Ance Ansone

BIOMETHANE SUSTAINABILITY ON THE PATH TOWARDS AN INNOVATIVE ENERGY SYSTEM

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Natural Sciences and Technology
Institute of Energy Systems and Environment

Ance Ansone
Doctoral Student of the Study Programme “Environmental Engineering”

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Scientific supervisor
Professor Dr. habil. sc. ing.
DAGNIJA BLUMBERGA

Associate Professor PhD
LĪGA ROZENTĀLE

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (PhD), the present Doctoral Thesis has been submitted for defence at the open meeting of the RTU Promotion Council on 20 August 2026, at 14:00, at the Faculty of Natural Sciences and Technology of Riga Technical University, Āzenes iela 12/1, Room 607.

OFFICIAL REVIEWERS

Dr. sc. ing. Gatis Bažbauers
Riga Technical University

D. sc. (Tech.) Timo Laukkanen
Aalto University, Finland

Dr. sc. ing. Anna Volkova
Tallinn University of Technology, Estonia

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (PhD) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Ance Ansone ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, Methodology, Results, Conclusions, 51 figures, 27 tables, and 28 equations; the total number of pages is 159. The Bibliography contains 222 titles.

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ABBREVIATIONS

5GDHS	Fifth Generation District Heating Systems
AD	Anaerobic Digestion
BIP	Biomethane Injection Point
CH_4	methane
CNG	Compressed Natural Gas, bioCNG – compressed biomethane, bioLNG – liquified biomethane
CO_2	compressed biomethane
DEN	liquefied biomethane
EK	carbon dioxide
ENTSOG	District Energy Network
ES	European Union
ETS 2	EU Emissions Trading System 2 (ETS 2). It covers fuel consumption in buildings, road transport, and certain industrial sectors. The objective of ETS 2 is to reduce greenhouse gas (GHG) emissions in the covered sectors by 62 % by 2030. Emissions trading under ETS 2 will be introduced in 2027.
H_2S	hydrogen sulphide
HP	Heat Pumps
LCA	Life Cycle Analysis
LNG	Liquefied Natural Gas, bioLNG – liquefied biomethane
MCA	Multi-Criteria Analysis
MCDA	Multiple Criteria Decision Analysis
MILP	Mixed-Integer Linear Programming
NECP	National Energy and Climate Plan 2030
N_2	nitrogen
O_2	oxygen
PSO	transmission system operator
ppm	parts per million
PGK	underground gas storage
RED II	Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance).
RED III	Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652
REPowerEU	Brussels, 18.5.2022, COM(2022) 230 final, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL

	COMMITTEE AND THE COMMITTEE OF THE REGIONS, REPowerEU Plan
SEG / GHG	greenhouse gases
SPRK	Public Utilities Commission of Latvia, national regulatory authority
SVID	assessment method for evaluating strengths, weaknesses, opportunities, and threats (SWOT analysis)
TOPSIS	MCDA – technique for order preference by similarity to ideal solution

INTRODUCTION

Biomethane has become one of the most significant renewable gaseous energy resources in the EU in recent years for achieving climate neutrality and energy supply security objectives.

The energy transition from the use of fossil energy resources to the integration of renewable energy sources into the existing energy system, as well as the development of new systems, provides system sustainability while simultaneously facing challenges. The development and integration of renewable gases into the existing energy structure is a multifaceted process influenced by technological, socioeconomic, and environmental aspects. In this context, biomethane is considered one of the most promising renewable gaseous energy resources, as it can utilise the existing natural gas infrastructure while contributing to the reduction of greenhouse gas emissions, the development of the circular economy, and the strengthening of energy independence. The development of biomethane is constrained by regulatory, economic, and technical challenges, which are often interrelated and require a multifaceted approach for their assessment.

Therefore, within the framework of this Doctoral Thesis, several research questions were formulated, for which answers and explanations were sought using a multifaceted methodological approach.

Research Questions

The general research problem addressed in the Doctoral Thesis is how biomethane can be sustainably, efficiently, and systematically integrated into the Latvian energy system and gas infrastructure to support decarbonisation, energy security, and circular economy objectives.

Accordingly, the following main research questions were formulated.

- What methods are appropriate for the systematic study of biomethane?
- What topics and challenges are currently relevant in scientific research; do these challenges correspond to the Latvian case; and which aspects remain insufficiently studied?
- How is biomethane integrated into energy systems in practice, and how is it utilised in cities?
- How can biomethane be integrated into the energy market, and how optimal is it as a gaseous fuel?
- What factors influence biomethane production, and how can production efficiency be improved?
- How economically justified is the production and utilisation of biomethane?
- What is the systemic role of biomethane, and what are its benefits?

Aim and Objectives of the Doctoral Thesis

The Doctoral Thesis aims to analyse the factors influencing the selection of biomethane as a suitable energy resource, its optimal integration and entry into the energy system, and to identify biomethane as a widely applicable feedstock and energy source across different sectors.

Within the framework of the Thesis, a scientifically grounded and practically applicable decision-support assessment framework is developed for the sustainable development and integration of biomethane into the Latvian energy system.

The analysis combines technical, environmental, economic, and regulatory assessments, as well as mathematical calculations, to support data-driven decision-making for the decarbonisation of the gas sector, the integration of biomethane into gas infrastructure, and the promotion of the circular economy.

To achieve this aim, the following research objectives were defined.

- To assess the energy potential of biomethane, including the analysis of biogas feedstocks and the quantification of the theoretical and technically available biomethane potential in Latvia.
- To develop and analyse biomethane integration infrastructure solutions by establishing and comparing three biomethane market integration scenarios: (1) direct connection to the natural gas system; (2) biomethane injection points (BIPs), or a virtual pipeline concept, where biomethane is transported in compressed form by road freight containers for injection into the gas system; and (3) supply outside the gas system directly to the end consumer.
- To perform a multi-criteria sustainability assessment using the TOPSIS method for the comparison of alternatives based on environmental, economic, and technical indicators.
- To analyse biomethane production performance and feedstock optimisation opportunities by conducting regression and statistical analyses using data from a full-scale biomethane production plant.
- To evaluate the relationship between the feedstock mix used, methane concentration, production costs, and greenhouse gas emissions.
- To analyse the Latvian and European Union regulatory and policy frameworks related to biomethane integration.

Hypothesis

By modelling biomethane integration into the energy system through optimised infrastructure solutions and a combined analytical approach (quantitative data and expert assessment), it is possible to identify biomethane integration scenarios that provide higher overall sustainability and economic efficiency compared to alternative options.

Scientific Novelty of the Doctoral Thesis

The scientific novelty of the research lies in the application and integration of several existing methods within a unified analytical framework to address the previously insufficiently studied issue of optimal biomethane development from multiple perspectives. The analysis encompasses technological, economic, social, and environmental aspects within a single systemic framework. An additional novelty is the comprehensive assessment of biomethane development specifically within the Latvian national context.

The Thesis develops an integrated analytical framework through the combined application of multiple methods, bringing together technological, economic, environmental, and regulatory aspects within a unified, multi-method and systematically structured approach.

A comparison of different biomethane integration scenarios into infrastructure has been carried out in Latvia using multi-criteria decision analysis based on the TOPSIS method. Furthermore, a conceptual decision-support model has been developed using TOPSIS, which can support biomethane development in emerging markets by integrating the principles of multi-criteria decision analysis. An analysis of biomethane production efficiency has been conducted using operational data from a full-scale Latvian biomethane production plant, examining the influence of feedstocks on production performance. An optimisation model for the evaluation of biomethane production and its integration into the energy system has also been developed. Finally, biomethane has been analysed not only as a substitute for natural gas but also as a versatile component of the existing energy system and a complementary element that supports transport sector decarbonisation, the development of district heating systems, and increased energy system flexibility, particularly in the context of decarbonisation and future renewable energy requirements.

Practical Significance

The practical significance of the Doctoral Thesis is closely linked to the implementation of national energy, climate, and regional development policies. The solutions developed in the Thesis serve as decision-support tools for potential biomethane consumers, producers, and infrastructure operators when evaluating and selecting biomethane connection strategies and production processes. They also provide support for policymakers, enabling them to objectively determine the most appropriate directions for targeted public support measures.

Based on the analysis of operational data from a real biomethane production facility, the Thesis provides practically applicable conclusions for optimising biomethane plant operations and feedstock utilisation, contributing to more efficient resource use and reduced production costs. The research findings also contribute to the planning of district heating system decarbonisation in cities and regions, as well as to the development of hybrid bioenergy systems, taking into account international experience and best practices.

The findings of the Doctoral Thesis can be practically applied in the implementation of regional development, circular economy, and waste management strategies by promoting the utilisation of local bioresources, strengthening regional economies, and reducing environmental impacts. The research results provide a practical foundation for improving national biomethane policy, planning investments in the gas sector, developing municipal district heating decarbonisation programmes, and supporting the transition of the transport sector towards the use of renewable energy sources.

Approbation of Research Results

The results of the Doctoral Thesis research have been presented in six international scientific publications.

1. Ansone, A., Rozentale, L., Bariss, U., & Blumberga, D. “Status and Potential Role of Biomethane in the Way Towards Gas Sector Decarbonization: Case study of Latvia,” 2024 IEEE 65th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 2024, pp. 1–7, https://doi.org/10.1109/RTUCON62997.2024.10830916
2. Ansone, A., Rozentale, L., Rochas, C., & Blumberga, D. (2026). Decision-Support Analysis of Biomethane Infrastructure Options Using the TOPSIS Method. Sustainability, 18(2), 1086. https://doi.org/10.3390/su18021086
3. Treimane, M., Ansone, A., & Rozentāle, L. (2026). Sustainable Biomethane Integration into Latvia’s Natural Gas Network. Environmental and Climate Technologies, 30(1), 89–101. https://doi.org/10.2478/rtuect-2026-0007
4. Ansone, A., Rozentale, L., & Blumberga, D. (2025). Toward an Integrated Approach – A Conceptual Framework for Complex Biomethane Development. Environmental and Climate Technologies, 29(1), 725–741. https://doi.org/10.2478/rtuect-2025-0048
5. Ansone, A., Rozentale, L., Pelss, M., Rochas, C., Blumberga, D. “Gaseous bioresources towards climate neutrality: Case study of Latvia,” Renew Energy, submitted for publication “Renewable Energy”, 2026 (submitted for review).
   https://papers.ssrn.com/sol3/papers.cfm?abstract_id=6066095.
6. Ansone, A., Brence, K., Rozentale, L., Rochas, C., & Blumberga, D. (2026). Integration of Biogas Utilisation in District Heating Systems. Energies, 19(1), 216. https://doi.org/10.3390/en19010216

The results of the Doctoral Thesis research have been presented at five international scientific conferences.

1. A. Ansone, L. Rozentale, U. Bariss, D. Blumberga, “Status and Potential Role of Biomethane in the Way Towards Gas Sector Decarbonization: Case study of Latvia,” 2024 IEEE 65th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 12.10.2024.
2. A. Ansone, L. Rozentale, and D. Blumberga, Evaluating Biomethane Market Entry Strategies: MCDA-Based Insights on Connection Scenarios Using TOPSIS, the 20th Conference on Sustainable Development of Energy, Water and Environment Systems, held October 5–10, 2025, Dubrovnik, Croatia.
3. M. Treimane, A. Ansone, and L. Rozentāle, “Sustainable biomethane integration into Latvia’s natural gas network,” Conference of Environmental and Climate Technologies, Riga, Latvia, 15.05.2025.

4. A. Ansone, L. Rozentāle, D. Blumberga, “Toward an integrated approach – a conceptual framework for complex biomethane development,” Conference of Environmental and Climate Technologies, Riga, Latvia 14.05.2025.
5. A. Ansone, L. Rozentale, M. Pelss, C. Rochas, and D. Blumberga, “Gaseous bioresources towards climate neutrality: Case study of Latvia,” 11th International Conference on Smart Energy Systems, Copenhagen, Denmark, 16.09.2025.

Structure of the Doctoral Thesis and Research Methods Applied

To achieve the aim and objectives of the Doctoral Thesis, the structure of the Thesis was designed with a focus on biomethane and is illustrated in Fig. 1. The Doctoral Thesis (1) integrates multiple aspects related to the physical market integration and utilisation of biomethane, as well as the analysis of associated influencing factors, (2) includes a comprehensive analysis through the application of various research methods, and (3) proposes diverse models with practical applicability, covering the entire biomethane value chain from production to end-use.

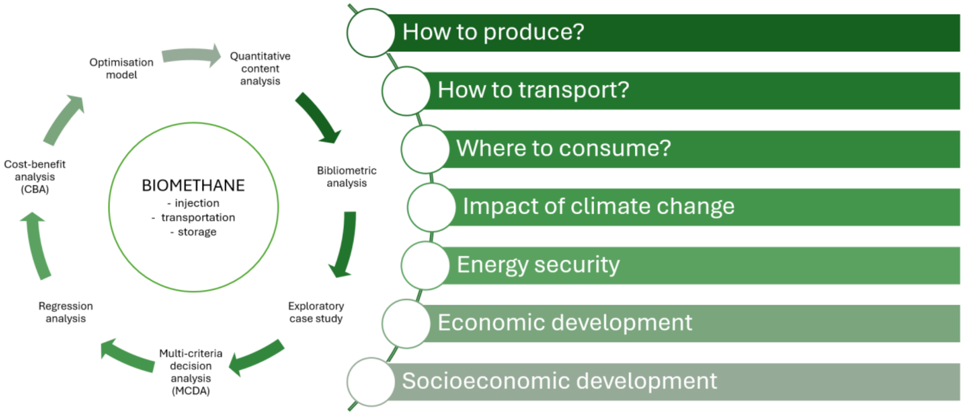

Fig. 1. Structure of the Doctoral Thesis.

The Doctoral Thesis has been developed using a multi-method research approach encompassing literature analysis, data processing, and examination of the regulatory framework.

