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Review on Gas-to-Liquids Conversion Technology: Lessons from Case Studies and Potential Strategies for Implementation in Tanzania

Joseph H. Kihedu[*1], William E. Mziray[1]

[1]Department of Mechanical and Industrial Engineering, University of Dar es Salaam, P.O Box 35131, Dar es Salaam, Tanzania.

*__Corresponding Author's E-mail:__ kihedu@udsm.ac.tz; ORCID: 0000-0002-7371-2688

ABSTRACT

This review paper explores the transformative potential of Gas-to-Liquids (GTL) technology for harnessing Tanzania's vast natural gas resources. With significant discoveries of natural gas reserves totalling up to 57 Tcf in fields such as Songosongo, Mnazi Bay, Block 1, 2, 3 and 4. Tanzania is positioned to leverage GTL technology to convert these resources into high-value liquid fuels like gasoline, diesel and naphtha. Review of GTL process, its products and applications has been done. By analysing successful GTL projects globally and drawing lessons applicable to Tanzania, this paper provides strategic recommendations for policymakers and stakeholders to foster GTL development. It further addresses the potential considerations that Tanzania may be required to attain with GTL implementation, including capital projections, technological complexities, and the need for supportive policy frameworks. GTL technology does not only promise to enhance energy security and reduce dependency on imported fuels but also offers substantial economic benefits through job creation, infrastructure development and increase export revenues. Adoption of GTL technology in Tanzania could play a pivotal role in diversifying the energy mix, enhancing economic growth and promoting sustainable development.

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INTRODUCTION

Tanzania is endowed with significant natural gas reserves which position it as a potential leader in the energy production sector in East Africa. The discovery of major gas fields such as Songo Songo in 1974, Mnazi Bay in 1982 and Block 1, 2, 3, 4 from 2010 to 2015, has opened up new avenues for energy production and economic growth. As of 2023, Tanzania's estimated natural gas reserves stand at approximately 57 Tcf of which Songo Songo field contributes 783 Bcf and Mnazi Bay 290 Bcf and 55.927 Tcf from Block 1, 2, 3 and 4. (EWURA, 2022a).

Natural gas production has been steadily increasing as new fields are brought online and infrastructure development takes place, making Tanzania one of the largest producers in Africa. Daily production ranges from 150 MMcfd to 200 MMcfd, primarily the Songo Songo field supplies around 92 MMcfd and Mnazi Bay field supplies around 80 MMcfd. The production range depends on the daily consumption rate (EWURA, 2022a). Therefore, the increase in consumption rate of natural gas results to the increase in production rate and vice versa.

Gas to Liquid (GTL) Technology is a technology that involve chemical processes for conversion of natural gas into high-quality liquid fuels such as gasoline, diesel, naphtha, and other petrochemicals. This technology has gained traction globally due to its ability to produce cleaner-burning fuels with lower sulphur emissions and reduced harmful emissions, such as particulate matter and nitrogen oxides when burned compared to conventional crude oil-derived fuels (Wood et al., 2012; Kamara and Coetzee, 2009; de Klerk, 2008). GTL has been utilized worldwide in countries including South Africa, Qatar, USA and Malaysia. GTL plants in such countries have exhibited economic and enviromental benefits in addition to the associated scientific break-through (Braide et al., 2024; Ajagbe, 2019). These plants have shown sustainability of GTL in terms of economic development, energy security, and job creation.

GTL fuels yet has shown great advantage through direct use of its products in energy conversion systems sych as petrol and diesel engines without the need for further upgrades. Thus due to the compatibilty with the existing energy conversion systems there will be less cost implications to the consumers of fuels produced through GTL.

METHODOLOGY

This study conducted a comprehensive literature review to explore the current status of the Gas-to-Liquids (GTL) technology. Also, the review covered three case studies from three from which Tanzania can take lessons towards implementation of GTL technology. Lessons taken include potential hindrance and possible strategies.

Literature search

Relevant articles and reports were selected using electronic databases. The search focused on articles published between 2010 and 2024 to capture GTL technology status as well as countries benchmarked as case studies. The following keywords were employed to ensure a comprehensive search of the literature:

i. Natural Gas Production in Tanzania,
ii. Natural Gas Utilization in Tanzania,
iii. Gas to Liquid Technology,
iv. Gas to Liquid Projects,
v. Performance of Gas to Liquid Projects.
vi. Gas to Liquid Implementation,
vii. Gas to Liquid Implementation Challenges,
viii. Gas to Liquid Implementation Hindrance and Barriers,
ix. Gas to Liquid Implementation Considerations, and
x. Gas to Liquid Implementation Strategies.

Literature screening

Literature addressing natural gas production and utilization in Tanzania, GTL technology status, GTL hindrance and barriers, GTL implementation considerations and strategies were included. Articles and reports that provide data on GTL project investment, operation and performance were also covered. Availability of typical GTL projects lead to focus of cases studies in Qatar, South Africa and Malasia.

Implementation strategies

Based on literatures on GTL status, hindrance, implementation considerations and strategies asa well as lessons form case studies, a set of potential strategies were selected, Basis of selected strategies is based on;

i. Common practice among GTL projects,
ii. Level of performance of particular GTL project, and
iii. Economic considerations and market potential.

RESULTS AND DISCUSSION

Utilization of Natural Gas in Tanzania

Currently, Tanzania utilizes natural gas in several key sectors including power generation, processing industry and domestic use. Figure 1 shows a summary of natural gas consumption in key sectors but also it suggests that natural gas utilization is relatively low compared to the available resource.

