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Toward an Integrated Approach – A Conceptual Framework for Complex Biomethane Development

Ance ANSONE[1*], Liga ROZENTALE[2], Dagnija BLUMBERGA[3]

[1–3]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV- 1048, Latvia*

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Abstract **– This research presents a conceptual framework for an interdisciplinary approach to national biomethane development, addressing the sector's complexity, gaps and the need for systemic analysis. Biomethane plays a key role in decarbonizing existing gas infrastructure, supporting a circular economy, and strengthening energy security by reducing reliance on fossil fuels. However, national-level uncertainties require both comprehensive and targeted strategies. The study highlights the value of establishing a centralized data bank gathering information from biogas and biomethane plants, natural gas infrastructure, connection cost estimates, and technical configurations. System dynamics modelling is proposed as a method to simulate the various elements of the biomethane system. Additionally, tools such as life cycle assessment (LCA) and multi-criteria decision analysis (MCDA) are identified to assess environmental, economic and technological impacts, therefore facilitating informed decision making. This creates theoretical integrated approach. TOPSIS is used in practical test scenario to evaluate balanced gaseous energy source. Test scenario results calculations showed biomethane as the most favourable scenario (score 0.68) across multiple sustainability and economic criteria, followed by hydrogen (0.45), which shows strong decarbonization potential but faces maturity and risk challenges, while natural gas (0.35) ranks lowest, reflecting its limited role in long-term sustainable energy transitions and being impacted by low climate performance. By applying interdisciplinary approach, it could help develop an efficient, flexible and sustainable biomethane sector.**

Keywords **– Biomethane; climate policy; energy transition; infrastructure modelling; renewable energy; system dynamics; TOPSIS.**

1. INTRODUCTION

The European Union's increasing demand for sustainable gases produced from renewable sources, among other, is to be used in the transport sector. The European Green Deal aims to achieve a 90 % reduction in transport-related greenhouse gas emissions by 2050 [1]. This can be done by integrating renewables into the transport energy mix. In 2023, renewable energy sources accounted for 10.8 % of energy used in transport across the EU, marking a 1.2 percentage point increase from the 9.6 % recorded in 2022. However, this still falls 18.2 percentage points short of the 2030 target, which aims for 29 % of transport energy to come from renewable sources. In, 2023 Sweden had the highest share of renewables in transport while Latvia has one of the lowest shares of renewables in transport, only 1.4 % [2]. Therefore, this can be seen as an opportunity for Latvia to increase its national renewable

*Corresponding author.
E-mail address: ansoneance@gmail.com

energy production also in gas sector, by developing biomethane production. Biomethane is a logical alternative to fossil natural gas, as this is also methane that is produced from renewable sources and can be injected into existing interconnected gas system. Increased biomethane production will also strengthen energy independence, local economies, security of supply and last but not least, great greenhouse gas emission reduction.

The global demand to transform towards renewable energy systems has gained significant motivation in recent years, driven by increasing climate change concerns and the need for energy security and independence [3], [4]. Within this context, biomethane has come up as a promising renewable gaseous fuel that can utilize existing natural gas infrastructure while offering substantial greenhouse gas emission reductions [5], [6]. Despite its potential, biomethane development faces numerous interrelated challenges crossing technical, economic, social, and policy sectors, particularly in growing markets such as Latvia [7], [8].

The Latvian energy sector currently stands at a challenging time in its green transition journey. While there are several biogas plants, and a pair that produces biomethane, these installations operate with suboptimal efficiency levels, failing to reach their full biomethane production potential [9], [10]. This indicates not only missed environmental opportunities but also unrealized economic gains for national economy [11], [12]. Current production inefficiencies stem from various factors, suboptimal feedstock utilization and limited technological integration [13], [14].

A significant gap exists in the development and implementation of integrated techno-socio-environmental assessment frameworks for biomethane policy development in Latvia [15], [16]. Existing approaches tend to operate in a way isolated, with environmental assessments conducted separately from technical feasibility studies and socioeconomic analyses [17], [18]. This fragmentation results in policy recommendations that fail to capture the complex links between different system components and stakeholder interests [19], [20]. Therefore, biomethane policies have often lacked the base, that is necessary for effective implementation and stakeholder acceptance [21], [22].

The biomethane sector also suffers from a shortage of sophisticated modelling and prediction tools, that are capable of optimizing production outputs under variable scenarios [23], [24]. Current approaches provide limited insights into how changes in feedstock composition, technological configurations, or policy incentives might affect biomethane output, quality, and environmental footprint [25], [26]. This knowledge gap significantly holds back evidence-based decision making among producers, investors, and policymakers, resulting in suboptimal resource allocation and missed opportunities for system optimization [27], [28].

Technical solutions must be adapted to local conditions while remaining economically viable for operators of varying scales [29], [30].

