Environmental and Climate Technologies
2026, vol. 30, no. 1, pp. 89–101
https://doi.org/10.2478/rtuect-2026-0007
https://content.sciendo.com

Sustainable Biomethane Integration into Latvia's Natural Gas Network

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Received 27.07.2025; accepted 10.01.2026

***Abstract* – This paper explores sustainable integration solutions for biomethane production and injection into Latvia's natural gas network, addressing the increasing importance of renewable energy in achieving energy independence and climate neutrality. The research investigates Latvia's biomethane potential, current infrastructure limitations, and feasible integration pathways, drawing comparisons with leading European practices. A multi-criteria methodology combining technical, environmental, and economic analyses is employed to evaluate biogas upgrading technologies, grid connection strategies, and regional implementation scenarios. The study identifies membrane separation as a highly efficient biogas upgrading method and highlights centralized biomethane injection points as an optimal integration model, particularly suited for Latvia's geographically dispersed biogas production sites. Results suggest that biomethane could replace up to 50 % of Latvia's current natural gas consumption, provided that adequate policy support and infrastructure investment are in place. The study concludes with recommendations to strengthen regulatory frameworks, modernize gas infrastructure, and promote regional cooperation to support a scalable and sustainable transition to biomethane. These findings offer a strategic roadmap for Latvia's energy sector, aligned with the European Green Deal and national climate targets.**

***Keywords* – Biogas upgrading; climate neutrality; energy independence; natural gas infrastructure; renewable gases; scenario modelling; sustainable energy systems.**

Nomenclature		
AD	Anaerobic digestion	–
CAPEX	Capital expenditure	€
CH_4	Methane	–
GHG	Greenhouse gas	–
GWh	Gigawatt hour	GWh
OPEX	Operational expenditure	€/year
TWh	Terawatt hour	TWh
Baseline scenario	On-site biogas use, no grid injection	–
Regional scenario	Shared biomethane injection points with grid access	–
Full integration scenario	Direct injection into transmission grid	–
MCA	Multi-Criteria Analysis	–

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1. Introduction

The integration of renewable gases into national energy systems is a critical step toward achieving energy independence, climate neutrality, and circular economy goals. For countries seeking to decarbonize while enhancing energy security, locally produced biogas and biomethane provide viable alternatives to fossil-based energy carriers. In the context of shifting European energy markets, driven by climate policy, price volatility, and geopolitical tensions, renewable gases have moved to the forefront of long-term energy strategy. Latvia, like many EU member states, is under increasing pressure to meet EU climate targets while simultaneously reducing its reliance on imported fossil fuels.

In this study, the term "sustainable" refers primarily to the integration process itself, encompassing infrastructure design, economic performance and environmental impact, rather than to the biomethane product alone.

Natural gas remains a strategically important component of Latvia's energy mix (~13 %), particularly in industry, district heating, and peak electricity generation as shown in Fig. 1. However, its fossil origin and near-total import dependence pose significant environmental and geopolitical risks. Following the disruption of traditional supply routes and heightened concern over energy resilience, biogas produced through the anaerobic digestion of organic waste has emerged as a sustainable and locally available alternative to conventional natural gas [1]. Biogas can be upgraded to biomethane, a gas with identical chemical properties to natural gas, and injected into the existing pipeline infrastructure.

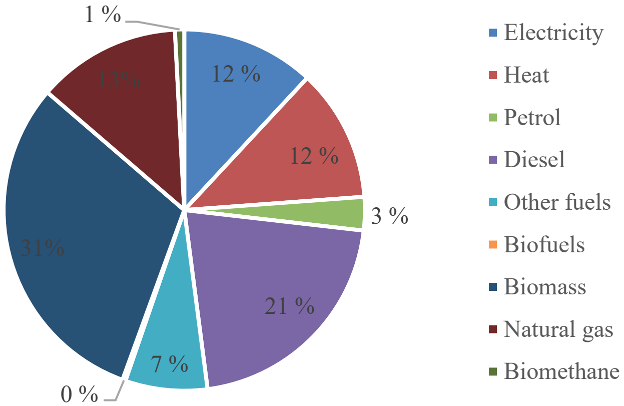

Fig. 1. Energy consumption mix in Latvia in 2023, % [12].

