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Biomethane production integrated into the natural gas infrastructure: a technological, economic, and environmental assessment

Biyometan üretiminin doğalgaz altyapısına entegrasyonu: teknolojik, ekonomik ve çevresel bir değerlendirme

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Biomethane Production Integrated into the Natural Gas Infrastructure: A Technological, Economic, and Environmental Assessment

Highlights

- ❖ *Biomethane can be directly integrated into existing natural gas infrastructure, enabling a cost-effective energy transition.*
- ❖ *Despite high initial investment costs, biomethane offers long-term benefits in energy security and domestic resource utilization*
- ❖ *Biomethane production significantly reduces greenhouse gas emissions and can achieve negative emissions under certain conditions.*
- ❖ *The widespread adoption of biomethane depends on supportive regulatory frameworks, incentives, and technological advancements.*

Aim

This study aims to evaluate the integration potential of biomethane into the natural gas infrastructure from technological, economic, and environmental perspectives. It seeks to identify the most suitable production technologies, analyze cost structures, and assess environmental benefits, while also examining the feasibility of biomethane deployment in Türkiye. The study further aims to provide strategic insights to support energy transition and policy development.

Design & Methodology

The study adopts a qualitative research approach based on a comprehensive literature review and technical-economic assessment. Biomethane production technologies, including anaerobic digestion, hydrothermal gasification, and hydrothermal carbonization, are analyzed comparatively in terms of efficiency, cost, and maturity. Economic evaluation is conducted using CAPEX and OPEX frameworks, while environmental impacts are assessed through greenhouse gas emission analysis. Additionally, infrastructure integration is examined considering technical standards, logistics, and grid compatibility.

Originality

This study provides a holistic evaluation of biomethane integration by combining technological, economic, and environmental dimensions within a single framework. Unlike many existing studies that focus on isolated aspects, this research offers a comprehensive analysis tailored to Türkiye's energy system. It contributes to the literature by linking production technologies with infrastructure integration and policy requirements, thereby presenting a strategic roadmap for biomethane development.

Findings

The findings indicate that biomethane is technically compatible with existing natural gas infrastructure and can be directly injected into the grid after purification. While anaerobic digestion is currently the most mature and cost-effective technology, hydrothermal methods offer higher efficiency potential in the long term. Although investment costs are relatively high, biomethane provides significant economic benefits such as reducing energy imports and enhancing supply security. Environmentally, biomethane significantly lowers greenhouse gas emissions and may achieve negative emissions depending on feedstock and process conditions.

Conclusion

In conclusion, biomethane represents a strategic and sustainable solution for energy transition due to its compatibility with existing infrastructure and its environmental advantages. However, its widespread adoption requires a well-defined regulatory framework, supportive policies, and investment incentives. For Türkiye, unlocking biomethane potential depends on integrating technological advancements with policy development. When supported appropriately, biomethane can play a key role in achieving energy security and climate targets.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Biomethane Production Integrated into the Natural Gas Infrastructure: A Technological, Economic, and Environmental Assessment

Araştırma Makalesi / Research Article

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ABSTRACT

This study evaluates the technological, economic, environmental, and natural-gas-infrastructure integration potential of biomethane production in Türkiye. Based on the national biomass resource assessment, animal, plant, forest, and municipal waste streams correspond to approximately 289,821,769.70 tons/year of biomass-based waste, a theoretical biogas capacity of about $13,364.04 \times 10^6 \text{ m}^3/\text{year}$, and a technically convertible biomethane potential of approximately 8.3 billion m^3/year . Under the upper scenario, total biomethane capacity reaches nearly 10.4 billion m^3/year , equivalent to almost 20% of Türkiye's 2024 natural gas consumption of about 53 billion m^3 . The technology comparison indicates that anaerobic digestion is the most mature near-term option, with 55-65% CH_4 in biogas, a gas yield of 2.5-6.0 kWh/kg organic dry matter (ODM), and 60-80% overall efficiency when coupled with combined heat and power (CHP). Hydrothermal gasification offers higher long-term conversion potential with an 8-12 kWh/kg ODM gas yield and 40-70% efficiency, whereas hydrothermal carbonization remains a complementary pathway with a 1-3 kWh/kg ODM gas yield and limited direct biomethane output. The economic analysis shows approximate CAPEX/OPEX values of €580,000/€286,000 per year for the reference HTG facility, €1.80 million/€832,984 per year for HTC, and €460,000/€271,000 per year for AD. Payback periods are estimated at around 3-4 years for lower-investment conversion cases and 5-6 years for new biomethane plant cases, indicating AD as the most feasible short-term pathway. The results show that biomethane can support natural gas substitution, import reduction, rural development, and greenhouse gas mitigation, provided that gas-quality standards, grid-injection rules, certification systems, investment incentives, and site-specific planning are implemented within the 2025-2053 roadmap.

Keywords: Biomethane, renewable energy, energy transition, sustainable energy systems, energy policies.

Biyometan Üretiminin Doğal Gaz Altyapısına Entegrasyonu: Teknolojik, Ekonomik ve Çevresel Bir Değerlendirme