Perhaps most crucially, there is a lack of comprehensive decision-making support tools designed specifically for emerging biomethane markets like Latvia [31], [32]. Stakeholders across the value chain lack integrated platforms that can at the same time address technical feasibility, economic viability, environmental impact, and social acceptance factors [33], [34]. This absence of broad decision support mechanisms leads to suboptimal investments, policy inconsistencies, and missed synergies between different system components [35], [36].

This research aims to address these interconnected gaps through the development of an interdisciplinary conceptual framework for smart energy transition planning with a specific focus on biomethane development in Latvia. By integrating technological, environmental, economic, and social dimensions, the framework seeks to provide a comprehensive approach to biomethane system optimization that transcends traditional disciplinary boundaries [37].

The research adopts a system thinking perspective that recognizes the complex interactions between technological innovation, environmental impacts, economic drivers, and social acceptance factors in shaping successful energy transitions [38], [39].

There also is a policy relevance of this work. As Latvia and similar countries formulate their national energy and climate plans, data driven approaches to renewable gas development become increasingly important [40], [41]. The proposed framework aims to inform policy design by providing insights into the potential contributions of biomethane to national climate targets, energy security objectives, and rural development goals [42].

In essence, this research addresses the high-priority need for systemic approaches to green gas transition planning that move beyond technological improvements to better deal with the complex socio-technical landscape within which energy transitions unfold [43], [44]. By developing an interdisciplinary conceptual framework tailored to the specific challenges and opportunities of biomethane development in Latvia, this work aims to contribute both theoretical insights and practical tools for accelerating sustainable energy transitions [45], [46].

2. METHODS AND METHODOLOGY

The aim is to create a useful roadmap with conceptual framework to facilitate biomethane development and smart energy transition by integrating various aspects for an interdisciplinary approach. One of the objectives of this study is to identify existing gaps in the biomethane sector and to establish a basis for comprehensive biomethane research and analysis to promote its development at the national level from environmental, climate, technological, economic and political aspects.

The methods and steps designed and applied in the comprehensive biomethane development project could be applied and used in other energy sectors, such as electricity, hydrogen, carbon capture and storage projects. By following research roadmap, that was developed by authors, it is possible to have wide energy system gap analysis and ensure future proof development ideas and plans based on data and modelling.

In addition, authors did a test scenario by applying one of the research methods in practice for biomethane evaluation in comparison with natural gas and hydrogen, by using multiple-criteria decision analysis method TOPSIS. Novelty of work is in integrating these methods into a single framework tailored to biomethane, advancing other previous renewable energy planning studies by aligning environmental, technical, and socio-economic dimensions within one structured workflow.

2.1. The Design of the Research

This interdisciplinary research integrates environmental science, engineering, and social sciences using a multi-step methodology creating the following research roadmap (Fig. 1).

2.1.1. Data collection

Data collection has a central role for data based research and decision making afterwards. Proper data can ensure effectiveness and data driven decision making process, while in the longer run creating a market development, competitiveness and efficient use of finances.

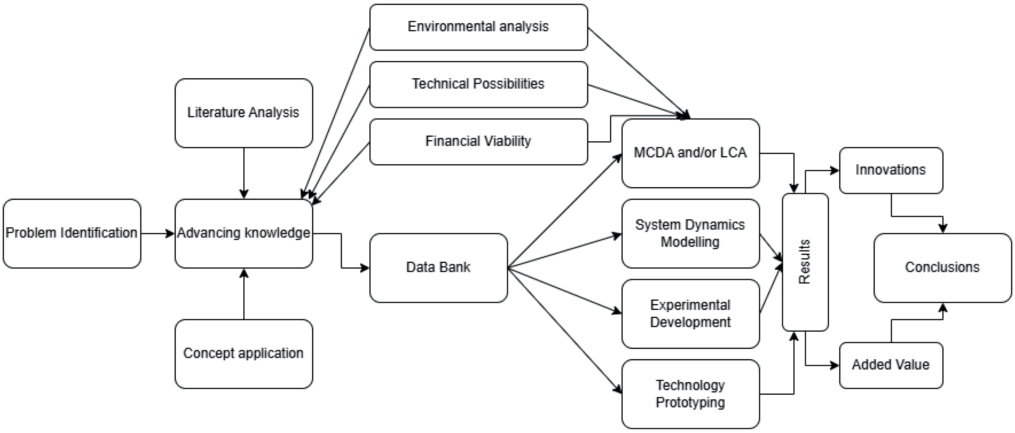

Fig. 1. Research roadmap developed by authors.

