RIGA TECHNICAL UNIVERSITY

Viktorija Terjaņika

CO_2 VALORISATION IN CIRCULAR ECONOMY

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Natural Sciences and Technology
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CO_2 VALORISATION IN CIRCULAR ECONOMY

Summary of the Doctoral Thesis

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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 RTU Promotion Council on 8th of January, 2026 at the Faculty of Electrical and Environmental Engineering of Riga Technical University, Āzenes iela 12–1, Room 607.

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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.

Viktorija Terjaņika ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, four chapters, Conclusions, 43 figures, 30 tables, and four appendices; the total number of pages is 312, including appendices. The Bibliography contains 486 titles.

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GENERAL CHARACTERISTICS OF THE THESIS

Actuality of the topic

In the context of growing environmental problems and the global community's desire for sustainable development, the valorisation of CO_2 is becoming especially relevant. CO_2, being one of the main factors of global warming, is formed as a result of industrial and energy processes and poses a significant threat to the ecosystem and public health. CO_2 valorisation is a promising direction in which CO_2 is viewed not as a waste, but as a resource that can be converted into useful products such as building materials, chemicals and fuel. This allows a reduction in emissions, a decrease in dependence on fossil sources and a strengthening and diversification of the country's economy and energy sector.

The realisation of carbon capture and utilisation (CCUS) technology's implementation possibilities at the regional level provides an opportunity to develop effective strategies for reducing emissions, combining environmental and economic benefits. The implementation of such approaches is important for achieving climate goals and supporting sustainable development, especially in carbon-intensive industries.

The purpose and tasks of the study

The Thesis comprehensively assesses the potential for the implementation of carbon capture, storage and utilisation (CCUS) technologies in Latvia, determines the requirements for the implementation of CCUS taking into account environmental, technological, legislative and social aspects, and develops an integrated methodology for the valorisation of CO_2. The aim is to develop an integrated methodology that identifies the requirements, drivers and challenges for CO_2 valorisation in Latvia.

To achieve this aim, the following objectives were established and completed:

1. To identify and characterise applicable CCUS technologies and assess their potential relevance for Latvia.
2. To determine key parameters and criteria for the effective utilisation of CO_2 in Latvia.
3. To map and analyse major CO_2 emission sources and potential utilisation sites across Latvia using spatial and technical data.
4. To evaluate opportunities and perspectives for the implementation of CCUS technologies in Latvia and the EU.
5. To assess public and business sector awareness, perceptions, and willingness to support or engage in CO_2 utilisation initiatives.
6. To explore opportunities for integrating CO_2 into the production of bioproducts and bio-based value chains.
7. To assess the environmental and social impacts of CCUS utilisation scenarios using life cycle and social life cycle assessment methods.

The proposed hypothesis

An integrated CO_2 valorisation technology can be applied to evaluate the possibility of CO_2 valorisation through the implementation of CCUS technologies in Latvia. When aligned with national legal frameworks, spatial and resource conditions, and societal acceptance, it has the potential to contribute to the country's circular economy development, reduce GHG emissions and support the creation of sustainable value chains specific to the Latvian context. The proposed CCUS implementation framework could unite enterprises with policymakers, academic and civil sectors to support regional CO_2 valorisation pathway development, starting with analysis and until implementation.

Scientific novelty of the Thesis

This Thesis proposes a novel, interdisciplinary methodology for assessing CO_2 valorisation pathways within the context of a circular economy, with specific application to Latvia. The developed approach combines legal, technological, environmental, and social aspects and integrates 10 analytical methods that are rarely applied in a unified framework in current research.

The following analysis methods were applied:

- systematic literature analysis – to identify trends, drawbacks in CCUS technology implementations and benchmark best practices in CO_2 valorisation;
- key performance indicator (KPI) method – to assess technical, economic, and environmental feasibility across scenarios;
- multi-criteria decision analysis (MCDA) – to enable structured comparison of valorisation options;
- ArcGIS (GIS) map creation and analysis – to visualise and assess the territorial applicability of CO_2 utilisation pathways;
- SWOT analysis – to capture strategic insights based on internal strengths and weaknesses, and external opportunities and threats;
- fuzzy logic cognitive mapping (FCLM) – to model interdependencies between social, technological and legal variables;
- survey (public and entrepreneurs) – to assess social acceptability and stakeholder engagement;
- greenhouse gas (GHG) emission inventory – to quantify emissions reductions in biomass and energy scenarios;
- life cycle assessment (LCA) – to assess the environmental impacts of CO_2 valorisation;
- social life cycle assessment (S-LCA) – to evaluate human and societal impacts linked to CO_2 valorisation.

While many of the applied methods have been applied individually in studies of CO_2 management or circular economy, this research is among the first to combine them into a comprehensive, scenario-based framework for evaluating CO_2 valorisation strategies.

The methodological innovation lies not in the novelty of individual tools, but in the systematic integration of both qualitative and quantitative analyses, enabling cross-sectoral evaluation of complex, context-specific CO_2 utilisation scenarios. The Thesis offers holistic integration of these methods into a unified decision-support framework, tailored to regional specificities and policy goals. This research is the first in Latvia to propose such an approach for CO_2 valorisation, grounded in the national legislative context and supported by both stakeholder-driven and data-based analyses.

The practical significance of the Thesis

The Thesis studies various technologies for reducing CO_2 emissions and requirements for the implementation of such technologies, which allows the determination of the necessary measures to improve the environmental situation in the region. The result of the study is the creation of a working map (roadmap) – an algorithm for policymakers and governments in considering the solution to the problem of reducing CO_2 emissions, finding the optimal solution and technological development for the region.

The structure of the Thesis

The Thesis is a collection of nine scientific publications that have been published in various scientific journals and are available for citation in scientific databases. Each article focuses on the problem of CO_2 emissions and describes methods for analysing and/or solving this problem. The articles describe the example of Latvia, but the solution can be applied in other countries as well.

The Thesis consists of an introduction and four chapters:

1. Literature analysis
2. Methodology of the analysis
3. Results
4. Discussion

The introduction describes the relevance of the topic under consideration, indicates the purpose of the study and the objectives set to achieve the aim, puts forward a hypothesis, describes the scientific novelty of the research being conducted and its practical significance.

Chapter 1 provides an overview of the topic under consideration – the problem of CO_2, potential technologies for reducing its amount in the atmosphere, and examples of other countries' experiences. Chapter 2 specifies the methods that were used to estimate the amount of CO_2, methods for its valorisation, and classification of alternatives for its use. Chapters 3 and 4 analyse the results obtained, discuss the results of the study, and put forward conclusions.

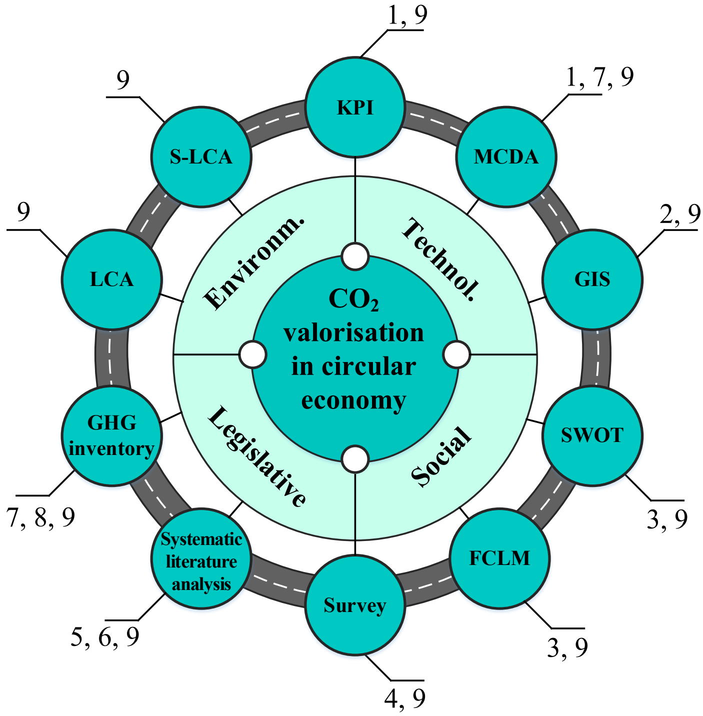

Fig. 1. Scheme of the Thesis.

Figure 1 presents the conceptual framework of the Thesis. The outer circle illustrates the analysis methods applied in the research. Each method has been validated through its use in a corresponding publication, with publication numbers indicated next to each analysis. All applied methods are integrated within four key aspects: environmental, technological, legal, and societal. Together, these aspects form a comprehensive basis for assessing the potential for CO_2 valorisation in Latvia.

This Thesis is based on the following scientific publications.

1. **Terjanika V.**, Pubule J., Gusca J., Blumberga D. Analysis of CO_2 Valorisation Options for Regional Development. *Environmental and Climate Technologies* 2021: 25(1): 243–253. doi: 10.2478/rtuect-2021-0017
2. **Terjanika V.**, Pubule J., Blumberga D. Regional Development Scenarios and Model Boundaries for CCU in the Energy Sector in Latvia. *IEEE* 2021. doi: 10.1109/RTUCON53541.2021.9711727
3. **Terjanika V.**, Pubule J. Barriers and Driving Factors for Sustainable Development of CO_2 Valorisation. *Sustainability* 2022: 14(9): 5054. doi: 10.3390/su14095054 (Q1)
4. **Terjanika V.**, Vetrinska L., Pubule J. CO_2 as a Resource. Society's Willingness to Pay Analysis. *Environmental and Climate Technologies* 2022: 26(1): 806–821. doi: 10.2478/rtuect-2022-0061

5. **Terjanika V.**, Zarins E., Balode L., Pubule J. Legal Framework Analysis for CO_2 Utilisation. *Environmental and Climate Technologies* 2022: 26(1): 917–929. doi: 10.2478/rtuect-2022-0069
6. **Terjanika V.**, Pubule J., Zarins E., Blumberga D. Policy Instruments for CO_2 Valorisation Support. *e-Prime – Advances in Electrical Engineering, Electronics and Energ*y 2023: 4: 100181. doi: 10.1016/j.prime.2023.100181 (Q2)
7. Viksne G., Vamza I., **Terjanika V.**, Bezrucko T., Pubule J., Blumberga D. CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios. *Environmental and Climate Technologies* 2022: 26(1): 1158–1168. doi: 10.2478/rtuect-2022-0087
8. **Terjanika V.**, Sanchez Valdespino A. A., Pubule J. Calculation of Greenhouse Gas Savings: Switch from Electricity Production to Biomethane. Case Study. *Environmental and Climate Technologies* 2023: 27: 836–849. doi:10.2478/rtuect-2023-0061 (Q2)
9. **Terjanika V**., Laktuka K., Vistarte L., Pubule J., Blumberga D. Co-creating low-carbon futures: An open innovation roadmap for regional CO_2. *Journal of Open Innovation: Technology, Market, and Complexity* 2025: 11(3): 100596. doi: 10.1016/j.joitmc.2025.100596 (Q1).

