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CO_2 VALORISATION IN CIRCULAR ECONOMY

Doctoral Thesis

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Annotation

In the context of worsening environmental problems and increasing measures to combat climate change, clear and bold decisions are needed to reduce emissions of carbon dioxide (CO_2), which is one of the main greenhouse gases. One way to do this could be valorisation, i.e., adding value to a product that is usually considered a by-product or waste. Today, CO_2 valorisation is becoming a strategically important area for many countries striving for sustainable development. CO_2 valorisation involves converting CO_2 emissions into useful products, which not only reduces emissions into the atmosphere but also creates new resources for the economy while simultaneously promoting the technological development of the country. Given the desire to transition to low-carbon technologies and achieve international climate goals, such as the Paris Agreement, the research and implementation of CO_2 valorisation technologies is a pressing issue. This process is especially important for regions where CO_2 emissions significantly exceed permissible standards and/or where innovative approaches are needed to improve the environmental situation.

This Thesis proposes an integrated methodology, that can be used as a roadmap for CO_2 valorisation that can serve as a tool for ministries and regional governments in developing a strategy to reduce greenhouse gas (GHG) emissions. The development of such a roadmap will allow efforts to be directed toward the practical implementation of CO_2 utilisation projects, which in turn will contribute to more rational use of carbon resources and support for sustainable development in various sectors of the economy.

The methodological section of the work consists of the analysis and application of various methods presented in a number of scientific publications. These publications cover a wide range of issues, from the analysis of CO_2 valorisation options for regional development and the study of barriers to sustainable implementation of technologies to the consideration of legal and economic aspects of CO_2 use in energy. In particular, the methods used include:

— Assessment of regional development scenarios for the integration of carbon capture and utilisation technologies in the energy sector;

— Analysis of the legal framework necessary to support CO_2 valorisation projects;

— Study of policy instruments that stimulate the implementation of these technologies;

— Study of factors that determine social readiness for the implementation of such technologies and the readiness of society to participate in the process through tax and other forms of support;

— Application of life cycle assessment (LCA) and social life cycle assessment (S-LCA) methods to analyse the sustainability of different CO_2 valorisation routes adapted to Latvian conditions.

The systematisation of these methods allows creation an integrated methodology, that includes sequential steps and recommendations for the implementation of CO_2 valorisation technologies.

The results of the Thesis highlight the possibilities and prospects for the practical application of the proposed roadmap at the level of regional and sectoral strategies for reducing carbon emissions. The conclusions emphasise the importance of integrating technical, economic, legal and social aspects to form a comprehensive CO_2 valorisation strategy.

The Thesis is based on ten publications that were developed and published during the creation of this work.

The Thesis consists of four chapters: literary analysis, methodology, results and discussion.

The first chapter, a literary analysis, examines the relevance of the problem, the current situation in the world and in Latvia, and the possibilities for reducing CO_2 emissions. Data from national statistics, Eurostat, Our World in Data, as well as examples and experiences from other countries are considered.

The second chapter describes the methodology for each of the steps-analyses proposed in the worksheet. The following methods and their combinations are used:

— Analysis of literary sources, statistical data, databases of regional administrations, technical sheets, standards;
— Descriptive and systematic literature analysis of legislation both national and international
— Key Performance Indicator analysis;
— Multi-Criteria Decision Analysis;
— Mapping in *ArcGis* programme;
— SWOT analysis;
— Fuzzy Logic Cognitive Mapping;
— Survey of respondents (public and entrepreneurs);
— Analysis of a bioproduct production process, calculation of stored and avoided CO_2;
— Life Cycle Assessment and Social Life Cycle Assessment.

The third chapter describes the results of applying the above methods of analysis.

The final chapter, Discussion, concludes the work and summarises the results obtained during the study.

Anotācija

Pieaugot vides problēmām un vienlaikus pastiprinoties centieniem ierobežot klimata pārmaiņas, kļūst arvien svarīgāk pieņemt izlēmīgus lēmumus, lai samazinātu oglekļa dioksīda (CO_2) emisijas – vienu no galvenajiem klimata pārmaiņu cēloņiem.. Viens no iespējamiem risinājumiem ir valorizācija, proti, pievienot vērtību produktam, kas parasti tiek uzskatīts par blakusproduktu vai atkritumu. Mūsdienās CO_2 valorizācija kļūst par stratēģiski nozīmīgu jomu daudzām valstīm, kuras tiecas uz ilgtspējīgu attīstību. CO_2 valorizācija ietver oglekļa dioksīda emisiju pārvēršanu lietderīgos produktos, kas ļauj ne tikai samazināt emisiju apjomu atmosfērā, bet arī radīt jaunus resursus ekonomikai, vienlaikus veicinot valsts tehnoloģisko attīstību. Ņemot vērā apņemšanos pāriet uz zema oglekļa satura tehnoloģijām un sasniegt starptautiskus klimata mērķus, piemēram, Parīzes nolīguma nosacījumus, CO_2 valorizācijas tehnoloģiju izpēte un ieviešana ir steidzams uzdevums. Šis process ir īpaši svarīgs reģioniem, kuros CO_2 emisijas ievērojami pārsniedz pieļaujamos standartus un/vai kur nepieciešamas inovatīvas pieejas, lai uzlabotu vides situāciju.

Šajā promocijas darbā tiek piedāvāts CO_2 valorizācijas ceļvedis, kas var kalpot par instrumentu ministrijām un reģionālajām iestādēm siltumnīcefekta gāzu emisiju samazināšanas pasākumu un stratēģiju izstrādē. Ceļveža izstrāde ļaus virzīt centienus uz praktisku CO_2 izmantošanas projektu īstenošanu, tādējādi veicinot racionālāku oglekļa resursu izmantošanu un ilgtspējīgas attīstības nodrošināšanu dažādās tautsaimniecības nozarēs.

Darba metodiskā daļa ietver dažādu analīzes metožu pielietojumu, kas aprakstīti vairākās zinātniskās publikācijās. Šīs publikācijas aptver plašu jautājumu loku — no CO_2 valorizācijas iespēju analīzes reģionālajai attīstībai un šķēršļu izpētes ilgtspējīgu tehnoloģiju ieviešanai līdz juridisko un ekonomisko aspektu izvērtēšanai CO_2 izmantošanā enerģētikas nozarē. Izmantotās metodes ietver:

— Reģionālās attīstības scenāriju novērtējums oglekļa uztveršanas un izmantošanas tehnoloģiju integrācijai enerģētikas sektorā;

— CO_2 valorizācijas projektu atbalstam nepieciešamā tiesiskā regulējuma analīze;

— Politikas instrumentu izpēte, kas veicina šo tehnoloģiju ieviešanu;

— Faktoru analīze, kas nosaka sabiedrības sociālo gatavību šādu tehnoloģiju ieviešanai un iesaistei procesā, tostarp ar nodokļu vai citu atbalsta veidu palīdzību;

— Dzīves cikla un sociālās dzīves cikla novērtēšanas metožu pielietojums dažādu CO_2 valorizācijas ceļu ilgtspējas analīzei, pielāgojot tās Latvijas apstākļiem.

Šo metožu pielietojums un sistematizācija ļauj izstrādāt holistisku ceļvedi, kurā iekļauti secīgi soļi un ieteikumi CO_2 valorizācijas tehnoloģiju ieviešanai.

Darba rezultāti iezīmē iespējas un perspektīvas piedāvātā ceļveža praktiskai izmantošanai reģionālo un nozaru stratēģiju līmenī oglekļa emisiju samazināšanai. Tie uzsver, cik būtiski ir integrēt tehniskos, ekonomiskos, juridiskos un sociālos aspektus, lai izstrādātu visaptverošu oglekļa dioksīda valorizācijas stratēģiju.

Darba pamatā ir deviņas publikācijas, kas tika izstrādātas un publicētas šī darba tapšanas laikā.

Darbs sastāv no četrām nodaļām: literatūras analīze, metodoloģija, rezultāti un diskusija.

Pirmā nodaļa – literatūras analīze – veltīta problēmas aktualitātes izpētei, aplūkojot pašreizējo situāciju pasaulē un Latvijā, kā arī oglekļa dioksīda emisiju samazināšanas iespējas. Tiek analizēti dati no nacionālās statistikas, Eurostat, Our World in Data, kā arī citu valstu pieredze un piemēri.

Otrajā nodaļā aprakstīta katra ceļveža posmā iekļautā analīzes metodoloģija. Tajā detalizēti izklāstītas izmantotās metodes un to kombinācijas

- Literatūras avotu, statistikas datu, reģionālo nodaļu datubāžu, tehnisko lapu, standartu analīze;
- Nacionālo un starptautisko tiesību aktu aprakstoša un sistemātiska literatūras analīze;
- Galveno darbības rādītāju analīze;
- Daudzkritēriju lēmumu analīze;
- Kartēšana *ArcGis* programmā;
- SVID analīze;
- Izplūdušās loģikas kognitīvā kartēšana;
- Respondentu (sabiedrības un uzņēmēju) aptauja;
- Siltumnīcefekta gāzu inventarizācija bioproduktos;
- Dzīves cikla analīze un sociālā dzīves cikla analīze.

Trešajā nodaļā ir aprakstīti augstākminēto analīzes metožu pielietošanas rezultāti.

Pēdējā nodaļa Diskusija noslēdz darbu un apkopo pētījuma rezultātus.

Pateicības

Šī promocijas darba tapšana ir bijis ne tikai akadēmisks, bet arī personīgs izaicinājums, un es vēlos izteikt pateicību visiem, kuri šajā ceļā mani atbalstījuši.

Vislielāko pateicību izsaku savai darba vadītājai, Jeļenai Pubulei, par profesionālu vadību, iecietību un iedvesmojošu attieksmi visā darba izstrādes laikā. Jūsu zināšanas, precizitāte un spēja uzdot būtiskus jautājumus man palīdzēja veidot dziļāku izpratni par pētījuma tēmu. Paldies par uzticēšanos, kritisko skatu un atbalstu brīžos, kad tas bija visvairāk nepieciešams.

Sirsnīga pateicība arī Rīgas Tehniskās Universitātes Vides Aizsardzības un Siltuma Sistēmu Institūta direktorei, Dagnijai Blumbergai, par ieinteresētību, atbalstu un rūpēm par institūta attīstību un doktorantu vajadzībām. Jūsu vēlme palīdzēt ir devusi būtisku ieguldījumu manā akadēmiskajā izaugsmē.

Pateicos arī kolēģiem, studiju biedriem un institūta darbiniekiem, ar kuriem kopā esmu dalījies idejās un pieredzē. Jūsu klātbūtne un iedrošinājums ir bijusi svarīga daļa šī darba tapšanas procesā.

Visbeidzot, no sirds pateicos savai ģimenei un tuvākajiem — par sapratni, pacietību un ticību man. Jūsu atbalsts ir bijis pamats, uz kura balstīties ik brīdī.

Paldies ikvienam, kurš bija līdzās!

CONTENT

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 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.

Current EU strategies demonstrate the need for joint solutions and cooperation across different sectors to achieve the EU objectives of reducing CO_2 emissions, developing a circular economy and promoting sustainability within sectors. This cooperation is essential for the implementation of CCUS technologies and technological development, as well as for reducing climate impacts.

The assessment methods unite researchers, industry, policymakers, and communities in a participatory framework for collaborative knowledge exchange and sustainability evaluation. This open innovation approach fosters iterative feedback, transparency in scenario selection, and co-creation of adaptive CO_2 valorisation strategies aligned with environmental and socio-economic goals.

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, determine the requirements for the implementation of CCUS taking into account environmental, technological, legislative and social aspects and to develop an integrated methodology for 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 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 till 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.

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 method – to assess technical, economic, and environmental feasibility across scenarios;
- Multi-Criteria Decision Analysis – to enable structured comparison of valorisation options;
- *ArcGis* 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 – to model interdependencies between social, technological and legal variables;
— Survey (public and entrepreneurs) – to assess social acceptability and stakeholder engagement;
— Greenhouse gas emission inventory – to quantify emissions reductions in biomass and energy scenarios;
— Life Cycle Assessment – to assess the environmental impacts of CO_2 valorisation;
— Social Life Cycle Assessment – 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

A study of 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 work 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 of the region.

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 work 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.

The first chapter 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. The second chapter specifies the methods that were used to estimate the amount of CO_2, methods for its valorisation, and classification of alternatives for its use. The third and fourth chapters analyse the results obtained, discuss the results of the study, and put forward conclusions.

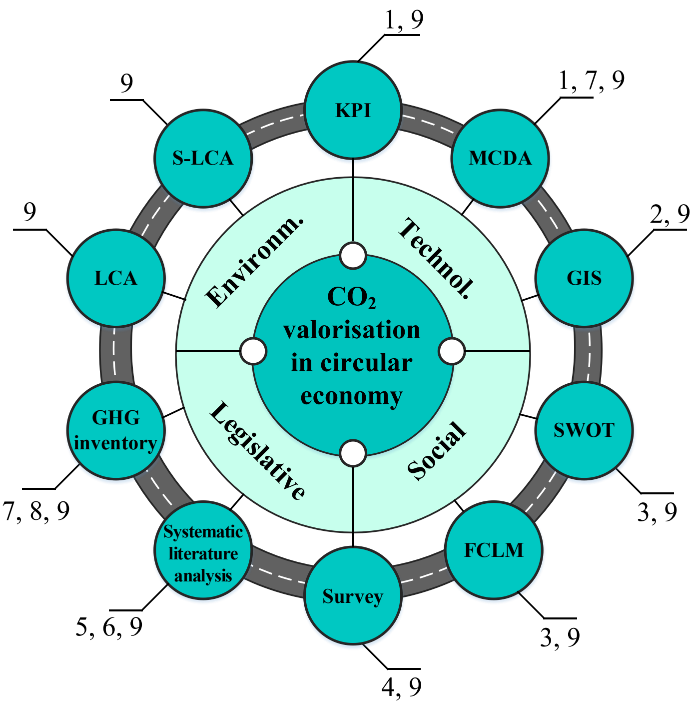

Fig. 1. Scheme of the Thesis.

Fig. 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 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).

Other publications, not related to the following 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 a solar pv panels in 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 specific analysis method, is part of the specific aspect (Table 1):

Table 1.

Scientific publications used in the doctoral Thesis

Aspects	Nr.	Publication title
Technological	1	Analysis of CO_2 Valorisation Options for Regional Development
Technological	2	Regional Development Scenarios and Model Boundaries for CCU in 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. LITERATURE ANALYSIS

The need to address climate change and reduce greenhouse gas emissions brings CO_2 valorisation to the forefront in both the scientific, technical and economic sectors, offering the opportunity to use this still underutilised product in the circular economy. CO_2 valorisation using CCUS technologies offers a promising approach to reducing the climate impact of production processes, while creating new economic development opportunities. The scientific community considers CCUS essential for carbon-neutral transitions because it minimises industrial CO_2 emissions while creating multiple opportunities to transform carbon into valuable resources. Moreover, CO_2 valorisation has the potential to contribute not only to regional development, but also to energy independence and security, providing the opportunity to produce alternative fuels.

EU strategies, including the Sustainable Carbon Cycles Communication and Net Zero Industry Act, highlight the need for collaborative innovation networks to meet 2030 and 2050 carbon neutrality goals. Open innovation drives CCUS technology toward system-wide transformation by integrating technological, social, and market-based approaches. CO_2 can be repurposed from waste to a valuable feedstock, fostering sustainable growth, regional resilience, and long-term climate goals.

In this work, various types of analyses are used for a comprehensive and multifaceted assessment of the possibilities and subsequent development of a CO_2 valorisation methodology. The analyses are based on various aspects – technical, social, natural and legislative, which allows for a comprehensive assessment of the impact of CO_2 valorisation on the environment and society. The integration of co-creative methods with spatial and environmental analyses plays a central role in translating abstract scenarios into practical planning tools.

The methodological algorithm of this study begins with an analysis of potential CO_2 valorisation pathways. A systematic literature review is conducted to identify global trends and best practices in the application of CCUS technologies, as well as to assess the availability and regulatory framework of these technologies within the context of Latvian and European Union legislation. At this stage, all possible scenarios are considered. In the next phase, a more detailed evaluation is carried out to determine whether the selected scenarios involve direct utilisation of CO_2. If not, it is assessed whether CO_2 emissions are potentially reduced through alternative mechanisms. Scenarios that do not meet either of these criteria are excluded from further consideration. However, for scenarios involving the application of CCU technologies, a more in-depth analysis is conducted, including the collection of quantitative data for the development of a Key Performance Indicator (KPI) framework, which subsequently serves as a basis for Multi-Criteria Decision Analysis (MCDA). MCDA enables the structured comparison of different CO_2 valorisation options based on a set of performance indicators. In cases if there is not enough data available, the respective scenario is excluded from further analysis. The final step involves assessing whether the selected scenarios are comparable with each other in terms of environmental and social impact. If so, a Life Cycle Assessment (LCA) is conducted to evaluate the environmental and societal implications of each CO_2 valorisation scenario.

In parallel, if CO_2 can be valorised not through CCU technologies but by an alternative way (e.g., by emission avoidance), a calculation of the potential CO_2 emission reduction within such a scenario is carried out. The algorithm of methodology is depicted in Fig. 2.

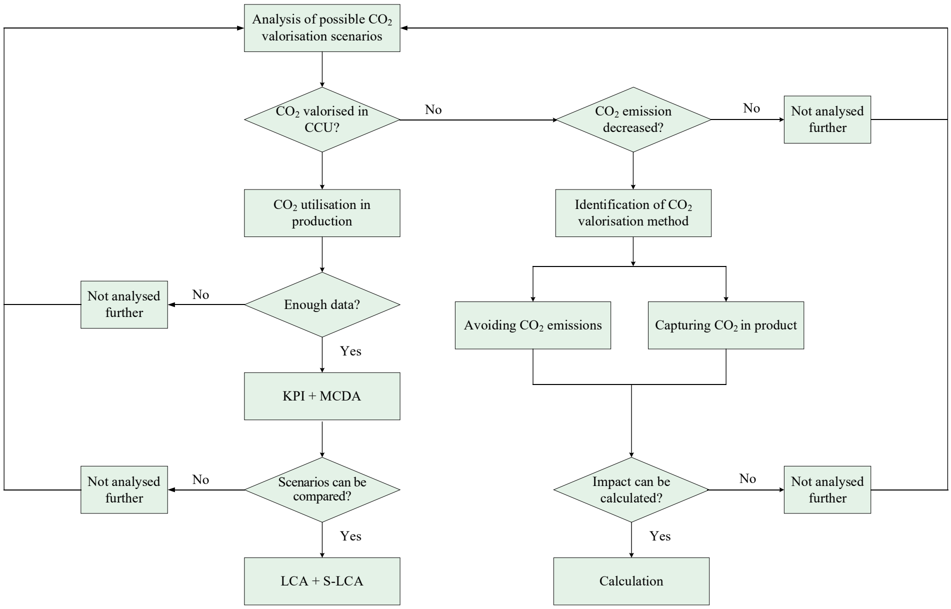


Fig. 2. Algorithm of the scenarios, chosen for specific analysis in the methodology.

In the Thesis, offered CO_2 valorisation methodology analyses various CO_2 valorisation scenarios. This diversity arises primarily due to limitations in the availability of necessary data. For instance, in the KPI–MCDA analysis, only scenarios for which sufficient indicators were available at the time of assessment were included. In subsequent stages, particularly steps 7 and 8, the focus shifted toward evaluating alternative pathways for reducing CO_2 emissions, rather than converting it into other products (or using it directly in processes such as algal biomass or biofuel production). The final, 9th step of the methodology, focuses on SAF-ethanol and methanol production. Other potential utilisation pathways, such as algal biomass and cement production, despite being analysed in step 1, were excluded because all analysed scenarios involve products from distinctly different categories. While SAF-ethanol and methanol are both fuel types and can be comparatively assessed, the injection of CO_2 into a product (e.g., in construction materials) and its utilisation in plant growth cannot be objectively compared within a single analytical framework.

The combination of different analytical methods together provides a holistic understanding of the CO_2 valorisation possibilities through CCUS technologies. Using this approach, the study aims to answer critical questions about the potential, challenges and implications of different CO_2 valorisation strategies. The selected analytical methods provide a robust basis for the developed CO_2 valorisation methodology, ensuring that technical, social, environmental and legislative aspects are thoroughly examined.

This chapter provides an analysis of the essential information required for the development of a CO_2 utilisation methodology. The chapter serves as a theoretical foundation, beginning with an examination of the current national context and global trends in the implementation of CCUS systems. Each section introduces a specific step of the methodology, with each step representing a distinct type of analysis.

1.1. Relevance of Key Performance Indicators in CO_2 Valorisation Context

The growing amount of CO_2 is a serious problem in today's world. The increase in the amount of CO_2 in the atmosphere has dramatic consequences – an increase in the average daily temperature on the planet, which results in the melting of glaciers and a rise in the world ocean level. The concentration of CO_2 rises by 2 ppm annually and has already reached 400 ppm and if the concentration does not stabilise at 450 ppm, the temperature may rise from 2.5° to 6.5 °C by 2100 (Eloy et al., 2020; IEA, 2025).

Seeing the growing amount of harmful emissions, how it affects the environment and people and what serious consequences it can cause in the future, the European Commission launched the Green Deal strategy initiative. The main aims of this strategy are to eliminate GHG emissions by 2050 (to become carbon neutral) and to decouple the economy from resource use. This leads to the major goal of the initiative – long-term climate neutrality (European Commission, 2023).

In December 2020, a new report was published, which focused on GHG emissions and on carbon emissions particularly and the potential to reduce them in each sector (European Parliament, 2020).