The research methodology uses a wide data collection approach to capture the complex interrelationships within the biomethane development ecosystem. Technical, economic, environmental, and social data needs to be gathered from biogas producers, biomethane plants, infrastructure operators, and the public through a combination of structured surveys, semi-structured interviews, and direct field measurements. Technical parameters including substrate composition, digester performance metrics, and upgrading efficiency needs to be collected from various operational biogas facilities, using standardized protocols, that could be adapted from Kougias *et al.* [47]. Economic data including capital expenditures, operational costs, and revenue streams can be obtained through confidential questionnaires distributed to plant operators, literature review and can be complemented by market analysis of biomethane value chains as outlined by Horschig *et al.* [48]. Environmental impact indicators such as greenhouse gas emissions, land use changes, and water consumption can be quantified using life cycle assessment methodology following ISO 14040/14044 standards [47], with system boundaries extending from feedstock production to biomethane injection into the grid. Social perception data can be collected through a stratified random sampling of respondents across rural and urban communities, using a survey as an instrument that assessed awareness, concerns, and acceptance factors regarding biomethane production facilities, adjusting methodological approaches developed by Sovacool and Ratan [49]. This comprehensive data collection framework can be essential to establish an integrated evidence base that tops traditional disciplinary boundary, enabling the development of holistic decision-support tools for stakeholders throughout the biomethane value chain [50]. The navigating of data sources enhances the robustness of findings while capturing the technical limitations, economic aspects, environmental impacts, and social dynamics that collectively shape biomethane development in relatively new markets [51].

2.1.2. System dynamics modelling

System Dynamics is a scientific approach where computer based modelling and simulation is used to go beyond the systems structure and study how and why complex systems develop over time [20]. System dynamics modelling was developed to simulate and understand complex systems, and how each of the parameters and parts of the systems impacts each other. This methodology utilizes flows, loops of feedback (positive and negative), and what is not least important - time delays to represent the interactions within systems such as economies, organizational structures or even whole ecosystems [52]. System dynamics helps to understand, explore and simulate how one larger or smaller part of the system, changes and impacts the whole system. This is a useful tool for business strategy development, policy making and research [53]. It can show non-linear feedback in biomethane supply chains.

2.1.3. Technology prototyping

The important part is to have practical value and this can be done by prototype development. Result can be a new technology prototype that will address the management of oxygen concentration and flow in the natural gas network from biomethane plants. It should be addressed that there is a need for assessment and determination of the most optimal model for the connection of biomethane production plants or the supply to end users, taking into account the challenges related to both the development, use of infrastructure and the quality of biomethane, also highlighting the potential of biomethane compared to the current situation. The modelling of the system at certain types of connections, capacities and quantities will significantly improve the assessment of the impact of these quality problems and make it possible to predict the impact on the infrastructure in order to optimise the transport and entry of biomethane into the system, while reducing technical barriers to the introduction of biomethane.

2.1.4. Experimental development

There are various possibilities on experimental development. The modelling approach is consistent with experimental development and industrial research, as it focuses on the development and testing of practical, measurable solutions. As part of experimental development, modelling can be used to optimize biomethane connection types or technologies, which will then be tested in practice.

Life Cycle Analysis (LCA) is a method for assessing the environmental impact of biomethane production and use throughout the life cycle – from resource extraction to the use of the final product. This method allows you to quantify both direct and indirect emissions, as well as to assess resource efficiency. LCA is important in sustainability analysis because it provides a systemic view of impacts throughout the cycle and quantifies unique environmental processes, for example in waste management. LCA is consistent with fundamental research and industrial research, as the results of this analysis can help lay the foundations for the development of new technologies, improving scientific understanding of the impact of the biomethane system. LCA data may also be needed in the experimental development process to compare the sustainability of different technologies and optimize their performance.

Multi-criteria analysis (MCDA) allows to compare different alternatives, taking into account several factors at once, such as technological costs, environmental impact, energy efficiency and societal acceptance. In the case of biomethane systems, the MCDA can help you choose the optimal technical solutions or investment models based on sustainability, economic and environmental criteria. MCDA is often used in industrial research and experimental development, since this approach is oriented towards decision-making in real conditions, taking into account a number of criteria that are relevant for the practical implementation of solutions. Its use helps to integrate various of information that can be useful in evaluating the development of technologies or processes before real implementation. Research activities cover several stages of research and development. The methods chosen indicate a move from industrial research to experimental development, since both fundamental analysis (LCA) and the testing of practical solutions (modelling and MCDA) can be carried out. Also, laboratory based bio-methanation experiments can be done to analyse and improve methane yield, in order to improve gas quality which has a significant impact on gas infrastructure.

In this research, also a test scenario by using MCDA method the technique for order preference by similarity to ideal solution (TOPSIS) is applied. TOPSIS was chosen for this test scenario as a commonly used MCDA method that helps to make decisions by ranking a set of alternatives based on how close each alternative is to the ideal desired solution [54]. To apply TOPSIS method in research, it is needed to construct the decision matrix, and the matrix has to be normalized.