The Author's publications not related to the Thesis.

10. Kramens J., Vigants E., Liepins I., Vernieks L., **Terjanika V.** Research of a Biomass Boiler with Stirling Engine Microgeneration Unit. *Environmental and Climate Technologies* 2021: 25(1): 587–599. doi: 10.2478/rtuect-2021-0043
11. Kramens J., Vigants E., Liepins I., **Terjanika V**. Research of biomass micro-cogeneration system integration with solar PV panels in a zero-energy family building. *Environment. Technology. Resources. Proceedings of the 13th International Scientific and Practical Conference* 2021: 1: 132–138. doi: 10.17770/etr2021vol1.6568
12. Bezrucko T., Lauka D., Laktuka K., Sniega L., Vamza I., Dzalbs A., **Terjanika V.**, Blumberga D. Bioeconomy towards green deal. Case study of citric acid production through fuzzy cognitive maps. *Environmental and Climate Technologies* 2022: 26(1): 684–696. doi: 10.2478/rtuect-2022-0052
13. Valtere M., Kaleja D., Kudurs E., Kalnbalkite A., **Terjanika V.**, Zlaugotne B., Pubule J., Blumberga D. The Versatility of the Bioeconomy. Sustainability Aspects of the Use of Bran. *Environmental and Climate Technologies* 2022: 26(1): 658–669. doi: 10.2478/rtuect-2022-0050
14. Kalnbalkite A., Brakovska V., **Terjanika V.**, Pubule J., Blumberga D. The tango between the academic and business sectors: Use of co-management approach for the development of green innovation. *Innovation and Green Development* 2023: 2(4): 100073. doi: 10.1016/j.igd.2023.100073 (Q1)
15. **Terjanika V**., Pubule J., Mihailova E., Zlaugotne B. Analysing Metal Melting Methods for Green Transformation of Scrap Metal: Case Study of Latvia using MCDA and SWOT Analysis. *Environmental and Climate Technologies* 2024: 28(1): 1–11. doi: 10.2478/rtuect-2024-0001 (Q2).

Every publication, besides using a specific analysis method, is part of a specific aspect (Table 1):

Table 1

Scientific Publications Used in the Doctoral Thesis

Aspects	No.	Publication title
Technological	1	Analysis of CO_2 Valorisation Options for Regional Development
Technological	2	Regional Development Scenarios and Model Boundaries for CCU in the Energy Sector in Latvia
Technological, environmental	3	Barriers and Driving Factors for Sustainable Development of CO_2 Valorisation
Social	4	CO_2 as a Resource. Society's Willingness to Pay Analysis
Legislative	5	Legal Framework Analysis for CO_2 Utilisation
Legislative	6	Policy Instruments for CO_2 Valorisation Support
Technological, environmental	7	CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios
Technological, environmental	8	Calculation of Greenhouse Gas Savings: Switch from Electricity Production to Biomethane
Technological, legislative, environmental	9	Co-creating low-carbon futures: An open innovation roadmap for regional CO_2

Approbation of the Thesis

1. International Scientific Conference CONECT 2021, 12–14.11.2021, Riga Technical University, Riga, Latvia.
2. 2021 IEEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 15–17.11.2021, Riga Technical University, Riga, Latvia.
3. International Scientific Conference CONECT 2022, 11–13.05.2022, Riga Technical University, Riga, Latvia.
4. 17th SDEWES Conference Paphos 2022, 06–10.11.2022, Paphos, Cyprus.
5. International Scientific Conference CONECT 2023, 10–12.05.2023, Riga Technical University, Riga, Latvia.
6. International Scientific Conference CONECT 2024, 15–17.05.2024, Riga Technical University, Riga, Latvia.
7. International Scientific Conference CONECT 2025, 14–16.05.2025, Riga Technical University, Riga, Latvia.

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1. METHODOLOGY

This chapter presents a comprehensive methodology for analysing CO_2 valorisation pathways, integrating both qualitative and quantitative approaches to assess the implementation and utilisation of CCUS technologies. This chapter observes various tools to assess CO_2 valorisation scenarios. These tools include KPIs, MCDA, SWOT analysis, GIS mapping, surveys, GHG inventories, LCA and S-LCA. Structured across nine sections, each focusing on a distinct analytical method, this chapter analyses various CO_2 valorisation scenarios to evaluate the optimal route for CCUS technology implementation.

Approach to Evaluating Key Performance Indicators

The first step in the methodology is to define the performance indicators to evaluate the feasibility and effectiveness of CO_2 valorisation scenarios. This is necessary to understand the requirements for technologies (for CO_2 valorisation) and the subsequent analysis of technologies already existing in Latvia.

A combination of methodologies was used during the research on the possibility of CO_2 valorisation: literature review, HORIZON2020 data analysis (H2020), key performance indicator (KPI) analysis and MCDA analysis.

Literature sources were used to search for methods of utilising CO_2 in production, its necessary parameters, quantities and other important data. The analysis included a review of available technologies, technical reports, and H2020 projects (32,000 in total, 242 of which included CO_2 utilisation/storage). After that, the KPI table was created. It consists of 47 general indicators (applicable to various sectors of production) and 28 production-specific indicators (which are applicable only for a specific area). Where possible, all indicators include CO_2. KPI quantitative data was used as a benchmark for the MCDA analysis. The algorithm is shown in Fig. 2.

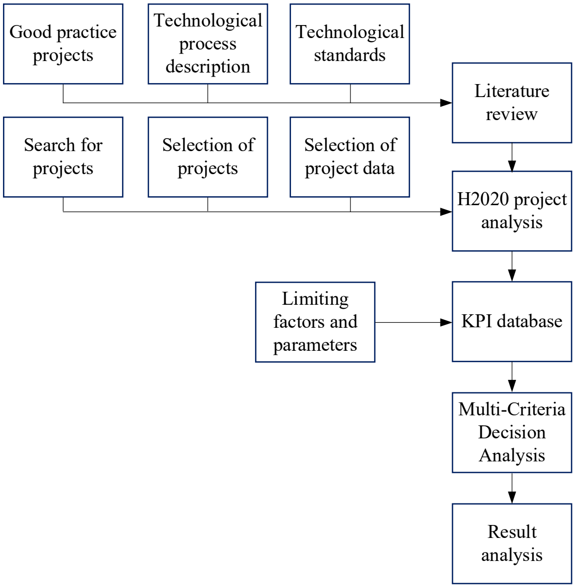

Fig. 2. Methodological scheme.

The main areas that got assigned indicator values (based on the H2020 projects as reference) are the production of methanol and cement, as well as refrigeration units and algal ponds. Alternatives selected for further analysis are the production of methanol, cement, algal ponds/greenhouses, food and beverages. TOPSIS was chosen as an analysis method, comparing the criteria (criteria and their values were selected based on the available data from H2020):

- amount of permitted additive in the CO_2 flow;
- electricity per 1 tonne of product;
- amount of CO_2 utilised;
- amount of CO_2 produced;
- simplicity of implementing the technology into the existing process.

Data Sources and Tools for Geospatial Mapping

The second step in the methodology, GIS-based analysis, is used to assess the geographic distribution of CO_2 sources and potential utilisation sites. This method was selected to visualise regional disparities, infrastructure gaps, and spatial dependencies that influence the practicality of CCUS implementation. The analysis is required for the identification of priority zones for CCUS deployment and assessing regional emission data, and possible proximity to industrial clusters.

To perform the analysis, the following steps were completed:

1. Analysis of literature sources to identify the possibilities of using both pure and industrial CO_2 in the production of new goods. The factors limiting the use of CO_2 in a particular technology have been identified.

2. Research of the national databases to identify CO_2 emitters and possible users in Latvia. The largest CO_2 emitters (permit A) are the industrial sector, energy sector and landfills. In the category with the B permit, the largest emitters are food and beverage, industrial, energy, chemical and refining. Where possible, data on the amount of CO_2 produced was taken from the company's annual reports.
3. Analysis of the missing data, filling it up by researching the statistical databases. In this research, there is no distinguishing the source of the produced CO_2, whether it was the result of heating the building or a by-product of the production process. The purpose of the research is to analyse the total amount of produced CO_2 and the possibility of its further use.
4. Mapping all the observed enterprises (CO_2 producers and utilisers) on the maps in the ArcGIS programme.

Framework for SWOT Analysis of CO_2 Valorisation

In the next step of the methodology, a SWOT analysis was carried out to conduct a comprehensive analysis of the possibility of capturing and/or using CO_2 at 3 levels: in the European Union, in Latvia and in companies. The use of SWOT, together with cartographic programs (ArcGIS), allows decision-makers to evaluate the proposed solutions to the problem, to prioritise them correctly. When the choice is made at high levels, this combination will help to ensure the transparency of the solution and its comprehensiveness.

For a more comprehensive analysis of the problem of technology implementation, an additional analysis was chosen – fuzzy logic cognitive mapping (FLCM). This analysis can be characterised as a way that displays fuzzy logical connections between various factors. FLCM models are beneficial when modelling complex systems and systems with a large number of factors influencing decision-making. The algorithm is shown in Fig. 3.