The European Commission has also revised targets for reducing amounts of CO_2 emissions. An increase in the emission reduction threshold from 40 % (compared to 1990) to 55 % by 2030 was proposed and subsequently approved. But even this target is not a final decision, since the European Parliament deliberates on lifting this threshold up to 60 % (European Commission, 2021a).

Emissions of GHG and especially CO_2 occur in many sectors, the main ones of which are energy sector (mainly combustion of fossil fuels), transport and industry. In the energy and industry sectors, many sources have high GHG emission levels, making them suitable for carbon capture technologies. According to statistical data, in 2022 energy sector emitted 33 % of CO_2 (in power generation 68 % of the sector emissions are from coal combustion, in electricity generation 20.9 % of emissions comes from natural gas). Comparing to 2000, energy sector shows a decline in CO_2 emissions, but still amount is too high (European Parliament, 2021; IEA, 2022c) (Fig. 3).

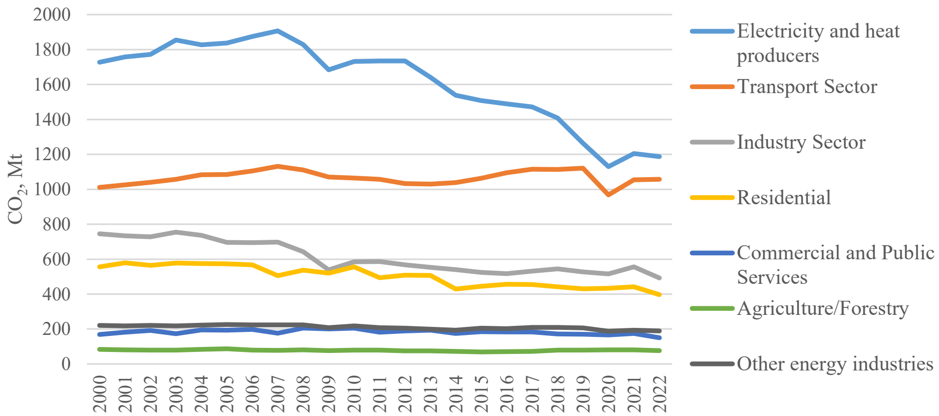


Fig. 3. CO_2 emissions in European Union 2020–2022, by sector (IEA, 2022c).

Despite the fact that in the period 2000 to 2025 the amount of CO_2 emissions in the European energy sector show a decline, this sector is still one of the leaders in terms of CO_2 emissions(IEA, 2025). While some countries are actively using the latest energy production technologies, others are experiencing stagnation in this sector, a slow transition to more environmentally friendly fuels and / or slow introduction of innovative technologies (European Parliament, 2021), (*Transitions to Low Carbon Electricity Systems: Key Economic and Investment Trends*, 2019).

Latvia is one of the countries, where total amount of CO_2 emissions is rising steadily.

The biggest amount of CO_2 emissions was produced in the energy sector, followed by manufacturing sector. Opposite to trend in Europe, in Latvia the difference in amount of emission between these two sectors is not so big (Fig. 4).

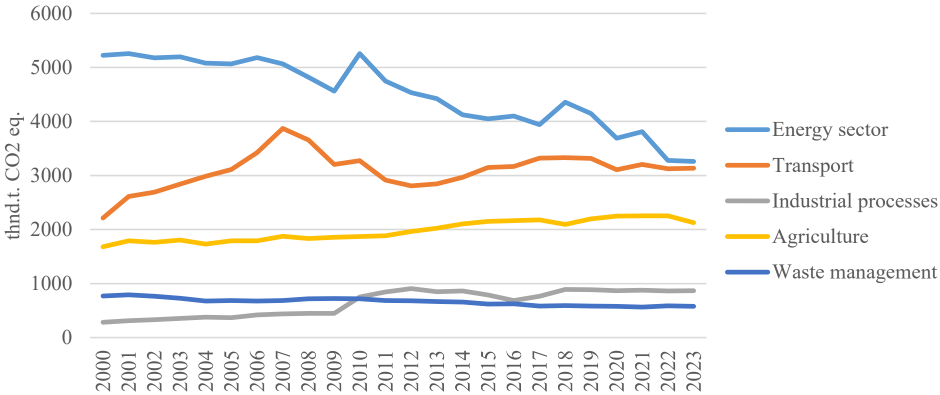


Fig. 4. CO_2 emissions in Latvia sectors in 2000–2023 (Official statistics portal, 2025).

Implementation of new technologies could help to decrease the environmental load – in Latvia energy sector shows decline in CO_2eq emissions, but it is mainly achieved because of biomass combustion (biogenic CO_2 is excluded from total CO_2 emission). However, it is still is not enough to meet new requirements regarding emission control (Eurostat, 2020). The slow modernisation of production processes and the transition of production to renewable energy sources, the lack of support for the introduction of new technologies, as well as the economic downturn do not contribute to the reduction of CO_2 in any country (Kudurs et al., 2020).

Despite the introduction of new, stricter standards for production and plans proposed in the European Union for the regulation of GHG, the amount of emissions in some countries is decreasing at an extremely slow rate (and in some sectors it is not decreasing at all), it is necessary to develop an alternative way of using CO_2 in the country (European Parliament, 2021). It is necessary to systematise the spheres of production and select those sectors that can use CO_2 for the manufacturing of products with increased added value. It is necessary to turn production waste into a valuable product – that is, it needs valorisation.

CO_2 can be used in various fields – as a raw material for the production of innovative fuels, in the chemical industry for the production of chemical substances, as an additional food for algae and as an additive in the cement sector, etc. The use of CO_2 in the manufacture of new materials and products is considered to be sustainable production. The production of new types of fuel helps to reduce the amount of emissions, and the use of a "waste product" as a raw material for other manufacturing processes will reduce the amount of CO_2 in the atmosphere, the introduction of new technologies will create additional jobs, which will have a positive effect on the economy as a whole (LVĢMC, 2020).

Within the framework of the H2020 program, many projects are being implemented, the purpose of which is the production of biofuel, using CO_2 as one of the resources. The MefCO_2 projects a good example of this use of CO_2. The project is a working technology that captures and uses CO_2 from a power plant in Germany. The plant uses coal for energy production, the combustion of which emits large amounts of CO_2, thus capturing and then using this CO_2 to produce methanol (as well as other valuable chemical compounds) reduces the plant's environmental load. This project demonstrates by its example the possibility of using industrial CO_2 for the production of goods with high added value, which has a positive effect on both the environment and the economy of the region (MEFCO2, 2019).

While CO_2 is increasingly seen as a resource within the circular economy, its use demands specific capture and purification technologies. CO_2 capture typically involves pre-combustion, post-combustion, or oxy-fuel combustion methods, each requiring energy-intensive separation, compression, and transport prior to utilisation, as well as specific technologies acquired. Some technologies allow utilisation of CO_2 without complex purification process, while others require as pure CO_2 as possible.

In the construction sector, CO_2 can be injected into concrete (carbonation process), where CO_2 reacts with calcium silicates to form solid carbonates during curing. Large-scale trials report a 3–5 % reduction in concrete's global warming potential, and over 200 plants worldwide are already adopting the technology (Cannon et al., 2021; Ravikumar et al., 2021).

In the steel industry, CO_2 is being repurposed as a reducing agent in emerging pilot processes. For example, plasma-based CO_2 splitting transforms CO_2 into CO, which can partially replace coke or coal in blast furnaces. Additionally, pilot CO_2 capture units on blast furnaces are being implemented, demonstrating the potential emission decrease in the sector(ArcelorMittal, 2024).

CO_2 is widely used in the chemical and by-chemical industries. It can be used in a "raw" form, that is, as a working fluid (for example, a refrigerant or supercritical CO_2) or a solvent. It can be utilised in production of syngas, methanol and fuel (Phoenix Initiative, 2018). During the fermentation of biomass CO_2 is released, which can be separated from the main stream and utlised in methanol, ethanol or biomethane production. In combustion processes (like boiler houses), CO_2 can be captured before, during or after combustion process. Technologically the easiest and the most implemented method is post-combustion capture using monoethanolamine (N. Wang et al., 2023).

The amount of CO_2 utilisation projects, as well as the demand for CO_2, is growing every year. In 2018, the leaders in the use of CO_2 were urea production and enhanced oil recovery, but as technology develops, the share of other sectors (such as the production of methanol and other chemicals) is growing. Annual demand for CO_2 is expected to be 272 $MtCO_2$ by 2025 (Bellona, 2012; IEA, 2019).

For the successful implementation of CO_2 utilisation technologies, it is essential to identify the optimal CCUS technology. To achieve this, it is important to determine the relevant parameters and requirements for the technologies under consideration. For instance, this may include the amount of CO_2 consumed per ton of product or the volume of CO_2 emitted during the production of a new product. Within the framework of the developed methodology, the identification of CO_2 parameters and the determination of the optimal scenario represent the first step.

1.2. Geographical Aspects of CO_2 Valorisation Potential

The second step in the process of implementing CCUS technology is the identification of CO_2 emission sources within the country and the locations where it can potentially be utilised.

The amount of CO_2 emissions is different in every sector of every country. According to statistics, the energy sector is a leader in the production of CO_2 emissions as in the world and the European Union, as in Latvia (Central Statistical Bureau Databases, 2020b), (Central Statistical Bureau Databases, 2020a), (Eurostat, 2020). According to (Central Statistical Bureau Databases, 2020b), in 2018 the largest amount of CO_2 emissions was recorded in the USA and China (10–50 % of the total amount of emissions). Germany is the leader in the European Union (2.08 % CO_2). The rest of the Union countries, including Latvia, look more optimistic against the general background and the amount of emissions in Latvia did not exceed 0.0 2% of the total CO_2 emissions in the world (which is better than in Lithuania (0.04%) and Estonia (0.05 %)).

According to government statistics, in 2023, 9 981 thsnd. tCO_2eq were produced in Latvia (excluding LULUCF and including indirect emissions). And although emissions are decreasing compared to previous years, this is achieved primarily through the transition from fossil fuels to biomass rather than the introduction of CCUS technologies (Official statistics portal, 2025; Skrebele et al., 2024). Installations for capturing and neutralising CO_2 directly at the site of its production can often be simply inaccessible for the region and / or the entrepreneur, and therefore there is no way to reduce the amount of CO_2 produced. Despite the positive aspects of introducing technologies for capturing and using CO_2 in industry, there are many factors that limit the use of a particular technology in practice.

The major and, perhaps, the main limiting factor for the use of CO_2 is the required level of its purification from impurities. For example, for the use of CO_2 in the food industry, it is necessary to ensure the purity of the gas up to 99.5 % (Dragerwerk AG, 2017), (Marchi et al., 2018). A similar level of purification can be provided either by an industry already initially aimed at the production of CO_2, or by certain processes of the chemical industry (as well as the food industry itself). In turn, biostations need a level of at least 95 %. As in the case of the food sector, the chemical industry and the food industry can also provide CO_2 for biostations as well (Leonzio et al., 2019; Sieborg et al., 2024). Because of this high level of purification required, before using CO_2 as soon as it is produced, it is necessary to first ensure its purity. The main emitter of CO_2 in Latvia is the energy sector, however, combustion of fuel emits not only CO_2, but other elements as well (Murugan et al., 2020), (EPA, 2023). Installation of additional elements is required to ensure the capture of CO_2 before, after or during combustion. The installation of such equipment entails additional financial and energy costs but makes it possible to reduce the amount of CO_2 produced at the enterprise and makes it possible to produce goods with increased added value.

However, CO_2 is not only a waste product of production, but also a potential resource for creating new high value-added products. Potentially, CO_2 can be used as a resource in the chemical industry for extraction of valuable chemical compounds, in the food industry for the carbonisation of products, as a refrigerant and energy fluid (Dragerwerk AG, 2017; Gullo et al., 2017; Leonzio et al., 2019; Muhammad Rashed & Shuichi, 2017; F. Zhang et al., 2020).

Another important sector for the use of CO_2 could be the energy sector. Nowadays CO_2 is increasingly utilised in the production of biofuel (for example, bioethanol, aviation fuel, dimethyl ether (DME), gasoline) (Djettene et al., 2024; Mishra et al., 2020; Rezaei & Catalan, 2024; J. Wei et al., 2017; Yao et al., 2020) CO_2 can also be used in algal ponds. According to (G. Li & Yao, 2024), CO_2 is able to speed up the metabolism of plants, thus increasing the rate of biomass growth significantly. Once the biomass reaches a sufficient amount, it can be used to produce biogas. Using CO_2 in the energy sector can significantly diversify this market, which will have a positive effect on the sector.

By identifying the possibilities for CO_2 utilisation and the technologies already available globally, it becomes possible to analyse in greater detail the sectors in Latvia that could potentially capture CO_2, as well as those that could utilise it. Depending on the place where CO_2 is produced (affects the share of possible impurities in the CO_2 flow), volume of CO_2 produced in a given region and the density of potential users, conclusions can be drawn regarding the feasibility of such projects. This type of analysis also makes it possible to identify clusters (hubs) of CO_2 producers and consumers, which may further enhance the effectiveness of CCUS implementation. Thus, the second step of the methodology – identification of CO_2 points – is being completed.

1.3. Strategic Importance of SWOT Analysis for CO_2 Valorisation

The next step in the methodology is to identify the opportunities, drawbacks, threats, and benefits associated with the implementation of CCUS. It is crucial to analyse these technologies at different levels – enterprise, national, and European Union – as this enables a comprehensive examination of the issue from multiple perspectives.

Mitigating CO_2 emissions is a top question in international and national arenas, likewise on the city level. This problem is national-wide, but it also consists of smaller tasks and challenges on the sectoral, legislative, economical and technological level. Existing CO_2 mitigation measures are primarily oriented towards wider deployment of low-carbon technologies of renewable energy sources and energy efficiency measures, focusing on energy production, distribution and energy use sectors, and transport.

CO_2 is generated in many sectors (Fig. 4). Although generated amount of CO_2eq emissions is showing a decrease, simultaneously utilisation of biofuels is showing a high incline (Fig. 5) (IEA, 2025).

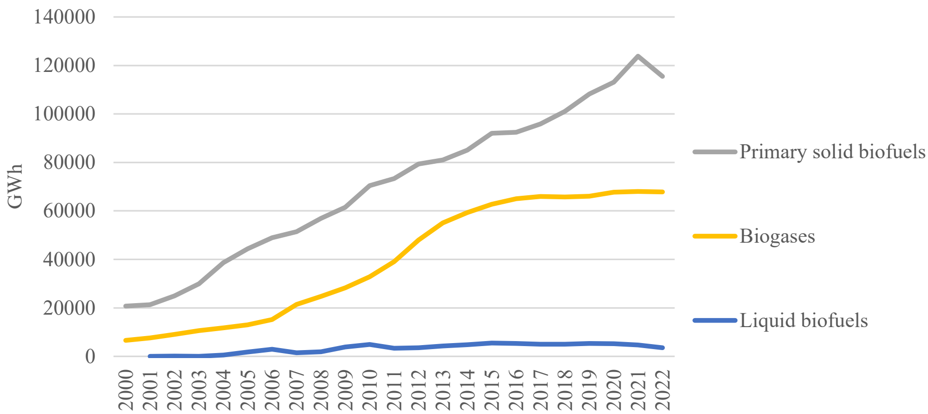


Fig. 5. Energy generation from biofuels in Europe, GWh (IEA, 2025).

Unfortunately, the transition to alternative energy sources reduces emissions primarily in the energy sector, while in other sectors – particularly in manufacturing – emission levels remain largely unchanged. There are many reasons why manufacturers are reluctant to install new technologies that reduce the amount of CO_2 they produce or capture and/or use CO_2.

The main reasons for the slow transition to renewable energy sources and the replacement of outdated technologies with new ones could be:

- The cost of technology and the payback period (International Energy Agency, 2021a);
- Complexity of technology and/or difficulty in maintenance (International Energy Agency, 2021a);
- Stubbornness and resistance of people – the human factor: people are afraid of losing their jobs. If new technologies are introduced into their lives too quickly, sooner or later, people might begin to grumble, and then sabotage the work (Epifanceva, 2018; Osipova & Menschikova, 2017);

- Bureaucracy (Epifanceva, 2018);
- Competition with existing technologies – due to conservatism, the transition to new technologies is slow. Old technologies have already shown and proven themselves, and the transition to new ones is often associated with the need for additional resources (personnel training, financial investments) (Epifanceva, 2018; Osipova & Menschikova, 2017);
- Competence of decision-makers (lack of information about new technologies, which interferes with making objective decisions) (Epifanceva, 2018; Osipova & Menschikova, 2017).

The Location of the enterprise could also be mentioned as a factor. If the enterprise is aimed at capturing and selling CO_2 too far from a potential buyer. A logical question arises about the practicality of such a decision. Gas capturing and transfer technologies can be too expensive for an acceptable payback period (Epifanceva, 2018; International Energy Agency, 2021a).

Another reason change is happening so slowly maybe the human factor – people are accustomed to a particular lifestyle and habits and therefore do not want to change. In the case of production, there may be two options – either the production itself offers an opportunity that pre-empts its time or the market is not flexible enough for changes. Even if the manufacturer proposes a new product, the market will not accept it, and the enterprise will suffer significant losses. Technological innovation may be too large-scale (severe or sudden) for the local community. The risks may be so great that society is initially too sceptical about paying attention and / or invest in this technology or development. The third problem in the group of human factors may be the fear caused by little knowledge regarding the technology. Fears that new technologies, built on the basis of old ones, can take away a person's job are often crucial when it comes to adoption and acceptance (Epifanceva, 2018; Osipova & Menschikova, 2017).

When deciding whether or not to implement a technology, it is essential to analyse the barriers and driving factors carefully. One of the simplest methods is performing the SWOT analysis (Strength, Weakness Opportunity, and Threats). SWOT analysis allows assessing all the risks and possibilities of using a particular technology or methodology at different levels – starting with the impact of the innovation on the national level and a more local one (for example, the enterprise level). Evaluation provides an opportunity to assess the feasibility of an innovation, take corrective actions to minimise potential risks and create a chain of stakeholders in the project (Aich & Ghosh, 2016). The comprehensive analysis allows identifying and providing information about external and internal factors that affect the project (or decision) both positively and negatively. With this data, the entrepreneur can determine the best scenario for performing (M. I. Khan, 2018).

To conduct a SWOT analysis, it is necessary to know what Carbon Capture technologies exist. These technologies can be divided into two large groups:

1. Capturing CO_2 and transporting it to places of further disposal (storage sites) or use for the production of new products.
2. Capture of CO_2 and its use in production right away

CO_2 capture technologies are pervasive in the manufacturing and energy sectors. Technologies that have already proven themselves are, for instance, adsorption and membrane systems (Hou et al., 2022) For example, the efficiency of pilot membrane plants can reach 80 % CO_2 (Hou et al., 2022), (Gkotsis et al., 2023), and installations using adsorption allow achieving a purity of the main CO_2 stream up to 95 % and recovery of the flow up to 80 % (Hou et al., 2022), (Karimi et al., 2023). CO_2 capture plants separate CO_2 from the overall production gas stream. Such technologies are usually installed in industries with a high content of CO_2 in the exhaust, for example, at heating stations and large industries (Eliasson et al., 2022).

As CO_2 is captured and removed, it must be transported (if it is impossible to use it in the same production). For long distances, it is preferable to use a pipeline, but it is possible to transport CO_2 by transport. In this case, it is necessary to ensure specific conditions (temperature –20–30 ºC, pressure 1.5–2.5 MPa), which, due to their technical complexity, are not suitable for sizeable CO_2 storage sites (Becattini et al., 2022).

For the analysis of CO_2 emissions, geographic modeling programs are actively used – the so-called Geographic Information System programs (GIS). The Group of GIS programs appeared relatively recently but has already established itself as a helpful program package in planning and resource management. It is possible to store, analyse, and process large data packages even from different and unrelated sources with such a program. The ability to plan problem-solving processes and make predictions in this program makes it possible to put forward quality solutions to problems (Cook & Pétursson, 2025). Due to the program's versatility, analyses can be combined with other methods, such as Multi-Criteria Analysis, AHP or SWOT (Vidya et al., 2024). Such a combination has the best effect on the quality of the analysis performed and justifies the results obtained. There are many disciplines in which a combination of GIS and an analytical program (MCDA, AHP, etc.) could be productively used, like development planning and modelling of urban and natural systems, organisation of traffic flow, etc. (Vidya et al., 2024). For example, a combination of GIS and MCE (Multi-Criteria Evaluation) was used by (Bilal et al., 2025). This combination made it possible to determine the best scenario for the use of water resources at three levels – the level of direct use of the water resource, the water channel – the level of resource accumulation (and its subsequent withdrawal) and the mixed level. In his work, the author claims that the combined use of both analysis methods (GIS and MCE) is a serious, high-quality and reliable way to assess various scenarios for solving complex problems. The combined use of both techniques facilitates the evaluation of multiple options and thereby enhances the decision-making process (Bilal et al., 2025). Mendas et al. also used the possibility of parallel use of various analysis methods to obtain more accurate results (Mendas et al., 2024). The author of this study shared a method for integrating MCDA analysis into the *ArcGis* environment. Nasehi et al. used a combination of SWOT analysis and GIS software in their work to determine the optimal scenario for the development of urbanisation (industrial zones) with the minimum possible impact on the environment (Nasehi et al., 2019). The use of SWOT analysis and cartographic programs allows decision-makers to evaluate the proposed solutions to the problem and to prioritise them. When the choice is made at high levels, this combination will help to ensure the transparency of the solution and its comprehensiveness (Comino & Ferretti, 2016; Treves et al., 2020).

The combination of various analysis methods makes it possible to neutralise the disadvantages of each method separately. For example, SWOT analysis alone helps in identifying the main influencing factors. By combining SWOT with GIS, these factors already acquire the basis and validity.