ÖZ

Bu çalışma, Türkiye'de biyometan üretiminin teknolojik, ekonomik, çevresel ve doğal gaz altyapısına entegrasyon potansiyelini değerlendirmektedir. Ulusal biyokütle kaynakları değerlendirmesine göre hayvansal, bitkisel, orman ve belediye atıkları yıllık yaklaşık 289.821.769,70 ton biyokütle esaslı atığa, yaklaşık $13.364,04 \times 10^6 \text{ m}^3/\text{yıl}$ teorik biyogaz kapasitesine ve yaklaşık 8,3 milyar $\text{m}^3/\text{yıl}$ teknik olarak dönüştürülebilir biyometan potansiyeline karşılık gelmektedir. Üst senaryoda toplam biyometan kapasitesi yaklaşık 10,4 milyar $\text{m}^3/\text{yıl}$ seviyesine ulaşmakta ve bu değer Türkiye'nin 2024 yılı yaklaşık 53 milyar m^3 doğal gaz tüketiminin neredeyse %20'sine karşılık gelmektedir. Teknoloji karşılaştırması, anaerobik çürütmenin kısa vadede en olgun seçenek olduğunu; biyogazda %55-65 CH_4 , 2,5-6,0 kWh/kg ODM gaz verimi ve CHP ile birlikte %60-80 toplam verimlilik sunduğunu göstermektedir. Hidrotermal gazlaştırma 8-12 kWh/kg ODM gaz verimi ve %40-70 verimlilikle uzun vadede daha yüksek dönüşüm potansiyeli taşıırken, hidrotermal karbonizasyon 1-3 kWh/kg ODM gaz verimi ve sınırlı doğrudan biyometan çıkışı nedeniyle tamamlayıcı bir yol olarak değerlendirilmektedir. Ekonomik analizde yaklaşık CAPEX/OPEX değerleri referans HTG tesisi için 580.000 €/286.000 €/yıl, HTC için 1,80 milyon €/832.984 €/yıl ve AD için 460.000 €/271.000 €/yıl olarak belirlenmiştir. Geri ödeme süresi düşük yatırımlı dönüşüm senaryolarında yaklaşık 3-4 yıl, yeni biyometan tesisi senaryolarında ise 5-6 yıl aralığındadır. Sonuçlar, biyometanın doğal gaz ikamesi, ithalatın azaltılması, kırsal kalkınma ve sera gazı azaltımı açısından önemli katkılar sunabileceğini; bunun için gaz kalite standartları, şebeke enjeksiyon kuralları, sertifikasyon sistemleri, yatırım teşvikleri ve yerel ölçekli planlamanın 2025-2053 yol haritası kapsamında birlikte geliştirilmesi gerektiğini göstermektedir.

Anahtar Kelimeler: Biyometan, yenilenebilir enerji, enerji geçişi, sürdürülebilir enerji sistemleri, enerji politikaları.

1. INTRODUCTION

Global energy systems are undergoing a significant transformation driven by rising energy demand, dependence on fossil fuels, and the necessity to combat climate change. While natural gas is considered a

transition fuel due to its relatively low carbon intensity, the development of renewable alternatives is inevitable to achieve sustainable energy systems in the long term. In this context, biomethane is considered a prominent solution due to its status as a renewable energy source

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and its high compatibility with existing natural gas infrastructure [1].

Biomethane is a gas produced by purifying biogas, which is obtained through biochemical or thermochemical processing of organic waste, and it has a high methane content. While the methane content of raw biogas typically ranges from 45% to 65%, purification processes during biomethane production increase this ratio to over 90%, ensuring the gas meets natural gas quality standards. This high methane content allows biomethane to be directly injected into natural gas transmission and distribution networks, enabling the efficient use of existing infrastructure [3,4].

Benzer çalışmalarda termal açıdan kollektör kanal için farklı kanal yükseklikleri, doğal konveksiyon koşulları, farklı plaka malzemesi gibi hususlar incelenebilir. Modelleme açısından ise çıkış sıcaklığı ve termal verim modellemesi farklı yapay zekâ teknikleri (Yapay Sinir Ağları ve Genetik Algoritmalar gibi) ve Hesaplamalı Akışkanlar Dinamiği yazılımları ile yapılarak tahmin hassasiyetleri karşılaştırılarak kullanılabilirlikleri elde edilebilir. Ayrıca giriş parametre sayılarındaki değişimlerin modellemeye etkisi incelenebilir.

Overall, Table 1 demonstrates that the transition from biogas to biomethane is not only a purification step but also a functional upgrade that increases fuel quality, grid compatibility, and market value. The higher methane content and energy density of biomethane enable broader use in natural gas infrastructure and transport applications; however, these advantages require

Additionally, depending on the type of feedstock used, biomethane production may, in some cases, have the potential for negative emissions [5,6].

Biomethane production can be achieved through various technological approaches. While anaerobic digestion—the most common method—stands out as a commercially mature technology with a wide range of applications, thermochemical methods such as hydrothermal gasification and hydrothermal carbonization, though offering higher efficiency potential, are still in the development phase [1,4]. There are significant differences among these technologies in terms of efficiency, cost, energy intensity, and scalability, and the selection of the appropriate technology depends on local conditions and the type of feedstock.

From an economic perspective, while biomethane production facilities require high initial investment costs, they provide significant long-term benefits such as enhancing energy supply security, supporting local economic development, and reducing energy imports. However, capital expenditures (CAPEX) and operating expenses (OPEX) costs vary significantly depending on factors such as the technology used, plant scale, feedstock availability, and energy prices. Therefore, the economic sustainability of biomethane projects is directly linked to appropriate policy tools and incentive mechanisms.

This study aims to evaluate the potential for integrating biomethane into the natural gas infrastructure through a comprehensive approach that considers technological,

Table1 . Comparison of biogas and biomethane

Biogas	Biomethane
50–70% CH ₄ , 30–50% CO ₂ , also contains H ₂ S, NH ₃ , and water vapor	95%+ CH ₄ (natural gas quality, purified)
Lower (approximately 20–23 MJ/m ³)	Higher (approximately 35–39 MJ/m ³)
Cannot be fed into the natural gas grid (pre-treatment required)	Can be injected directly into the natural gas grid
On-site consumption (CHP systems, boilers)	Can be transported via pipeline, can be stored as CBG/LBG
Electricity and heat production (on-site)	Electricity, heat, vehicle fuel , and direct use as a substitute for natural gas
May contain H ₂ S, NH ₃ , and particulates → additional purification required	Cleaner, low-emission combustion
On-site use and low market value	Natural gas equivalent, higher market value
Lower (basic biogas plant)	Higher (biogas + upgrading unit)
Widespread, mature technology	Newer, rapidly gaining traction

additional upgrading investment, gas quality control, and compliance with injection standards.

