Biomass-to-Liquid, Gas-to-Liquid, and Coal-to-Liquid Pathways: Comparative Techno-Economic and Policy Perspectives

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Abstract
Innovative liquid fuel technologies, including Biomass-to-Liquid (BTL), Gas-to-Liquid (GTL), and Coal-to-Liquid (CTL), have received renewed attention as the world moves towards cleaner and safer energy systems. These technologies help aid energy diversification, increased fuel flexibility, and decreased reliance on crude oil, but their development is hampered by technical, economic, environmental, and policy challenges. This paper examines BTL, GTL, and CTL technologies comparatively, focusing on their relative costs, energy efficiencies, and their evolution vis-à-vis policy frameworks in the global North and in resource-rich, developing countries. With its theoretically carbon-neutral marketed BTL remaining aligned to renewable energy goals despite challenges of scale, high feedstock costs, and land use. In gas-rich countries like Qatar, GTL has matured commercially, providing high-quality, albeit capital-intensive, fuel and serving as a source of carbon emissions in the absence of effective carbon capture. Coal-rich countries, like South Africa, have energy independence due to CTL, but it remains the most carbon-intensive fuel and poses its own challenges requiring stringent regulatory control and strong economic incentives for decarbonisation. From case studies conducted in Nigeria, South Africa, and Qatar, I observe that while technologies can assist in energy diversification in the short and medium term, their long-term sustainability depends on carbon policy, fiscal creativity, and cross-border cooperation on net-zero emissions. The study demonstrates that future adoption of BTL, GTL, and CTL systems should focus on aligned techno-economic models, systemic carbon pricing, and transition policies that account for energy security and sustainability.

Keywords: Biomass-to-Liquid (BTL), Gas-to-Liquid (GTL), Coal-to-Liquid (CTL), Techno-Economics, Energy Policy

Introduction

The transition to non-traditional petroleum to other types has become the center of the discussion of energy in the world, particularly, after the Paris Agreement, and the net-zero commitments (IEA, 2021; IPCC, 2022). It is obvious that renewable energy and electrification are the stories of transition; however, liquid fuels remain the invaluable tools in the hard-to-abate sectors, such as the aviation sector, heavy industry, and military (Hoek and Tang, 2013; Armaroli and Balzani, 2011). This fact predetermines the relevance of the unconventional paths- BTL, GTL and CTL- that could substitute or supplement the products of crude oil origin.

However, the technologies have also made matters regarding their economic competitiveness, carbon footprint, and their integration with the evolving policy frameworks difficult (Kober et al., 2020; Ejiogu et al., 2019). BTL technologies have a potential of an unlimited source of liquid fuel but they are restricted by problems of biomass logistics and land-use. GTL offers a monetization strategy of

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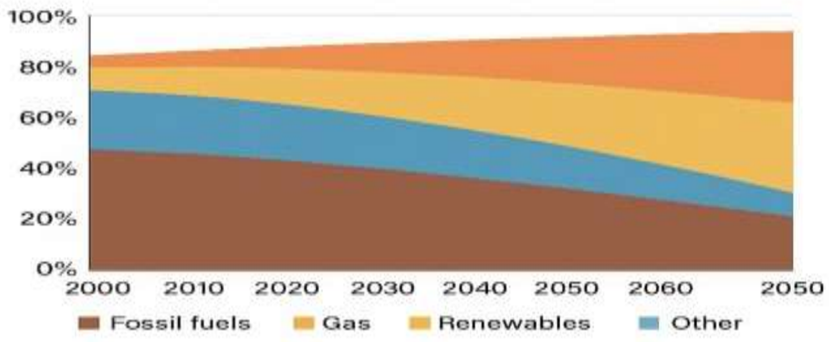
large quantities of natural gas, particularly to the states, which burn associated gas, yet not to carry out during the periods of varying oil prices and excessive capitals (Wood et al., 2012). In the coal-rich nations like South Africa, CTL remains attractive, but it fundamentally cannot be used in the context of decarbonization without CCS (Dieterich et al., 2020).

Figure 1. Global Energy Mix Forecast to 2050



(Source: IEA World Energy Outlook, 2023)

The fossil fuel deposits diminish gradually although they remain on the peak until mid-century and renewable sources grow continuously. Despite the growing exponentially rate of renewable, fossil fuels still constitute more than fifty percent of the total primary energy in the world by the year 2050 as the policies scenario indicates. Still, gas remains the most crucial as far as the transition fuel is concerned, and the reduction of coal is the most acute. This prediction puts CTL, GTL and BTL into context: CTL is growing less and less important as coal use drops; GTL is doing well as it still uses gas, but the renewable growth, BTL, needs subsidies to counter competitors. The figure reveals the irreconcilability between decarbonization and fossil dependence, which forms the rationale of the significance of alternative liquids.

The Purpose and Research Questions

The three overlapping objectives of this paper are: to establish the techno-economic feasibility of the three technologies BTL, GTL, and CTL in resource heterogeneous conditions; the environmental and sustainability implications of each technology, in particular, lifecycle carbon emissions, land use, and ecological trade-offs; and to establish how national and international policy frameworks influence or constrain the use of these technologies. On the basis of these objectives, the following research questions have to be answered in the study: What are the comparative techno-economic strengths and weaknesses of BTL, GTL and CTL? How will environmental sustainability concerns affect their short and long term energy transition competitiveness? And what are the most significant tools of policy and regulation to enable their integration into national energy plans and to fulfill the international commitments on climate change?