Thus, the third step of the methodology is completed. It provides insight into the key factors influencing the implementation of CCUS technologies and enables informed and targeted action.

1.4. Public and Business Attitudes Towards CO_2 Utilisation

While the first three steps of the methodology primarily focused on the theoretical aspects (technology analysis, examination of the current situation in the country, and the potential for technology implementation), this step is necessary to determine public opinion – both from citizens and entrepreneurs – who can directly influence the effectiveness of CCUS technology implementation, as climate change affects not only production sectors, but also society. However, society may also be the key to start implementing CO_2 decreasing technologies and to mitigate the amount of CO_2 emissions, as climate change affects every person regardless of the place of residence, social status, and beliefs (IPCC, 2022).

It has been proven that human activity destroys the balance of CO_2 (IPCC, 2022). Even though in Latvia, in comparison with other countries, the amount of CO_2 produced is not so large, even this amount must be taken into account since the consequences caused by CO_2 emissions will affect every inhabitant of the planet (IEA, 2025). Thus, it is essential to begin changes not with enterprises, but earlier – with the public, by understanding their habits and mindset, which form the foundation for all subsequent actions.

CO_2 Utilisation Possibilities

By 2021, 65 commercial CO_2 capture and storage (CCS) installations have been installed worldwide. In 2021, 102 more stations were under construction (Global CCS Institute, 2021a). In turn, 27 installations allow capturing and using CO_2 in the world for 2021. However, another 71 are in varying construction stages, and another 97 have been announced for construction (IEA, 2022a).

CCS is considered as a technology that has the potential to significantly reduce CO_2 emissions both in the manufacturing sector and in the world as a whole. The purpose of these technologies is to prevent CO_2 from being released into the air. Later, this captured CO_2 is transported to certain places intended for long-term storage of CO_2. An alternative to storing gas can also be its utilisation in other industries (Xu et al., 2021).

The principle of operation of the CCS technology can be described as follows – the capture of CO_2, its subsequent purification and liquefaction. The next step is the transportation of liquefied CO_2 to the places of its further storage or use. Usually, special pipes or transport (for example, gas ships) are used for transportation. As for CO_2 storing – for these purposes' geological formations (for example, which previously contained oil or gas) or suitable underwater deposits are usually used (Stokke et al., 2022).

According to the European Commission (IOGP, 2019), both carbon capture and storage (CCS) and carbon capture and utilisation (CCU) technologies have great potential to reduce the amount of CO_2 in the atmosphere significantly. However, it should be borne in mind that one cannot rush and act thoughtlessly in this matter despite the seriousness of the situation. Such behavior can cause significant financial losses (Coll et al., 2021). The installation of CCU units is a large-scale process that requires a substantial investment of both resources and finances. Such technologies indicate that they are sufficiently developed for their more active use. The technologies are also long-term enough to be beneficial in the long run. According to the (Coll et al., 2021), the Zero-Net plan will require significant changes to the economy. Technology development needs, commercialisation, and public acceptance will need to be considered.

It is also necessary to balance two scenarios – which technology to use – CCS or CCU? The choice of technology depends on how effectively a country will be able to reduce emissions in the long term, but it also potentially impacts changes in the quality of life for society. This can raise concerns among people and lead to reluctance in adopting such technologies. On the other hand, a lack of understanding of CCUS may also result in the closure of such projects (Allen et al., 2018; Coll et al., 2021; IOGP, 2019).

Lack of public awareness of the possibilities of using CO_2 is also a problem. Each resident can contribute to reducing the amount of generated emissions. Lifestyle, decisions made in everyday life – all this can leave its mark on ecology. And although studies indicate that climate change is the second most important issue for EU residents (European Union, 2019) (in the case of Latvia, this issue ranks 11th out of 13), in Latvia, residents have shown more concern and responsibility for climate change.

Willingness to Pay

Before introducing any changes in the country's legal system, it is essential to know the public's opinion on these changes (Thomas et al., 2022).

According to (J. Ren et al., 2023; Syed & McLean, 2022), general well-being consists of three main factors – the national economy (production), the environment, and the public. With this in mind, when analysing people's opinions and their desire to promote change, it is worth interviewing the production sector (i.e., manufacturers) and people (i.e., the public). Such an analysis can provide a practical insight into the opinion of residents about the problem of CO_2 emissions and their desire to implement carbon capture/use systems. This is especially important given people's concerns about the environmental risks allegedly associated with such installations (Galiègue & Laude, 2017).

It is believed that the calculation of the cost of installing and maintaining CCS and CCUS technologies is a complex and costly process. The technologies are also expensive due to their relatively low prevalence (Galiègue & Laude, 2017). According to (von Rothkirch & Ejderyan, 2021), the high cost of capture processes and high energy costs are severe barriers to acquiring these installations. Additionally, when evaluating the entire life cycle of a CCS, it is necessary to consider social, natural, and economic aspects – how they change under the influence of CCS. Financial flows are also significant and closely related to these aspects (Hu et al., 2025). The longer CCS remains financially unaffordable to entrepreneurs, the longer it is more profitable to pay carbon emissions quotas than to modernise production and install CCS and/or CCU. The more extended public opinion uncertainty (technology adoption) remains, the longer the government will procrastinate with climate change (Galiègue & Laude, 2017), (Brad et al., 2024), (Standal et al., 2023).

For a more efficient and faster implementation of CCS and CCU systems, it is necessary to consider the public's opinion and whether it is ready to "pay" for environmental improvement.

There are several assessment methods survey and questionnaire in one of the survey's tools. For example, (Seo, 2017) advised stated preferences method – involves asking a person directly how much he evaluates a particular aspect (technology, thing, service, etc.). The purpose of this type of survey is to create a hypothetical market in which respondents make decisions about certain products (Seo, 2017). It can be found out not only the maximum price that a person is willing to pay (willingness to pay) but also whether he agrees to receive compensation for not using the technology (willingness-to-accept compensation) (Halkos et al., 2022; Hofstetter et al., 2021; Xiong & Kong, 2017). This type of study is carried out in cases where there is no connection between the ecosystem and services, or these links are not strong enough to be valued monetarily.

This type of research is based on a questionnaire survey of the target audience. Suggested answers usually represent non-market values, such as quality of life, environment, certain characteristics, etc. These analysis methods are especially useful when it is necessary to determine the impact on non-market goods associated with significant values if these values can be expressed by sampling (O'Mahony, 2021).

The objective of this step in the methodology is to determine the opinion of two groups – the public and entrepreneurs – regarding the issue of CO_2 emissions and their willingness to pay for mitigating the consequences caused by emissions. The results of this analysis may potentially assist in making decisions about the optimal CCUS technology and in preparing the public for the planned activities.

1.5. Role of Legislation in Shaping CO_2 Valorisation Pathways

An equally important task is to assess the feasibility of implementing CCUS technologies from a legislative perspective. It is crucial to determine the extent to which these technologies are addressed in the country's laws and what exactly is stated in the legal framework. Additionally, it is important to analyse the legislation of other countries – since Latvia is a member of the European Union, it is likely that if something is not currently addressed in the legislation, it will be in the future. This could either stimulate the adoption of CCUS technologies or create challenges.

CO_2 Utilisation / Valorisation Concept

According to the European Parliament and the Council (European Commission, 2021b), it is necessary to expand the scope of technologies to capture and subsequently store CO_2 (either in special storage facilities or in ecosystems).

The European Union actively supports the development and launch of CCU (Carbon Capture and Utilisation) and CCS technologies. Horizon Europe has also been actively calling for integrating carbon capture and/or use systems (CCUS) into industrial centres. This would help significantly reduce the amount of carbon emissions created and, in the long term, reduce the cost of CO_2 capture. In the future, the captured CO_2 could be used to produce carbon-negative biofuels (European Commission, 2021h). To determine the possibility of capturing CO_2, it is necessary to analyse the existing legislation of both the European Union and Latvia.

CO_2 Utilisation in Products – CCS / CCU Technologies

Innovative installations for capturing and using CO_2 are actively discussed at the national and European levels and global levels. When talking about such technologies, the European Commission group asks two critical questions:

- How do we make CCS and CCUS plants efficient but, at the same time, environmentally friendly enough? What are the actual climate benefits of these technologies?
- How to consider climate mitigation of CO_2 in complex products – chemical compounds, fuels, etc. Since CO_2 will remain bound in the product for a different period and then be released into the atmosphere (European Commission, 2020).

Given that captured carbon can be further utilised for the production of chemicals and fuels, questions regarding the environmental sustainability – and, equally importantly, the cost-effectiveness – of such technologies are frequently raised. Ongoing studies around the world are assessing the long-term benefits of both CCS and CCUS installations (Hong, 2022; Leeson et al., 2017; Mikhelkis & Govindarajan, 2020; Shogenova et al., 2021).

Undoubtedly, the environmental impact of such installations remains a broad and widely debated topic. Given that these facilities enable the utilisation of CO_2 that would otherwise be released into the atmosphere – and in some cases allow for its direct removal from the air – CCUS plants offer significant long-term environmental benefits.

Currently, it is CCS installations that can effectively work with large enterprises. This technology can be upgraded to BECCS – Bioenergy Carbon Capture and Storage, and then CCS can generate so-called "negative emissions" by using CO_2 from the atmosphere. Innovative methods could help complete the Paris Agreement (Slade et al., 2022).

According to the International Energy Agency, to achieve these goals, it is necessary to increase the capacity of such installations tenfold (International Energy Agency, 2017). According to the Global CCS Institute, to achieve this goal, at least 2.5 thousand more CO_2 capture units with a capture efficiency of up to 1.5 million tons of CO_2 per year must be installed worldwide by 2040 (Global CCS Institute, 2018). At the end of 2020, CCS units were capturing 73 million tons per year, while by the end of 2021, productivity increased to 111 million tons per year (Global CCS Institute, 2021b). Even though CCS does not directly use CO_2 but only allows it to be placed in storage (rather than emitted into the atmosphere), according to (International Energy Agency, 2021b), net-zero emissions cannot be achieved without such technologies.

Analysing the CCS and CCUS installations, it can be concluded that both technologies are still quite expensive due to their high energy consumption (Ghiat et al., 2025; Tariq et al., 2025; Xie et al., 2025). Production with CCS installed uses much more energy than production without it to extract, for example, oil (Rissman & Orvis, 2017). According to the statements of (Global CCS Institute, 2021b), the cost of installing a CCS depends on many factors – the scope of production, the type and quality of the resource, the extraction of CO_2 immediately from the stream, or whether it needs to be isolated from concentrated stream gas, etc. However, as technology advances, the price of such plants is falling, and plants are becoming more and more the subject of discussions about cheap methods of decarbonisation (Parliamentary Advisory Group on CCS, 2016).

Currently, the situation with CO_2 utilisation in production in the European Union cannot be called even. In some countries, technologies allow the use of CO_2 now, while in others, the economic and technological base requires additional investments. It is needed to attract extra political leverage and possible funding (Group of Chief Scientific Advisors, 2018).

Thus, the analysis of existing legislation provides the opportunity to determine the accessibility of CCUS technologies and how effectively the developed legislation supports their implementation.

1.6. Policy Support of CCUS Technologies Introduction

This step complements the previous one and helps to understand legislative trends at the European Union level. It gives theoretical basis to the analysis (presented in Section 2.6) of legislative support of CCUS technologies in the European Union and number of on CCUS technologies aimed legislative documents.

The European Union's (EU) target of achieving climate neutrality and reducing GHG emissions by 2050 require all Member States to weight their emissions and the potential to reduce these emissions. EU countries could achieve the EU's goals and climate settings by enabling both the private sector and the scientific community to make technological advances in carbon capture and utilisation. However, for this to be possible, the legislator would need to develop a clear strategic and regulatory framework for using CCU technology.

The European Commission stated in its report of 15 December 2021 that "in 2018, the EU economy consumed around one billion tonnes of biogenic (45 %) and fossil (54 %) carbon and only a tiny proportion of the carbon currently used is recycled carbon (1 %)" (European Commission, 2021c). The EU is in demand for carbon in its various production processes. In the same document, the European Commission also sets a target of 300 to 500 Mt CO_2 utilised by 2050.

Although, measures to reduce the amount of CO_2 are being taken – new regulations and laws are being adopted. The European Union has reduced its GHG emissions, so it only makes sense to review the EU's common policy, which has led Member States to reduce GHG emissions by up to 24 % since 1990 (Fig. 6) (Lyons et al., 2021).

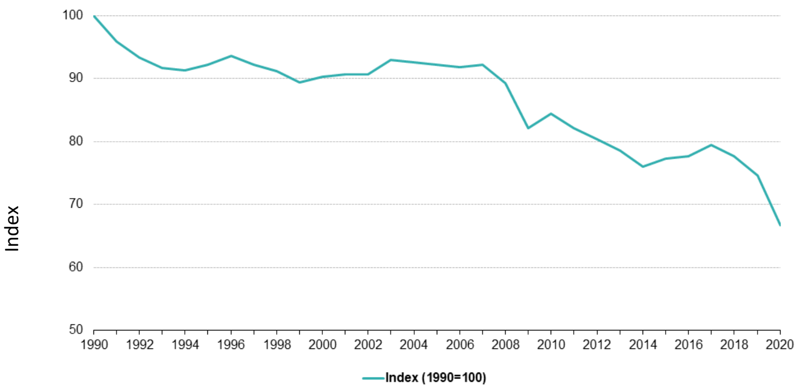


Fig. 6. Total GHG emissions in the European Union, excluding land use, land use change and forestry, but including international aviation (Lyons et al., 2021).

According to (IEA, 2025; NASA, 2021), the amount of emissions only from the combustion of fossil fuels (oil, coal) is growing every year. A slight drop in 2020–2021 was due to stagnation due to COVID-19, but this reduction is expected to be reversed in the coming years (Fig. 7).

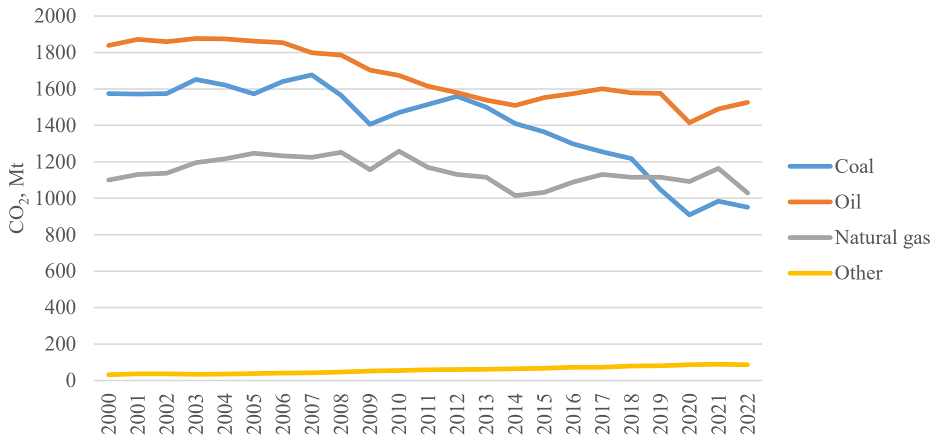


Fig. 7. Annual CO_2 emissions in the world from fossil fuel (excluding land-use)(IEA, 2025).

As stated by (European Environmental Agency, 2021), the amount of emissions should be reduced – activities aimed at modernising several sectors (manufacturing, transport, energy, etc.) should start now and be implemented as soon as possible. Emissions reduction is a global measure. Each country will have to do its part to achieve the result; otherwise, the consequences will affect everyone. The basis of the changes in each country's legislative framework is a well-developed system of laws that allows the country to move towards a more environmentally friendly development.

Despite the potential benefits of CO_2 valorisation, there currently needs to be more policy instruments in place to support its development and implementation. This is partly due to the fact that CO_2 valorisation technologies are still in the early stages of development and commercialisation, and there needs to be more awareness and understanding of the potential benefits of these technologies. Therefore, policy instruments that can incentivise the development and adoption of CO_2 valorisation technologies are crucially needed. Such instruments can include carbon pricing mechanisms, tax incentives, and research and development funding. These policy instruments can play a critical role in accelerating the development and deployment of CO_2 valorisation technologies while also contributing to achieving climate change goals and sustainable development objectives. The research of the CCS4CEE project also points to the need for more elaboration of policies regarding carbon capture and storage (CCS) technologies. If national strategies (i.e. NECP and Long-Term Support) concern such technologies, then only superficially. However, regarding the role of CCS, policies should be clear and consistent and allow regional collaboration in this area (Fabiszewska-Solares & Laskowski, 2022). As (Hruby et al., 2022) indicates, in Central and Eastern Europe, fiscal and public finance policies are only available for the CCS pilot projects. The lack of financial support and favourable conditions for maintaining CCS projects is a crucial drawback for such high-class technologies. The absence of sufficient supportive policies is also indicated by (Cordova et al., 2022), (Fuss & Johnsson, 2021), (Lefvert et al., 2022). Nonetheless, according to the IRENA report (Lyons et al., 2021), carbon capture technologies are essential, especially in sectors with high CO_2 emissions that are otherwise very difficult to reduce (Fig. 8).

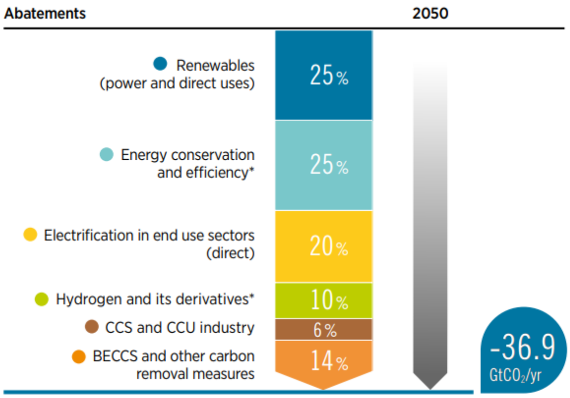


Fig. 8. Carbon emissions abatements, IRENA report (Lyons et al., 2021).

However, for the countries of Europe to achieve energy and climate targets, national governments should reconsider the role of CCS and include it in national strategies.

Thus, the objective of this step in the methodology is to is to analyse the legislative framework of the European Union countries and determine their elaboration regarding the fight against CO_2 emissions. Even though the European Union Regulation 2021/1119 (European Commission, 2021j) indicates countries to the need to reduce CO_2 emissions, the document does not define technologies and ways in which these reductions could be achieved. Each country has the right to determine which technologies and/or measures to use to complete the task. In this regard, in the section 2.6. regarding policy framework, particular attention is paid to legislation system aimed at innovative technologies that capture carbon and either put it in underground storage or use it in producing a new product (CCU), thereby using the principles of the circular economy, as since the awareness and availability of this information can contribute to the promotion of similar technologies in other countries.

1.7. The Significance of GHG Inventories in Biomass Utilisation and Energy Planning

CO_2 emissions can be reduced in various ways – by utilising CCS and CCU technologies to capture already generated emissions and either store them or use them in the production of other products. Emissions can also be reduced by modernising production and/or transitioning to the manufacture of a different product whose production generates fewer emissions, thus avoiding CO_2. Another method involves using what is considered waste in the production of a new product. In this way, the CO_2 contained in the waste is not released into the atmosphere during waste processing, but rather, it is incorporated into the new product (i.e., stored CO_2).

This step of the methodology specifically examines the possibility of reducing CO_2 emissions in the forestry sector through their storage in a new product.

Forestry, like other production sectors, is also responsible for a portion of CO_2 emissions. However, increasing demand of wooden products are making a challenge to improve the sector in such a way, so it is more ecological, sustainable and creates less waste and CO_2 emissions. On the other hand, wooden products may be a solution for CO_2 decrease, as wood, as material, may be considered as carbon capturing material (Muizniece & Blumberga, 2018), (Tripathi et al., 2019), (Kazulis et al., 2017), (Raunkjaer Stubdrup et al., 2016), (Veitmans & Grinfelds, 2016).

Forestry practices produce large amounts of waste and residues from the harvestable yield. This can present significant management problems, as the discarded biomass can hurt the environment. Meanwhile, sustainable energy sources and raw material feedstocks are required with increasing global urbanisation and rising demand for construction products and materials. Forestry waste and logging residues are under-utilised resources for energy and material production. To date, there has been little activity to utilise these resources in a "low carbon" way. It is estimated that for every 1 m^3 of logged wood material removed, 1 m^3 of wastes and residues (e.g., stumps, branches, greenery) is left in the forest. Currently, of all wood-derived biomass produced globally, 20 % can be accounted as primary production loss left in the woods to decay, which could instead be used as a feedstock for a variety of products, including the production of fuels, polymers and building materials and products (Tripathi et al., 2019).

Wood, like products made from it, has a significant advantage over other building materials – they are an essential source of CO_2 sequestration. It has been observed that there exists a direct correlation between the amount of CO_2 sequestered and the amount of wood-derived biomass harvested to produce high-added value products – with increasing amounts of wood harvested or rising efficiency of timber used, the amount of carbon sequestration is also increased (Muizniece & Blumberga, 2018). The overall decarbonisation solutions can be achieved if sustainable carbon cycles, including using Carbon Capture and Utilisation technologies, are implemented (Fig. 9) (Kazulis et al., 2017; Raunkjaer Stubdrup et al., 2016; Veitmans & Grinfelds, 2016).