The importance of biomethane extends beyond its technical compatibility and is also critical for its environmental impacts. By being derived from organic waste, biomethane supports the circular economy approach and ensures that methane emissions are captured and converted into energy before being released into the atmosphere. Since methane has a much higher global warming potential than carbon dioxide, biomethane production could make significant short-term contributions to combating climate change.

economic, and environmental dimensions. Within this scope, biomethane production technologies are analyzed comparatively, cost structures are examined, and environmental impacts are identified. Additionally, the feasibility of integrating biomethane into Türkiye's natural gas grid is evaluated, and strategic recommendations for energy policy are presented.

2. METHOD

This study adopts a qualitative research approach to assess the potential for integrating biomethane into the

natural gas infrastructure and was conducted within the framework of a comprehensive literature review and a technical-economic evaluation. The study's methodology consists of three main components: (i) analysis of biomethane production technologies, (ii) economic evaluation, and (iii) environmental impact analysis.

2.1. Research Approach and Data Sources

The data used in the study were compiled from international academic publications, industry reports, and technical documents related to biomethane production processes. In particular, comprehensive studies on biogas and biomethane technologies [3,4,6] and reports from international energy agencies and industry organizations [1,2] form the primary data sources. Additionally, a significant portion of the technical and economic data used in this study was obtained from a report containing detailed analyses focused on Türkiye.

2.2. Technological Assessment Approach

In evaluating biomethane production technologies, the primary production methods—anaerobic digestion, hydrothermal gasification (HTG), and hydrothermal carbonization (HTC)—were examined. These technologies were analyzed comparatively based on criteria such as efficiency, energy intensity, technology maturity, and application areas. In particular, hydrothermal technologies were examined within a separate evaluation framework because these processes occur under high-temperature, high-pressure conditions [7-9].

The technological analysis also took into account upgrading technologies used in the process of converting biogas into biomethane. In this context, primary, secondary, and advanced upgrading methods used to increase the methane content of the gas and bring it into compliance with grid standards were evaluated. This approach ensures the assessment of technical feasibility for integrating biomethane into the natural gas infrastructure [4].

2.3. Economic Analysis Method

The economic evaluation was conducted within the framework of capital expenditures (CAPEX) and operating expenses (OPEX) to identify the cost structure of biomethane production processes. Within the scope of the analysis, cost components were detailed using example plant data specific to hydrothermal gasification technology. These components include reactor systems, gas purification units, energy consumption, labor costs, and maintenance and repair costs.

In determining the unit cost of gas production, parameters such as gas production capacity, energy efficiency, the type of raw material used, and the selected technology were considered. Additionally, the impact of economies of scale on costs was evaluated, and different technology scenarios were compared. This approach enables a multidimensional analysis of the economic feasibility of biomethane production [1].

2.4. Environmental Impact Assessment

In this study, the environmental impacts of biomethane were assessed, with particular focus on greenhouse gas emissions. In this regard, the potential of biomethane production to reduce methane emissions and its contribution to carbon reduction through the substitution of fossil fuels were analyzed. Given methane's high global warming potential, the emission-reduction effects of biomethane production processes were supported by literature [5].

Additionally, the negative emission potential of biomethane production, depending on the type of feedstock used, has been included in the scope of the evaluation. This analysis contributes to determining the role of biomethane in energy systems in line with net-zero targets.

2.5. Integration Analysis Framework

The integration of biomethane into the natural gas infrastructure has been addressed from both technical and logistical perspectives. In this context, the quality standards, pressure requirements, and infrastructure compatibility necessary for injecting biomethane into the grid have been analyzed. Additionally, alternatives for the transportation and storage of biomethane (compressed and liquefied biomethane) have been evaluated. Thanks to this multidimensional methodological approach, the integration of biomethane into energy systems has been analyzed holistically, encompassing technical, economic, and environmental aspects.

3. BIOMETHANE PRODUCTION TECHNOLOGIES

3.1. Main Production Methods

3.1.1. Anaerobic digestion

Anaerobic digestion (AD) is the most widely used biochemical process in biomethane production. In this method, organic waste (agricultural waste, animal manure, food waste, and sewage sludge) is broken down by microorganisms in an oxygen-free environment to produce biogas. The resulting biogas typically contains 50–70% methane (CH_4) and 30–50% carbon dioxide (CO_2). When this gas undergoes upgrading processes to increase the methane content to over 90%, biomethane is obtained [6].

Anaerobic digestion technology is currently recognized as the most widely used method for biomethane production due to its commercial maturity, adaptability to a wide range of feedstocks, and relatively low operational risk [1].

3.1.2. Hydrothermal gasification (HTG)

Hydrothermal gasification is a thermochemical process in which wet biomass is converted into the gas phase in a supercritical water environment under high temperature (360–700°C) and pressure (210–350 bar). The synthetic gas produced by this method consists of components such

as methane, hydrogen, and carbon dioxide, and, after appropriate purification, biomethane can be produced.

One of the most significant advantages of HTG technology is that it allows processing waste with high moisture content without the need for drying. Additionally, high methane yield and continuous production are among its key advantages. However, high investment costs, energy requirements, and limited technological maturity are significant disadvantages.

3.1.3. Hydrothermal carbonization (HTC)

Hydrothermal carbonization is a process carried out at 180–250°C and 10–50 bar, in which biomass is converted into a carbon-rich solid product (hydrochar), along with gaseous and liquid products. While the gas phase produced in the HTC process contains methane and carbon dioxide, this method is more suited to solid fuel production than to biomethane production.