Development of the Non-Conventional Liquid Fuel Technologies

Biomass-to-Liquid (BTL)

The Biomass-to-Liquid technology was invented at the end of the 20th century when governments desired renewable solutions to petroleum in form of liquid. The BTL can be applied to turns lignocellulosic biomass to liquid hydrocarbons, such as forestry residues, agricultural waste and energy crops, according to the gasification process and Fischer-Tropsch (FT) conversion (Tijmensen et al., 2002; Hamelinck, 2004). It grew along with guidelines on

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renewable energy by the European Union and policies on second-generation biofuels by America. The promising side of BTL is that it is renewable and can be utilized in the waste streams and it can be easily integrated with the existing transport fuel infrastructure. However, the growth of businesses has been minimal due to high capital-based conditions, feedstock collection problems and indirect land-use impact that is threatening food security and biodiversity (Dimitriou et al., 2018; Larson et al., 2009). By doing so, BTL is neither realistic nor aspirational despite being well aligned to long-term decarbonization goals.

Gas-to-Liquid (GTL)

The Gas-to-Liquid routes gained more popularity in the late 20th century as a new method of FT synthesis was evolving, and as the stranded or flared natural gas needed to be commercialized. The business innovations comprise Shell Bintulu GTL plant in Malaysia that began operations in 1990s and Pearl GTL in Qatar, the biggest GTL project in the world with the capacity of 140,000 barrels per day (Wood et al., 2012; Carlsson, 2005). GTL is low-sulfur diesel and jet fuel of good quality hence it has competitive advantage in clean fuel markets. This Escravos GTL project was deemed as a flagship project of flare mitigation of GTL, in addition to how to curb environmental externalities in resource endowed states (Onwukwe, 2009). But as much as they are too expensive, it is claimed that they have risen by 2.5 billion to over 10 billion dollars- is one of the examples of financial risks in an attempt to scale GTL in unstable regulatory environments (Faith, 2024). GTL is thus a proven and costly route that is only accessible in nations that are well endowed with gas as well as having stable fiscal regimes.

Coal-to-Liquid (CTL)

The first of the three is Coal-to-Liquid that was initially employed by Germany during World War II to reduce oil shortages, and was subsequently invented by the Sasol group in South Africa under the apartheid embargo (Reed et al., 2001; Kamara and Coetzee, 2009). The Sasol facilities have proceeded to be international standards whose synthetic fuels are manufactured to fulfill a significant percentage of the liquid fuel needs of South Africa. The best advantage of CTL is that it can make the liquid fuels to be self-dependent particularly in the economies that are vulnerable to the oscillations of the oil imports. However, its intensity of carbon is incomparable, as the CTL fuel contains nearly twice the amount of CO 2 in its lifecycle compared to the situation with petroleum (unless it is not supplemented with carbon capture and storage (CCS)) (Dieterich et al., 2020). In addition, CTL plants require excessive amount of water which is a significant disadvantage in dry regions. Since CTL may provide strategic energy security, the future of its sustainability fully depends on the possibility of climate policies to allow the use of such high-carbon directions within the framework of more restricting net-zero strategies.

Comparative Technological Maturity

A comparison of the three pathways reveals that the difference in the maturity of technologies is sharp. CTL is a business reality but unsustainable in the setting without CCS, GTL has become business large scale and niche due to its high cost, and BTL is a commercially immature technology with potential (Hoek et al., 2013; Kober et al., 2020). The division symbolizes the wealth, government backing and the business climate that characterizes every path. GTL and CTL provide some near term remedy to energy security needs to resource endowed states and BTL is a long term solution that is more sustainable until breakthroughs are made in the provision of feedstock and reducing costs.

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Table 1. Evolution Timeline of CTL, GTL, and BTL with Milestones and Major Projects

Year/Period	CTL (Coal-to-Liquids)	GTL (Gas-to-Liquids)	BTL (Biomass-to-Liquids)
1920s–1940s	Fischer–Tropsch process developed in Germany; used in WWII for synthetic fuels	Laboratory-scale experiments in converting gas to liquids	Early biomass gasification trials in Europe
1950s–1970s	Sasol begins CTL operations in South Africa under apartheid (1955)	Early GTL pilot plants in the US and Europe	Research into wood gasification resurfaces during oil shocks
1980s–1990s	Sasol expands CTL to meet domestic demand	Shell’s Bintulu GTL (Malaysia, 1993) becomes first commercial plant	European Union funds biomass gasification–FT pilot projects
2000s	Sasol Secunda expansion; CTL peaks in South Africa	Pearl GTL (Qatar, 2011) launched as largest GTL facility globally	Choren BTL pilot in Germany, supported by EU renewable directives
2010s–2020s	CTL faces climate and cost challenges; stagnant outside South Africa	Escravos GTL (Nigeria, delayed, 2014); GTL plants in Qatar dominate	EU pushes BTL within bioeconomy strategy; cellulosic ethanol advances

(Sources: Sasol, Shell, IEA)

As indicated in the table, CTL is the most ancient and proven technology that had been developed under the pressure of energy security (Germany, South Africa), and GTL had not yet become commercially viable in the 1990s, with the Bintulu plant of Shell, and its scaled up in the 2000s in Qatar. The youngest and youngest path is BTL that is linked to the policies of renewable energy in contrast to the supply of the resources. This chronology identifies contextual repercussion, endowments of resources and policy drivers as possible drivers of one or more of these paths.

Methodology

Techno-Economic Framework

The paper employs a techno-economic model which compares the efficiency indicators (CAPEX), operating expenses (OPEX), and efficiency of BTL, GTL and CTL with that of the conventional petroleum refining. The cost structures were found in international Energy Agency (IEA) databases, peer-reviewed studies, and in reports of companies (Albrecht et al., 2017; Swanson et al., 2010). Feedstock related logistics (coal mining, gas flaring, biomass residues collection) were also devised so as to illustrate region related advantages and bottlenecks. The technique allows comparing the costs/barrel of synthetic fuel and the same of crude oil under varying market conditions in a breakeven state.

