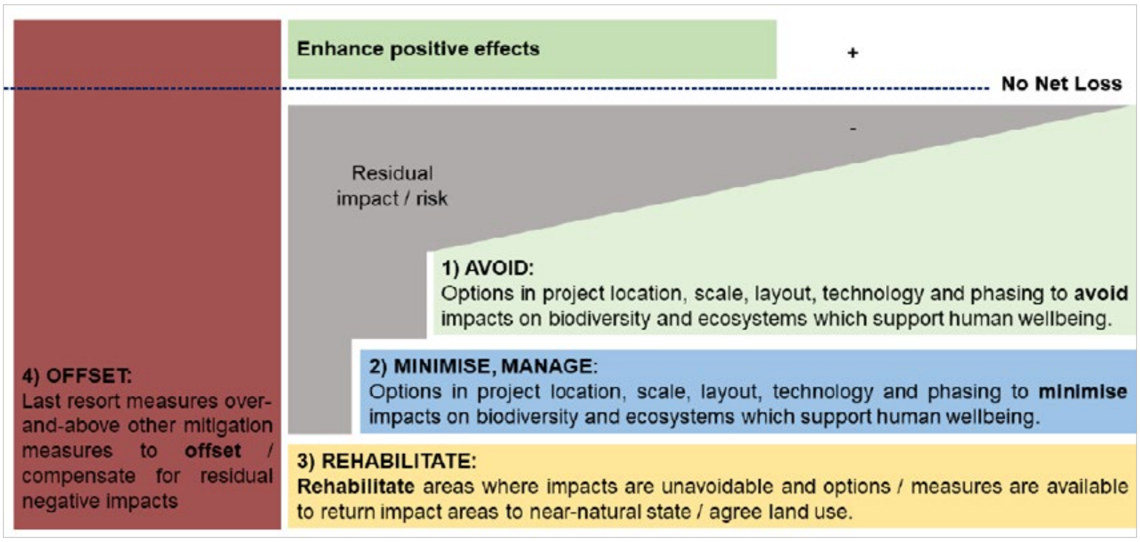
To achieve a good B-BBEE rating (e.g., Level 4+), entities need to score well across all elements, not just focus on ownership. To date, GH_2 projects are not considered sector specific, which means the Generic codes are applicable (DTIC, B-BBEE Codes, B-BBEE Acts, Strategies & Policies, 2023).

3. Environmental and social feasibility

The proactive assessment of potential environmental and social (E&S) impacts is crucial in the early stages of GMeOH project development. This early assessment serves as a strategic tool for pinpointing optimal development sites and refining project specifications, thereby establishing a project plan with minimised risks. The goal is to forecast, circumvent, lessen, or compensate for any significant detrimental impacts, while simultaneously amplifying the positive effects of the development. This process also involves identifying necessary environmental authorisations (ADB et al., 2016).

Neglecting E&S considerations in the preliminary stages of project planning can lead to critical project weaknesses, causing delays, escalating costs due to efforts in rectifying environmental harm, and jeopardising the project's social licence to operate[27].

The mitigation hierarchy, depicted in Figure 17, is a cornerstone principle in sustainable development, offering a structured approach to the planning and execution of development projects. The most effective strategy to mitigate negative impacts is their outright avoidance, which is most feasible during the initial stages of project planning and is closely linked to the selection of the project site. When avoidance is not entirely possible, other strategies in the hierarchy – **minimising, rehabilitating, and offsetting impacts** – are applied. These secondary strategies come into play after all possibilities for avoidance have been fully explored. Gaining insight into the potential adverse E&S impacts and the corresponding mitigation strategies for the proposed development is key to determining whether these negative impacts can be adequately reduced to acceptable levels.



1) AVOID: Options in project location, scale, layout, technology and phasing to **avoid** impacts on biodiversity and ecosystems which support human wellbeing.

2) MINIMISE, MANAGE: Options in project location, scale, layout, technology and phasing to **minimise** impacts on biodiversity and ecosystems which support human wellbeing.

3) REHABILITATE: **Rehabilitate** areas where impacts are unavoidable and options / measures are available to return impact areas to near-natural state / agree land use.

4) OFFSET: Last resort measures over-and-above other mitigation measures to **offset** / compensate for residual negative impacts

Figure 17: The mitigation hierarchy (after Rio Tinto, 2008)

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[27] *"Social license to operate refers to the perceptions of local stakeholders that a project, a company, or an industry that operates in a given area or region is socially acceptable or legitimate" (Raufflet, 2013)*

3.1 Site identification and selection

Selecting an optimal site or a combination of sites is a pivotal factor in the successful implementation of a GMeOH project. Technical aspects, often referred to as "pull" factors, that enhance a site's suitability for GMeOH production include factors like robust RE resources, accessible and sustainable CO_2 sources, available infrastructure, and market proximity (refer to sections 2 and 3). However, these advantageous technical attributes may overlap with regions that pose considerable E&S challenges, potentially rendering the project untenable from an E&S standpoint.

A methodical, multi-tiered approach is recommended for assessing geospatial suitability, integrating both technical and E&S considerations. This approach typically begins with a broad-scale analysis to identify several potential regions for further exploration. Subsequently, a more detailed site screening is conducted, evaluating alternative locations, establishing a business case, and ultimately making crucial decisions (as depicted in Figure 18).

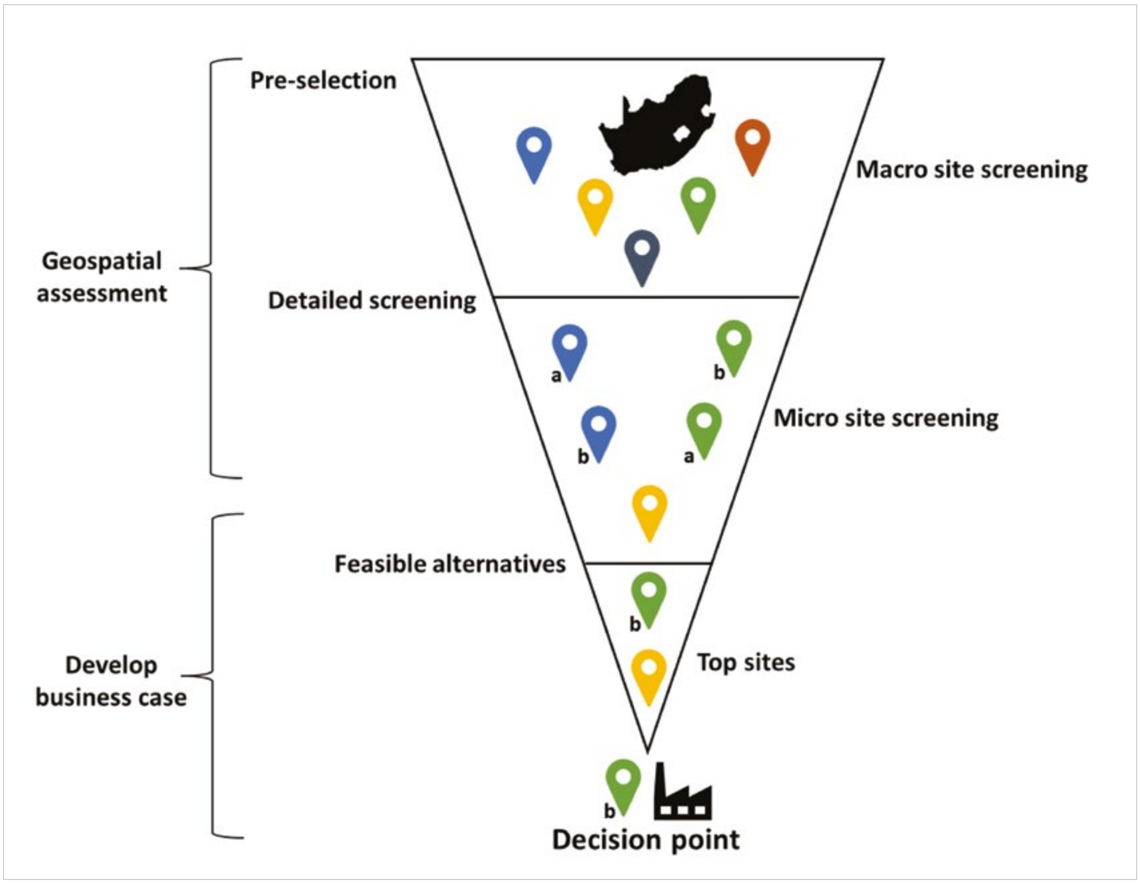

Figure 18: A stepwise approach to identifying suitable regions and selecting feasible GH_2/PtX sites (Nielsen, n.d.)

Numerous spatial analysis tools and datasets, often available at no cost, can aid in pinpointing sites that offer a viable resource opportunity while maintaining an acceptable E&S risk profile (see Table 5 for examples). For project proponents lacking in-house capabilities to effectively utilise and interpret this spatial data at a macro-level, engaging an Environmental Assessment Practitioner (EAP) early in the project planning phase is advisable. The EAP can conduct an environmental screening study (ESS) for the top site selections to provide informed guidance for site-specific decision-making. This early involvement of an EAP and the subsequent ESS are crucial steps in ensuring that chosen sites balance both the technical feasibility and the E&S sustainability of the GMeOH project.

Table 5: List of key freely available spatial software, tools and data sources useful for development site selection (non-exhaustive)

Description	Access	
Software		
QGIS	Geographic information system (GIS) software used to create, view and analyse spatial data in various formats. Some technical capability required.	https://qgis.org/
Google earth	Software that superimposes satellite images, aerial photography, and GIS data onto a 3D globe. Data in compatible KMZ/KML format can be viewed and created.	https://earth.google.com/intl/earth/download/
Tools		
Web-based online screening tool	Geographically based web-enabled application, which allows a proponent intending to submit an application for environmental authorisation in terms of the South African Environmental Impact Assessment (EIA) Regulations 2014, as amended to screen their proposed site for any environmental sensitivity. Developed and maintained by the Department of Forestry, Fisheries and the Environment (DFFE).	https://screening.environment.gov.za/screeningtool/
SAHRIS (South African Heritage Resources Information System) PalaeoMap	Fossil sensitivity map for palaeontological and geological heritage resources that guides and assists developers, heritage officers and practitioners in screening paleontologically sensitive areas at the earliest stages of the development cycle. Curated by the South African Heritage Resources Agency (SAHRA).	https://sahris.sahra.org.za/map/palaeo

Description	Access	
Property search	Property Search Web Application, curated by the Chief Surveyor-General, allows for the search and viewing of South African cadastral data (incl. farm / land parcel name and number, surveyor general code).	https://csggis.drdlr.gov.za/
South African GH_2 potential atlas	An online GH_2/PtX Potentials Atlas representing the relative suitability for the production of GH_2 and its derivatives across South Africa, focussing on the export and local GH_2 markets.	http://www.bit.ly/SAGH2atlas
Global solar atlas	Quick and easy access to solar resource and photovoltaic power potential data globally.	https://globalsolaratlas.info/map
Global wind atlas	Web-based application developed to help policymakers, planners, and investors identify high-wind areas for wind power generation virtually anywhere in the world, and then perform preliminary calculations.	https://globalwindatlas.info/en
BioEnergy atlas	The Bioenergy Atlas for South Africa (BEA) generalisable feasibility model was developed to assess investment feasibility into bioenergy conversion technologies	https://bea.saeon.ac.za/modelling-feasibility/
Data Sources		
BGIS (Biodiversity GIS)	Spatial biodiversity information for South Africa, curated by the South African National Biodiversity Institute (SANBI). Notable datasets include provincial conservation planning (incl. Critical Biodiversity Areas) and outputs from the National Biodiversity Assessment (incl. Threatened Ecosystems, wetlands and rivers) that may be considered as environmental constraints to new development.	http://bgis.sanbi.org/

Description	Access	
EGIS (Environmental GIS)	Spatial environmental information for South Africa, curated by DFFE. Notable datasets include the South African Protected Areas Database, National Land Cover, Renewable Energy EIA Application Database, Renewable Energy Development Zones and Electricity Grid Infrastructure Corridors.	https://egis.environment.gov.za/
SAHRIS heritage sites	Heritage sites repository, recording, geocoding and archiving all known, recorded heritage sites in South Africa, including archaeological, cultural, living and built heritage. Datasets of particular interest include declared and graded heritage sites. Curated by SAHRA.	https://sahris.sahra.org.za/allsitesfinder
StepSA (Spatial Temporal evidence for planning South Africa) Socio-economic indicators	Census data on population, employment and economic production per economic sector aggregated as mesozones. Developed by CSIR.	http://stepsa.co.za/socio_econ.html
WASA (Wind atlas South Africa)	South African wind resources mapped through the development, verification, and employment of numerical wind atlas methods to enable large scale of exploitation of wind energy in South Africa.	http://wasadata.csir.co.za/wasa1/WASAData
SolarGIS	Collection of solar resource maps to help the solar industry with development of solar projects.	https://solargis.com/maps-and-gis-data/download
BioEnergy atlas data catalogue	Various bioenergy data including feedstock information.	https://bea.saeon.ac.za/data-catalogue/

During the PFS phase, multiple critical factors contribute to the attractiveness of a potential site for development. These factors must be carefully evaluated in relation to significant environmental sensitivities, which could limit or impose constraints on the suitability of the site.

Restrict / constrain suitability:

- Protected areas (terrestrial and marine),
- Watercourses (wetlands, rivers, estuaries),
- Threatened ecosystems,
- Agricultural fields (crops),
- Heritage features,
- Proximity to human settlements,
- Land use planning and zonation,
- Critical biodiversity areas.

Enhance suitability:

- Favourable resource potential for wind, solar PV, CO_2 and water source,
- Renewable Energy Development Zones[28] and Electricity Grid Corridors[29] – geographic areas where environmental permitting (see section 4) for RE and electricity grid developments are streamlined,
- Conformance with existing land use planning and zonation,
- Proximity / access to existing infrastructure and services,
- Disturbed areas with little or no conservation value.

3.2 Impact and mitigation identification

At PFS stage, an in-depth understanding of the project design is crucial to determine the E&S impacts. The production of GH_2 GMeOH involves a range of activities and outputs, each with its distinct impact mechanisms. These mechanisms include:

- Decarbonisation initiatives,
- Emissions, including potential fugitive releases,
- Processes of electricity generation,
- The intricacies of supply chains,

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[28] https://egis.environment.gov.za/redz

[29] https://egis.environment.gov.za/egi

- Financial investment and its implications,
- Creation of employment opportunities and skill development,
- Production and management of water resources,
- Development of infrastructure,
- Land clearance activities,
- Potential conflicts arising from land use,
- In-migration of job seekers,
- Generation of waste products,
- Risks associated with explosions, leaks, and spills.