The most significant advantage of HTC is the ability to process wet biomass directly and obtain products with high carbon density. However, it has limited application due to its lack of direct primary status for biomethane production and its low level of commercialization.

3.2. Comparative Evaluation of Technologies

Biomethane production technologies exhibit significant differences in efficiency, cost, maturity, and applicability. While anaerobic digestion stands out for its low investment risk and high technology maturity, hydrothermal gasification is considered a more complex and costly technology, despite its higher potential for efficiency [4].

Anaerobic digestion processes typically operate in batch or semi-continuous systems and occur at lower temperatures and pressures. In contrast, HTG processes require high temperature and pressure, resulting in higher energy intensity but potentially higher methane yield. HTC, on the other hand, is a technology focused primarily on carbon production and plays an indirect role in biomethane production.

From an efficiency-potential perspective, anaerobic digestion (AD) provides the most balanced performance under current conditions. The supporting assessment indicates that AD typically produces a medium-quality biogas stream with approximately 55-65% CH₄, a gas yield of about 2.5-6.0 kWh/kg organic dry matter (ODM), and an overall energy efficiency of roughly 60-80% when coupled with combined heat and power (CHP). This makes AD suitable for near-term biomethane deployment because it combines mature operation, stable biogas generation, and efficient energy recovery from agricultural, municipal, and food-waste feedstocks.

Hydrothermal gasification (HTG) has a higher theoretical efficiency potential, particularly for wet biomass and high-moisture organic residues. The supporting comparison reports a gas yield of approximately 8-12 kWh/kg ODM and an overall efficiency potential of about 40-70%, with a product gas containing H₂, CO, and CH₄. Therefore, HTG may offer stronger long-term

conversion potential than conventional AD, but its practical efficiency depends heavily on heat integration, high-pressure operation, gas cleaning, and further technological maturity.

Hydrothermal carbonization (HTC) has a more limited direct biomethane efficiency potential because the process is mainly oriented toward hydrochar or solid fuel production rather than methane-rich gas generation. The supporting assessment reports a lower gas yield of about 1-3 kWh/kg ODM, a gas phase mainly associated with CO₂ and limited CH₄, and a low thermal efficiency profile. Accordingly, HTC should be interpreted as a complementary wet-waste valorization route rather than a primary biomethane production pathway; its energy advantage is more closely related to solid fuel recovery and carbon-rich product formation [10].

From an economic perspective, anaerobic digestion facilities have lower CAPEX and OPEX, whereas hydrothermal technologies require higher initial investment and operating costs. However, in the long term, HTG technology is expected to become competitive, particularly given its high yield and continuous production advantages.

3.3. Assessment in Terms of Grid Compatibility

One of the most critical factors in integrating biomethane into the natural gas infrastructure is the gas's compliance with quality standards. Raw biogas cannot be fed directly into the grid due to the carbon dioxide, hydrogen sulfide, and other contaminants it contains; therefore, it must undergo purification processes. As a result of these purification processes, the methane content of biomethane typically reaches 96–98% and achieves a quality equivalent to that of natural gas [3].

The conversion of biogas produced through anaerobic digestion into biomethane is widely feasible thanks to existing purification technologies, and its integration into the natural gas grid is technically possible. In hydrothermal gasification processes, while the composition of the resulting gas is more variable, compliance with grid standards can be achieved using appropriate gas processing and separation technologies. The integration of biomethane into the grid offers a significant advantage by allowing the use of existing pipeline infrastructure. This reduces the need for new infrastructure investment and enhances flexibility in energy systems. Additionally, the ability to transport biomethane in compressed (bio-CNG) or liquefied (bio-LNG) forms increases access to various application areas.

In conclusion, when selecting among biomethane production technologies, not only technical and economic factors but also grid compatibility and infrastructure integration must be considered. In this context, while anaerobic digestion is the most feasible method under current conditions, hydrothermal technologies hold significant potential as alternatives in the future.

4. ECONOMIC ANALYSIS

The economic evaluation of biomethane production is examined within the framework of investment costs, operating expenses, technology-specific cost differences, and market dynamics. In this section, the economic sustainability of biomethane production systems has been analyzed from multiple perspectives.

Operating expenses, on the other hand, include raw material procurement, energy consumption, labor, maintenance and repair, and consumables. It has been determined that the annual operating cost for the same example plant is approximately €286,000, and that raw material procurement and labor costs, in particular, account for a significant share of the total cost. Additionally, energy consumption is a major cost factor

Table 2. Capital Expenditures (CAPEX)

Component / Equipment	Specification	Approximate Cost (€)
Reactor System	Steel resistant to high pressure (20–30 MPa) and temperature (300–600 °C)	200,000
Heating Unit	Electric heaters or a superheated steam generator	90,000
High-Pressure Pump	To pump the biomass-water mixture into the reactor	40,000
Feeding System	Mixer, bunker, tank, etc.	30,000
Gas Separation and Collection Unit	Gas-liquid separator, condenser, filter	45,000
Catalyst System (Optional)	Fixed-bed or liquid-phase catalyst reactor	25,000
Control and Automation	PLC systems, SCADA, sensors, and safety systems	50,000
Building / Infrastructure	Concrete flooring, insulation, water, and gas lines	55,000
Installation and Commissioning	Installation, testing, training, and permitting processes	45,000
Total		580,000

Table 3. Operating Expenses (OPEX)

Expense Item	Characteristic	Approximate Cost (€)
Raw Material Procurement	Biomass waste from the municipality or the private sector	75,000
Water Consumption and Treatment	Process water and wastewater treatment if necessary	15,000
Energy (Electricity/Gas)	Heating, pumps, control systems	40,000
Labor Costs	2 operators + 1 engineer (shift work)	75,000
Maintenance, Repair, and Spare Parts	Valve, gasket, and pump maintenance; scheduled shutdowns	15,000
Catalyst / Chemical	Catalytic converter replacement (if applicable)	20,000
Gas Cleaning Consumables	Filters, absorbents, condenser fluids	25,000
Waste Disposal	Removal of solid residues and the liquid phase	12,000
Insurance and Permit Costs	EIA, licenses, emission permits	9,000
Total		286,000

4.1. Investment and Operating Costs

The economic structure of biomethane production facilities consists of two main components: capital expenditures (CAPEX) and operating expenses (OPEX). Capital expenditures include reactor systems, gas purification units, energy infrastructure, automation systems, and facility construction costs. Particularly in advanced technologies such as hydrothermal gasification, investment costs increase significantly due to the need for equipment capable of withstanding high temperatures and pressures.