Environmental Assessment

Anenvironmental sustainability assessment conducted in accordance with the standards of ISO 14040 and in the modes of IPCC was carried out with the help of the lifecycle analysis (LCA) framework (IPCC, 2022). The cradle-to-grave effects involved in this evaluation were the extraction of feedstock, efficiency of the conversion, transport logistics, and combustion of end-use. The metrics that will be put into consideration are the carbon intensity (kg CO 2e/GJ), water

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consumption per barrel and land-use effects, particularly on BTL. Traditional petroleum refining and later on the application of CCS situations was made out as comparative standards.

Institutional Review and Policy

The study also employed a comparative policy analysis framework and examined the fiscal incentives, the carbon pricing mechanisms, and institutional preparedness in Nigeria, South Africa, and Qatar. A triangulation of policy documents and energy transition plans with regulatory reports with global data which was made available by the World Bank Carbon Pricing Dashboard (World Bank, 2023; ETP Nigeria, 2022) was done. The framework facilitated mapping the effect of fiscal regimes, governance forms and international agreements like those of the Paris accord on the competitiveness and sustainability of BTL, GTL and CTL tracks, in respective national contexts.

Techno-Economic of BTL, GTL and CTL

Capital and Operating Costs

One of the features which predetermine the high level of adoption of the alternative liquid fuel pathways is their competitiveness. The investment of over 810 billion capitals to build the plants on the global scope and the production cost per unit of 35 to 60 dollars depending on the feedstock and plant size is typical of GTL projects (Wood et al., 2012; Faith, 2024). Although CTL has a rather low capital intensity at the start of its operations, in comparison with GTL, it must face higher operating costs due to coal handling, carbon capture and large water treatment facilities (Reed et al., 2001). The most expensive is BTL, where the price of production is between 60 and 120 dollars per barrel, as it indicates the inefficient preparation of technologies, as well as a lack of feedstock logistic capabilities (Dimitriou et al., 2018). The advantage cost curves identify the structural weakness of the strategy: in the absence of sustained high prices on crude oil, or in the absence of effective carbon taxes on petroleum fuels, BTL and CTL have a disadvantage in competition with GTL.

Feedstock Supply Chains and Availability

The availability of feedstock is the economic basis of either of the two pathways. GTL suits well in gas rich fields whereby strangled or flared gas can be used to generate revenue as in Nigeria and Qatar (Onwukwe, 2009; Odumugbo, 2010). CTL also plays out in regions that are abundant in coal such as South Africa whereby synthetic fuel can be self-sustaining on its local coal reserves (Kamara and Coetzee, 2009). On the contrary, BTL is highly dependant on biomass residue collection and sustainable land management, and feedstock logistics may often take more than a half of total costs (Swanson et al., 2010). Additionally, the food/energy crop conflict is a problem with severe socio-economic consequences particularly within the food insecure regions (Evans et al., 2010). As such, although the endowment of feedstock creates a national comparative advantage, it is a common occurrence that the vulnerabilities of supply chains are usually used to determine the economic sustainability of any particular technology as the future.

Scalability,Competitiveness and Efficiency

GTL is also superior in conversion rates, with an average of 6065 that is higher as compared to CTL, which ranges between 4555 depending on how the plant is designed (Masuku et al., 2019; Dalai and Davis, 2008). BTL is not efficient (only 3550 percentages due to the small size of the demonstration plants and the lack of logistic optimization) (Albrecht et al., 2017). Scalability is disproportionate: GTL has been globalised, CTL has been commercial at scale in South-Africa, and BTL is still predominantly pilot project in both Europe and North-America.

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Competitiveness is less technologically viable, therefore, than policy supportive and market disposition. GTL competes when the cost of gas price is low, CTL in every situation when the price of energy security is high and renewable options are supported by subsidies or carbon credits (Dimitriou et al., 2018).

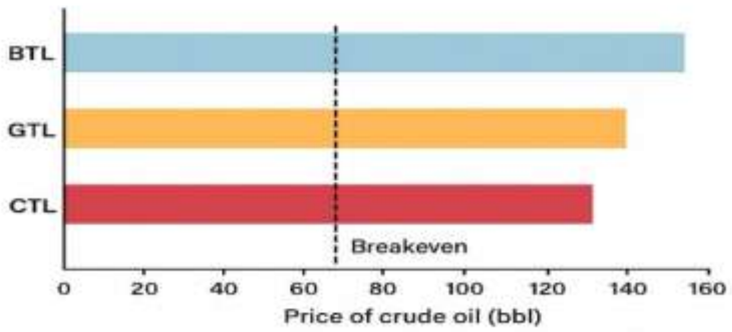
Table 2. Comparative GTL, CTL, BTL (per barrel oil equivalent) Capital and Operating Costs, 2023 estimates.

Pathway	Capital Cost ($/bbl)	Operating Cost ($/bbl)	Breakeven Oil Price ($/bbl)	Technology Maturity
CTL	60–80	25–35	85–110	Commercial, declining competitiveness
CTL	60–80	25–35	85–110	Commercial, declining competitiveness
BTL	100–120	35–45	120–140	Pre-commercial, high-cost, R&D dependent

(Sources: Swanson et al., 2010; Reed et al., 2001; Wood et al., 2012).

Both CTL and GTL are proven commercially but very capital intensive. GTL is also cheaper to run than CTL especially where a supply of gas is high. The most intense situations will be faced by BTL where breakeven price is significantly higher than the historic oil averages and it will be unable to compete unless it has a strong policy support. Cost curve reveals that the volatility of oil prices is a tremendous determinant of viability of projects, especially CTL and GTL.