1. LITERATURE REVIEW

Biogas is a gas produced from renewable resources that consists primarily of methane (CH_4) and carbon dioxide (CO_2), while other minor components include hydrogen sulfide (H_2S), nitrogen (N_2), and oxygen (O_2). Biomethane is produced through the anaerobic degradation and digestion of organic materials, such as agricultural residues, food waste, and sewage sludge [1]–[5].

By removing impurities from biogas, biomethane is obtained. Biomethane is a sustainable and renewable alternative to fossil methane that can replace fossil natural gas, while its development continues to face political, technical, and economic challenges.

1.1. European Union and Latvian Strategic Objectives for Biomethane Production

According to the REPowerEU Plan, published by the European Commission in May 2022 with the objective of gradually phasing out fossil fuel imports and promoting (1) clean energy production, (2) energy savings, and (3) diversification of energy supplies within the European Union (EU), one of the key targets is to increase sustainable biomethane production to 35 billion cubic metres, or approximately 370 TWh, by 2030 [6], [7]. For comparison, biomethane production in the EU in 2020 was ~ 32 TWh [8], which means that, within a relatively short period of time, biomethane production in the EU must increase 11.6 times. The estimated biomethane potential in the EU by 2030 is 44 billion cubic metres, or ~ 430 TWh [9]. Therefore, the estimated EU biomethane potential for 2030 is approximately 16 % higher than the production target of around 370 TWh, creating potential benefits for existing gas transmission and storage systems, as well as for economic development and the achievement of sustainability objectives at the national level.

As countries set increasingly ambitious net-zero emission targets, the transition to renewable energy systems is becoming both an environmental necessity and an economic opportunity. In Latvia, a key challenge is the underutilised potential for biomethane production. At the same time, the NECP already outlines potential measures for promoting biomethane development by 2030.

1.2. Energy Consumption Forecasts

In 2024, the first biomethane production plant connected to the national natural gas entry-exit system commenced operation in Latvia, with a production capacity of up to 100 GWh per year. According to the Eurostat energy balance for 2021, 0.07 billion m^3 of biogas, equivalent to 0.42 TWh (assuming a calorific value of 6 kWh/m^3 for conversion), was produced in Latvia, without distinguishing between different biogas production pathways [10]. However, at that time, there were no biomethane production plants connected to the gas supply system that would allow biomethane to enter the Latvian energy market.

According to official national statistics, annual natural gas consumption in Latvia in 2025 was 8.8 TWh [11]. Although gas consumption is expected to gradually decline in the coming years, it is projected to remain relatively stable in the medium term. This decline is driven by factors such as warmer winters, which reduce natural gas consumption, lower industrial demand, and the transition from gaseous fuels to renewable energy technologies. Nevertheless, certain sectors will continue to require gaseous fuels, where biomethane could serve as an ideal renewable alternative.

The Latvian Energy Strategy 2050 provides long-term planning guidelines that include various development scenarios for Latvia’s energy sector that may materialise by 2050, based on the currently established national objectives and factors that could influence the future development of the energy sector. Natural gas (fossil methane) plays a significant role in Latvia’s energy balance, and it is important that gaseous energy resources continue to contribute to energy supply security and the balancing of renewable electricity generation capacity within the energy system in the long term.

Based on the overall energy consumption projections presented in the Strategy, Fig. 1.1 summarises the forecast structure of gaseous energy resource consumption.

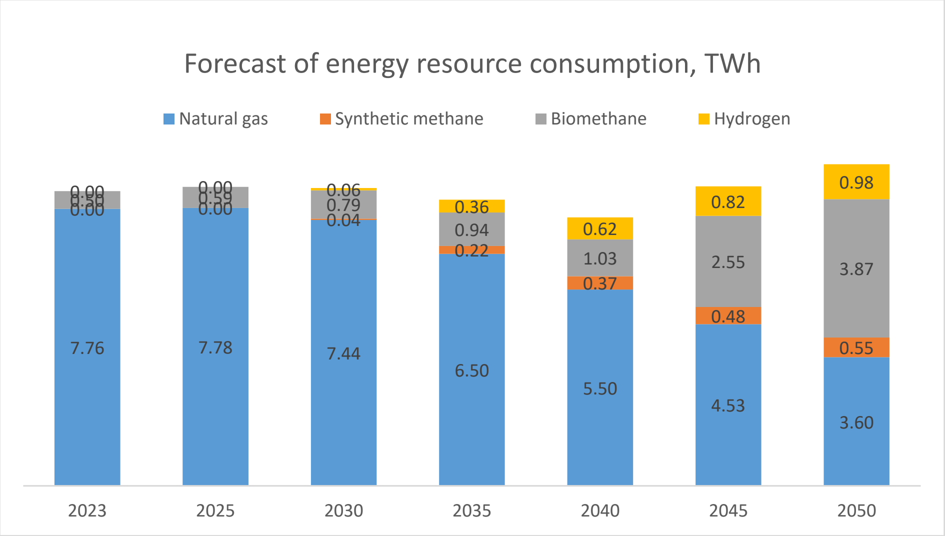

Fig.1.1. Forecast of Gas Consumption in Latvia for 2023–2050, TWh [compiled by the author based on [12]].

Biomethane consumption is also projected to increase by more than sevenfold, from 0.5 TWh in 2023 to 3.87 TWh by 2050, exceeding natural gas consumption. The Latvian Energy Strategy projected natural gas consumption at 7.76 TWh for 2023, while the actual natural gas consumption reached 8.2 TWh. In 2025, natural gas consumption in Latvia amounted to 8.83 TWh, indicating that actual consumption exceeded the forecast prepared for 2025. This confirms the continued importance of gas in the structure of energy consumption [13].

1.3. Biomethane Deployment in the European Union and Latvia

More than 21 000 biogas plants are in operation across Europe, collectively producing approximately 234 TWh annually and supplying around 7 % of the European Union's gas demand [14]. Overall, it can be concluded that the production of renewable gases that can be used as substitutes for fossil methane is gradually increasing.

A gradual increase in biomethane volumes injected into the European gas system can also be observed across most European countries. During the period from October 2024 to September 2025, the largest biomethane volumes were injected in France, Germany, Denmark, Italy, and the Netherlands (Fig. 1.2). The high figures observed in France and Germany are consistent with data showing the largest installed biomethane production capacities in these countries.

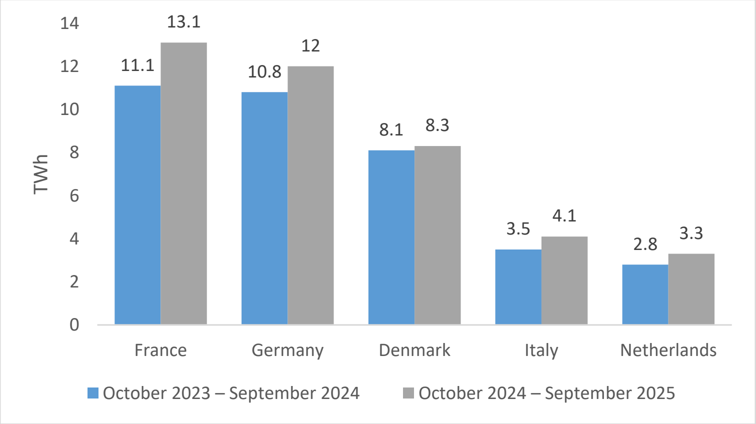

Fig.1.2. Countries with the largest biomethane grid injection, TWh [15].

The substantial production volumes observed in these countries are not coincidental but rather the result of targeted, long-term, and comprehensive support policy mechanisms that have been implemented over a significantly longer period than in Latvia. The purpose of these support mechanisms is to reduce investment risks for producers and to guarantee or stimulate demand, thereby facilitating the development of the biomethane market.

Although the biomethane volumes injected in the Baltic States and Finland remain relatively small compared to those of France or Germany, they should nevertheless be regarded as an important step in the regional development of renewable gas production (Fig. 1.3). This lower level of development is, among other factors, associated with historically limited state support mechanisms and the relatively recent development of a detailed regulatory framework aimed at strengthening the role of biomethane.

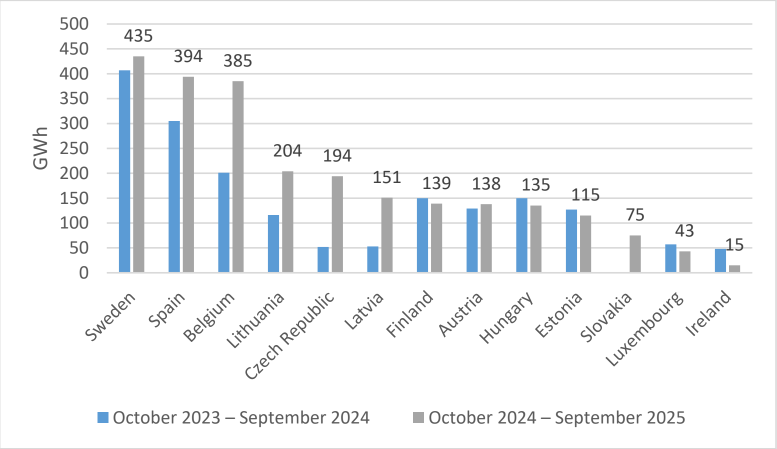

Fig.1.3. Injected biomethane for other countries, GWh [15].

The total volume of biomethane injected in the Baltic States and Finland during the reporting period from October 2024 to September 2025 reached 609 GWh, or 0.6 TWh. Compared to Finland and the other Baltic States, Latvia's biomethane sector is at a similar stage of development. The development direction is also similar, with a gradual transition from decentralised biogas production towards upgrading to biomethane quality, injection into natural gas infrastructure, and use in transport, energy and industry, including through gas exports.

In 2025, a total of 0.17 TWh of domestically produced biomethane was injected into the Latvian gas supply system, representing a 143 % increase compared to the first year of biomethane injection (2024), when 0.07 TWh was injected into the system.

The Latvian energy sector is currently undergoing a complex transition towards the use of renewable energy. This transition involves moving away from fossil energy sources towards the deployment and consumption of new renewable energy capacities, while also addressing long-term planning challenges and responding to international geopolitical developments.

1.4. Characteristics of Biomethane, Production Feedstocks, and Its Advantages

Biogas production using anaerobic digestion technology is a widely applied approach for the sustainable utilisation of organic waste and the promotion of the circular economy. Biogas consists primarily of methane (CH_4) at 50–80 %, carbon dioxide (CO_2) at 20–50 %, ammonia (NH_3) at 0–300 ppm, hydrogen sulfide (H_2S) at 50–5000 ppm, nitrogen (N_2) at 1–4 %, and oxygen (O_2) at less than 1 %.

When assessing the correlation between a specific feedstock and its potential impact on the amount of methane produced in biogas, several influencing factors must be considered. Feedstock characterisation requires the evaluation of its physicochemical properties, including moisture content and organic matter content.

Gas yield, or the volume of methane produced, is commonly expressed as the volume of generated biogas or pure methane (CH_4) per unit of volatile solids (VS), total solids (TS), or fresh matter (FM).

In general, the main feedstocks can be grouped into three categories according to their biogas yield per tonne of volatile solids (VS):

- low yield: < 300 m^3 biogas/t VS (lignocellulosic biomass, cattle manure, and pig manure);
- medium yield: 300–500 m^3 biogas/t VS (poultry manure and municipal waste);
- High yield: > 500 m^3 biogas/t VS (slaughterhouse wastewater and potato starch processing wastewater).

Depending on the feedstock, approximately 190–1100 m^3 of biogas can be produced per tonne of volatile solids (VS); although in practice this range may be even wider when a wider variety of feedstocks is analysed. Consequently, this consideration may be particularly relevant for producers whose primary objective is to maximise the methane concentration in the produced gas [16].

Biomethane can be utilised for heat and electricity generation, district heating, industrial applications, transport, and energy system balancing. Its compatibility with existing gas infrastructure, energy storage capabilities, and role in the circular economy and bioeconomy demonstrate the importance of biomethane in the decarbonisation of the energy sector.

1.5. Risks to Gas Infrastructure Associated with an Increased Share of Biomethane

In Latvia, one of the most valuable energy infrastructure assets is the Inčukalns Underground Gas Storage (UGS), with an active gas storage capacity of approximately 24 TWh. The increasing production of biomethane and its injection into the gas system, both in Latvia and other countries, creates a growing number of technical risks and potential adverse impacts that must be carefully assessed, particularly with regard to the long-term operational stability and continuity of underground gas storage facilities. In Latvia, the Inčukalns UGS is also facing new oxygen-related risks resulting from the unprecedented increase in the share of renewable gases in the system.

The quality requirements for both natural gas and biomethane injected into the system specify a maximum permissible oxygen (O_2) concentration of 0.5 mol%. However, for gas injected into the section of the natural gas transmission system directly connected to the Inčukalns UGS, the permitted oxygen concentration is limited to 0.02 mol%. This is because even small amounts of oxygen can trigger various chemical and microbiological processes that may affect the facilities and geological structure of the underground gas storage [17]. These processes may result in financially significant infrastructure damage, reduced storage efficiency, and, consequently, may pose risks to the security of gas supply.

The concentrations of oxygen, carbon dioxide, and hydrogen sulfide present in biomethane may create risks of triggering biochemical and geochemical reactions within the underground gas storage facility. Such reactions may cause corrosion, negatively affect well performance, and impact dehydration, desulfurisation, and gas compression processes.

Protecting strategic assets while ensuring the transition towards renewable energy requires a balance between technical feasibility, regulatory compliance, and forward-looking investments. The storage operator ensures system oversight through regular system inspections, planned repair works, modernisation activities, maintenance, gas quality control, and overall system monitoring in accordance with established procedures. Cooperation with other system operators and biomethane producers also plays an important role, including biomethane injection testing, continuous gas quality monitoring, and collaboration in defining technical requirements.