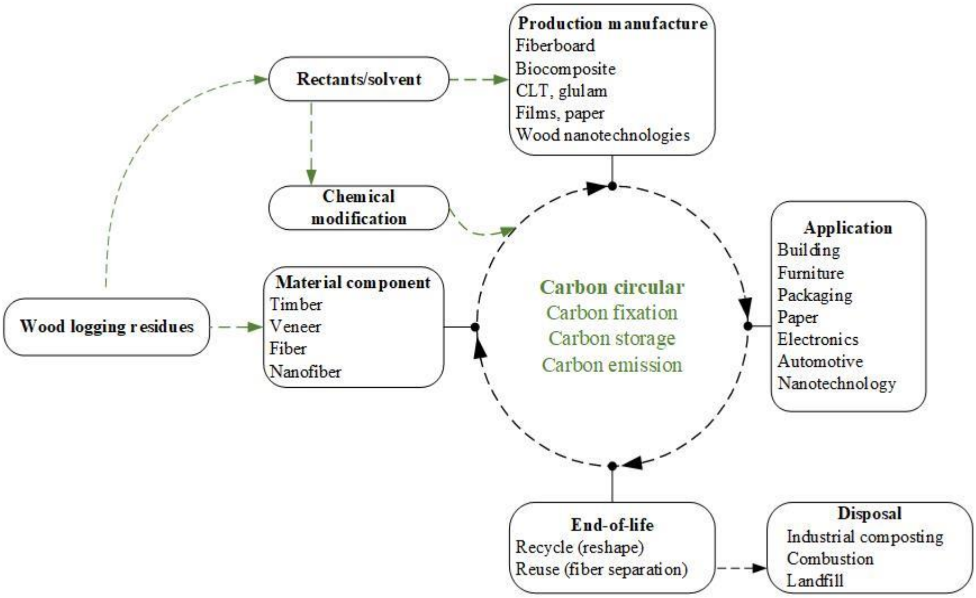


Fig. 9. The sustainable carbon cycle of wood logging residues (Tripathi et al., 2019).

In the wood-based product sector, significant potential for CO_2 sequestration can be attributed to the production of wood-based panels and engineered wood products (FAO et al., 2020). In a 2017 study about carbon storage in wood products, the carbon sequestration potential of three different wood-based panels was reviewed – oriented strand board (OSB), particleboard (PB) and medium density fiberboard (MDF). According to the IPCC methodology, all three of these products are included in the national inventory reports as harvested wood products that store carbon, thus decreasing the overall CO_2 balance in the atmosphere. It was calculated that 1 m^3 of PB and OSB sequester 720 kg of CO_2 each and that a cubic meter of MDF sequesters 820 kg of CO_2, considering the amount of emissions from material production (Dieffenbacher Gmbh, 2023).

However, despite this advantage, producing such panels is quite an energy-intensive process. The Best Available Techniques (BAT) Reference Document to produce Wood-based Panels states that the average amount of thermal energy required to produce 1 m^3 of the material is 0.955 MWh for PB, 0.4 MWh for OSB and 1.65 MWh for MDF panels. The average amount of electrical energy required to produce 1 m^3 of the material is 0.155 MWh for PB, 0.115 MWh for OSB and 0.505 MWh for MDF panels (Tellnes et al., 2017). In turn, producing such thermal insulation materials as Ecowool and mineral wool requires 0.00416 MWh and 0.200 MWh of electricity per cubic meter of product. The use of rigid board insulation material can be an alternative to these wood-based panels as their production process requires fewer energy resources.

Although the CO_2 sequestration benefits of the rigid board insulation material will be lower than that of OSB, PB and MDF panels, considering the lower density of wood in the material, it will require less energy and raw materials to manufacture can be regarded as a high added value product. There is a wide range of insulation materials available today, each with its advantages and disadvantages. However, modern consumers care not only about the physical and mechanical properties of the material but also about the environmental impact. Manufacturing insulation materials could become one of the future challenges of the forestry industry of Latvia. Generating by-products and residues in the harvesting and manufacturing processes is inevitable. Currently, forestry companies mainly use these by-products to produce energy or sell them to other companies. Exporting these by-products is still inefficient since they are now sold as low-added value products. As companies in the forestry sector move to increase the efficiency and productivity of their production, the utilisation of wastes and residues previously considered low value is becoming an increasingly attractive option. Using these by-products to manufacture thermal insulation is one of the potential solutions for increasing their value (Trobiani Di Canto et al., 2023).

This analysis not only explores the potential for CO_2 storage in the forestry sector but also provides an opportunity to assess the potential for the industry's development in the direction of CCUS, which could potentially have a positive impact on the social and technological development of regions.

1.8. Motivation for Transition to Biomethane Production

Another method of reducing CO_2 emissions, as mentioned in the previous section, is altering the final product to one whose production generates fewer emissions. This step of the methodology is a continuation of the previous one and examines the practical application of CCUS technology – such as in the production of renewable fuels.

Biomethane is a renewable gas that can be obtained from biogas purification (depending on the system, biogas can contain ~50–60 % methane (CH_4), which is classified as low-grade biogas), the remaining 40–50 % are products in the form of CO_2 (Abd et al., 2023; Ayub et al., 2022; IEA Bioenergy, 2020). The purification process involves the removal of CO_2, leaving pure methane. The resulting CO_2 is of sufficient purity to be sold or redirected to other industries (e.g., greenhouses, pharmacy, etc.), thus promoting CCU technologies. At the same time, increasing the CH_4 content in the mixture raises the calorific value of the gas, making fuel much more valuable. The leading technology for CO_2 removal is Pressure Swing Adsorption (PSA), which working principle is based on adsorption differences of components and reagents (Abd et al., 2023; Meng et al., 2022). Biomethane has characteristics similar to fossil natural gas, making it a potential substitute for this fuel. An additional plus is the ability to use the same equipment and infrastructure, as well as the "compatibility" of these two gases – they can be safely mixed (D'Adamo et al., 2023; Fubara et al., 2018; Ghiat et al., 2021; Luo et al., 2023).

Latvia already has everything necessary for the development and further production of biomethane. The first biogas stations appeared in the country in the 1990s, and their main resource is biomass and agricultural waste. As of 2019, 53 biogas production stations were registered in the country; however, several stations were closed due to several financial and political decisions (Latvijas Gaze, 2022a).

Advantages of Biomethane

Even though, at the moment, natural gas occupies up to a quarter of the world energy resource market (International Gas Union, 2021), it has the lowest carbon footprint. The importance and necessity of other low-carbon gases are also increasingly recognised. Such gases can be biomethane produced in anaerobic processes, syngas, and even low-carbon hydrogen. The current production rate and the prices for the mentioned types of gas show the importance of their production in the future. Although the benefits of biomethane production often come down to financial considerations, it is essential to remember that biomethane production is also beneficial from an environmental and sustainability point of view, as the carbon footprint that is left behind the biomethane is much lower than it is for more conventional types of fuel (D'Adamo et al., 2023; Keogh et al., 2022; Shirizadeh & Quirion, 2022).

Biogas and biomethane are both renewable gases that have the potential to help reduce GHG. Using biomethane in a network created for natural gas and its subsequent replacement does not require additional financial investments or the development of new and / or other infrastructure. The existing gas transport network in Latvia can already be used for biomethane. This fact is a critical condition in the fight against the reduction of emissions and decarbonisation of the gas sector, which, in addition, can provide an affordable price for the consumer and bring diversification into the energy sector. Another advantage of biomethane is that it can be stored and produced permanently and constantly. This fact will balance intermittent energy from other renewable energy sources, such as windmills (Hamelin et al., 2021; Latvijas Gaze, 2022b; Richards & Al Zaili, 2020; Sangannavar et al., 2022). Reducing anthropogenic emissions is a complex task; therefore, every decision to reduce our impact on the climate is significant and tangible in the long term (Esposito et al., 2019).

This analysis in the methodology will allow for the determination of the potential amount of avoided CO_2 emissions.

1.9. Sustainability Perspective through Life Cycle Assessments

The final step in the methodology is the analysis of the impact of CCUS technologies on both society and the environment. This includes evaluating potential social and ecological outcomes, assessing public perception, and identifying both the benefits and challenges these technologies may present in the long term.

As Tam et al. (Tam et al., 2023) pointed out, technical solutions alone are not sufficient. Any proposed solution and its alternatives must be thoroughly analysed. The more aspects and criteria considered, the more accurate and comprehensive the assessment. A life cycle analysis of a product or process provides valuable insights into the environmental effects of planned activities. LCA is a key tool for addressing the challenges of increasing carbon emissions and evaluating their potential for further utilisation.

Environmental Life Cycle Assessment (E-LCA), one of the pillars of the LCA, assesses the potential environmental impact of a product or process. It takes into account resource use (including extraction and processing), energy consumption, and the use of natural materials such as water, soil, and air across all stages of the product lifecycle (Life Cycle Initiative, 2023).

Social Life Cycle Assessment, a complementary method to LCA, focuses on the social aspect – examining how actions impact the public and workers. Companies and organisations can use S-LCA to identify opportunities to reduce their carbon footprint while adopting more socially responsible practices. From a social perspective, S-LCA evaluates the effects on local communities and promotes equitable sustainability efforts. Integrating S-LCA into decision-making allows for a more holistic approach to addressing carbon emissions and building a sustainable future (Zarauz et al., 2025). As noted by Larsen et al. (Larsen et al., 2022), S-LCA can be a critical tool for highlighting the materials and product manufacturing phase, which often has a particularly significant impact on human health.

The European Green Deal and the EU's path to climate neutrality by 2050 encourage member states, including Latvia, to pursue innovative solutions, which includes also CCUS technology implementation.

The source and composition of CO_2 emissions in Latvia highlight the energy production sector as the primary area for the application of CCU technologies. The largest emitter of CO_2 is heat production plants, which in 2022 produced 24.2 % of total CO_2eq emissions in Energy sector (Skrebele et al., 2024) (Fig. 10). Energy sector can become an optimum solution for CCUS technologies, as it can offer both CO_2 production and CO_2 utilisation.

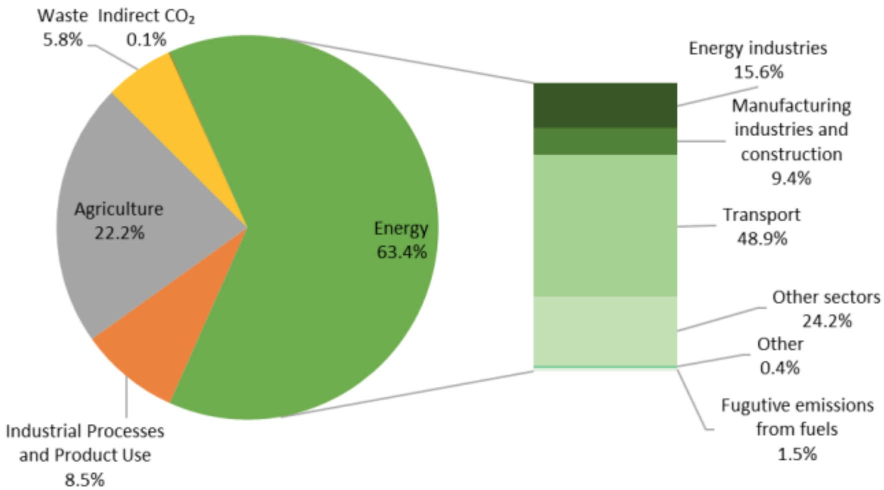


Fig. 10. CO_2 emissions in Latvia, 2022 (Skrebele et al., 2024).

Since a relatively large portion of emissions originates not in cities but in rural areas, the energy sector could serve as a driving force for the implementation of CCUS technologies in these regions, thereby stimulating not only the reduction of emissions but also the technological, economic, and social development of local areas (Calvillo et al., 2025; B. Lee et al., 2025; WANG et al., 2025). In this context two scenarios for CO_2 utilisation are being analysed: its use in methanol and ethanol production. The goal is to assess the potential environmental and social impacts of these scenarios. By evaluating both environmental and social factors, the analysis aims to identify potential sustainability issues and contribute to the development of more responsible, future-proof technologies.

The European Union Joint Research Centre report on CCUS (ITUL et al., 2023) emphasises the need to establish new pathways for CO_2 valorisation and the creation of carbon-based materials. It highlights promising advancements in photoelectrochemical conversion of CO_2 into selective gaseous products (such as methane) and liquid fuels (such as methanol and ethanol). The report also stresses the importance of conducting LCA of CCUS options to evaluate their overall impacts.

Based on the conclusions of the literature review, this research evaluates the sustainability aspects of two CO_2 utilisation scenarios – methanol and sustainable aviation fuel (SAF) ethanol production – in the context of Latvia. The sustainability assessment addresses potential environmental impacts of CO_2 use, its effect on human health, labour rights, working conditions, social equity, economic viability, and other key social and economic factors.

Life cycle analysis is the final step in the proposed CO_2 utilisation methodology and provides a comprehensive view of the examined scenarios in terms of their impact on society and the environment.

2. 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 Carbon Capture, Utilisation, and Storage (CCUS) technologies. Based on the theoretical framework established in Chapter 1, this chapter observes various tools to asses CO_2 valorisation scenarios. These tools include KPIs, MCDA, SWOT analysis, Geographical Information System (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 optimal route for CCUS technology implementation.

2.1. Approach to Evaluating Key Performance Indicators

The first step in the methodology, as outlined in Section 1.1, 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.

For completing the task, a combination of methodologies was used during the research on the possibility of CO_2 valorisation: literature review, HORIZON2020 data analysis (H2020) (European Comission, 2021)Key performance indicators analysis and Multi-Criteria Decision 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 and their requirements for the use of CO_2 in various production areas, for example, the chemical industry, food, construction, energy production, etc. These parameters allow the creation of the KPI table – a table in which the most important factors for CO_2 utilisation are collected. Next step after H2020 project analysis is to select main CO_2 utilisation scenarios (based on the number of available KPI for comprehensive scenario analysis). Quantitative data obtained from these projects serve as benchmarks in the KPI table.

Based on the acquired KPI, Multi-Criteria Decision Analysis was carried out, the purpose of which is to determine the optimal area of CO_2 valorisation, which would be applicable in Latvia. An algorithm of the analyses applied in this research is depicted in Fig. 11.

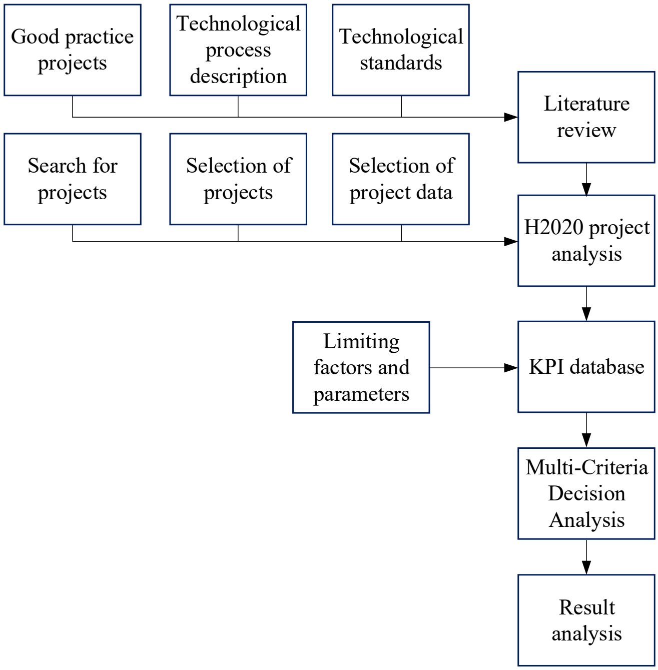


Fig. 11. Methodological scheme.

Key Performance Indicators

Key Performance Indicators are known to be an efficient way to compare various solutions and technologies in a definite area. They can be slightly changed depending on the field of the observed production (Lo Cascio et al., 2018).

The KPIs are based on parameters that are generally known at the production stage and are aimed at quantifying such parameters as energy consumption and potential savings, economic benefits from the introduction of a particular technology, the impact of production on the environment, etc. used in various production areas. Performance indicators may be specific to a production area or can be common to various areas (Lo Cascio et al., 2018).

One of the tasks in this part of work was to create a KPI table. During the analysis of literature, technical reports and descriptions, as well as H2020 projects, a KPI table was compiled, consisting 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.

Analysing the H2020 program, out of more than 32,000 projects, it was possible to sort out 242 projects in which CO_2 is planned to be used for the manufacturing of new products. Of the already made sample, only 30 projects had enough data for further work – filling in the created table of Key Performance Indicators (the process of project processing for indicator development is shown in Fig. 12).

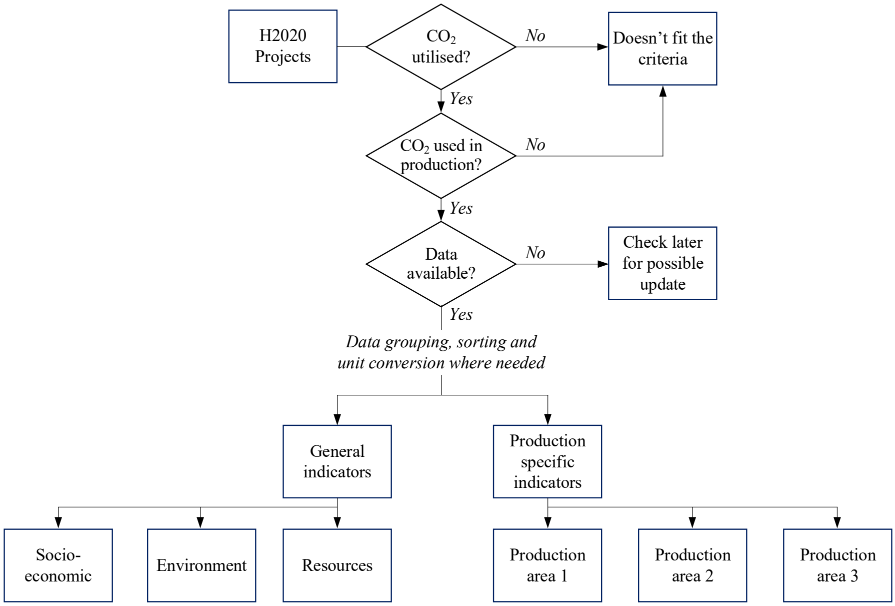


Fig. 12. Algorithm of H2020 project processing and KPI database compiling.

Unfortunately, at this stage, the amount of information available does not allow assigning a value to each created indicator. Summarising all the information and data obtained, only 4 potential directions of CO_2 use can be identified and only 5 indicators can be used for further multi-criteria decision analysis.

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. The table includes general indicators that can be applied in any area and production specific indicators, which, in turn, relate to a specific area of production. Where possible, indicators include CO_2. For example, the main indicators are such indicators as electricity consumption per ton of product produced / ton of CO_2 produced (MWh/t and MWh/tCO_2), the amount of CO_2 required to produce a ton of product and the amount of CO_2 created during the production of a ton of the final product (tCO_2 utilised/t product, tCO_2 generated/t product), as well as the ratio of required and generated CO_2 (tCO_2 utilised/tCO_2 generated), etc.

Multi-Criteria Analysis

Multi-Criteria Analysis was carried out to analyse the degree of importance of each CO_2 valorisation option (methanol production, cement production, algae ponds / greenhouses, food and beverage production). Choosing the right analysis method, TOPSIS was chosen as the most appropriate (Pacheco et al., 2021), (Chauvy et al., 2020).

To analyse the options for using CO_2, several criteria have been used:

- Amount of permitted additive in 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 existing process.

The criteria and their values were selected based on the available data from H2020.

All indicator values that have been used in the analysis are shown in Table 2.

Table 2.

Key Performance Indicators used in MCDA

	Methanol Production	**Cement Production**	**Food and Beverages**	**Algae ponds and Greenhouses****
Permitted additive amount in flow, %	5	10	1.2	30
Electricity consumption, MWh/t	0.0559	0.819	0.01	0.025
Amount of CO_2 utilised, tCO_2/t	1.4	0.06	1.8	2
Amount of CO_2 produced, tCO_2/t	4	0.4005	0.5	0.257
Simplicity of implementing the technology*	5	5	3	2

*Indicator was measured on a scale 1 to 5, where 1 – simple and 5 – difficult, based on the literature review and H2020 project descriptions.

** Average value

2.2. 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 identification of priority zones for CCUS deployment and assessing regional emission data, possible proximity to industrial clusters.

To perform the analysis, the following steps were completed:

1. The analysis of literature sources was carried out in order 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. Using state databases State Environmental Service and Ministry of Environmental Protection and Regional Development, a database of Latvian A and B category companies emitting CO_2 has been compiled (VVD, 2022), (State Environmental Service, 2020), (Ministry of Environmental Protection and Regional Development Republic of Latvia, 2020). The base includes data such as the name of the enterprise, its location (address and coordinates), the category of the permit for polluting activity (A or B), the type of activity and the amount of emissions produced. This analysis did not consider category C enterprises. In the group of enterprises with a permit A there were the largest producers of the industrial sector (e.g. Schwenk), the energy sector (e.g. Rīgas Siltums) and landfills. The group of companies with a category B permit includes enterprises of various sectors – food and beverage, industrial, energy, chemical and refining. With regard to the energy sector, this analysis did not differentiate between types of heating systems (centralised or decentralised). Where available, data on CO_2 emissions were obtained from companies' annual reports.
3. Unfortunately, the mentioned government agencies did not always contain the necessary data on the amount of CO_2 emitted, or the data were outdated. Because of this, the missing emission data were taken from the Latvian Centre for Environment, Geology and Meteorology portal (LVGMC, 2020). In this part of work, there is no separation in the source of the produced CO_2 – either it was the result of the heating of 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. Having filled in the table with all the necessary data, the points of both the production of CO_2 and its potential use were marked on the maps of Latvia in the *ArcGis* programme.