In an example hydrothermal gasification facility, the total investment cost is estimated to be approximately €580,000 by 2026, with the majority of this cost attributed to the reactor system, heating unit, and automation infrastructure. This highlights the decisive role of technology selection in determining initial investment requirements [1,4].

in processes that require high temperatures and pressures. In this context, the economic performance of biomethane production facilities varies significantly depending on factors such as facility scale, technology used, access to feedstock, and energy prices [1]. The approximate Capital (CAPEX) and Operating (OPEX) costs for a facility with a daily gas production capacity of 150–200 m³ are provided at Table 2 and Table 3.

Based on the detailed cost data compiled in the supporting report, hydrothermal carbonization (HTC) and anaerobic digestion (AD) show different investment and operating cost profiles. HTC requires several thermochemical process units such as heaters, a reactor, flash tanks, drying equipment, and wastewater treatment systems. Therefore, its cost structure is driven mainly by high-value process equipment and utility consumption. AD, by contrast, operates under milder process conditions and its cost structure is shaped mainly by the

digestion tank, biogas cleaning unit, feedstock supply, labor, and routine maintenance [11].

Table 4. Hydrothermal Carbonization (HTC) Capital Expenditures (CAPEX)

Capital Component	Approximate Cost (€)
Heat exchangers (H1, H2, H3)	32,983
Mixer	5,110
Direct-fired heaters	354,063
Reactor	436,051
Flash tanks	145,276
Pumps	57,237
Centrifuge	55,028
Crusher	10,739
Dryer	131,535
Filter	1,359
Pelletizer	30,907
Total on-site equipment cost	1,260,288
Additional site/equipment item	21,526
Utilities	230,727
Contractor fee and contingencies	30,251
Land	30,251
Facility start-up	151,254
Working capital	79,765
Total	1,804,062

The HTC CAPEX estimate indicates that the reactor and direct-fired heaters are the dominant investment items. The on-site equipment cost reaches approximately €1.26 million, while additional items such as utilities, start-up, land, contractor fees, and working capital increase the listed capital requirement to about €1.80 million. [11].

For HTC, annual operating expenses are dominated by methane consumption, labor-related operations, wastewater treatment, and maintenance. The relatively high wastewater treatment cost is important because the HTC process produces a considerable liquid phase that must be managed before discharge or reuse [11].

For a small-scale AD facility with an approximate daily gas production capacity of 150-200 m³, the estimated CAPEX is about €460,000. The largest single item is the anaerobic digestion tank, followed by infrastructure, installation/commissioning, the heating system, the biogas cleaning unit, and digestate treatment equipment. [11].

The AD OPEX estimate is approximately €271,000 per year. Feedstock supply and labor are the largest cost categories, while energy use, gas cleaning consumables, chemicals, maintenance, digestate management, and permit-related expenses form the remaining operating cost items. This supports the assessment that AD is generally a more economical short-term option than hydrothermal technologies, particularly for agricultural, municipal, and food waste streams [10].

4.2. Cost Differences by Technology

Considering the cost data presented in Section 4.1, technology selection clearly determines the economic profile of biomethane production. The reference hydrothermal gasification facility has an estimated CAPEX of €580,000 and annual OPEX of €286,000, while HTC reaches a much higher capital requirement of approximately €1.80 million and annual operating expenses of €832,984 due to reactor, heating, utility, labor, maintenance, and wastewater treatment needs. In contrast, anaerobic digestion shows the lowest short-term cost burden, with an estimated CAPEX of €460,000 and annual OPEX of €271,000 for a 150-200 m³/day facility.

Table 5. Hydrothermal Carbonization (HTC) Operating Expenses (OPEX)

Operating Expense	Annual Cost (€)
Electricity	90,431
Methane	243,346
Labor-related operations	160,000
Maintenance	121,003
Property taxes and insurance	15,125
General overheads	76,176
Wastewater treatment	126,903
Total	832,984

Therefore, AD appears to be the most feasible near-term option for small- and medium-scale biomethane deployment, whereas hydrothermal technologies should be considered longer-term alternatives where higher process efficiency, wet biomass utilization, and technological progress can offset their higher cost levels. In terms of payback periods, the cost data in Section 4.1 should be interpreted together with the expected annual net cash flow. A simple payback period can be estimated as CAPEX divided by annual net cash flow; therefore, biomethane sales, electricity and heat revenues, gate fees, by-product income, incentives, carbon credits, and OPEX directly affect the result. Based on the investment scenarios in the supporting assessment, lower-investment biomethane conversion projects may achieve an indicative payback period of approximately 3-4 years, whereas higher-investment new biomethane plant cases

Table 6. Anaerobic Digestion (AD) Capital Expenditures (CAPEX)

Component / Equipment	Approximate Cost (€)
Anaerobic Digestion Tank	140,000
Heating System	40,000
Gas Storage Unit	35,000
Mixers	25,000
Biogas Cleaning Unit	40,000
Condenser and Filtration	15,000
Automation and Control	25,000
Storage and Treatment Unit	40,000
Building / Infrastructure / Ground	55,000
Installation and Commissioning	45,000
Total	460,000

may require approximately 5-6 years. Accordingly, AD is expected to have the shortest payback period, approximately 3-4 years under favorable revenue and incentive conditions and around 5-6 years in less favorable new-build cases, because it has the lowest CAPEX (€460,000) and OPEX (€271,000/year).