Despite its technical viability and environmental promise, biogas integration into Latvia's natural gas infrastructure remains underdeveloped. As of 2023, over 50 biogas plants are operational across the country with a combined installed capacity of approximately 60 MW [1]. However, only a limited number of facilities are currently connected to Latvia's natural gas grid. As of 2024, two operational biomethane injection points exist in the vicinity of Iecava, operated by JSC "Bovogas" and JSC "BM Holding", both connected to the distribution system [2]–[4]. Nearly all remaining biogas production in Latvia is still utilized for on-site combined heat and power generation [4]. This limited application restricts the scalability and strategic value of biogas. A notable turning point occurred in 2024, when JSC "Balticovo" launched the country's first biomethane production unit based on poultry manure, injecting renewable gas into the interconnected pipeline system. This project demonstrates both technical feasibility and regulatory progress, serving as a model for wider adoption [5].

Latvia's theoretical biomethane potential is estimated at roughly 4 TWh annually, which is nearly half of Latvia's current natural gas consumption [6]. This potential is distributed across various waste streams, including agricultural residues, wastewater sludge, and biodegradable municipal solid waste. Harnessing this resource could substantially decarbonize the gas sector and contribute to Latvia's renewable energy targets. However, realizing this potential is contingent upon overcoming several key challenges, including limited access to the gas grid, high capital expenditure for upgrading and injection systems, and regulatory uncertainty. Nevertheless, as illustrated in Fig. 2, Latvia holds a moderate biogas potential compared to other European countries, with higher resource availability than many Southern and Eastern European states [7]. Latvia is positioned among the medium-potential countries, with a feedstock structure dominated by forestry residues and energy crops, reflecting the significant role of forest biomass resources and agricultural land availability in the national biomethane potential [5], [6].

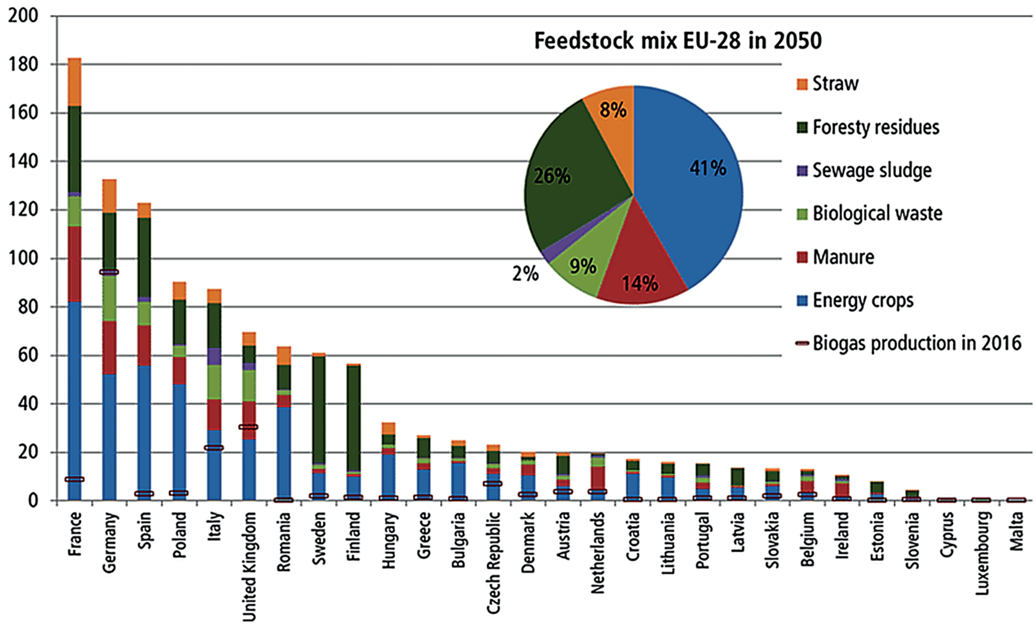

Fig. 2. Technical biomethane potential EU28 by Member State and by feedstock, TWh/yr [8].