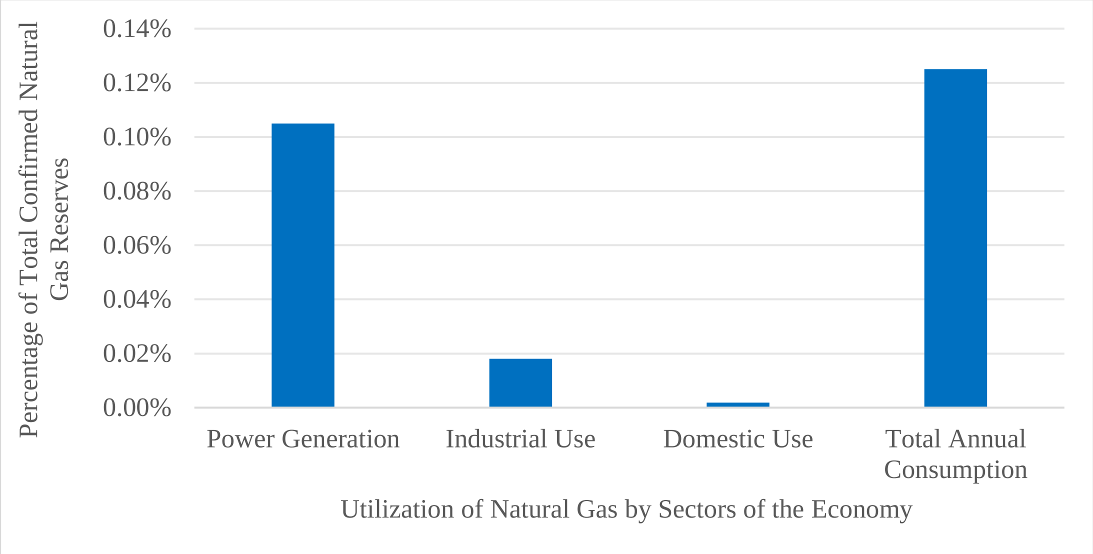

Figure 1: Utilization of Natural Gas in Tanzanian (Source: EWURA, 2020)

Power Generation

As of 2023, about 60% of Tanzania's electricity generation capacity comes from natural gas. The country has a total installed electricity generation capacity of 1,013 MW which is derived from natural gas-fired power utilizing plants (MEW, 2019). Table 1 shows list of power plants which utilize natural gas.

Table 1: Natural Gas Power Plants (Source: EWURA, 2022a)

Power plant	Installed capacity (MW)	Maximum consumption (MMscfd)
Songas	189	46
Ubungo Gas Power Plant 1	102.5	22
Ubungo Gas Power Plant 2	129	30
Ubungo Gas Power Plant 3	112.5	22
Tegeta Gas Power Plant	43.7	45
Kinyerezi I	150	30
Kinyerezi II	248.2	37
Mtwara	30.4	2.4
Somanga	7.5	7.74
TOTAL	**1,013**	**242.14**

Processing Industry

Natural gas is used as a fuel source by processing industry including cement production, steel making and for production of ceramic materials. The industrial sector consumes about 30 to 40 Mscfd of natural gas (EWURA, 2023). Table 2 shows list of industrial consumers of natural gas in Tanzania.

Table 2: Industrial Consumers of Natural Gas (Source: EWURA, 2022a)

Name of customer	Average consumption (Mscfd)	Location	Usage	Supplier
Dangote Cement Factory	12.32	Mtwara	Power and Heating	TPDC
Tanzania Portland Cement Limited (AG)	5.46	Tegeta-Wazo	Heating Kilns	PAET
Goodwill Ceramic Factory	3.90	Mkuranga	Power and Heating	TPDC
Kioo Glass	2.67	Chang' ombe	Heating	PAET
Said Salim Bakhresa Ltd	0.89	Chang' ombe	Boiler	PAET

Domestic Use
While still in its early stages, there is a push to expand the use of natural gas for residential purposes, such as cooking and heating, particularly in urban areas like Dar es Salaam. Currently, 0.001 Tcf/year is used for domestic consumption which is relatively low but growing (EWURA, 2022b).

Overview of GTL Technology

The GTL process primarily involves three stages: Gas reforming or manufacturing, Fischer-Tropsch synthesis and product upgrading as shown in Figure 2. Stage one applies for solid fuels only while stage two and stage three apply for both solid and gaseous fuels. Yet, stage two plays a crucial role in converting gaseous fuel liquid fuel while stage three adds value of liquid fuel to suit specific use.

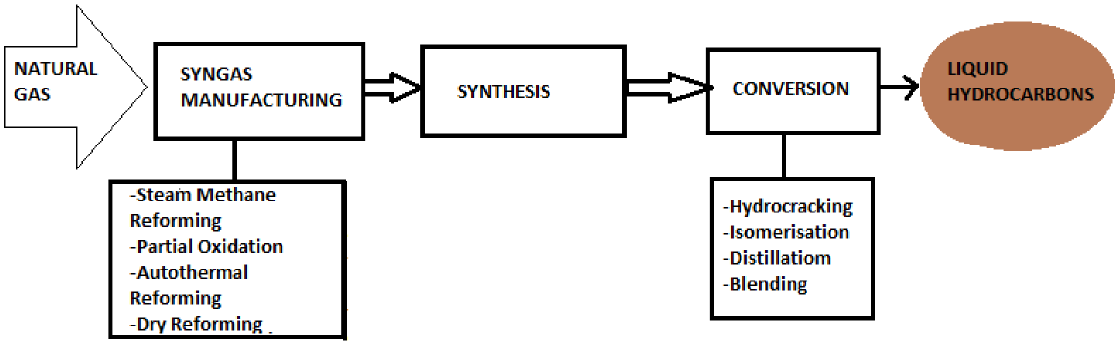

Figure 2: Three main procedures of GTL process (Source: Klerk, 2011; Enger et al., 2008; Sie, 1998)

Gas Reforming
The process begins with the reforming of natural gas, typically methane, into a synthesis gas (syngas), which is a mixture of hydrogen (H_2) and carbon monoxide (CO). This is achieved through methods such as steam methane reforming (SMR) or auto-thermal reforming (ATR) (Wood et al., 2012; Klerk, 2011; Newsome, 1980).

The production of syngas is a critical step, as its composition significantly influences the efficiency and yield of the subsequent Fischer-Tropsch synthesis. This is typically done through steam reforming or partial oxidation, where the feedstock (natural gas) reacts with steam or oxygen to produce a mixture of CO and H_2 as indicated in Equation 1 and Equation 2;

$CH_{4(g)} + H_2O_{(steam)} \rightarrow CO_{(g)} + 3H_{2(g)}$ --*(1)*

$CH_{4(g)} + \frac{1}{2}O_{2(partial\ oxidation)} \rightarrow CO_{(g)} + 2H_{2(g)}$ ---------------------------------*(2)*

Fischer-Tropsch Synthesis

The FT synthesis often referred to as the Fischer-Tropsch process, is a conversion process that dates back to the early 20th century. It was developed by two German chemists, Franz Fischer and Hans Tropsch, in 1925 while they were working at the Kaiser Wilhelm Institute for Coal Research in Mülheim an der Ruhr, Germany (Dancuart and Steynberg, 2007; Sie, 1998). The initial motivation behind the development of the Fischer-Tropsch process was to create a method for producing liquid fuels from carbon-rich sources such as coal. This was particularly significant during periods of geopolitical tension, such as World War II, when Germany was seeking alternatives to imported oil (Schulz, 1999).