These drivers manifest in various impacts, both beneficial and adverse, leading to changes in:

- Biodiversity and ecological dynamics,
- Macroeconomic factors, energy planning, and GHG emissions,
- Local economies, community well-being, and livelihoods,
- Land management, usage patterns, and water resources.

The mitigation hierarchy, outlined in Table 6, offers a framework for enhancing the positive impacts and minimising the negative ones. This early understanding of the impact drivers and the resultant E&S implications of GMeOH production assists in identifying potential risks, mitigation strategies, management actions, and necessary permits as detailed in section 5.

Table 6: Options to mitigate negative impact and enhance positive impacts[30]

Response class	Example
Avoidance	Avoiding highly sensitive ecological areas and cultural heritage sites (screening undertaken before EIA phase)
Impact mitigation	Reducing negative impacts if avoidance is not possible through thoughtful design and implementation, as well as thorough and consistent monitoring of the effectiveness of impact mitigation measures.
Restoration	Restoring damaged ecological habitats to their original state after disturbance
Offsetting	Compensating for residual impacts on the environment by enhancing or restoring equivalent habitats elsewhere
Co-locations	Mixed land-use synergies e.g., agrivoltaics which involves the use of land for both solar panels and agriculture
Community engagement	Actively involving local communities in decision-making processes related to land use, for example.
Good governance	Policy clarity, government efficiency, transparency, credibility, participatory decision-making
Economic instruments	Privatisation, incentives, subsidies, taxes, capital investment
International collaboration	Collaborating with other nations to, for example, share knowledge, technology, and resources
Knowledge instruments	Research and skills development, including technical innovation, training, and reskilling
Regulatory instruments	Where regulations could be passed to minimise potential harm or increase the benefits of proposed developments

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[30] *Additional positive impacts could be the sale of excess electricity (due to oversizing of RE capacity), leading to additional revenue, alleviation of loadshedding, and power made available to communities and local farmers (e.g., for irrigation)*

4. Authorisations, approvals and permits

During the PFS phase, a critical task is to meticulously investigate the necessary environmental authorisations, planning consents, and other regulatory permits essential for executing the proposed development. This exploration includes understanding the Authorisation and operational requirements for different project segments, such as RE sources, water supply systems, hydrogen production facilities, CO_2 capture, storage and transportation and methanol synthesis units. These components may be geographically separated, managed by distinct operators, or entail varied impacts and requisite mitigation or management strategies during their operation. Consequently, separate approvals for each component might be necessary. Additionally, it is vital to anticipate the duration of the entire permitting process, providing a realistic timeline for project implementation. Key environmental authorisations and permits that must be addressed are presented in the following sections.

4.1 Environmental authorisation

The National Environmental Management Act (NEMA)[31] in South Africa stipulates the Environmental Impact Assessment (EIA) regulations of 2014, as amended, under Chapter 5[32]. These regulations are pivotal for overseeing the preparation, evaluation, submission, processing, and decision-making on applications for Environmental Authorisation (EA). Their primary purpose is to regulate activities that require environmental scrutiny, with a dual aim: to mitigate negative environmental impacts and to amplify positive outcomes.

Under NEMA's EIA regulations, certain "listed activities" necessitate an EA:

- **Listing Notice 1:** Activities requiring a Basic Assessment (BA) process.
- **Listing Notice 2:** Activities necessitating a comprehensive scoping and EIA process.
- **Listing Notice 3:** Specific activities within designated provinces that require a BA process.

A full scoping and EIA processes includes two phases:

1) Scoping phase, which aims to identify key issues that will be considered during the assessment phase, as well as a plan of study for the assessment stage, subject to a PPP; and

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[31] South Africa. 1998. National Environmental Management Act No. 107 of 1998.

[32] South Africa. 2017. Amendment to the Environmental Impact Assessment Regulations, 2014. (Notice 326). Government Gazette, 40772, 07 April 2017.

2) Assessment phase, which includes an impact assessment, mitigation measures and an Environmental Management Programme (EMPr), subject to a PPP, and upon which the competent authority (CA) will decide whether to grant EA.

A BA process does not include a scoping phase, only an assessment phase (as described above), and usually has shorter decision turn-around timeframes.

Depending on the complexity of the development proposal, the entire scoping and EIA process, including pre-EIA planning, monitoring, and specialist assessment, up to decision by the CA, may take 2 – 5 years. The BA process does not include a scoping phase, only the assessment phase, and usually has shorter timeframes.

Key listed activities relevant to GMeOH production include, but are not limited to:

- Development of facilities or infrastructure for the **generation of > 10 MW electricity from a renewable resource.**
- The development and related operation of infrastructure >1,000 m in length for the **bulk transportation of sewage, effluent, process water, waste water, return water, industrial discharge or slimes.**
- The development of facilities or infrastructure for the **off-stream storage of water,** including dams and reservoirs > 50,000 cubic metres.
- The development and related operation of facilities or infrastructure, for the **storage, or for the storage and handling, of a dangerous good** > 80 cubic metres.
- The development of structures with a **footprint** > 50 square metres **in the coastal public property.**
- The development and related operation of facilities for the **desalination** of with a design capacity to produce > 100 cubic metres of treated water per day.
- The development of facilities or infrastructure for **any process or activity which requires a permit or licence** or an amended permit or licence in terms of national or provincial legislation governing the generation or **release of emissions, pollution or effluent.**
- The development and related operation of facilities or infrastructure for the **bulk transportation of dangerous goods:**
    - in gas form, outside an industrial complex, using pipelines > 1,000 m in length, with a throughput capacity > 700 tonnes per day,
    - in liquid form, outside an industrial complex, using pipelines, > 1,000 m in length, with a throughput capacity > 50 cubic metres per day.
- The development and related operation of facilities or infrastructure for the **treatment of effluent, wastewater or sewage** with a daily throughput capacity > 15,000 cubic metres.

- The **clearance of an area** > 20 hectares or more of indigenous vegetation.
- The development and related operation of facilities or infrastructure for the **treatment of effluent, wastewater or sewage** with a daily throughput capacity > 15 000 cubic metres.
- The **development of a road** > 1 km long with a reserve > 30 metres, or when the catering for more than one lane of traffic in both directions.

The scoping and EIA process comprises two phases:

1. Scoping phase: Identifies critical assessment issues and develops a study plan for the assessment stage, incorporating a Public Participation Process (PPP).
2. Assessment phase: Involves detailed impact assessment, mitigation strategies, and an Environmental Management Programme (EMPr), again incorporating a PPP. The Competent Authority (CA) bases its EA decision on this phase.

Effective environmental screening and site selection, particularly avoiding environmentally sensitive areas, significantly enhance the likelihood of successful EA application.

EIA processes must be executed by qualified, independent EAPs leading a team of expert specialists (e.g., ecologists, agricultural scientists, avifauna experts, etc.). It is the responsibility of the project proponent or developer to commission the EAP.

4.2 Environmental management programme

For development activities necessitating EA, the formulation of a comprehensive EMPr is imperative. This EMPr serves as a critical tool to ensure environmentally responsible project execution.

Key objectives of an EMPr (Hill, 2000) include:

- Adherence to relevant environmental regulations and guidelines at local, provincial, national, or international levels.
- Monitoring of environmental performance to assess the effectiveness of impact management strategies.
- Adaptability in responding to changes and unforeseen events throughout the project lifecycle.
- Continuous feedback mechanism for improving environmental management practices.

As mandated by the NEMA, an EMPr should comprehensively outline all proposed measures for managing, mitigating, or rectifying environmental impacts identified during the EIA process. These measures should include all stages of the development, including planning, design, pre-construction, construction, operation, maintenance, environmental rehabilitation, and eventual project closure. Additionally, ongoing monitoring and auditing are required to ensure adherence to the EMPr stipulations.

The EMPr adopts a structured approach, articulating a clear goal and objectives, followed by detailed management actions aimed at achieving these objectives. To facilitate understanding and implementation, these components are typically organised in a tabular format, illustrating the interconnections between the overarching goal, corresponding objectives, actionable measures, responsibilities, and specific monitoring criteria and targets.

The components of the management plans are:

- **Activity/aspect:** Identification of potential positive or negative impacts requiring management or mitigation.
- **Objectives:** Clear goals for managing or mitigating environmental impacts linked to the identified activities or aspects.
- **Mitigation/management actions:** Detailed actions to enhance positive impacts and mitigate or eliminate negative ones, considering factors like responsibility, methodology, frequency, resource allocation, and prioritisation.
- **Monitoring:** Essential monitoring actions required to verify the achievement of objectives, detailing methodology, frequency, and responsible parties.

An EMPr should be viewed as a dynamic document, evolving with the project's progression. It should be regularly reviewed and updated to incorporate new information or additional actions for upholding environmental management principles throughout the project's life cycle.

4.3 Heritage approval

The National Heritage Resources Act (NHRA)[33] governs the process of identifying, assessing, managing, and conserving heritage resources within South Africa. According to section 38 (8) of the NHRA, any Heritage Impact Assessment (HIA) necessitated by laws outside the NHRA (such as the NEMA) must comply with the HIA criteria set forth in the NHRA itself. This integration of the HIA into the EIA process ensures a comprehensive evaluation of potential heritage impacts. Additionally, even in scenarios where an EA is not mandated, certain activities specified in section 38 (1) of the NHRA still require approval concerning heritage impacts.

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[33] *South Africa. 1999. National Heritage Resources Act No. 25 of 1999.*

4.4 Air emission licence

The National Environmental Management: Air Quality Act (NEM:AQA)[34] aims to protect the environment, prevent pollution and ecological degradation towards sustainable development. It contains a list of activities, which require an Air Emissions Licence (AEL) as well as associated minimum emissions standards. Of interest is Category 6 on "The production, or use in production of organic, which applies to installations producing, using or storing more than 100 tonnes per annum of the listed compounds". Other aspects, such as any residual atmospheric emissions from biomass combustion related to the carbon source must also be considered. The AEL application process may be integrated / conducted concurrently with the EIA process.

4.5 Water use Licence

The National Water Act (NWA)[35] focuses on safeguarding and sustainably managing South Africa's water resources. According to section 21 of the NWA, certain water use activities necessitate obtaining a Water Use Licence (WUL). These activities encompass both consumptive and non-consumptive water uses. Consumptive uses include actions like extracting water from a watercourse, storing water, and discharging waste or wastewater into a water resource. Non-consumptive uses involve activities that affect the flow of water bodies, such as impeding or diverting the flow and modifying the beds or banks of watercourses. The process for applying for a WUL can be coordinated and executed alongside the EIA process.

4.6 Coastal discharge permits

The National Environmental Management: Integrated Coastal Management Act (NEM:ICMA)[36] outlines essential considerations for activities along the coast that necessitate EA. These considerations include the potential impacts on socio-economic activities, coastal environmental processes, the coastal protection zone, and coastal public property. In scenarios where effluent, such as brine from a desalination facility, is planned to be discharged into the ocean, obtaining a Coastal Waters Discharge Permit (CWDP) is mandatory.

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[34] *South Africa. 2004. National Environmental Management: Air Quality Act No. 39 of 2004.*

[35] *South Africa. 1998. National Water Act No. 36 of 1998.*

[36] *South Africa. 2008. National Environmental Management: Integrated Coastal Management Act No. 24 of 2008.*

4.7 Use of vehicles in a coastal area

The National Environmental Management: Integrated Coastal Management Act (NEM:ICMA) also includes regulations governing the usage of vehicles within coastal areas[37]. For activities such as the construction and maintenance of infrastructure, which might include desalination facilities and their associated pipelines, it is mandatory to acquire a specific permit for the operation of vehicles in these coastal regions[38].

4.8 Subdivision of agricultural land

The Subdivision of Agricultural Land Act, as amended, (SALA)[39] is concerned with the sustainable and productive use of agriculturally zoned land. Two approvals are required from the National Department of Agriculture, Land Reform and Rural Development (DALRRD) if a proposed RE facility is located on agriculturally zoned land:

No objection letter for the change in land use issued by the Deputy Director General (Agricultural Production, Health and Food Safety, Natural Resources and Disaster Management). This No Objection is one of the requirements for receiving municipal rezoning, and requires a motivation supported by good evidence (e.g., an agricultural specialist opinion) that the development will not significantly compromise the future agricultural production potential of the development site. It is advisable to apply for this as early in the process as possible. A positive EA does not assure No Objection from DALRRD.

Consent for long-term lease in terms of the SALA. If the DALRRD No Objection Letter has already been obtained, the SALA approval should not present any difficulties. SALA approval can only be applied for once EA and a Municipal Rezoning Certificate (see section 4.9) has been obtained.

4.9 Land use rezoning

Development of industrial facilities on land zoned for agriculture or any other unrelated land use requires rezoning to an applicable category (e.g., commercial or industrial). Rezoning applications are usually considered and decided by the relevant local municipality in terms of its applicable land use planning by-laws.

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[37] *South Africa. 2014b. Control of use of vehicles in the coastal zone. (Notice 496). Government Gazette, 37761, 27 June 2014.*

[38] *Coastal area means: coastal public property; littoral active zone; and any area between the high-water mark and up to 500 metres landwards of the high-water mark where dunes, wetlands, mangroves, lagoons, salt marshes, salt pans, mud flats occur, but not exceeding the boundary of the coastal zone as determined in the NEM:ICMA.*

[39] *South Africa. 1970. Subdivision of Agricultural Land Act No. 70 of 1970.*

4.10 Licence to operate a major hazardous installation

The Major Hazardous Installation (MHI) Regulations[40] of the Occupational Health and Safety Act (OHSA)[41] provides a list of dangerous substances and quantity thresholds beyond which MHIs must be registered or Licenced.

Exceedance of the following quantities of methanol at any establishment is subject to the requirements of the MHI Regulations:

- > 50 tonnes (low hazard),
- > 500 tonnes (medium hazard),
- > 5,000 tonnes (high hazard).

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[40] *South Africa. 2023. Promulgation of Major Hazard Installation Regulations. (Notice 2989) Government Gazette, 47970, 31 January 2023.*

[41] *South Africa. 1993. Occupational Health and Safety Act No 85 of 1993.*

5. Safety requirements

In South Africa, the production of methanol is tightly regulated to ensure safety, environmental protection, and adherence to quality standards. These regulations encompass a range of codes and standards that govern the entire process. While some of these regulations align with international practices, others are specific to the legal framework of the country. Here are some important factors to consider:

The OHSA is a key piece of legislation that governs workplace safety in South Africa. Alongside its related regulations, the OHSA sets out guidelines for handling hazardous chemicals, maintaining safe working conditions, providing appropriate training for employees, and implementing emergency response plans. Compliance with the OHSA is of utmost importance in methanol production facilities to safeguard the health and safety of workers.