Policy alignment is critical. While Latvia has introduced strategic frameworks such as the National Energy and Climate Plan and Latvia's Energy Strategy 2050, implementation has its challenges comparing to some other EU countries. Countries like Germany, France, and Denmark have already established nationwide biomethane injection systems supported by financial incentives, streamlined permitting, and long-term purchase guarantees. Latvia's current support mechanisms are quite new and evolving, therefore biomethane production is gradually increasing very recently. Moreover, the complexity of gas grid access, including technical standards, pressure requirements, and cost-sharing mechanisms, creates further barriers for smaller producers [9].

This paper aims to identify sustainable solutions for integrating biomethane into Latvia's gas network, evaluating technical approaches, economic feasibility, and environmental benefits. Using a multi-criteria framework and scenario-based modelling, the study assesses potential integration pathways in the Latvian context and compares them with successful models implemented across the EU. The findings contribute to the growing body of research on renewable gas systems and support Latvia's strategic objectives under the European Green Deal and Fit for 55 package [7], [8].

The scientific justification for biomethane integration as a climate mitigation and environmental protection solution is based on three main mechanisms: direct substitution of fossil natural gas, reduction of uncontrolled methane emissions from organic waste streams, and systemic efficiency gains through the utilisation of existing gas infrastructure. Biomethane produced from agricultural residues, forestry by-products and organic waste replaces fossil-based natural gas on an energy-equivalent basis, leading to substantial life-cycle greenhouse gas emission reductions, typically in the range of 70–80 % compared to conventional natural gas [9], [10].

In addition, controlled anaerobic digestion and upgrading prevent uncontrolled methane emissions that would otherwise arise from manure management, waste storage and landfilling, thereby addressing both climate change mitigation and local environmental pollution. The integration of biomethane into the existing gas network further enhances system efficiency by enabling large-scale seasonal balancing, reducing flaring and curtailment losses, and avoiding additional transport-related emissions associated with decentralised energy use [11]. Together, these mechanisms provide a scientifically grounded basis for considering biomethane grid integration as an effective pathway for simultaneous climate change mitigation and environmental pollution reduction.

Despite the growing body of research on biomethane production and grid injection in Europe, there is still a limited number of studies focusing on country-specific integration strategies that simultaneously combine technical feasibility, economic performance and multi-criteria decision analysis in the context of small and geographically dispersed producers. In the Latvian case in particular, existing studies mainly address biogas potential or individual technological aspects, while comprehensive scenario-based assessments of sustainable biomethane integration pathways remain scarce. Therefore, this study addresses this research gap by developing and comparing Latvia-specific integration scenarios using a combined technical, economic, environmental and multi-criteria framework.

2. METHODS AND METHODOLOGY

This study employs a multidisciplinary methodological approach to evaluate sustainable integration pathways for biomethane into Latvia's natural gas network. The approach was designed to reflect the complexity of the subject matter, combining technical, economic, and environmental dimensions within a structured analytical framework. To ensure robustness and policy relevance, the methodology integrates both qualitative and quantitative analyses and is grounded in official national data and industry-specific developments. The research process is structured into five main stages: (1) data gathering, (2) technical analysis, (3) economic and (4) environmental assessment, (5) multi-criteria analysis (MCA), and (6) scenario modelling.

2.1. Methodological Framework and Research Algorithm

To ensure a transparent and reproducible research design, the study follows a structured six-step methodological framework that links data collection, technical assessment, economic evaluation, environmental analysis, multi-criteria decision analysis and scenario modelling. The overall research algorithm is presented below in Table 1.