Changes within underground storage formations may also occur over extended periods of time. Consequently, there remains considerable uncertainty regarding the reactions and formations that may develop within the storage reservoir under changing gas compositions and operating conditions.

1.6. Challenges and Opportunities for Biomethane Development and Market Integration

There are approximately 50 biogas plants in Latvia with a total installed electrical capacity of 60.5 MW, the development of which towards biomethane production could contribute to the decarbonisation of the gas sector, energy supply security, and the circular economy [18]. Several solutions are available for the integration of biomethane into the market. These include a direct connection of a biomethane production plant to the interconnected gas system, biomethane injection through a biomethane injection point (BIP), or supply outside the gas system directly to end consumers.

The development of biomethane is constrained by high investment costs, feedstock availability and logistics, compliance with gas quality requirements, regulatory uncertainty, and the lack of a long-term development strategy. At the same time, amendments to the Energy Law regarding the development of biomethane injection points and the measures envisaged in the National Energy and Climate Plan (NECP) create favourable conditions for the integration of biomethane into the transport, district heating, electricity generation, and gas sectors [13].

1.7. Focus on Biomethane Plant Connection to the Gas System and Market Integration Scenarios

There are three main scenarios through which biomethane can enter the energy market: (1) a direct connection, where the biomethane production plant is directly connected to the gas transmission or distribution system through a pipeline connection; (2) the use of a biomethane injection point (BIP), where biomethane is transported by vehicles for injection into the gas system; and (3) off-grid solutions, where biomethane is transported directly from the production plant to the end consumer without using the gas system.

Each of these scenarios is important because the optimal pathway for biomethane market integration depends on a range of environmental, economic, and technical factors. Direct system connections may provide advantages in terms of capacity availability for biomethane producers but require significant upfront infrastructure investments. Injection through a BIP can reduce costs for individual biomethane producers, as they do not need to establish their own system connection, and offers benefits when the production facility is located sufficiently close to a BIP with suitable road infrastructure.

BIPs provide an alternative for producers who are unable to construct a direct system connection due to distance-related or legal challenges, such as difficulties in reaching agreements with landowners regarding pipeline construction or restrictions associated with protected areas. Solutions that completely bypass the existing gas infrastructure, referred to as off-grid solutions, offer flexibility and accessibility but are associated with additional logistical complexities. They also face legal challenges related to biomethane traceability during transportation outside the gas system, as detailed procedures and responsibilities for off-grid biomethane utilisation remain insufficiently developed in several EU Member States.

As concluded by Ferrari et al., reducing transport costs and greenhouse gas emissions requires the identification of optimal plant locations, as well as the upgrading of existing biogas facilities to biomethane production. Appropriate plant siting can reduce both greenhouse gas emissions and operating costs [19]–[21].

Most existing studies primarily focus on technological upgrading or overall sustainability impacts, without addressing aspects related to infrastructure selection and the combination of different integration pathways to identify the best environmental, economic, and technical performance. Based on this identified research gap, the present study is guided by the following research questions and scientific contributions.

To address issues that have not been sufficiently examined in previous studies regarding the systematic comparison of biomethane integration pathways, this research focuses on two key research questions: 1) Which biomethane market integration pathway provides the most balanced performance when environmental, economic, and technical criteria are assessed simultaneously? 2) How robust is the ranking of the evaluated scenarios to changes in decision-maker priorities, and under what conditions might alternative integration pathways become preferable from the perspective of infrastructure planning and energy policy development?

Therefore, it is useful to evaluate each biomethane market integration scenario against a range of environmental, economic, and technological parameters in order to determine which option is the most suitable when multiple aspects are taken into consideration.

2. METHODOLOGY

One of the objectives of the study is to create a conceptual framework to promote the development of biomethane and the smart energy transition by integrating different aspects for an interdisciplinary approach. Following the research plan developed by the author, it is possible to conduct an extensive analysis of the shortcomings of the energy system and provide ideas and plans for future development based on data and modelling, also for the assessment of other energy resources.

Table 2.1

Linking Research Questions to the Methodology Used

Research question	Method used	Results
What methods are suitable for the systemic study of biomethane?	Quantitative counter-analysis	The most suitable research methods for this study have been selected
What topics and problems are relevant in scientific research; whether the challenges are consistent with the case of Latvia; What has not yet been extensively studied?	Bibliometric analysis	The main challenges and the free research niche have been identified. It has been identified which topics are widely represented and in which areas there is still a shortage
How is biomethane integrated into energy systems in practice, how is it used in cities?	Exploratory case studies	Lessons learned on the results of the integration of renewable gas into urban heating
Analysis of biomethane integration; how to integrate it into the energy market; suitability as an optimal gaseous fuel?	Multi-criteria decision analysis (TOPSIS method)	With the involvement of industry experts and mathematical calculations, results have been obtained for optimal integration of biomethane into the system, evaluation as an energy resource, and calculation of its optimal applicability.
What influences biomethane production and how to improve production efficiency?	Regression analysis	The impact of the raw materials used on the amount of biomethane produced has been determined
How economically justified is the production and use of biomethane?	Cost-benefit analysis (CBA)	Monetary assessment of costs
What is the systemic role of biomethane, and what are the benefits?	Optimisation model	Development framework

Table 2.1in a concise manner which method was used to answer the relevant research question within the framework of this Doctoral Thesis.

The novelty of the study is the integration of these methods into a single system adapted to biomethane, thus improving previous research on renewable energy planning, and harmonising environmental, technical and socio-economic aspects into a structured workflow.

2.1. Quantitative Content Analysis

One of the methods used in the study is quantitative counter-analysis, also known as content analysis. Counter-analysis is a method of textual data analysis that allows you to systematically analyse literary sources, identify the main topics, approaches and methodological directions, as well as categorise information in a structured way. This method is used to interpret the information available from different sources, identifying key approaches, such as the analysis and evaluation of biomethane systems [22].

In this study, quantitative content analysis is applied to the systematic analysis of the scientific literature and the theoretical evaluation of the main research methods. The literature review was conducted using the Scopus and ScienceDirect scientific databases, as well as other sources related to energy systems. The analysis employed keywords targeted to the research topic, including biomethane, production, renewable gas systems, biomethane integration, LCA, system dynamics, and multi-criteria decision analysis.

As a result of the content analysis, several frequently applied methods were identified, including system dynamics, life cycle assessment, and multi-criteria decision analysis, the latter being analysed in greater detail separately. These methods were structured and evaluated to assess their potential application in the analysis of biomethane system development, sustainability, and infrastructure.

The methods identified through the content analysis provide a structured basis for evaluating approaches to biomethane system analysis and serve as the theoretical foundation for the subsequent analytical methods applied in this research.

2.2. Bibliometric Analysis

Bibliometric analysis was used to identify gaps in research, topics that have not yet been extensively studied, or which scientific research is less represented in the analysis of biomethane-related issues. Bibliometric analysis is a systematic analysis of the literature that allows you to identify trends in a particular industry based on quantitative indicators. It has three main steps: collecting data from appropriate databases, reviewing and standardising data, and subjecting this data to various methods of bibliometric analysis. This research method relies on large data sets selected, for example, based on finding specific keywords, the number of citations, authors, countries, frequency of the topic in scientific publications, etc., but the interpretation of the results often involves both quantitative and qualitative approaches [23], [24].

In this study, the *VOSviewer* software was used due to its high-quality visualisation capabilities and efficient data processing. It is widely applied in bibliometric analysis and citation studies for the creation and visualisation of so-called bibliometric networks [25].

The bibliometric analysis was conducted using the Elsevier Scopus and Web of Science databases. Within the framework of the Doctoral Thesis, the analysis was carried out in September 2025. These databases were selected as the most appropriate sources due to their extensive coverage and the availability of a large number of high-quality scientific publications.

The relevance assessment of publications was based on the following selection criteria identified by the author: keywords, document type, publication period, and language of publication. Five groups of keyword combinations were used in the publication selection process, reflecting the key challenges examined in detail in the Doctoral Thesis: 1) construction of connections for biomethane injection into the natural gas system; 2) biomethane injection through dedicated injection points in the natural gas transmission system; 3) transportation of biomethane to refuelling stations for use as a transport fuel; 4) production of new high-value-added products from biomethane; and 5) infrastructure challenges arising from biomethane quality.

At the same time, the objective of the bibliometric analysis was to assess whether the challenges identified in the Latvian context are equally prevalent and scientifically investigated challenges in other countries and regions worldwide.

2.3. Exploratory Case Study

An exploratory case study is one of the qualitative research methods, and its purpose is to gain an in-depth understanding of a particular issue or phenomenon [26]. The study applies a narrative review approach through the analysis of scientific literature, Latvian regulatory acts, the NECP 2030, and expert opinions from the energy sector. In addition, a structured comparative analysis was conducted on the use of biogas and biomethane in district heating systems by evaluating two representative European case studies: the district heating system of the city of Meppel in the Netherlands and the *Backbone* energy system modelling framework in Finland.

The Meppel case illustrates the optimisation of a local-scale hybrid energy system that combines biogas-based cogeneration, heat pumps, thermal energy storage, and district heating. In contrast, the Backbone model represents large-scale regional optimisation of interconnected electricity, district heating, and biomass supply systems.

The analysis was conducted by evaluating and comparing modelling approaches, energy efficiency and emission indicators, operational flexibility, renewable energy integration, and the impacts of policy measures and investments. The methods applied in this study are based on a structured literature review approach designed to systematically collect and evaluate existing scientific literature on the use of biogas and biomethane in district heating systems.

Based on the findings and insights obtained from the analysis, it is possible to provide an overview of the significant potential and practical applications of these renewable gases.

2.4. Multi-Criteria Decision Analysis Using the TOPSIS Method

Multi-Criteria Decision-Making (MCDM) methods are widely applied in scientific research and have become valuable tools in modern decision analysis, offering systematic approaches for the evaluation and ranking of alternatives in various contexts. These methods are effective in addressing complex problems where decision-makers must simultaneously consider multiple, often conflicting, criteria in order to identify optimal solutions.

One such method is the technique for order preference by similarity to ideal solution (TOPSIS), which was selected for this study. The calculations were performed using Microsoft Excel.

Evaluation matrices were developed for the analysis; however, the availability of reliable and comprehensive data was limited. Therefore, an expert assessment approach was adopted. Experts with extensive experience in environmental and energy engineering research, gas infrastructure specialists with engineering and technical backgrounds, and policy experts working in the fields of energy and economic development were asked to evaluate the developed criteria by assigning numerical values.

The expert ratings were aggregated to calculate average scores, and the resulting mean values were entered into the evaluation matrix for further analysis. The steps for calculating TOPSIS are described in Equations (2.1) to (2.6) [27]. Input is decision data *V* and a set of weights *w*, but the output is a measure of proximity *r* [28]. The first step is normalisation, where for each assessment $v_{m,k}$ the following normalisation must be carried out:

$$u_{m,k} = \frac{v_{m,k}}{\sqrt{\sum_{k=1}^{K} v_{m,k}^{2}}}, \quad m = 1,\dots,M, \quad k = 1,\dots,K, \tag{2.1}$$

where $v_{m,k}$ denotes alternatives $A_k(k = 1, 2,\dots, K)$ assessment of the criterion $C_m(m = 1, 2,\dots, M)$.

The tricky step is weighted normalisation, where for each normalised assessment $u_{m,k}$ it is necessary to carry out weighted normalisation calculations, where $p_{m,k}$ is the normalised value of the performance indicator $v_{m,k}$:

$$p_{m,k} = w_m u_{m,k}, m = 1,\dots,M, k = 1,\dots,K. \tag{2.2}$$

The third step is to determine the positive (PIA) and negative ideal alternative (NIA) using Euation (2.3):

$$\text{PIA} = p^{+} = \{p_1^{+}, p_2^{+},\dots, p_M^{+}\} \text{and NIA} = p^{-} = \{p_1^{-}, p_2^{-},\dots, p_M^{-}\}, \tag{2.3}$$

where p_m^{+} = max $\{p_{m,k} | 1 \le k \le K\}$ and p_m^{-} = min $\{p_{m,k} | 1 \le k \le K\}$, $m = 1, \dots, M$. It contains the best (ideal) and worst (negative) values of each criterion.

The fourth step is the calculation of Euclidean distances from each alternative A_k and both a positive ideal solution and a negative ideal solution:

$$D_k^+ = \sqrt{(p_k - p^+)^T + (p_k - p^+)}, k = 1, ..., K, \tag{2.4}$$

and

$$D_k^- = \sqrt{(p_k - p^-)^T + (p_k - p^-)}, k = 1, ..., K, \tag{2.5}$$

where $p_k = [p_{1,k}, p_{2,k}, ... p_{M,k}]$.

The fifth step is a measure of proximity – the coefficient (r_k) calculation for each alternative A_k:

$$r_k = \frac{D_k^-}{D_k^+ + D_k^-}, k = 1, ..., K. \tag{2.6}$$

After that, a clear ranking is made based on the relative proximity to the ideal solution. The benefit of using TOPSIS is that values with different units of measurement can be compared. The best solutions can be identified and analysed regardless of the units of measurement used [29]–[31].

To achieve the research goals, the TOPSIS method was applied several times as three separate models to answer individual research questions. With the help of the models, the answers to the following questions are evaluated: I – which is the optimal gaseous fuel; II – how to ensure optimal market integration of biomethane from the point of view of physical integration; and III – what are the effective alternatives to the application of biomethane. In order to make the methodology applied and the use of models logically understandable, this methodology is visualised in Fig. 2.1.

