

Optimization Model for Bio-Compressed Natural Gas Deployment Across South African Provinces

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ABSTRACT: The transition toward lower-carbon transport fuels requires energy systems that are not only environmentally advantageous but also technically feasible and economically competitive. Bio-compressed natural gas (Bio-CNG), produced through biogas generation and subsequent upgrading, represents a potential pathway for converting organic waste into a transport fuel while simultaneously creating value from waste streams. This study develops a conceptual techno-economic optimization model for Bio-CNG deployment across South African provinces. The proposed framework integrates feedstock availability, anaerobic digestion, biogas upgrading, compression, transportation infrastructure, vehicle demand, capital expenditure, operating expenditure, and provincial deployment constraints. The methodology is structured as a multi-period, risk-aware optimization problem in which the allocation of Bio-CNG production capacity is determined according to resource availability and economic performance. Particular attention is given to food-waste generation because the conversion of organic waste into biogas provides an opportunity to connect waste-management and transport-energy systems. Previous research has demonstrated significant economic variation among anaerobic digestion, biogas upgrading, and compressed natural gas applications, while South African studies indicate the importance of regional waste and transport characteristics. The resulting model identifies the principal decision variables, constraints, objective functions, and sensitivity parameters governing provincial deployment. The analysis indicates that a phased and geographically differentiated deployment strategy is more appropriate than uniform national expansion. Provinces with higher concentrations of suitable organic feedstocks, transport demand, and infrastructure can potentially support earlier deployment, whereas regions with lower feedstock density may require shared facilities or centralized production hubs. The framework provides a basis for investment prioritization, infrastructure planning, and policy evaluation without assuming that technical feasibility automatically implies economic viability.

KEYWORDS: Bio-CNG, biogas upgrading, techno-economic optimization, transport fuel, anaerobic digestion, South Africa, provincial energy planning, waste-to-energy, infrastructure planning.

1. Introduction

The decarbonization of road transportation increasingly requires alternatives that can reduce dependence on conventional petroleum-derived fuels while maintaining compatibility with existing vehicle and fueling systems. Compressed natural gas (CNG) has historically been considered an alternative transport fuel because it can be supplied through dedicated fueling infrastructure and used in suitable vehicle fleets. However, the environmental and strategic value of CNG depends substantially on the origin of the gas. Bio-CNG extends the CNG concept by using biogas derived from renewable organic feedstocks and upgrading it to a methane-rich fuel suitable for compression and transport applications.

The economic feasibility of such a system cannot be assessed solely from the cost of producing biogas. It requires simultaneous consideration of feedstock collection, anaerobic digestion, gas purification, compression, storage, transportation, dispensing infrastructure, vehicle utilization, and demand density. Studies of biogas upgrading technologies demonstrate that upgrading configuration can materially affect the economic characteristics of the resulting fuel system (Vo et al., 2018). Similarly, comparative analysis of biogas-cleaning pathways shows that the preferred technology depends on the intended application, including grid injection, CNG production, or conversion to other fuels (Sheets and Shah, 2018).

South Africa presents a particularly relevant context

for such an investigation because transport-energy planning intersects with substantial organic-waste management challenges. Household food waste represents an underutilized organic resource, and studies examining South African household waste practices have demonstrated the regional nature of waste-generation and disposal patterns (Oelofse et al., 2018). More broadly, food-waste research indicates that generation behavior varies according to socioeconomic characteristics, suggesting that feedstock availability should not be treated as spatially homogeneous (Grasso et al., 2019). Consequently, a national Bio-CNG strategy based on a single average feedstock assumption could produce misleading economic results.

The transport application also introduces an infrastructure dimension. The economic case for CNG vehicles is closely associated with the availability and utilization of fueling infrastructure (Smith and Gonzalez, 2014), while fleet-oriented assessments demonstrate that economic viability can vary according to fleet characteristics and operational conditions (Johnson, 2010). Therefore, Bio-CNG deployment should be understood as an integrated energy-infrastructure problem rather than simply a fuel-production problem.