Thus, the Fischer-Tropsch (FT) process is a chemical reaction that converts a mixture of carbon monoxide (CO) and hydrogen (H_2) also known as syngas into liquid hydrocarbons, such as synthetic fuels (diesel, gasoline, and jet fuel), waxes, and other chemical products. This exothermic chemical reaction having heat of reaction, ΔH= -167 KJ/mol takes place in the presence of a catalyst, typically cobalt or iron, under high pressure between 10 to 45 bar and temperature range of 200 to 350°C taking place in a special designed reactor through the following chemical reactions (de Klerk, 2008);

$CO_{(g)} + 2H_{2(g)} \rightarrow (-CH_2-)n_{(l)} + 3H_2O_{(l)}$ -- *(3)*

$(2n+1)H_2 + nCO_{(g)} \rightarrow C_nH_{2n+2} + H_2O_{(l)}$ -- *(4)*

Equation 3 indicates that for every molecule of carbon monoxide and two molecules of hydrogen, a hydrocarbon chain like an alkane and water are produced. The hydrocarbon chains can vary in length, leading to the formation of different liquid products. The reactions are facilitated by a metal catalyst, commonly iron or cobalt, which is used to speed up the chemical reactions without being consumed in the process. These reactions can be represented by Equation 5 through Equation 7.

(Open flame) $CH_{4(g)} + ½\ O_{2(g)} \rightarrow CO_{(g)} + H_2O_{(l)}$ ----------------------------------- *(5)*

(Catalyst bed) $CH_{4(g)} + H_2O_{(l)} \rightarrow CO_{(g)} + 3H_{2(g)}$ ------------------------------------ *(6)*

(Catalyst bed) $2CO_{(g)} + H_{2(g)} \rightarrow (-CH_2-)n_{(l)} + CO_{2\ (g)} + 3H_2O_{(l)}$ --------------- *(7)*

Product Formation

Depending on the operating conditions (temperature, pressure) and the type of catalyst used, the Fischer-Tropsch process can produce a range of hydrocarbon products (Martinelli et al., 2020; Kamara and Coetzee, 2009).

a. **Low-temperature Fischer-Tropsch (LTFT) between 200 and 240°C**: Typically produces long-chain hydrocarbons like waxes and heavy oils, which can be further refined into diesel and lubricants.
b. **High-temperature Fischer-Tropsch (HTFT) between 300 and 350°C**: Produces lighter hydrocarbons, including gasoline and olefins, which can be used as chemical feedstocks or fuel components.

For Pressure:

a. **Lower Pressures between 10 and 20 bar:** These are often used in LTFT processes with cobalt catalysts, focusing on liquid fuels like diesel.
b. **Higher Pressures between 20 and 45 bar:** Higher pressures are more common in HTFT processes, where iron catalysts may be used, or when the process aims to produce a broader range of hydrocarbons, including gasoline and chemicals.

Product Upgrading

The hydrocarbon products from the FT synthesis are further refined and upgraded to produce high-quality liquid fuels such as gasoline, diesel, naphtha, and lubricants. This stage involves hydrocracking, hydro isomerization and distillation processes. This enhances the fuel properties, making GTL products cleaner and more efficient compared to conventional fuels (de Klerk, 2008). Hydrocracking is the process of breaking down long hydrocarbon chains having C>20 , such as base oil, waxes, and paraffins, into shorter hydrocarbon chain products. This process is occurs under the condition of high pressure of 35 to 200 bar and high temperature of 260°C to 425°C in the presence of a catalyst and hydrogen. The hydrocracking process increase the production of middle distillates including diesel and jet fuel (Dancuart and Steynberg, 2007).

The isomerization is applied after hydrocracking, for the purpose of converting straight chain hydrocarbons into branched hydrocarbons. This process improvess the cetane number in diesel, octane number but also flow properties making such fules in low temerature environment conditions (Martinelli et al., 2020; de Klerk, 2008).

Another process involved is distallation which involves separation of various liquid components of GTL products on the basis of their boiling points. This proces is important because it separates liquid fractions such as petrol, diesel, kerosene, jet fuel and naptha, Such liquid fuels can then be used as fuels or as raw material for further chemical processing in petrochemical industry (Martinelli et al., 2020). In special circumstances, the end products from GTL process are blended with other additives to meet specific market standards and requiremnts. For instance GTL diesel can be blended with cetane additives to improve overal cetane number and therefore enhance its quality (Botes et al., 2011;Kamara and Coetzee, 2009).

Figure 3, shows typical sequence of steps involved in converting natural gas into liquid hydrocarbon fuels. The setup requires an external power supply to drive the the process. This proces involves syngas production, Fischer-Tropsch synthesis as well as product upgrading. Also energy required for compression, cooling and refining must come from external heat sources, say electricity. With such setup, operation cost is normally higher compared to the GTL plant system that with self powering system.