2.3. Framework for SWOT Analysis of CO_2 Utilisation

The next step in the methodology is an analysis of Strengths, Weaknesses, Opportunities and Threats (SWOT) aimed at determining the possibility of capturing and/or utilisation of CO_2, potential internal and external factors that may affect CO_2 valorisation within the territory of Latvia. As a qualitative tool, SWOT enables the synthesis of policy, market, and technological insights that may not be captured through purely quantitative means. For a more comprehensive analysis, data from Section 2.2 have also been used. The use of SWOT analysis in combination with cartographic programs, allows decision-makers to evaluate the proposed solutions to the problem and 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 (Treves et al., 2020). The algorithm of the performed research is depicted in Fig. 13.

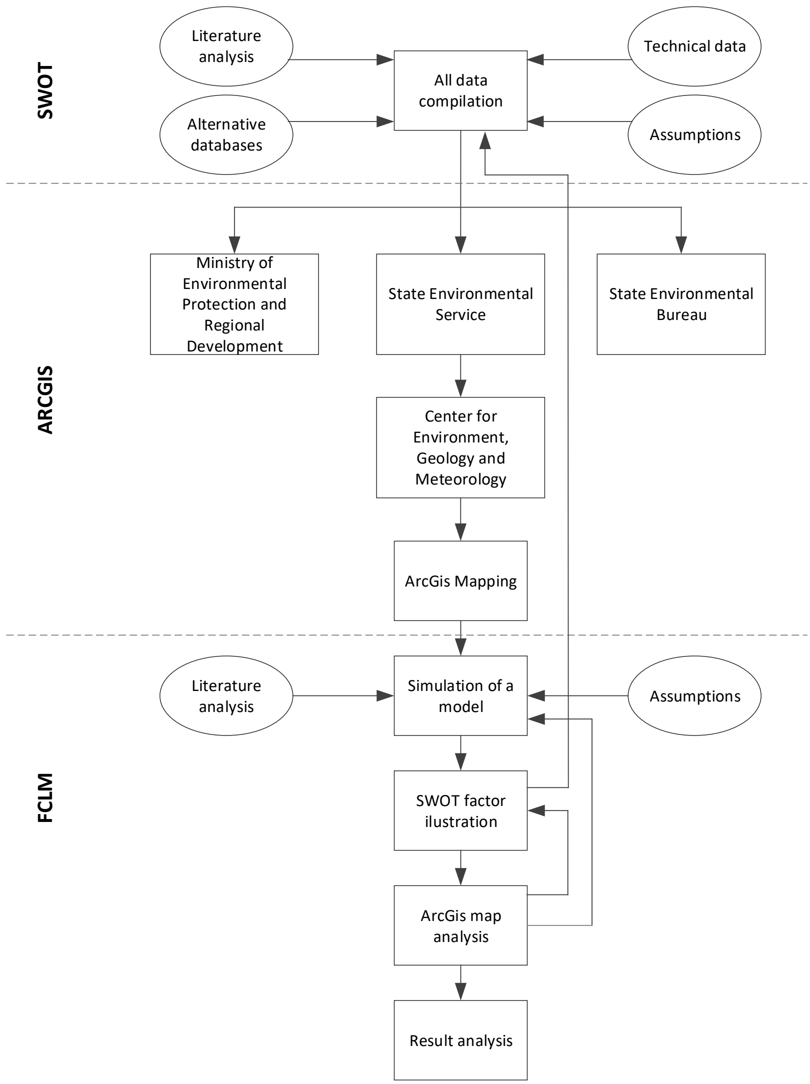


Fig. 13. The algorithm of the performed work.

SWOT Analysis

The purpose of a SWOT analysis is to identify key factors, both external and internal, that may influence the process or task under consideration. The analysis groups these factors into four groups and two categories (Allah et al., 2024; Fernandez et al., 2024; Sinha & Chaturvedi, 2019):

— Internal factors – strengths and weaknesses of the problem under consideration
— External factors – opportunities and threats that can be caused from outside

SWOT analysis is used to identify opportunities and threats nationwide and strengths and weaknesses within the enterprise. To ensure a qualitative analysis, this study used the opinion of all stakeholders who received a permit for polluting activities of category A (48 enterprises) and B (610 enterprises). Subsequently, all these enterprises were marked on *ArcGis* maps.

Following CO_2 valorisation options have been observed: a) CO_2 capture and utilisation in Europe; b) CO_2 capture and utilisation in the case of Latvia; c) CO_2 capture directly at the place of production, processing and transportation / reusing.

Combination of *ArcGis* Maps and SWOT

One of the factors influencing the decision to implement the use / transportation of CO_2 is the distance from the manufacturer to the buyer. Geographical analysis can indicate whether the distance within one country is an obstacle to CO_2 valorisation. This could also potentially define so-called CO_2 production and use clusters based on specific criteria (e.g. required CO_2 purity and/or volume).

Fuzzy Logic Cognitive Mapping

Fuzzy Logic Cognitive Mapping (FLCM) can be used as an effective decision-making tool in a complex of risk assessment analysis and management. Tools like it can save much time, especially when analysing complex systems of interdependent factors is needed. FLCM tools make it possible to analyse and simulate the possible scenarios of the proposed decision and its development and visualise it (Bakhtavar et al., 2020). By identifying key factors or analysing the likely future of scenarios, it is possible to see its weak points at the beginning of project development and make the necessary decisions and corrections in advance. Identifying key factors and their relationships is the main aspect of this analysis. This allows to explore possible scenarios and helps collect the necessary information already at the decision-making stage (Bakhtavar et al., 2020; Barbrook-Johnson & Penn, 2022; Borisov et al., 2019).

The FCLM has proven to be an excellent tool for analysis. Many factors do not have formulated quantitative and / or qualitative data, as well as for discussions, negotiations and finding consensus among many parties (Borisov et al., 2019). FCLM models are beneficial when modelling complex systems and systems with a large amount of factors influencing decision making (Ketipi et al., 2020; Poczeta et al., 2020).

Based on the performed literature analysis, results of the SWOT, *ArcGis* maps, as well as interviews with experts, an FCLM analysis was carried out using a free-access program *Mental Modeler* (Modeler, 2024). This step of the CO_2 valorisation methodology allows identification of the factors that have the greatest impact on the implementation and/or utilisation of CCUS technologies. Factors of a political nature and public were considered. Using the factors specified in the SWOT analysis, the *ArcGis* results and performed literature analysis, flows affecting the new technology introduction have been depicted.

2.4. Survey Design and Stakeholder Engagement Methods

This step of the methodology presents the design and distribution of survey aimed at understanding perceptions, awareness, and acceptance of CO_2 valorisation among the general public and entrepreneurs. This method provides a crucial social aspect to the otherwise technical assessment.

According to the literature analysis, conducting a survey is a great way to get the opinion of a large number of people (Knight et al., 2024; Stantcheva, 2023; Suzuki et al., 2022). A survey can be made in various areas. Still, the goal is often similar – to find out the opinion of a person or a group of people on a particular topic (Y. Zhang et al., 2021). The method is suitable because it is cheap, fast, and accurate to collect the correct information (Stantcheva, 2023). An additional advantage of this method is its versatility – the survey can be conducted both face-to-face and remotely – by phone or via the Internet. As part of this work, the survey was conducted electronically, as there were still several restrictions due to COVID-19 that prevented the face-to-face survey of respondents.

The main instrument of the survey is a questionnaire. Its quality is the main factor. The success and accuracy of the study depend on its structure, the formulation of questions, and the correctness of the chosen audience (Stantcheva, 2023). In this part of work, the study was carried out according to the following algorithm (Fig. 14):

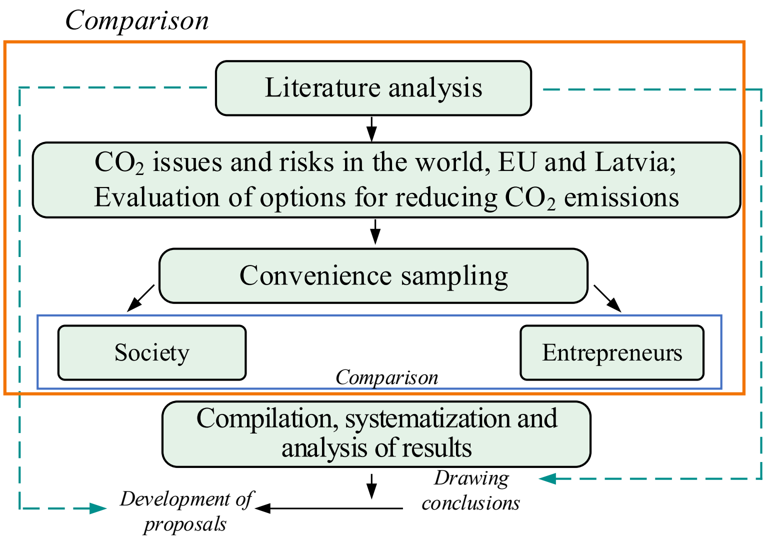


Fig. 14. Algorithm of the survey.

Literature analysis and identification of the main factors influencing the implementation of CCS and CCUS units form the basis of the work. Without this information, it is impossible to formulate accurate questions for the respondents qualitatively. 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.

To determine people's opinions on CO_2 emissions, convenience sampling was conducted. This type of selection is chosen, when more random selection is not feasible, possible or practical to do (K. A. Sirwan, 2024). Convenience sampling is chosen, as it gives insight of the young people (in case of society's survey) and entrepreneurs of specific area (in case of entrepreneurs' survey) opinion about the problem studied. The public survey was carried out electronically and anonymously among university staff and students. The public was asked to answer 9 questions (in addition to the main ones about age, education received and profession currently occupied). All questions were closed-ended. Using a questionnaire, 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 survey of entrepreneurs was conducted anonymously and electronically. Enterprises were selected based on the State Environmental Service databases, depending on their field of activity (agriculture, manufacturing, boiler houses, forestry). The questionnaire for entrepreneurs consisted of 5 questions (in addition to the main questions about the scope of the enterprise, its "age" and the degree of importance of the issue of CO_2 emissions for their particular 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 (for example, too high energy bills, favourable conditions for obtaining subsidies for upgrades, etc.). Questions 2 and 3 were open-ended and entrepreneurs were asked to indicate the motives/reasons for reducing the amount of CO_2 emissions in their enterprise, as well as measures that could motivate them to change. Also, entrepreneurs were asked to indicate what part of their income they are ready to give to combat CO_2 emissions.

The information obtained makes it possible to judge the public's opinion about the problem objectively.

2.5. Legal Review Method for National and International CO_2 Policies

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 step consists of descriptive and systematic literature analysis of both international and national legal law regarding the issue of CO_2 emissions. The research 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 questions (see Fig. 15).

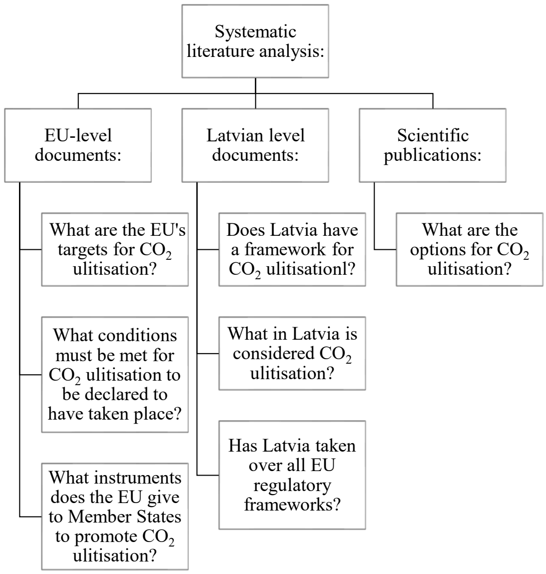


Fig. 15. Systematic literature analysis steps

Before governing structures make decisions, they must familiarise themselves with the legislation. Each country of the European Union is obliged to comply with the laws of its own country and the laws of the European Union (United Nations, 2015). In parallel, when developing specific steps, the responsible structures should pay attention to similar solutions and their implementation experience in other countries. 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 made on the laws of several countries of the European Union – Great Britain (EU member until 2020), Germany, Sweden, Lithuania, and Estonia. The first three countries are selected based on their technological development. In turn, the analysis of the legislation of Lithuania and Estonia is based on the fact that these two countries are Latvia's neighbours, and laws in these countries are often adopted with an eye to each other. In the case of a positive experience in one country, this decision will likely be made in a neighbouring country.

2.6. Assessment Criteria for Supportive Legislative Measures

Systematic Literature Analysis

Section 2.6 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 European Union member states. The goal is to assess how supportive policy environments influence the viability and scaling of CCUS technologies.

Literature analysis, as main tool of this step, is necessary to get a complete picture of the legislation system and to build a knowledge base on the research topic. 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 (European Commission, 2021j) 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 (Snyder, 2019).

For the systematic analysis of the literature, two groups of documents were selected, and each of them raised its questions:

EU-level documents:

- What are the EU's targets for CO_2 recovery?
- What conditions must be met for CO_2 recovery to be recognised?
- What tools does the EU provide the Member States to promote CO_2 recovery?

Scientific papers:

- What are the possibilities for CO_2 utilisation?
- What is the experience of other countries and cases?

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, which 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. Only official documents (such as policies, scientific documents and reports) were included in the research. The same criteria were implemented to all scientific research papers. Only those papers were observed that are not older than five years. Older document was used only in case if no recent paper was found.

This method used two types of keywords: direct and general or indirect. Keywords were selected through literature and systematic literature analysis (Table 3).

Table 3.

Keywords used in the systematic literature analysis

Direct keywords	**Indirect keywords**
CO_2 / CO_2 utilisation / CCU	CO_2 / CO_2 capture
CO_2 / CO_2 utilisation	CO_2 / CO_2 storage
	CO_2 / CO_2 storage / CCS
	CO_2 / CO_2 binding
	CCS

The information gathered by the EEA on the climate policies of the EU Member States was analysed (European Environmental Agency, 2021).

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 work were selected:

- P1 – country uses the EU ETS;
- P2 – GHG emissions mark-ups in the country are taxed;
- P3 – the country has tax rebates to meet climate targets;
- P4 – the country is increasing the number of renewable energy resources in the field of energy;
- P5 – energy efficiency works are being carried out in the country;
- P6 – the country has restrictions or prohibitions on GHG emissions;
- P7 – the country uses the LULUCF sector to reduce emissions;
- P8 – the state provides funding for research into GHG emission reduction technologies;
- P9 – GHG capture is taking place in the country;
- P10 – the use of CCS technologies is taking place or is planned in the country;
- P11 – the use of CCU technology is taking place or is planned in the country.

These categories were then assigned values according to their relevance to the aims and objectives of the work:

- If the country has at least one policy instrument or the policy falls into categories P1, P2, P3 or P5, one point is awarded;

— If the country has at least one policy instrument or the policy falls into categories P4, P6 or P7, two points were awarded;
— If the country has at least one policy instrument or the policy falls into categories P8, P9, P10 or P11, three points were awarded.

The difference in the number of points is explained by the complexity (financial, legislative, technical) of the policy's adoption and/or implementation.

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.

2.7. GHG Inventory Methodology for Logging Residue Scenario

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 like a description of the production process and needed feedstock calculation of the amount of CO_2 that can be stored in the final product. As for the energy sources for the rigid board production, three different scenarios have been compared using the multicriteria analysis method. All steps of the methodology are seen in Fig. 16.

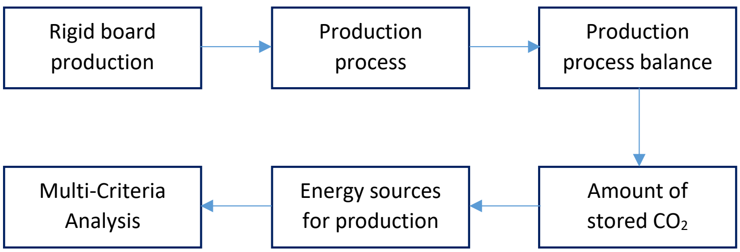


Fig. 16. Algorithm of the methodology.

The rigid board is produced similarly to medium-density fibreboard (MDF) boards from refined and dried wood fibres derived from wood chips, generally called the "dry" process. After drying, the material goes through forming, pressing and profiling. A simplified manufacturing process of rigid board insulation panels is shown in Fig. 17. The refined and dried wood fibres are mixed with resin, formed into a mat, and then pressed and cured. Curing occurs by passing steam through the mat to heat it slightly. Unlike general MDF production, the press is not a high-pressure and heated press. The slight temperature increase and the small amount of water cure the resin. The resin used for rigid board production is exclusively pMDI (polymeric methylene diphenyl diisocyanate). Rigid board is produced in various thicknesses ranging from 18 to 244 mm and in densities ranging from 100 to 220 kg/m^3. It is mainly used for insulation purposes, and the raw boards are passed through a profiler to produce a tongue-and-groove finish (Tellnes et al., 2017).

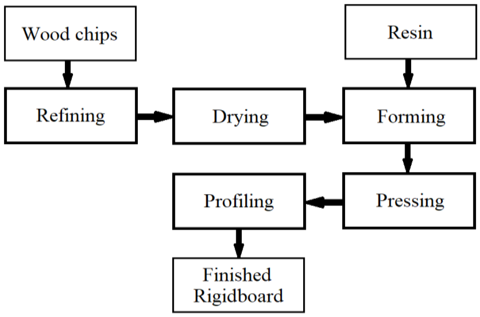


Fig. 17. Simplified rigidboard manufacturing process (Tellnes et al., 2017).

The primary feedstock for manufacturing the new rigidboard boarding panels is logging residues, mainly from coniferous trees, the dominant tree species harvested in Latvia. The logging residues used for the production of chips will especially be branches, smaller logs and possibly stumps that are not used in conventional production. It is assumed that all needles and other greenery will fall off or be removed from the feedstock while in storage and manufacturing. To produce fibreboard insulation panels, wood fibres of strong and uniform quality must be obtained. Although MDF and other fibreboard producers traditionally use Roundwood as a raw feedstock, novel methods of cleaning and sorting waste wood or production residues from other woodworking industries have enabled alternative sources of wood materials on dedicated production lines (Tellnes et al., 2017). A study about the chase characteristics of wood chips produced from logging residues concluded that wood chips produced from logging residues have a moisture content of 50 % and are suitable for use in small and medium size boilers (Balkan Green Energy News, 2019). It is assumed that the wood chips obtained from logging residue feedstocks will be of sufficient quality to produce fibreboard panels.

The material balance of the new fibreboard insulation panel is shown in Table 4. Material density is assumed maximum for rigid board production from the BAT Reference Document for Wood-based Panels (Tellnes et al., 2017). Material balance was chosen based on fibreboard and insulation board data from the Forest Product Conversion Factors document (U.S. Department of Energy, 2016), assuming an increased bark and decreased wood content. The weight content of bark, binders and fillers, moisture and wood in one cubic meter of the finished insulation panel were calculated based on the chosen material density and material balance.

For the new fibreboard insulation material manufacturing process, the standard dry manufacturing process was chosen from the BAT Reference Document for the Production of Wood-based Panels (Tellnes et al., 2017), modified for rigid board production (Fig. 16).

Table 4.

Fibreboard insulation material balance

	Content, kg/m^3	**Balance, %**	**Source**
Density	220	100	(Tellnes et al., 2017)
Bark	6.6	3	(U.S. Department of Energy, 2016)
Binders and fillers	11	5	(U.S. Department of Energy, 2016)
Moisture	13.2	6	(U.S. Department of Energy, 2016)
Wood	189.2	86	(U.S. Department of Energy, 2016)

It is assumed that the new plant would produce 300 000 m^3 of fibreboard insulation material annually, based on average plant capacities in the industry (Tellnes et al., 2017). To calculate the specific amounts of heat and electric energy needed to produce 1 m^3 of the material, existing insulation material manufacturing plant data was used. Assuming that an existing plant has an electrical capacity of 5 MW and a heat capacity of 10 MW (Danish Energy Agency, 2020) and operates for 8000 hours annually, the manufacturing plant would require 0.13 MWh of electricity and 0.26 MWh of thermal energy to produce 1 m^3 of fibreboard insulation material. Energy consumption for the most energy-intensive manufacturing processes is shown in Table 5. The drying of the wood fibres consumes the most energy, mainly in the form of thermal energy, as the fibres need to be dried from a moisture content nearing 100 % to 5 %. The dryers also need to be ventilated, using mechanical ventilators that consume electricity. The second most energy-intensive process is refining the fibres, which requires powerful motors that consume the most electricity. Thermal energy is also needed for refining to supply hot steam for cooking and washing wood chips. The pressing of the fibreboard mat requires thermal energy in the form of steam and electricity for the press rollers; however, for the production of rigid board insulation, the energy consumption is minimised, as the temperature required is relatively low. Lastly, all other processes requiring electricity are grouped, such as chipping, sawing and profiling (Tellnes et al., 2017).

Table 5.

Energy consumption for production

Manufacturing process	**Electricity, MWh/m^3**	**Thermal energy, MWh/m^3**
Drying	0.03	0.16
Refining	0.08	0.08
Pressing	0.01	0.02
Chipping, sawing, profiling	0.01	–
Total	0.13	0.26

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. Only standards relevant to forest-based building materials and biogenic carbon were used. The standards used can be grouped into those that deal only with building materials (ISO-21930, EN-15804, CEN/TR-16970, EN-16485) and those which cover all products (PAS-2050, ISO/TS-14067, PEF). The standards can also be distinguished by geographical coverage, as some are international standards (ISO-21930, PAS-2050, ISO/TS-14067), and others are specific to Europe (EN-15804, CEN/TR-16970, EN-16485, PEF) and have stronger links to government regulation (Abbas et al., 2020; Ioannis Tsiropoulos et al., 2018). 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 (Latvijas Radio, 2022):

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

where

mCO_2	mass of CO_2 sequestered, $kgCO_2$;
$m_{dry}(timber)$	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.