The Environmental Conservation Act provides guidelines for environmental protection, including regulations on air emissions, water quality, waste management, and environmental impact assessments. Methanol production facilities must adhere to these regulations to minimise their environmental impact and obtain the required permits for operation.

The South African National Standards, issued by the South African Bureau of Standards, cover various aspects of methanol production processes. These standards include equipment design, safety protocols, product quality, and environmental management.

The Chemical and Hazardous Substances Regulations established by government departments such as the Department of Labour or the Department of Environment, Forestry, and Fisheries, set guidelines for handling hazardous substances like methanol. Compliance with these regulations is crucial for the safe handling, storage, and transportation of methanol within South Africa.

The NEMA establishes frameworks for environmental management and conservation. It requires conducting EIAs for industrial projects, ensuring compliance with environmental regulations, and obtaining necessary permits before initiating methanol production activities.

If methanol production involves feedstock or processes related to the petroleum or liquid fuels industry, additional regulations under bodies like the Department of Mineral Resources and Energy may apply. This could include licensing requirements and compliance with specific industry standards.

6. Stakeholders

Stakeholder identification during PFS stage aims to form an early understanding of the needs and expectations of those with interest, both within and outside the project environment. The roles of various stakeholders and their inter-relationships will contribute to project risk and viability (Smith, 2000).

For GMeOH development in the South African context, five main stakeholder groups may be considered (Figure 19):

Project developer; Investors; Financiers; Shareholders.	• Direct role in conceptualising and realising the project idea.
Public sector; Authorities; Decision-makers.	• Veto players with legislative prerogatives and mandates to fulfil.
Non-Government Organisations; Local communities.	• Those likely to be indirectly impacted (positively or negatively) by the project being realised. Veto players underpinning the 'social Licence to operate'.
Off-takers; Customers.	• Central to the business case and a successful project.
Consultants; Contractors; Suppliers.	• Central to the planning, implementation, operation and maintenance of the project.

Figure 19: Stakeholder landscape framework

In view of the PFS, the **project developer** itself is the central stakeholder. It is essential to present the relevant company information and activities, and to provide proof of performance. In addition, the PFS shall present information about the shareholders and ownership structure of the project developer (or consortium of project developers) as well as meaningful financial information for the last 2-3 financial years. If applicable, the PFS should describe the established relationships with the relevant stakeholders and summarise the discussions held up to the time the PFS was prepared, as well as list potential bottlenecks and points of friction.

The **public sector** plays an important role in pursuing the GMeOH project idea, especially in terms of considering and approving various permit and licence applications. The public sector splits into entities that operate at the local / municipal level and those that are operating at the provincial and national level. In South Africa, municipalities regulate RE generation (embedded generation) through by-laws, policies and distribution grid access. They also procure energy services and oversee building standards, and thus should be considered already at PFS level. A recent study commissioned by H2.SA under the project "Renewable H_2 Market Potential and Value Chain Analysis" explores all relevant stakeholders along the value chain that are directly linked to (i) the production, transport or use of GH_2 or its derivatives in South Africa, (ii) support GH_2 projects and/or (iii) have a role in shaping the GH_2 investment climate.

Besides local authorities, it is critical that project developers start consulting and engaging directly with local **communities, non-government organisations** and other relevant representatives of civil society early towards securing a 'social licence to operate'. Transparency of key and realistic project information is key to building trust in the project idea. Community development agreements are an effective mechanism to involve communities and agree on engagement terms such rights, roles, responsibilities and dispute resolution mechanisms (Organisation, 2023). H2.SA also provides a tool kit for community engagement (Brandt, 2023).

The market environment and financial viability of a GMeOH project currently dictates that most of the GMeOH will likely be produced for export or as shipping fuel. Therefore, much of the attention in developing the project idea must be directed to overseas / export stakeholders / **customers and off-takers** respectively. A possible off-take agreement is central to financial project implementation, especially for risk assessment. Project finance requires a predictable revenue stream and financiers require long-term 'take or pay' off-take arrangements with creditworthy customers (Organisation G. , 2022). Apart from off-take of the produced GMeOH product, other additionalities such as excess RE or produced water, may also be sold to other private and public customers who may be identified during PFS stage stakeholder analysis.

Finally, **suppliers** and others forming part of the supply chain to realise a GMeOH project are a key stakeholder group that should be identified early the project planning process. Depending on how the project ownership is structured suppliers can represent the majority of external stakeholders, for example, when the inputs required to produce GMeOH (RE, water, GH_2, CO_2) are outsourced.

7. Typical Project schedule / development phases

The PFS stage of a GMeOH project idea may already include early project schedule planning. Following the PFS, the project idea may move on and iterate amongst stages of feasibility studies, engineering design, permitting towards commissioning and operation (Table 7). Each development phase has its own considerations, decision points and outcomes.

It is important to note that the various components associated with realising a GMeOH project (desalination facility, RE plant, Electrolyser, CO_2 sourcing, methanol synthesis, storage and transport) is a complex interconnected system for which planning and development schedules may be interdependent or disjunct.

The PFS (Phase 1) and feasibility study (Phase 2) aim to determine whether a project can move to the next phases with relative certainty.

During the engineering (Phases 3 – 4) the project description and specifications start to take shape. The details from the engineering phases are necessary to identify and pursue applicable permits. In terms of environmental permitting, and following best practice environmental practices, the permitting and environmental assessment / planning should be undertaken iteratively and inform each other – ultimately to de-risk the project. For example, a preliminary design may impinge on a heritage feature that has been discovered on site. Amending the project layout to avoid the identified heritage resource (i.e., implement the first step of the mitigation hierarchy – avoidance (refer to section 3)) will safeguard the heritage resource, increase the odds of receiving favourable authorisation and increase social acceptability.

The permitting and preconstruction monitoring phase (Phase 5) also requires consideration of potential long-lead items and permit / authorisation / approval validity periods. For example, in the case of wind energy development, pre-construction bird monitoring at the proposed site may require surveys extending over several seasons. Additionally, wayleaves from authorities to construct / upgrade roads may only be valid for a period of 12 months. As such, it is important to keep a record of permits required, the actions and time required to obtain specific permits and the validity period of those permits.

The procurement phase (Phase 6) may overlap with the permitting phase, especially where consulting services must be procured to facilitate or provide input into approvals. Similarly, procurement may extend into the construction phase to procure materials and equipment as the need arises.

Construction (Phase 7) will commence once the project components are “shovel ready”. During construction and operations any management plans (e.g., the EMPr) must be diligently and adaptively implemented. Once construction is complete, the facility/ies forming part of the GMeOH development can be commissioned (Phase 8) and proceed to the operations and maintenance phase (Phase 9).

At the facilities’ end-of life (Phase 10) aspects of life extension or decommissioning with associated reuse and recycling of materials must be considered.

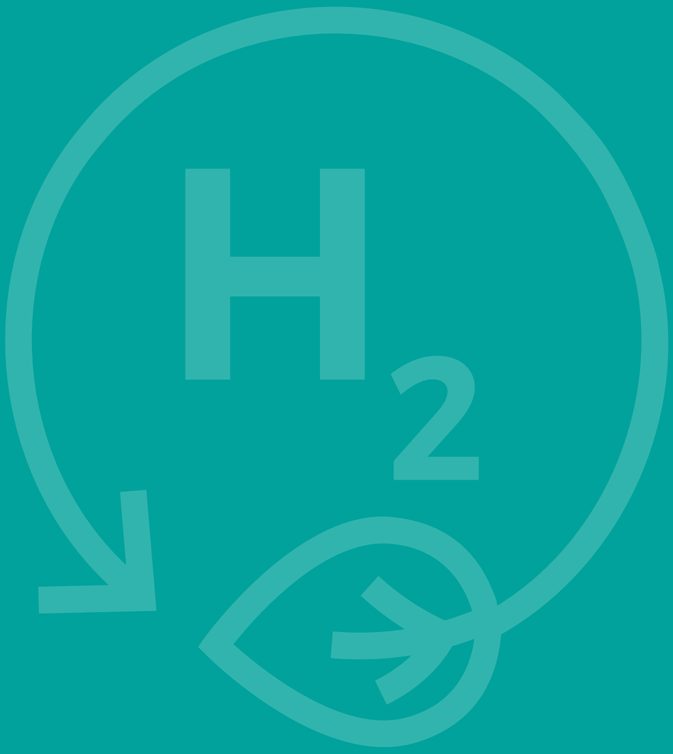
Table 7: Typical project development phases and relative timing

Phase				Considerations and outcomes	Relative timing →																	
Conceptualisation		1	Prefeasibility	• Need and desirability. • Project idea and options (location, technology). • Applicable regulation. • Stakeholder identification. • High-level techno-economic and financial feasibility. • Outline (incl. timeframes) of activities / studies already conducted, in progress and planned.	•																	
		2	Feasibility	• Early design concept. • Risk assessment. • High-level EPC needs. • Stakeholder engagement. • Detailed techno-economic and financial feasibility. • Determine bankability.		•	•															
		3	Preliminary engineering	• Indicative project schedule. • Site selected and specific conditions. • EPC requirements.			•	•	•													
		4	Detailed engineering	• Final project schedule. • EPC requirements. • Design specifications.					•	•	•	•										

Phase				Considerations and outcomes	Relative timing →																	
Conceptualisation	Execution	5	Permitting and pre-construction monitoring	• Specialist studies (required as input to environmental permits). • Environmental and planning permits. • General due diligence.			•	•	•	•	•	•										
		6	Procurement	• Land lease / purchase agreements. • Request for Proposals / Quotations. • Contract awards and performance management.						•	•	•	•	•								
		7	Construction	• Method statements. • Adaptive implementation of Environmental Management Programme (EMPr).										•	•	•	•	•				
		8	Start-up and commissioning	• As-built drawing. Installation compliance reports. • Training. • Maintenance and operation manuals Adaptive implementation of EMPr. • Testing.															•			
		9	Operations and maintenance	Supply chain management. Performance monitoring and inspection. Adaptive implementation of EMPr.																→→		
		10	Decommissioning / end-of-life	Reuse and recycle material, components, and equipment. Adaptive implementation of EMPr.																		→•

PART 2:

Green methanol
Pre-Feasiblity Study Example



PART 2:

Green methanol Pre-Feasiblity Study Example

This section discusses a succinct case study example of a GMeOH project, applying the guidance set out in Part 1 B[42]. The case study particularly showcases the most critical and pertinent aspects of a PFS, including site selection, project design, techno-economic feasibility E&S feasibility and financial assessment. It is crucial to note that this PFS example must not be interpreted as an accurate forecast for guiding development decisions but serves as an illustrative how-to-guide for conducting a PFS.

For the purpose of the techno-economic and financial analysis, we propose a GMeOH project with an annual production capacity of 100,000 tonnes of GMeOH, located near the Port of Richards Bay, South Africa. This production scale is considered reasonable for start-up project initiators.

Additionally, the Richards Bay area presents a significant potential in GMeOH production, particularly for zero carbon shipping fuels, due it is proximity to some biogenic carbon sources, RE potential, including for offshore wind, and the existing port operations.

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[42] *The archetype project is not a real project, but does represent a realistic project for the purposes of this PFS example.*

8. Pre-Feasibility Study for a proposed green methanol production facility near Richards Bay, South Africa

8.1 Proposed project

The proposed GMeOH project consists of:

- 100,000 tonnes per year nominal methanol synthesis plant
- Biogenic CO_2 source from a biomass combustion plant to be purchased externally
- PEM or high-pressure alkaline Electrolyser (size will be the result of optimisation)
- Utility scale battery (size will be the result of optimisation)
- Hybrid RE facility consisting of solar PV and wind technologies (size will be the result of optimisation)
- Water source to be purchased externally

The IMO considers renewable methanol a pivotal fuel in decarbonising the maritime industry due to its compelling environmental and operational benefits. Renewable methanol significantly lowers GHG emissions, including CO_2, SOx, NOx, and particulate matter, aligning with the IMO's ambitious emission reduction targets for 2030 and 2050. Methanol's compatibility with existing internal combustion engine technologies facilitates relatively straightforward vessel retrofitting, offering a pragmatic path for the industry's transition to cleaner energy sources. Additionally, methanol's safety record, liquid state at ambient conditions, and existing global distribution networks simplify storage and bunkering operations. This fuel's adoption helps shipping companies comply with stringent environmental regulations, including MARPOL Annex VI, underscoring its role in the maritime sector's sustainable transformation. Because of this and the position of South Africa regarding international maritime transport routes and major ports, the use of the produced GMeOH as maritime fuel has been considered as the principal off-take of the fuel.

8.2 Site selection

Richards Bay, located in the KwaZulu-Natal province of South Africa, presents itself as an ideal location for the establishment of the GMeOH production facility, considering its unique combination of resources, infrastructure, and strategic positioning.

One of the key factors in selecting Richards Bay (Figure 18) for the GMeOH plant is its proximity to an existing 40 MW biomass power plant located inside a mill. For the purposes of this pre-feasibility study, information on existing biomass installations can be (and has been) accessed via the clean energy access tool of the European Commission's Joint Research Centre, available on the African Knowledge Platform[43]. The presence of this plant can offer a readily available source of biogenic CO_2, which is crucial for sustainable methanol production. This assumes that the CO_2 can be purchased from the owner / operator of the biomass plant.

Richards Bay is endowed with substantial RE resources, specifically in terms of solar and wind energy potential (Figure 20). The region's climatic conditions are conducive for PV and wind turbine installations, including offshore, ensuring a steady and reliable supply of RE for the electrolysis of water to produce GH_2 as an essential input for the GMeOH synthesis. This abundance of renewable resources guarantees high operational efficiency and aligns with the sustainability objectives of the project.

The location of Richards Bay, home to one of South Africa's largest commercial ports, offers strategic advantages for the project. The proximity of the project to the port and its ancillary infrastructure allows for export of the GMeOH and/or to provide it as shipping fuel. This proximity to off-take is an advantage for commercial operations, especially in view of CAPEX reductions. Additionally, the port's well-established infrastructure supports the import of necessary equipment and technology for the development of the methanol production plant. This logistical convenience is critical for the efficient project development, operations and maintenance of the plant.

Richards Bay's established industrial base is a significant asset. The existing infrastructure reduces initial capital outlay for the development of the new facility. Moreover, the presence of various industries creates potential local demand for GMeOH off-take, which can be used as a feedstock in other chemical processes or as a clean-burning fuel. Rail connection as a transport option practically to everywhere in the country is available and the grid infrastructure can be considered significant and reliable. In view of the potential environmental and societal impacts of the project, the availability of existing infrastructure minimizes the ecological impacts of the development. Figure 18 presents an excerpt from the South African GH_2 potentials atlas, which is based on a multi-criteria assessment of various push and pull-factors for project siting with an emphasis on E&S criteria. The chosen location for the GMeOH plant indicates a well-suited area for RE deployment and plant operations (light green), but aspects such as high population density will require attention from a safety perspective.