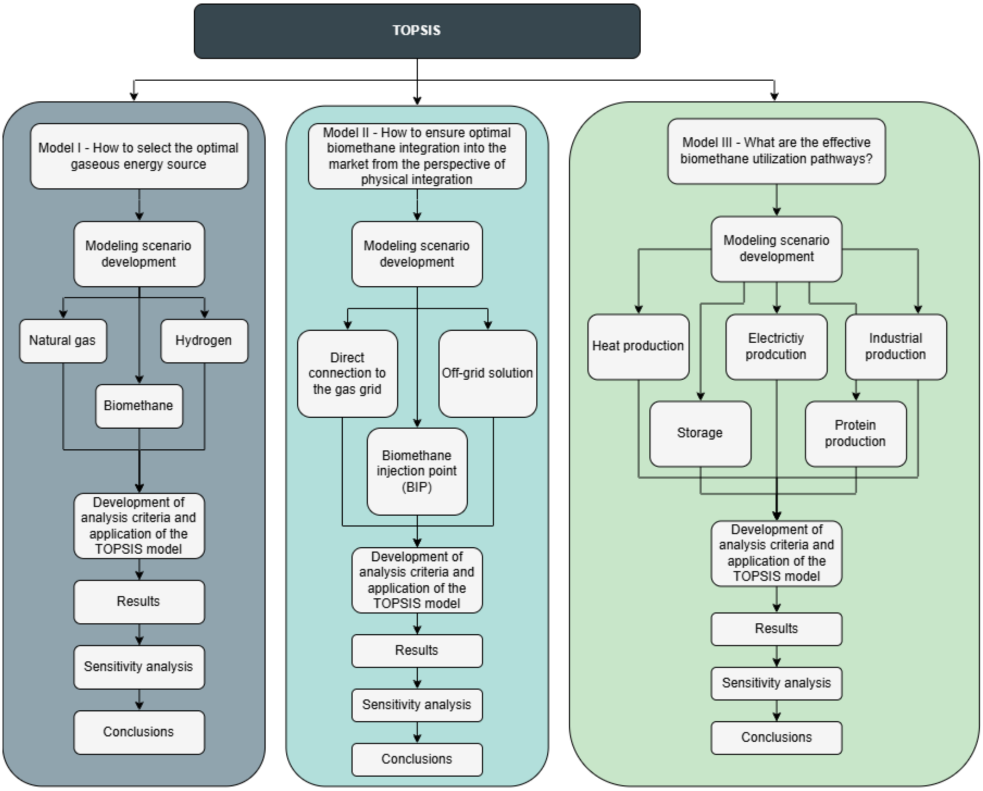

Fig. 2.1. TOPSIS application methodology.

In each of the ways of application of TOPSIS, the common methodological principles and process logic were observed. What is different is the scenarios that were compared in each of the cases.

2.5. Regression Analysis

Using full-scale biomethane plant operational data over a seven-month period, covering the entire biomethane value chain from the receipt of raw materials to the input of biomethane into the interconnected gas system. Correlation analysis was used to identify the most influential variables affecting biomethane quality and yield, according to the approaches described in [32] and [33]. Regression analysis was then used to obtain the analytical relationship between the composition of the raw materials and the process parameters, as shown in [34], [35], and [36].

Raw materials were divided into four groups: animal waste, agricultural waste, waste from the food industry and municipal or industrial sludge. The mathematical description of the regression analysis and the equations used are summarised in Equations (2.7)–(2.13). Using the original data, the regression equation has the following form:

$$y = b_0 + b_1 x_1 + b_2 x_2 + \cdots + b_n x_n, \tag{2.7}$$

where y is a dependent variable, b_0 is the free regression term, $b_1 \ldots b_n$ are regression coefficients, and $x_1 \ldots x_n$ are independent variables. The significance of the coefficients should be assessed. This is a multiple regression pattern. The single-factor regression model is described by Equation (2.8):

$$y = b_0 + b_1 x. \tag{2.8}$$

To evaluate the statistical significance of coefficients $b_0 \ldots b_n$, Equations (2.7.) and (2.8.) uses *t-test* is applied. The test statistics follow the Student's t-distribution by

$$f = m - (n + 1), \tag{2.9}$$

where m is the size of the sample, and n+1 is the number of calculated parameters, including the intercept.

Quantity m describes the amount of data subject to statistical analysis, and n denotes the number of independent variables in the regression equation. To estimate the regression factors, the t-statistics calculated by the computer for each factor are compared with the critical value $|t|$>tab, derived from the Student's t-distribution table according to the chosen level of significance P and degrees of freedom f. In the processing of energy-related data, the significance level is often used = 0.05, corresponding to the probability of reliability $1-P = 0.95$.

If the condition $|t|$>tab is fulfilled for a certain coefficient, then the coefficient is considered statistically significant and must remain in the regression equation. Otherwise, the corresponding term must be removed and the analysis repeated until all remaining coefficients are statistically significant.

The resulting regression equation reflects the mathematical model of the phenomenon being analysed, and it must be evaluated further.

The assessment is carried out using variance analysis using Fisher's criterion F. For this, the ratio of the dependent variable variance to the variance of residues is taken into account:

$$F\ (f_1\,, f_2) = \frac{S_{reg}^2(f_1)}{S_{atl}^2(f_2)}, \tag{2.10}$$

where $S_{reg}^2(f_1)$is a variance explained by regression, and $S_{atl}^2 \times (f_2)$ is the average of the balance. The remainder is defined as the difference between the observed value of the dependent variable and the value calculated from the regression equation, $y_i - y_i^{apr}$.

Degrees of freedom f_1 and f_2 necessary for the assessment of the Fisher's criterion F are calculated as follows:

$$f_1 = m - 1,\ f_2 = m - n. \tag{2.11}$$

If the calculated value of criterion F exceeds the critical value obtained from the F-distribution tables, taking into account the degrees of freedom f_1 and f_2 and the chosen level of significance P, then the regression equation is considered statistically significant. In this case, the equation adequately describes the experimental data and can be considered feasible.

If linear single-factor or multivariate regression models do not satisfactorily describe the analytic phenomenon, higher-order models should be considered. This usually involves the introduction of nonlinear terms into the model. Where possible, the nonlinear terms of independent variables are converted into new variables, allowing the regression equation to remain linear relative to its parameters (i.e., it becomes a linearisable nonlinear model).

For example, in the case of two independent variables, a nonlinear regression equation can be written in a general form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_2^2 + b_5x_1 \times x_2. \qquad (2.12)$$

This equation can be linearised by introducing new variables that correspond to nonlinear terms:

$$x_3 = x_1^2;\ x_4 = x_1^2;\ x_5 = x_1 \times x_2.$$

Using these substitutions, the linearised regression equation can be expressed as

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5. \qquad (2.13)$$

Coefficients b_0... b_5 in Equation (2.13) are determined using the least squares method (or another estimation method), and their statistical significance is assessed using *t-test*. The overall relevance of the regression equation is assessed using Fisher's criterion F, as described above. One of the main tasks of regression analysis is to choose the most suitable model.

2.6. Cost-Benefit Analysis (CBA)

A cost-benefit analysis (CBA) was applied to evaluate the economic feasibility of different potential solutions. Similar to the bibliometric and multi-criteria analyses conducted by the author, three scenarios were selected for the cost-effectiveness assessment: 1) biomethane injection into the natural gas system directly from the production plant; 2) transportation of biomethane by road to a biomethane injection point (BIP); and 3) direct delivery of biomethane to the end consumer without using the gas system.

The assessment included initial investments or capital expenditures (CAPEX), operational expenditures (OPEX), fuel costs (for Scenarios 2 and 3), as well as estimated revenues and project payback periods. The CAPEX calculation included all one-time costs required to initiate the project, while OPEX covered expenses associated with system operation, including equipment operation, energy consumption, labour resources, maintenance, and repair activities.

To comprehensively assess the economic viability of biomethane integration into the Latvian natural gas system, capital and operational expenditures were analysed together with potential revenues, allowing for the calculation of project payback periods. In addition to direct operating and capital costs, the analysis also considered indirect economic and external benefits, including the avoidance of carbon emission allowance costs, the reduction of uncontrolled emissions, and the promotion of circular economy principles.

2.7. Optimisation Model

An optimisation model is a mathematical representation of a decision problem in which one or more performance indicators (objective functions) are maximised or minimised subject to a set of technical, economic, or environmental constraints.

The optimisation model was developed in Microsoft Excel to identify the economically optimal methane (CH_4) concentration level in biomethane production under balanced production costs and revenues. In this study, the model was based on the assumption that the production cost curve increases exponentially with higher CH_4 concentrations due to the use of more expensive feedstocks, increased energy consumption during processing, and additional upgrading requirements. Conversely, the revenue curve reflects the potential market value and increases with higher methane content due to the higher calorific value and market price per unit of energy.

The intersection of these two curves determines the optimal CH_4 concentration at which the profit margin is maximised. The dataset includes CH_4 concentration (%), feedstock quantities (t), and revenue values (EUR) associated with biomethane sales. The optimisation approach analysed the impact of varying biogas CH_4 concentrations on levelised production costs and profitability by evaluating representative scenarios with CH_4 concentrations of 50 %, 55 %, and 59 %.

In addition, the impact of carbon pricing (ETS 2) was assessed by evaluating how the avoidance of CO_2 emissions or participation in emissions trading affects the economic optimum of biomethane production. This approach provides a framework for assessing how changes in feedstock composition, process efficiency, and policy instruments influence the economic sustainability of biomethane production.

3. RESULTS

3.1. Results of the Quantitative Content Analysis

The results of the quantitative content analysis identified the theoretical benefits of various methods and provided justification for the selection of specific methods used to address the research questions of this study. The selected methods were subsequently applied in detail in dedicated sections of the Thesis. The following section presents the key findings and conceptual outcomes derived from the quantitative content analysis, obtained without the direct application of these methods, while identifying them as suitable approaches for future studies depending on their specific objectives.

The results indicate that the development of a comprehensive biomethane research framework requires the establishment of a data repository, infrastructure mapping, system dynamics modelling, life cycle assessment (LCA), and multi-criteria decision analysis (MCDA). Data repositories and infrastructure mapping facilitate the identification of production trends, assessment of regional capacities, more accurate infrastructure planning, and modelling of supply security. System dynamics modelling enables the analysis of biomethane production volumes, infrastructure development, policy impacts, market demand, and investment flows, while also allowing the evaluation of different development scenarios.

LCA provides a comprehensive assessment of the environmental impacts of biomethane production throughout its life cycle, while MCDA enables the simultaneous evaluation of environmental, economic, and technical aspects, supporting decision-making under conditions of uncertainty. The analysis identified twelve benefits associated with the use of data repositories and infrastructure mapping as integrated analytical tools. Furthermore, MCDA and/or LCA can provide at least six advantages for the planning of alternative scenarios and systems, including the evaluation of technological and investment alternatives and support for decision-making processes.

The results demonstrate that an integrated research approach can provide a robust foundation for increasing biomethane production at local, national, and regional levels. At the same time, the developed approach may also be applied in the assessment of other energy carriers.

3.2. Results of the Bibliometric Analysis

The results of the bibliometric analysis differed significantly depending on the keyword sets used for publication retrieval, despite the fact that all five searches were based on the common keyword “biomethane”. The *VOSviewer* bibliometric network maps illustrated keyword co-occurrence patterns.

The bibliometric analysis examined five main research directions related to biomethane development: biomethane injection into the gas system, biomethane injection points, biomethane utilisation in transport, biomethane trade, and oxygen-related risks to gas infrastructure.

The first bibliometric analysis focused on biomethane injection into the gas system through pipeline connections (biomethane + grid + infrastructure). The resulting map formed several distinct thematic clusters, including technology (methane, natural gas, pipelines), environmental impacts (emissions, CO_2, GHG), energy transition (renewable energy, decarbonisation, hydrogen), and biogas production/anaerobic digestion processes. This confirms the assumption that biomethane integration into gas infrastructure cannot be analysed in isolation.

The second bibliometric analysis was conducted to understand publication trends related to biomethane injection through dedicated biomethane injection points. Keywords such as “pipelines”, “gas”, and “compressed natural gas” were located at the periphery of the map with relatively weak interconnections. This indicates that infrastructure is mentioned in the literature but is not analysed in detail, while the primary focus of publications is directed towards:

- biogas and biomethane production processes;

- greenhouse gas emission effects;
- optimisation and energy system modelling.

Consequently, the second bibliometric analysis suggests that the construction of biomethane injection points and their techno-economic justification remain insufficiently studied topics within the scientific literature.

The third bibliometric analysis focused on biomethane use in transport and revealed a clearly defined body of literature addressing the role of biomethane in transport sector decarbonisation. Unlike the previous two maps, two dominant clusters emerged: an emissions/environmental cluster and a natural gas/transport technology cluster. The results indicate that, in the transport context, biomethane is primarily viewed as a fuel rather than as a solution for biomethane integration into energy systems.

The fourth bibliometric analysis examined scientific research trends related to biomethane trading and the development of markets for associated by-products. The resulting map was substantially denser and more multidimensional, highlighting five major clusters: by-products and waste; markets and economics; life cycle assessment and environmental impacts; circular economy; and investment and cost-effectiveness. Therefore, the fourth bibliometric analysis demonstrates that biomethane trading is the broadest and most interdisciplinary research area among those examined.

The fifth bibliometric analysis focused on challenges and risks to natural gas infrastructure associated with excessive oxygen content in biomethane. In the scientific literature, oxygen-related issues are predominantly discussed in the context of waste and wastewater management. The results indicated that elevated oxygen concentrations are more frequently studied in relation to aerobic digestion systems than to gas infrastructure impacts.

Overall, the results demonstrate that biomethane integration into gas infrastructure is analysed in the literature from an interdisciplinary perspective, encompassing technological, economic, and environmental dimensions. Significant attention is devoted to emission reduction, economic feasibility, and energy system decarbonisation. At the same time, biomethane infrastructure development, the construction of biomethane injection points, and their techno-economic assessment remain relatively underexplored research areas. Within the transport sector, biomethane is primarily analysed as an emission reduction measure utilising existing natural gas infrastructure, while biomethane market development is considered in the context of the circular economy, climate policy, and the transformation of natural gas markets. Studies on oxygen content mainly focus on production processes, whereas infrastructure-related impacts receive comparatively limited attention.