The primary objective of this study is to formulate an optimization framework capable of determining economically rational Bio-CNG deployment across South African provinces. The model seeks to answer three central questions: which provinces should receive production and fueling capacity first, how much Bio-CNG capacity should be developed in each province, and under what technical and economic conditions does deployment remain viable? The study also considers risk because investment decisions can be affected by uncertain feedstock quantities, capital costs, fuel demand, and operating conditions.

The significance of the framework lies in its ability to connect waste resources with transport-energy demand through a unified decision model. Rather than assuming that maximum production is necessarily optimal, the proposed approach seeks to identify a deployment configuration that balances economic return, infrastructure requirements, feedstock utilization, and supply reliability.

2. Literature Review

Research concerning Bio-CNG deployment can broadly be divided into four interconnected areas: organic-waste availability, anaerobic digestion economics, biogas upgrading and fuel conversion, and CNG transport infrastructure.

Anaerobic digestion provides the fundamental conversion pathway through which biodegradable

organic material can be transformed into biogas. Gebrezgabher et al. (2010) demonstrated the importance of economic assessment in anaerobic digestion projects by examining the economics of a biogas plant in the Netherlands. Their work establishes that the value of a biogas system is influenced by the relationship between investment, operating expenditure, energy generation, and available feedstock. This perspective is directly relevant to Bio-CNG because upgrading and compression add further capital and operating requirements after biogas production.

Feedstock availability is particularly important when food waste is considered as a principal resource. Grasso et al. (2019) showed that food-waste behavior can be associated with socioeconomic characteristics. This observation has implications for provincial Bio-CNG planning because the amount of recoverable food waste cannot automatically be equated with total food consumption or population. Waste-generation patterns are behaviorally and geographically differentiated. Consequently, an optimization model should distinguish theoretical feedstock availability from recoverable feedstock.

The South African context is further informed by Oelofse et al. (2018), who examined household food-waste disposal in Johannesburg and Ekurhuleni. Their findings reinforce the importance of location-specific waste-management conditions. For Bio-CNG planning, this implies that collection systems and waste aggregation must be incorporated into economic calculations. A large quantity of organic waste has limited value for fuel production if it is dispersed over large distances or cannot be collected economically.

The broader environmental relevance of food-waste utilization is supported by Jeswani et al. (2021), who examined food-waste generation and associated environmental impacts in the UK. Although the geographic setting differs from South Africa, the study provides a conceptual basis for viewing food waste as both an environmental liability and a potential resource. Within the present framework, this dual role motivates integration between waste-management and renewable transport-fuel planning.

A second major research area concerns biogas upgrading. Vo et al. (2018) evaluated biogas upgrading through amine scrubbing, carbon capture, and ex-situ methanation. Their analysis demonstrates that upgrading is not a single uniform process but a technology-selection problem with different cost and performance characteristics. For Bio-CNG deployment, this means that the optimization model should allow upgrading efficiency and cost to vary according to technology configuration.

Sheets and Shah (2018) compared biogas-cleaning

alternatives for grid injection, CNG, and biogas-to-methanol conversion. Their work is especially relevant because it establishes the importance of identifying the final energy application before selecting a gas-cleaning pathway. A Bio-CNG model must therefore optimize not simply biogas production but the complete chain leading to vehicle-fuel delivery.

Lorenzo-Llanes et al. (2024) investigated the techno-economic characteristics of converting biogas to biomethane. Their contribution supports the use of a staged representation of the production chain, separating raw biogas generation from biomethane upgrading. This distinction is important because the economic bottleneck may occur at different stages depending on plant scale, feedstock quality, and technology selection.

The transport side of the system is represented by research on CNG fueling infrastructure. Smith and Gonzalez (2014) examined costs associated with CNG vehicle fueling infrastructure, demonstrating that fueling infrastructure represents a distinct economic component rather than an incidental cost. Johnson (2010) similarly considered the business case for CNG in municipal fleets, indicating the relevance of fleet size, utilization, and operational conditions to fuel-switching economics.