Figure 2. Comparative Cost Curves of BTL, GTL, CTL vs. Crude Oil Refining Breakeven



Source: Swanson et al. 2010), Albrecht et al. (2017), IEA 2021

This figure highlights the sensitivity of the prices of oil to the unconventional liquid fuels. It shows why CTL has been effective in South Africa in sanctions (where the substitutions needed to be necessary politically) but not in open markets. GTL can survive in the gas rich states like Qatar with low feedstock. The BTL is far beyond the breakeven of oil which means that it must be policy-interfered with i.e. price on carbon or subsidies.

Trade-OffsEnvironmentaland Sustainability

Lifecycle Carbon Intensity

When compared to the other two routes, CTL is the carbon heavy route that has 110120 kg CO 2e/GJ in comparison to petroleum fuels that have 90 kg CO 2e/GJ unless carbon capture and storage is

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included (Dieterich et al., 2020). However, GTL is much more successful (average 8095 kg CO 2e/GJ) even there, but even there, it does not reach lifecycle reductions without CCS (Alsudani et al., 2023). In comparison, BTL can potentially offer a near zero or even a negative emission in case of biomass residues and sustainable forestry practices are used particularly when implemented together with carbon sequestration technologies (Swanson et al., 2010). These advantages can be offset by indirect changes in land use though which lead to carbon leakage effects (Evans et al., 2010). The relative carbon intensity represents that without stringent environmental regulations, CTL and GTL can lead the economies into high-carbon traps and fail to achieve net-zero pledges.

Ecological, Land and Water risks

The environmental compromise does not just take place in the carbon emissions. The water requirements of CTL plants are quite high as they require up to 8-10 barrels of water per barrel of liquid fuel plant, which is not feasible in water strained countries like South Africa (Kamara and Coetzee, 2009). The GTL plants also have negative effects on the environment in terms of gas field development and methane leakages compared to the more water-intensive type (Sonibare and Akeredolu, 2004). Land-use competition is the greatest threat of BTL: extension of energy crops can pose a threat

to biodiversity due to the vegetable growing (Bernical et al., 2013). Besides, biomass harvesting in unsustainable amounts is a threat of soil erosion and deforestation that hurts the renewability of biomass. These risks underline the need of coordinated models of sustainability which consider various ecological factors.

Role of CCS and SDGs Consonance.

The new reality of CTL and GTL sustainability is carbon capture and storage (CCS). Synfuels made using coal and CCS can reduce the intensity of emissions by 40 percent, though it would be expensive and outside the infrastructure divide in the case of Sasol (Sikarwar et al., 2016). In the example of BTL, coupling of gasification to bioenergy CCS (BECCS) may also be feasible to make it one of the few negative-emission pathways, which can be made compatible with the aims of the Paris Agreement (IPCC, 2022). Altogether, all these pathways overlap with the multiple Sustainable Development Goals (SDGs), including affordable energy (SDG 7), climate action (SDG 13) and responsible consumption (SDG 12). Nevertheless, they are going to threaten water security (SDG 6) and food security (SDG 2) unless they are properly managed.

Figure 3. Lifecycle CO_2 Emissions of BTL, GTL, CTL Compared to Conventional Oil

(Source: IPCC AR6 2022, IEA 2022)

The intensity of emissions (kg CO 2e/GJ) bar chart. CTL: 110–120; GTL: 80–95; Oil: ~75; BTL: 20–40. The most carbon intensive is CTL nearly twice the crude oil in the one, GTL a little higher and BTL drastically less. The chart demonstrates the carbon paradox: CTL and GTL have the ability to achieve energy security and enable the resources to be monetized but

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will worsen climate footprints unless CCS is employed. The explanation as to why BTL is the sole way through which net-zero goals can be achieved is because it can be easily scaled to a certain degree. The policy dilemma highlighted in the discussion is short term energy security and long term commitments on climate.

Table3.EnvironmentalTrade-offs Matrix for CTL, GTL, and BTL

Impact Dimension	CTL	GTL	BTL
CO_2 Emissions (kg CO_2e/GJ)	110–120	80–95	20–40
Water Intensity (liters/GJ)	Very high (400–500)	High (300–400)	Moderate (100–150)
Land Use Impact	Low	Low	High (if feedstock not sustainably managed)
Biodiversity Risks	Low	Low	Moderate–High (depending on biomass sourcing)

(Sources: Swanson et al., 2010; Kamara & Coetzee, 2009; IPCC, 2022)

There are also sharp contrasts in the table CTL is the most carbon intensive and water dependent that is why it could not be implemented in compliance with the climate requirements. GTL is medium because it is better but, nevertheless, it produces more than conventional oil unless it is used together with CCS. BTL has the lowest carbon intensity considering the agriculture practices with dangers of altering land-use and deteriorating biodiversity. This identifies the contradiction between land impact and carbon efficiency in fuels that are renewable.

Policy and Regulatory Structures

Regimes of Fiscal Support and Subsidy

The fiscal policies have remained in the frontline in the establishment of the competitiveness of alternative liquid fuels. High tax concessions, state-sponsored financing and the production-sharing deals have been used by Qatar and other countries to attract international investors into GTL (Carlsson, 2005). Contrastingly, the state protection and subsidies have been one of the traditional factors supporting South Africa CTL industry to make up the high cost of production that shows the political economy in supporting its continuity (Kamara and Coetzee, 2009). The case of GTL in Nigeria and the Escravos project, in particular, is helpful in explaining the risks of having weak regulatory institutions where the excess costs are added by an ineffective fiscal control system (Faith, 2024). In each of the scenarios, subsidies can lessen the original risks but they are found to distort markets without the carbon pricing procedures.