3.3. Exploratory Case Study Analysis

Within the exploratory case study analysis, the experience of other countries in using biogas and biomethane as components of sustainable energy systems was examined, with a particular focus on their application in district heating systems. 5th generation district heating and cooling (5GDHC) networks are still at an early stage of development; however, several such systems are already operating across Europe, many of which originated as pilot projects.

These systems differ significantly from conventional district heating and cooling technologies. For example, they supply water to decentralised water-source heat pump stations at temperatures ranging from 0 °C to 30 °C, offering several advantages compared to traditional district heating systems. The benefits of 5GDHC include higher source temperatures in heating mode and lower source temperatures in cooling mode compared to ambient air, resulting in improved seasonal system performance. Another advantage is that district-scale solutions can incorporate seasonal thermal energy storage in urban environments where the installation of individual ground-source heat pumps may be constrained. Furthermore, the diversity and simultaneity of building energy demands increase opportunities for recovering excess heat from cooling processes and reusing it for heating purposes.

The exploratory case study analysis confirmed that upgrading biogas to biomethane enables its injection into the gas system and transportation while significantly reducing greenhouse gas emissions. Life cycle assessment (LCA) studies indicate that replacing fossil gas with biogas in cogeneration systems can reduce emissions by 70–90%, with the main benefits resulting from the avoidance of methane emissions and the substitution of fossil fuels.

District energy networks and 5GDHC systems provide extensive opportunities for renewable energy integration, thermal energy storage, and emission reduction. However, their development is constrained by high investment costs, technical complexity, and limited operational experience. The case study of the city of Meppel demonstrated that the most sustainable solution is a biogas-based cogeneration system supplemented by natural gas backup boilers, achieving more than 80 % lower CO_2 emissions than conventional heating systems.

The Finnish Backbone modelling framework further confirmed that the integration of biomass, biogas, heat pumps, and energy storage technologies can substantially reduce emissions while maintaining energy system security and flexibility. Overall, the results demonstrate that the integration of local renewable energy resources into energy systems provides significant sustainability benefits and contributes to the decarbonisation of the energy sector.

The structured comparison offers a broader perspective, ranging from city-scale energy microsystems (Meppel) to the modelling of national and regional energy systems (Backbone).

3.4. Results of the Multi-Criteria Decision Analysis Using TOPSIS

The TOPSIS method was applied to evaluate 1) the most suitable gaseous energy carrier by comparing natural gas, biomethane, and hydrogen; 2) the most appropriate biomethane market integration pathway, including direct connection, BIPs and off-grid biomethane transportation; and 3) the most effective biomethane utilisation alternatives.

1. TOPSIS model – choosing the optimal gaseous energy source

In the context of biomethane development, it allows stakeholders to identify solutions that are environmentally and socio-economically justified, thus making MCDA an essential tool for driving sustainable innovation and investment strategies. Therefore, the TOPSIS method was used for comparison to evaluate biomethane as one of the gaseous energy sources compared to natural gas and hydrogen (Table 3.5).

Table 3.1

Normalised Decision Matrix for the Assessment of Gaseous Fuels

	Scenario 1 Natural gas	Scenario 2 Biomethane	Scenario 3 Hydrogen	Criteria weights
Reduction of GHG emissions (t CO_2eq savings (not generated) per year)	0.258	0.701	0.664	0.0833
Reduction of air pollutants (e.g. NOx, SOx, particulate matter), % reduction	0.324	0.648	0.689	0.0833
Impact on waste management, t waste/year	0.095	0.953	0.286	0.0833
Profit potential (market, subsidies, value of carbon credits), EUR/MWh	0.543	0.699	0.466	0.0833
Technological maturity, *technological readiness level* 1–10	0.703	0.597	0.387	0.0833
Elasticity of raw materials (range of biomass to be recycled/used), number of types of raw materials pcs.	0.103	0.879	0.465	0.0833
System/infrastructure compatibility (how easy it is to integrate gas into existing infrastructure or use in the transport sector), *technical readiness level* 1–10	0.717	0.574	0.395	0.0833
Job creation potential (number of jobs created per unit of investment)	0.394	0.630	0.669	0.0833
Policy and regulatory alignment (compliance with renewable energy targets, subsidies, targets), rating 1–10	0.393	0.628	0.589	0.0833
Contribution to the circular economy (nutrient processing, valorisation of digestate), rating 1–10	0.089	0.798	0.532	0.0833
Technological risks (probability of operational problems or risk of underperformance), probability of failure %	0.352	0.956	0.755	0.0833
Market risks (price sensitivity, policy volatility), rating 1–10	0.600	0.388	0.600	0.0833

When comparing the scenarios, the same weighting of the criteria was used for all criteria to ensure an equivalent assessment and an objective comparison. This provides a balanced approach to comparison. The challenge with using a lot of criteria is that the impact of each criterion is reduced, since their weight in this case is relatively negligible, also when performing a test and changing the weights of the criteria within the framework of the established methodology, where the sum of the weights of the criteria must be 1 or 100 %, nevertheless the results come together very similar and such small weights do not have a significant effect on a large set of criteria. Based on the expert assessment, the following scenario assessments for gaseous fuels were obtained, as shown in Fig. 3.1.

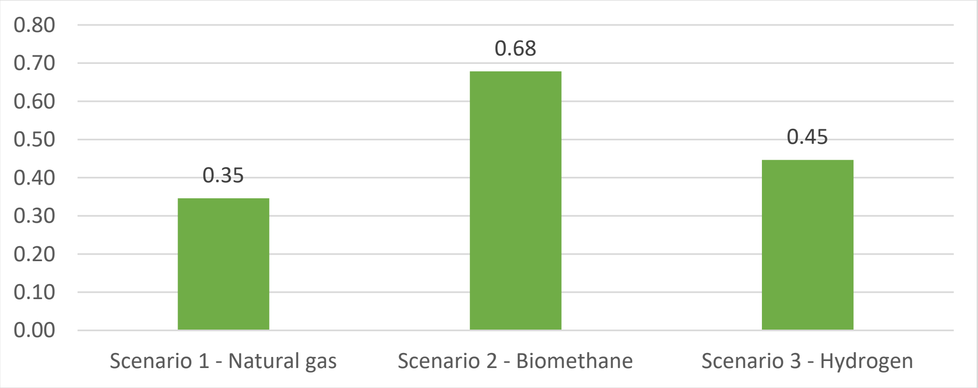

Fig. 3.1. Classification of biomethane scenarios based on twelve different criteria.

According to the above criteria, the comparison shows that the most balanced form of gaseous energy carrier from various considerations and assessments is biomethane with a result of 0.68, hydrogen with a score of 0.45 in second place, and fossil natural gas with the lowest score of 0.35 in third place.

In addition, to see the impact of each criterion, the normalised results of the impact of the criteria are calculated and summarised in Fig. 3.10.

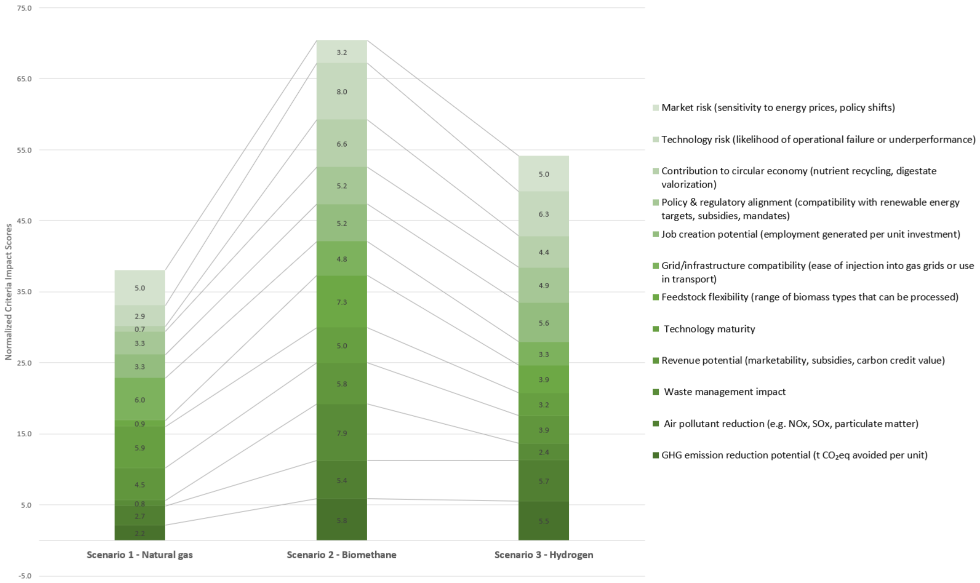

Fig. 3.2. Comparison of the levels of the criteria for normalised indicators.

The results presented in Fig. 3.2 indicate that biomethane (Scenario 2) achieved the highest cumulative score across all 12 criteria, demonstrating that it represents the most favourable option in the multi-criteria assessment. Hydrogen (Scenario 3) ranked second, while natural gas (Scenario 1) showed the weakest overall performance, with a cumulative score that was significantly lower across almost all criteria.

At the same time, natural gas demonstrated relative strengths in policy and regulatory alignment (6.0) and technology maturity (5.9), but performed poorly in terms of revenue generation potential (0.7) and job creation potential (0.9). Biomethane achieved consistently high scores in waste management impact (8.0), feedstock flexibility (7.9), and policy and regulatory alignment (7.3), indicating broad sustainability advantages. Hydrogen performed well in policy and regulatory alignment (5.6) and greenhouse gas emission reduction potential (5.7), but ranked lower with respect to technology risk (2.4) and job creation potential (3.2–3.9).

In addition, a sensitivity analysis was conducted to examine the influence of criterion weights on the evaluated alternatives. To assess the robustness of the multi-criteria decision analysis results, a sensitivity analysis was performed using the TOPSIS method. Sensitivity analysis enables the evaluation of how changes in individual criterion weights affect the relative ranking of the analysed alternatives.

The sensitivity analysis results were structured into two main groups by combining related criteria to facilitate a logical interpretation of the results. The first group (Fig. 3.3) examined the sensitivity of the outcomes to environmental and technical criteria, which characterise the physical infrastructure, system performance, and environmental impacts.

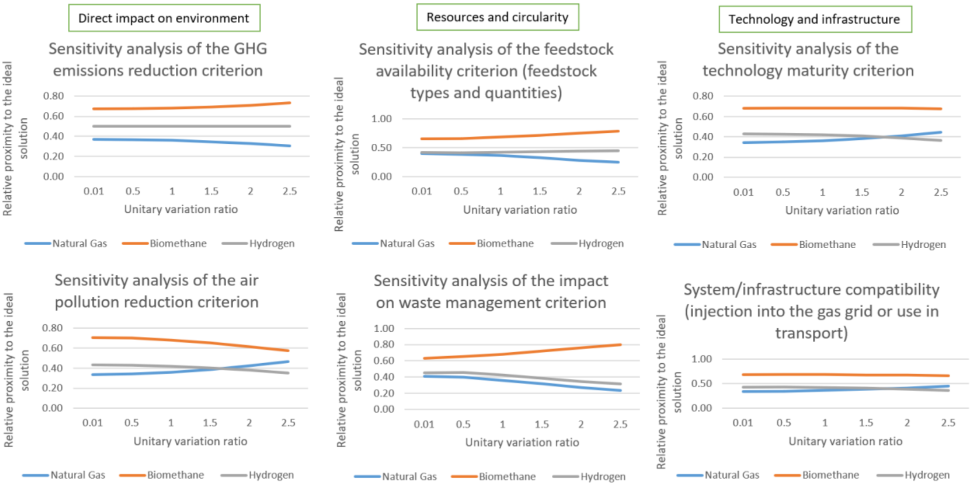

Fig. 3.3. Sensitivity analysis for environmental and technical criteria.

Sensitivity analysis in the group of environmental and technical criteria has a relatively high stability of results. In the group of environmental and technical criteria, the biomethane scenario maintained the highest score across the range of variations in the weights of the criteria, in particular the GHG emission reduction, air quality and circular economy criteria.

The second group (Fig. 3.4) analyses the sensitivity of the results to economic, market and regulatory aspects, which generally determine the effective use of solutions.

Fig. 3.4. Sensitivity analysis for economic, market and policy criteria.

The criteria for the group of economic, market and regulatory criteria are mostly robust, for example, an analysis of the sensitivity of revenue potential, market risks, job creation and policy harmonisation criteria shows that the criterion does not have a bearing on ranking. The biomethane scenario remained dominant in the criteria of revenue potential and the circular economy. The highest sensitivity was observed in the criterion of technological risks, which in some cases may affect the mutual assessment of alternatives. Overall, the results demonstrate the robustness of the biomethane scenario under different criteria priorities.

2. TOPSIS model – how to ensure optimal integration of biomethane into the market

The following is a summary of the integration scenarios – direct connection, BIP, off-system assessment and assessed environmental, economic, technical criteria.

Table 3.2

Normalised Decision Matrix for the Environmental Criteria Scenario

	Scenario 1	Scenario 2	Scenario 3	Criteria weights
CO_2 emissions, t CO_2 eq./year	0.318	0.578	0.751	0.2
Supply chain sustainability	0.664	0.576	0.476	0.2
Environmental risks, risk index	0.452	0.579	0.678	0.2
Air quality benefits, kg NOx, SOx, PM reduction per year, %	0.694	0.532	0.486	0.2
Resource efficiency, %	0.684	0.527	0.505	0.2

When comparing the scenarios, the same weighting of the criteria was used for all environmental, as well as successive economic and technical criteria to ensure the same assessment and possible objective comparison. The results are shown in Fig. 3.5.