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[43] https://africa-knowledge-platform.ec.europa.eu/energy_tool

Table 8: Social-environmental features and associated constraints rating used to identify potential sites for an example GMeOH development near Richards Bay

⬛	**Restricted / Avoid**	Protected Areas: National Parks, Nature Reserves, Private Nature Reserves, Mountain Catchment Areas, Protected Environments, Wilderness areas.
		Critical biodiversity areas (category 1 and 2)
		Aquatic features: watercourses, rivers and wetlands
		Agriculture: horticulture, viticulture, pivot irrigation (incl. rooibos), shade nets, subsistence farming, food gardens
		Land use / cover: built-up areas, urban, residential, villages, smallholdings, commercial.
▒	**Constrained**	Land use / cover: mines and quarries
		Agriculture: rainfed annual crops / planted pastures; strip field cultivation, smallholdings, old fields
		Aquatic features: watercourses, rivers and wetlands (32 m buffer)
🟩	**Open**	Remaining areas

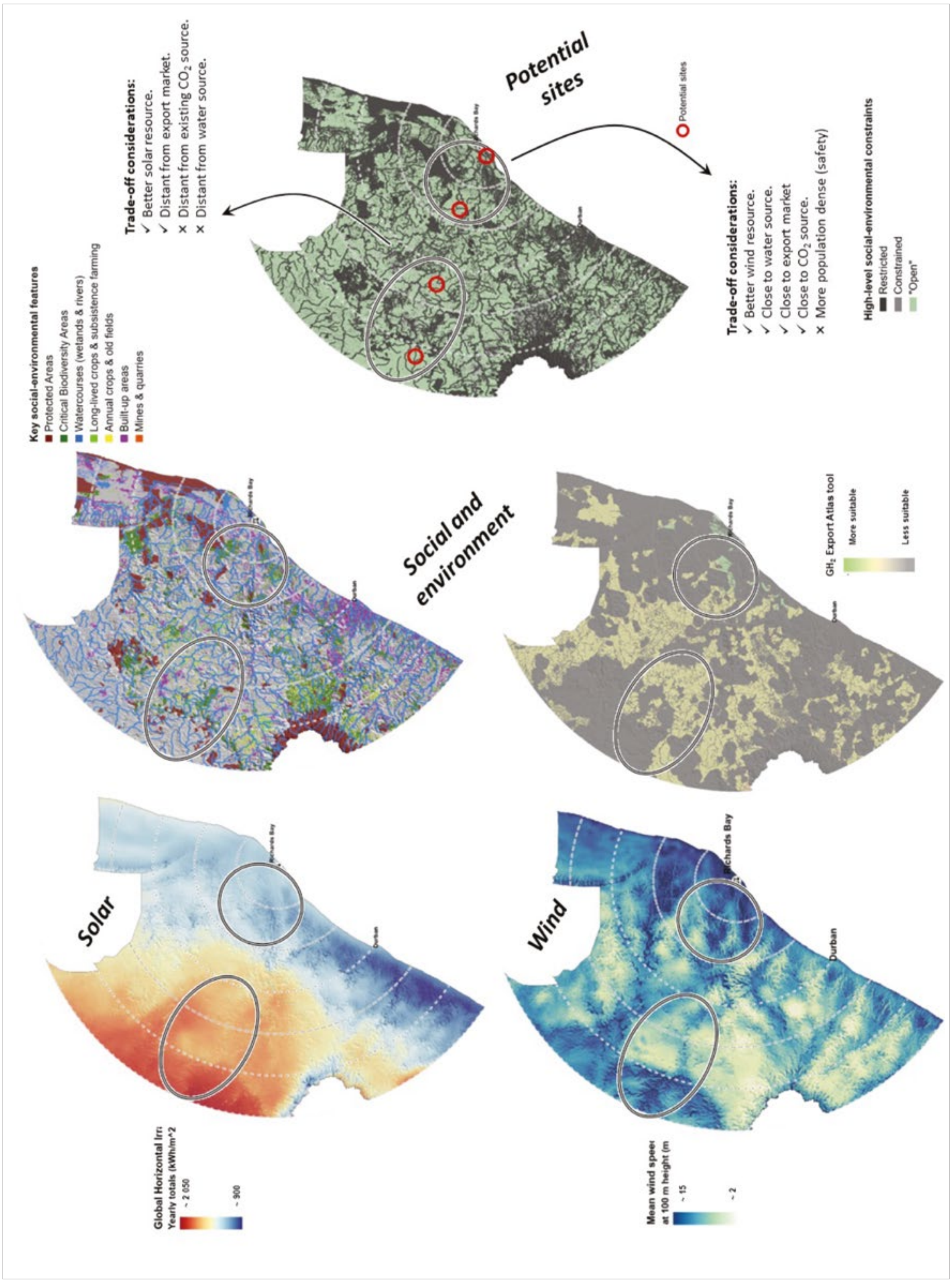

Figure 20: Example of early-planning development site selection during PFS stage, considering renewable energy resources, available tools and key social-environmental constraints to identify the most feasible potential sites. In this case, the site in Richards Bay was selected.

Notwithstanding this, further steps in siting the exact location will be necessary at later stages of the feasibility assessment of the project idea, including the determination of land ownership and availability amongst other things, which are not yet assessed at pre-feasibility stage.

For the siting of the project at hand, the combination of the various parameters discussed make it an ideal choice for further assessment and as a use-case for this pre-feasibility assessment, namely:

- Nearby biomass power plant,
- Strong RE resources,
- Strategic port access, existing industrial infrastructure,
- Proximity to off-take,
- Potential for economic development and job creation,
- Favourable environmental and social conditions,
- Alignment with national energy policies,
- Supportive government framework throughout the Richards Bay SEZ.

The region's existing industrial footprint allows the plant to be integrated into the landscape with limited additional environmental disturbance. Moreover, the focus on RE sources and carbon capture aligns with global environmental standards and local conservation efforts. By selecting Richards Bay for the methanol plant, the project aligns with South African emission reduction targets and commitments under the Paris Agreement and may provide for political buy-in.

8.3 Preliminary design

For the design of the plant operations, we make the following assumptions:

- Installation of the electrolyser and methanol synthesis plant alongside the biomass power plant, minimising the need for CO_2 transportation infrastructure,
- The desalination plant is assumed to be installed nearby at a location by the sea,
- The very high proximity of the methanol synthesis plant with the port (~6 km) facilitates the end fuel logistics. Also, Richards Bay port has existing road and railroad infrastructure,
- Wind turbines can be installed anywhere at the seaside, where the potential is high. An offshore wind turbine park could be considered,
- The PV systems are assumed to be installed on available land in the proximity of the methanol synthesis plant.

8.4 Techno-economic feasibility

For the techno-economic feasibility, we base our following assessment of the envisaged GMeOH plant on a PtX cost tool provided by H2.SA as Excel spreadsheet. Table 9 summarises the main parameters for the project. The build-up year is 2029.

Table 9: Techno-economic data

Parameter	Value	Notes, Comments, References
Location	Port of Richards Bay	· Biomass power plant proximity: Richards Bay mill nearby · RE resources: Strong solar and wind potential · Port access: Strategic location with large commercial port · Industrial infrastructure: Existing industrial base (SEZ/ IDZ) in Richards Bay
Power plant type	PV on single axis trackers & Wind	
Hydrogen production	PEM or high pressure alkaline electrolyser	It is anticipated that the variable operation of the Electrolyser will decrease considerably the LCOM so one of these two technologies needs to be chosen. The costs are comparable.
Electricity transmission from PV / wind to the plant.		Grid installation cost is foreseen between the PV / wind parks and the main facility.
CO_2 source	Biomass plant	Short-cycle carbon commercially available technology. There are comparable commercial projects being deployed globally[44].
CO_2 capture consumed energy	Own energy by the power plant	Biomass energy is renewable and energy efficiency interventions for optimal integration of the capturing sub-system can decrease the energy requirements.

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[44] https://www.eralberta.ca/projects/details/hinton-bioenergy-carbon-capture-and-storage-project/

Parameter	Value	Notes, Comments, References
Available CO_2 resource	1 MW à 9,210.6 tonne CO_2/year 1 tonne of MeOH needs 1.52 tonne of CO_2.	Emissions from biomass plant: 1,204 g CO_2/kWh (Pamela L. Spath, 2006). Capture efficiency: 90% higher efficiencies are achievable but at increased cost (Jiang, Achieving zero/negative-emissions coal-fired power plants using amine-based postcombustion CO_2 capture technology and biomass cocombustion, 2020) Average uptime: 8,500 h (Yang, 2021). Theoretical CO_2 needs: 1.37 tonnes of CO_2 to produce 1 tonne of methanol (Ravikumar, 2020). Typical methanol plant carbon efficiencies can range from 89-95%[45].
Cost of CO_2	All-inclusive price of USD 75/tonne.	USD 50 – 100/tonne of CO_2[46]
Nominal methanol plant capacity	100,000 per year	With ongoing advancements in technology and increased government support, the capacity of individual renewable methanol plants is expected to rise from 5,000-10,000 metric tonnes of methanol per year to 50,000-250,000 metric tonnes per year or more over the next five years.[47]
Conversion of CO_2 to methanol	95%	(Van Antwerpen, 2023)
Methanol production process efficiency (MJMeOH/MJfeed+RE consumed)	88%	(Van Antwerpen, 2023)
SEC – Methanol synthesis (MS) (kWh/kgMeOH)	0.36 kWh/kgMeOH	(Van Antwerpen, 2023)

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[45] https://www.digitalrefining.com/article/1002891/methanol-from-co2-a-technology-and-outlook-overview

[46] https://www.iea.org/commentaries/is-carbon-capture-too-expensive

[47] https://www.methanol.org/renewable/

Parameter	Value	Notes, Comments, References
Methanol synthesis plant	CAPEX: USD 128/tonne GMEOH/year OPEX: 33.15% of CAPEX	A model was developed in DWSIM, an open-source chemical process simulator, and the techno-economic analysis plugin was utilised to determine the costs. Real market prices of the various components were assumed.
Electrolyser efficiency (MJH2/MJRE consumed)	54%	54% efficiency for all operation points (Van Antwerpen, 2023).
Battery efficiency	85% 90%	There are references of 90% (Jamroen, 2022).
Single-Axis-Tracking (SAT) PV (utility scale)	CAPEX: USD 800/kW OPEX: USD 15,807/ MW/y	0.4% degradation per year. The 2029 values of CAPEX (including equipment and installation costs) and OPEX were obtained from the NREL advanced technology database.
Wind (onshore)	CAPEX: 1,006 USD/kW OPEX: 39,355 USD/MW/y	0.1% degradation per year. The 2029 values of CAPEX (including equipment and installation costs) and OPEX were obtained from the NREL advanced technology database.
Electrolyser	CAPEX: 1000 USD/kW OPEX: 1.5% of CAPEX	[48] and (Vartiainen E. C.-W., 2022).
Battery	CAPEX: 193.51 USD/kW OPEX: 48,377 USD/MW/y	The 2029 values of CAPEX (including equipment and installation costs) and OPEX were obtained from the NREL-advanced technology database.
Discount rate	6%	

In the next step, the assessment must determine the sizing of the various components based on a techno-economic optimisation. The plant's design and optimisation require a careful balance between technological capabilities and economic viability. Typically, such a complex optimisation would be approached through sophisticated simulation

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[48] https://www.energypolicy.columbia.edu/demystifying-Electrolyser-production-costs/

models and algorithms for multi-objective techno-economic optimisation (at feasibility stage). However, for the purpose of this study the usage of the PtX cost tool offers a pragmatic and reasonable method for pre-feasibility assessment.

The optimisation of the GMeOH production facility revolves around several critical variables. As part of this pre-feasibility assessment, the following parameters are considered for optimisation:

- Electrolyser oversizing,
- Hybrid generation; ratio / split between PV and wind,
- RE plant oversizing,
- Hydrogen storage capacity (in days of supply),
- Battery storage capacity (in hours of supply).

The primary objective of the optimisation is to identify a configuration that achieves the lowest LCOM while ensuring a set system uptime (of at least 90%), and maintaining non-depleting battery bank and hydrogen storage throughout the year.

The optimisation includes a series of trial-and-error simulations, progressively refining the system design by adjusting the variables based on empirical knowledge and the initial boundaries of the search space.

- The initial phase of the optimisation process should focus on understanding the limits of the operational parameters by adjusting multiple variables simultaneously.
- Following this exploratory stage, the optimisation should be done in a sequential manner, prioritising:
  - the hybrid generation split, followed by
  - the sizing of the hydrogen and battery storage systems,
  - the electrolyser capacity, and ultimately,
  - the installed power of the RE sources.

This sequential approach, although pragmatic, inherits the risk of converging towards a local minimum, potentially overlooking more optimal solutions. However, given the stage of project ideation, this strategy offers a firm balance between depth of analysis and practicality. The use of the Excel spreadsheet for this optimisation has several advantages. Primarily, its user-friendly interface and the absence of licensing fees significantly reduce the barriers to evaluating the feasibility of the project, allowing for a broader exploration of potential investments without the immediate need for specialised consultancy services or expensive software packages. By facilitating the initial assessment, project proponents can make informed decisions on whether to proceed with more detailed feasibility studies. On the downside, the risk of converging on local minima due to the sequential adjustment of variables of the tool is a notable limitation, which is negligible at pre-feasibility stage.