Table 7. Anaerobic Digestion (AD) Operating Expenses (OPEX)

Expense Item	Approximate Cost (€)
Feedstock Supply	75,000
Energy (Heating + Electricity)	40,000
Labor	75,000
Maintenance / Repair	15,000
Chemicals and Consumables	20,000
Gas Cleaning Consumables	25,000
Digestate Output Management	12,000
Permits, Insurance, and Licenses	9,000
Total	271,000

The reference HTG case is expected to fall in the moderate-to-long range, approximately 5-6 years or longer, due to its higher CAPEX (€580,000) and comparable OPEX (€286,000/year), although higher methane yield and continuous operation may shorten the payback period. HTC is expected to have the longest and most uncertain payback period, generally beyond 6 years and potentially 8 years or more, because its CAPEX (€1.80 million) and annual OPEX (€832,984/year) are substantially higher and the process is mainly associated with hydrochar production rather than direct biomethane generation. Therefore, under comparable market conditions, the expected payback ranking is AD first, HTG second, and HTC last [10].

There are significant differences in cost structures among the technologies used in biomethane production. While anaerobic digestion technology stands out for its relatively low investment and operating costs, thermochemical methods such as hydrothermal gasification and hydrothermal carbonization are considered higher-cost systems [4].

Operating under low-temperature, low-pressure conditions in anaerobic digestion facilities reduces equipment costs and energy consumption, thereby lowering overall costs. In contrast, the requirement for high temperatures (360–700°C) and pressures (210–350 bar) in hydrothermal gasification technology increases CAPEX and OPEX.

In hydrothermal gasification systems, additional components such as catalysts, salt separation systems, and gas purification units also increase costs. However, the fact that these technologies offer higher methane yields and continuous production advantages may lead to lower unit gas costs in the long term.

Since hydrothermal carbonization generally focuses on solid fuel production rather than biomethane, its economic evaluation is limited to biomethane.

Furthermore, the low level of commercialization for this technology increases the uncertainty around cost data.

In conclusion, while anaerobic digestion is the most economical option in the short term, the competitiveness of hydrothermal methods is expected to increase in the long term as technological advancements advance.

4.3. Economic Feasibility and Market Potential

The economic feasibility of biomethane production depends not only on the cost structure but also on market conditions, energy prices, and policy support. Since biomethane is an energy carrier equivalent to natural gas, it can compete directly in existing energy markets and become economically more attractive, particularly during periods of high natural gas prices.

Biomethane projects offer significant economic benefits by enhancing energy supply security, utilizing local resources, and reducing energy imports. Additionally, these projects create positive impacts in areas such as rural development, job creation, and waste management.

However, the widespread adoption of biomethane production depends largely on incentive mechanisms and the regulatory framework. Renewable energy subsidies, carbon pricing mechanisms, and biomethane certification systems significantly enhance the economic viability of projects [2].

When assessed specifically for Türkiye, although the potential for biomethane production is high, it cannot be fully realized due to the current market structure and regulatory shortcomings. Therefore, establishing appropriate incentive mechanisms and developing policies to support the integration of biomethane into the natural gas infrastructure are critical to the development of the biomethane market.

5. ENVIRONMENTAL IMPACTS

Biomethane production and use offer significant environmental benefits in the process of decarbonizing energy systems. This section examines biomethane's impact on greenhouse gas emissions, its potential for negative emissions, and its contribution to carbon reduction from multiple perspectives.

5.1. Greenhouse Gas Emissions

One of the most important parameters in assessing the environmental impacts of biomethane is greenhouse gas emissions. Unlike fossil fuels, biomethane has a circular carbon structure because it is produced through the processing of organic waste. This allows the carbon dioxide released during biomethane combustion to be sequestered again by biomass within a short carbon cycle [5].

Biomethane production plays a critical role, particularly in controlling methane (CH₄) emissions. Methane has a global warming potential approximately 20–28 times higher than that of carbon dioxide and, despite remaining

in the atmosphere for a shorter period, has a powerful impact on climate change. Capturing methane released from the uncontrolled decomposition of organic waste and converting it into energy significantly reduces total greenhouse gas emissions.

Additionally, the use of biomethane in the transportation sector enables emission reductions, particularly by replacing fossil fuels such as diesel and gasoline. Evaluations conducted using the "Well-to-Wheel" approach have demonstrated that biomethane has significantly lower lifecycle greenhouse gas emissions [1].

5.2. Negative Emission Potential

One of biomethane's most notable features is its potential for negative emissions under certain conditions. Negative emissions refer to a net reduction in atmospheric carbon dioxide. This occurs particularly depending on the type of feedstock used in biomethane production and the production process [12].

In particular, during the processing of agricultural waste, animal manure, and organic waste, capturing methane that would otherwise be released into the atmosphere under natural conditions and converting it into energy can reduce net greenhouse gas emissions to negative levels. Furthermore, integrating carbon capture and storage (CCS) technologies into biomethane production processes further enhances the negative emissions effect.

Furthermore, the use of organic fertilizers (digestate)—a byproduct of biomethane production processes—in agriculture creates an indirect mechanism for carbon sequestration by increasing carbon accumulation in the soil. This makes it possible to consider biomethane not only as an energy source but also as a carbon management tool [6].

5.3. Carbon Reduction Contribution

Biomethane provides significant reductions in carbon emissions when used as a substitute for fossil fuels. While it has a lower carbon intensity compared to natural gas, coal, and petroleum derivatives, biomethane further reduces net emissions when it replaces these fuels. In particular, the use of biomethane in the transportation, heating, and industrial sectors directly contributes to decarbonizing energy systems.