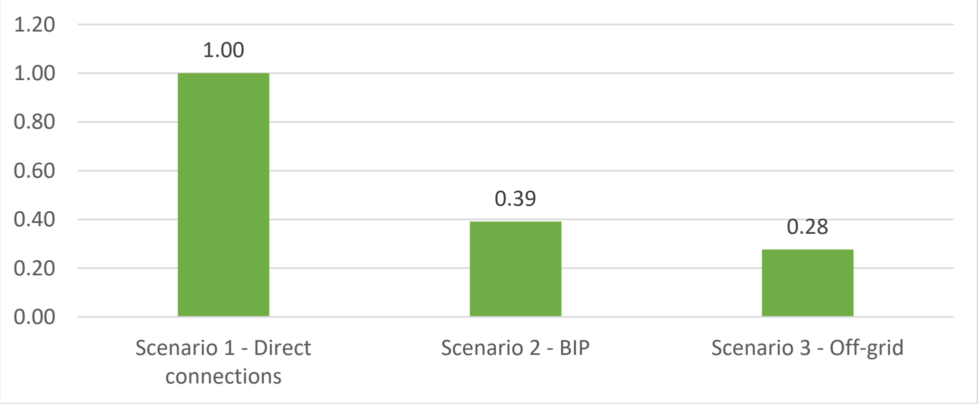

Fig. 3.5. Classification of biomethane scenarios based on environmental criteria.

The results of the environmental assessment clearly showed that, from an environmental point of view, the best way to connect biomethane plants is through direct connection.

The direct connection was followed by the use of biomethane input points with a score of 0.39, and outside the system, the use of biomethane lags slightly behind with a score of 0.28. Both of these alternatives lag far behind the ideal result, respectively, from an environmental point of view, due to the risks of transportation and leakage. When making regular connections to the system or to the end-user, the establishment of a direct connection of a biomethane plant to the gas system has the least negative environmental impact.

Table 3.7 provides an economic assessment of the normalised decision matrix for all three scenarios using expert-defined results.

Table 3.3

Normalised Decision Matrix for the Economic Criteria Scenario

	Scenario 1	Scenario 2	Scenario 3	Criteria weights
Impact on labour, jobs per EUR 1 million investment	0.496	0.608	0.620	0.2
Levelised energy costs, EUR/MWh	0.546	0.559	0.624	0.2
Positive impact on gas market flexibility, gas availability	0.631	0.599	0.492	0.2
Impact of economic aspects on gas users, EUR/MWh	0.553	0.567	0.611	0.2
Economic risks to the implementation of the scenario	0.590	0.577	0.565	0.2

The economic indicators of three biomethane integration scenarios were assessed (Fig. 3.6), to process expert assessments as well as possible according to five main economic criteria.

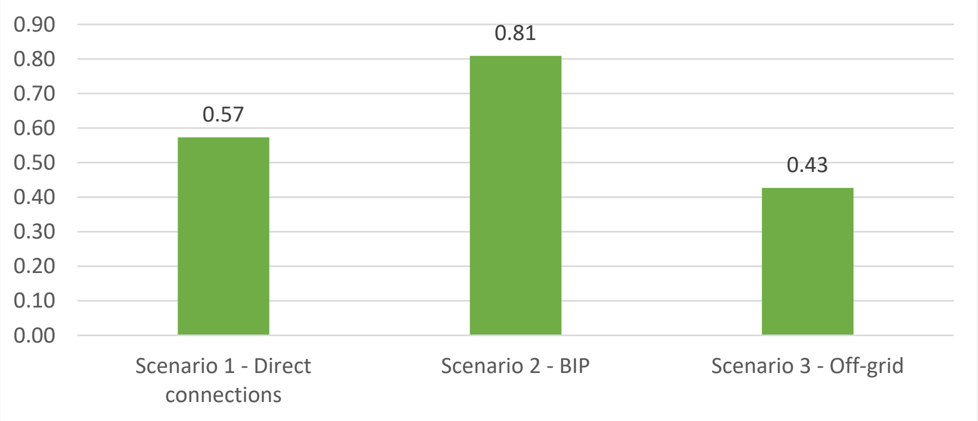

Fig. 3.6. Classification of biomethane scenarios based on economic criteria.

These results indicate that Scenario 2, which involves the use of a biomethane injection point (BIP), demonstrates the most favourable economic profile among the evaluated alternatives. With a Ci value of 0.81, this scenario is closest to the ideal solution, indicating a superior balance across all economic criteria, particularly in terms of market flexibility and profitability.

Scenario 1, which represents direct network connections, achieved a moderate performance score ($C_i = 0.57$). This reflects a balanced but less optimal trade-off between employment benefits and economic risks.

In contrast, Scenario 3, based on off-grid solutions, exhibited the lowest level of economic suitability ($C_i = 0.43$). The results suggest that although such systems may offer certain local advantages, they are comparatively less favourable when broader economic dimensions are considered, including system-wide cost-effectiveness and market integration.

Overall, the TOPSIS assessment highlights the economic viability of the biomethane injection point infrastructure compared to the more centralised or direct alternatives. The results provide a quantitative basis for prioritising policy and investment decisions that support energy system decarbonisation when economic considerations are the primary decision-making criterion.

The next section (Table 3.8) presents the technical assessment of all three scenarios based on the normalised decision matrix and expert evaluation results.

Table 3.4

Normalised Decision Matrix for the Technical Criteria Scenario

	Scenario 1	Scenario 2	Scenario 3	Criteria weights
Complexity of implementation	0.629	0.643	0.438	0.2
Technical risks, probability of malfunctions, %	0.423	0.634	0.647	0.2
Effect of oxygen content, concentration of O_2 in gas, %	0.553	0.623	0.553	0.2
Density of road transport, car/day	0.435	0.585	0.684	0.2
Use of gas pipelines (% of capacity)	0.728	0.609	0.315	0.2

The technical performance of the three biomethane integration scenarios was assessed in order to best process the expert assessments against five key technical criteria (Fig. 3.7).

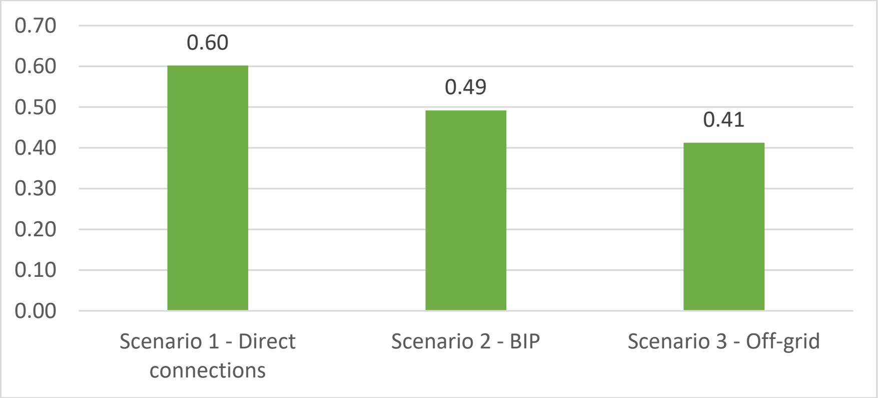

Fig. 3.7. Arrangement of biomethane scenarios based on technical criteria.

These results indicate that Scenario 1, which involves the direct connection of biomethane production facilities to the existing gas network, demonstrates the strongest and most favourable technical performance. With a C_i value of 0.60, this configuration offers a comparatively high level of technical suitability, likely due to its compatibility with existing infrastructure, established operational practices, and minimal technological disruption.

Scenario 2, which centralises gas injection through a designated biomethane injection point (BIP), achieved a moderate technical score (C_i = 0.49). Although technically less favourable than direct connections, this scenario still demonstrates a viable implementation potential.

Scenario 3, representing off-grid systems, achieved the lowest technical score (C_i = 0.41). This result indicates significant challenges related to technological maturity, system integration, and long-term scalability. While the score is relatively close to that of Scenario 2, greater risks and complexities arise from the fact that biomethane delivery from bioCNG transport units is not integrated into a standardised, highly secure national gas infrastructure, but rather supplied directly to end users whose technical connection requirements, pressure levels, flow rates, and operational conditions may vary considerably.

Although such systems may provide advantages in remote or isolated locations, their broader technical implementation within the existing gas infrastructure framework appears less feasible.

Overall, the TOPSIS assessment of the technical criteria identifies direct system connections (Scenario 1) as the technically strongest alternative.

To further evaluate and compare the obtained results, the author conducted an additional TOPSIS matrix assessment by integrating and consolidating the previously obtained environmental, economic, and technical evaluation results. In the integrated matrix, the outcomes of the environmental, economic, and technical analyses were combined and reassessed, resulting in the following normalised decision matrix.

Table 3.5

Normalised Decision Matrix for Integrated Criteria Analysis

	Scenario 1	Scenario 2	Scenario 3	Criteria weights
Environmental criteria matrix	0.902	0.353	0.249	0.333
Matrix of economic criteria	0.531	0.749	0.395	0.333
Matrix of technical criteria	0.553	0.743	0.378	0.333

The best results of the three biomethane integration scenarios were assessed and compared using the results of the assessment of environmental, technical and economic criteria.

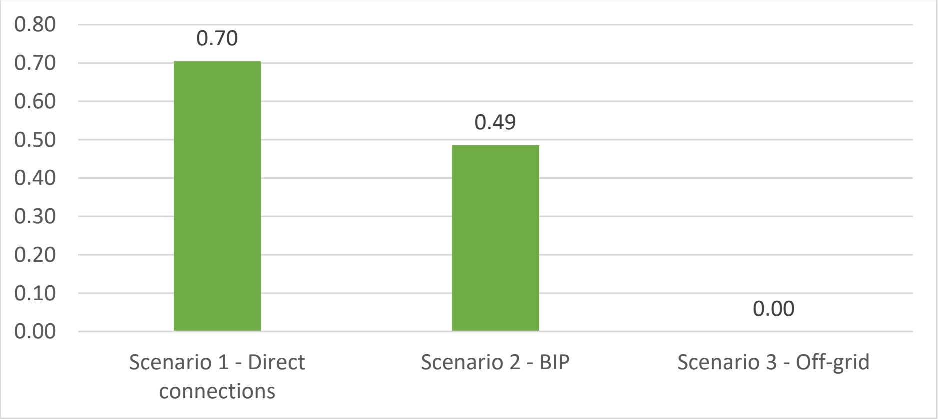

Fig. 3.8. Classification of biomethane scenarios based on the matrix of integrated criteria.

The analysis indicates that Scenario 1, which involves the direct integration of biomethane producers into the existing natural gas system, represents the most balanced and favourable solution across all evaluated dimensions. A relative closeness coefficient of 0.70 demonstrates a strong synergy between environmental benefits (e.g., emission reductions), economic performance (e.g., moderate costs and manageable risks), and technical compatibility (e.g., infrastructure readiness and scalability).

Scenario 2, based on biomethane injection points (BIPs), achieved an intermediate integrated score of 0.49, reflecting certain trade-offs between its economic strengths and technical limitations. Although this configuration offers operational and economic advantages, its comparatively lower environmental and technical performance reduces its overall attractiveness. Nevertheless, it remains a highly desirable option when economic considerations are prioritised.

In contrast, Scenario 3, representing off-grid solutions, obtained a score of 0.00, indicating the greatest distance from the ideal solution when all dimensions are evaluated simultaneously. This result reflects the fact that Scenario 3 corresponds to the negative-ideal solution, demonstrating the weakest performance across all evaluated criteria.

The sensitivity analysis confirmed that within the environmental criteria group, the direct connection scenario consistently maintained the highest evaluation across the entire range of criterion weights. The BIP scenario exhibited only minor fluctuations as the importance of specific environmental criteria increased. The off-grid solution maintained a relatively stable evaluation, with changes in environmental criterion weights having little influence on its overall ranking.

Within the economic criteria group, the BIP scenario proved to be the most robust solution, maintaining a high evaluation regardless of changes in criterion weights. The assessment of the direct connection scenario improved as greater weight was assigned to positive impacts on the gas market, levelised energy costs, and impacts on gas users, while its score declined when greater importance was assigned to employment-related criteria. The off-grid solution exhibited the opposite trend, becoming more competitive as the importance of employment-related impacts increased.

Within the technical and infrastructure criteria group, the BIP scenario also demonstrated relatively high stability. The evaluation of the direct connection scenario improved as greater importance was assigned to technical risk and infrastructure utilisation criteria. The off-grid solution performed better when higher weights were assigned to road transport intensity and implementation complexity criteria. The oxygen-content impact criterion exhibited low sensitivity and did not significantly affect the relative ranking of the alternatives.

The sensitivity analysis of the integrated assessment revealed an opposite relationship between the direct connection and BIP scenarios, while the off-grid solution consistently remained the lowest-ranked alternative. As the importance of environmental criteria increased, the suitability of the direct connection scenario improved. Conversely, when economic and technical criteria were prioritised, the evaluation of the BIP scenario improved.

It can therefore be concluded that the selection of the optimal solution depends on the priorities established by decision-makers. When environmental considerations are dominant, direct connection to the gas system is the preferred option. When economic and technical considerations are prioritised, the use of a biomethane injection point may be more justified. However, when seeking the most balanced overall solution, direct connection to the gas system should be regarded as the preferred alternative.

3. TOPSIS model – what are the alternatives to the effective use of biomethane

The evaluated biomethane utilisation pathways (presented in Table 3.4) included:

- *storage/injection into the gas system* encompasses all forms of biomethane injection into the natural gas system, including supply to underground gas storage facilities (provided that the gas complies with the applicable gas quality requirements), delivery to end users through pipelines, or export to other markets;
- *heat generation* – the direct use of biomethane for heat production, for example in district heating systems or industrial boilers, involving the conversion of biomethane into another form of energy;

- *electricity generation* – the on-site combustion of biomethane for electricity production, typically using combined heat and power (CHP) plants or gas engines, representing another form of energy conversion;
- *Industrial production* – the use of biomethane as a feedstock or process fuel in large-scale industrial facilities, including the chemical, fertiliser, and cement industries.
- *protein production* – an innovative biotechnological application in which biomethane serves as a substrate for the production of single-cell protein or other high-value bioproducts.