By substituting the masses of carbon and CO_2, Eq. (1) becomes:

$$mCO_2 = m_{dry}(timber) \cdot 0.5 \cdot \frac{44}{12} = m_{dry}(timber) \cdot 1.833 \quad (2)$$

where mCO_2 is the mass of CO_2 sequestered in the finished product and $m_{dry}(timber)$ is the dry weight of timber in the finished product.

Only the CO_2 sequestered from the wood and bark content for 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 fibreboard 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. Indeed, producing heat and power from the most environmentally friendly renewable sources would be the best way to minimise emissions from manufacturing. However, this may not always be the most technologically and economically viable option. Thus, energy production for product manufacturing needs to be assessed from an environmental point of view while considering the technological and economic aspects. Three energy production scenarios were evaluated based on the proposed manufacturing plant capacity of 5 MW electrical capacity and 10 MW heat capacity (Latvijas Radio, 2022), current trends in the sector and possible future technologies. Technological, economic and environmental data for the three proposed scenarios are shown in Table 6. The capacities of the energy production plants were chosen according to the required minimum heat capacity of the manufacturing plant of 10 MW, as all the process heat needs to be produced on-site to meet heat and steam requirements. The electrical power of the energy production plant can be lower than the electrical demand of the manufacturing plant, as electricity can also be supplied from the grid. The first proposed scenario is to produce heat and power with a biomass combined heat and power (CHP) plant, which would use wood chips as fuel. The chosen CHP technology is a wood chip boiler combined with a steam turbine. The second proposed scenario is a natural gas CHP plant with a gas turbine technology well suited for industrial processes. The third proposed scenario is a wood biomass combustion plant (CP) producing only thermal energy, using wood chips as fuel, combined with Solar Photo-voltaic (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.

Table 6.

Technological, economic and environmental parameters of proposed energy production scenarios

Parameter	Wood biomass CHP	Natural gas CHP	Wood biomass CP + PV panels	Sources
Electrical capacity, MWe	5	7.5	4	(LSM.lv, 2022), (Balkan Green Energy News, 2019), (U.S. Department of Energy, 2016), (Danish Energy Agency, 2020)
Thermal capacity, MWth	12	10.7	12	(Balkan Green Energy News, 2019), (LSM.lv, 2022), (U.S. Department of Energy, 2016)
Electrical efficiency, %	25	29.2	–	(U.S. Department of Energy, 2016), (Abbas et al., 2020)
Thermal efficiency, %	60	41.4	85	(U.S. Department of Energy, 2016), (Abbas et al., 2020)
Total efficiency, %	85	70.6	85	(U.S. Department of Energy, 2016), (Abbas et al., 2020)
Capital costs, EUR/kWa	3310	1510	965b	(Ioannis Tsiropoulos et al., 2018)
O&M costs, %CAPEX	2	2.5	2b	(Ioannis Tsiropoulos et al., 2018)
Fuel cost, EUR/MWh	25	81.2	25	(Latvijas Radio, 2022), (LSM.lv, 2022)
NO_x emissions, g/MWhc	29	27	9.1	(U.S. Department of Energy, 2016), (EPA, 2017)
CO emissions, g/MWhc	8	31.5	2.5	(U.S. Department of Energy, 2016), (EPA, 2017)
VOC emissions, g/MWhc	0	27	0	(U.S. Department of Energy, 2016), (EPA, 2017)
PM emissions, g/MWhc	44	0	13.6	(U.S. Department of Energy, 2016), (EPA, 2017)
CO_2 emissions, kg/MWhd	0	202	0	(Cabinet of Ministers, 2018)

a Based on the electrical capacity for CHP and thermal capacity for CP
b Does not include the cost of PV panels
c Applies to electricity produced for CHP and thermal energy for CP
d Applies to both electrical and thermal energy produced

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. Still, they are recalculated according to the thermal capacity of the combustion 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.

The capital costs and O&M costs for the Solar PV panels are chosen according to the peak capacity of Solar PV panel installation. 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 (Danish Energy Agency, 2020).

A multicriteria analysis using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method compares the three energy production scenarios. Using the TOPSIS method, the proposed scenarios or alternatives are evaluated for the ideal possible solution. The alternative that is the closest to the ideal solution is considered to be the best scenario (Darzi, 2024). 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 chosen for the analysis are shown in Table 7. The values of the criteria were calculated using data from Table 7 and applied to the manufacturing plant's selected electrical and thermal energy demand parameters, with the annual plant production capacity of 300 000 m^3 of fiberboard insulation material. The criteria values were calculated relative to one cubic meter of the finished product.

To perform the multicriteria analysis, the criteria weights need to be determined. The criteria weights were determined using the Analytical Hierarchy Process (AHP) method. The criteria were first ranked in importance, prioritising economic and technological criteria, and then ranking the environmental criteria by their global warming potential. The weights of each criterion were then determined according to their rank, consequently comparing them to each other(Darzi, 2024).

Table 7.

Chosen criteria for the multicriteria analysis

Technological criteria	**Economic criteria**	**Environmental criteria**
Fuel energy content, GJ/m^3	Capital costs, EUR/m^3	NOx emissions, g/m^3
	Fuel costs, EUR/m^3	CO emissions, g/m^3
	O&M costs, EUR/m^3	VOC emissions, g/m^3
	Bought/sold electricity, EUR/m^3	PM emissions, g/m^3
		CO_2 emissions, kg/m^3

With the obtained criteria weights, the results of the multicriteria analysis were calculated. The result is shown as a relative closeness coefficient to the ideal solution. The results can have a value ranging from 0 to 1, with the ideal solution being a value of 1. The closer the coefficient of a proposed alternative is to the maximum value of 1, the closer it is to the ideal solution.

2.8. Transition Emission Analysis: Switch to Biomethane Production

As indicated in Section 1.8, another method for reducing CO_2 emissions is avoidance method. This step examines the effectiveness of biogas plant's transition from biogas production to the production of biomethane and its subsequent integration into the natural gas grid. Step helps understand the possibility of such transition and compliance with European legislation for such initiatives.

The analysis includes calculations related to this transition, specifically GHG emission savings, while taking into account resource heterogeneity. This work did not account for the distance to the grid injection point. It is also assumed that the plant uses the Pressure Swing Adsorption (PSA) method for the transition process, as it is effective and suitable for working with gas mixtures generated by non-homogenous feedstock (Durán et al., 2022).

Biogas Plant Case Study

The biogas station is located in the central region of Latvia, Zemgale, with 5 500 people living in the area of the plant. The total area of the region is 311.6 km^2 (Fig. 18).

Fig. 18. Region of the location of the Biogas Plant (ArcGis, 2021).

According to (State Environmental Service, 2022) and a personal interview with the biogas station manager, in 2021, the station used just over 57 thousand tons of substrates. In total, 13 substrates were involved in the production – milk whey, sludge, chicken manure, beer yeast, grass silage, immature grain crops silage, maize silage, and spoiled grains (Table 8). 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.

Table 8.

Substrates and their quantities used in the biogas plant case study in 2021

Substrate	**Amount, t/year**	**Methane yield, Nm^3/t** (State Environmental Service, 2022)
Sediments of flotation from milk powder factory	3 982.7	682.7
Milk whey	16 829.78	36.9
Sludge	8 852.2	47
Chicken manure	5 419.3	55.4
Beer yeast	169	505.8
Immature grain crops silage	852.4	54.6
Maize silage (2021)	15 258.3	106
Maize silage (2020)	3 602	106
Maize silage (2019)	12.3	106
Grass silage (2021)	803.4	100
Grass silage (2020)	612	100
Grass silage (2019)	513.4	100
Spoiled/immature grains	72	122.2
TOTAL	57050.6	

GHG Savings Calculation

The calculation of GHG was carried out based on Directive 2018/2001/EU ((European Commission, 2021k; European Parliament, 2018; Zaucha et al., 2025) directive is a continuation of REDI 2009, which sets out methods for controlling the sustainable and ecological production of biofuels. Additionally, a network of stakeholders, such as producers and consumers, has been established within REDI. To participate in such a network, each participant must obtain certification from REDcert and ISCC. REDcert, in turn, is a quality assurance and assessment scheme for indicators such as sustainable production, traceability of documentation, etc. REDcert is accepted throughout Europe (Certifications Control Union, 2021a), (Certifications Control Union, 2021b).

There are two ways to calculate the amount of GHG saved – actual value and default value-based (European Parliament, 2018). Given that the default methodology relies on a limited and specific set of biogas feedstocks – namely wet manure, dry manure, and municipal solid waste – this study applied a value-based calculation method to estimate GHG emission savings more accurately.

Eq. (3) shows the calculation of emissions in case of co-digestion of various substrates in biomethane production from biogas:

$$E= \sum Sn \cdot \left(e_{ec,n} + e_{td,feedstock,n} + e_{1,n} - e_{sca,n}\right) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr} \quad (3)$$

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;
$e_{td,feedstock,n}$	Amount of emissions from the transport of feedstock *n* to the digester, CO_2eq/MJ final product;
$e_{l,n}$	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;
$e_{td, product}$	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. (4):

$$e_{ec}, e_{td}, e_p, e_u = \frac{\sum amount\ of\ material\ input \cdot Emission\ Factor\ of\ the\ aterial}{Yieled\ or\ quantity\ of\ the\ material} \quad (4)$$

Eq. (1) and (2) are the basis for the following calculations. Even though parameter e is calculated in [gCO_2/MJ of the final product (CH_4)], it is also recommended to calculate it per mass of the intermediate product (as [gCO_2/kg product]) and only at the end allocate the parameter to the final product.

2.9. 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.

In this case, two CO_2 utilisation scenarios are considered – the 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. Potentially, the production of such bio- and renewable fuels will help diversify the country's energy market, promote sustainable technological development and create new jobs. Life Cycle Assessment and Social Life Cycle Assessment will allow comparison of both scenarios and determine the optimal solution. Below are descriptions of the scenarios and the parameters used in the LCA and S-LCA analyses.

Description of Scenarios

— Scenario 1 – Methanol production

CO_2 utilisation in methanol production, particularly when renewable energy sources are used, is a promising application. Methanol is a key feedstock in the chemical industry, commonly used as a solvent, fuel, and in the production of formaldehyde, acetic acid, and other chemicals (Khojasteh-Salkuyeh et al., 2021). The use of CO_2 in methanol production (as a CCU application) represents a relatively mature technology (Guo et al., 2025; Morimoto et al., 2021; B. P. Ren et al., 2023; Rezaei & Catalan, 2020). While methanol has traditionally been produced from natural gas, using CO_2 as a feedstock offers significant advantages, including the potential to reduce the overall carbon footprint of the process.

One approach to CO_2 utilisation involves combining captured CO_2 with biogas to produce syngas – a mixture of hydrogen and carbon monoxide – which is then reformed into methanol after the removal of water. Another route involves using industrial or atmospheric CO_2, which, after capture, is converted into syngas via the reverse water-gas shift (RWGS) reaction (Khojasteh-Salkuyeh et al., 2021; Nouri et al., 2025; Ugwu et al., 2022). Several catalytic technologies exist for this conversion. These include systems such as the $Cu/ZnO/Al_2O_3$ catalyst and the Haldor Topsoe catalyst, both of which have been successfully demonstrated at pilot and commercial scales (Carbon Recycling International, 2022; Ravn, 2020; Yusuf & Almomani, 2023). In the context of this work, the focus is on methanol production from a combination of biogas and CO_2.

The project "*Creating added-value chemicals from bio-industrial CO_2 emissions using integrated catalytic technologies*" (European Commission, 2021d) highlights that converting CO_2 into bio-organic chemicals, including methanol, can lead to more sustainable and environmentally friendly production methods while reducing sector-specific emissions. Similarly, the project "*Selective CO_2 conversion to renewable methanol through innovative heterogeneous catalyst systems optimised for advanced hydrogenation technologies (microwave, plasma, and magnetic induction)*" (European Commission, 2021l), aims to develop hydrogenation-based methods for converting CO_2 into renewable methanol.

Currently, Latvia imports all of its fuel, making energy security a critical concern. Establishing domestic methanol production from CO_2 could enhance the country's energy independence, create new jobs and therefore promote regional technological, social and economic development. Taking these points into account, methanol production is considered one of the most promising strategic technologies for future energy resilience.

— Scenario 2 – Sustainable Fuel Production

CO_2 can be utilised to produce sustainable fuels like ethanol, which can significantly reduce emissions from the transport sector (Seber et al., 2022). Synthetic aviation fuel or sustainable aviation fuel (SAF) can be produced in different ways – out of biomass and using Direct Air Capture (DAC) technology. DAC technology looks the most promising, as it requires little number of resources and takes CO_2 straight from the atmosphere, making a direct contribution to reducing CO_2 emissions. Sustainable fuel production typically involves the electrolysis of water to produce hydrogen, which is then combined with CO_2 through the Fischer–Tropsch synthesis process. Another approach involves using methanol as an intermediate, starting with the hydrogenation of CO_2 to form methanol. This methanol is then transformed into hydrocarbons through processes like methanol-to-olefins (MTO). Like the modified Fischer–Tropsch synthesis (MFTS), this pathway is capable of producing a diverse range of hydrocarbons, with the final product distribution strongly influenced by the chosen catalysts and the specific operating conditions designed to maximise conversion efficiency (Bernardi et al., 2023; Collis et al., 2022; He et al., 2024; Jiang et al., 2023; Karekar et al., 2023; Nordic Electrofuel, 2023; Pio et al., 2023; Ramos-Fernandez et al., 2025; Suppiah et al., 2021). Although the conversion of CO_2 into ethanol offers environmental advantages, the process is energy-intensive (Nordic Electrofuel, 2023; Recharge & Collins, 2021).

Sustainability assessment

Environmental Life Cycle Assessment evaluates a range of environmental indicators such as particulate matter emissions, water usage, toxicity, and others – each of which is linked to sustainability and environmental performance. The main impact categories considered in Environmental LCA are: Human Health, Ecosystems, and Resources.

In contrast, Social Life Cycle Assessment includes a more diverse set of indicators. These may involve aspects such as workplace safety, health and accident rates, fair wages, and the added social value of processes and technologies. S-LCA aims to assess how technologies and processes affect people, particularly workers, communities, and consumers (Larsen et al., 2022).

S-LCA observes 25 sub-indicators within five main categories, following the UNEP/SETAC Guidelines (Akhtar et al., 2023; Bayazıt Subaşı et al., 2024; Liu et al., 2025; Roche et al., 2025):

- Labor rights & Decent work – Working hours, child labour, forced labour, etc;
- Health & Safety – Occupational injuries, exposure to hazards;
- Society – Contribution to economic development, local employment;

— Governance – Corruption prevention, transparency, and legal compliance;
— Community – Infrastructure investments, cultural respect, and social benefits.

Each sub-indicator is scored using the *SimaPro Social Hotspot* Database. The scoring follows the SHDB's internal methodology, which assigns qualitative risk levels (e.g., low, medium, high) converted into point values: 1 = low risk, 2 = medium risk, 3 = high risk, and 4 = very high risk. For each sub-indicator, weighting factors from the SHDB was applied and aggregated the results at the category and scenario level using the ReCiPe Endpoint method (Akhtar et al., 2023; Bayazıt Subaşı et al., 2024; Roche et al., 2025).

Normalisation was applied using region-specific and sector-specific benchmarks available in SHDB to assess the relative performance of scenarios.

Both types of LCA follow a similar methodological framework, as outlined in ISO 14040 and ISO 14044 standards (ISO, 2006a, 2006b). This methodology includes four key phases:

– Goal and Scope Definition;
– Life Cycle Inventory (LCI) Analysis;
– Life Cycle Impact Assessment (LCIA);
– Interpretation.

This study examines two scenarios for the valorisation (i.e., beneficial use) of CO_2 through fuel production. The two scenarios are:

– Scenario 1: CO_2 utilisation for the production of methanol;
– Scenario 2: CO_2 utilisation for the production of sustainable aviation fuel (SAF-ethanol).

The Functional Unit (FU) chosen for both scenarios is 1 kg of CO_2 treated in each respective scenario.

Goal and Scope

The goal of conducting E-LCA of CO_2 utilisation in fuel production is to evaluate the social and environmental impacts associated with the production, use, and disposal of CO_2 in two scenarios: methanol production in biogas facilities and Sustainable Aviation Fuel (SAF-ethanol) production. Both the E-LCA and S-LCA aim to analyse all life cycle stages of CO_2 utilisation, encompassing upstream and downstream processes, to provide a comprehensive understanding of its potential implications.

The scope of the S-LCA and E-LCA includes the following elements:

— Identification of relevant social and environmental issues related to CO_2 utilisation in methanol and SAF-ethanol production scenarios;

- Assessment of potential impacts, both positive and negative, associated with CO_2 utilisation in each scenario;
- Recommendations for improving the social and environmental sustainability of CO_2 utilisation based on the analysis outcomes.

Both assessments adopt a gate-to-gate approach, focusing on the impacts directly associated with the CO_2 utilisation process within the production facilities. For the S-LCA, the *SimaPro Hotspot* database is used, while the E-LCA relies on the *OpenLCA ProBass Basic 2024* database. The analysis methodology applied in both cases is the ReCiPe Endpoint method (OpenLCA, 2025; Pré, 2024b, 2024a; SHDB, 2024). The spatial scope of the analysis is sectoral, concentrating on specific production processes. The results aim to compare the two scenarios and determine the optimal pathway for CO_2 utilisation in Latvia. However, due to regional similarities in CO_2 emissions profiles, geographical context, and legislative frameworks concerning carbon capture and utilisation (CCU), the findings may also be applicable to neighbouring countries such as Lithuania and Estonia.

Inventory and Boundary Analysis

The boundaries of both scenarios are set gate to gate.

- Scenario 1 – Methanol production

Input materials:

- S-LCA: construction of the facility, raw materials, consumables (e.g., catalysts and solvents), water, electricity, mechanical and electrical equipment.
- E-LCA: water, electricity, heat (partially recovered from the output), and methanol (recycled from the output).

Production process: The conversion of biogas and water into methanol through a chemical reaction, catalysed by suitable substances.
Output products: Methanol, water, and heat.
System boundaries:
- Excluded from the analysis:
  - S-LCA and E-LCA: transportation of raw materials and final products (i.e., methanol), as well as end-use by consumers.
  - E-LCA only: construction of the facility and machinery.

The average total cost of constructing and operating the methanol production plant, along with the detailed inventory data used for the E-LCA, is presented in Table 9.

Table 9.

Average total costs and inventory of methanol production

Average Total Costs (S-LCA) (Pérez-Fortes et al., 2016)		**Inventory (E-LCA)** (Alamia et al., 2024; Gholizadeh et al., 2025; H. Li et al., 2025; Marmier, 2023; Ramos-Fernandez et al., 2025; Rigamonti & Brivio, 2022)	
Equipment	**Value**	**Input**	**Value**
Electrolysis, M €	147.8	CO_2, kg	1.37
Heat exchanger, M €	47.4	H_2, kg	0.19
Compression, M €	46.8	Electricity, MJ	2.44
CO_2 purification, M €	13.5	Biogas, m^3	1.58
Furnace, M €	7.2	Heat, MJ	4.86
Turbines, M €	3.3	CH_4, kg	0.66
Distillation Column M €	1.6	**Output**	
Pressure valves M €	1.3	Water, kg	0.56
Reactor M €	1	Heat, MJ	15.64
Pumps M €	0.2	CO_2, kg	1.37
Construction, €/tMeOH	1281.8	Biogas, m^3	1.56
Utilities and materials		Urea (as N), kg	0.78
Raw materials, M €/y	26	Potassium (as K), kg	0.96
Consumables (catalysts. solvents), M €/y	4	Phosphate (as P), kg	0.64
Electricity needs, MWh/tMeOH	11.9	NH_3, kg	0.00154
Water needs, tH_2O/tMeOH	92.3	CH_4 (as digestate), kg	0.0221
Methanol production, tMeOH/y	1320	SO_2, kg	0.0000776
Plant lifetime, y	20	NO_x, kg	0.00113
Working days, d/y	360	CO, kg	0.000603
		NMVOC, kg	0.000013
		CH_4, kg	0.00182

– Scenario 2 – SAF-ethanol production:

Input materials:

– S-LCA: construction materials, mechanical and electrical equipment.
– E-LCA: CO_2 (supplied externally), enzymes, potassium carbonate, ammonium chloride, electricity, and water.

Production process: SAF is produced from CO_2 and H_2O via chain of reactions – direct synthesis of hydrocarbon from CO_2, purification, conversion, separation, oligomerisation and hydrogenation.
Output products: Ethanol.
System boundaries:

– Excluded from the analysis:
  - S-LCA and E-LCA: prior purification of CO_2, transportation of raw materials and final products to end-users.
  - CO_2 is assumed to be supplied from an external source (not captured from air), and no cost is incurred by the plant for its acquisition.

- E-LCA only: construction of the facility.

The average total cost of constructing and operating the SAF-ethanol production facility, as well as the detailed inventory data for the E-LCA, is presented in Table 10.

Table 10.

Average total costs and inventory of SAF-ethanol plant construction

Inventory of SAF-ethanol (S-LCA) (Kosonen, 2020; Timmons & Terwel, 2022; M. Wang & Yu, 2024)		**Inventory (E-LCA)** (Chakraborty et al., 2024; Espada et al., 2021; He et al., 2024; Hirunsit et al., 2024; Jiang et al., 2023; U. Lee et al., 2021; Ramos-Fernandez et al., 2025; Suppiah et al., 2021)	
Equipment	**Value**	**Input**	**Value**
Carbon Capture, M €	24.4	CO_2, g	2046.6
Water Electrolysis, M €	48.1	Water, L	40.5
Reverse water gas shift (RWGS), M €	4.3	Sulfuric acid, kg	885.6
Fermentation, distillation, M €	6.8	Electricity, MJ	85.86
Construction cost, M €	194.5	Ammonia, kg	885.6
Utilities and materials		Catalyst, kg	0.114
Electricity, M €/y	24.3		
Hot water, M €/y	0.4		
CO_2	–		
Enzyme, M €/y	1.4		
Potassium carbonate, M €/y	0.07		
Process water, M €/y	0.01		
Deionised water, M €/y	0.9		
Ammonium chloride, M €/y	2. 05		
SAF-ethanol production, t/y	34393		
Plant lifetime, y	30		
Working days	360		

3. RESULTS

This chapter presents and interprets the results obtained from the analysis methods outlined in Chapter 2. The findings illustrate the outcomes and implications of each methodological step applied in assessing CO_2 valorisation opportunities.