The following normalization is done for each evaluation $v_{m,k}$:

$$u_{m,k} = \frac{v_{m.k}}{\sqrt{\sum_{k}^{K} = 1_{m,k}^{v^2}}}, m = 1,...,M, k = 1,...,K \ , \quad (1)$$

where $v_{m,k}$ represents the evaluation of alternative A_k (k =1, 2, …, K) with respect to the criterion C_m (m = 1, 2, …, M). Then following is weighted normalization, where for each normalized evaluation $u_{m,k}$ is required for the calculations of weighted normalization, where $p_{m,k}$ – normalized value of the performance score $v_{m,k}$:

$$u_{m,k} = \frac{v_{m,k}}{\sqrt{\sum_{k}^{K} = 1_{m,k}^{v^2}}}, m = 1,...,M, k = 1,...,K. \quad (2)$$

Then follows the determination of positive (PIA) and negative ideal alternative (NIA) by using Eq. (3):

$$\text{PIA} = p^+ = \{p_1^+, p_2^+, ..., p_M^+\} \text{ and NIA} = p^- = \{p_1^-, p_2^-, ..., p_M^-\}, \quad (3)$$

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, …, M. It contains the ideal and worst values for each criterion.

Equations (4) and (5) are used to calculate the Euclidean distances from each option A_k and the positive and negative ideal solutions:

$$D_k^+ = \sqrt{(p_k - p^+)^T + (p_k - p^+)}, \ k = 1,...,K, \quad (4)$$

and

$$D_k^- = \sqrt{(p_k - p^-)^T + (p_k - p^-)}, \ k = 1,...,K, \quad (5)$$

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

The final step is the calculation of closeness measure coefficient (r_k) for each alternative A_k:

$$r_k = \frac{D_k^-}{D_k^+ + D_k^-}, \ k = 1,...,K. \quad (6)$$

Afterwards a clear ranking, based on the relative closeness to the ideal solution is done. One of the other positive outcomes of using TOPSIS is that values with various units can be compared, and units themselves are not the focus of the evaluation. The best solutions can be determined and analysed regardless of the units used [54].

Results for TOPSIS analysis for test scenario comparing three alternative gaseous energy sources – natural gas (scenario 1), biomethane (scenario 2) and hydrogen (scenario 3) is shown in the results section. It was assumed that hydrogen is produced from renewable electricity, meaning it is green hydrogen. These gaseous sources were analysed to find optimal source based on various climate, economic, technical and market aspect which were formulated as 12 criteria:

1. GHG Emission Reduction Potential (avoided t CO_2eq per MWh or kg in case of hydrogen);
2. Air Pollutant Reduction (reduced NO_x, SO_x, particulate matter);
3. Waste Management Impact;
4. Revenue Potential (is the product high demand, price level and subsidies, ETS);
5. Technology Maturity;
6. Feedstock Flexibility (range of biomass types that can be processed);
7. Grid/Infrastructure Compatibility (is it easy to integrate with existing grid and transport infrastructure);
8. Job Creation Potential;
9. Policy & Regulatory Alignment (compatibility with renewable energy targets, acceptance in legal acts);
10. Contribution to Circular Economy;
11. Technology Risk (operational challenges and failures, incident risks);
12. Market Risk (sensitivity to energy prices, market demand, policy stability).

Criteria scores were developed by experienced experts in the energy field, equal weights were applied to all criteria without need to have balanced results.

In addition, authors created new normalized criteria impact score. This was developed to compare which criteria could have the highest impact for scenarios of each gaseous energy carriers. In the future this could also help decision makers to know in certain situations what can be impactful and what is not. Normalized criteria impact score can be calculated based on TOPSIS data. This can only be done after full TOPSIS and is not part of actual TOPSIS analysis.

After creating the normalized decision matrix, the values for each criterion were copied without proceeding to the calculation of distance and closeness coefficients of the full TOPSIS method. To facilitate result data, the normalized values were multiplied by 100. That resulted in scaled scores were then used in visualisation to compare the relative contribution of each criterion across the three scenarios. This visualization highlights which criteria exert the strongest influence in each scenario, even though it does not represent the final TOPSIS closeness coefficients.

2.2. Data Sources and their Importance

Accurate and comprehensive data sources are essential in system dynamics modelling to ensure the validity, reliability, and applicability of model outcomes. High-quality data enable modelers to quantify system behaviour, calibrate variables, and validate simulation outputs. In the context of biogas systems, four key categories of data can be selected – operational data from biogas plants, infrastructure characteristics, environmental indicators, and socioeconomic metrics. Biogas plant operational data (such as feedstock input, energy output and other relevant records)- should be collected directly from plant monitoring systems and analysed using time-series analysis to identify performance trends and system bottlenecks. Infrastructure characteristics, including transportation logistics and methane leak rates, can be obtained through technical surveys and other assessments. Environmental indicators like CO_2 reduction potential require LCA methodologies, integrating emissions data from feedstock sourcing, plant operation, and energy substitution scenarios. Socioeconomic indicators, including job creation, energy access, and circular economy, should be gathered through mixed-method approaches such as structured surveys and stakeholder interviews, followed by statistical analysis of available data. The integration of these diverse data sources supports the development of robust, models that reflect both technical processes and broader system impacts.

This integrated approach can be effectively applied to electricity or hydrogen research as well. For example, in hydrogen infrastructure planning, operational data from electrolysers and fuel cells, infrastructure metrics such as pipeline capacity, or pipeline costs, environmental indicators including lifecycle emissions from hydrogen production pathways, and socioeconomic aspects like security of supply can be similarly collected and analysed.