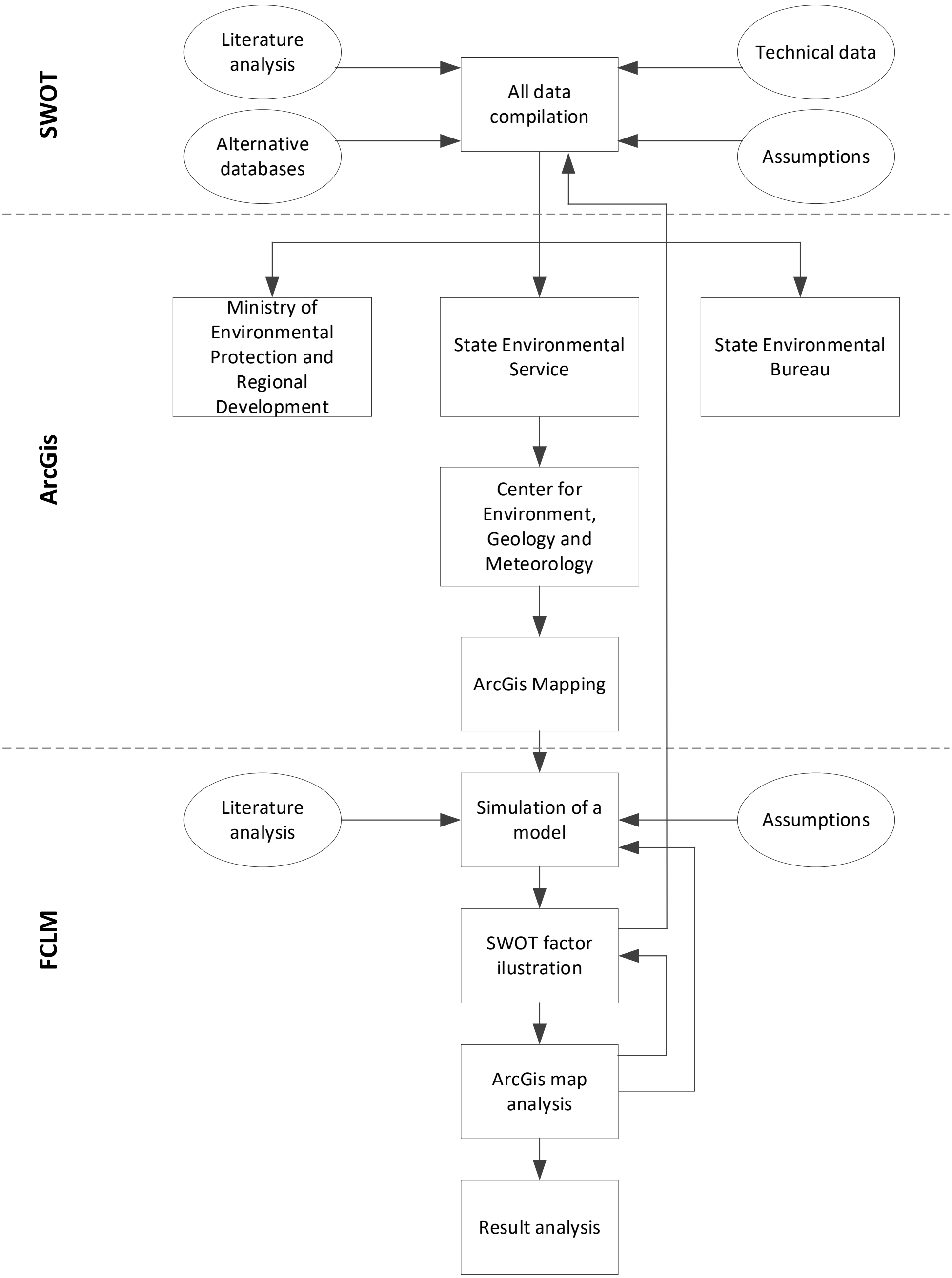

Fig. 3. The algorithm of the performed study.

Survey Design and Stakeholder Engagement Methods

This step of the methodology presents the design and distribution of a survey aimed at understanding perceptions, awareness, and acceptance of CO_2 valorisation among the public and entrepreneurs. This method provides a crucial social aspect to the otherwise technical assessment. The survey (convenience sampling method) of respondents was chosen as the primary research tool. The survey was conducted electronically (via questionnaire), as there were still several restrictions due to COVID-19 that prevented the face-to-face survey of respondents.

Literature analysis and identification of the main factors influencing the implementation of CCS and CCUS units form the basis of the work. Next was the definition of the target audience of the survey. This survey was designed for two main groups: entrepreneurs and the public. The purpose of the study was to find out people's opinions about CO_2 emissions, possible actions to reduce them, and the willingness of respondents to pay for these emissions.

The public was asked to answer 9 closed-ended questions (in addition to the main ones about age, education received, and profession currently occupied). Respondents were asked to indicate their opinion on the importance of CO_2 emissions issues and what issues related to emissions seem to them to be particularly relevant both globally and for the country, and specifically for them. Particular attention was paid to the question of public opinion – whether it is worth making any changes in the country in order to combat emissions, as well as the opinion/readiness of people themselves to financially and actively invest in this fight.

The questionnaire for entrepreneurs consisted of five questions (in addition to the main questions about the scope of the enterprise). Respondents were asked to indicate particularly important reasons for making changes to upgrades in their enterprise in the context of CO_2 emissions, as well as what could motivate them to change.

The study was carried out according to the algorithm presented in Fig. 4.

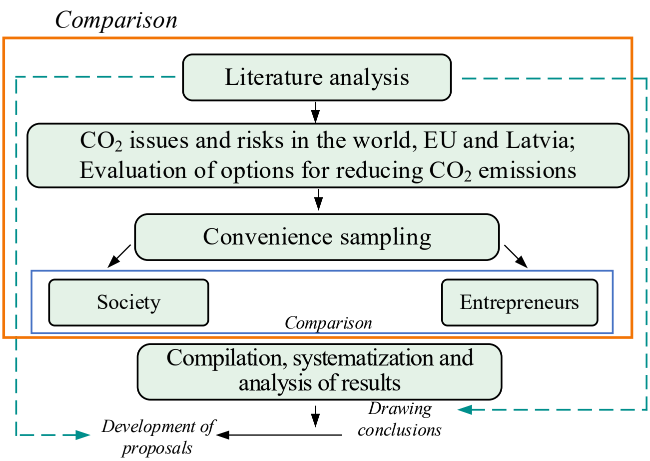

Fig. 4. Algorithm of the survey.

Legal Review Method for National and International CO_2 Policies

The next step of the methodology is a comparative legal review method, which is applied to examine regulatory frameworks governing CO_2 utilisation at both national and international levels. This method relies on structured content analysis of legal texts, policy documents, and strategic frameworks. It aims to identify regulatory gaps, alignment with climate targets, and the enabling or restrictive nature of current laws.

The study included a search and subsequent accounting for CO_2, CCS, CCUS, CCU, carbon/CO_2 utilisation, carbon/CO_2 capture, and carbon/CO_2 storage. The analysis of legislative sources on the opportunities provided for using, capturing, and storing CO_2 was based on the political framework, policy instruments, and CO_2 emission utilisation legislation in Latvia and the European Union. Three groups of documents were selected for the systematic literature analysis: EU-level documents, Latvian-level documents, and scientific publications, and each raised its own questions (see Fig. 5).

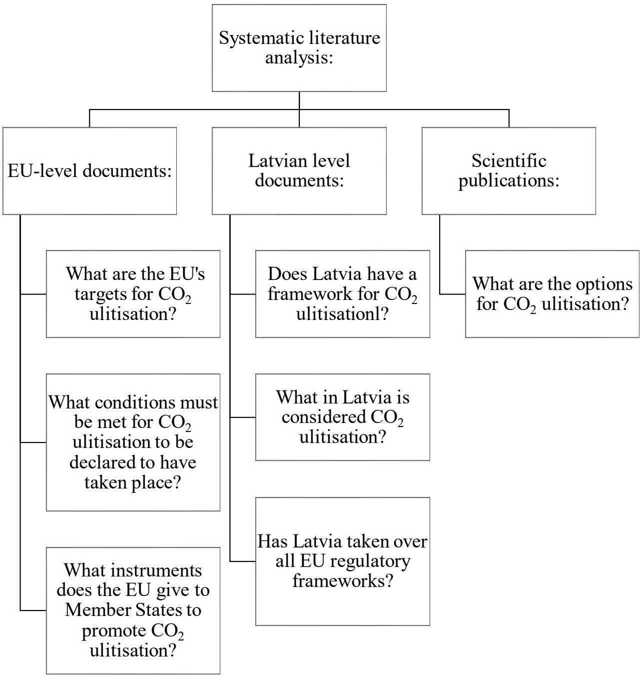

Fig. 5. Steps of the systematic literature analysis.

Exploring the extent to which the country's government is aimed at capturing/recycling CO_2, this research analysed the national laws of Latvia and the European Union. Additionally, a study was performed on the laws of several EU countries: Great Britain (EU member until 2020), Germany, Sweden, Lithuania, and Estonia.

Assessment Criteria for Supportive Legislative Measures

Section 1.6 extends the previous section by focusing specifically on mechanisms that promote, support CO_2 valorisation and motivate CCUS introduction. This step analysis presents a systematic analysis of the legislation of EU member states. The goal is to assess how supportive policy environments influence the viability and scaling of CCUS technologies.

The systematic literature analysis of policy instruments for CO_2 valorisation support involves a comprehensive and structured approach to identify, evaluate, and synthesise relevant literature related to policy instruments that support the development and implementation of CO_2 valorisation technologies. Literature analysis included documents from 3 groups:

1) world-class documents, such as the Paris Climate Agreement;
2) documents at the EU level, such as Regulation (EU) 2021/1119 of the European Parliament and the Council;
3) examples of other countries in the fight against climate change and scientific literature.

Systematic literature analysis is an essential tool for analysing the research question. This method differs from the usual literature analysis in that it is based on a predefined question for which answers are systematically sought.

A search strategy is developed to identify relevant literature on policy instruments for CO_2 valorisation support. This involves identifying relevant keywords, databases, and search terms. A keyword search was chosen as an optimal analysis tool. The search had its inclusion and exclusion criteria to ensure that only relevant literature was included in the analysis. Only those policies were analysed that included technologies and/or measures for CO_2 capture and/or valorisation in any stage of readiness. Analysis includes policies regardless of the language in which the documents were written. However, only the languages of the European Union were considered. Withdrawn policies were not included in the analysis. The same criteria were implemented for all scientific research papers (not older than five years). An older document was used only in case no recent paper was found.

The first task was to understand which countries have the most significant climate policies, encompassing policies and policy instruments. In the second step, these policies and policy instruments were categorised by impact and type. Thirdly, the most important categories for the topicality of the study were selected. These categories were then assigned values according to their relevance to the aims and objectives of the study. When each country's policies and instruments were analysed, categorised and evaluated, the results were summarised to see which public policy instruments and policies were most relevant to the objectives set out in the work.

GHG Inventory Methodology for Logging Residue Scenario

The next step in the methodology is determining the amount of CO_2 that can be stored in a new product. The production of rigid board wood insulation material was chosen. The production methodology consists of steps such as a description of the production process and needed feedstock, as well as calculation of the amount of CO_2 that can be stored in the final product. Three different scenarios have been compared using the multicriteria analysis method. All steps of the methodology are seen in Fig. 6.