3.1. Findings from KPI Assessment of CO_2 Valorisation

Key Performance Indicator analysis

In the process of analysing the methods of CO_2 valorisation, both existing and on-going 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 (e.g., Electric energy per 1 tonne product, Water consumption per 1 tonne final product, Produced CO_2 and required CO_2 ratio), 12 – environment-related (e.g., Total emission during production process and Possible CO_2 capture system efficiency), 18 – economy-related (e.g., Costs of CO_2 if buying, Total costs for CO_2 if doing nothing). The table (Annex A) also includes 28 indicators specific to the scope of potential CO_2 applications, for example, methanol production (CO_2 conversion rate), cement production (CO_2 emissions per tonne of cementitious materials produced), use of algae and greenhouses (CO_2 fixation by plant). Despite the large number of indicators compiled, further analysis is required. It is necessary to fill in as many indicators as possible to enable a better MCDA analysis, which would include more criteria for assessing the scenarios of the potential utilisation of CO_2 as a resource. In the future, when the other indicators receive their benchmark values, they will also be used for analysis.

Multi-Criteria Decision Analysis Results

Quantitative production data from literature sources, technical descriptions, Good Practice projects and H2020 projects were used for the MCDA analysis. During the analysis of the literature and projects H2020, 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 the utilisation of CO_2 in these areas are the most developed and accessible. There are also many examples of good practices available, allowing to learn from the experience and implement it in Latvia. Some technologies, such as the carbonisation of beverages, have long been known in the country (the production of alcoholic beverages, for example), while others are still not applied broadly or not used at all (for example, the production of methanol).

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 from 1 to 5). Results of MCDA analysis with the closest to ideal value of each scenario are depicted in Fig. 19.

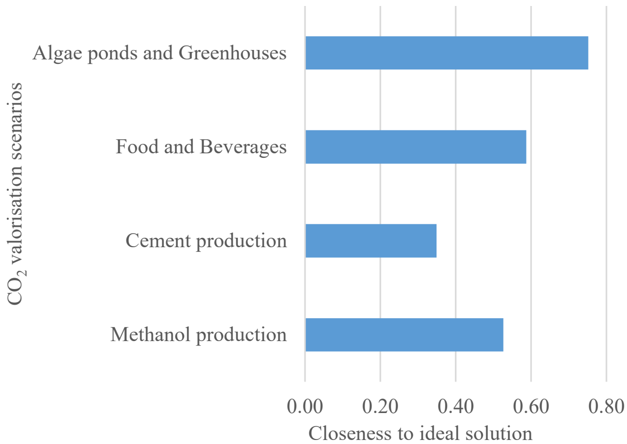


Fig. 19. CO_2 valorisation MCDA results.

The MCDA analysis showed that the optimal scenario for the CO_2 valorisation could be algae ponds/ greenhouses and the food industry (Fig. 19). Algae ponds are an attractive option as algae can absorb large amounts of CO_2. According to literary sources, there is no need to supply CO_2 completely purified from impurities, which greatly facilitates the use of this technology. By adding CO_2, algae grow much faster. When the mass is sufficient, it can be used as biofuel or fertiliser, which is an additional advantage of this scenario (Ishaq & Crawford, 2023; C. Zhang et al., 2024).

A good example of the use of algal biomass is the H2020 project IPHYC-H2020. In this project, microalgae are used for wastewater treatment. Plants purify water from phosphorus and nitrogen compounds, and to speed up metabolism receive specially introduced CO_2. Once the microalgae have reached a sufficient mass, they are used in energy production. Thus, water purification becomes not only more efficient and environmentally friendly, but also produces much less CO_2 (and with sufficient technology improvement, it can potentially become a carbon-neutral process), but also allows the production of biofuel (biomethane), and from digestate – an environmentally friendly and efficient fertiliser, which also has a positive effect on the amount of emissions in the country (Anto et al., 2020; I-PHYC, 2020; Romagnoli et al., 2020). Such algal installations can potentially be installed in regional governments. This would help not only produce valuable goods (like biofuel) and reduce the amount of CO_2 emissions, but also increase the efficiency of the agricultural sector in the region (Ievina & Romagnoli, 2020; Pastare & Romagnoli, 2019).

The second scenario, the food industry, is just as good. CO_2 can be used both as a gas to protect against pests and to extend product shelf-life, and as a substance to carbonate beverages (Dragerwerk AG, 2017; Hosseini et al., 2023). As an additional way of using CO_2 – refrigeration units and as a dry cleaning agent. CO_2 is a valuable and often irreplaceable element of the food industry, however, for its utilisation, it is necessary to make sure that the gas is highly purified (at least 98 %) (Dragerwerk AG, 2017; Hosseini et al., 2023).

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 (Ghiat et al., 2021). In the scenario of CO_2 utilisation for methanol production, one of the key advantages of locating stations in regional areas is their proximity to biomass suppliers. This geographic advantage has the potential to significantly reduce logistics costs. However, the construction of such bioconversion facilities requires substantial capital investment, which is often beyond the financial capacity of regional governments. In parallel, food and beverage manufacturers may also benefit from locally produced CO_2 or CO_2 sourced from nearby facilities. It can be utilised not only for product carbonation but also as a preservative, a refrigerant in cooling systems, and an environmentally friendly cleaning agent for technical equipment (Dragerwerk AG, 2017; X. Zhang et al., 2019; Z. Zhang et al., 2021).

3.2. Spatial Distribution of CO_2 Valorisation Potential

CO_2 Producers and Potential Consumers

According to data obtained from State Environmental Service 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 (Fig. 20).

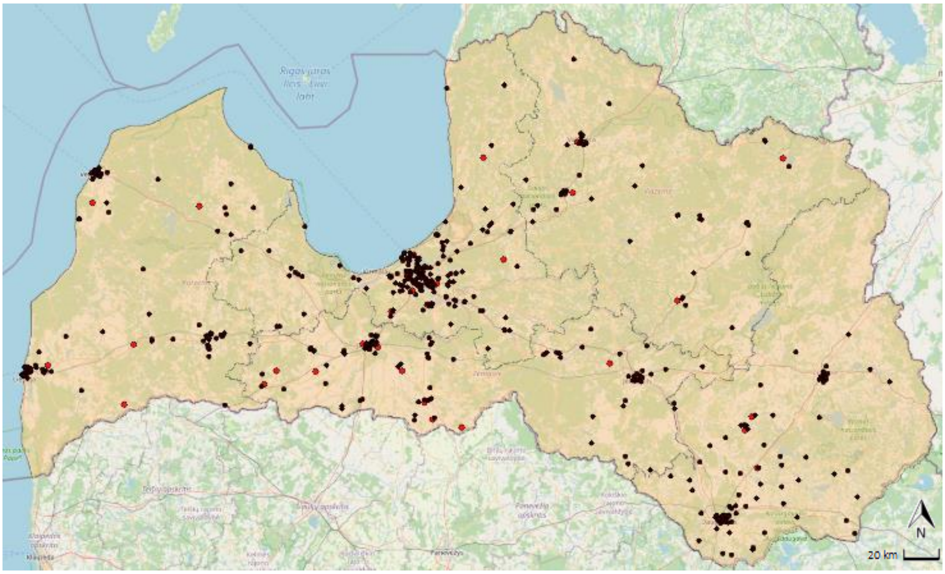


Fig. 20. CO_2 production sites A category companies (red) and B category companies (black).

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

By analysing the list of potential consumers of CO_2, a list of enterprises was compiled. These include those enterprises, the main activity of which is related to the production of energy (bio-stations, landfills), food and beverages, algal pools / greenhouses. The ratio of CO_2 producers and potential utilisers shows how few enterprises from the second category are currently in the country (Fig. 21).

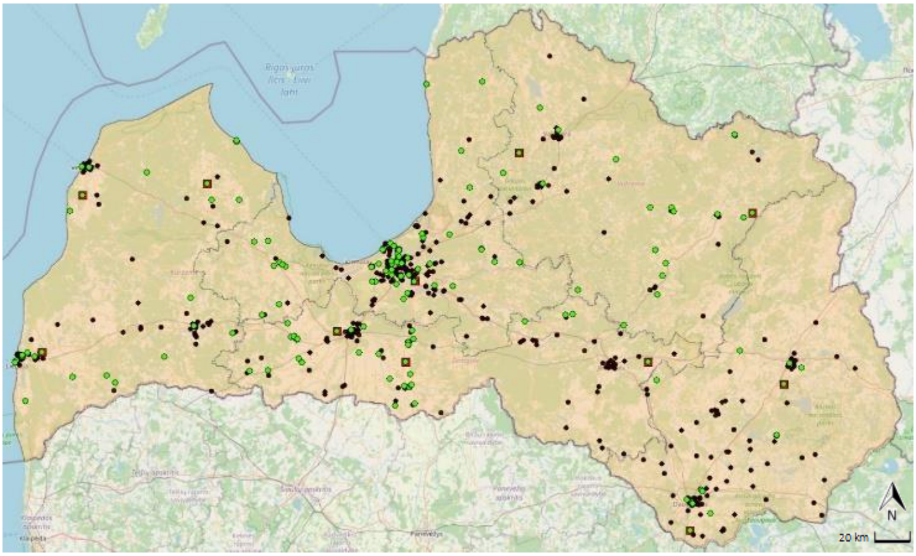


Fig. 21. Sites of CO_2 production (brown) and potential utilisation (green).

On the region scale, results show that producer / consumer ratio, although it can be considered important, is still not decisive in determining the "pollution" of the region (Table 11).

Table 11.

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

As can be seen in Table 11, Riga region and Kurzeme produce the largest amount of CO_2 in the country (64.42 % and 25.94 %, respectively), however, the greatest difference in the number of places for the production of CO_2 and its consumption is observed in Latgale, a region with relatively a small share of CO_2 in the country. Such a large difference can be explained by the density of industrial institutions, population and the level of development of the regions.

Such a large amount of CO_2 emissions in the Riga region is explained by the large number of production facilities located closer to the capital, where the main sales market for the manufactured products is located. There are also large producers in the Riga region (often with a category A polluting activity permit). This, for example, is the energy sector – the main stations of Rigas Siltums themselves in 2019 produced more than 180 thousand tons of CO_2, which is equal to 7.49 % of CO_2 emissions in the region. Other large enterprises with a declared large amount of CO_2 produced are "Putnu fabrika Ķekava" (11100.83 tCO_2, 0.45 %), Olainfarm (10219.42 tCO_2, 0.42 %) and Latvijas Finieris (6828.00 tCO_2, 0.28 %).

A number of large factories are also located in Kurzeme. However, unlike the Riga region, in Kurzeme the leader is not the energy sector, but the industrial sector – the cement production of Schwenk in 2019 generated 793917.68 tCO_2 or 80 % of the region's CO_2 emissions. The second place is followed by energy production in Liepaja – Liepājas Enerģija (43632.00 tCO_2, 4.44 %).

According to (Food and Veterinary Service, 2021), there are currently 50 biogas plants in the country that could potentially use CO_2 to increase the plant's productivity. The stations are located mainly in rural areas of the regions (for example, the southern part of Kurzeme, flat areas of Vidzeme), but there is no region where the station would not exist (Fig. 22).

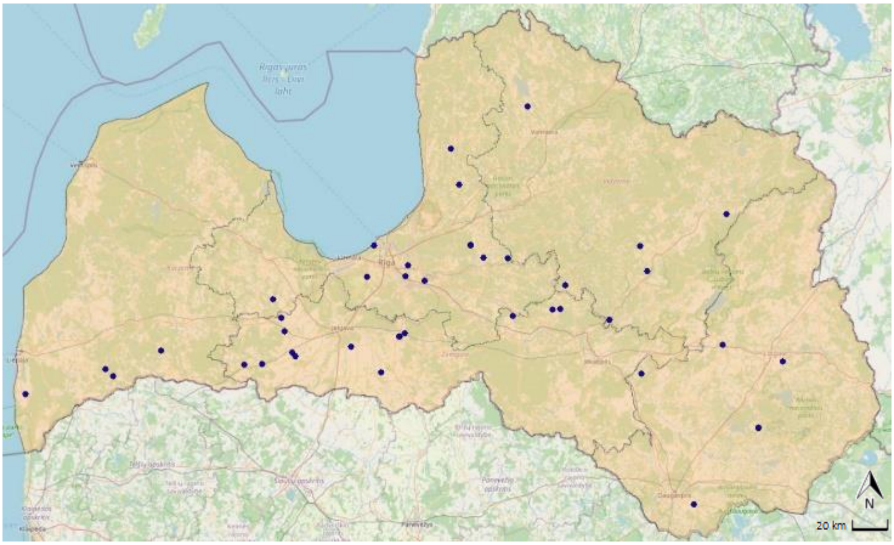


Fig. 22. Sites of biostations in Latvia.

According to the literature sources (Chen et al., 2018; Das et al., 2020), algal ponds can also be used for both CO_2 recovery and energy production. Algae are plants that, under favourable conditions, quickly gain mass, which can be used as biomass in biogas stations. The remaining digestate, in turn, can be used as fertiliser in agricultural areas, increasing the yield of grain and other crops. Plant residues can then also be used in the production of energy in biostations, in this way enclosing the circular economy cycle. Unfortunately, at the moment there is not a single active algal pond in Latvia.

Landfills can also potentially utilise CO_2 for energy production (Yan et al., 2021; Yaqoob et al., 2021).

Boundaries of CCU Implementation

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 (for example, the chemical and food industries), the CO_2 purification level must be at least 99.5 %. Installations with such a high level of efficiency can often be financially disadvantageous. The economic component of the modernisation issue is the second, but not least limiting factor. However, companies aiming to reduce the amount of CO_2 generated can count on financial assistance from European funds (European Commission, 2021f, 2021e).

Such installations for carbon capture and purification can be installed in various production places and, for example, in boiler houses. The purity of the CO_2 obtained at the outlet directly depends on the efficiency of the technology used (EPC Group, 2020). In the ideal case, the percentage of purification can reach 99 % and such CO_2 can potentially be used in biogas stations, and, for example, in algal ponds. The advantage of these ponds is the fact that plants do not need perfectly pure CO_2 to speed up metabolism. According to (Chen et al., 2018; Das et al., 2020), the maximum allowable amount of impurities in the supplied CO_2 can reach 30 %.

3.3. Identified Strengths, Weaknesses, Opportunities and Threats of CO_2 Valorisation

SWOT Analysis

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 using / transporting CO_2 are a severe factor. Since every year the requirements for "cleanliness" of the production process will only grow, sooner or later entrepreneurs will face the need to either completely redesign the production line to reduce the amount of CO_2 already at this stage or modify the existing lines so that the produced gas would be used further – either in the same production or in some other. At the moment, if an entrepreneur decides to improve production, he can apply for financial assistance from European projects and funds (European Commission, 2021e; Zapantis et al., 2019); however, to receive more severe support, it is necessary to provide a truly innovative project (European Commission, 2021e, 2021g). If no measures by the state are taken (both at the national level and the level of the European Union), CO_2 emitters are unlikely to seek to invest in the modernisation of enterprises to reduce the amount of CO_2 generated. 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 (Apeaning et al., 2025; Tello, 2025; Tian et al., 2025). However, in parallel with the introduction the new taxes, the government should subsidise measures aimed at decarbonisation of the industrial and energy sectors, compensate electricity costs and/or give financial help in the acquisition of the necessary installations to reduce the amount of CO_2 produced, capture, transport and/or reuse (Apeaning et al., 2025; Tello, 2025; Tian et al., 2025).

Detailed analysis of CO_2 valorisation through CCUS technology implementation is presented un subsection below (Tables 12–14).

CO_2 capture and utilisation in Europe

Technologies for carbon capture and storage are called CCS and for storage and/or utilisation – CCUS, respectively. The so-called "major" factors affecting CO_2 capture and utilisation/storage are factors within the European Union – political divisions, bureaucracy, etc. However, at the same time, at this level, a vital factor can be called the influence of other countries on each other and the opportunity to exchange experience and knowledge (Table 12).

Table 12.

CO_2 capture and utilisation in Europe

Strength	Weaknesses
Influence of large countries of the Union on small ones, the ability to apply sanctions in case of non-fulfilment of obligations	Prolonged response and action of each participating country separately
Improving the quality of life for residents of the European Union (improving air, environment, health, additional jobs) (UNCTAD, 2019)	No unity in making mandatory and unpopular decisions
Cooperation of countries on the issue of CCUS technologies, the ability to finance technology development and innovation in the sector	Different financial situations of each country (International Energy Agency, 2021a; UNCTAD, 2019)
Diversified development of CCS and CCUS technologies (applicable in various production sectors)	Different levels of technological development
Support for renewable energy and the phasing out of non-renewable ones	Not all countries have developed a clear-enough regulatory system for CCS and CCUS implementation (Slade et al., 2022)
Knowledge about energy efficiency and required measures (Mukeshimana et al., 2021)	CCUS technologies are still in the development stage (UNCTAD, 2019)

Continuation of Table 12.

	In the case of storage – suitable underground storage facilities are required, the imperfection of laws (the ability to find loopholes for default) (Rassool, 2020)
	Low level of public awareness of the problem and public acceptance of changes (Witte, 2021)
Opportunities	**Threats**
The opportunity to change the economic situation in the world for the better	The ecological situation is deteriorating faster than countries react to it and act
Great world experience in the field of CCUS technologies – there is an opportunity to use and share best practices and mistakes (thus stimulating the further development of the sector)	An unstable political situation, epidemics (as well as major disasters and cataclysms) and their consequences (economic decline)
An increase in the CO_2 tax and the price of CO_2 quotas (stimulation of a faster installation of CCUS technologies)	An increase in electricity prices, the development of technologies will increase the technological gap between countries (UNCTAD, 2019)
	The gap in experience and knowledge regarding CCS technologies (Slade et al., 2022)

CO_2 Capture and Utilisation in Latvia

The next level of CO_2 utilisation/storage is the national level. At this level, the main factors are bureaucracy, low awareness and/or inertia of people responsible for innovations, financial problems (for example, high cost of technology) and lack of technology representatives in the country. The problem is also a lack of practical experience in using this type of technology. However, the introduction of new technologies may provide new jobs, contribute to the development of the production sector in Latvia, and attract additional investments in production (Table 13).

Table 13.

CO_2 capture and utilisation in Latvia

Strength	Weaknesses
The need for changes	No or too little help from the state (Bernal-Torres et al., 2025; López Fernández & Oliver, 2025)
Requirements for reducing CO_2 emissions at the legislative level	High cost of technology (Bäcklund et al., 2024; Bernal-Torres et al., 2025; Kiselev et al., 2017)
The ability to attract foreign investors	Lack (or small number) of specialists and or representatives in this field in the country (Bäcklund et al., 2024; Bernal-Torres et al., 2025)
Additional jobs	The slow introduction of technologies due to the inertia and unresponsiveness of entrepreneurs (Kiselev et al., 2017)
The development of an enterprise and satellite enterprises	The extremely negative reaction from entrepreneurs in the case of mandatory introduction of CO_2 capture technologies
An extremely positive impact on the environment and human health	Low awareness of investors about CCS and CCUS technologies (International Energy Agency, 2021a; López Fernández & Oliver, 2025; Zapantis et al., 2019)
Knowledge about energy efficiency and required measures	
Opportunities	**Threats**
The opportunity to receive project financing from European funds (European Commission, 2021e)	Economic instability (caused by instability from the outside – exchange rates, politics, etc.) (Kiselev et al., 2017)
The ability to attract specialists from other countries	An increase in the price of electricity
Decrease in the amount of CO_2 emissions in the country	
The development of the production sector	

CO_2 Capture and Utilisation in Companies

This group considers all aspects of CO_2 capture at the place of its direct production, processing (purification and compression) and transportation to places of further use or resale, and the scenario of its use immediately at the same company (Table 14).

At this level, the main positive factors can be called the development of the sector the chance to attract funds for the company's development. By installing CO_2 capture units, it is possible to sell the dioxide, thus obtaining additional financial benefits. If CO_2 is used at the company, the captured dioxide can be returned to production (if the quality of CO_2 meets production requirements). However, financial problems are serious obstacles – high prices for the acquisition, installation and maintenance of technology can jeopardise the entire production as such, and the payback time of the purchase can be too long. If the company itself does not use CO_2 and there is no one nearby who could buy it, then the purchase of the unit also does not seem to be a profitable solution.

Table 14.

CO_2 capture and utilisation in companies

Strength	**Weaknesses**
Knowledge of technology	The need to acquire new technologies (Bäcklund et al., 2024; Kiselev et al., 2017)
Additional income for production (CO_2 is a by-product that can be sold or utilised)	The high cost of technology may put at risk the existence of the company (Bernal-Torres et al., 2025; Kiselev et al., 2017)
Variety of technologies	Lack of free space for technology installation
Easy to install CO_2 capture systems	The need to redo an existing production process
Synergy with an existing company (transportation)	Additional financial costs associated with the maintenance of new installations (Kiselev et al., 2017)
The technological advantage over competitors (utilisation)	The need to create a logistics network (transportation)
No dependence on CO_2 suppliers (utilisation)	
Confidence in the quality and purity of captured CO_2 (utilisation)	
Opportunities	**Threats**
Additional jobs	Increasing requirements for CO_2 quality
Possibility to attract funding from the EU and the state	Too long technology payback time

Continuation of Table 14.