Climate Pledges and Carbon Pricing

The use of carbon pricing mechanisms has direct implications on CTL, GTL and BTL in the world. More than 60 jurisdictions now have carbon taxes or emissions trading schemes, covering at least 23 percent of the global greenhouse emission (World Bank, 2023). And in these regimes CTL would make the uncompetitive without CCS, and GTL would make moderate risk. Conversely, BTL will have a winning hand because its renewable issue and emission of low lifecycle will earn the company higher carbon credits (Swanson et al., 2010). South Africa, Nigeria and Qatar are dissimilar: South Africa already has its carbon tax, albeit softened by exemptions; Nigeria has no binding system of carbon prices; and Qatar did not have the pledge to explicit carbon pricing at all, relying on the efficiency targets (ETP Nigeria, 2022). It is this heterogeneity of policy that produces a

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significant shift in the viability of the pathway.

International Level Climate Agreements and ESG Pressures

The international climate governance also influences the domestic policy structures. The emphasis on nationally determined contributions (NDCs) in Paris Agreement has made resource-intensive economies to reconsider the compatibility between CTL and GTL and decarbonization on a long-term basis (Hoeek and Tang, 2013). Moreover, the investors and multilateral institutions exert environmental, social, and governance (ESG) pressure, which are becoming a more influential factor in financing on sustainability performance. Sasol, on the other hand, can be criticized by the shareholders concerning its carbon-intensive CTL operations, whereas Pearl GTL by Shell is relatively favorable in the context of its ESG indicators as it produces less sulfur (Bezergianni et al., 2018). These dynamics underscore the multiplication effect of the financial markets throughout the world in acerbating the policy risks of the carbon-intensive pathways.

National Energy Transition Policies

The decision on how BTL, GTL and CTL will be integrated in the long-term plans is made at national energy transition plans. Nigeria has a bridge fuel in the Energy Transition Plan (2022), where GTL is one of the partial solutions to gas flaring, but not much attention is paid to biomass opportunities (ETP Nigeria, 2022). A shift toward coal and CTL conflicts reduction in relation to the streams of climate finance is highlighted by the Just Energy Transition Partnership of South Africa (IEA, 2021). Qatar, in its turn, continues to concentrate on GTL as the element of the general hydrocarbon diversification program, taking advantage of its enormous gas reserves to gain a competitive edge (Agbonifo, 2015). These two differing tactics are the actual reflections of how the political economies and resources endowment make the priorities of the countries even at the same decarbonisation pressures in the global world.

Figure 4. Global Carbon Pricing Schemes and Coverage (2023)

Source: World Bank Carbon Pricing Dashboard, 2023)

A planetary map of territories that have a carbon tax or the emission trading system (ETS). Good coverage in EU, Canada, and part of the Asian regions; no coverage in Africa and Middle East. Most of the nations that invest in CTL and GTL (Nigeria, Qatar, South Africa) lack well established carbon pricing. This facilitates the survival of carbon intensive pathways in a long period of time. It is because of the absence of pricing of carbon in Africa and the Gulf and this is why CTL and GTL still proceed to take place despite the high emission. BTL on the other hand becomes

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competitive in jurisdictions having high carbon tax (EU). Thus, viability is a factor of geography and whatever occurs depends on policy landscapes and not technology.

Table 4. Policy Comparison Matrix Across Case Study Countries

Dimension	Nigeria	South Africa	Qatar
Fiscal Incentives	Weak, fragmented, project-specific	Historically strong CTL subsidies; current phaseout	Robust GTL incentives, sovereign financing
Carbon Pricing	None; policies on flare gas monetization	Carbon tax (weak enforcement, exemptions)	None; efficiency targets emphasized
Climate Commitments	Energy Transition Plan (gas-centered)	Paris Agreement NDC, Just Transition framework	NDC focused on efficiency, not pricing
Institutional Capacity	Weak regulatory institutions, delays	Moderate; policy coherence challenges	High; streamlined approvals

(**Sources**: ETP Nigeria, 2022; IEA, 2021)

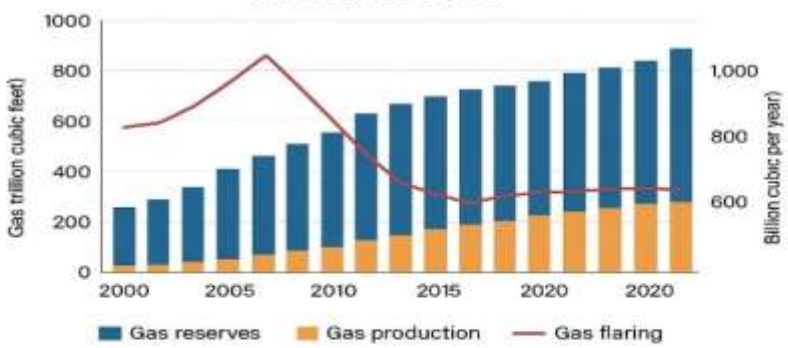
The institutional control and financial governance of the fiscal regime in Nigeria is poor which is a disadvantage to GTL and BTL projects. South Africa CTL industry has been performing well due to subsidy and it is becoming constrained due to the challenges of carbon tax and climate. Qatar is a high capacity state, which is capable of financing GTL growth on the basis of resource endowment and fiscal soundness. The table brings out the fact that institutional quality and compatibility of the policy directly affect the economic viability of the liquid fuel pathways.

Case Studies

Nigeria: Gas Wealthy but Policy Weak.