TABLE 1. RESEARCH ALGORITHM

Step 1. Data collection	**Step 2. Technical assessment**	**Step 3. Economic assessment**	**Step 4. Environmental assessment**	**Step 5. Multi-criteria analysis (MCA)**	**Step 6. Scenario modelling**
National energy balances, official statistics, policy documents, operational data from Latvian biogas plants and case study information from the first biomethane injection project were collected and systematised. These data provide the baseline for all subsequent analyses.	Biogas upgrading technologies and grid injection models were evaluated with respect to methane recovery, energy consumption, scalability and compatibility with the existing Latvian gas infrastructure.	Capital expenditures (CAPEX), operational expenditures (OPEX), revenues and payback periods were calculated for each integration scenario based on unified technical and market assumptions.	Greenhouse gas (GHG) emission reductions were estimated by comparing biomethane substitution pathways with conventional fossil natural gas, including avoided CO_2 and CH_4 emissions and co-benefits related to digestate utilisation.	A Simple Additive Weighting (SAW) method was applied to compare scenarios using four main criteria: technical feasibility, economic viability, environmental benefit and scalability.	Three development scenarios representing different levels of infrastructure integration were modelled and compared to identify the most sustainable integration pathway for Latvia.

2.2. Data Sources and Baseline Assumptions

The analysis is based on a combination of national statistical data, official policy documents and operational information from existing biogas and biomethane projects in Latvia. Core data sources include national energy balances, the National Energy and Climate Plan, infrastructure operator reports and publicly available project documentation.

To ensure consistency and comparability across scenarios, a unified set of baseline assumptions was applied throughout the technical, economic and environmental analyses. Annual biomethane production was fixed at 20 000 MWh for each scenario. The distance between production sites and injection or consumption points was assumed to be 10 kilometres. The biomethane market price was assumed at 70 EUR/MWh, reflecting recent European market averages and national policy benchmarks.

These baseline assumptions define the reference conditions for scenario modelling and ensure that observed differences between scenarios result from infrastructure configuration and integration strategy rather than from external parameter variation.

The first phase of the study involved a comprehensive review and collection of data from public sources, national strategic documents, and industry case studies. The data used were obtained from Latvia's national energy balance reports, policy frameworks, and operational data from existing biogas plants [5], [12]. Core national planning instruments were central to this phase, including the National Energy and Climate Plan 2021–2030, Latvia's Energy Strategy 2050, and the State Waste Management Plan 2021–2028. These documents provided both baseline figures and strategic targets relevant to biomethane development. In addition, market-specific information was gathered from technology providers and stakeholders involved in Latvia's first biomethane injection project. Special attention was given to the case of JSC "Balticovo", which launched biomethane production from poultry manure and became the first facility in Latvia to inject biomethane into the interconnected gas system. This case served as a reference point for evaluating real-world implementation potential [12].

The second stage focused on the technical analysis of biogas upgrading and grid injection technologies. Multiple biogas upgrading methods were examined, including water scrubbing, pressure swing adsorption, chemical absorption, and membrane separation. Based on comparative performance data and Latvian context factors (plant size, input variability, energy use), membrane separation was selected as the most appropriate technology (see Fig. 3). It offers high methane (CH_4) purity levels (typically > 96 %), low parasitic energy demand, operational simplicity, and modular scalability, making it suitable for decentralized deployment across rural Latvia [13]. In parallel, infrastructure models for biomethane injection into the gas network were assessed. These included direct connections from individual production sites to local or national pipelines, and centralized injection facilities that serve multiple producers. The technical viability of each model was analysed in terms of pipeline compatibility, pressure regulation, access costs, and alignment with existing gas infrastructure [14].

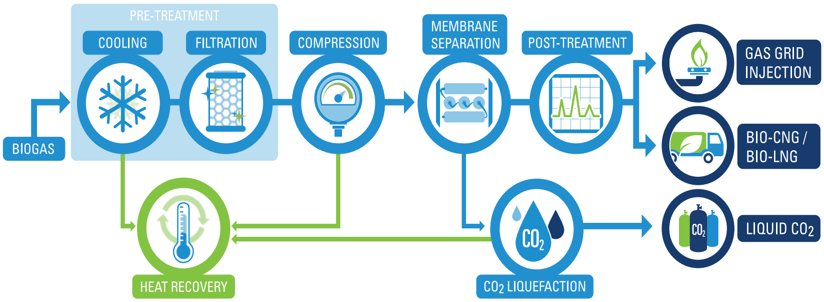

Fig. 3. Biogas upgrading process using membrane separation technology [15].