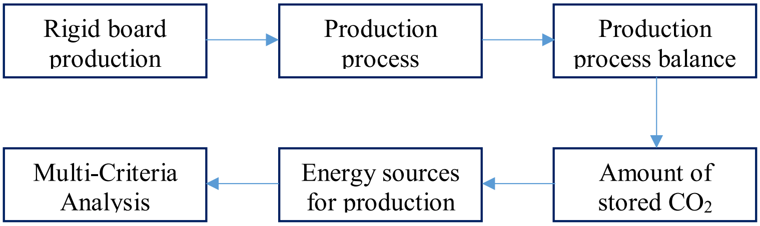

Fig. 6. Algorithm of the methodology.

For the new fiberboard insulation material manufacturing process, the standard dry manufacturing process was chosen from the BAT Reference Document for the Production of Wood-based Panels, modified for rigid board production. Material balance was chosen based on fiberboard and insulation board data from the Forest Product Conversion Factors document. The weight content of bark, binders and fillers, moisture and wood in 1 m^3 of the finished insulation panel were calculated based on the chosen material density and material balance.

It is assumed that the new plant would produce 300,000 m^3 of fiberboard insulation material annually. Assuming that an existing plant has an electrical capacity of 5 MW and a heat capacity of 10 MW and operates for 8000 h/a, the manufacturing plant would require 0.13 MWh of electricity and 0.26 MWh of thermal energy to produce 1 m^3 of fiberboard insulation material.

To calculate the possible amount of CO_2 stored in the material, eight different standards for biogenic carbon accounting in products were reviewed and used. As there currently exists no scientific consensus on which standard and method are the most appropriate for use, an average value derived from all standards was proposed.

The initial calculation for CO_2 stored in the material is assumed to be the same for all standards and is calculated:

$$mCO_2 = m_{\mathrm{dry}}(\mathrm{timber}) \cdot C_f \cdot \frac{m.m_{CO_2}}{m.m_C}, \quad (1)$$

where

mCO_2 mass of CO_2 sequestered, $kgCO_2$;

$m_{\mathrm{dry}}(\mathrm{timber})$ dry weight of timber in the finished product, kg;

C_f percentage of carbon in dry matter (for timber = 0.5);

$m.m_{CO2}$ molecular mass of CO_2 = 44 g/mol;

$m.m_C$ atomic mass of carbon = 12 g/mol.

Only the CO_2 sequestered from the wood and bark content of the new product is calculated. The carbon content for bark is assumed to be the same as wood (50 %).

To maximise the CO_2 storage potential of the new fiberboard insulation material, the energy production sources for the manufacturing process need to be reviewed and analysed, as energy production is the single most significant source of emissions and can potentially offset the avoided CO_2 stored in the product material. However, using renewable energy sources may not always be the most technologically and economically viable option. Three energy production scenarios were evaluated based on the proposed manufacturing plant capacity of 5 MW electrical capacity and 10 MW heat capacity:

1) to produce heat and power with a biomass CHP plant, use wood chips as fuel;
2) a natural gas CHP plant with a gas turbine technology;
3) a wood biomass CP producing only thermal energy, wood chips as fuel and combined with PV panels for electricity production.

To evaluate environmental impacts, five different emission values were considered for each scenario: NO_x, CO, VOC, PM and CO_2.

The capital costs of the standalone biomass combustion plant are assumed to be 30 % lower than the costs of the same thermal capacity CHP plant. Similarly, emission levels for the standalone biomass combustion plant are assumed to be the same as for the biomass CHP plant. Still, they are recalculated for a total thermal efficiency of 85 % instead of 60 % and apply only to the thermal energy produced.

A solar PV panel installation with an electrical capacity of 4 MWe is assumed to have a peak capacity of 5.4 MWp. The capital costs for an installation of this size are 510 EUR/kWp, and O&M costs 6.5 EUR/kWp.

Three scenarios were compared using the MCDA TOPSIS technique. The criteria were selected according to the opinion of experts whose work profile is directly related to construction, sustainability and innovation, as well as the literature analysis. The criteria weights were determined using the AHP method.

Transition Emission Analysis: Switch to Biomethane Production

Another method for reducing CO_2 emissions is the avoidance method. This step examines the effectiveness of a biogas plant's transition from biogas production to the production of biomethane and its subsequent integration into the natural gas grid. This step helps understand the possibility of such a transition and compliance with European legislation for such initiatives. The study contains calculations of this transition – GHG savings, considering the resource heterogeneity. This study did not account for the distance to the grid injection point.

The biogas station is located in the central region of Latvia, Zemgale, with 5500 people living in the area of the plant. The total area of the region is 311.6 km^2.

According to the acquired information, in 2021, the station used just over 57 thousand tons of substrates. In total, 13 substrates were involved in the production. This amount produced 5,621,708 Nm^3 of biogas during the specified period with a calorific value of 29,860.417 MWh. Biogas was used to produce 11,325.577 MWh of thermal energy and 11,619.62 MWh of electricity.

The calculation of GHG was carried out based on Directive 2018/2001/EU (REDII).

There are two ways to calculate the amount of GHG saved: actual value and default value-based. Considering that the default method is based on a limited and specific type of resource for biogas (wet manure, dry manure, municipal public waste), the actual value-based calculation method of GHG savings was used in the study.

Equation (2) shows the calculation of emissions in the case of co-digestion of various substrates in biomethane production from biogas:

$$E = \sum Sn \cdot \left(e_{ec,n} + e_{td,\text{feedstock},n} + e_{1,n} - e_{sca,n}\right) + e_p + e_{td,\text{product}} + e_u - e_{ccs} - e_{ccr}, \quad (2)$$

where

E	total amount of emissions from the biomethane production (before energy conversion), kg CO_2eq/ton;
Sn	share of feedstock (type n), in a fraction of input to the digester;
$e_{ec,n}$	amount of emissions from the extraction/cultivation of feedstock (type n), gCO_2eq/MJ final product;
$e_{td,\text{feedstock},n}$	amount of emissions from the transport of feedstock n to the digester, CO_2eq/MJ final product;
$e_{1,n}$	annual emissions from carbon stock changes due to land usage for feedstock type n, gCO_2eq/MJ final product;
$e_{sca,n}$	emissions savings from improved agricultural management of feedstock type n, gCO_2eq/MJ final product;
e_p	emissions from processing, g CO_2/MJ final product;
$e_{td,\text{ product}}$	emissions from transport and distribution of biomethane, gCO_2eq/MJ final product;
e_u	emissions from the fuel in use, g CO_2/MJ final product;
e_{ccs}	emissions savings from carbon capture and geological storage, gCO_2eq/MJ final product;
e_{ccr}	emission savings from carbon capture and replacement, gCO_2eq/MJ final product.

Parameters e_{ec}, e_t, e_p, and e_u are calculated according to Eq. (3):

$$e_{ec}, e_{td}, e_p, e_u = \frac{\sum \text{amount of material input} \cdot \text{Emission Factor of the aterial}}{\text{Yieled or quantity of the material}} \quad (3)$$

Equations (2) and (3) are the basis for the following calculations.

LCA and S-LCA Methodologies for CO_2 Valorisation Projects

The final step of the proposed methodology is the life cycle and social life cycle analysis of CCUS technologies. This step analyses life cycle emissions, resource use, labour conditions, and community impacts. The combined method supports a holistic sustainability assessment across the value chain.

This section provides methodology for and analysis of two CO_2 utilisation scenarios – production of methanol and SAF-ethanol. Both products can be used as an energy source, both as a stand-alone fuel and as an alternative to fossil fuels. The goal of conducting an LCA of CO_2 utilisation in production is to assess the social and environmental impacts associated with the production, use, and disposal of CO_2 in the scenarios. The LCA and S-LCA analyse the aspects related to the entire life cycle of CO_2 utilisation, including the upstream and downstream processes, to provide a comprehensive understanding of the potential social implications of CO_2

utilisation. Both LCAs take a gate-to-gate approach, analysing the impacts associated with the entire life cycle of CO_2 utilisation in facilities. For the S-LCA, the *SimaPro Hotspot* database is used, while the LCA relies on the *OpenLCA ProBass Basic 2024* database. The analysis methodology applied in both cases is the ReCiPe Endpoint method. The spatial scale of the analysis is sectoral, as the study analyses specific production processes. The analysis compares two scenarios and shows which would be the optimum for CO_2 utilisation in Latvia.

2. RESULTS

This chapter presents and interprets the results obtained from the analysis methods outlined in Chapter 1. The findings illustrate the outcomes and implications of each methodological step applied in assessing CO_2 valorisation opportunities.

Findings from KPI Assessment of CO_2 Valorisation

In the process of analysing the methods of CO_2 valorisation, both existing and ongoing projects for the use of CO_2 in production and projects from the H2020 program were researched. During the analysis of H2020 projects (the purpose of which is to use CO_2 in the production of new products), a list of key indicators was created and completed.

The created table of Key Indicators includes 47 general indicators, of which 17 are related to energy, water and materials, 12 are environment-related, and 18 – economy-related. The table also includes 28 indicators specific to the scope of potential CO_2 applications, for example, methanol production, cement production, use of algae in algal ponds and greenhouses.

As for the MCDA, it was stated that the optimal ways to valorise CO_2 are its use in the production of chemicals, methanol, as well as food and beverages, and the production of cement (as an element of additional carbonisation). Technologies for using CO_2 in these areas are the most developed and accessible.

The scenarios were evaluated according to such criteria as electricity consumption (per unit of manufactured product), permissible amount of impurities in the CO_2 stream (%), the amount of CO_2 produced (per ton of product), and simplicity/availability of technology (on a scale of 1 to 5). The results of the MCDA analysis, with the closest ideal value for each scenario, are depicted in Fig. 7.

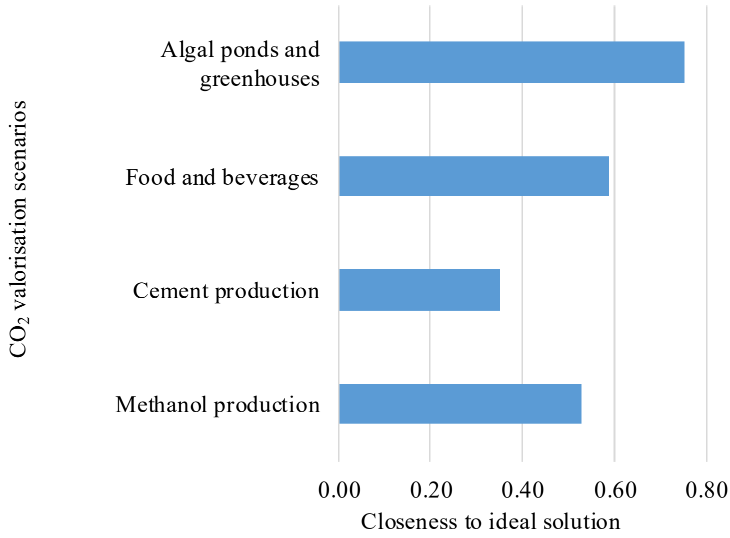

Fig. 7. CO_2 valorisation MCDA results.