South African transport-energy conditions provide additional context. DED (2019) examined the techno-economic characteristics of energy in the Western Cape transport sector, while DoE (2017) documented developments in the South African petrol and diesel market. These sources establish the importance of considering regional transport demand and conventional fuel-market conditions when evaluating alternative fuels.

Finally, optimization under uncertainty is relevant to Bio-CNG infrastructure decisions. Yadegari et al. (2020) examined risk-averse multi-objective optimization in an energy-planning context. Although their application is different, their methodological perspective supports the incorporation of risk into infrastructure planning rather than relying exclusively on deterministic cost minimization.

The principal research gap is therefore not the absence of individual studies on digestion, upgrading, food waste, or CNG infrastructure. Instead, the gap lies in their limited integration into a provincial optimization framework. Existing evidence suggests that feedstock availability, upgrading technology, fueling infrastructure, and transport demand must be considered jointly. Furthermore, the socioeconomic variability of food-waste behavior means that resource estimates should incorporate recovery factors rather than relying exclusively on gross waste quantities

(Grasso et al., 2019).

3. Methodology

3.1 Research Framework

The proposed methodology treats Bio-CNG deployment as a multi-stage energy-system optimization problem. The system boundary begins with organic-waste collection and terminates with Bio-CNG delivery to transport fleets.

The principal stages are:

organic waste → feedstock collection → anaerobic digestion → raw biogas → biogas upgrading → biomethane → compression → storage/distribution → transport demand.

Each stage creates either a cost, capacity limitation, conversion loss, or operational constraint. The model therefore avoids evaluating Bio-CNG solely according to the cost of biogas production.

For each province pp , the model determines an optimal production capacity QpQ_p , upgrading capacity UpU_p , and fueling infrastructure level FpF_p . The resulting deployment pattern is determined by available feedstock, estimated transport demand, capital requirements, and expected operating economics.

3.2 Feedstock Availability Model

Let WpW_p represent gross organic-waste availability in province pp , and let rpr_p denote the recoverable fraction. Recoverable feedstock is therefore represented as:

$$Wprec = WprpW_p^{rec} = W_p r_p$$

The recovery coefficient is essential because not all generated food waste can be economically collected. Collection accessibility, source separation, transport distance, and existing waste-management practices affect the value of rpr_p . The importance of regional and behavioral differences is consistent with the evidence that food-waste behavior varies across socioeconomic contexts (Grasso et al., 2019).

The model can further introduce a collection-cost function:

$$Ccol,p = ccol,pWprecC_{col,p} = c_{col,p}W_p^{rec}$$

where $ccol,pc_{col,p}$ represents the province-specific cost of collecting and aggregating feedstock.

3.3 Biogas Production

If ypy_p denotes the specific biogas yield per unit of recoverable feedstock, estimated biogas production becomes:

$$Bp = ypwprecB_p = y_pW_p^{rec}$$

The actual usable quantity can be represented using a digestion efficiency parameter η_d :

$$B_{puse} = B_{p\eta_d} B_p^{\{use\}} = B_p \eta_d$$

This formulation permits sensitivity analysis because digestion efficiency can vary with feedstock composition and operational conditions. Economic studies of anaerobic digestion indicate that plant economics depend substantially on the interaction between feedstock characteristics, plant scale, and operating costs (Gebrezgabher et al., 2010).

3.4 Biogas Upgrading and Bio-CNG Production

Raw biogas cannot automatically be treated as transport-grade fuel. It requires upgrading to increase methane concentration and remove undesirable components. Let η_u represent upgrading efficiency:

$$M_p = B_{puse} \eta_u M_p = B_p^{\{use\}} \eta_u$$

where M_p is the quantity of usable biomethane.

The upgrading cost is represented as:

$$C_{up,p} = C_{cap,u,p} + c_{up,p} M_p C_{\{up,p\}} \\ = C_{\{cap,u,p\}} + c_{\{up,p\}} M_p$$

where $C_{cap,u,p}$ is upgrading capital expenditure and $c_{up,p}$ is variable upgrading cost.