Nigeria, the most populous nation in Africa, boasts of the largest proven natural gas reserves in the continent but faces the current day challenge of chronic flaring and underutilization (Sonibare and Akeredolu, 2004). This kind of project was launched in partnership with Chevron and NNPC in order to demonstrate the value flare gas monetization. However, increasing the costs to over 10 billion dollars served as the sign of negligence in governance and misalignment of the contract (Faith, 2024). Despite these failures, the flare gas commercialization program and the agricultural residue biomass potential in Nigeria can assist the country to eliminate excessive dependence on oil in case fixation of the fiscal regimes occurred (Agbonifo, 2016). However, GTL and BTL investments are risky unless there is certainty in the regulation.

Figure 5. Nigeria's Gas Reserves, Production, and Flaring Trends (2000–2020)



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(Source: NNPC Annual Statistical Bulletins, Enerdata 2023)

The dual-axis line chart of the established gas reserves (slow but steady growth), production (slow but steady increase), and flaring (slow and still high). Nigeria is blessed with gas and it is not maximizing the gas, it is not developed fully on flare cutting and is still in its advanced stage. This figure puts the Nigerian GTL problem into perspective: Nigeria has the largest reserves in the African continent, but its infrastructure is weak and policy integration leads to waste in form of flaring. It is possible that GTL reduces the flaring but as seen in Escravos GTL, it does not succeed owing to the exorbitant costs and poor governance.

(Source: Faith, 2024)

The phenomenal rise of project costs from $2.5 billion to over $10 billion shows un-structural problems in the Nigerian project management and institutional framework. Investors lost confidence in the project because its cost overruns were more than 300% and it became unviable economically though technically viable.

The way the projects were done gives an idea how weak governance, regulatory uncertainty and contractual ambiguity can turn viable projects into a fiscal burden. This case is a warning that emerging economies need to be fiscally responsible and reform their institutions to get infrastructure for energy transition.

Institutional weaknesses of Nigeria are portrayed in the case of Escravos GTL. The delay and the increase of the project by four times of the initial estimates entrusted the investor confidence, and in this regard the project became weak. Despite the presence of the rich gas fields, a poor regulatory framework and contractual ambiguities rendered GTL non-competitive, which proved that resource endowment itself is not a sure key of success.

South Africa: Dependency and Climatic Strains CTL

South Africa is also unique since the national producer of CTL in the globe, the Sasol Secunda plant supplies about a third of the national liquid fuel requirements (Kamara and Coetzee, 2009). This dominance is manifested of past energy security needs in the apartheid but a carbon lock-in has been established now. The CTL sector generates a volume of more than 60 MtCO 2 annually, which is contributing a large percentage of the national output (IEA, 2021). Water consumption is another burning problem as the Sasol plants consume vast amounts of water in a water-constrained country. South Africa does not have a large carbon tax due to exemptions and is, however, a sign of the pressure mounting on the CTL

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reduction policy (Ejiogu et al., 2019). The socio-economic risk of leaving CTL is based on the dependence on employment, decarbonization and energy security change. therefore, South Africa is a significant pilot of the

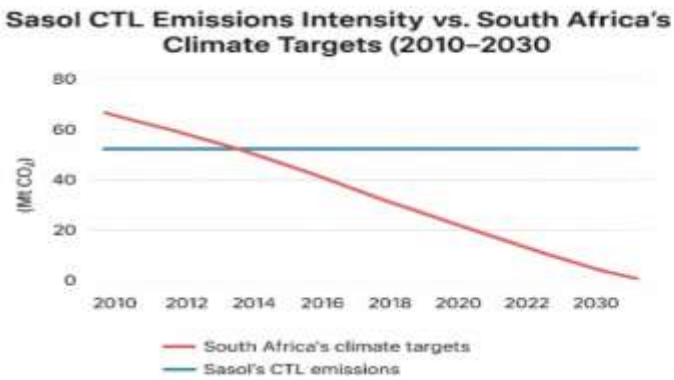

Figure 6: (Source: Sasol Annual Reports, IEA, 2021, South Africa NDC 2021)

The figure indicates the structural lock-in of CTL: it retains people at the workplace and the fuel running but puts climate commitments in jeopardy. Without either of these, CCS or radical downsizing CTL stands to risk being a stranded asset. It is this contradiction that explains why South Africa has had a problem balancing it's Just Transition script with its reliance on fuel products composed of coal.

Table 5. Sasol CTL Production, Costs, and CO_2 Output

Metric (2020)	Value	Source
Annual Production	~150,000 bbl/day	Sasol Annual Report
Production Cost	$90–100/bbl	IEA (2021)
CO_2 Emissions	60 Mt/year	Sasol
Share of National Emissions	~20%	IEA (2021)

(Sources: Sasol annual reports, IEA, 2021)

South Africa is a country that manufactures a huge quantity of liquid fuel at colossal environmental expense. Having reached almost a fifth of national CO 2 emissions, South Africa has a high degree of climate-policy tension with CTL. The cost of production is expensive and in combination with the carbon tax, one can say that CTL can become economically unsustainable without CCS.

Qatar: GTL as a Success Story

The optimal case of GTL commercialization is Qatar because it exploited massive gas reserves and strong fiscal policies to attract massive investment. Pearl GTL project is an enormous GTL plant that it is estimated to have cost 19 billion dollars and which has become the largest plant globally in the production of high quality diesel, jet fuel and lubricants (Carlsson, 2005). The advantage of Qatar is that it is backed by sovereign funding, has simplified regulatory regimes and access to inexpensive feedstock. Compared with the carbon-absorbing CTL in South Africa or the erratic GTL trials in Nigeria, it has been revealed that the richness of resources accompanied by stability of the institutions can be used to prevent other competitors to be at the top of the global market (Wood et al., 2012). However, the

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future sustainability of gas-based solutions is doubted by a growing challenge to global climate.