The MCDA analysis showed that the optimal scenario for the use of CO_2 could be algal ponds/greenhouses and the food industry. Algal ponds are an attractive option, as algae can absorb large amounts of CO_2, grow faster and then this biomass can be used as biofuel or fertiliser. The second option would be the food industry – CO_2 can be used as a gas to protect against pests and to extend product shelf-life, and as a substance to carbonate beverages. Additional ways of using CO_2 are refrigeration units and as a dry-cleaning agent. CO_2 is a valuable and often irreplaceable element of the food industry; however, for its use, it is necessary to make sure that the gas is highly purified (at least 98 %).

Technologies for using CO_2 in greenhouses and algal ponds are relatively inexpensive, which is a definite advantage for the introduction of this technology in the regions. Another advantage of installing algal ponds in the regions is the fact that there is enough space for the construction of such installations.

Spatial Distribution of CO_2 Valorisation Potential

According to data obtained from SES databases, there are 48 A-category enterprises and 610 B-category enterprises in Latvia that emitted CO_2 in 2019. Enterprises are located mainly in the Riga region, where the distance to a potential consumer is the smallest.

The territory of the Riga region contains 64 % of all CO_2 producers in the country, while in Vidzeme, this amount is slightly less than 2 %.

By analysing the list of potential CO_2 consumers, a list of enterprises was compiled. These include those enterprises, the main activity of which is related to the production of energy, food and beverages, and algal pools/greenhouses. According to the results, the amount of CO_2 producers is much bigger than CO_2 utilisers (Table 2).

Table 2

CO_2 Ratio in Regions

	CO_2 produced/consumer ratio	CO_2 per consumer, %	CO_2 per region, %
Kurzeme	4.76	1.04	25.94
Zemgale	2.79	0.08	3.23
Vidzeme	2.68	0.10	1.97
Latgale	7.29	0.32	4.43
Riga region	3.98	1.15	64.42

There is a large number of production facilities located in the Riga region (also with an A category pollution permit), like boiler houses, food production facilities, pharmaceutical companies, and wood processing companies. In the Kurzeme region, the biggest CO_2 emitter is the cement production facility.

Unfortunately, a number of restrictions impede the implementation of CSSU technologies. One of the main limitations is the required purity of CO_2. For many processes, the purification level must be at least 99.5 %. Installations with such a high level of efficiency can often be financially disadvantageous. However, companies aiming to introduce CCSU technologies can apply for the European funds.

Identified Strengths, Weaknesses, Opportunities and Threats of CO_2 Valorisation

The results of the SWOT analysis show that at the level of entrepreneurs, concerns for financial stability in the case of using technologies for capturing and utilisation/transporting CO_2 are a severe factor. Financial instability is the main problem in CCSU implementation. However, since every year the requirements for "cleanliness" of the production process will only grow, sooner or later entrepreneurs will face the need to reduce the amount of generated CO_2 in every possible way. To apply for financial assistance from the European funds, the company will have to provide a truly innovative project. If the government introduces new taxes (or increases existing ones) and increases the cost of CO_2, entrepreneurs will have no choice but to improve production lines. However, in parallel with the introduction of the new taxes, the government should subsidise measures aimed at decarbonisation of the industrial and energy sectors, compensate electricity costs and/or provide financial help in the acquisition of the necessary installations. Another possibility to motivate entrepreneurs and make CCSU technologies more attractive is to change the taxation system, as it was done in the United States. Every company can receive a tax credit for every captured metric ton of CO_2. To really contribute to the introduction and active use of CCSU, it is necessary to pay great attention to the research and development of appropriate technologies.

The results of SWOT analysis were combined with the maps, created in ArcGIS programme. ArcGIS maps showed that the “producers” and “consumers” enterprises are located near (or in) large cities. This fact can be attributed to the positive, since in urban conditions, due to the dense population, changes occur more often. In turn, regional enterprises can supply the produced CO_2 to biofuel production plants, which would also positively affect the level of regional development. Due to the fact that the factories are located within the city area, the people working in these factories are less sensitive to a possible reduction in the workforce. However, new technologies require an increased level of knowledge and, possibly, additional training.

Further, combined SWOT and ArcGIS results were used in FLCM analysis to obtain a picture of the influence of various factors on each other and the relationship between them (in this case, picture of the relationships at the national level, Fig. 8).

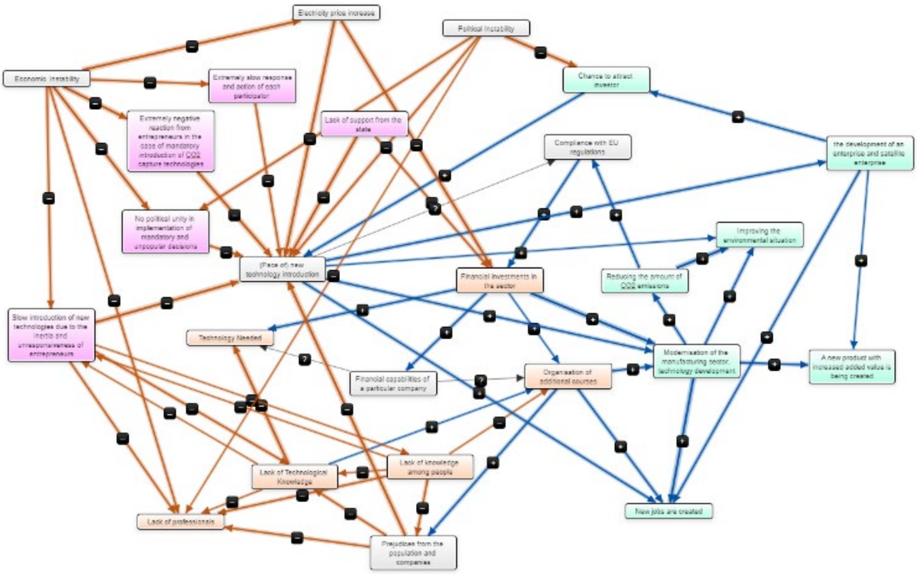

Fig. 8. Results of FLCM analysis.

Blue lines represent a positive impact on the factor, and orange lines represent a negative one. Grey lines represent neutral or potential impact. Pink blocks are political factors; grey are external factors, green are positive for both the enterprise and society, and orange are negative.

The main factor most influenced by others is the speed of implementing new technologies.

The speed of technology implementation is influenced by political factors and the so-called public, such as prejudice about the dangers of CO_2 and the need for change.

All the factors listed in the SWOT analysis appear in the FLCM. However, the FLC allows seeing the entire chain visually and assessing what is the primary factor and what is secondary in a clearer way.

Survey Outcomes: Perceptions of CO_2 Emissions Among Stakeholders

Public opinion

To carry out this step of the methodology, an anonymous survey was organised electronically via the Internet. The questionnaire was sent to 189 people, and answers were received from 82 respondents. According to the results, most of the respondents were in an age range of 19–25 years (42 %) and 26–40 years (40 %). 28 % of respondents have higher professional education, and 22 % have a bachelor's degree. It should be taken into account that many educational institutions strive to inform students about environmental problems and how to solve them; therefore, all respondents are competent people.

According to the results, 93 % of the respondents are aware of the CO_2 emission problem. 48 % are concerned about the problem, but 51 % acknowledged they don't have enough information about the problem, or they don't care about it. Only 16 % of the respondents believe that the CO_2 problem is relevant for Latvia. From all the possible answers, respondents believe that reduction of emissions is more crucial to society itself (57 %). 52 % of the respondents are certain about the need to reduce the amount of CO_2 emissions, and 70 % are ready to change their habits to decrease their impact on climate change.

Survey of entrepreneurs

A survey of entrepreneurs was conducted. Unfortunately, the feedback was scarce – only 11 % of the questionnaires were completed.

40 % of the respondents work in the agricultural sector, 20 % in manufacturing; the remaining 40 % in the chemical industry, production sector, metalworking and ship repair sector. 90 % of the respondents have been working for more than 20 years. Only half of the respondents stated that the problem of CO_2 emissions is not so relevant to them. However, since most respondents are involved in the agricultural sector, such a result was expected. According to the answers, for 50 % of the respondents, the most relevant reason in the context of CO_2 emission reduction is compliance with requirements and legislation. Respondents admitted that it may be financially difficult for them to comply with the requirements of the legislation, and in case of more strict legislation and taxation, they will consider the possibility of changing the location of their business. Some respondents suggest acting in a more long-term perspective and adopting laws that will be most effective in the context of Latvia but will not cause irreparable damage to the industrial sector. According to the answers received, 70 % of the respondents are ready to install additional equipment, which would reduce CO_2 emissions in their facility. 40 % of the respondents are ready to invest in green technologies, but no more than 10 % of their monthly income.

All interviewed companies recognised the importance and necessity of modernisation despite the factors. They also acknowledged their readiness to participate in one way or another in the policy of reducing the amount of CO_2 emissions.

Comparative Analysis of CO_2 Legislation Across Jurisdictions

International legislation regarding environmental protection has several laws and agreements. Not all adopted documents are binding, but they carry several recommendations and methodologies for both countries and entrepreneurs. These laws and directives primarily aim to mitigate climate change and reduce CO_2 emissions.

The Commission of the European Union intends to promote the development of CCSU. Both the existing experience and all proposed innovations and projects are analysed. In October 2021, a forum dedicated to the issue of CCUS technologies was held, and this event can be considered a successful step in the right direction. All listed legislative documents of the European Union are summarised in Table 3.

Table 3

European Laws and Funds

Name	For whom	Goal
Paris Agreement	All countries that signed the document (191)	To control and limit the global temperature rise
European Climate Law	All EU countries	A tool to limit global temperature rise
ETS	All EU countries + EEA	A tool for controlling and reducing the amount of emissions
Modernisation fund (Kyoto Protocol)	BG, EST, LV, LT, HU, RO, PO, CR, SL, CR	To boost technologies; Up to 30 mln. ETS permits
Innovation Fund	All EU countries	To boost CCUS technologies; ~ 2.5 bln. euros
CCS Directive	All EU countries	To help implement CCS technologies

As a country of the European Union, Latvia, like any other member state, must comply with the regulations and laws of the Union. If necessary, the national-level rules can be changed; however, the legislation of the European Union and the regulations adopted by it are a priority for implementation and cannot be ignored in case of any confrontation with local laws. Thus, Latvia has 7 different documents to reduce or account for CO_2 emissions (Table 4).