By applying system dynamics modelling complimented with data from various sectors, researchers in the future could simulate integrated scenarios for technology scaling, policy interventions and market development. This enables data driven decision making that supports sustainable transitions in energy systems, ensuring that technical, environmental, and social dimensions are addressed.

2.3. Added Value and Innovation

It is important to recognize what is currently missing in sector and to develop innovative approaches. Value added concepts are needed for renewable energy projects to be accepted by the funders, society and also it is needed to ensure value of the project in long-term, after its implementation. Innovative concept in energy sector must be cost-effective, with novel functionalities or advanced environmental performance. Innovations for biomethane projects can be tested through system dynamics modelling, as well as eco innovative biomethanization technologies.

To create a research roadmap for a nationwide biomethane upscaling or any other renewable cross sectoral energy project, a structured, integrated approach is recommended to ensure comprehensive systemic thinking, stakeholder engagement, and scenario planning. By integrating multiple research methods - System Dynamics, LCA, MCDA and practical experiments it is possible to ensure smart energy planning for biomethane or other any other renewable energy source development.

3. RESULTS

Biomethane is promising to decarbonize existing gas infrastructure, ensure circular economy, strengthen security supply and energy independence, especially from fossil fuels, but due to the uncertainties on a country level, it would be effective to do complex biomethane challenge analysis in a comprehensive manner, but it is possible to do individual problem solving as well.

There are certain potential possibilities and positive outcomes of comprehensive biomethane analysis and research on a national level.

3.1. Data Bank and Infrastructure Mapping (Conceptual Result)

The development of a data bank and infrastructure mapping are identified as essential elements for a comprehensive and high-quality national biomethane development study. The development of a data bank provides a single database with structured information on the following.

Biomethane producers (they can be divided and grouped by region, city, nationally, and potentially expanded to include other surrounding countries). Benefits of such mapping include enhanced policy planning, optimized regulatory oversight, and improved investment strategies. By having a centralized view of biomethane producers, stakeholders can identify production trends, assess regional capacities, and pinpoint areas for infrastructure development. Additionally, it facilitates cross-border cooperation, supports energy transition goals, and enables more accurate forecasting of supply and demand dynamics. The database can also aid researchers and developers in identifying innovation opportunities and promote transparency and collaboration among industry players.

The data bank would also include detailed information on the existing natural gas infrastructure, including key assets such as underground gas storage, which is a sensitive infrastructure, that can be impacted by biomethane increase into the energy system. Including such data provides several benefits, such as, it enables a clearer understanding of the compatibility between biomethane and current gas systems, supports strategic planning for capacity optimization, and assists in identifying potential investment needs. Additionally, it allows for more accurate modelling of supply security and seasonal demand fluctuations, which is crucial for ensuring a stable and efficient energy transition.

An important feature is cost estimates for different connection options of biomethane production facilities, including provisions for reverse flow configurations. Having access to this type of financial and technical data brings several key advantages. First, it enables real-time updates to optimization models, ensuring that planning and decision-making processes remain responsive to changing market and infrastructure conditions. Additionally, it supports detailed analysis of the resilience and adaptability of the gas network, particularly in scenarios of fluctuating supply or demand. The availability of cost data helps stakeholders compare the feasibility of different connection strategies, guiding both private and public investments more efficiently. It also promotes transparency and informed decisions for biomethane producers and gas infrastructure operators, and even financing parties. Furthermore, tracking cost trends over time can inform policy development and subsidy design, making it easier to align financial support mechanisms with actual infrastructure needs and market dynamics.

A publicly accessible data bank on biomethane, that is hosted on open data platforms like Zenodo could significantly enhance transparency, collaboration, and innovation across the energy sector. By making structured, high-quality data openly available, researchers, policymakers, investors, and industry stakeholders can make informed decisions based on shared, reliable information. Public access also fosters academic research, supports evidence-based policymaking, and encourages private sector engagement by reducing information asymmetry. It also enables cross-border cooperation and benchmarking, particularly valuable in an evolving sector like renewable energy. Moreover, open data empowers local communities, non-governmental organizations, and environmental groups to participate in the energy transition dialogue, promoting accountability and public trust in sustainable energy initiatives.

At the same time relevant cybersecurity threats of such sensitive information and data privacy must be evaluated separately and toughly. Preventive measures such as multi-factor authentication implementation, encrypting sensitive data and other shall be implemented.

3.2. System Dynamics Modelling (Conceptual Result)

System dynamics modelling offers a structured approach to understanding and even shape the development of the biomethane sector at the national level by simulating the complex relationships and interactions between different elements of the system. Since system dynamics takes into account dependencies, feedback and, crucially, system delays, it is a method that can predict and effectively test different development scenarios and influencing factors of the sector. By modelling key variables such as biomethane production volumes, infrastructure expansion, policy impacts, market demand, investment flows and environmental benefits, among others, system dynamics can provide a broadly applicable picture of the development of the sector over time.

Such simulation can reveal valuable insights. Infrastructure or policy bottlenecks that slow down the deployment of biomethane.