Different upgrading technologies can be represented by technology-specific values of η_u , capital expenditure, and operating expenditure. This structure reflects the comparative findings that alternative biogas-cleaning pathways have different economic characteristics depending on the intended end use (Sheets and Shah, 2018; Vo et al., 2018).

3.5 Compression and Distribution

After upgrading, biomethane must be compressed and supplied to vehicle users. Let C_{pcomp} represent compression capacity. The capacity constraint is:

$$Q_p \leq C_{pcomp} Q_p \leq C_{pcomp}$$

The associated cost can be expressed as:

$$C_{comp,p} = C_{cap,c,p} + c_{comp,p} Q_p C_{\{comp,p\}} \\ = C_{\{cap,c,p\}} + c_{\{comp,p\}} Q_p$$

Fueling infrastructure must also be included. Let F_p represent the number or effective capacity of fueling facilities. The infrastructure expenditure is:

$$C_{fuel,p} = c_{fuel,p} F_p C_{\{fuel,p\}} = c_{\{fuel,p\}} F_p$$

The inclusion of fueling infrastructure is justified by CNG infrastructure studies demonstrating that vehicle-fueling costs form a significant component of the overall

economic case (Smith and Gonzalez, 2014).

3.6 Provincial Demand Constraint

Let D_p represent potential provincial Bio-CNG transport demand. The model imposes:

$$Q_p \leq D_p$$

This prevents the optimization process from recommending production volumes that cannot be consumed locally.

For provinces with limited demand but substantial feedstock, the model can permit interprovincial transport:

$$Q_p \rightarrow j \leq T_{pj} Q_p \leq T_{pj}$$

where T_{pj} represents the feasible transfer quantity from province p to province j .

This creates an important strategic choice between decentralized production and centralized regional hubs.

3.7 Economic Objective Function

The core objective is to minimize total discounted system cost:

$$\min Z = \sum_p (C_{cap,p} + C_{op,p} + C_{col,p} + C_{up,p} \\ + C_{comp,p} + C_{fuel,p} + C_{trans,p} - R_p) \\ = \sum_p (C_{\{cap,p\}} + C_{\{op,p\}} \\ + C_{\{col,p\}} + C_{\{up,p\}} + C_{\{comp,p\}} \\ + C_{\{fuel,p\}} + C_{\{trans,p\}} - R_p)$$

where R_p represents revenue or economic value obtained from Bio-CNG sales.

An alternative formulation can maximize net present value:

$$NPV = \sum_t (TR_t - C_t(1+r)^t - C_0) \\ NPV = \sum_t (TR_t - C_t(1+r)^t - C_0)$$

where r is the discount rate and T is the project horizon.

The optimization can also incorporate a risk penalty:

$$\min Z_{risk} = E[Z] + \lambda Risk(Z) \\ = E[Z] + \lambda Risk(Z)$$

where λ represents the decision-maker's risk aversion. This structure is consistent with the broader methodological relevance of risk-aware optimization in energy-system planning (Yadegari et al., 2020).

3.8 Multi-Objective Extension

A purely financial objective may favor locations with high demand and low operating costs while underestimating waste-management benefits. A multi-objective formulation can therefore combine economic

and resource objectives:

$$\min F = (NPV - 1, E_{waste}, E_{emissions}, RISK) \setminus \min F = (NPV^{-1}, E_{waste}, E_{emissions}, RISK)$$

where the objectives represent economic performance, unutilized waste, environmental impact, and investment risk.

A weighted formulation can be written as:

$$F = \alpha C + \beta W + \gamma RF = \alpha C + \beta W + \gamma R$$

where α , β , and γ represent decision-maker priorities.

This formulation is particularly useful when policymakers seek to balance economic development with waste diversion and transport-fuel substitution.

4. Results / Findings

The conceptual optimization framework produces several important findings concerning the spatial and economic deployment of Bio-CNG across South African provinces. The principal finding is that uniform provincial deployment is unlikely to be economically optimal. Instead, the model favors differentiated deployment according to the interaction between recoverable feedstock, transport demand, infrastructure requirements, and production costs.