To further enhance the tool's utility, project developers are encouraged to perform multiple runs with varied initial conditions, thereby expanding the explored search space and increasing the likelihood of identifying more globally optimal solutions. The techno-economic results of the optimisation are presented in the following tables:

Table 10: Techno-economic results of the analysis

Parameter	Unit	Value
Levelised cost of hydrogen (USD/kgH2)	USD/kgH2	2.91
Levelised cost of methanol (USD/kgMEOH)	USD/kgMeOH	1.106
Methanol plant capacity factor	% of 8,760 hrs/yr	90%
RE (Solar and Wind) power plant capacity	MW	411
Battery capacity	MWh	7
Electrolyser capacity	MW	167
H_2 Storage capacity	kg	54,444
Total power generation	MWh / 8,760 hrs	1,106,382
Energy consumed by Electrolyser	MWh / 8,760 hrs	921,045
Energy consumed by methanol plant (MWh/yr)	MWh / 8,322 hrs	32,497
Energy consumed by CC plant (MWh/yr)	MWh / 8,322 hrs	0
Energy used to charge battery (MWh/yr)	MWh / 8,322 hrs	357
Excess power generated (curtailed or sold to grid) (MWh/yr)	MWh / 8,760 hrs	152,839
Total power generation	MWh / 8,760 hrs	1,106,382
Energy consumed by Electrolyser	MWh / 8,760 hrs	921,045
Hydrogen production	t / 8,760 hrs	17,729

Table 11: CAPEX results

Component	Value (USD)
Power plant	382,913,765
Balance technology	1,435,212
Electrolyser	121,310,757
Hydrogen storage	89,559,598
Methanol plant	70,407,040
Total capital cost	**665,626,371**

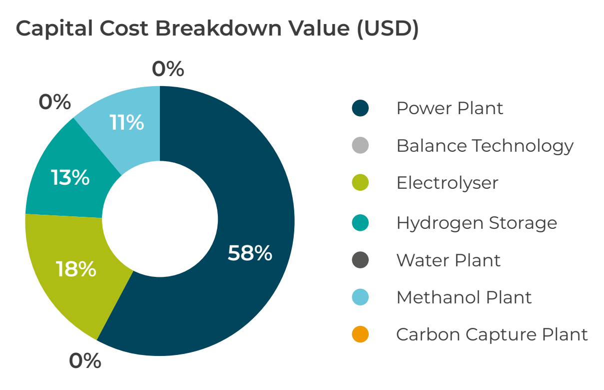

Table 12: Levelised cost results

LCOM	Value (USD)
RE farm CAPEX	0.34
Transmission CAPEX	0.02
Balance tech. CAPEX	0.00
Elec. CAPEX	0.11
H_2 storage CAPEX	0.08
MEOH CAPEX	0.06
Power plant OPEX	0.14
Elec. OPEX	0.04
Stack replacement	0.02
H_2 storage OPEX	0.03
MEOH OPEX	0.24
Wholesale CO_2	0.11
Elec. sales	- 0.07
Total	**1.106**

Table 13: Optimisation results

Variable	Optimised value
Hybrid generator split	36% Solar, 64% Wind
Battery storage	2 hours
Hydrogen storage	1 day
Electrolyser oversizing	50%
Oversizing of renewable energy	140%

As the results show, the tonne of GMeOH at the proposed site/ plant can be produced at USD 1,106 while total CAPEX of the investment amounts to some USD 665 million. The values obtained are aligned with cost of GMeOH quoted in various study reports.

As has been described in the previous sections, methanol finds application in multiple sectors including the chemical industry as a key feedstock to manufacture a wide range of products including plastics, resins, textiles, and paints. It is also crucial in producing acetic acid, which has applications in adhesives, coatings, and solvents. The solvents are then used in multiple industries like pharmaceutical, cosmetics and pains.

For this case study, the sale of GMeOH as a maritime fuel can be considered as an emerging green methanol market with potential bankable off-take for which broader economic and regulatory considerations are pivotal. The introduction of the CBAM by the EU underscores a shifting paradigm where the environmental footprint of products, including their logistics chain emissions, becomes a crucial determinant of market access and competitiveness. This regulatory framework aims to level the playing field for cleaner energy sources by imposing a carbon price on imports of certain goods from outside the EU, thus potentially rendering GMeOH more attractive despite its higher production costs.

Moreover, the potential introduction of carbon taxes in various jurisdictions seeks to internalise the environmental externalities associated with "non-clean" logistics trails. Such fiscal measures could significantly affect the total cost of ownership and the market appeal of grey methanol, which is directly influenced by fluctuating oil prices. The correlation of grey methanol prices to oil markets introduces a volatility element that can, at times, narrow the cost differential between green and grey methanol. Notably, during periods of heightened oil prices, such as those witnessed during the Ukraine conflict, green methanol emerges as a cost-competitive alternative.

Furthermore, the strategic importance of reducing greenhouse gas emissions in line with global climate commitments enhances the attractiveness of GMeOH. The IMO's endorsement of renewable methanol as a key fuel in the maritime industry's decarbonisation efforts exemplifies the growing recognition of its environmental and operational benefits. This shift is not merely regulatory but aligns with an increasing consumer and corporate demand for sustainable products and practices. The combination of regulatory measures like CBAM, potential carbon taxation, alongside the pressing need for decarbonisation, paints a more nuanced picture of the market dynamics. These factors collectively contribute to a competitive landscape where green methanol's current higher upfront costs may be offset by its long-term economic and environmental benefits, positioning it as a viable and sustainable alternative in a rapidly evolving energy market.

8.5 Environmental and social feasibility

In the process of selecting the optimal site for the project, comprehensive attention was given to critical E&S features that could potentially jeopardise the project's feasibility. This evaluation was conducted at broad geographical scales to proactively identify and exclude areas with insurmountable E&S challenges, such as protected areas, thereby ensuring that the project remains within the bounds of environmental and social acceptability.

The decision to position key components of the project, including the desalination plant, Electrolyser, and methanol synthesis facility within a designated SEZ, aligns perfectly with the area's planned developmental objectives. This strategic placement within the SEZ not only bolsters the E&S feasibility of the project but also leverages the benefits associated with such zones, such as streamlined regulatory processes and enhanced infrastructural support. The centralisation of most processes, excluding desalination, within a single location further streamlines the project's execution, simplifying both management and environmental impact mitigation.

For the GMeOH production facility in Richards Bay, South Africa, several key environmental and community considerations must be addressed for each component of the project. These considerations are vital for ensuring sustainable operations and maintaining good relations with local communities and other stakeholders. As the project progresses into more detailed development planning phases, the following aspects need to be meticulously considered.

- **Solar PV Facilities**
    - **Agricultural activity conflicts:** The primary concern with solar PV facilities is their potential conflict with local agricultural activities. Exploring agrivoltaic solutions with local farmers is advisable. Agrivoltaics, combining agriculture and solar energy production, may impact solar energy yield and the overall techno-economics of the GMeOH project.
    - **Micrositing:** Careful micrositing of the solar PV arrays is essential to mitigate any site-specific environmental sensitivities.

- **Wind energy facilities**
    - **Birdlife impact:** The impact on local birdlife is a significant concern for wind energy facilities. Comprehensive birdlife monitoring over multiple seasons, potentially extending to a year, is required to inform EIAs and ensure wildlife protection. Early engagement with organisations such as Birdlife South Africa is crucial.
    - **Visual impact:** The visual impact of wind turbines, especially in a region known for nature-based tourism, must be assessed. The west coast area's tourism appeal, including attractions like the spring flower season, should not be adversely affected.
    - **Offshore wind exploration:** Exploring offshore wind as an alternative or additional source of energy for the project may present fewer visual and ecological impacts.

- **Electrolyser plant**
    - **Electrolyser micrositing:** Similar to solar PV, the wind turbine locations should be strategically chosen to avoid any fine-scale environmental sensitivities.
    - **Community engagement**: Engaging with the local community regarding the Electrolyser plant, especially addressing any hydrogen safety concerns, is essential. Clear communication about the safety measures and benefits of the project will aid in gaining community support.

- **Water / hydrogen pipeline**
    - **Infrastructure alignment:** To minimise environmental impact, new pipelines for water and hydrogen should preferably align with existing linear infrastructures like roads and railways. This approach reduces the need for additional vegetation clearance and landscape fragmentation.
    - **Community outreach:** Ongoing community engagement is vital, especially in addressing concerns about hydrogen transport and safety.

- **Desalination facility**
    - **Brine disposal:** The disposal of brine into the ocean is a significant environmental concern. Detailed dispersal modelling is required to identify a suitable outfall location that ensures effective dilution and mixing with minimal ecological impact.
    - **Stakeholder engagement:** Early engagement with stakeholders, including fisheries and other coastal and ocean users, is crucial to address any potential conflicts or concerns.
    - **Facility oversizing:** Oversizing the desalination facility to supplement local water supply could offer additional benefits. Engaging potential off-takers, such as other industries and local municipalities, is recommended to explore synergistic opportunities.

- **Methanol synthesis plant**
    - **Integration with existing infrastructure:** The methanol synthesis plant should be integrated thoughtfully with existing industrial infrastructure in Richards Bay to maximise efficiency and minimise environmental impact.
    - **Emission control:** Implementing stringent emission control measures to ensure minimal environmental impact, particularly in air quality.
    - **Safety measures:** Robust safety measures are essential, given the plant's chemical processes and the potential risks associated with methanol production.

- **Overall considerations**
  - **Sustainability:** All components of the GMeOH project must adhere to stringent sustainability criteria, ensuring minimal environmental impact and Maximising positive social outcomes.
  - **Regulatory compliance:** Compliance with all relevant South African environmental regulations, including obtaining necessary permits and conducting thorough EIA processes.
  - **Transparent communication:** Maintaining transparent and open communication with all stakeholders, including local communities, environmental groups, and government authorities, to ensure the project aligns with local needs and environmental protection goals.

In summary, careful planning and community engagement, along with adherence to environmental best practices, are crucial for the successful implementation of the GMeOH project in Richards Bay. These measures will ensure that the project not only contributes to the renewable energy landscape but also respects and enhances the local environment and community livelihoods.

8.6 Conclusion

The decision to co-locate the Electrolyser and methanol synthesis plant with an existing biomass combustion plant is a key feature of the project. This approach not only streamlines the production process by providing an immediate carbon source but also significantly reduces infrastructural and logistical expenditures. The proximity of the facility to areas with high RE potential, particularly solar and wind energy, further enhances its efficiency. The efficient utilisation of these renewable resources is facilitated by adequate grid connectivity, ensuring that the electrolysis process and methanol synthesis are powered effectively.

Another critical component of the project is the desalination facility, strategically located by the ocean. This positioning allows for direct access to seawater, which, after undergoing the desalination process, is supplied to the Electrolyser. This setup ensures a reliable and consistent water supply, essential for hydrogen production.

The techno-economic feasibility considered various optimisation options and showed that the lowest cost at which methanol can be produced is USD 1,106/tonne at a capacity factor above 90% is achieved using Electrolyser oversizing of 40% above methanol plant design requirements, RE oversizing 140% above the Electrolyser capacity, at a solar fraction of 36%.

Regarding E&S feasibility, micro-siting of each component is a priority. The project involves detailed site assessments to ensure that renewable energy installations, particularly solar PV and wind turbines, as well as the desalination plant, are placed in environmentally compatible locations. This approach minimises potential disruptions to natural habitats and landscapes and ensures compatibility with local environmental conditions.

Environmental monitoring forms another cornerstone of the project's E&S strategy. Implementing robust systems to monitor air and water quality, biodiversity, and land use changes is crucial. This monitoring ensures the project adheres to environmental standards and regulations, maintaining its sustainability credentials.

Community engagement is equally important. The project prioritises early and ongoing dialogue with local communities and stakeholders. This engagement aims to address potential concerns, provide transparent information about the project's benefits and safety measures, and foster positive relationships. Effective communication and local stakeholder involvement are essential for the social acceptability and success of the GMeOH project.

Ensuring all project components align with sustainability principles and comply with national and regional environmental regulations is crucial. This includes obtaining the necessary permits, conducting comprehensive EIA, and integrating sustainable practices into all project phases.

In conclusion, this PFS for the exemplified GMeOH production facility in Richards Bay, South Africa, presents a compelling business case for sustainable fuel production. Situated in a region with an abundant RE resource base, the project leverages solar and wind power to drive an electrolyser for hydrogen production, integrating CO2 capture from an existing biomass combustion plant. This innovative approach not only reduces the carbon footprint but also capitalises on local resources and infrastructure, enhancing cost-effectiveness and sustainability.

The strategic co-location with the biomass plant and proximity to RE sources minimise logistical challenges and operational costs. The addition of a desalination facility ensures a steady water supply, crucial for electrolysis, further bolstering the project's sustainability profile. With an emphasis on environmental and social compatibility, including comprehensive community engagement and adherence to stringent environmental standards, the project is poised to contribute significantly to South Africa's green economy.

The business case is strengthened by the potential for high market demand for GMeOH as a maritime fuel but also as a chemical feedstock. By addressing key technical, economic, and environmental challenges through innovative solutions, the Richards Bay GMeOH project stands as a model for sustainable industrial development, offering significant economic, environmental, and social benefits.

PART 3:

Green methanol Pre-Feasiblity Study Example – Financial assessment

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Green methanol Pre-Feasiblity Study Example – Financial assessment

In the third part of this study, we focus on the financial assessment of the GMeOH case study located near the Port of Richards Bay, South Africa. By analysing relevant financial variables and parameters, we look into a potential off-take opportunity in the maritime sector, for which we calculate and assess key indicators such as the net present value (NPV), return on equity (ROE) and internal rate of return (IRR), with an emphasis on the ROE an investor can expect under different scenarios. In addition, we carry out a brief risk assessment of the GMeOH project as expected by a financing partner and present likely financial solutions.

9. Financial Assessment

9.1 Methanol as means to reduce GHG in various applications and industries - the shipping sector as early mover

As outlined in chapter 1.3, methanol can be used for a variety of applications. For instance, methanol is used for the production of acetic acid and formaldehyde, in the manufacturing of foams, windshield washer fluids, plywood subfloors, and many other plastics, for which it is a platform chemical. More recently, the possibility of blending high octane methanol with gasoline as well as biodiesel for the production of high-octane fuel as well as the use for fuel cells came into focus, thereby reducing emissions.

To date, the worldwide supply of approximately 111 million tonnes (the total production capacity being 170 million tonnes) is mainly produced by steam reforming from natural gas and coal,[49] while there is no significant amount of GMeOH produced and available on the global market up to now. This is increasingly changing since decarbonisation efforts are growing internationally and selected industries have already taken the first steps towards greening their production and products. This opens up a wide range of opportunities for project developers who are focusing on the production of GMeOH, one of which is currently emerging in the maritime sector.

Originally launched in 2021 at the Conference of the Parties (COP) 26, the Clydebank Declaration aims to achieve net zero emissions in shipping by 2050. This involves establishing zero emission shipping routes, including port infrastructure and vessels to serve as green shipping corridors. The Clydebank Declaration has been signed by 22 countries[50]. The green shipping corridors announced between Los Angeles and Shanghai and between Antwerp and Montreal are among the first and most significant to date and will provide important data for the establishment of further corridors between other major global shipping routes.

In its very own effort to decarbonisation, the 2023 IMO GHG strategy envisages a reduction in carbon intensity of international shipping by at least 40% by 2030 (as an average across international shipping), including the ambition to embrace zero or near-zero GHG emission technologies, fuels, or energy sources, aiming for them to constitute at least 5%, with an aspiration towards 10%, of the energy consumed by international shipping by 2030. To reach the target, an IMO committee will draw up a package of measures by 2025, which should include a standard for the CO2 intensity of marine fuels.