The third stage involved an economic and environmental assessment of biomethane integration options. Cost categories evaluated included CAPEX for upgrading systems, compression equipment, and pipeline construction, as well as OPEX for energy use and maintenance. Investment benchmarks were derived from recent EU and regional infrastructure reports, including sector-specific studies noting pipeline construction costs of over € 6 million per kilometre in developed areas [16]. In parallel, the study assessed environmental performance based on avoided GHG emissions. Biomethane was evaluated as a substitute for fossil natural gas, with its life-cycle emissions significantly lower due to the reuse of organic waste and prevention of CH_4 leakage from manure storage, food waste decomposition, and wastewater treatment. The use of digestate as a natural fertilizer was also factored in as a co-benefit, contributing to reductions in synthetic fertilizer use and improving nutrient cycles in agriculture [8].

The environmental assessment focuses on the estimation of avoided greenhouse gas emissions resulting from biomethane substitution of fossil natural gas. Emission reductions include avoided CO_2 emissions from fossil fuel combustion and avoided CH_4 emissions from uncontrolled organic waste decomposition. The assessment follows a comparative approach, expressing environmental performance as relative GHG reduction per unit of energy supplied.

2.3. Multi-Criteria and Scenario Modelling Approach

The multi-criteria and scenario modelling approach integrates technical, economic and environmental performance indicators into a unified decision-support framework. Three development scenarios representing increasing levels of biomethane grid integration are evaluated consistently across all analytical dimensions.

In the fourth stage, MCA was performed to systematically compare the integration options based on a defined set of indicators. The MCA included four key evaluation dimensions: (1) technical feasibility, (2) economic viability, (3) environmental benefit, and (4) scalability. These criteria were selected to reflect both policy objectives and practical implementation challenges in the Latvian context. Each criterion was assigned a weight based on its relevance to national strategic priorities, stakeholder feedback, and literature benchmarks. For instance, scalability was emphasized to ensure the chosen solution could be extended from a pilot phase to a broader national implementation. Technical feasibility considered both proven performance and compatibility with local conditions, while economic viability included capital cost thresholds, financing availability, and lifecycle returns. Environmental benefits were defined in terms of carbon intensity reduction, waste valorization, and alignment with climate neutrality goals. The MCA allowed for the comparison of various upgrading and injection configurations under a unified evaluation framework, improving transparency in decision-making [12].

The final stage of the methodology was scenario modelling, aimed at projecting the long-term implications of different biomethane integration strategies under varying levels of intervention. In this study, the baseline, regional injection and full integration development pathways correspond directly to Scenario 1, Scenario 2 and Scenario 3 used in the economic and multi-criteria analysis. Scenario 1 represents the baseline case with on-site biogas use and no grid injection. Scenario 2 corresponds to the regional injection model with shared injection points and road transport of biomethane. Scenario 3 represents full integration through direct injection into the gas transmission system. This unified scenario structure is applied consistently throughout the technical, economic, environmental and multi-criteria assessments.

Three distinct development scenarios were created based on national priorities and EU-level decarbonisation goals. Scenario 1 represents a minimal intervention approach, in which current self-consumption practices continue, and no grid connections are pursued.

Scenario 2 models the establishment of regional biomethane injection points, which aggregate output from multiple decentralized biogas producers for injection into the gas grid at shared, centralized locations. This model supports more efficient infrastructure use and lowers entry barriers for smaller producers by enabling shared investment in upgrading and injection technologies. In some cases, this infrastructure may be developed directly by the unified gas transmission and storage system operator, which can ensure equal access and system compatibility. In Latvia, the transmission system operator JSC "Conexus Baltic Grid" has already launched the development of public biomethane injection points, aimed at creating standardized and accessible interconnection hubs across the country [17].