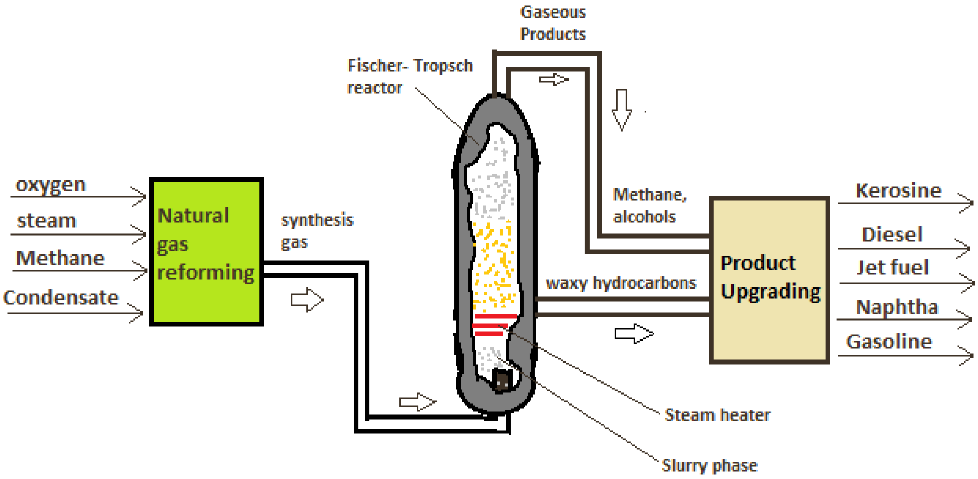

Figure 3: Diagram of GTL process without self-powering system (Source: Braide et al., 2024; Botes et al., 2011)

Figure 4, shows the GTL process with a self-powering system utilizing a spark plug and a turbine showcasing a more energy-efficient approach to converting natural gas into liquid fuels. In this setup, the system generates its own energy by harnessing the gaseous products produced in the FT process. A spark plugs initiates combustion, driving the turbine to generate power that can be used to maintain the high temperatures and pressures required for syngas production and other stages. The exhaust gases are not wasted; instead, they are recycled into the syngas production process through a reforming method, where they are reprocessed to form additional syngas. This closed-loop design reduces reliance on external power sources, enhances overall energy efficiency and minimizes waste, contributing to both cost savings and a smaller environmental footprint.

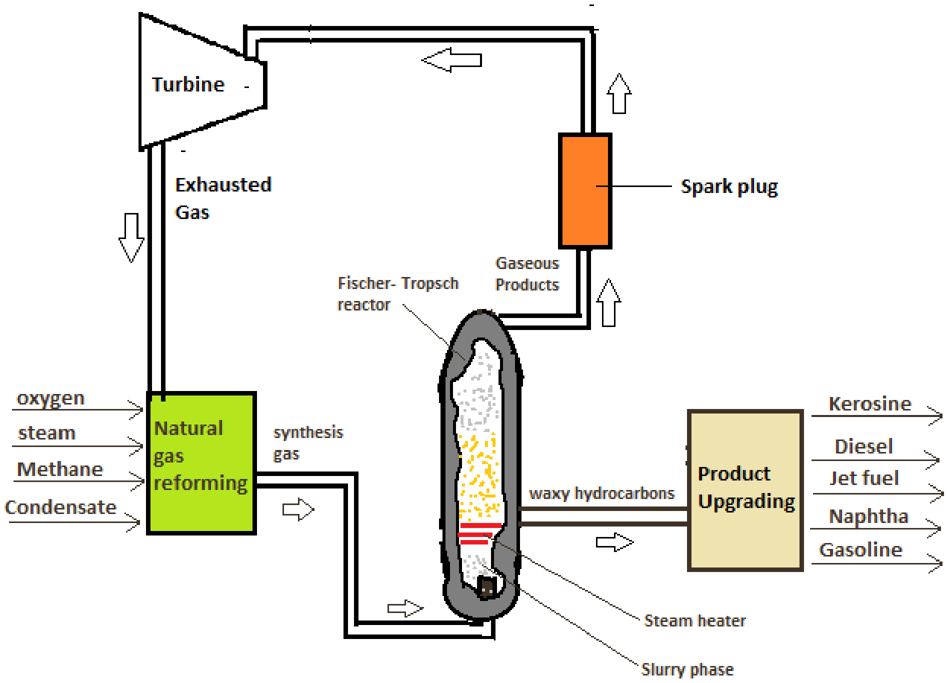

Figure 4: Diagram of GTL Process with Self-Powering Optional System (Source: de Klerk, 2012; Wood et al., 2012)

Products and Applications

GTL technology produces several key products with diverse applications across various sectors from normal simple machine engines to heavy-duty machine engines. These can be in the transportation, agriculture, manufacturing and mining industries.

Gasoline

GTL gasoline is a high-quality, ultra-clean liquid fuel produced by converting natural gas into synthetic hydrocarbons through the Fischer-Tropsch process. It is characterized by its near-zero sulfur content and low levels of aromatics, making it an environmentally friendly alternative to conventional gasoline. GTL gasoline is compatible with existing internal combustion engines and offers a cleaner-burning option that reduces emissions of harmful pollutants (Botes et al., 2011; Kamara and Coetzee, 2009).

Diesel

GTL diesel is a premium fuel characterized by its high cetane number and virtually sulfur-free composition, making it ideal for use in modern diesel engines. Its superior combustion properties result in reduced emissions of particulates and nitrogen oxides, contributing to improved air quality (Botes et al., 2011; Kamara and Coetzee, 2009).

Naphtha

GTL naphtha serves as a feedstock for the petrochemical industry, where it is used in the production of plastics, synthetic rubber, and other chemicals. Its high purity and low aromatic content enhance the efficiency of chemical processes (Botes et al., 2011).

Lubricants and Waxes

The GTL process can also yield high-quality lubricants and waxes, which are used in a variety of industrial and consumer applications. These products benefit from GTL's ability to produce uniform and tailored hydrocarbon structures. The initial product formed is base oil which it requires 1% of its total volume of additives such as viscosifiers to be use as a lubricant (Klerk, 2011).

Comparison of GTL with other Gas Conversion Technologies

Gas-to-Liquids (GTL) technology is one of several processes used to convert natural gas or other carbon-rich feedstocks into valuable liquid fuels and chemicals as shown in Table 3. To understand its significance, it's helpful to compare GTL with other competing technologies, such as Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG). GTL technology differs significantly from LNG and CNG in that it produces liquid hydrocarbons directly from natural gas, such as diesel, naphtha, and lubricants, which are ready for use in existing infrastructure without requiring extensive modifications. LNG involves cooling natural gas to a liquid state for transportation, but it must be re-gasified before it can be used as a fuel, making it more suitable for regions where natural gas pipelines are impractical (Wood et al., 2012; Bao et al., 2010).