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[49] *https://www.researchdive.com/8500/methanol-market and accessed in June 2024*

[50] *Australia, Belgium, Canada, Chile, Costa Rica, Denmark, Fiji, Finland, France, Germany, Ireland, Italy, Japan, the Republic of the Marshall Islands, Morocco, the Netherlands, New Zealand, Norway, Spain, Sweden, the UK, and the United States of America*

On this basis, fuels that cause particularly high emissions could be gradually phased out. Moreover, the IMO is planning a price mechanism for GHG emissions - similar to the EU Emissions Trading System (ETS). These and other medium-term measures are due to come into force in 2027.

The switch to GMeOH fuel follows strong customer demand from shipping companies for environmentally friendly fuels, which are currently envisioning science-based targets for reducing carbon emissions or making their supply chains carbon-free. Methanol is a well-known fuel. Methanol ship engines, fuel supply technology and bunkering solutions are commercially available worldwide. Leading shipping companies have already taken their decision to use GMeOH as their preferred future shipping fuel including AP Moller-Maersk (Maersk), CMA CGM, COSCO, Methanex Waterfront Shipping and Stena, just to name a few.

As a pioneer, Maersk aims to reach net-zero GHG emissions by 2040 across its business. The company has signed seven GMeOH partnerships around the world plus a recent off-take agreement, which significantly de-risk the initial stages of Maersk's net-zero journey and supports expectations for a competitive GMeOH market towards 2030. Because of its estimated demand and price, it shows that GMeOH currently is the most viable low-emission solution for ocean shipping that can have a significant impact in this decade. Maersk is spending USD 7 billion on the fleet upgrade. The number of dual-fuel engines on order has now gone up to 19, with the first large ocean-going vessel due to enter into operation still in 2024. Maersk is internally calculating with GMeOH prices up to USD 2,500 (AHK, 2023). This results in a concrete business case for the case project at hand, which we will examine in the following chapters and subject to a brief financial assessment, as part of this pre-feasibility study.

9.2 Cost model

9.2.1 Cash flow overview

As it will be the case for any capital-intensive project, the first step of the financial project assessment during pre-feasibility will be the layout of all anticipated incoming and outgoing cash-flow streams during the project's entire lifetime. Inflows are sales revenues, loan disbursements and equity inflow. Outflows are CAPEX, OPEX, loan repayments, interest, as well as replacement investments. All monetary movements must be booked at the time they occur, and they will be discounted to their present value.

The cash flow overview must specify where and when the project will be able to generate sufficient income to cover the cost and when financing from outside sources is necessary. The GMeOH-project at hand involves massive initial investments, requiring a heavy financial input from the start and thus also long amortisation periods of up to 25 years. CAPEX, which constitute a major part of expenditures, cannot be changed any more once the investment is completed, therefore reduction in cost after learning curve effects have been realised will not affect these investments any more.

As regards the financial and economic characteristics of the project in question, we refer to chapter 8, namely:

- A lifetime of 25 years,
- Initial investment of almost USD 665 million plus 10% contingencies, adding up to a total of USD 732 million,
- Batteries and Electrolysers have to be replaced during the life-time of the project,
- Annual OPEX are estimated at around USD 52 million including 5% contingencies[51],
- Additional income from surplus electricity resulting from the necessary oversizing of the RE-facilities, which is sold at a cost price (USD 3.38 cents/kWh) and which will yield an annual income of USD 6.6 million, reducing the net-OPEX to USD 45.8 million.

Although there is a very heavily "front-loaded" cost characteristic, the (discounted) OPEX share of 43% is higher than with green hydrogen or green ammonia projects, which is mainly due to the fact, that the CO_2 will have to be purchased. Nevertheless, there is still a high portion of CAPEX (57%), which have to be financed at the beginning, whereas revenues as well as current cost will stretch over a period of 25 years, being subject to unforeseen changes in price and demand, but also in political, technological and economic developments. Therefore, banks as well as investors will think carefully about their engagement in such a venture and will require that project developers with an immaculate track record present off-take agreements with trustworthy buyers to minimise risks.

The price as well as the quantity of the GMeOH produced and available for sales will define the revenues of the project during its lifetime. It will be important for the project development that the production cost will be at a competitive level with other GMeOH projects since we assume that a new market for GMeOH (as a shipping fuel) is emerging in view of the above-mentioned IMO endeavours and other regulatory affects as it was explained in chapter 1.3. Price signals, however, will also stem from the market for grey methanol for which it will be important to observe, whether and to what extent surcharge mechanisms like the European Cross Boarder Adjustment Mechanism (CBAM) may affect these prices. The World Bank lists 73 emission trading system initiatives worldwide (implemented or under serious consideration)[52], hence carbon duties in various forms can be expected by 2030 in many parts of the world.

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[51] *We have estimated the contingencies at only 5%, since OPEX are occurring annually and unlike for CAPEX learning effects over the years can be expected*

[52] *World Bank, carbon pricing dashboard as of March 31, 2023, https://carbonpricingdashboard.worldbank.org/map_data*

For the financial assessment at the pre-feasibility stage, the project developer must thus examine the following questions in order to find suitable project financing:

- What premium are buyers willing to pay for a tonne of GMeOH?
- Will there be any government subsidy available for the project?
- To what extent may tax and surcharge mechanisms for fossil MeOH worldwide affect competition for the project?
- Results of the cost model before financing

Table 14 contains a summary of the cost and quantity data of the GMeOH project in question, a detailed spreadsheet can be found in Annex 1 and Annex 2.

Table 14: Overview on capital cost (CAPEX) and operational cost (OPEX) of the GMeOH project

CAPEX	Capacity	Cost/ Unit	Total Capex USD m	OPEX		Cost/ Unit	Total OPEX US$ m
Power Plants	411	MW	382,9	Power Plants			12,688
Balance technology			1,4	Balance technology			0,179
Electrolyser	167	MW	121,3	Electrolyser			3,639
Hydrogen storage	54444	kg	89,6	Water			0,201
Methanol plant	100 000	t p.a.	70,4	Hydrogen storage			2,239
				Methanol plant			21,218
				CO_2 (purchased)	Tonne CO_2	USD 75	9,653
				Carbon Credit			-
TOTAL			**665,6**	**Total OPEX (p.a.)**[a]			**49,8**
Contingencies	10%		67	Contingencies		5%	2,5
TOTAL ESTIM. CAPEX			**732,2**	Total OPEX (p.a.)	(islanded)		**52,3**
a) Opex, which are marginally different each year have been averaged. *Replacement investments have been included in CAPEX*				Excess power sold at cost (MWh p.a./USD/kWh)			6,6
NPV-discount rate		8%		**Total OPEX (p.a.)**	**(minus power sales)**		**45,8**
Price increase p.a.		0%	(in the case of real price calculation)				
Mean degradation Rate		0.21%	= weighted average of wind 0,1% p.a. sun 0.4% p.a.				
Solar/wind fraction		36%	64%				

For the calculation, we assume that the plant will be built in 2029 with start of production in 2030. The construction time is very likely to be longer than one year and actual work will start before, but we assume that all cost will be paid in 2029 as an average. Since probably down-payments will have to be made earlier, while some final payments will only be made after commissioning, this seems to be a reasonable simplification.

The first level of cost analysis will show the levelised cost of GMeOH LCOM[53], which is calculated as the quotient of lifetime costs by the lifetime net production of the GMeOH (both figures discounted to their present value). Of course, the value is very sensitive to the ***discount rate.*** The discount rate should represent the opportunity cost of capital. Sometimes the WACC[54] is used, although this is not quite correct, since the WACC depends not only on the ROE and the interest rate on loans, but also on the individual project leverage, which is the relation between loans and equity. LCOM is a ***mere cost indicator*** independent from the sales price of GMeOH and also independent from any financing cost.

Table 15 shows the results of the levelised cost depending on the discount rate and the level of anticipated contingencies. We have estimated unforeseen CAPEX increases at 10% and we have used a discount rate of 8%, resulting in the LCOM of ***USD 1,273/tonne.*** In the techno-economic assessment, no contingencies were applied and the discount rate remained at 6%, resulting in a LCOM of ***USD 1,106/tonne.***

Table 15: Levelised cost of green methanol (LCOM) in USD/tonne depending on contingency level and discount rate

		Discount rate		
	0%	**6%**	**8%**	
Contingencies	0%	813	1,106	1,203
	5%	828	1,136	1,238
	10%	843	1,166	1,273

Considering that in South Africa lending interest rates are around 13%, a discount rate of 8% might appear low. However, deposit interest rates are between 6.5 and 7% p.a., the repo rate of the South African central bank is presently also at 8 %. **For the further assessment it must be noted that 8% is defined in real terms,** whereas the lending rate is a nominal value. With an inflation rate of around 6% in South Africa the real value of the lending rate would come down to just 6.6%. To reach an IRR for the above mentioned (real) 8%, the project would need a sales price (ex-factory) equal to

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[53] *(G)-LCOM:* $\frac{NPV\ of\ total\ cost\ (CAPEX+OPEX)}{NPV\ of\ total\ ammona\ output\ in\ tons}$ NPV: $\sum_{t=1}^{n}\frac{R_t}{(1+i)^t}$ *NPV: whereas t= time (here: year), i= discount rate,* R_t *= CAPEX + OPEX in each time period (here: in USD for cost and in tonnes for MeOH).*

[54] *WACC = weighted average cost of capital. WACC=* $r_e \times w_e + r_d \times w_d$*:* r_e *= return rate of equity (ROE),* r_d *= interest rate of debt,* w_e*= share of equity,* w_d*= share of debt.*

the LCOM of USD 1,273/tonne. In this case the NPV would be exactly zero (see Annex 1). If, however, financing cost are included (see next chapter), prices must be higher to reach a satisfactory result. In chapters 9.3.3 and 9.3.4 the financing model will be further refined by considering the consequences of national and international inflation rates for the financial result.

9.3 Financial feasibility of the GMeOH project

9.3.1 Financial solutions for the GMeOH project

Whereas chapter 9.2 focused on the economic analysis of the project (resulting mainly in the LCOM and IRR), the pre-feasibility assessment should in a next step explore the ***anticipated financial attractiveness of the project.*** This analysis examines income minus cost of the project and, consequently, the volume as well as the sources of finance needed.

The project's income will – with the exception of a small amount from sales of excess electricity – generate from the sales of GMeOH at prices which, at this early stage of market development, may, in the absence of price signals, only be estimated by the developer.

Sources of finance for the GMeOH project will be:

1. ***Equity providers*** with the expectation of a risk adequate ROE, which will be fluctuating and depend on cost and revenues,
2. ***Commercial loans,*** in which annuity payments are relatively stable once agreed upon,
3. ***Subsidies*** and/or ***concessional loans*** by governments and Development Financial Institutions (DFIs) to enable the project to take off in spite of unfavourable conditions.

As interviews with several banks in South Africa have shown, the leverage (ratio between loan and equity) for this and comparable sized projects would be 60 (loans) to 40 (equity), requiring a substantial share of risk-taking by equity investors, with the interest rate in ZAR at a minimum of 13% p.a. In foreign currency the interest rate will be even higher if handled by a local bank. It should be noted that interest payments, based on a loan of 60% of total CAPEX will increase the total project cost from USD 1.311 billion (discounted CAPEX and OPEX) to USD 1.675 billion (Figure 21).

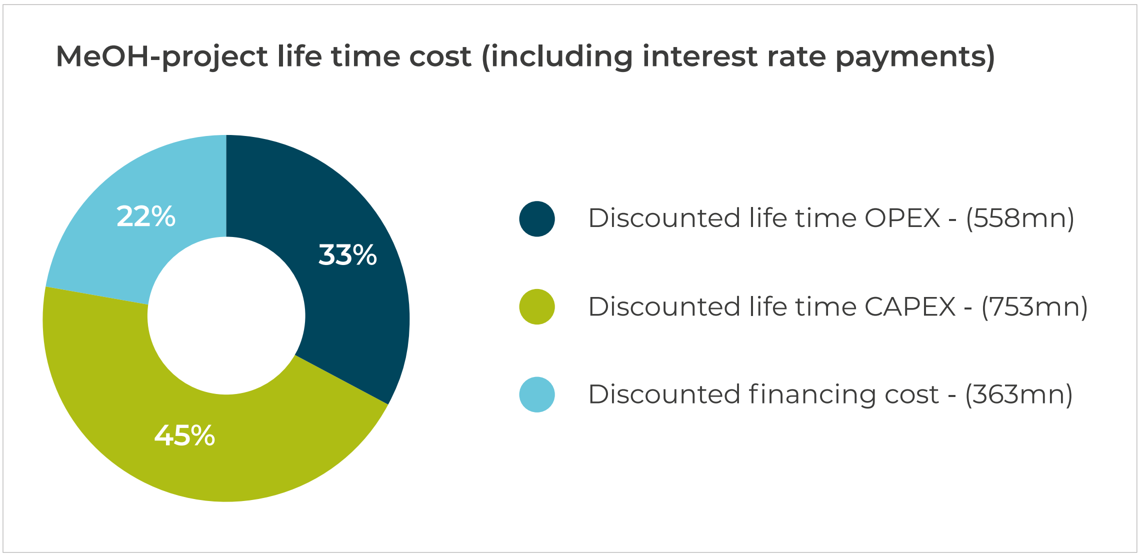

Figure 21: Life time cost-shares of the GMeOH-project

Therefore, for the GMeOH project, the high commercial interest rate causes a much lower ROE of only 2.6% (compared to the IRR of 8%), based on the above LCOM-price of USD 1,273/tonne. There might be possibilities for project developers to benefit from cheaper export credits from supplier's banks, but it should be taken into account that in this case the investor will have to bear the exchange rate risk. This might ultimately lead to the same or even higher cost, unless all GMeOH produced can be sold in the respective foreign currency. Forward contracts for such long periods, even if offered by banks, are also expensive.

Table 16 shows the ROE at different sales prices: For a real ROE of 8% a price of USD 1,510/tonne would be necessary, prices of USD 1,605/tonne and USD 1,655/tonne would result in a ROE of 10% or 11%, respectively.

Table 16: Return on equity depending on price for GMeOH

GMeOH price USD/tonne	ROE (real)
1,510	8.0%
1,605	10.0%
1,655	11.0%
1,700	11.9%

In the following, the cost model and the basic calculations for the financial pre-feasibility of the project are subjected to various considerations and analysed in depth.

In a first step, we assume that the project can secure Maersk as the off-taker for the GMeOH.