Table 4

Legislative Documents on CO_2 in Latvia

Name	**Goal**
Law on Pollution	To prevent and/or reduce the negative impact caused by climate change
Procedure for auctioning emission allowances allocated in Latvia	Set of rules for emission trading
Methodology for Calculating Greenhouse Gas Emissions	To assess the impact of specific planned and/or already implemented climate change measures
Climate Law	To limit climate change and ensure adaptation to climate change in the country. Under development. Will replace the law "On Pollution."
GHG Monitoring and Reporting	Procedures for monitoring, calculating, and reporting the GHG emissions
Air Pollution Reduction Action Plan 2020–2030.	Developed within the law "On Pollution." Aimed at reducing the amount of emissions, costs, and loss of working time caused by air pollution due to health problems and visits to the doctor
National Energy and Climate Plan	Determines the basic principles, goals, and directions of action of the Latvian state energy and climate policy

Additionally, in this research, legislation on the reduction of CO_2 was compared between countries of the European Union (and Great Britain). It can be concluded that, despite poorly developed legislation in the Baltic countries, there is a possibility to cooperate in the implementation of CCSU technologies.

Evaluation of Policy Instruments Supporting CO_2 Technologies

The EU has 27 Member States, each with its own measures to mitigate climate change, developed through EU recommendations and regulations (the "top-down" approach) and those that countries have implemented on their initiative. A review of the information gathered by the

EEA provides an opportunity to conclude the diversity and scope of EU Member States' policy instruments.

According to the results of the research, Belgium has the largest share of policies and policy instruments – 213 documents, followed by France (184). The minimum number of policies and policy instruments is defined for Cyprus (13) (Fig. 9).

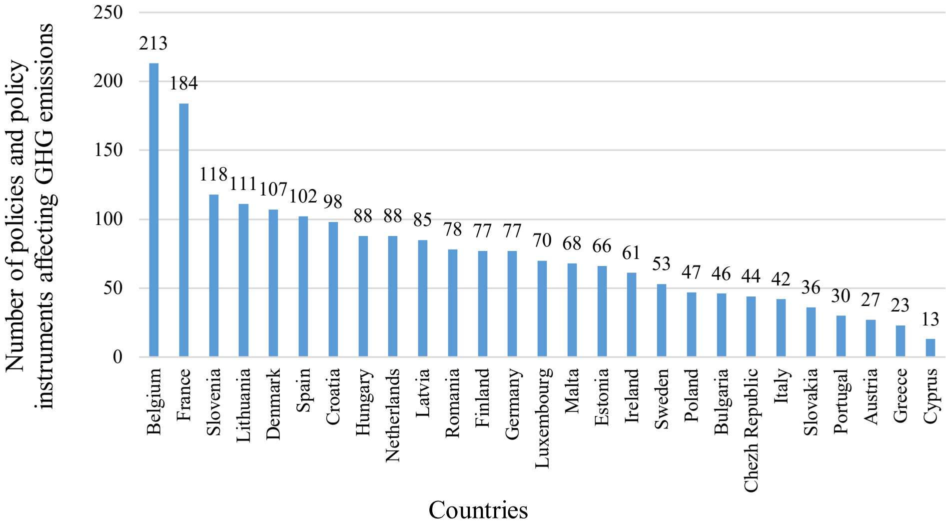

Fig. 9. Number of policies and policy instruments affecting GHG emissions in EU Member States.

When evaluating each country's policies and policy instruments, they can be grouped into several categories. The study included eleven categories (P1–P11).

From Table 5, it can be seen that all 27 Member States are increasing the share of RES in their sectors and have regulations that restrict or ban GHG emissions. Some countries have a CO_2 taxation system. Several countries are ready or have already implemented CCS/CCU technologies.

Table 5

Categorisation of Policies and Instruments Affecting GHG Emissions

	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	Total
Austria	1	–	–	2	1	2	2	3	3	–	–	14
Belgium	**1**	**1**	**1**	**2**	**1**	**2**	**2**	**3**		**3**	**-**	**16**
Bulgaria	1	–	–	2	1	2	2	–	3	–	–	11
Czech Republic	1	1	–	2	1	2	2	–	–	–	–	9
Denmark	1	1	1	2	1	2	2	–	–	–	–	10
France	1	1	1	2	1	2	2	–	–	–	–	10
Greece	1	–	–	2	1	2	2	–	–	–	–	8
Croatia	**1**	**1**		**2**	**1**	**2**	**2**	**3**	**3**	**3**	**-**	**18**
Estonia	1	1	–	2	1	2	2	–	–	–	–	9
Italy	1	–	1	2	1	2	–	–	–	3	–	10
Ireland	1	1	–	2	1	2	–	–	–	–	–	7
Cyprus	1	–	–	2	1	2	2	–	–	–	–	8
Latvia	1	1	–	2	1	2	2	–	3	–	–	12
Lithuania	**1**	**1**	**1**	**2**	**1**	**2**	**2**	**3**	**3**	**-**	–	**16**
Luxembourg	1	1	–	2	1	2	2	–	–	–	–	9
Malta	1	1	–	2	1	2	2	–	3	–	–	12
Nederland	1	1	1	2	1	2	2	3	–	–	–	13
Poland	–	1	–	2	1	2	2	3	3	–	–	14
Portugal	1	1	-	2	1	2	2	3	–	–	–	12
Romania	1	1	1	2	1	2	2	–	–	3	–	13
Slovakia	1	1	–	2	1	2	2	–	–	–	–	9
Slovenia	1	1	–	2	1	2	2	3	–	–	–	12
Finland	1	1	–	2	1	2	2	–	–	–	–	9
Spain	1	1	–	2	1	2	2	–	–	–	–	9
Hungary	1	–	1	2	1	2	2	–	–	–	–	9
Germany	1	1	1	2	1	2	2	–	–	–	–	10
Sweden	**1**	**1**	**1**	**2**	**1**	**2**	**2**	**3**	**3**	**3**	–	**19**
Total	26	20	10	27	27	27	25	9	8	5	0	

Four Member States achieved the best results, given the importance of policies and policy instruments: Sweden (19), Croatia (18), Lithuania (16) and Belgium (16). This is due to the intensive activities in these Member States in categories P8–P10. Therefore, when developing the regulatory framework for the inclusion of CCS and CCU, small countries would need to look toward these countries.

Emissions Data from Biomass-Based Product Scenario

In this step of the methodology, the amount of stored CO_2 per 1 m^3 of the new fiberboard insulation material has been analysed. Standards based on the EN-15804 offer the highest amount of CO_2 stored in 1 m^3 of the product – 359 $kgCO_2/m^3$, while the lowest amount of CO_2 stored can be attributed to ISO-14040/44 – 90 $kgCO_2/m^3$. Considering all standards, an average value of 270 $kgCO_2/m^3$ stored can be assumed as the final result if no single carbon accounting method is chosen.

The calculated criteria values and weights for the MCDA of three different energy production scenarios are shown in Table 6.

Table 6

Criteria Values and Weights

	Wood biomass CHP	Natural gas CHP	Wood biomass CP + PV panels	Criteria weight
Fuel energy content, GJ/m^3	1.56	2.26	1.10	0.079
Capital costs, EUR/m^3	12.68	38.01	8.45	0.210
Fuel costs, EUR/m^3	55.17	37.75	47.80	0.288
O&M costs, EUR/m^3	1.10	0.94	0.89	0.152
Bought/sold electricity, EUR/m^3	3.84	–9.45	19.77	0.110
NO_x emissions, g/m^3	3.14	4.95	2.36	0.028
CO emissions, g/m^3	0.86	5.78	0.64	0.016
VOC emissions, g/m^3	0	4.95	0	0.020
PM emissions, g/m^3	4.7	0	3.5	0.040
CO_2 emissions, kg/m^3	0	90	0	0.057

The results of the MCDA of the scenarios are shown in Fig. 10.

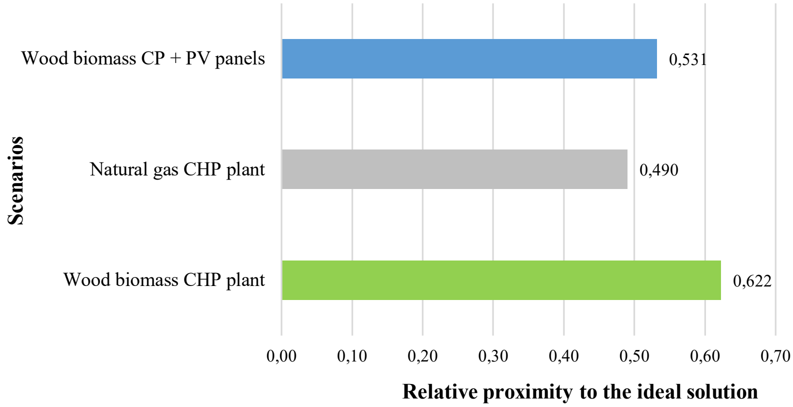

Fig. 10. Multicriteria analysis results.

The results of the MCDA show that the best scenario for energy production for the manufacturing plant is the wood biomass CHP plant (0.622). The scenario with natural gas utilisation shows a close result despite being last. However, taking into account the increase in share of RES on the energy market, it could be possible that the share of natural gas would decrease in the future. More detailed studies should be carried out, which should consider both quantitative and qualitative data, including data and opinions of experts and companies in the field. Social and political aspects should also be reviewed in further studies.

Impact of Final Product Shift on GHG Emissions

Calculation of emission parameters

The $e_{ec,\,n}$ parameter only applies to maize silage, grass silage and immature grain crops. A biogas plant does not do any of the soil carbon accumulation, like crops covering, improved manure management or composting for soil improvement. Thus, these parameters cannot account for emissions savings.

The parameter $e_{l,n}$ is the annual emission from the change in carbon stock. This change arises due to land use for the sake of the substrate n. In the case of the biogas plant, there were no changes; therefore, $e_{l,n} = 0$ (similar values will be for the parameters e_{ccs}, e_{ccr}, $e_{sca,n}$).