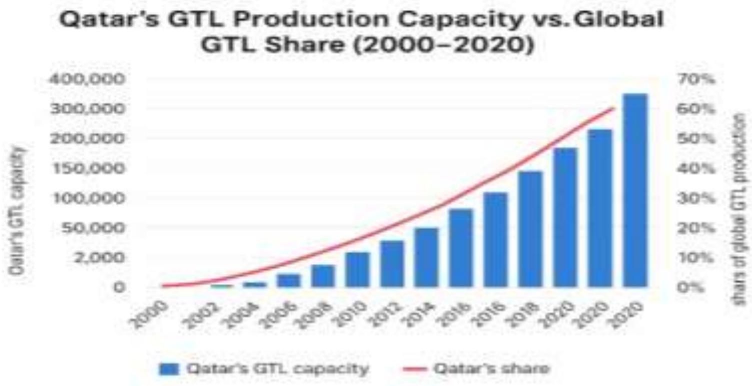
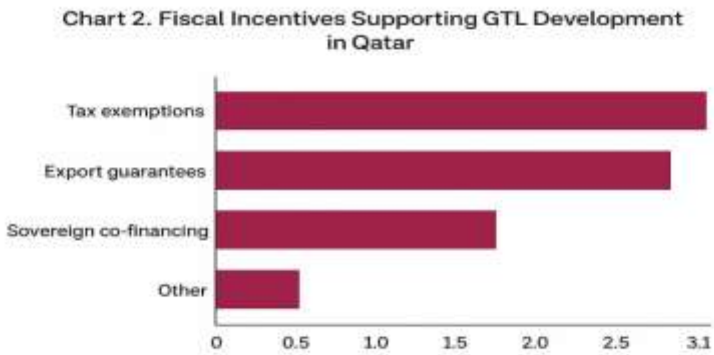


Figure 7:(Source: Shell, QP Annual Reports, IEA, 2021)

The figure indicates the success story of Qatar: having a high amount of gas as well as the financial and institutional support, Qatar has become the GTL hub in the world. It is unlike in Nigeria which has the same number of gas reserves and does not operate due to the ineffectiveness of the policy.



(Source: Carlsson, 2005; Wood et al.,2012)
Qatar's inspiring GTL story revolves around the presence of a strong fiscal architecture, which served to reduce the investment risk with tax exemptions. The low-risk, high-certainty environment they created was conducive to foreign capital flow and stable returns.

Through the fiscal and policy coherence, the natural endowments converge to databases competitive industries. Success in the energy transition in the hydrocarbon sector is controlled more by governance than geology; that is, the capacity to marry fiscal incentives, industrial strategy and sustainability success.

The Pearl and Oryx GTL projects have also managed to become successful in the world because of the sound fiscal structure of Qatar. This combination of tax holidays, sovereign funding, and guaranteed markets constituted the low-risk investment environment, which Qatar created, which is quite opposite to the challenges in Nigeria. It demonstrates that the policy stability and the state capacity are determinants of scaling GTL.

Discussion and Synthesis

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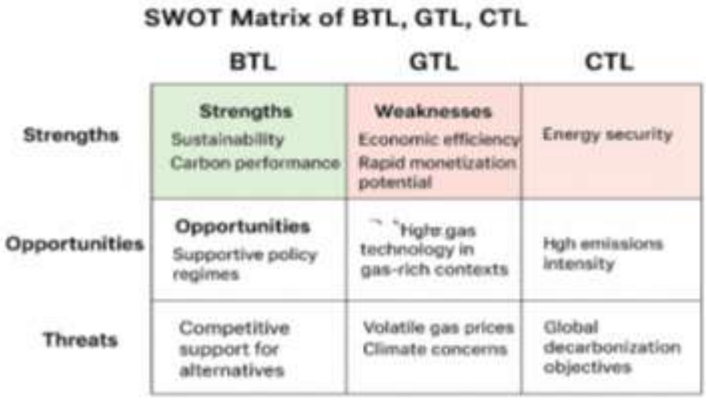
Comparative evaluation of all three technologies including BTL, GTL, and CTL suggest that a set of mutually complementary techno-economic and policy concessions exist. BTL remains to be not a feasible long-term course but has long-term prospects because of the issues of costs and magnitude, therefore also demanding policy support and breakthrough innovations (Swanson et al., 2010). GTL itself is a commercially implemented gas-rich state-proven technology, and is, however, capital-intensive, carbon-heavy, and cannot stand climate without CCS, unless modified (Alsudani et al., 2023). The output of CTL is energy secure in areas in which coal is fairly abundant yet the emission package is not compatible with net-zero transitions, unless paired with CCS (Dieterich et al., 2020). The comparative advantage of each route according to the state of affairs in the country is largely defined by the national environment according to resource bases, fiscal security and regulatory constructions according to the case studies.



(Constructed from synthesis of literature, comparative analysis. e.g., IEA, Sasol, IPCC)

A summary of strengths, weaknesses, opportunities, and threats of every path in a quadrant-based chart. BTL: the most on sustainability and least on economics. GTL: the most efficient in monetization of gas, which is subject to change in gas price. CTL: it is good on energy security, bad on the emissions. The SWOT points out that it is not the best way. BTL is future-compatible; however, GTL represents an option of medium-term availability in states with a high level of gas; CTL is increasingly becoming incompatible with climate policy. The figure concludes the paper and shows the relative balance between the economic, environmental and policy trade-offs.