Table 3: Comparison of GTL Diesel Properties with Conventional Diesel (Source: Kurevija et al., 2007)

Fuel Properties	GTL Diesel	Low Sulphur EU 2005 Diesel
Lower Calorific Value, MJ/kg (MJ/L)	43.8 (33.53)	42.7 (35.44)
Density in kg/dm^3	0.765	0.83

Cetane number	≈ 70	45 – 50
Kinematic viscosity cSt in mm^2/s	≈ 2.0	2.5 – 4.0
Total Sulphur in ppm	< 1.0	8
GHG emission from production process, (kg equivalent in CO_2 per MJ)	0.0336	0.0191
GHG emission from combustion process (kg equivalent in CO_2 per MJ)	0.0667	0.0639
Total life cycle GHG emission in kg	0.1003	0.083

Conversely, CNG refers to compressed natural gas that can then be used directly as automotive fuel. CNG requires specialized system installation in order to be compatible for petrol and diesel engine. While LNG and CNG still stands among the common methods for transporting and using natural gas, GTL provides best option for producing liquid hydrocarbon fuels usable in common engines (Ajagbe, 2019; Dancuart and Steynberg, 2007).

Case Studies of GTL Projects

Tanzania can derive lessons that can lead in adoption of the GTL technology from already successful plants from varieous countries, some of which are discussed in this paper.

Qatar Pearl GTL Plant

The Pearl GTL plant construction was completed towards the end of 2012, by then making it the world largest GTL plant. This was truly a ground breaking project that stands as one of strategies for utilizing innovation towards solving energy challenges across the globe while emphasing on enviromental sustainability (Figure 5). Located in Ras Laffan Industrial City, the Pearl Plant is a joint venture for Qatar National Oil Company and SHELL. According to design capacity, Pearl GTL plant can produce up to 1.6 billion cubic feet per day, equivalent to 140,000 barrel per day (bpd) of the liquid hydrocarbon fuels such as gasoline, diesel, kerosene, jet fuel and base oils (SHELL, 2023).

Figure 5: Qatar Pearl GTL Plant (Source: SHELL, 2023)

The plant utilizes advanced GTL technology based on the FT process, which converts natural gas into synthetic liquid fuels and chemical products. The technology used in Pearl GTL allows for the production of clean fuels with almost zero sulfur content and very low levels of other pollutants, qualifying them environmentally friendly alternative fuels to conventional fuels (SHELL, 2023). The construction of the Pearl GTL plant consumed about $19 billion, making it one of the largest energy projects globally. The said plant contributes remarkablly to Qatar's GDP but also contributes in diversifying the Qatar's energy portfolio, reducing overwhelming reliance on crude oil exports, and positioning the country as a lead in energy market (SHELL, 2023). Key success factors for Pearl GTL plant can be assessed in terms of yearly production rate, annual profit margin and operation cost, as shown in Table 4.

South Africa Mossel Bay GTL Plant

Mossel Bay GTL plant in South Africa is operated by South African National Oil Company (PetroSA). It was commissioned in 1992 as first GTL plant in the world with capacity to produce about 45,000 barrels per day (Steyn et al., 2005). It utilizes natural gas condesate from offshore blocks of Bredasdorp Basin as its feedstock. Mossel Bay GTL plant products products including; unleaded petrol, diesel, fuel oil, kerosenel and petrochemicals (Mabena, 2005).

The Mossel Bay plant utilizes GTL technology for commerical purposes. It produces ultra clean low sulfur but also low aromatic synthetic fuels. The project had the business plans targeting at developing of domestic refining and liquid fuels, developing logical infrastructure, marketing and trading of oil and petrochemicals (Wood et al., 2012; Mabena, 2005). This step has made South Africa less dependand on imported convectional fuels. It contributes to economic development through job creations by employing approximately 1,800 people directly and more than 5,000 indirect jobs. Mossel Bay GTL plant has over almost 20 years running while depending on the domestic feedstock which are the small gas pockets. The plant has resulted to the intoduction of newly discovered gas field that had to be developed in order to extend the plants lifespan (Mabena, 2005). Descriptive key success factors include annual production rate, yearly profit margin and operation cost of Mossel Bay GTL Plant is as shown in Table 4.

Malaysia Bintulu GTL Plant

The Bintulu GTL plant in Malaysia (Figure 6) is another facility among global Gas-to-Liquids (GTL) industry. The plant represents an advanced application of GTL technology for conversion of natural gas into high valued liquid fuels and petrochemicals. As operated by Shell, the Bintulu plant has maintained instrumental position in demonstration of commercial viability of the GTL technology and its potential benefits to countries with abundant natural gas resources (SHELL, 2023). Commissioned in 1993, Bintulu GTL plant has a capacity to produce approximately 14,700 bpd of synthetic liquid fuels, including clean diesel, kerosene, and naphtha. The plant processes natural gas from nearby fields, converting it into high-quality, environmentally friendly liquid (SHELL,2023; Mabena, 2005).

Figure 6: Malaysia Bintulu GTL Plant (Source: Heerden and Consultation, 2021)

The Bintulu plant employs the FT process, a key component of GTL technology, to convert natural gas into liquid hydrocarbons. Shell's version of the technology, known as Shell Middle Distillate Synthesis (SMDS), is particularly effective in producing high-quality, low-sulfur diesel and other liquid fuels that meet stringent environmental standards. The plant also produces specialty chemicals used in the production of detergents, lubricants, and other industrial products (SHELL, 2023). The Bintulu GTL plant has contributed significantly to Malaysia's economy by adding value to its natural gas resources, reducing dependence on imported refined products, and providing high-quality synthetic fuels for domestic use and export. The plant has also created jobs, fostered technological innovation, and stimulated the growth of related industries in the region. Additionally, Bintulu's products are exported to markets in Asia and beyond, contributing to Malaysia's trade balance. Key success factors are yearly production rate, annual profit margin and operation cost of Bintulu GTL Plant (Table 4).

The profitability scale demonstrated by existing GTL plants in Qatar, South Africa, and Malaysia underscores the lucrative potential of GTL technology. While the initial investment is substantial, the long-term financial returns can be equally significant, with high profit margins and the ability to generate consistent revenue streams.