Interactions and potentially seek the optimal configuration between short-term investments and long-term sustainability goals.

Benefits include, for example, the increased deployment of biomethane that can reduce dependence on natural gas, influence prices or change emission trajectories, achieving the greenhouse gas emission reduction and renewable energy share targets set in the National Energy and Climate Plan for 2030.

Modelling tests different policies, market or technological pathways, based on needed scenarios, that includes subsidies, carbon prices or technological cost reduction.

Time frames, which show how long it takes for investments or regulations to have a measurable financial impact and whether it is positive or negative.

Overall, the system dynamics model allows stakeholders to test strategies and develop more flexible policies to increase biomethane production, which is in line with energy and climate goals.

3.3. Life Cycle Analysis (LCA) (Conceptual Result)

The use of LCA in the context of biomethane development provides and can provide a number of insights that improve both scientific understanding and practical decision-making.

The LCA results provided a comprehensive assessment of the environmental impact of biomethane production throughout its life cycle – from raw material extraction and processing to injection into the gas network and final use. This analysis reveals the main stages with the highest greenhouse gas emissions and resource consumption, highlighting opportunities to reduce environmental impacts by improving process efficiency, raw material and technology selection. By quantifying both direct and indirect emissions, LCA offers robust data to help choose more sustainable production methods and compare the environmental performance of alternative technologies.

Together, LCA and MCDA are powerful tools in the transition from industrial research to experimental development. Their integrated use can provide an objective alignment of environmental and strategic interests, which in turn also helps to optimize potential systems before large-scale development.

3.4. Multi-Criteria Decision Analysis (MCDA) – Test Scenario Findings, Practical Application of One of the Conceptual Framework Methods

The use of MCDA is a valuable tool both as a standalone study and as a complement to LCA. It allows for the assessment of different technological and investment alternatives based on a balanced set of criteria, including environmental impact, cost-effectiveness, energy efficiency and technological feasibility. MCDA helps to prioritize investment and policy choices that not only meet environmental objectives, but also meet economic and technical efficiency, for example, how to ensure that biomethane is injected into the system or otherwise reaches its end-user.

In the context of biomethane development, this allows stakeholders to identify solutions that are not only environmentally sound but also economically viable and publicly supported, making MCDA an essential tool for guiding sustainable innovation and investment strategies. It is useful for comparison, therefore, TOPSIS method was applied to evaluate biomethane as one of the gaseous energy sources in comparison with natural gas and hydrogen, results of the calculations are shown in Fig. 2.

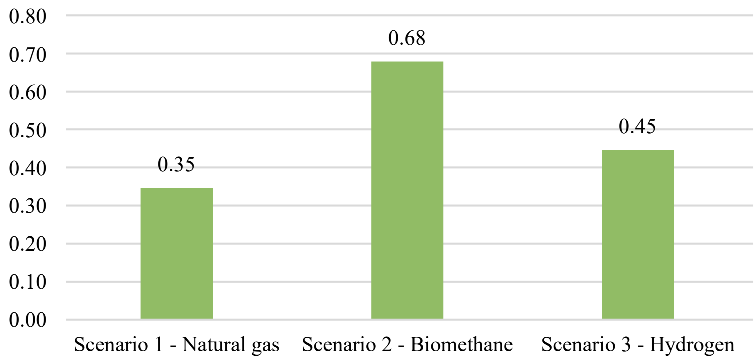

Fig. 2. Ranking of biomethane scenarios based on twelve various criteria.

According to the aforementioned criteria, biomethane (score of 0.68) is the best-balanced gaseous energy carrier from a variety of angles, with hydrogen as second best with score of 0.45 and fossil natural gas as the third option with lowest score of 0.35. The normalized criteria impact scores are computed and aggregated in Fig. 3 to visualize the impact of each criterion.

As depicted in Fig. 3, biomethane (scenario 2) shows the highest cumulative score across all 12 criteria, suggesting it is the most favourable option in terms of multi-criteria performance. Hydrogen (scenario 3) ranks second, natural gas (scenario 1) performs the weakest overall, with significantly lower cumulative scores across nearly all indicators. At the same time natural gas shows relative strength in policy & regulatory alignment (6.0) and technology maturity (5.9) but is weak in revenue potential (0.7) and job creation potential (0.9). Biomethane achieves consistently strong scores across waste management impact (8.0), feedstock flexibility (7.9), and policy & regulatory alignment (7.3), indicating a broad sustainability advantage. Hydrogen showed good result in policy & regulatory alignment (5.6) and GHG emission reduction potential (5.7), but lags in technology risk (2.4) and job creation potential (3.2–3.9). Biomethane dominates in criteria linked to circular economy, waste management, and flexibility. Hydrogen can be considered promising for decarbonization (GHG reduction, regulatory fit), but its immaturity and risks limit its current competitiveness. Natural gas is with lower values in most sustainability related criteria; therefore, this could mean reduced role in long term.