Studies conducted at the European level indicate that biomethane can play a significant role in reducing transportation-related greenhouse gas emissions and could account for up to approximately 25% of total emissions[2]. This highlights that biogas is a critical alternative, particularly in sectors where electrification is challenging (e.g., heavy-duty transport, shipping).

However, biomethane's carbon reduction potential varies depending on feedstock availability, production technology, energy inputs, and distribution processes. Therefore, the life cycle assessment (LCA) approach is

crucial for accurately evaluating the environmental performance of biomethane projects[5].

6. INTEGRATION INTO THE NATURAL GAS INFRASTRUCTURE

The effectiveness of biomethane in energy systems depends not only on production processes but also on its ability to integrate into existing natural gas infrastructure. This section addresses the integration of biomethane into the grid, covering technical requirements, logistics, and infrastructure needs, with a specific focus on its feasibility in Türkiye.

6.1. Technical Requirements

The most fundamental requirement for integrating biomethane into the natural gas grid is ensuring that the gas quality meets national and international standards. Raw biogas cannot be fed directly into the grid due to its content of carbon dioxide (CO₂), hydrogen sulfide (H₂S), moisture, and other trace components; therefore, it must undergo upgrading processes. As a result of these processes, the methane content of biogas is typically increased to 96–98% and attains a quality equivalent to natural gas [3].

Another critical factor for grid injection is pressure and flow parameters. To be injected into the transmission or distribution grid, biomethane must be brought to an appropriate pressure and the gas flow controlled. For this purpose, biomethane injection stations are used; these stations ensure gas measurement, monitoring of its quality, and safe injection into the grid.

Additionally, parameters such as the Wobbe index, calorific value, and gas composition must comply with standards to ensure the gas's compatibility with the network. These technical requirements are critical for the seamless integration of biomethane into the existing natural gas infrastructure [4].

6.2. Logistics and Infrastructure Requirements

Transporting biomethane from the production point to the consumption point requires significant logistical planning. When direct access to the natural gas grid is not possible, alternative transport methods for biomethane are used. Among these methods, compressed biomethane (bio-CNG) and liquefied biomethane (bio-LNG) stand out.

While bio-CNG enables the transportation of biomethane by compressing it under high pressure, bio-LNG allows for the storage and transportation of the gas at a higher energy density through liquefaction. These technologies facilitate the integration of biomethane produced in remote regions into energy markets.

From an infrastructure perspective, additional investment requirements exist for biomethane integration. These include injection stations, gas purification units, measurement and control systems, and storage and

transportation equipment. Additionally, the role of distribution companies is critical for the acceptance and management of biomethane within the network.

To ensure cost-effectiveness in biomethane logistics, production facilities must be located near the grid, or appropriate transportation infrastructure must be developed. This necessitates the consideration of geographical and infrastructure factors during the planning phase of biomethane projects.

6.3. Feasibility for Türkiye

Türkiye possesses significant potential for biomethane integration due to its extensive natural gas transmission and distribution network. However, the current lack of regulations regarding the integration of biomethane into the grid and the insufficient clarity of technical standards prevent this potential from being fully realized.

To expand biomethane production in Türkiye, the regulatory framework must first be strengthened. Establishing quality standards for biomethane injection into the natural gas grid, clarifying licensing processes, and developing incentive mechanisms are critical to this process. Renewable gas policies and certification systems implemented in the European Union serve as an important reference for Türkiye.

Additionally, Türkiye's high potential for agricultural and organic waste offers a significant opportunity for biomethane production. Harnessing this potential will not only enhance energy supply security but also make important contributions to waste management and rural development.

Based on the national biomass resource assessment in the supporting compilation document, Türkiye has a substantial biomethane production potential derived from animal, plant, forest, and municipal waste streams. The total amount of these biomass-based waste resources is approximately 289,821,769.70 tons/year, while the theoretical biogas capacity is estimated at about $13,364.04 \times 10^6 \text{ m}^3/\text{year}$. Assuming an average methane content of 65% in biogas and a 98% upgrading efficiency, the technically convertible biomethane potential corresponds to approximately 8.3 billion m^3/year . Under the upper potential scenario, Türkiye's total biomethane capacity reaches approximately 10.4 billion m^3/year , which is equivalent to nearly 20% of the country's 2024 natural gas consumption of about 53 billion m^3 . These figures indicate that national biomethane deployment could make a measurable contribution to natural gas substitution, import reduction, and energy supply security, provided that feedstock collection, upgrading facilities, grid injection standards, and investment incentives are developed in an integrated manner [13-15].

However, the feasibility of biomethane projects is directly linked to investment costs, market conditions, and energy prices. Therefore, an integrated approach supported by public policies is essential for the successful

integration of biomethane into the natural gas infrastructure.

7. DISCUSSION

While the integration of biomethane into the natural gas infrastructure is technically and economically feasible, it presents opportunities and challenges that vary by country. This section discusses Türkiye's biomethane potential within the framework of technology selection, strategic priorities, and policy requirements.

7.1. Opportunities and Challenges in Türkiye

Türkiye possesses significant potential for organic waste production due to its extensive agricultural activities, livestock sector, and growing urban population. This situation provides a strong feedstock base for biomethane production. Additionally, the country's well-developed natural gas transmission and distribution infrastructure provides a significant advantage for integrating biomethane into the existing energy system.

The expansion of biomethane production presents a strategic opportunity to reduce dependence on energy imports and enhance supply security. Given Türkiye's high dependence on energy imports, the use of domestic and renewable resources creates a significant economic and political advantage.