Table 6. Swot Matrix of Btl, Gtl, and Ctl Pathways

Pathway	Strengths	Weaknesses	Opportunities	Threats
CTL	**Energy security, coal abundance**	**High CO_2, water-intensive**	**CCS integration**	**Carbon taxes, ESG pressures**
GTL	**Proven at scale, high-quality fuels**	**High capital costs, emissions**	**Gas monetization, flare reduction**	**Gas price volatility, climate risks**
BTL	**Low-carbon, renewable**	**High costs, land use conflicts**	**Bioeconomy, SDG alignment**	**Food vs. fuel debates, biomass scarcity**

The SWOT analysis shows that the use of CTL and GTL may be considered in case of resource-sufficient and temporary security needs, but they are vulnerable to

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climate policy due to the carbon intensity. The most futuristic one is BTL, which has a sustainability advantage, but requires cost reduction and disruptive innovation in the research and development. The synthesis combination enhances that national situations and the global climate management through which the paths shall live.

Key Findings

Given the trade-offs between energy security, climate alignment, and economic viability that GTL, CTL, and BTL present, the comparative analysis suggests key differences. GTL and CTL options provide high short-term fuel security but lack CCUS, remain economically unviable and climate damaging. BTL can achieve decarbonisation, even negative emissions with BECCS, but is constrained by governance, costs, and scalability issues. Treated in isolation, the net negative emissions potential will not suffice to generate the policies required to ensure effective governance, fiscal, institutional, and environmental oversight with a view to aligning synthetic fuel policies with the net-zero target of the country.

Recommendations

Governments should attach CCUS as a conditional policy for new GTL and CTL ventures, alongside time-bound subsidisation and standardised policies to address first-mover and infrastructure risks. The complementary construction of CO_2 transport hubs and clear long-term liability arrangements for climate-irreversible synthetic fuel production will encourage private investment. Enabling legislation should support demonstration-scale BTL projects through R&D funding, co-financed pilot plants that meet climate and ecological standards for biodiversity, soil, and food security, and performance incentives.

Lifecycle emissions and fossil fuel subsidies must also be taxed and balanced within a carbon pricing comprehensive framework taxation, emissions trading, or hybrid systems. Transition financing will provide clarity in revenue allocation and strategic financing encouraging private investments. In regions with economically reliant CTL and GTL industries, Just Transition programmes need to focus and clearly outline retraining, reuse of infrastructure, and industrial sequencing that involves phased retrofits, locked closures, and deployment of economically viable low carbon alternatives to minimise socioeconomic disruption.

To conclude, Just Transition programmes need retraining, infrastructure reuse, and integrated industrial sequencing that involves phased retrofits, locked closures, and deployment of economically viable low carbon alternatives to minimise socioeconomic disruption. Finally, regional and cross-border collaborations in the governance of CO_2 transport and storage infrastructure will be necessary to balance developing blended finance mechanisms and knowledge systems, and export credit and cross-recognition of shared governance systems to equitably, resiliently, and efficiently consolidate integrated decarbonisation strategies. This will ensure that unconventional liquid fuels will undermine globally net-zero while supporting national energy and development goals.

Conclusion

The comparative analysis of BTL, GTL, and CTL indicates that the paths lie quite different in the trade-off range amid the energy security, economic sustainability, and compatibility to climate. GTL and CTL may supply high amounts of liquid fuels over short durations when there is a feedstock endowment, but their business sustainability is strongly pegged on low feedstock prices, sovereign fiscal subsidies, and the existence of capital - environment, which can change drastically with markets or investor spirit. BTL in its turn is naturally consistent with long-run decarbonization ambitions, and can be used with BECCS as a negative emission alternative, but it is only scalable to

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dispersed feedstocks, is high-unit cost and real risks of negative land-use impacts when a strong governing body is not present.

Technically, the pathways are different in terms of conversion efficiency and water intensity as well as lifecycle emissions in ways which are open to practical policy implications. The negative aspect of the CTL historical maturity is that it has gigantic carbon and water footprint; GTL is only increasing the quality of its products and can reduce the local polluting emissions but creates gigantic lifecycle CO 2 not to mention the absence of CCUS; BTL is potentially effective not only due to the chemical transformation but because of the regulation of biomass sustainability and logistics. Thus, the technological solutions (i.e. incremental efficiency gains) will not be sufficient, on their own, economically meaningful decarbonization will have to be supplemented with tools of engineering (carbon pricing, specific subsidies and regulatory requirements) and the investment into CO_2 transportation and long-term storage.

National context is significant in the context of policymaking. The example of Nigerian points to the fact that gas abundance can be an economic engine only when fiscal institutions and the contracting apparatus remain healthy; South Africa demonstrates that historical CTL capacity can be conducive to the establishment of political and social lock-ins that ensure the impossibility of decarbonization; Qatar teaches that sovereign funding and the planning system are the keys to the growth of GTL. The policy problem in both these contexts is largely a matter of timing: short-term energy security and industrial objectives must be worked out in the medium-term and long-term climate commitments. Reconsideration can be done - but only with a dedicated sequencing exercise, which would speed the realization of the CCUS-enabled operations where they are required, an increased investment in low-carbon solutions where they can be achieved, and the protection of livelihoods and the local economies in the process.

Finally, these routes play different strategic purposes across the time period. Some transitional measures that may be taken in the near term to prevent disruptive shortages in the supply include GTL and CTL (with CCUS) as nations build renewable supply and electrification. BTL (and bio-derived fuels with BECCS) of the three can only feasibly offer net-zero liquid fuels pathways to hard-to-abate liquid fuels, assuming the governance, feedstock sustainability and cost reduction routes are governed. The policy imperative, in that case, is, not to pick a winner but to work out adaptive, transparent and economically responsible solutions that will entice investments to proven-lower-carbon designs and seek to cope with social and economic risks.

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