Towards GTL Implementation in Tanzania

Despite the promising prospects, the implementation of GTL in Tanzania may face several hindrance including requirements on high capital and operational costs and technological complexities associated with establishment of GTL plants. Successful implementation of GTL will require strategic planning, investment in capacity building and fostering partnerships with international stakeholders. As stated in the National Natural Gas Policy for Tanzania that provides detailed technical and economic analysis which guide the selection of the energy project for implementation (Tanzania Natural Gas Policy, 2013). Therefore, comprehensive review of potential impact of GTL technology on Tanzania's natural gas sector is required. His part of the paper examines the economic, environmental, and social implications of GTL adoption and offers strategic recommendations for overcoming the challenges associated with its implementation. By leveraging GTL technology,

For Tanzania, investing in GTL technology is crucial for achieving energy independence in the liquid fuel industry. Unlike LNG, which primarily focuses on transporting natural gas, GTL allows Tanzania to convert its natural gas resources into high-value liquid fuels that can replace imported diesel and gasoline. This reduces the country’s dependence on foreign oil and positions Tanzania as a potential exporter of clean fuels to neighboring regions. Moreover, GTL’s ability to produce cleaner-burning fuels with lower emissions aligns with global trends toward reducing greenhouse gas emissions and combating climate change, making it an environmentally responsible choice for Tanzania’s future energy supply.

GTL Implementation Considerations

The implementation of Gas-to-Liquids (GTL) technology in Tanzania, while promising, is not without achieving certain considerations. These challenges span technical, financial, regulatory, and market dimensions, each requiring careful consideration to ensure successful adoption and integration into the country's energy and economic framework.

Technical and Financial Considerations

GTL plants require significant capital investment, often reaching billions of dollars. The construction of GTL facilities involves complex engineering and advanced technologies, contributing to high upfront costs (Ramberg et al., 2017; Bao et al., 2010; Ogugbue et al., 2007). Additionally, operational costs are substantial, driven by energy consumption, maintenance and skilled labor requirements. Table 5, shows the classification of different GTL plants with their minimum required CAPEX for their establishment and their production capabilities. Figure 5, shows how the capital is divided into different operating stages towards accomplishing the goal of establishing a GTL plant.

Table 5: GTL Plants Classification by Size (Source: Braide et al., 2024)

	large	Small	Mini	Micro
Gas feed rate (MMscfd)	~/>100	~/>10	~/>1	~/> 0.1
CAPEX ($)	>500, 000, 000	>100, 000, 000	>10, 000, 000	>1, 000, 000
Liquid output (bpd)	>10, 000	>1000	>100	>10

Figure 7, Shows the distribution of CAPEX in the GTL project reflecting on the complexity and importance of each process stage in the GTL process. The largest portion is dedicated to the FT Synthesis Unit because it is the core process where syngas is converted into hydrocarbons, making it both technologically intensive and costly. Offsites and Syngas Units require significant investment as they involve the infrastructure necessary to support the plant and the crucial step of producing syngas from natural gas. Utilities play a major role in providing power and water, vital for running the entire facility. The smaller percentages for the Air Separation Unit and Hydrogen Unit correspond to the essential, though more specialized, processes involved in providing oxygen and hydrogen for synthesis and refining. Lastly, the Upgrading Units and Water Disposal Units receive lower allocations because they are focused on refining the final product and environmental management, which are important but less resource-intensive compared to the main production processes. This distribution reflects the prioritization of the most technically demanding and critical components of the GTL operation.

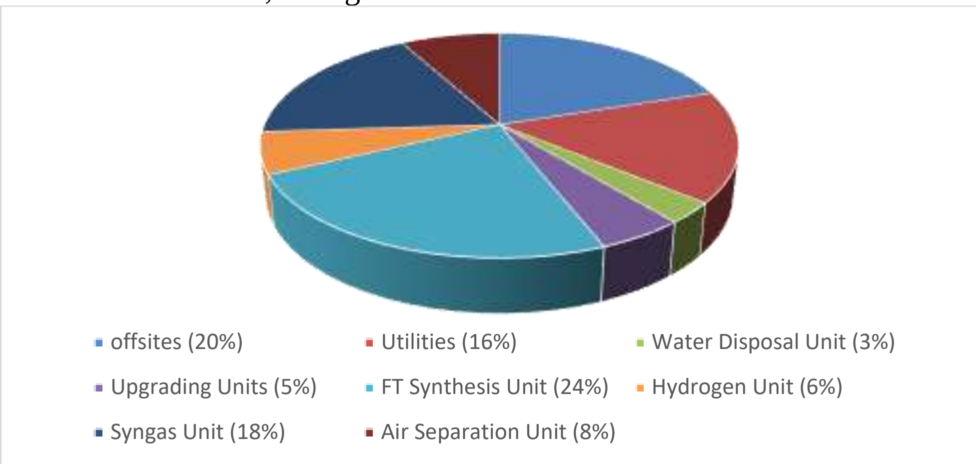

Figure 7: GTL project CAPEX Breakdown (Source: de Klerk, 2012)

Technological Considerations

The GTL process is technologically intricate, it faces significant technological complexities around the FT synthesis, syngas production, product upgrading and other auxiliary processes. These complexities include maintaining reactor efficiency, catalyst deactivation, energy-intensive operations, and scaling the process for industrial use. The GTL process also requires advanced control systems to manage heat, mass transfer and ensure product quality (de Klerk, 2008). In this stages, advanced computerization and automation are inevitable. Each stage requires precise control over process conditions to optimize yield and efficiency.

GTL Infrastructure Development

The success of GTL projects depends on the availability of supporting infrastructure, including natural gas extraction and transport systems, syngas production units, Fischer-T8 reactors and product upgrading facilities. Additionally, storage tanks, power generation systems, and advanced process control technologies are necessary to manage energy-intensive operations and ensure safety. Environmental management infrastructure, such as emissions control and waste treatment systems, is essential to meet regulatory standards. This infrastructure is crucial for ensuring the efficiency, safety, and economic viability of GTL plants, though it involves significant capital investment (Braide et al., 2024; Ogugbue et al., 2007).

GTL Regulatory and Policy Framework Considerations

GTL process is significantly impacted by regulatory and policy frameworks, particularly in areas such as environmental regulations, carbon pricing, natural gas availability and trade policies. Strict emissions standards and carbon taxes can increase operational costs, while supportive measures like tax incentives, investment grants and favorable natural gas pricing can enhance project viability and attractiveness of GTL investments (Braide et al., 2024). Energy transition policies and international climate agreements may either support or hinder GTL adoption depending on the national focus on reducing carbon emissions or ensuring energy security. Balancing these factors is essential for successful GTL implementation.