However, there are some structural barriers to the development of the biomethane sector. Chief among these are regulatory gaps regarding biomethane production and grid integration. Additionally, high initial investment costs, difficulties in accessing financing, and market uncertainties pose risks for investors. From a technical perspective, the remote location of biomethane production facilities relative to the grid and logistics costs stand out as significant limiting factors.

7.2. Technology Selection and Strategic Priorities

Technology selection for biomethane production is a critical factor that directly influences the project's economic and technical success. Under current conditions, anaerobic digestion technology is considered the most suitable and feasible option for Türkiye due to its maturity, low risk profile, and broad application scope [1].

However, advanced technologies such as hydrothermal gasification offer significant long-term potential, particularly for the utilization of waste with high moisture content and achieving higher yields. Nevertheless, the high costs and limited commercialization level of these technologies restrict their widespread use in the short term.

From a strategic perspective, a two-phase approach can be recommended for Türkiye. In the first phase, the focus should be on anaerobic digestion projects that can be rapidly integrated into existing infrastructure; in the second phase, the goal should be to develop and

disseminate hydrothermal technologies through R&D investments. This approach will provide short-term economic benefits while enhancing long-term technological competitiveness.

7.3. Policy and Regulatory Needs

The development of the biomethane sector depends largely on the establishment of an appropriate policy and regulatory framework. The lack of a comprehensive, holistic legal framework for biomethane production and grid injection in Türkiye is one of the most significant factors limiting the sector's development.

In this context, the priority is to establish technical standards for integrating biomethane into the natural gas grid and to clarify licensing processes. Additionally, the creation of incentive mechanisms for renewable gases will increase investor interest in the sector. The renewable energy directives and biomethane certification systems implemented in the European Union provide a guiding model for Türkiye [2].

The development of carbon pricing mechanisms and emissions trading systems also ranks among the key tools that could enhance biomethane's economic competitiveness. Furthermore, support mechanisms and public-private partnerships that facilitate the financing of biomethane projects will contribute to the sector's sustainable growth.

In conclusion, the integration of biomethane into Türkiye's energy system depends not only on technological and economic factors but also on a robust policy and regulatory framework. Therefore, developing a comprehensive, long-term strategy is critical to the growth of the biomethane sector.

8. CONCLUSION

This study demonstrates that integrating biomethane into the natural gas infrastructure is a feasible and strategic option from technical, economic, and environmental perspectives. The analyses conducted have shown significant differences among the technologies used in biomethane production. At the same time, anaerobic digestion stands out as the most mature and economical method under current conditions; advanced technologies, such as hydrothermal gasification, although with higher yield potential, are still in development.

The results of the economic assessment indicate that biomethane production requires high initial investment costs; however, it can make significant long-term contributions to energy supply security, the use of domestic resources, and the reduction of energy imports. This situation demonstrates that biomethane is a strategic energy source not only from an environmental but also from an economic perspective. From an environmental perspective, biomethane can significantly reduce greenhouse gas emissions by controlling methane

emissions and replacing fossil fuels, and, in some cases, it can achieve negative emissions.

In conclusion, biomethane offers a significant opportunity for Türkiye in both energy security and combating climate change. The fact that biomethane is compatible with existing natural gas infrastructure provides a significant advantage during integration. However, to realize this potential in Türkiye, technical standards must be clarified, the regulatory framework developed, and investment incentives increased. In conclusion, when supported by an appropriate policy framework and technological investments, biomethane can play a significant and sustainable role in Türkiye's energy transition.

Beyond these findings, the proposed roadmap has broader strategic implications for Türkiye's energy transition. The 2025-2030 period should be interpreted as a foundation phase in which legal definitions, gas-quality standards, certification rules, pilot grid-injection projects, and regional feedstock inventories are established. The 2030-2035 period should then focus on capacity expansion through clustered anaerobic digestion plants, upgrading units located near distribution networks, and targeted incentives that reduce financing risk. In the 2035-2053 period, full integration can support a more diversified gas system by combining grid injection, bio-CNG/bio-LNG use, carbon-reduction mechanisms, and export-oriented renewable gas certification.

The roadmap also indicates that biomethane should not be evaluated only as an alternative fuel, but as a cross-sector strategy connecting waste management, rural development, energy security, and climate policy. Türkiye's estimated upper biomethane potential of approximately 10.4 billion m³/year shows that domestic biomass resources could substitute a measurable share of natural gas demand if feedstock collection, upgrading capacity, grid access, and market incentives are coordinated. In this respect, the most practical near-term strategy is to prioritize mature anaerobic digestion projects using agricultural, municipal, and food-waste streams, while supporting hydrothermal technologies through demonstration projects and R&D for high-moisture residues.

Future research should therefore move from general potential assessment toward more site-specific and decision-oriented studies. Priority research areas include GIS-based mapping of biomass resources and grid proximity, regional techno-economic models that incorporate CAPEX, OPEX, feedstock logistics, payback periods, and incentive scenarios, and life-cycle assessment studies that quantify greenhouse gas reduction and negative-emission potential under different feedstocks. Additional studies should also examine pilot-scale biomethane injection performance, gas quality monitoring, Wobbe index compliance, pressure management, certification/guarantee-of-origin

mechanisms, carbon pricing, and the comparative feasibility of biomethane use in heating, industry, transport, bio-CNG, and bio-LNG applications. These directions would provide a stronger evidence base for translating the proposed roadmap into implementable national policy and investment programs.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in their work did not require approval from an ethics committee and/or any special legal authorization.

AUTHORS' CONTRIBUTIONS

Mehmet Şerif SARIKAYA: Carried out concept development, field analyses, and data collection.

İclal GÜNEY ARSLAN: Carried out concept development, field analyses, and data collection.

Tayfun MENLİK: Performed capacity calculations and determined site selection mechanisms.

Adnan SÖZEN: Developed a forecasting methodology for the future, validated the methodology, and conducted the academic review of the article.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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