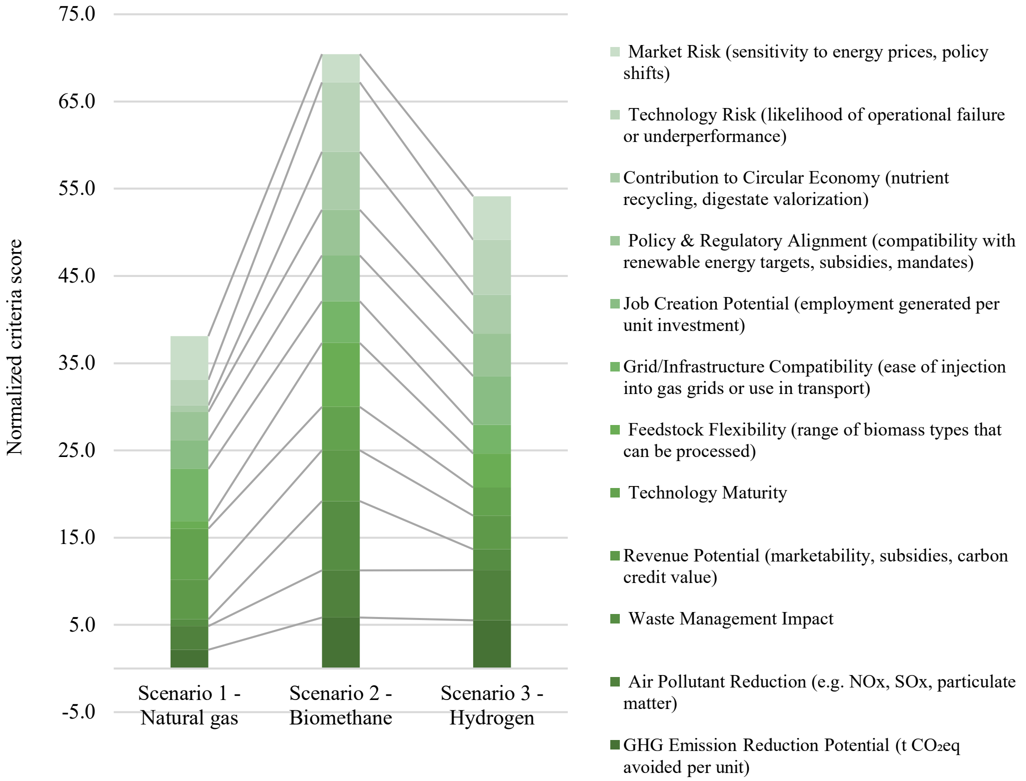

Fig. 3. Criterion level comparison of normalized performance.

3.5. Integrated Research Benefits

All potential integrated research benefits are showed in Fig. 4.

In a successful, integrated study, not only a qualitative theoretical base is need, but also experimental development and the applicability of practical research in real life. Fig. 4 summarizes the potential research benefits that can be achieved by using certain methods. Vertical cells indicate methods that can be used separately or combined for integrated problem solving. The top horizontal block shows the title, and below it, the benefits of each method are identified and separated by colour.

For example, by developing data bank and doing mapping, this can help enhance policy planning, optimize regulatory oversights, improve investment strategies, facilitate cross-border cooperation etc. Twelve benefits are identified for using data bank and mapping as method for integrated analysis, system dynamics can provide, but not limited to at least nine impactful benefits since it is broadly applicable and can test various scenarios, various policies etc. MCDA and/or LCA can provide at least six gains for planning various scenarios and systems such as allows assessment of technological and investment alternatives and supports decision making.

Integrated research can potentially provide a solid foundation for increasing biomethane production locally, nationally and potentially also regionally, and at the same time designed approach can be applied for other process and energy carrier evaluation.