GTL Market and Economic Viability Considerations

Price Volatility of Oil and Gas Market Dynamics

The profitability of GTL projects is sensitive to fluctuations in global oil and gas prices because it tends to be constant. Low natural oil and gas prices make GTL production more cost-effective, while high oil prices increase the competitiveness of GTL fuels. However, when oil prices fall or gas prices rise, GTL becomes less economically viable. Fluctuating demand for GTL products, driven by oil price changes, impacts the overall success of GTL projects (Damayanti et al., 2024; Wood et al., 2012). Figure 8, 9, and 10 show the consumption, price and exchange rate fluctuations of some other refined petroleum products as reported by EWURA yearly reports. (EWURA, 2022b; EWURA, 2022a; EWURA, 2020; MEW, 2019; EWURA, 2018; EWURA, 2017; EWURA, 2015-2010).

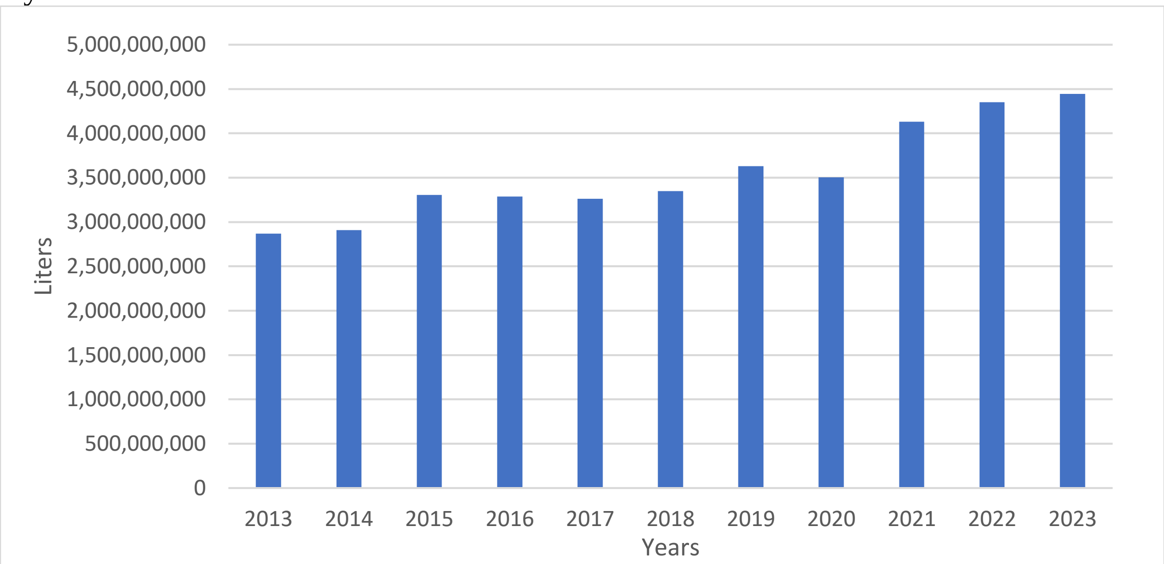

Figure 8: Refined petroleum products consumption in Tanzania

Figure 9: Petrol and Diesel Price in USD per MT

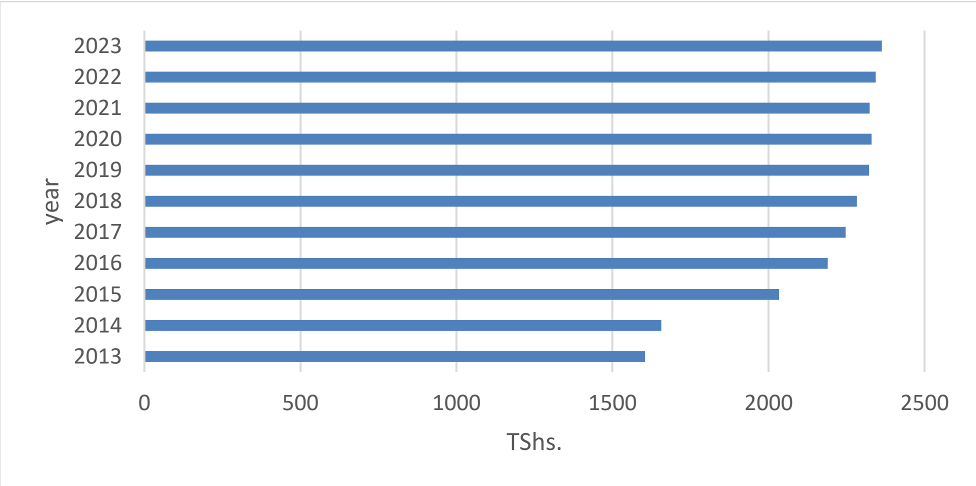

Figure 10: Increase in exchange rates of 1 USD to TZS for oil purchase

Environmental and Social Considerations

Environmental Impact

While GTL products offer cleaner-burning alternatives to conventional fuels, the GTL process itself is energy-intensive and can have significant environmental impacts if not managed properly. Emissions, water usage, and waste management are key environmental considerations that must be addressed (Hickman et al., 1993). Implementing best practices and advanced technologies such as Carbon Capture, Utilization, and Storage (CCUS), Energy Efficiency Optimization and Greenhouse Gas Offset Programs can minimize the environmental footprint of GTL operations.

Community Engagement and Social Benefits

The development of GTL projects can bring social benefits, including job creation and community development. However, it is essential to engage with local communities and stakeholders to ensure that projects are socially inclusive and contribute to local development (Ogugbue et al., 2007). Transparent communication and collaboration with affected communities can enhance social acceptance and project success.

CONCLUSIONS AND RECOMMENDATIONS

The Gas-to-Liquids (GTL) process offers Tanzania a transformative opportunity to capitalize on its substantial natural gas reserves, translating them into significant economic and social benefits. As the country stands on the cusp of an energy revolution, GTL technology could be a critical driver for achieving sustainable development, energy security and industrialization. The reasons why Tanzanians should actively engage in and invest in GTL processes are compelling and multifaceted. Tanzania can enhance its energy security, drive economic growth, and contribute to sustainable development.