First, feedstock concentration emerges as a primary determinant of plant location. A province may possess substantial theoretical organic-waste resources but remain unsuitable for a large Bio-CNG facility if recoverable feedstock is geographically dispersed. Consequently, the optimization model distinguishes gross waste availability from economically collectable waste. This distinction is particularly important because household food-waste behavior varies across socioeconomic contexts (Grasso et al., 2019), while South African evidence demonstrates location-specific household food-waste disposal conditions (Oelofse et al., 2018).

Second, plant scale creates an economic trade-off. Larger anaerobic digestion and upgrading facilities can potentially distribute fixed capital expenditure across greater fuel output, but larger facilities may simultaneously increase feedstock transportation requirements. The optimum therefore occurs where economies of scale are balanced against collection and distribution costs. The economic relevance of scale and plant operating conditions is consistent with previous anaerobic-digestion economic analysis (Gebrezgabher et al., 2010).

Third, upgrading technology substantially influences the optimal system configuration. Since raw biogas requires treatment before use as a transport fuel,

technology selection affects both conversion efficiency and operating expenditure. The literature demonstrates that upgrading and cleaning technologies differ according to application and economic characteristics (Vo et al., 2018; Sheets and Shah, 2018). Accordingly, the optimization model should permit technology selection rather than imposing a single upgrading technology nationally.

Fourth, demand density strongly affects infrastructure utilization. A province with sufficient feedstock but low transport-fuel demand may produce Bio-CNG at an economically attractive production cost but fail to utilize fueling infrastructure efficiently. Conversely, high-demand transport corridors may justify Bio-CNG imports from nearby production hubs. CNG infrastructure studies indicate that the utilization of fueling infrastructure is central to its economic viability (Smith and Gonzalez, 2014).

Fifth, the model supports phased deployment. Initial investment is most economically defensible in locations where feedstock aggregation, transport demand, and infrastructure utilization can be achieved simultaneously. Subsequent deployment can expand toward provinces where costs are initially higher but network integration reduces marginal infrastructure requirements.

Finally, risk-aware optimization changes the preferred deployment pattern. A deterministic model may favor aggressive investment in the lowest-cost provinces, whereas a risk-adjusted model can allocate capacity more gradually to reduce exposure to uncertainty in feedstock supply, capital costs, and demand. This is particularly important for infrastructure with substantial upfront investment.

Overall, the findings indicate that Bio-CNG deployment should be treated as a network optimization problem rather than a collection of independent provincial projects. Regional hubs, interprovincial distribution, phased capacity additions, and differentiated technology choices can potentially produce more robust outcomes than a uniform national strategy.

5. Discussion

The findings demonstrate that the economic case for Bio-CNG depends on the interaction of multiple system components rather than on the cost of feedstock alone. The proposed framework contributes theoretically by integrating waste-resource availability, biological conversion, gas upgrading, compression, transport demand, and infrastructure into a unified optimization structure. Such integration addresses an important limitation of isolated techno-economic studies, in which individual process stages may be economically attractive without necessarily producing an economically viable

complete fuel system.

One of the most important implications concerns the treatment of food waste as an energy resource. The presence of organic waste does not automatically imply that all of it should be diverted to anaerobic digestion. Collection, separation, and transportation impose additional costs. Furthermore, household behavior affects the quantity and quality of recoverable material. Grasso et al. (2019) provide evidence that food-waste behavior varies according to socioeconomic factors, reinforcing the argument for province-specific rather than nationally averaged feedstock assumptions. This issue becomes particularly relevant when scaling the model from individual municipalities to provincial systems.

The model also highlights a potential contradiction between maximizing plant capacity and minimizing total system cost. Large centralized facilities can benefit from scale economies, but excessive centralization can increase feedstock transportation distances. Conversely, numerous small plants reduce collection distances but may face higher unit capital and upgrading costs. The appropriate configuration is therefore likely to be a network of strategically located facilities rather than either complete centralization or complete decentralization.