Table 3.6

Normalised Data Matrix Multicriteria Analysis

Criteria	Storage	Heat generation	Electricity generation	Industrial production	Protein production
Technological	0.466	0.487	0.436	0.508	0.313
Economic	0.382	0.504	0.493	0.499	0.327
Climate	0.624	0.306	0.368	0.381	0.487
Environmental	0.515	0.411	0.463	0.428	0.411
Socio-economic	0.484	0.452	0.484	0.479	0.314

The normalised matrix presented in Table 3.4 reflects the aggregated expert assessments, where higher values indicate more favourable performance with respect to each criterion. Finally, the average normalised score was calculated for each end-use category, enabling the alternatives to be ranked according to their overall suitability for biomethane utilisation.

The MCDA results, presented in Fig. 3.9, reveal that storage and injection into the gas system achieved the highest overall score, indicating that experts perceive this pathway as the most practical and impactful method of biomethane utilisation. Its strong performance across all five criteria reflects the flexibility and scalability of this option, enabling biomethane to be stored in underground gas storage facilities, transported through existing gas infrastructure, and distributed to various consumer groups, including potential export to neighbouring markets.

However, storage and transportation are only possible when biomethane and its constituent components comply with stringent gas quality requirements.

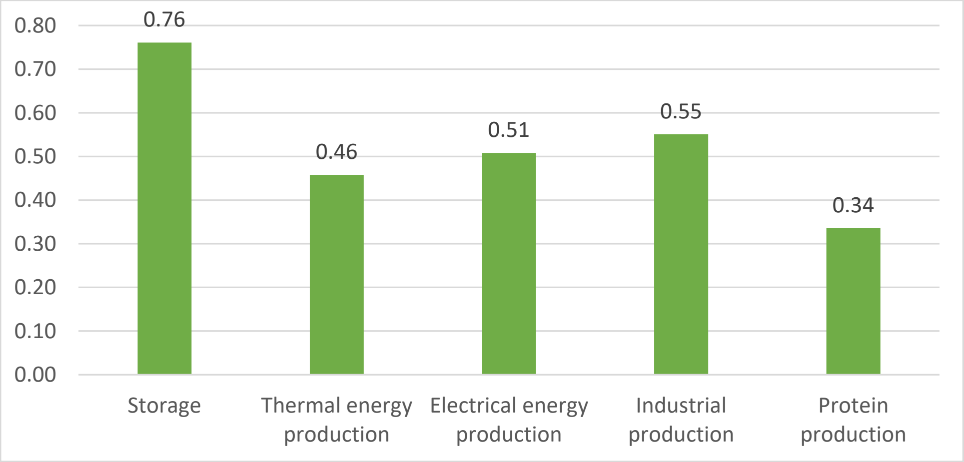

Fig. 3.9. Optimal methods for the use of biomethane – comparative MCDA results showing the relative suitability of different end-use options for biomethane.

In order to assess the impact of the criteria, a sensitivity analysis was carried out in addition to the scenarios calculated in the TOPSIS analysis (Fig. 3.10).

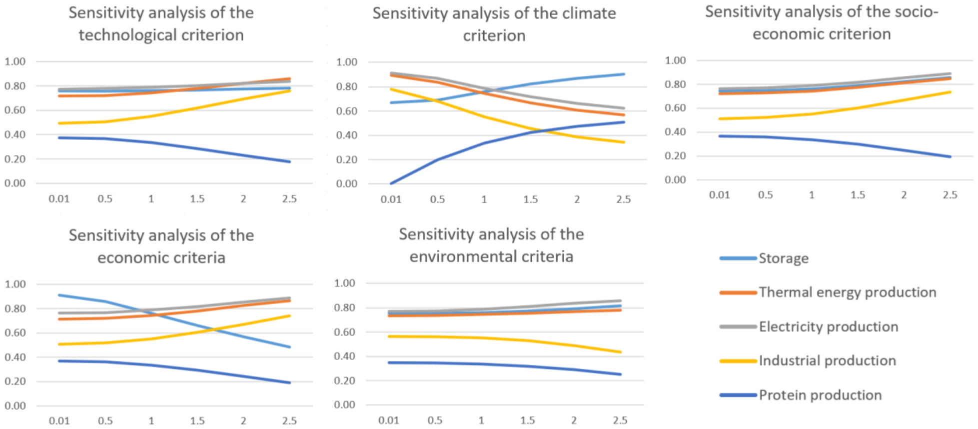

Fig. 3.10. Sensitivity analysis for TOPSIS model by biomethane application types.

The assessment of alternatives is generally influenced by the weights of the groups of criteria, however, in some cases, trends are stable and sensitivity analysis showed that the choice of alternatives depends to a large extent on the desired priorities; however, in most cases, the production of electricity and heat combines a high relative proximity to the ideal value with a relatively stable trajectory, and is therefore considered to be the most competitive alternative overall. Storage becomes dominant mainly within the group of climate criteria; industrial production retains mediocre competitiveness, while protein production as a whole demonstrates a lower relative proximity to the ideal value and is a less desirable alternative in different categories.

3.5. Results of Regression Analysis – Analysis of the Efficiency of Biomethane Production Volume (Productivity)

The study presents a case analysis of a Latvian biomethane production plant using monthly feedstock input data from September 2024 to June 2025. These data were used to evaluate the effectiveness of specific feedstock components and their influence on methane yield.

Regression analysis was performed to assess the relationship between the proportion of individual feedstock components and the methane (CH_4) concentration in the produced raw biogas. Of the 18 analysed substrates, only those with a coefficient of determination (R^2) greater than 0.4 were retained for interpretation, ensuring that only statistically significant or at least moderately strong correlations were considered.

Overall, six feedstock components met this criterion, as shown in Fig. 3.11. Among these, dairy production by-products, poultry manure, and dairy cattle manure exhibited a positive correlation with methane concentration, indicating that a higher share of these substrates increased the methanogenic potential of the feedstock mixture. In contrast, milk lactose, flotation residues, and wastewater from the food processing industry showed a negative correlation, suggesting that increasing their proportion was associated with lower CH_4 concentrations.

Overall, animal-derived substrates tended to have a positive effect on methane yield and gas quality, whereas liquid or process-derived residues demonstrated an inhibiting or diluting effect.

It should be emphasised that the strongest predictive relationships are those where the R^2 values approach 1. This was observed for dairy production by-products ($R^2 = 0.786$), which showed the strongest positive contribution to methane concentration, and for milk lactose ($R^2 = 0.687$), which exhibited the strongest negative correlation. Furthermore, interactions between substrates may influence overall digestion performance, as certain components may enhance or inhibit the degradation efficiency of others.

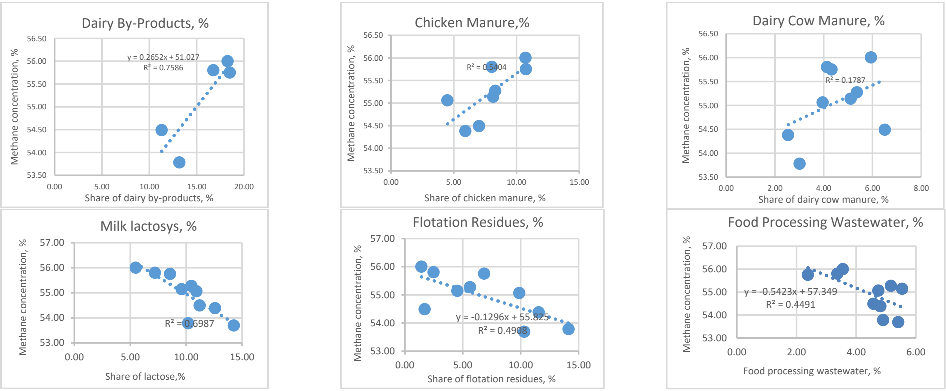

Fig. 3.11. Methane concentration in biogas based on various feedstocks.

Therefore, these findings should not be interpreted as universally applicable but rather as indicators of specific patterns observed in this particular biogas production facility. Nevertheless, the results reveal consistent trends that may reflect broader causal relationships between feedstock composition and biogas quality.

The results also revealed a clear positive linear correlation between the concentration of methane in the biogas produced and the corresponding greenhouse gas (GHG) emissions, expressed as a tonne of CO_2 equivalent per tonne of raw materials. As shown in Fig. 3.11, higher CH_4 concentrations were consistently associated with increased GHG emission values. In particular, when methane concentrations increased from 51 % to 59 %, estimated GHG emissions increased from around 10.2 t CO_2 eq/t to 11.8 t CO_2 eq/t.

This trend can be explained by the higher energy content and combustion potential in biomethane with higher CH_4 purity, which proportionally increases CO_2 emissions by normalising the amount of energy produced per tonne. In other words, while a higher concentration of methane indicates better gas quality and calorific value, it also produces a higher carbon dioxide equivalent when expressed as total energy consumption. It is important to underline that this increase in carbon dioxide equivalent does not indicate a greater climate impact per unit of useful energy; this is the effect of normalising emissions per ton of raw materials, and not on the MWh of biomethane produced.

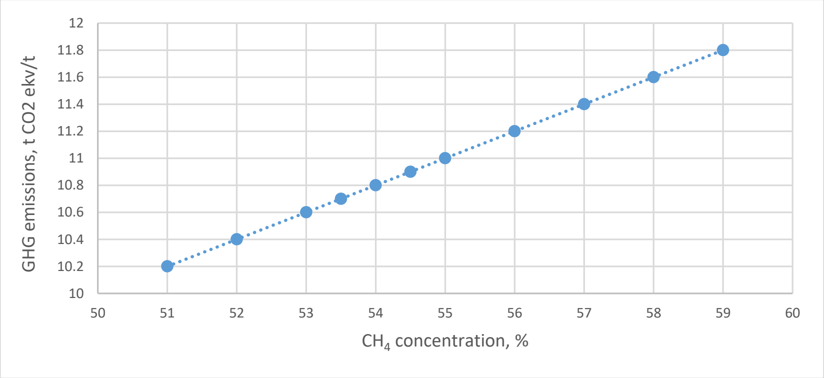

Fig. 3.12. GHG reduction analysis.

Interpreting these results together with the analysis of the composition of raw materials, these results show that some substrates that increase CH4 concentrations (e.g. dairy by-products and manure) indirectly contribute to higher estimated GHG emissions per tonne of raw materials. In contrast, raw material components that reduce methane concentrations (e.g. flotation residues and wastewater) produce lower emission factors. This indicates that the choice and proportion of types of raw materials affect the quality of biomethane and also have a measurable impact on the total carbon footprint of the production process. Therefore, while increasing the concentration of CH4 improves the efficiency of biogas and the amount of energy produced, it simultaneously increases the carbon intensity per unit of energy, highlighting the need to optimise gas quality in a balanced way with ecological greenhouse gas performance.

3.6. Results of the Cost-Benefit Analysis

Taking into account the cost parameter indicators described in the methodology part and the data used in them, the total cost of capital and operating costs for all three scenarios were calculated.

Table 3.7

Total costs of CAPEX and OPEX for all Scenarios

	CAPEX (EUR)	**OPEX (EUR/year)**
1. Scenario (direct connection)	17 050 000	1 112 275
2. Scenario (BIP)	6 400 000	808 400
3. Scenario (off-grid solution)	5 200 000	757 847

The cost-benefit analysis showed that the highest capital investments are required for a direct biomethane plant connection to the natural gas system (approximately EUR 17 million), while the biomethane injection point (BIP) solution requires capital investments of approximately EUR 6.4 million, and the off-grid solution approximately EUR 5.2 million. The results indicate that a direct connection is more suitable in areas with well-developed natural gas infrastructure, the BIP solution is more appropriate in regions where pipeline construction is not economically justified, while the off-grid solution is best suited for specific market segments, such as the transport sector.

Following the assessment of capital investments and operational expenditures, the next stage focused on revenue generation and the calculation of payback periods in order to further evaluate the economic viability of each scenario.

$$REVENUE = 20\,000 \times 70 = 1\,400\,000\ \frac{\mathrm{EUR}}{\mathrm{year}} \tag{3.1}$$

Comparing the payback periods of all three scenarios (see Table 3.11), it becomes evident that Scenario 3 is the most economically viable, as it has the shortest payback period.

Table 3.8

Comparison of Scenarios

	CAPEX (EUR)	**OPEX (EUR/year)**	**Forecast generated of revenue (EUR)**	**Payback period (years)**
Scenario 1	17 050 000	1 112 275	1 400 000	59.2
Scenario 2	6 400 000	808 400	1 400 000	10.8
Scenario 3	5 200 000	757 847	1 400 000	8.1

Although Scenario 3 – off-grid delivery – provides the shortest payback period (approximately 8.1 years), Scenario 2 – transportation of biomethane to a BIP – may become a more sustainable and systemic solution in the long term, despite its relatively longer payback period (approximately 10.8 years). One of the main reasons is the stability of this model and its potential to increase delivery volumes, as access to the natural gas system provides access to a much broader range of consumers, including households, the industrial sector, and district heating systems.

To assess the impact of various factors on the economic viability of biomethane integration, a sensitivity analysis was conducted to determine how changes in economic, technological, and policy variables affect the payback period in each scenario.

As biomethane functions as an alternative to natural gas, its price largely depends on fossil fuel price dynamics, renewable energy demand, and national regulatory frameworks. If the market price of biomethane increases by 10 % (from EUR 70/MWh to EUR 77/MWh), annual revenues in all scenarios increase from EUR 1 400 000 to EUR 1 540 000. As operating costs remain unchanged, the payback period decreases as follows:

- in Scenario 1, from 59.2 years to 50.6 years;
- in Scenario 2, from 10.8 years to 9.3 years;
- in Scenario 3, from 8.1 years to 6.6 years.