Scenario 3 involves direct integration into the national gas transmission system, with individual biogas plants upgraded to inject at high pressure and meet full grid compatibility standards.

Each scenario was evaluated across multiple timeframes, with consideration of regulatory evolution, funding availability, and market demand. The scenarios were constructed to highlight trade-offs between capital cost, emissions reduction, and implementation complexity [7].

Together, these five methodological stages provide a comprehensive and replicable framework for assessing renewable gas integration strategies in national energy systems. The approach balances technical rigor with policy relevance and is designed to inform both investment decisions and long-term planning in the Latvian energy sector.

3. RESULTS

The results of this study provide a comprehensive, evidence-based evaluation of Latvia's potential to integrate biomethane into its natural gas infrastructure. The findings are structured into four main thematic areas: technical feasibility, economic performance, environmental impact, and scenario-based development pathways. Together, these results form a multidimensional view of Latvia's readiness and requirements for a national-scale biomethane integration strategy.

3.1. Technical Assessment Results

Technical feasibility analysis confirmed that the production of biomethane from Latvia's agricultural, industrial, and municipal organic waste streams is technically viable and can meet the quality requirements for injection into the existing gas grid. Latvia's feedstock base – primarily poultry manure, food processing residues, wastewater sludge, and silage – was found to be rich in biogas potential and broadly aligned with EU trends. Among the upgrading technologies assessed, membrane separation emerged as the most suitable for Latvia's context due to its high CH_4 recovery efficiency (typically above 96 %), compact footprint, and operational simplicity [13]. Unlike more capital-intensive technologies such as water scrubbing or chemical absorption, membrane separation is also more adaptable to small and medium-sized facilities.

In addition to upgrading technology selection, the study assessed two primary models for grid injection. The first involves direct connections between individual biogas plants and nearby pipeline infrastructure, allowing for on-site upgrading and compression. The second model consists of centralized biomethane injection points, where biogas from several producers is collected, upgraded, and injected at a single shared point. The analysis showed that while both models are technically feasible, centralized biomethane injection points are more compatible with Latvia's biogas landscape, which is characterized by small, geographically dispersed producers [18]. Centralized systems also reduce the duplication of equipment and lower unit costs per volume of gas injected.

3.2. Economic Performance and Environmental Impact Results

The results indicate that large-scale, plant-specific pipeline connections are cost-effective only for a limited number of facilities located near high-pressure transmission pipelines. The capital costs for establishing individual injection points – including compression, metering and grid compliance – can quickly exceed economically viable thresholds when considered at small production scales. Conversely, centralised injection points combined with road transport of biomethane represent a more economically efficient solution for smaller producers. In peri-urban areas, pipeline construction costs may reach up to approximately 6.2 million EUR per kilometre, underlining the importance of strategic site selection.

Table 1 summarizes the comparative economic performance and environmental benefits of the three scenarios. Scenario 1 exhibits the highest capital investment requirements and the longest payback period (59.2 years), making it economically unattractive. Scenario 2 significantly improves economic feasibility, reducing the payback period to 10.8 years, while

Scenario 3 achieves the most favourable economic performance with a payback period of 8.1 years.

From an environmental perspective, all scenarios provide substantial greenhouse gas mitigation benefits through the substitution of fossil natural gas with renewable biomethane. The estimated annual CO_2 emission reductions range from 13 640 to 14 918 tonnes of CO_2 per year, with Scenario 3 delivering the highest environmental benefit due to its higher system efficiency and direct integration into the transmission network. These results demonstrate that scenarios offering superior economic performance simultaneously achieve the largest climate mitigation effects.

TABLE 2. COMPARATIVE EVALUATION OF BIOMETHANE INTEGRATION SCENARIOS

	CAPEX, €	**OPEX, €/year**	**Estimated income, €/year**	**Payback period, years**	**GHG reduction, tonne CO_2/year**
1st scenario	17 050 000	1 112 275	1 400 000	59.2	13 640
2nd scenario	6 400 000	808 400	1 400 000	10.8	13 637.75
3rd scenario	5 200 000	757 847	1 400 000	8.1	14 917.75

3.3. Multi-Criteria Analysis Results

As regards MCA, the normalized performance scores for each scenario and evaluation criterion are presented in Table 3, while the corresponding weighted scores and final ranking are shown in Table 4.