Biogas plant works with different substrates; therefore, the parameters must be calculated for each. The type of fuel used should also be considered since the emission factor (EF) depends on it. Having data on logistics and utilisation and the necessary calculation formula, we get that the $e_{td,\text{feedstock},n}$ parameter for the station is 0.0015 $kgCO_2eq/t$ for one type of substrate. The total GHG emissions of all 13 substrate types equal 1.96 $kgCO_2eq/t$.

Emissions from the process on the biogas plant

The next step is to determine the emissions from the processes at the biogas plant for a period of one year. For this parameter – ep_1, it is required to know the amount of energy spent on biogas production, as well as the loss of methane (assumed to be ~ 1 %, according to the RED). Each resource used – electricity and heat – also has its own emission factor. Parameter ep_1 for the biogas plant equals 2.70 $kgCO_2eq/m^3CH_4$.

Next, it is necessary to calculate the emissions from the biogas treatment process and its supply to the system (ep_2). Biogas processing is the last stage of its production. It is this stage that includes the transfer of biogas to biomethane. Emissions from processing biogas to biomethane should take the biomethane yield per year, regardless of the amount of biomethane subject to further certification.

Since biomethane will be used in the network in the future, it is necessary to know the emissions obtained during its transportation and distribution. The biogas processing plant must check the savings potential of the biomethane that will be put into circulation. This means identifying emissions from the stages of compression and transport of biomethane through natural gas networks, as well as compression of biomethane at a particular station, to make sure that the final product meets the requirements of this station.

Substrate allocation

Many different substrates are used in biomethane production – each of them must be analysed separately for the considered period. For a correct calculation of biomethane yield from each substrate, the number of tons of each substrate delivered to the biogas station must be multiplied by 10 % – losses that, according to certification systems (REDcert and ISCC) usually occur and therefore are taken into account. Further, the proportion of methane in each type of substrate is calculated.

Total amount of emissions

Now that the proportion of methane yield in each substrate has been found, it is necessary to allocate this proportion (%) to the total calculated biomethane yield (total methane minus 1 % losses). After acquiring the values of the parameters e_{ec}, $e_{td,\text{feedstock},n}$, e_{p1}, e_{p2} and $e_{td,\text{product}}$, for each substrate used, these values are summed up for use in the following formula to determine the total emissions based on 1 Nm^3 of biomethane:

$$\text{Total emissions per m}^3\ \text{CH}_4 = \frac{(e_{ec}+e_{td,\text{feedstock},n}+e_{p1}+e_{p2}+e_{td,\text{product}})}{\text{Total usable amount of biomethane}}. \quad (4)$$

Knowing that for the observed biogas plant, the sum of all parameters for all substrates is 25,246,762.29 $kgCO_2eq$/year, and the total amount of biomethane is 4,261,983.48 Nm^3/year, using Eq. (4), it has been determined that the total amount of emissions is 5.92 $kgCO_2eq/m^3$ or 16.45 gCO_2eq/MJ emissions.

GHG savings calculation

The last step is to calculate the directly stored emissions from biomethane. The Member States of the European Union have the right to produce only that biomethane, the GHG emissions of which do not exceed the established value of 24 gCO_2eq/MJ. This value is based on a fossil fuel comparator, E, as well as a minimum allowable emission retention value of 35 %. In the case of the biogas plant, the amount of emissions saved is 80.36 %. However, this value reflects the rate of 1 % loss. PSA losses can be as high as 5 %. Thus, the smallest amount of saved emissions is 76.34 %

Environmental and Social Impacts Based on LCA and S-LCA

Social life cycle assessment

Analysis of the main factors showed that the methanol production scenario has more impact on all observed main categories than the SAF-ethanol production scenario (Fig. 11).

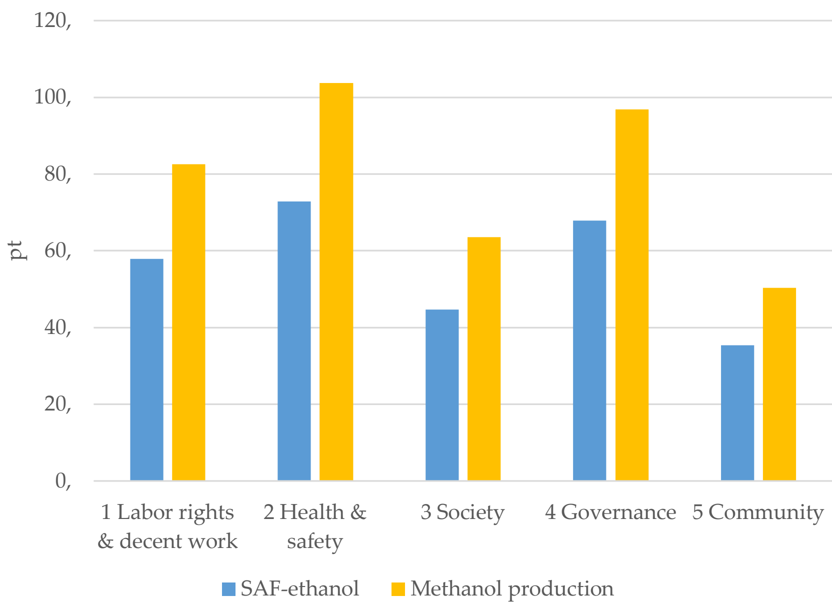

Fig. 11. Main categories, global annual per capita, weighted.

Both methanol and ethanol production processes require various chemicals throughout the lifespan of the production facility, but both scenarios feature relatively inexpensive equipment in the long term. When examining the results by category, both scenarios show the most significant impact in the following categories: 2A – Occupational Toxicity and Hazard, 2B – Injuries and Fatalities, 3F – Poverty and Inequity, 4A – Legal System, and 4C – Democracy and Freedom of Speech.

The most significant impact on methanol production is the construction stage of the plant itself, followed by electricity and water consumption.

SAF-ethanol production is similar to the methanol production scenario – the construction factor has the most significant impact on all categories, followed by electricity consumption (which is especially high in DAC technology) and the amount of necessary chemicals.

Life cycle assessment

Both scenarios show that they have a significant impact on global warming, with methanol production having a greater effect in this category.

Methanol production has a significant impact on the "Global Warming" category as the process involves large amounts of chemicals and, if not controlled, creates emissions to the air. Additionally, the production and utilisation of potassium, urea, and phosphates is a complex and energy-intensive process that influences the overall environmental impact, while utilisation of nitrogen compounds has a negative impact on human health, terrestrial ecosystems and fine particulate matter indicators.

Ethanol production requires a significant amount of energy, as well as chemical reagents. Utilisation of ammonia and sulfuric acid has a negative impact on categories Fine Particulate Matter, Terrestrial Ecotoxicity and Global Warming.

3. DISCUSSION

The study evaluates the potential of CO_2 valorisation through the implementation of CCUS technologies in Latvia, focusing on their application in rural and industrial contexts. The results highlight several viable pathways for CO_2 valorisation, but their practical implementation faces significant challenges.

As a first step of the methodology, the study offers KPI and MCDA analysis. The results identified algal ponds/greenhouses and food industry applications as the most feasible CO_2 utilisation pathways due to their technological simplicity and high CO_2 consumption. However, their economic and scalability limitations are notable. Algae-based systems, while effective in CO_2 uptake, require significant land and water resources, which may compete with agricultural priorities in rural Latvia. Compared to studies in regions like the Netherlands, where algae- and greenhouse-based CCU is supported by dense industrial clusters and government subsidies, Latvia's sparse infrastructure and limited funding pose barriers.

The Key Performance Indicator table developed in the study is a valuable tool for comparing industries, but its current limited data restricts its applicability. Using a larger number of indicators can increase the accuracy of the result, making it more appropriate and applicable to the specific conditions.

In the second step of the methodology, the possibilities of using CCU technologies in various sectors were analysed. The potential for CO_2 utilisation in biogas and biofuel production is promising, particularly in Latvia's agricultural regions like Latgale and Kurzeme. However, the high capital costs of retrofitting biogas plants for CO_2 capture, as noted in similar projects, pose a significant barrier.

The study's assumption of biomass availability does not take into account potential supply chain constraints, such as seasonal variations or competition with food production, which have been critical limitations in other projects. The absence of operational biomass production sites (like, for example, algal ponds) for biofuel production in Latvia further underscores infrastructural gaps compared to other countries, where such facilities are supported by the government. The focus on Riga's boiler houses as major CO_2 emitters highlights a regional challenge, but does not take into account the lack of necessary infrastructure. Other countries' experience demonstrates that integrated CCUS networks require significant investment in pipelines and storage sites, which Latvia currently lacks.

The SWOT and FLCM reveal that political and financial barriers dominate CCU adoption in Latvia. The human factor, including public and stakeholder resistance, is another critical barrier, as seen in abandoned CCS projects due to public opposition. For more comprehensive results, an economic analysis should be applied, which would include the ETS factor, as carbon pricing significantly influences investment decisions in CCUS.

Entrepreneurs worldwide and in Latvia need to assess their impact on the environment and the activities they can carry out in their enterprise. The survey results highlight low public awareness and limited entrepreneurial willingness to invest in CCUS, reflecting similar findings in European contexts. The low response rate from entrepreneurs (11 %) suggests potential sampling bias, limiting the generalisability of findings. A more detailed questionnaire and survey, with wider respondent selection, should be done in order to acquire detailed data. For CCUS implementation, Latvian industrial and agricultural sectors suffer from a lack of legislative and financial support, a challenge also observed in other European countries' CCUS efforts.

The analysis of EU legislative frameworks reveals Sweden's leadership in CCUS policy, driven by detailed and complementary regulations. Latvia's less developed framework, with vague CCS/CCU guidelines, mirrors challenges in other Baltic states. Developing clear, incentive-based legislation, as seen in Sweden's policy, could accelerate adoption. However, the study's focus on legislative analysis does not take into account practical implementation challenges, such as enforcement capacity, which may hinder progress.

Sweden's high score in legislative support for CCUS contrasts with Latvia's maturing CCUS framework. The IPCC emphasises that delayed action increases future emission reduction burdens, a warning relevant to Latvia's slow policy progress. Belgium's extensive policy portfolio (213 policies) suggests that quantity alone is insufficient without coherence, as Sweden's fewer but targeted laws demonstrate much better results in CO_2 valorisation. Latvia could adopt Sweden's model of integrating CCUS incentives with renewable energy policies to enhance economic feasibility, but this requires overcoming bureaucratic inertia and securing EU funding.

The seventh step of the methodology offers the analysis of CO_2 valorisation by its storage in another product. The proposed wood fiberboard insulation material offers a novel CO_2 storage solution combined with an optimal energy source, but the environmental benefits of CO_2 storage vary significantly across accounting standards. This variability introduces uncertainty in claiming a contribution to climate neutrality. The preference for wood biomass CHP over fossil-based energy aligns with sustainability goals but assumes a stable biomass supply, a limitation that is not fully addressed.