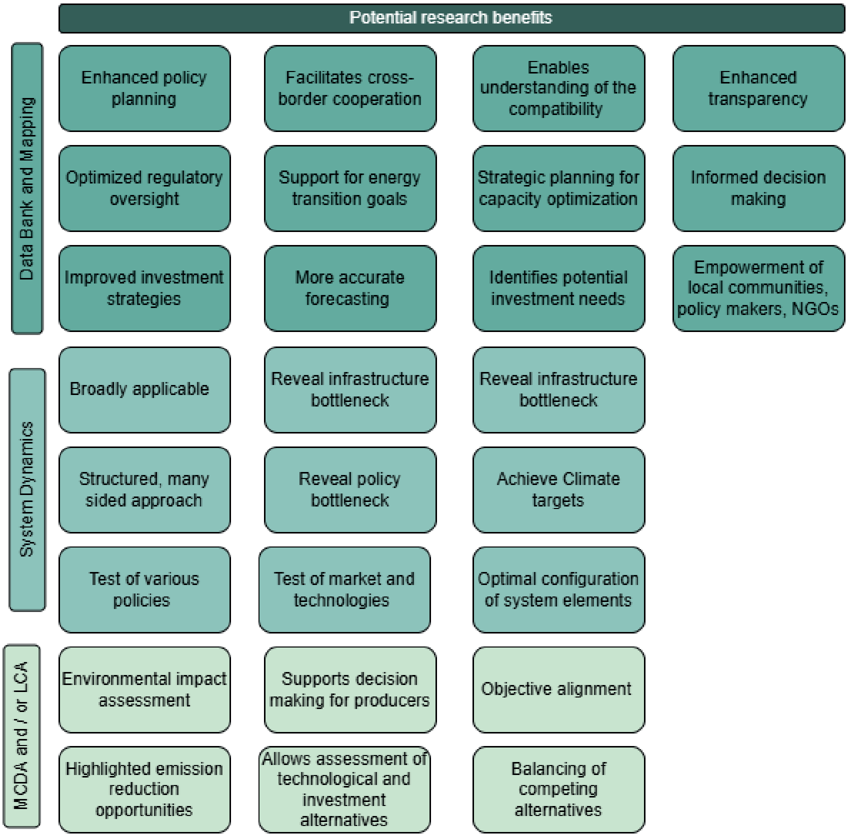

Fig. 4. Integrated research benefits identified by authors.

4. DISCUSSION/CONCLUSION

The development of biomethane creates a pathway for decarbonizing existing gas infrastructure, advancing the circular economy, and enhancing energy security and independence, particularly in reducing reliance on fossil fuels. However, biomethane deployment at a national level presents complex challenges. This research emphasizes the need for a comprehensive and interdisciplinary framework to analyse and address these challenges systematically.

While on a national level uncertainties can complicate uniform strategies, individual problem solving approaches remain viable and can be highly effective when used in a broader systemic application.

A key recommendation emerging from this study is the establishment of a national biomethane data bank combined with infrastructure mapping. Such a platform would centralize high-quality, structured information on biomethane producers, existing natural gas infrastructure, connection cost scenarios, and reverse flow capabilities. This would serve multiple strategic purposes, including policy optimization, improved investment planning, enhanced regulatory oversight, and stakeholder transparency. A publicly accessible data database, that could be potentially hosted on open platforms could further encourage cross-sectoral cooperation, academic research, and public engagement, aligning with principles of open science and participatory energy governance.

System dynamics modelling was identified as a powerful tool for simulating complex elements and feedback loops in biomethane system development. By having variables such as production volumes, infrastructure needs, policy impacts, and investment flows, system dynamics provides a strong method of forecasting outcomes and identifying bottlenecks. It enables stakeholders to test different policy and market scenarios, evaluate the timing and effectiveness of interventions, and design flexible, adaptive strategies aligned with national energy and climate goals.

Complementary to system dynamics, life cycle assessment (LCA) and multi-criteria decision analysis (MCDA) offer crucial insights for both scientific understanding and practical decision making. LCA facilitates a detailed evaluation of the environmental impact of biomethane production across its entire value chain, while MCDA enables balanced assessments of technological and investment alternatives using a wide set of criteria. Together, these tools help identify pathways that are not only environmentally sustainable but also economically and technically viable. This integrative approach supports informed decision-making in situations characterized by uncertainty and competing priorities.

Test scenario results from TOPSIS calculations showed biomethane as the most favourable scenario (score 0.68) across multiple sustainability and economic criteria, followed by hydrogen (0.45), which shows strong decarbonization potential but faces maturity and risk challenges, while natural gas (0.35) ranks lowest, reflecting its limited role in long-term sustainable energy transitions and being impacted by low climate performance.

Potential research benefits can be achieved through different analytical methods. The use of a data bank and mapping enables twelve distinct benefits, including enhanced policy planning, optimized regulatory oversight, improved investment strategies, and strengthened cross-border cooperation. System dynamics offers at least nine benefits, showing its applicability for testing policies, scenarios, and systemic interactions. Meanwhile, MCDA and LCA approaches provide at least six key advantages, particularly in assessing technological and investment alternatives and supporting decision making in complex planning contexts. All together these methods show strong complementary potential for integrated energy and sustainability analysis.

There is also importance of transitioning from theoretical models to practical experimentation. The development of a prototype for an eco-innovative biomethanization technology represents a critical step towards practical implementation. Laboratory testing of gas quality and methane optimization can help improve technologies, reduce oxygen concentrations in the final product, and therefore reduce technological risks. These experimental results, supported by modelling and system analysis, can validate infrastructure adaptations that are important for long-term strategies. A national biomethane development strategy could serve as a crucial foundation for coordinating efforts across sectors, aligning policy frameworks, and prioritizing investments. By setting clear goals, timelines, and regulatory pathways, such a strategy is one of the tools that can enhance stakeholder confidence, attract funding, and ensure that biomethane development progresses in a structured manner.

Integrated and interdisciplinary approach to biomethane development, that combines infrastructure's data, system modelling, impact assessment, and technological innovation, can positively improve national biomethane development and thereby contribute to decarbonization. This integrated framework not only addresses current challenges but also provides useful framework for future innovation and applications in renewable energy sector.

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