TABLE 3. NORMALIZED PERFORMANCE SCORES AND CRITERION WEIGHTS FOR THE SCENARIOS

Criterion	**Weight**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Capital expenditure (CAPEX)	0.30	0.30	0.81	1.00
Operating expenditure (OPEX)	0.20	0.68	0.94	1.00
GHG emissions	0.30	0.91	0.91	1.00
Technical feasibility	0.20	0.75	1.00	0.63

The results indicate that Scenario 3 achieves the highest overall weighted score (0.926), followed closely by Scenario 2 (0.904), whereas Scenario 1 exhibits substantially lower performance (0.649). Scenario 3 performs best in terms of economic indicators and GHG emission reduction, while Scenario 2 achieves the highest technical feasibility score. Scenario 1 is penalised mainly due to high capital investment requirements and lower technical performance.

TABLE 4. WEIGHTED SCORES AND FINAL RANKING OF BIOMETHANE INTEGRATION SCENARIOS

Scenario	**Weighted score calculation**	**Final score**
Scenario 1	(0.30×0.30) + (0.20×0.68) + (0.30×0.91) + (0.20×0.75)	0.649
Scenario 2	(0.30×0.81) + (0.20×0.94) + (0.30×0.91) + (0.20×1.00)	0.904
Scenario 3	(0.30×1.00) + (0.20×1.00) + (0.30×1.00) + (0.20×0.63)	0.926

These results confirm that both Scenario 2 and Scenario 3 represent robust integration pathways, with Scenario 3 demonstrating the strongest overall performance under the applied weighting scheme.

3.4. Scenario Modelling Results

Scenario modelling was conducted to evaluate the long-term strategic implications of different integration pathways, each reflecting distinct levels of infrastructure development, investment commitment, and policy support. The scenarios were developed to simulate realistic trajectories for biomethane integration under Latvia's national conditions and in alignment with EU energy and climate targets.

Baseline scenario assumes a continuation of the status quo, with biogas used exclusively on-site for electricity and heat generation. While this approach is low-cost and operationally simple, it limits the contribution of biomethane to national decarbonisation goals and energy diversification. No grid injection infrastructure is developed, and emission reductions remain localized and marginal.

Regional injection scenario provides intermediate pathway, where biomethane is produced and upgraded directly at the biogas production site, typically compressed on-site as bioCNG and then transported by truck to a central injection hub. This model is currently the only practical integration pathway used in Latvia, as there are no existing policy frameworks or infrastructure models that support raw biogas collection and central upgrading near injection points [17]. Nevertheless, the use of shared injection infrastructure allows small and medium-scale producers to access the gas network without building their own injection terminals. This system provides modular scalability and leverages mobile transport solutions, which are well-suited to Latvia's dispersed agricultural landscape. While centralized upgrading remains uncommon, the ongoing development of public biomethane injection points offers strategic flexibility for further expansion [3], [17].

Full integration scenario involves direct connection of biogas plants to the national gas transmission grid, with full upgrading and compression at each site. It represents the most capital-intensive option, requiring significant upgrades to plant infrastructure and adherence to strict grid standards. While this pathway delivers the highest potential for fossil gas substitution and emissions reduction, it entails the greatest regulatory and financial challenges and is less feasible for small operators [19].

After comparing the three scenarios using the multi-criteria framework, the second option – regional injection hubs – was identified as the most viable short to mid-term strategy for Latvia. It offers a high degree of technical and logistical feasibility, provides tangible environmental benefits, and maintains economic rationality for both public and private stakeholders. It also lays the foundation for future expansion into full national integration if supported by appropriate policy and financial instruments [5], [7].