Economic Growth and Diversification

Investing in GTL technology has the potential to diversify Tanzania's economy, reducing its reliance on traditional sectors such as agriculture and mining. GTL plants convert natural gas into high-value liquid fuels, which are essential for industrial activities and transportation. These products can either be consumed domestically, reducing the need for imports, or exported to generate foreign exchange. By establishing a GTL industry, Tanzania can create new revenue streams, stimulate industrial growth and attract both local and foreign investments. Moreover, the development of a GTL industry can lead to the growth of ancillary industries, such as petrochemicals, creating a ripple effect that benefits the broader economy. This diversification is crucial for building economic resilience, particularly in a global market that is increasingly volatile and susceptible to shocks in commodity prices.

Job Creation and Skill Development

The establishment of GTL plants would create numerous job opportunities across various skill levels. Starting from the very first stage of construction as well as the routine operational stage, GTL innovative industry would be a great investment that will contribute to employment generation in Tanzania. Hand in hand with job creaction, GTL requirement of the development of skilled labour will require investment in education and training. This with involve multi-national collaborations and partnership with global academic and research institutions as well as international technology providers. This will aid Tanzania to ensure it has acquired the knowledge and experts required to manage and operate the GTL plants. This will help Tanzanian local expertises to be competive in goble scale due to their overall workforce capacity.

Energy Security and Environmental Benefits

GTL technology can play an important role in enhancing energy security by providing Tanzania with an alternative source of liquid fuels that are cleaner and more environmentally friendly than traditional petroleum-based fuels. GTL produced fuels realeases lower emissions such as sulfur oxides, nitrogen oxides, and particulates, contributing to improved air quality and public health. Through GTL technology Tanzania will have the consistency of keeping a control in the oil price fluctuation and secure alteration of other economic projects that depend on fuel prices supporting the country's long-term development goals.

Strategic Positioning in the Global Energy Market

As global demand for cleaner energy sources increases, Tanzania has a unique opportunity to position itself as a key player in the international GTL market. The country's strategic location, coupled with its vast natural gas reserves, provides a competitive advantage for exporting GTL products within the East African region and to global markets. By becoming a hub for GTL production, Tanzania can attract international trade and investment, enhancing its geopolitical significance and economic influence. In additionaly, the establishment of GTL industry will open doors towards international collaborations and partnerships. Mentioned partnership can speed up advanced adoption of current GTL technologies, making Tanzania to be able to influence global enegry strategies, policies and practices.

Social Development and Poverty Alleviation

Investment of GTL technology links economic and enviromental impacts and attains even social impacts. The revenues that can be generated from GTL projects, can then be used in development of social infrastructures like, healtcare facilities, schools, transportation facilities and housing while improving Tanzanians quality of life. GTL investment will results to development regional areas where the GTL plant will be located leading to access of essential social services, infrastructure and economic opportunities. Through enganging with GTL technology, Tanzania benefit from wealth generated from its natural resources directly is involved in improving its people's living standards.

Recommendations

This study recommends further studies to be conducted on situation analysis as baseline research for potential opportunies offred by Gas to Liquids (GTL) technology. The analysis may include the existing policies and need strengthen them for encouraging GTL investment. With clear and supportive regulations such as tax breaks, subsidies and simplified licensing process, Tanzania will be able to attarct both local and foreign investors.

Further more, addition of GTL technology into the national energy strategy of Tanzania will lead in achievement of energy security and economic diverstification. Government crucial investments in GTL plants in the country should be coupled with promoting technological advancements as well as research and development strageties to ensure adaption. Also Public Private Partnerships (PPPs) can be explored and be allowed to play an important role in emphasing risk sharing and leveraging the expertise of experienced players arounf the globe.

Establishment and implementing training programs by establishing collaborations with academic and research institutions while fostering innovation through technology research centres will ensure development of skilled labor capable of maintaining and operating GTL plants. Training efforts should provide platform for engaging local communitties towards common understanding of importance advantange and purpose of GTL. Tanzania stands in an advantageous pivotal step towards economic growth and energy independence and a sustainable future through GTL technology.

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Table 4: Investment costs, operation costs, profits, annual production and success factors for GTL case studies (Source: SHELL, 2023; Ogugbue et al., 2007; Mabena, 2005)

Case Study	Investment Cost (USD)	Operation Cost (USD/year)	Estimated Annual Profit (USD/year)	Operation Cost (USD/year)	Estimated Annual Profit (USD/year)	Yearly Production (MMbbl)	Key Success Factors
Qatar Pearl GTL Plant	$19 billion	$1.5 - $2 billion	$3 - $4 billion	$1.5 - $2 billion	$3 - $4 billion	50.4	**Government Support:** Creative supportive policies and regulatory frameworks attracted international investments. **Resource Details:** Qatar's natural gas reserves of 872.27 TcF. **Strategic Partnership:** Collaboration between Shell and Qatar Petroleum leveraged both technical expertise and financial base. **Technological Adaptation:** State-of-the-art technologies for efficient GTL production and product quality improvements. **Market Diversification:** Primarily focused on high-value GTL products like fuel, lubricants and petrochemicals.
South Africa Mossel Bay GTL Plant	$2.5 billion	$300 - $400 million	$400 - $600 million	$300 - $400 million	$400 - $600 million	16.2	**Government Support:** Government invested in research and development for energy security through GTL plant. **Resource Details:** Rserves of natural gas of around 1.5 Tcf **Strategic Partnership:** Local partnerships, limited international collaboration. **Technological Adaptation:** Ongoing technological improvements ensures competitiveness. **Market Diversification:** Focused on local markets and securing energy stability for the country.
Malaysia Bintulu GTL Plant	$1.6 billion	$150 - $200 million	$200 - $300 million	$150 - $200 million	$200 - $300 million	5.292	**Government Support:** Encouraging policies frameworks for innovation and energy diversification. **Resource Details:** Natural gas reserves of about 83 Tcf **Strategic Partnership:** International and local partnerships. **Technological Adaptation**: Implemented innovative technologies with focus on specialty products. **Market Diversification:** Targeted niche markets, including waxe and base oils, enabling access to high-demand markets.