9.3.2 Optimistic case (Maersk) – new market

As it was shown before, one may consider a fair (real) RoE to be achievable at a price of USD 1510/tonne and above. If MAERSK (and potential other off-takers) are indeed willing to offer a much higher price of up to USD 2,500/tonne, the ROE would escalate to 18% in real and 27.8% in nominal terms under the above conditions, but without a further price hike for the GMeOH during the entire project life. In this case the loan repayment could be reduced to eight years without harming the project's cash flow, reducing the ROE to around 20% (due to earlier loan repayments). However, since the commercial interest rate (13%) is lower than the ROE, there would be a considerable leverage effect and it would indeed pay off for the investors to have a longer repayment period or alternatively to negotiate for better loan terms because of the shorter time frame and thus lowering the risk.

It can be assumed that Maersk will select the off-taker meticulously and, from a certain point in the market formation, will also issue invitations to tender, and adjust its pricing policy to the new market movements, provided that the first volumes of GMeOH are secured. Against this background, it will not be possible to increase the GMeOH price and ROE significantly. Especially since, as we assume, the developer must expect competition to inevitably push the price down; and this consideration must form part of the financial assessment.

9.3.3 Price development and nominal calculation

There is no question that the project will generate attractive returns with the appearance of Maersk or similar off-takers offering attractive prices. However, for a pre-feasibility assessment (and later on at feasibility study stage) it will be helpful and important to explore other, less optimistic, scenarios too in order to identify break-even prices and conditions.

For this purpose, we can take the CO_2 price adjusted grey methanol price as a basis. For classification, the 2024 methanol market price fluctuates around USD 575/tonne in Europe and the United States. Under the assumption of an annual increase of some 3%, the price for grey MeOH could rise to around USD 690/tonne in 2030. Based on a CO_2 content of between 1.37 and 1.52 CO_2/tonne of grey MeOH (average 1.45[55]) and a present price of EUR 81/tonne in the European ETS, this would add USD 117/tonne and result in a gross price of around USD 800 per tonne (fob). It is very likely that by 2030 the carbon tax may augment and be introduced in most countries worldwide, therefore one may expect an even higher gross price of around USD 900/tonne.

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[55] *The amount of CO_2 emitted depends on the end-use of methanol and it ranges from 1.375 (fully burned) up to 2.19 tonnes of CO_2. A mean value of 1.45 is therefore a conservative estimate. The figure 2.19 applies for applications in the energy and transport sectors where MeOH is burned. This would bring the price of grey MeOH to an even higher value and would be favourable for green MeOH. At present, methanol is not yet part of the EU-list of substances to be included in the EU-CBAM, so it is still open what amount of CO_2 will be defined by the EU-authorities and whether this rule will be taken over by other countries.*

If only this estimated price of USD 900/tonne could be reached for the GMeOH project, this would mean a negative real ROE of -7.5% and the project idea would not survive without additional financial support.

Since it is quite likely that (1) sales will go abroad to a great extent and (2) investors will also be more interested in returns in international currency than in ZAR, we may simulate the development of nominal prices and costs in USD-terms; First of all, one may assume that OPEX will, in USD-terms, not rise at the same rate as in ZAR-terms. Apart from that, whereas technical progress will not affect CAPEX, it is likely that there will be some effects on current cost. That said we can assume that OPEX will not rise much more than 2% p.a., most likely less.

For the assumed sales price of GMeOH (ex works) we shall take the above-mentioned price of USD 900/tonne as point of departure. We believe that this is a minimum price, since it is not sure that the GMeOH price will really follow the price for grey methanol as a new GMeOH market is being established. Based on the present level of information at hand, the following scenarios do thus still contain some guesswork.

Starting with the above price of USD 900/tonne in 2030 (start of production) we assume a potential price increase for methanol between 6% and 9% p.a. and OPEX increases between 0% and 3% p.a. Any lower price increases will not lead to a satisfactory ROE, even price hikes of 6% and 7% p.a. will generate only (nominal!) ROEs of below 10%. In other words: If by 2030 a price of at least USD 900/tonne cannot be reached, an annual price increase of at least 8% would be necessary to reach an ROE, which appears attractive for potential investors.

Table 17: Nominal ROEs under the assumption of different price scenarios for MeOH as well as for OPEX

	Inflation of OPEX (in USD-terms)				
Annual price increase MeOH in USD-terms	**0%**	**0.5%**	**1%**	**2%**	**3%**
6%	7.7%	7.4%	7.1%	6.5%	5.7%
7%	9.4%	9.2%	9.0%	8.5%	7.9%
8%	11.1%	10.9%	10.7%	10.3%	9.8%
9%	12.7%	12.6%	12.4%	12.0%	11.6%

As mentioned above, we are not insinuating that prices will rise by 8% p.a. and more, although it will not be unlikely, taking into account the very probable huge demand for green fuels in the process of decarbonising the world industry as well as land-, air- and sea traffic.

If in the course of the feasibility study, it should be realised that such price increases are unlikely and prices are rising slower, there is still the possibility for a ***contract for difference*** (CfD) model, subsidising prices during the first 10-15 years of operation. With the objective of supporting the de-carbonisation and reaching the objectives of the Paris Agreement there could also be the alternative of granting ***concessional loans*** by DFI's as well as supplying ***grants*** by governments or international donor institutions.

9.3.4 Subsidy needs and potential sources

As it can be seen in Table 17, the ROEs (nominal!) under non-optimistic conditions are better if we assume a relatively high price increase for GMeOH. However, it is doubtful whether these can be attractive enough for investors considering the relatively risky nature of the project. To enhance the financial feasibility of the project under current market conditions, project developers must explore and plan with suitable and sufficient financial support at least for the first decade of the operating time. There are several options of support: grants, interest rate-, price- and investment- subsidies and many combinations thereof. The effects of such support schemes on the ROE must be thoroughly assessed on the basis of best suitable scenarios in the ***feasibility study***, to be able to pursue the project idea further.

For exemplary reasons, we may consider the effects of a partial soft loan from a DFI, which carries an interest rate of 2%. Table 18 shows the effects of three different combinations of concessional loans (2% p.a.) and commercial loans (13%) under similar price developments as shown in Table 16. In order to reduce complexity, the OPEX price increase has been assumed to remain at 2% p.a. Again, for the sales price of GMeOH (ex works) we shall use the *starting price of USD 900/tonne, as for the calculation above with results compiled in Table 4.*

Table 18: ROEs under the assumption of different price scenarios for MeOH as well as for OPEX on the basis of weighted average (*)) between the commercial interest rate of 13% and the concessional interest rate of 2%

	Loan blending 2% and 13%:		
	25/75	**50/50**	**75/25**
Annual price increase MeOH, in USD-terms	10.25%*)	7.5%*)	4.75%*)
6%	8.0%	9.2%	10.6%
7%	9.9%	11.1%	12.9%
8%	11.6%	12.8%	14.5%

As expected, the ROEs improve: A blending of 50/50 (resulting in a weighted interest rate of 7.5%) will reach an ROE of 11.1% at an annual GMeOH price increase of 7%. In case of a 75/25 mixture a 6% price increase would be sufficient for an ROE of 10.6%.

Of course, such a subsidy would also create some cost for the financing party. For a DFI, which is very likely to have access to lower interest rates, the discounted cost (at a refinancing rate of 8% p.a.) would range between USD 92.3 and 276.8 million for a repayment period of 25 years, for the investor or debtor the savings, compared to the commercial interest rate of 13%, would range between USD 127 and 381 million (Table 19).

Table 19: Cost and cost savings of an interest rate subsidy by a DFI in USD million

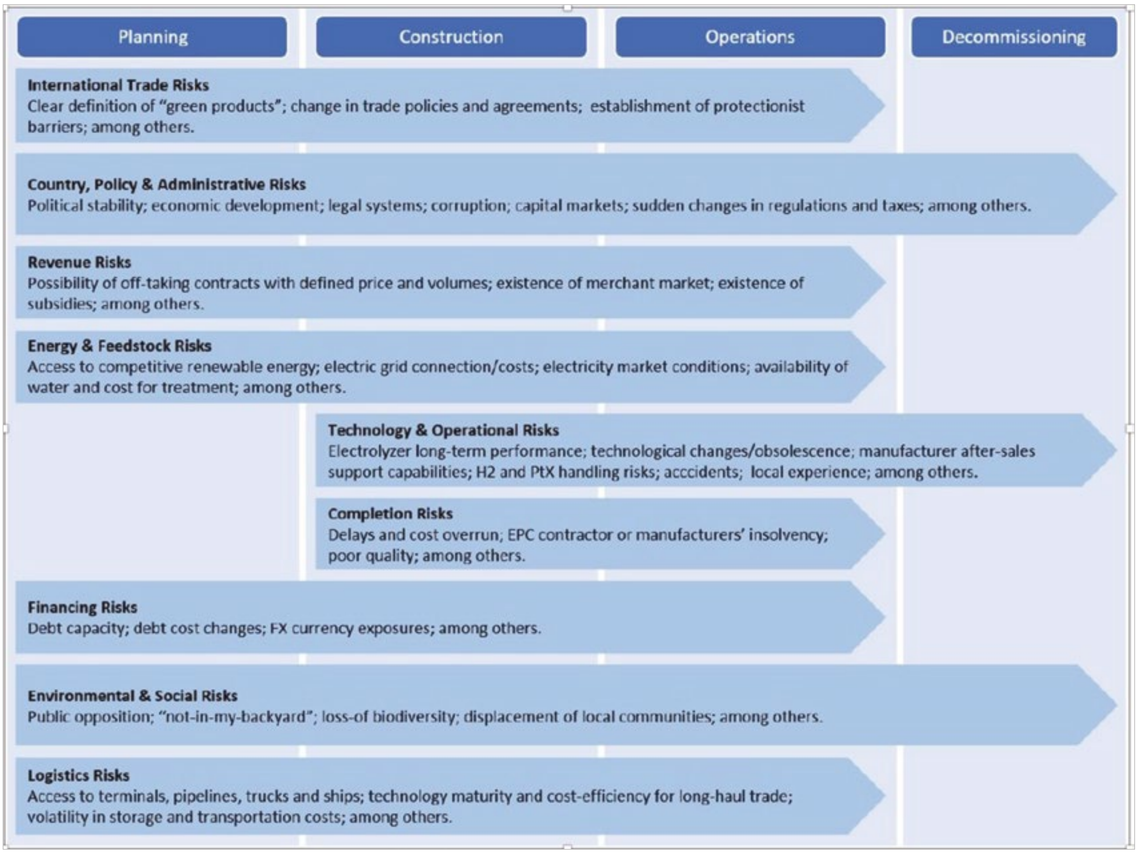
		Cost for investor	Savings for investor	Cost for DFI
Blended Interest rate 10.25%	473	-127.0	-92.3	
Blended Interest rate 7.5%	346	-254.0	-184.5	
Blended Interest rate 4.75%	219	-381.0	-276.8	

The examples in Table 18 and Table 19 demonstrate the effects of a subsidy. There are numerous combinations of subsidies, including grants and price subsidies, in particular as a CfD scheme. To make a meaningful calculation considering such schemes and how they would apply for the project at hand, the project developer must have a bit more certainty and insights about the actual price development and also about the chances to secure off-take (agreements alike the above exemplification with Maersk).

9.4 Risks and risk mitigation

There are considerable risks for the GMeOH project, which make financing challenging. Risk assessment is an intrinsic part of pre-feasibility and is particularly important for financing partners if and when they shall consider the project for financing (or funding of further steps of project development such as the feasibility study).

The main perceived risks for the project before and during its life cycle are summarised in the simplified diagram below *(Figure 22):*



Planning

Construction

Operations

Decommissioning

International Trade Risks
Clear definition of "green products"; change in trade policies and agreements; establishment of protectionist barriers; among others.

Country, Policy & Administrative Risks
Political stability; economic development; legal systems; corruption; capital markets; sudden changes in regulations and taxes; among others.

Revenue Risks
Possibility of off-taking contracts with defined price and volumes; existence of merchant market; existence of subsidies; among others.

Energy & Feedstock Risks
Access to competitive renewable energy; electric grid connection/costs; electricity market conditions; availability of water and cost for treatment; among others.

Technology & Operational Risks
Electrolyzer long-term performance; technological changes/obsolescence; manufacturer after-sales support capabilities; H2 and PtX handling risks; acccidents; local experience; among others.

Completion Risks
Delays and cost overrun; EPC contractor or manufacturers' insolvency; poor quality; among others.

Financing Risks
Debt capacity; debt cost changes; FX currency exposures; among others.

Environmental & Social Risks
Public opposition; "not-in-my-backyard"; loss-of biodiversity; displacement of local communities; among others.

Logistics Risks
Access to terminals, pipelines, trucks and ships; technology maturity and cost-efficiency for long-haul trade; volatility in storage and transportation costs; among others.

Figure 22: Financing of PtX Projects in non-OECD Countries. For H2Global-Stiftung. (Frankfurt School, 2023).

For the GMeOH project, three major financial risks stand out apart from the technical risks[56]:

1) If the optimistic path, e.g. with Maersk as the direct off-taker, cannot be taken by the project developer for any reason, the GMeOH project, alike similar size first mover projects, will most probably have to lean on subsidies to enhance bankability.

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[56] *Note that this study focusses on financial risks only.*

These may come in the shape of a grant, subsidised interest (financing support) or operational and investment support like price subsidy, for example in form of a CfD scheme. It should be noted that such subsidy can easily reach a few hundred million USD if the entire life time of the project shall be covered.

2.) The second risk for the project is ***increases of CAPEX*** during construction. These are usually caused by delays, by unexpected events or simply price increases of equipment or installation cost. For the financial assessment of the project, it is advisable to build in contingencies for CAPEX, as it has been the case for this exemplary project; 10% of overall CAPEX plus another 5% for OPEX *(see Table 13)*. A CAPEX increase of 30% (instead of the already anticipated 10%) would require an unlikely GMeOH price of USD 1,900/tonne to reach an ROE of at least 10%. As CAPEX accounts for a large proportion of total costs, any increase has a very strong impact on the project result. Thus, it is worthwhile for the project developer to monitor potential savings and impending cost increases very closely from the outset.

Careful and comprehensive planning is a decisive factor and guarantees that a project remains within the expected budget and is prepared for possible shortcomings.[57] At the time of writing, a GMeOH project of this size has not been built yet. Project developers might consider as part of their pre-feasibility study whether to start such a first mover project on a smaller scale or in steps, unless experience with financing such large-scale interventions has substantially increased by 2029.