These results demonstrate that an increase in the biomethane price significantly improves the return on investment across all scenarios. At the same time, government support mechanisms, such as subsidies, tax incentives, and changes to the emissions trading system, can substantially enhance the financial attractiveness of renewable energy projects. If the government were to provide a 20 % capital investment subsidy, the initial investment costs would decrease as follows:

- in Scenario 1, from EUR 17 050 000 to EUR 13 640 000;
- in Scenario 2, from EUR 6 400 000 to EUR 5 120 000;
- in Scenario 3, from EUR 5 200 000 to EUR 4 160 000.

Taking into account the reduction in capital investments, the payback period would also decrease accordingly:

- in Scenario 1, from 59.2 years to 47.4 years;
- in Scenario 2, from 10.8 years to 8.9 years;
- in Scenario 3, from 8.1 years to 6.5 years.

The results show that appropriate government support instruments can make economically viable even those projects that initially appear too capital-intensive, such as the solution described in Scenario 1. However, the calculations indicate that even with substantial government support, it is very difficult to recover investments in connection infrastructure within a reasonable timeframe. The relationship between methane concentration and feedstock-related production costs was also assessed, and the results are presented in Fig. 3.13.

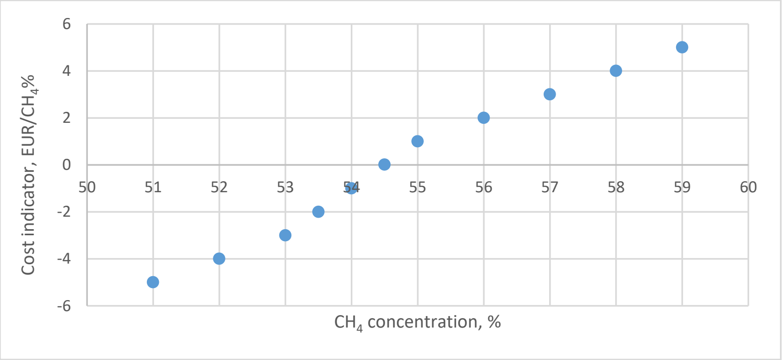

Fig. 3.13. The cost of raw materials based on the concentration of methane.

Combined with the previous findings, the results reveal a trade-off between gas quality, greenhouse gas performance, and production costs. Achieving higher CH_4 concentrations improves the calorific value and energy output of biogas, but it also increases carbon intensity and raises production costs per unit of energy. Therefore, an optimal biogas production strategy should focus on balancing the feedstock composition in a way that maximises both economic efficiency and environmental sustainability.

3.7. Results from Optimisation model

The regression analysis (Section 3.5) identified which feedstock categories were associated with variations in methane content. The regression analysis provided an empirical basis for the optimisation model, in which methane content in biogas is used as the output indicator.

To visualise and evaluate the economic efficiency of biogas production in relation to methane concentration, a two-curve optimisation model was developed. This model overlays normalised monthly biomethane (as the final product) revenue and biogas production cost curves as a function of CH_4 concentration. The optimisation model does not include an analysis of the upgrading process, as the associated costs are assumed to be comparable across all scenarios. The curves are derived from empirical data and plotted across the full observed range of CH_4 concentrations. This approach makes it possible to identify the methane concentration level at which the relationship between production costs and revenues reaches a theoretical equilibrium point.

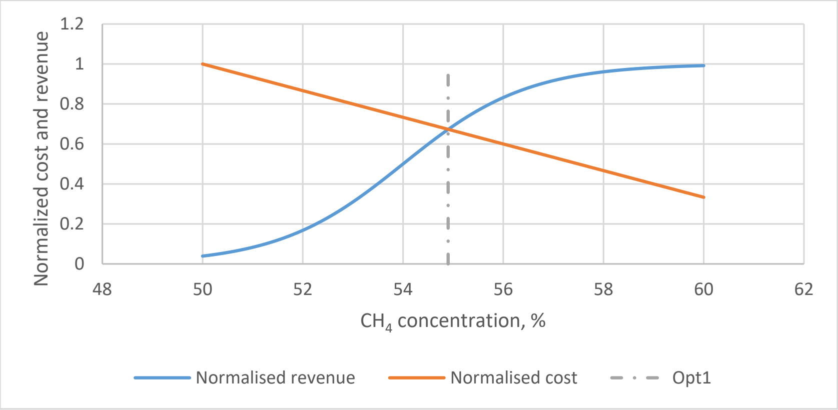

Fig. 3.14. Theoretical optimisation model: revenues and costs against CH_4 concentration.

This visualisation in Fig. 3.14 reveals the key economic dynamics.

The normalised production cost curve generally decreases as CH_4 concentration increases, as a higher methane content improves gas quality and enables greater energy output per unit of processed feedstock.

Conversely, the normalised revenue curve initially increases with CH_4 concentration, reflecting higher energy sales volumes. However, at higher concentrations, it may plateau or slightly decline, possibly due to diminishing marginal gains or fluctuations in the total volume of processed feedstock.

The intersection of these two curves marks the critical threshold at which normalised revenues equal normalised costs. This intersection, denoted as Opt1, represents the CH_4 concentration at which operational profitability reaches equilibrium.

Based on the analysed data, the optimal CH_4 concentration in biogas is approximately 54.9 %, where the normalised cost and revenue curves intersect. Below this point, production costs exceed revenues, indicating inefficient operation. Above this point, although revenues may continue to increase, the marginal benefits diminish relative to the reduction in the cost curve.

Therefore, this intersection point, Opt1, defines the economically optimal methane concentration for plant operation. Operating close to this concentration may provide the most balanced return on operational investment.

Figure 3.15 illustrates the impact of the European Union Emissions Trading System 2 (ETS 2) on the economic performance of biogas production at different methane (CH_4) concentrations. It compares normalised biogas production costs with normalised total biomethane revenues, including the carbon revenue premium generated through ETS 2, as a function of CH_4 content in biogas.

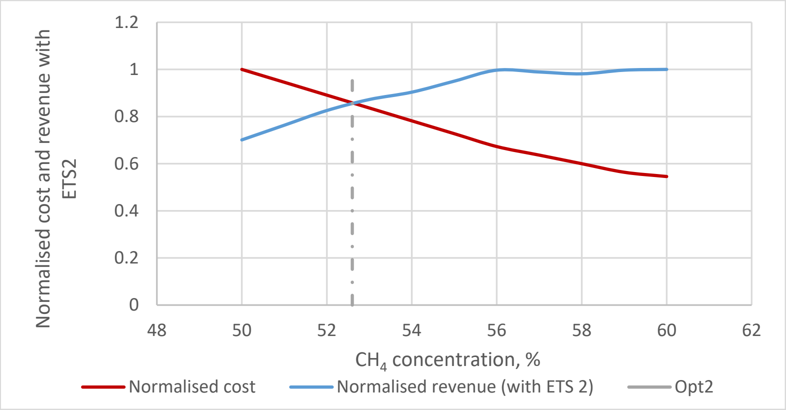

Fig. 3.15. Theoretical optimisation model: revenues with ETS 2 and costs against CH_4 concentration.

In the second model, ETS 2 revenues are added as a fixed premium (EUR 5/MWh) to biomethane revenues. This reflects the financial benefit derived from avoided CO_2 emissions or the sale of emission allowances under the European Union Emissions Trading System (ETS 2). As a result, the normalised revenue curve shifts upward, particularly at lower CH_4 levels where baseline revenues are weaker. The new optimal point, Opt2, is approximately 52.6 % CH_4. This indicates that even biogas with a lower methane content becomes economically viable due to carbon credit revenues.

In the context of both biogas production models with and without ETS 2 policy support, the optimisation curve represents the overall economic distance between production costs and the maximum achievable biomethane revenues as a function of CH_4 concentration. It is a conceptual curve that illustrates how close or far the system is from its maximum performance at each methane concentration level. In Figs. 3.14 and 3.15, the optimisation curve is shown as a graphical curve above the Opt1 and Opt2 points, combining actual costs with the gap between current revenues and the highest achievable revenue level. It can be interpreted as a penalty curve – the higher its value at a given CH_4 percentage, the further that point is from the economic optimum.

The ETS 2 incentive reduces the gap between costs and revenues, particularly within the 50–54 % CH_4 range, effectively lowering the profitability threshold.

4. CONCLUSIONS

1. The results of the regression analysis confirm that feedstock composition is a statistically significant factor in determining the volume and efficiency of biomethane production. The feedstocks used affect the concentration of methane produced, thereby demonstrating the need for producers to optimise feedstock flows and their mixtures in biomethane production plants. In the specific case study, the strongest positive relationship with methane concentration was found for dairy production by-products ($R^2 = 0.786$), indicating that the share of these substrates increased the potential for a higher methane concentration. A negative correlation ($R^2 = 0.687$) was found in the study for milk lactose, where a higher share of milk lactose in the mixture reduced the methane concentration in the gas produced. The structure of the feedstocks used in production can directly affect methane concentration and, consequently, the efficiency of biomethane production.
2. The cost-benefit analysis shows that the economic viability of biomethane is conditionally dependent on external market and policy factors, particularly the dynamics of energy prices and emission allowances.
3. The results of the multi-criteria analysis show that the effectiveness of biomethane integration solutions is relative, and that the optimal choice changes significantly depending on the weight of the selected criteria and the priorities of the system. Biomethane as a gaseous energy resource achieved the highest score ($C_i = 0.68$), compared with hydrogen ($C_i = 0.45$) and natural gas ($C_i = 0.35$). The results of the specific study indicated that the direct connection of a biomethane production plant is the most optimal solution from an environmental ($C_i = 1.00$) and technical perspective ($C_i = 0.60$), while from an economic perspective, alternative delivery methods may be preferable, such as the use of a biomethane injection point ($C_i = 0.81$) or direct delivery to the user ($C_i = 0.43$). By integrating the obtained results into a single matrix, the direct connection of a biomethane production plant can generally be considered the most optimal solution ($C_i = 0.70$), followed by the biomethane injection point ($C_i = 0.49$), while, according to the integrated matrix, the lowest performance is achieved by biomethane delivery outside the gas system ($C_i = 0.00$).
4. The optimisation model confirms that biomethane development should be assessed as an element of the energy system, rather than as an isolated solution, taking into account its interaction with other energy sources and consumption sectors. In the optimisation model, the theoretical equilibrium point was determined at a methane concentration of 54.9 %, where the normalised cost and revenue curves intersect. By including an ETS 2 incentive of 5 EUR/MWh, a lower methane concentration also becomes economically justified, with the optimal methane concentration point shifting to 52.6 %, indicating that policy incentives can expand economically justified biomethane production.
5. The multi-method framework (TOPSIS, regression analysis, CBA and optimisation model) used in the Thesis shows that the application of individual methods helps to assess a specific solution, while the application of several methods helps to develop a transparent and comprehensive assessment across different aspects.

6. The development of biomethane in Latvia is limited by technical, market-related and stable regulatory environment factors, which affect the scale of its implementation and the pace of development.
7. At an early stage of market development, flexible solutions, such as biomethane injection points, are particularly important, as they make it possible to overcome infrastructure limitations and accelerate the entry of biomethane into the market.
8. The research results indicate that biomethane development requires the implementation of a multifaceted integration approach, where one individual method or improvement will not deliver the expected benefit in the development of such a complexly affected system. At the same time, in Latvia it is necessary to continue developing direct connections and biomethane injection points, as well as to consider the usefulness of applying biomethane delivery outside the system in certain cases.
9. Biomethane is suitable for integration into the energy system as a stable and flexible energy resource that is not affected by the availability of solar or wind energy. It is particularly suitable for sectors where electrification is limited, while also promoting the use of local resources and reducing import dependence.
10. The development of biomethane requires a predictable and stable policy environment that reduces investment risks and provides long-term clarity for market participants, where the support experience of Western European countries shows that stable conditions are followed by stable sectoral growth.
11. The developed analytical framework can be used by the sector and by policymakers to assess support mechanisms, determine infrastructure development priorities and analyse the impact of different scenarios.
12. The limitations of the study are related to data availability and the scope of the analysis, as, for example, the regression analysis is based on data from one Latvian biomethane production plant obtained for a specific period. Therefore, these results cannot be fully applied to all biomethane production plants, and this indicates the need for further research.
13. The results of the Doctoral Thesis confirm the proposed hypothesis; at the same time, the optimal solution for biomethane integration scenarios is not universal, as it depends on the weight of the evaluation criteria, infrastructure availability, market maturity and national policy support mechanisms. Taking into account the conclusions of the Doctoral Thesis, the hypothesis is not confirmed as one solution being superior to another; rather, it is confirmed as a methodologically justified possibility to identify comparatively more optimal biomethane integration scenarios depending on the priorities set.
14. The research results demonstrate that the integration of biomethane into Latvia’s energy system is technically feasible, economically justified and systemically important, but its successful development requires a coordinated, data-based approach between infrastructure, market and policy.

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Ance Ansone was born in Riga in 1993. She obtained a Bachelor's degree in Environmental Science (2015) from Riga Technical University (RTU) and a double Master's degree in Environmental Science from RTU and in Environmental Engineering from Vilnius Gediminas Technical University in 2017.

Since 2014, her professional experience has developed in the fields of energy, sustainable development, and the transition to renewable energy resources. She gained professional experience at the RTU Institute of Energy Systems and Environment and at the Energy Market and Infrastructure Department of the Ministry of Economics, specialising in gas market, infrastructure, and energy policy issues. Since 2020, she has been working in the Business Development Division of JSC "Conexus Baltic Grid". Her professional activities are related to international cooperation, gas market development, and promoting the integration of renewable gases.

Her research interests focus on the sustainability of biomethane, its integration into the existing energy system, and the role of renewable gases in the development of accessible and sustainable energy infrastructure.