4. DISCUSSION/CONCLUSION

The findings of this study confirm that Latvia holds considerable untapped potential to integrate biomethane into its national gas system. With over 50 operational biogas plants generating energy from agricultural, food industry, and municipal waste streams, the technological foundation for scaling up renewable gas is in place. However, as of the time of this study, none of these facilities were connected to the national gas grid, and their output remained confined to on-site electricity and heat generation. This underscores a major disconnect between Latvia's renewable energy capacity and its utilization within national infrastructure planning. The successful commissioning of JSC "Balticovo's" biomethane injection project marks a turning point for future successful biomethane plan developments in Latvia. By demonstrating the technical and regulatory feasibility of biomethane injection into the gas grid, the project provides proof of concept that can serve as a model for replication [12].

The comparative analysis of integration models indicates that the development of dedicated biomethane injection points represents the most practical and scalable solution for Latvia in the short to medium term. While fully centralized upgrading and injection hubs pooling gas from multiple producers are not currently implemented or planned in Latvia, the emerging model of shared injection infrastructure, where biomethane is upgraded and compressed on-site and transported to public injection points, addresses key barriers for small and mid-sized producers. This setup supports access to the gas network without requiring each producer to invest in complex injection infrastructure, making it especially suitable for Latvia's fragmented agricultural sector, where livestock and crop-based biogas production is widely dispersed. The planned expansion of public injection points by the transmission system operator enables greater logistical and economic flexibility, even without centralized upgrading [15], [17].

In contrast, full-scale integration into the national transmission system is beneficial from an emissions standpoint, however it demands significantly higher capital investment and operational complexity. Such projects require advanced upgrading and compression technology, pressure compatibility, grid synchronization, and rigorous compliance with injection standards. The permitting and regulatory burdens for these projects are also considerably higher, often exceeding the capacity of small operators to navigate independently [13].

From an economic perspective, one of the most significant barriers to biomethane integration remains the high cost of infrastructure, particularly pipeline extensions and gas compression systems. Most biogas production facilities in Latvia are located in rural or peri-urban areas, often far from high-pressure gas transmission pipelines. This geographic disconnect necessitates either the construction of dedicated injection extensions or the transport of upgraded biomethane to centralized injection points. Nevertheless, recent policy initiatives in Latvia creating EU funded program for biomethane project development indicates a shift toward strategic support for overcoming these economic barriers.

Environmental analysis further reinforces the value of biomethane integration. Biogas sourced from organic waste streams carries an inherent emissions mitigation benefit. When upgraded and injected into the gas grid, biomethane can replace fossil natural gas with much less lifecycle GHG emissions. Biomethane supports both climate mitigation and the principles of sustainable land management.

Policy coherence and institutional readiness are pivotal to unlocking this potential. A comparison with EU frontrunners such as Germany and Denmark reveal that technical capacity alone is insufficient. These countries have successfully deployed biomethane at scale not only due to strong technological bases but also due to long-term policy stability, feed-in tariffs, injection guarantees, and integrated rural energy programs. Latvia's current framework, while evolving, remains fragmented. Inconsistent permitting standards, uncertainty over return on investment, and limited coordination between stakeholders continue to slow progress. Streamlining the permitting process, expanding eligibility for support schemes, and establishing clear grid access protocols will be essential for market maturation.

In conclusion, this study affirms that Latvia possesses both the resource base and technical capability to integrate biomethane into its gas system in a manner that supports national energy, environmental, and economic objectives. The most strategic and achievable path forward involves a phased rollout, beginning with the development of regional injection hubs that serve clusters of existing biogas producers. This model is adaptable, scalable, and well-suited to Latvia's rural and agricultural profile. Over time, this foundation can evolve into more advanced forms of integration, including direct transmission system connections, contingent on technical upgrades and policy incentives.

To ensure long-term success, the Latvian government and energy sector must prioritize regulatory clarity, investment de-risking, and alignment with EU decarbonisation mechanisms. Cross-border knowledge exchange, public-private partnerships, and the adaptation of best practices from more mature biomethane markets will also accelerate development. With the right conditions in place, biomethane can become a core pillar of Latvia's transition to a low-carbon, secure, and sustainable energy system.

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