3.) Most likely there is an ***exchange rate risk*** for the project, since the major part of the machinery and equipment will be imported and will have to be paid in international currency like USD or EUR. Looking at a five-year period, the ZAR shows a slow, but still constant devaluation versus the USD, which indicates that in the time frame under consideration, chances are that there is a depreciation against major world currencies. Currency risks for the loan repayment can be avoided by taking up a loan in ZAR and arrange with the bank that suppliers are paid according to the supply contract directly from the loan disbursements. Since most payments will be affected in a relatively short period at the beginning, the risk appears to be bearable and time spans for one to two years (for intermediate and final payments) can be hedged by a forward contract. If, however, loans should be taken up in foreign currency at a foreign bank, which might be tempting since this might be cheaper than the South African-interest rates, potential currency fluctuations should be taken into consideration. Forward contracts for such long periods of up to ten years are either very expensive or unavailable, so the best alternative will be to conclude off-take agreements in the same currency as the loan ("natural hedge"). This will also keep potential dividend payments to foreign investors protected from currency devaluations.

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[57] Bent Flyvberg and Dan Gardener, How big things get done, New York 2023

9.5 Conclusion and recommendations for financing

Financing is a very crucial issue for capital intensive projects like this, since almost all CAPEX (57% of total life time cost) will have to be financed during the initial project phase. Although cost savings are likely while operating the GMeOH plant, future economies of scale will not affect previous expenses. Since the GMeOH project will have a life time of 25 years including a period of 20 years for the repayment of loans, all financing institutions as well as potential equity investors will have a very thorough look on the future prospects of the plant, in particular whether incoming cash flows can cover cost, and private equity investors will only be attracted if a risk-adequate return can be expected.

As it was outlined, high market demand for GMeOH as a maritime fuel can be expected. Therefore, it is not unlikely, that an off-taker like Maersk offers good prices that promise a veritable business, even if they are most likely below of the USD 2,500/tonne mark. Of course, this would be an ideal situation for any investor, since an ROE of over 20% can be achieved even under full commercial financing. It would also be possible to reduce the amortisation period of the loan to ten years even and consequentially negotiate for better financing conditions.

If this turns out to be unlikely, a ***less optimistic case*** will have to be investigated further in order to highlight break-even conditions for the project: The project can only achieve a satisfactory ROE if market prices for GMeOH will rise by at least 8% annually. If such a price increase is not attainable, the project will ***have to be supported*** by concessional loans, grants, price subsidies or a combination of those instruments. There are several public institutions who are prepared to support GH_2-based ventures in order to enable projects to get off the ground, to gain knowledge and to be able to achieve lower prices in the future. However, such support will come at a price: If, for example, 50% of the CAPEX could be financed by a soft loan with interest rates of 2% p.a., the subsidy cost (for the DFI) would be USD 184 million, which amounts to a quarter of the investment cost of the plant. It might even require an additional support element, because a satisfactory nominal ROE of 9.2% (Table 18) could only be achieved under the assumption that the sales price for MeOH will rise by 6% p.a. With a soft loan of 75% of total loan needs, an ROE of 10.6% could be reached at cost of USD 277 million. It is suggested that during a ***feasibility study***, which sheds more light on likely price developments, this scenario including the subsidy need should be investigated more thoroughly to explore in particular:

- To what extent and at what prices will a separate market for GMeOH develop?
- Which effects will tax and duties like the CBAM and eventually other international carbon taxation schemes have on the market?
- What is the minimum return (ROE) of the GMeOH project in order to attract private national and international investors?
- Regarding the South-African framework: will a project be more domestically or more internationally focused? A project with mainly international investors will require a different financial and currency setup than a domestic project.
- Which financial support schemes are available?

Annex 1:

Calculation and important key indicators of the base case (MeOH-market price equals -LCOM)

Annual calculation, year	0	1	2	3	4	5	6	7	8	9	10	11
	in USD million (unless indicated otherwise)											
CAPEX	732	-	-	-	-	-	-	-	-	-	-	-
Loan -(minus grant, if any)[d]	439	417	395	373	351	329	308	286	264	242	220	198
Equity	293											
Grant[d]												
Methanol production capacity (tonnes)		91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500
Average degradation PV and wind % p.a.		0,0	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%
Methanol output (tonnes)		91 500	91 310	91 120	90 930	90 741	90 552	90 364	90 176	89 988	89 801	89 615
Price USD Methanol p.ton		1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7
Sales income from Methanol sales Mn USD		116	116	116	116	115	115	115	115	115	114	114
Total income (U$ million)		116	116	116	116	115	115	115	115	115	114	114
Total OPEX		52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3
Income from excess power sales (U$ M.)		6,6	6,5	6,5	6,5	6,5	6,5	6,5	6,5	6,4	6,4	6,4
OPEX+CAPEX	732,2	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3
OPEX+CAPEX (minus sales excess electricity)	732,2	45,8	45,8	45,8	45,8	45,8	45,8	45,8	45,8	45,9	45,9	45,9
EBITDA		70,7	70,4	70,2	69,9	69,7	69,4	69,2	68,9	68,7	68,4	68,2
Depreciation[e]		34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5
EBIT		36	36	36	35	35	35	35	34	34	34	34
- Interest		57	54	51	49	46	43	40	37	34	31	29
Profit/Loss before tax		-21,0	-18,4	-15,8	-13,2	-10,6	-8,0	-5,4	-2,7	-0,1	2,5	5,1
Tax		0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,7	1,4
Profit/Loss after tax		-21,0	-18,4	-15,8	-13,2	-10,6	-8,0	-5,4	-2,7	-0,1	1,8	3,7
+ Depreciation		34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5
- Loan repayment		22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0
Free Cash Flow (Investor) after tax	-292,9	-8,4	-5,8	-3,2	-0,6	2,0	4,6	7,2	9,8	12,4	14,4	16,3
Total Cash Flow without finance (before tax)	-732	70,7	70,4	70,2	69,9	69,7	69,4	69,2	68,9	68,7	68,4	68,2
d) In case of grant the grant is deducted from the loan only												
e) construction time in one year is slightly simplified												

ROE investor (after tax)	2,6%	
Total IRR (before tax)	8,0%	
NPV investor (after tax), 8% discount rate	-186	USD million
Total NPV (before tax), 8% discount rate	-	USD million
Interest rate loan	13,0%	
WACC	8,8%	

	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total discounted
		in USD million (unless indicated otherwise)													
	51	-	-	-	-	-	-	-	1,44	-	-	-	-		753
	176	154	132	110	88	66	44	22	0						
	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	976 742
	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	
	89 428	89 242	89 056	88 871	88 686	88 502	88 318	88 134	87 951	87 768	87 585	87 403	87 221	87 040	960 247
	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	1272,7	
	114	114	113	113	113	113	112	112	112	112	111	111	111	111	1 222
	114	114	113	113	113	113	112	112	112	112	111	111	111	111	1 222
	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	558
	6,4	6,4	6,4	6,4	6,4	6,3	6,3	6,3	6,3	6,3	6,3	6,3	6,2	6,2	69
	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	52,3	1 291
	45,9	45,9	45,9	45,9	46,0	46,0	46,0	46,0	47,4	46,0	46,0	46,0	46,1	46,1	1 222
	67,9	67,7	67,4	67,2	66,9	66,7	66,4	66,2	64,5	65,7	65,4	65,2	64,9	64,7	732
	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	348
	39	39	39	38	38	38	38	37	36	37	37	37	36	36	384
	26	23	20	17	14	11	9	6	3						363
	13,5	16,1	18,7	21,3	24,0	26,6	29,2	31,8	33,0	37,0	36,8	36,5	36,3	36,0	21
	3,7	4,4	5,1	5,8	6,5	7,2	7,9	8,6	8,9	10,0	9,9	9,9	9,8	9,7	26
	9,9	11,8	13,7	15,6	17,5	19,4	21,3	23,2	24,1	27,0	26,8	26,7	26,5	26,3	-5
	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	348
	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0						216
	-34,4	18,5	20,4	22,3	24,2	26,1	28,0	29,9	29,3	55,7	55,5	55,3	55,2	55,0	-186
	67,9	67,7	67,4	67,2	66,9	66,7	66,4	66,2	64,5	65,7	65,4	65,2	64,9	64,7	958

		Discout	Undisc
Sales (1000 tonnes)	8%	960	2 231
CAPEX+OPEX (USD m) - electr.sales	8%	1 222	1 881
OPEX minus electr. sales (USD m)	8%	490	1 148
OPEX (USD m)	8%	558	1 308

CAPEX+OPEX (USD m) without electr.sales		1 291	

Levelised Cost USD MeOH/t	8%	1 273

Levelised Cost USD MeOH/t	0%	843

Levelised OPEX Cost USD MeOH/kg	8%	581
Levelised USD MeOH/kg islanded		1 344

Annex 2:

Calculation based on inflationary scenario (nominal prices): scenario with annual price increase of 8% for GMeOH and 2% for OPEX

Annual calculation, year	0	1	2	3	4	5	6	7	8	9	10	11	
	in USD million (unless indicated otherwise)												
CAPEX	732	-	-	-	-	-	-	-	-	-	-	-	
Loan -(minus grant, if any)[d]	439	417	395	373	351	329	308	286	264	242	220	198	
Equity	293												
Grant[d]													
Methanol production capacity (tonnes)		91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	
Average degradation PV and wind % p.a.		0,0	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	
Methanol output (tonnes)		91 500	91 310	91 120	90 930	90 741	90 552	90 364	90 176	89 988	89 801	89 615	
Price USD Methanol p.ton		900,0	972,0	1049,8	1133,7	1224,4	1322,4	1428,2	1542,4	1665,8	1799,1	1943,0	
Sales income from Methanol sales Mn USD		82	89	96	103	111	120	129	139	150	162	174	
Total income (U$ million)		82	89	96	103	111	120	129	139	150	162	174	
Total OPEX		52,3	53,4	54,4	55,5	56,6	57,8	58,9	60,1	61,3	62,5	63,8	
Income from excess power sales (U$ M.)		6,6	6,7	6,8	7,0	7,1	7,2	7,4	7,5	7,7	7,8	8,0	
OPEX+CAPEX	732,2	52,3	53,4	54,4	55,5	56,6	57,8	58,9	60,1	61,3	62,5	63,8	
OPEX+CAPEX (minus sales excess electricity)	732,2	45,8	46,7	47,6	48,6	49,5	50,5	51,5	52,6	53,6	54,7	55,8	
EBITDA		36,6	42,1	48,1	54,5	61,6	69,2	77,5	86,5	96,3	106,9	118,4	
Depreciation[e]		34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	
EBIT		2	8	14	20	27	35	43	52	62	72	84	
- Interest		57	54	51	49	46	43	40	37	34	31	29	
Profit/Loss before tax		-55,1	-46,7	-37,9	-28,5	-18,6	-8,1	3,0	14,9	27,5	40,9	55,3	
Tax		0,0	0,0	0,0	0,0	0,0	0,0	0,8	4,0	7,4	11,1	14,9	
Profit/Loss after tax		-55,1	-46,7	-37,9	-28,5	-18,6	-8,1	2,2	10,9	20,1	29,9	40,3	
+ Depreciation		34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	34,5	
- Loan repayment		22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	
Free Cash Flow (Investor) after tax	-293	-42,5	-34,1	-25,3	-16,0	-6,1	4,4	14,8	23,4	32,6	42,5	52,9	
Project cash flow	0	-42,5	-34,1	-25,3	-16,0	-6,1	4,4	14,8	23,4	32,6	42,5	52,9	
Total Cash Flow without finance (before tax)	-732	36,6	42,1	48,1	54,5	61,6	69,2	77,5	86,5	96,3	106,9	118,4	
d) In case of grant the grant is deducted from the loan only													
e) construction time in one year is slightly simplified													

ROE investor (after tax)	10,3%	
Total IRR (before tax)	12,5%	
NPV investor (after tax), 8% discount rate	176	USD million
Total NPV (before tax), 8% discount rate	527	USD million
Interest rate loan	13,0%	
WACC	11,9%	

	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Total discounted
		in USD million (unless indicated otherwise)													
	51	-	-	-	-	-	-	-	1,44	-	-	-	-		753
	176	154	132	110	88	66	44	22	0						
	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	91 500	976 742
	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	0,21%	
	89 428	89 242	89 056	88 871	88 686	88 502	88 318	88 134	87 951	87 768	87 585	87 403	87 221	87 040	960 247
	2098,5	2266,4	2447,7	2643,5	2855,0	3083,3	3330,0	3596,4	3884,1	4194,9	4530,5	4892,9	5284,3	5707,1	
	188	202	218	235	253	273	294	317	342	368	397	428	461	497	1 859
	188	202	218	235	253	273	294	317	342	368	397	428	461	497	1 859
	65,0	66,3	67,7	69,0	70,4	71,8	73,2	74,7	76,2	77,7	79,3	80,9	82,5	84,1	663
	8,2	8,3	8,5	8,6	8,8	9,0	9,2	9,4	9,5	9,7	9,9	10,1	10,3	10,5	83
	65,0	66,3	67,7	69,0	70,4	71,8	73,2	74,7	76,2	77,7	79,3	80,9	82,5	84,1	1 395
	107,8	58,0	59,2	60,4	61,6	62,8	64,1	65,3	68,1	68,0	69,3	70,7	72,1	73,6	1 333
	79,8	144,2	158,8	174,6	191,6	210,1	230,0	251,6	273,5	300,2	327,5	356,9	388,8	423,2	1 259
	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	348
	51	116	130	146	163	181	201	223	245	272	299	328	360	394	911
	26	23	20	17	14	11	9	6	0						363
	25,4	92,7	110,1	128,7	148,7	170,0	192,8	217,2	244,8	271,5	298,8	328,2	360,1	394,5	548
	6,9	25,0	29,7	34,8	40,1	45,9	52,1	58,7	66,1	73,3	80,7	88,6	97,2	106,5	191
	18,6	67,7	80,4	94,0	108,5	124,1	140,7	158,6	178,7	198,2	218,1	239,6	262,9	288,0	357
	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	28,7	348
	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0	22,0						216
	-25,7	74,4	87,1	100,7	115,2	130,8	147,5	165,3	184,0	226,9	246,8	268,3	291,5	316,6	176
	-25,7	74,4	87,1	100,7	115,2	130,8	147,5	165,3	184,0	226,9	246,8	268,3	291,5	316,6	
	79,8	144,2	158,8	174,6	191,6	210,1	230,0	251,6	273,5	300,2	327,5	356,9	388,8	423,2	3 576

		Discout	Undisc
Sales (1000 tonnes)	8%	960	2 231
CAPEX+OPEX (USD m) - electr.sales	8%	1 333	2 250
OPEX minus electr. sales (USD m)	8%	600	1 465
OPEX (USD m)	8%	663	1 675

CAPEX+OPEX (USD m) without electr.sales		1 395	

Levelised Cost USD MeOH/t	8%	1 388

Levelised Cost USD MeOH/t	0%	1 008

Levelised OPEX Cost USD MeOH/kg	8%	690
Levelised USD MeOH/kg islanded		1 453

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