The upgrading stage presents another critical trade-off. Previous studies demonstrate that biogas purification technologies differ in economic and technical performance (Vo et al., 2018). Therefore, the optimal solution may involve different upgrading technologies at different scales. A technology that is economically attractive for a large centralized plant may not be optimal for a smaller regional facility. This supports the use of technology-selection variables within the optimization model.

Transport infrastructure is equally significant. The business case for CNG fleets depends on fueling requirements and infrastructure economics (Johnson, 2010), while direct infrastructure cost assessments show that station development can represent a substantial component of total project expenditure (Smith and Gonzalez, 2014). Therefore, Bio-CNG projects should prioritize fleet clusters and high-utilization transport corridors rather than relying exclusively on geographic proximity to feedstock.

The South African context further suggests that policy and market conditions should be incorporated into scenario analysis. The existing petrol and diesel market provides the competitive benchmark against which alternative transport fuels must be evaluated (DoE, 2017). Regional transport-energy characteristics, such as those documented for the Western Cape, reinforce the need for geographically differentiated

analysis (DED, 2019).

Risk is another significant consideration. A project with the lowest expected cost may not be the most desirable investment if it is highly sensitive to feedstock shortages or demand fluctuations. The risk-aware structure proposed here therefore provides a more realistic representation of infrastructure decision-making than deterministic optimization alone. The methodological relevance of risk-averse optimization is supported by the broader energy-planning literature (Yadegari et al., 2020).

There are, however, limitations. The framework is conceptual and does not establish province-specific optimal capacities without detailed empirical datasets. Actual implementation would require reliable information on organic-waste quantities, collection rates, methane yields, upgrading performance, capital costs, transport demand, station locations, and fuel prices. Furthermore, socioeconomic food-waste patterns should be estimated using sufficiently granular local data rather than transferred directly from other geographic contexts.

The framework should therefore be interpreted as a decision-support architecture rather than a final investment prescription. Its principal practical value is its ability to identify which variables have the greatest influence on deployment decisions and to compare centralized, decentralized, and hybrid configurations.

6. Conclusion

This study developed a techno-economic optimization framework for Bio-CNG deployment across South African provinces. The framework integrates the complete value chain from organic-waste recovery to transport-fuel delivery, including anaerobic digestion, biogas upgrading, compression, fueling infrastructure, distribution, and provincial demand.

The analysis demonstrates that economically efficient deployment cannot be determined by feedstock availability alone. The optimal location and scale of Bio-CNG facilities depend on the simultaneous interaction of recoverable waste, plant scale, upgrading technology, transport demand, infrastructure utilization, and distribution costs. Food-waste availability should particularly be evaluated using recoverability rather than gross generation because socioeconomic and geographic factors influence waste-management behavior (Grasso et al., 2019).

The proposed model also supports risk-aware and multi-objective decision-making. Instead of optimizing solely for minimum production cost, policymakers and investors can evaluate economic return, infrastructure requirements, waste utilization, and investment risk simultaneously. Such an approach is more appropriate

for a developing Bio-CNG network where infrastructure investments are long-lived and uncertainty can significantly affect project outcomes.

A phased deployment strategy appears preferable to immediate nationwide expansion. Initial facilities can be concentrated in areas where feedstock aggregation and transport demand jointly support high infrastructure utilization, while regional hubs can subsequently supply neighboring demand centers. This approach can reduce the risk associated with premature infrastructure expansion and enable operational experience to inform later investment decisions.

Future research should populate the proposed framework with province-level datasets and conduct detailed sensitivity, scenario, and uncertainty analyses. Particular attention should be given to feedstock recovery rates, biomethane yields, upgrading technology costs, CNG station utilization, conventional-fuel prices, and interprovincial transport costs. The resulting empirical optimization model could provide policymakers with a quantitative basis for prioritizing Bio-CNG investments and designing waste-to-energy strategies aligned with South Africa's transport-energy transition.

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