The eighth step of the methodology offered another way of CO_2 valorisation – through avoidance by changing the final product. The Latvian biogas plant's transition from biogas to biomethane production demonstrates significant emission savings (76.34–80.34 %), which is comparable to other similar projects. However, the REDcert method's complexity and reliance on standard emission factors introduce uncertainties, particularly for diverse substrates. The study's focus on a single plant limits its generalisability, as regional variations in substrate availability affect outcomes.

In the last step of the methodology, LCA and S-LCA of methanol and SAF-ethanol production were performed. The results highlight their potential but also significant energy demands. Methanol's high volatile emissions and high energy demand underscore the need for renewable energy integration to enhance sustainability. SAF-ethanol's impact on the environment depends mainly on the energy source, the catalysts used and the development of the technology. The lack of sufficient energy infrastructure in Latvia limits scalability. Retrofitting existing biogas plants for methanol production could reduce social and environmental impacts, but public acceptance remains a barrier.

CONCLUSIONS

A comprehensive analysis of the possibilities for CO_2 capture and utilisation was carried out in this study, presenting an approach to ensuring sustainable development and economic decarbonisation, particularly in the context of Latvia. The conducted analyses encompass both applied sciences and the regulatory and social frameworks, enabling the development of a holistic understanding of the potential integration of CCU into the energy and industrial infrastructure.

The assessment of CO_2 as a valuable resource within the circular economy framework emphasises the importance not only of reducing emissions but also of creating new value-added chains in which CO_2 is treated as a feedstock rather than waste. The conversion of CO_2 into liquid fuels, construction materials, chemicals, and fertilisers is considered a realistic pathway toward economic and environmental synergy, particularly in rural areas. The focus on rural Latvia is significant, as these regions show the greatest potential for utilising biogenic CO_2 streams and developing small-scale, energy-efficient production systems.

The regulatory analysis revealed legislative gaps that hinder the large-scale deployment of CCU in EU countries, including Latvia. It highlights the mismatch between rapidly advancing technologies and an outdated regulatory framework. While CCUS has the potential to become a component of national climate policy, this is currently unfeasible under the existing legal framework.

The analysis of applied technical solutions enabled an assessment of the potential for utilising CCUS technologies, including the application of CO_2 emission reduction methods in the biogas-to-biomethane conversion model and in CO_2 storage within products, thus creating materials with high added value. Such approaches contribute to the technological and economic development of both the sector and the region.

Taken together, the results of the conducted analyses demonstrate that the successful deployment of CCU in Latvia requires coordinated efforts across technological, regulatory, economic, and social aspects. Only through their integration can the transition to a low-carbon, sustainable economy be achieved, along with the fulfilment of climate commitments at both national and European levels.

Transitioning from general analysis to practical application, the presented analyses collectively form a structured methodology designed for entrepreneurs, public authorities and policymakers. This methodology serves as a roadmap for the implementation of CCUS technologies, aimed at the sustainable reduction of CO_2 emissions. It covers key stages – from initial assessment of local potential and technological adaptation to regulatory alignment and public engagement – providing a holistic approach to implementing climate-neutral strategies at both regional and national levels (Fig. 12).

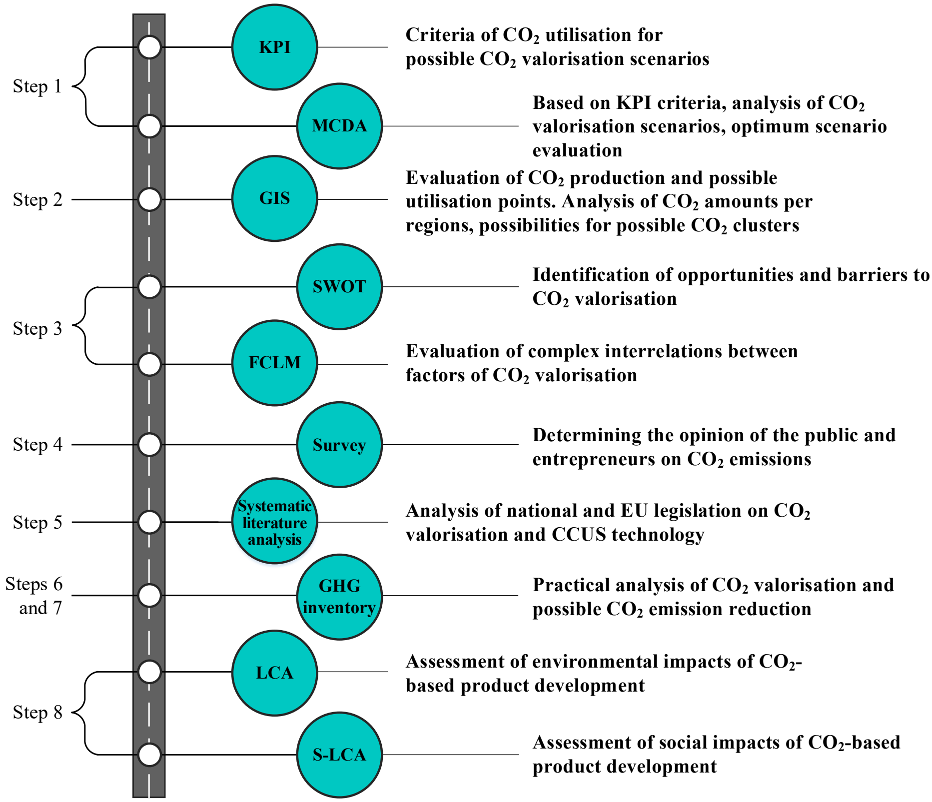

Fig. 12. CO_2 capture and utilisation integrated methodology/roadmap.

Due to a lack of available data, different CO_2 valorisation scenarios have been analysed. These variations introduce methodological inconsistency. For more accurate and comparable results, it is necessary to apply the same set of scenarios consistently across all stages of the analysis.

The objectives set for the Thesis have been completed – potential for the implementation of CCUS technologies in Latvia has been assessed. The aim of the Thesis has been completed, and the integrated methodology for CO_2 valorisation has been created.

The results of this study indicate that the hypothesis was confirmed and that Latvia possesses potential for the implementation and utilisation of CCUS technologies for CO_2 valorisation. Despite relatively weak legislation in the field of CCUS, the country already has existing infrastructure suitable for biofuel (methanol) production. If biogas-producing plants switch to biomethane production, they could substantially reduce the amount of emitted CO_2, thereby improving environmental performance at the regional level and supporting the European Union's decarbonisation targets. Moreover, the adoption of new CCUS technologies would contribute to the technological advancement of the regions.

Thesis maps out the complete CO_2 valorisation pathway (Fig. 13) from emission sources to potential end-uses while providing Latvia with a strategic framework tailored to regional CO_2 utilisation. Central to this effort is the application of an open innovation ecosystem that promotes a continuous knowledge exchange. The ecosystem-based approach surpasses conventional linear planning by promoting dynamic collaboration and solution ownership among stakeholders. The approach allows designing context-specific and scalable valorisation strategies that reflect regional characteristics, economic conditions, and technological readiness.

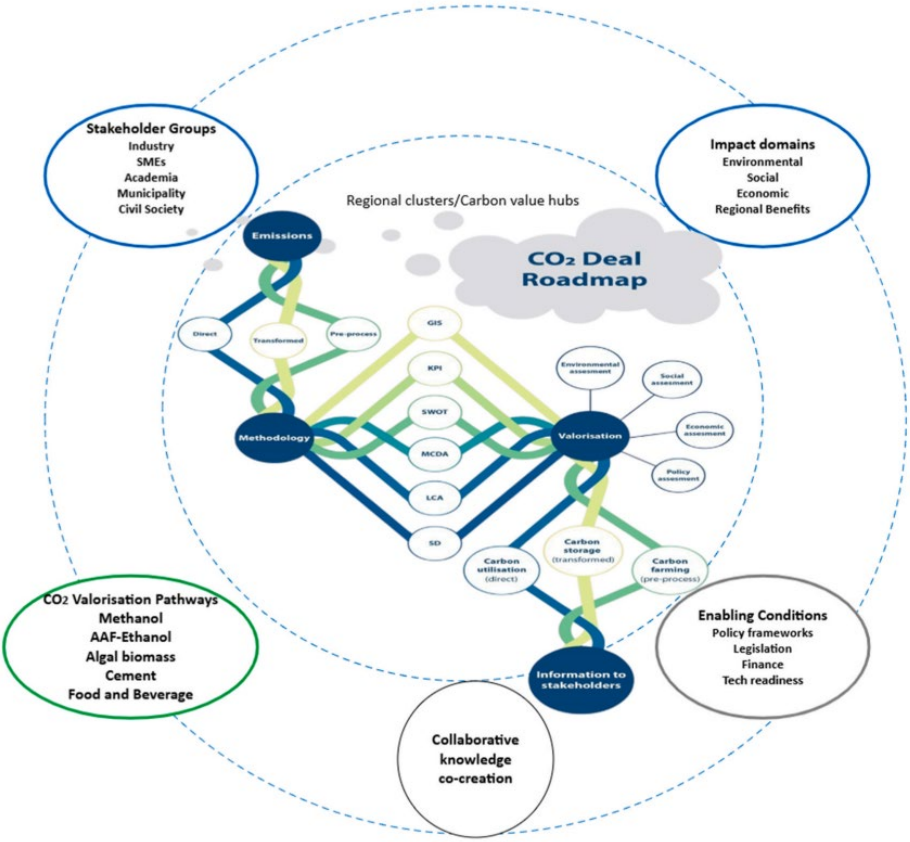

Fig. 13. CO_2 valorisation roadmap.

The roadmap (Fig. 13) enables cross-sectoral collaboration through its structured co-development phases, which start with joint CO_2 source identification followed by collective scenario design and evaluation using agreed criteria. Academic researchers supplied analytical tools to the project while industry stakeholders delivered emissions data and operational knowledge. The governmental actors ensured policy goals matched the scenarios, and civil society members emphasised local environmental and social issues. The consolidated contributions used multicriteria decision-making tools to allow stakeholder preferences to determine which pathways to prioritise. The roadmap functions as both a technical document and a social platform which enables stakeholders to develop collective ownership of CO_2 valorisation strategies. The roadmap establishes alignment with environmental, social, and economic impact domains through enabling conditions that include policy frameworks, financial support, legislative frameworks, and technological development.

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