Chance to get foreign investment	Absence of a representative of the technology manufacturer in the country (Bernal-Torres et al., 2025)
Possibility to reduce the amount of generated emissions	Distance from a potential buyer (transportation)
Sustainable development	Dependence on the CO_2 buyer(transportation)
The ability to reduce the price of the final product, which will attract additional buyers (utilisation)	Conservatism and unwillingness to change (utilisation)
	Alternative resources to CO_2 (utilisation)

According to Table 14, it becomes evident that in both cases – as for the producer-supplier of CO_2 (produced and sold) and for the producer-consumer (at the same company), the main problems are financial difficulties – new equipment requires significant financial investments and the company is not always ready to take risks for the sake of possible profit. Another problem, which is unlikely to be solved shortly, is the technological issue. There are no representatives of enterprises producing such complex equipment in Latvia, and if this equipment fails, the company risks downtime and financial costs. Fears of this particular plan, the lack of confidence that they will be supported at the state level (funds and subsidies) – this is what does not allow modernising the often-outdated production sector at a sufficiently fast pace.

However, despite such serious barriers, for both parties, there are also excellent reasons for taking risks and acquiring new technologies for using CO_2 in production – confidence in the quality of the supplied resource (CO_2) and that these supplies will be continuous, the ability to save on resource (which, most likely, will only get more expensive every year). To modernise an existing production, it is possible to attract funds and/or participate in international projects, such as H2020 (European Comission, 2021).

As a main finding of SWOT analysis is that financial assistance is highly important in all levels of CCUS implementation (entrepreneurs, national and international). Many CCUS projects are still in the pilot or early TRL stage, making it even more difficult to acquire funding, as most of the funds work either with projects already in the final stage of development and at the stage of popularisation, or with an enterprise of a certain size, with a certain annual turnover, or work in a particular sector (Wyns et al., 2019). Even if it is possible to attract sufficient funding already at the stage of project development, in the future, only demonstration projects will not be able to interest potential investors. Another possibility to make CCS and CCS technologies more attractive is to change the taxation system as it was made in the United States. Every company can get a tax credit for every captured metric ton of CO_2 (CATF, 2018; Office of the Law Revision Counsel United States Code, 2021). To really contribute to the introduction and active use of CCS and CCUS installations, it is necessary to pay great attention to the research and development of appropriate technologies; the enterprise must be able to invest in projects that are still based mainly on the research of various institutes and organisations, as well as large companies (de Medeiros Costa et al., 2021; Saito et al., 2019).

***ArcGis* Map and SWOT analysis**

Geographical analysis indicated CO_2 production and its potential valorisation points, which allows to analyse the feasibility of using CO_2 on a national scale. One of the factors affecting the speed of introduction of new technology also depends on the human factor. *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 – a place where due to the dense population, changes occur more often. People react more quickly to what is happening in the neighbouring production and also modernise theirs (Cowie et al., 2020; UNCTAD, 2018). In turn, regional enterprises can supply the produced CO_2 to biofuel production plants, which would also positively affect the level of regional development.

At the presence of demand from the potential consumer, the produced CO_2 will not be emitted into the atmosphere but will be used to create new products with a high added value. According to literature sources (Anwar et al., 2020; Umar et al., 2025), CO_2 can have many applications that relatively little financial investment can be realised. This is, for example, the food industry – in large cities, there is a production or processing of various food products, as well as cleaning safe cleaning agents. The food industry, in the course of its activity, produces CO_2 of a high degree of purity (especially the alcohol industry – yeast emits almost pure CO_2) – it can be used in the chemical industry (Anwar et al., 2020; Umar et al., 2025).

Large amounts of CO_2 are generated in boiler houses located throughout the country. This gas contains many impurities, making it unsuitable for chemical or food industry. However, if there are greenhouses nearby, this gas, albeit in small quantities, can be used as a catalyst for plant growth (G. Li & Yao, 2024). Large greenhouses, for example, are located at SIA Getlini and SIA Ziedi landfills. The heat generated during the decomposition of garbage is sent to greenhouses, allowing the harvesting vegetables and flowers even at an atypical time for this. If CO_2 was supplied to these greenhouses along with heat energy, the yield could be increased (R. Wang et al., 2015). Alternatively to greenhouses, CO_2 can be valorised in algae ponds – in both cases the amount of impurities in CO_2 flow may be up to 30 %. (G. Li & Yao, 2024; R. Wang et al., 2015). Unfortunately, in Latvia, large enough greenhouses are not widespread, and there are no industrial-scale algal ponds. This means that all CO_2 produced and liquefied (in the case of transportation) for further utilisation must be processed with a high degree of purification, which undoubtedly entails additional costs.

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. In an urban environment, such skills are also easier to acquire than if production is located in rural areas (OECD, 2020; UNCTAD, 2018). Competition with existing classical technologies plays a vital role in developing innovative technologies. The urban environment is also a more conducive environment for introducing new technologies, since people are less conservative than residents of rural areas (Cowie et al., 2020; UNCTAD, 2018).

FCLM and SWOT analysis

Having received the results of the previous two analyses – SWOT and *ArcGis* maps, the FCLM analysis was performed. The combination shows the influence of various factors on each other and the relationship between them. In this case, the scheme of relationship at the national level was taken observed – the influence of politics and entrepreneurs within the country (Fig. 23).

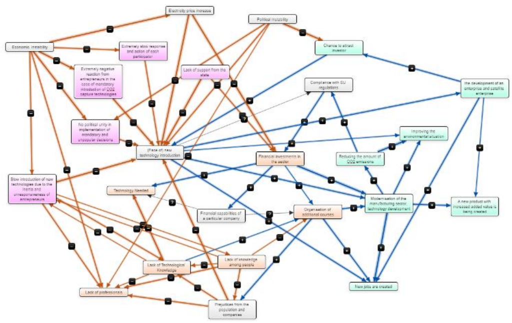
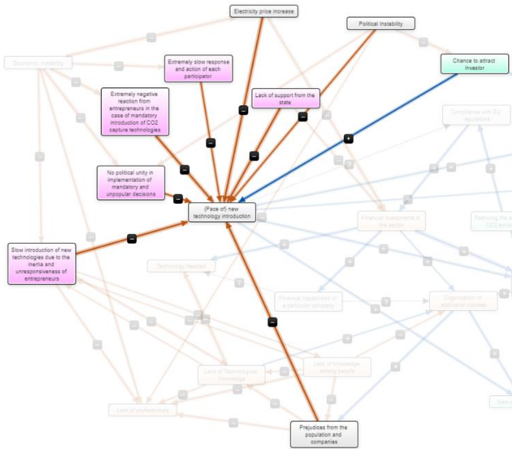


Fig. 23. Results of FCLM analysis (Annex B).

Blue lines show a positive impact on the factor, and orange lines – are a negative one. Grey lines represent neutral or potential impact. Pink blocks are political factors; grey are external, 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 (Fig. 24).



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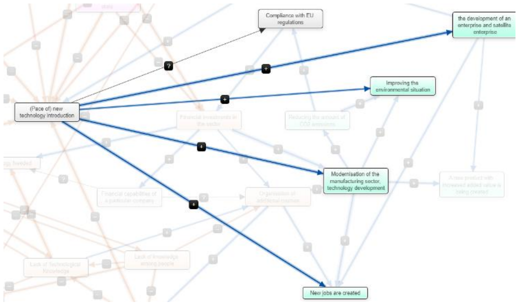


b

Fig. 24. Factors, a) influencing the rate of introduction of technologies, b) which are influenced by the rate of introduction of new technologies (Annex C and D).

The speed of technology implementation is influenced by political factors (inertia of political forces, lack of unity in the adoption of critical CO_2 requirements, extremely negative attitude of politicians and influential entrepreneurs to the implementation of mandatory requirements for CO_2 emissions, etc.), and the so-called – public, such as prejudice about the dangers of CO_2 and the need for change. An important role is also played by the lack of educational events where people would receive information about the seriousness of the problem and the need for modernisation. Since the introduction of technologies and the organisation of additional training and educational courses for citizens and workers, require financial investments, this factor may be key in fulfilling the obligations undertaken to reduce the amount of CO_2 produced in the production sector.

All the threats and weaknesses, advantages and opportunities listed in the SWOT analysis appear in the FCLM analysis. However, the FCLM analysis allows seeing the entire chain visually and assessing what is the primary factor (political factor and funding) and what is secondary (lack of awareness of the population and lack of skill in working with new technologies).

3.4. Survey Outcomes: Perceptions of CO_2 Emissions Among Stakeholders

Public's Opinion

To carry out this step of the methodology, an anonymous survey was organised. The survey was conducted anonymously, electronically via the Internet. One hundred eighty-nine people received the questionnaire, but only 82 respondents sent answers. The survey of the convenience sampling questionnaire involved university staff and students. The purpose of the questionnaire was to conduct a comprehensive analysis. The number of completed questionnaires may have been influenced by the respondents' lack of interest in the topic and limited time to fill out the survey. According to the results, most of the respondents are women (77 %), and summing up the age of the respondent; the leading group is in the range of 19–25 years (42 %) and 26–40 years (40 %). This questionnaire allowed getting the opinions of people of different ages. Of the respondents, 17 % noted that they were in the group of 41–60 years. Of the respondents, 28 % of respondents have higher professional education, and 60 % of respondents have degrees – bachelor's (22 %), secondary vocational (16 %), secondary (18 %), and master's (4 %). Of all the responses received, 11 % of respondents indicated that they had not yet received higher education and 1 % had a doctorate degree. In general, it can be concluded that the respondents' level of education is reasonable. It should also be taken into account that many educational institutions strive to inform students about environmental problems and how to solve them. Therefore, it can be assumed that the other answers of the respondents are the answers of competent people.

Public Awareness of the CO_2 Emission Problem

The first question in the questionnaire was aimed at determining public awareness of the problems of CO_2 emissions and therefore was asked as "*Have You ever heard of the CO_2 emission problem?*" The answer to this question was almost unanimous – 93 % of the respondent answered in the affirmative.

Importance if the CO_2 Problem to the Public

The aim of the next question ("*Does the problem of the CO_2 emission bother You and seem urgent*") was to find out the public opinion on this problem and what do they think about it. The answers to this question were divided – 48 % of respondents answered that they were concerned about CO_2 emissions, but 32 % responded that they had too little information to answer this question competently and confidently (Fig. 25). This means that educational institutions should pay more attention to environmental issues and CO_2.

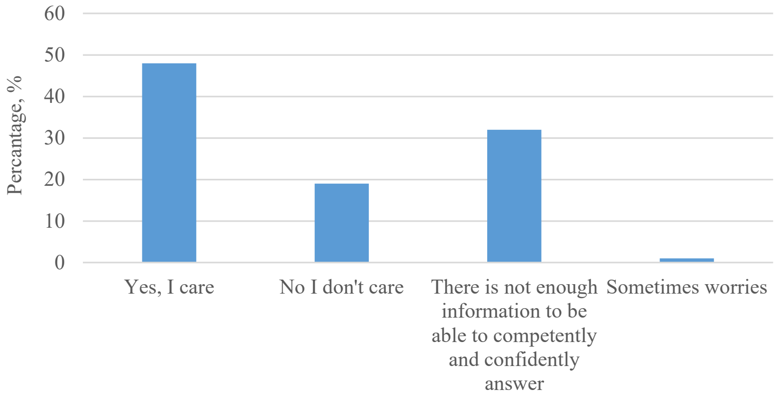


Fig. 25. Answers on does the problem of CO_2 emission bothers respondents.

However, it should be noted that 19 % of respondents marked the option "*No, I don't care*" Considering that 32 % of those who answered about the lack of information also cannot give precise details on emissions, in total, this is 51 % of people who do not see a problem in CO_2 emissions or do not consider this problem to be relevant.

The Most Significant and Relevant Impact of CO_2 Problem in Public's Opinion

The question "*Indicate the reasons that seem to You the most significant and relevant*" is more in-depth, and its main task was to find out what precisely the respondent considers the most important in the problem of CO_2 emissions – the impact on human health, the impact on the environment, and the problems caused by changes in the socio-economic sphere of life or caused by changes in "behavior nature" – an increase in the average annual temperature, an increase in the water level, climate instability, and so on. It is assumed that this question was answered by those who answered "*yes*" to the previous question, "*Do You care about the CO_2 problem*". The question allowed selecting of multiple answers. The response options "*Effects on human health*" and "*Climate change and environmental impacts*" were marked by the respondents almost the same number of times – 38 and 37 times, respectively. According to this question and the results obtained, the impact of climate change on the economy is the least of public concern (Fig. 26).

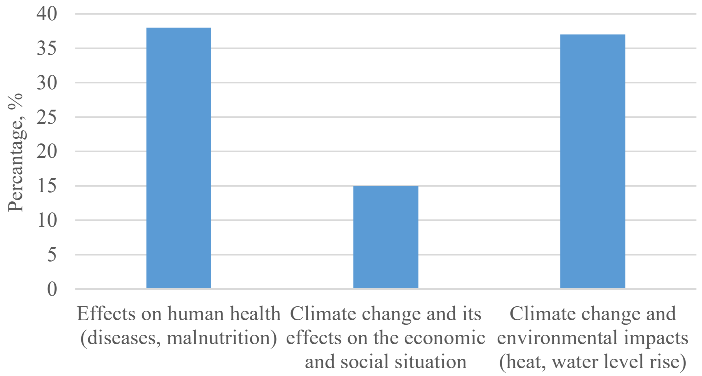


Fig. 26. Reasons why the problem seems relevant.

Reasons why CO_2 Problem Doesn't Seem Relevant

Since one of the previous questions had the option to answer "*No, I don't care*", the next question – "*Why does the CO_2 problem seem irrelevant to You?*" – was designed to determine the reason for this position. Similar to the previous question, the responses of the two groups differed (Fig. 27).

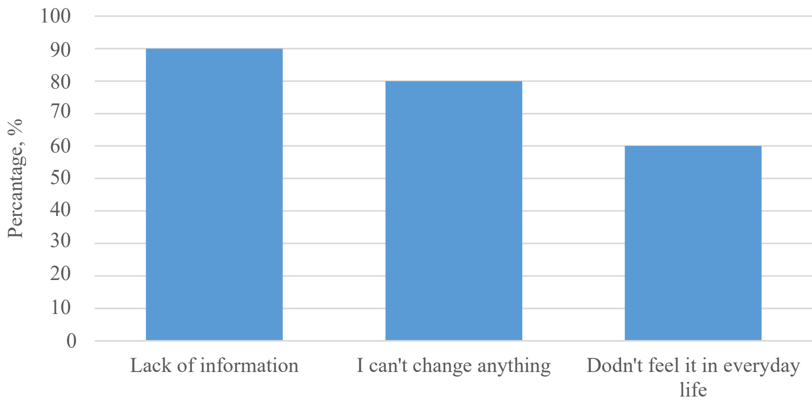


Fig. 27. Reasons why the problem seems irrelevant.

Based on the answers provided, it can be assumed that the main reason for not realising the problem is the lack of information among people. If more people talked about how much the climate has changed in the last few years (a period that is easier to observe), it would be easier to understand the magnitude of the emissions problem and the consequences of inaction. Also, speakers noted the option "*I can't change anything*". This answer is similar to psychology –

"*I can't change anything, and therefore I won't do anything*". This inspires specific fears that the public will not do anything to reduce the amount of emissions created by them shortly. There is a need for educational events that tell what the average person can do to improve the climate.

How Relevant is the Problem of CO_2 Emissions for Latvia

The purpose the question "*In Your opinion, is the problem of CO_2 emission relevant for Latvia?*" was to determine the attitude of the inhabitants of Latvia to the problem – how relevant it is in the context of the country.

As follows from the results obtained, most of the respondents answered that the problem of CO_2 emissions is relevant to Latvia. However, 18 % responded that there are more critical problems in the country. It is oppressive that almost a quarter of the respondents could not answer this question. As a result, the votes were divided almost equally – 58 % against 42 %. However, even though only 16 % more people recognise the relevance of the problem for Latvia, it is necessary to conduct educational activities that would tell and show how CO_2 emissions affect Latvia.

For Whom the Reduction of CO_2 Emissions May Be the Most Important and Relevant

The question "*Mark the Groups of People/Institutions for Whom, in Your Opinion, the Reduction of CO_2 Emissions May Be the Most Important and Relevant*" was aimed to determine who should be most concerned about CO_2 emissions in the public's opinion. There were several possible answers to this question (Fig. 28).

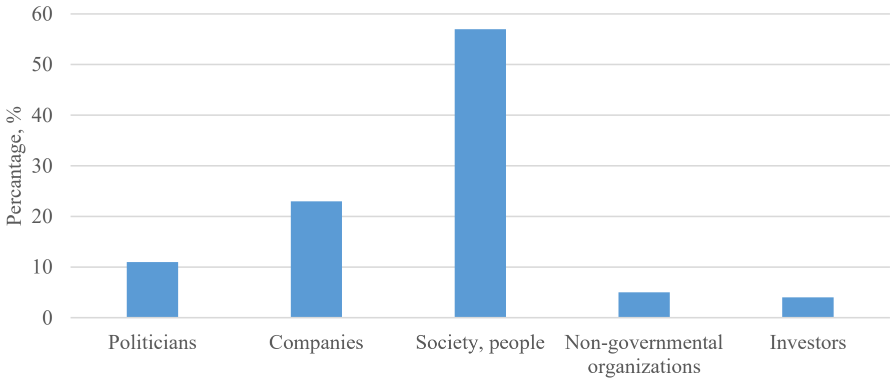


Fig. 28. To whom the reduction of emissions is more critical in Latvia on respondent's opinion.

The answers to this question were distributed according to expectations – the public believes that the issue of emissions is essential to the public itself. And only then do companies (entrepreneurs) follow. Non-government organisations and investors received the least number of points, which means that the public is confident that such changes are not critical for these organisations. According to the results of this issue, the public is confident that climate change and the consequences they cause will primarily affect ordinary people, and not investors. Companies can suffer due to the introduction of new laws that complicate the work of the enterprise.

In general, the result of the question indicates that the public understands that there is a problem, and it is essential for every person.

The Need for Action

To assess the readiness of people to act, several questions were asked about the need to reduce the amount of emissions. Thus, the questions were asked: "*Do You think it is necessary to reduce the amount of CO_2 emissions?*", "*Are You doing anything now to reduce the amount of CO_2 emissions in Your daily life?*" and "*What actions would You be willing to take to reduce the negative impact of CO_2 emissions?*"

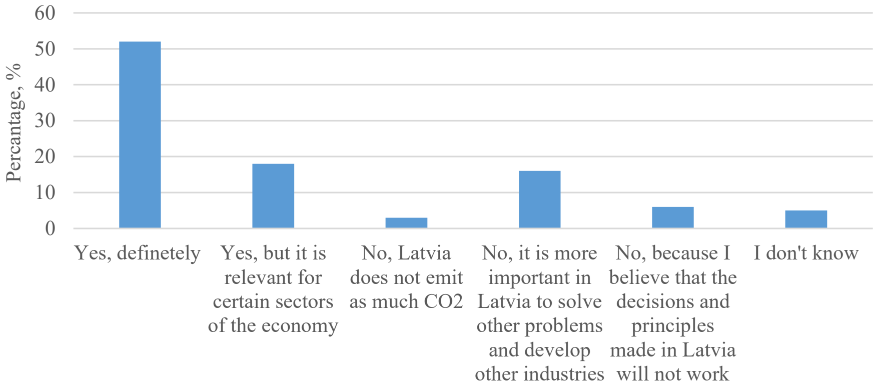
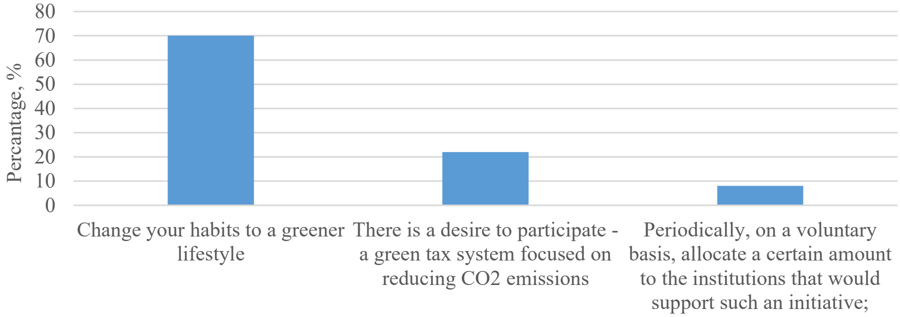


Fig. 29. The necessity to reduce CO_2 emissions on respondent's opinion.

The questionnaire showed that it is necessary to reduce the amount of emissions and the option that the reduction is relevant for specific sectors (Fig. 30). This result raises questions about the people's trust in the system of laws in the country and their effectiveness in practice. The authorities should be told what measures were planned, how they were implemented, and what results were obtained. This would allow residents to have confidence in the system. Also, many people are sure that there are more pressing problems than CO_2 emissions (16 % of the total responses) (Fig. 29).

According to the results (Fig. 30(a)), 70 % of respondents are ready to change their habits if it helps to reduce CO_2 emissions. At the same time, almost a quarter of the respondents answered that they were prepared to participate in the "green tax system" (22 %). In turn, answering the question of what they are doing now in everyday life (Fig. 30(b)), the answers were divided almost evenly – 47 % of respondents believe that they buy more environmentally friendly products, but 50 % answered that they do nothing due to certain factors (for example, lack of finances to buy more expensive, but more "green" products).



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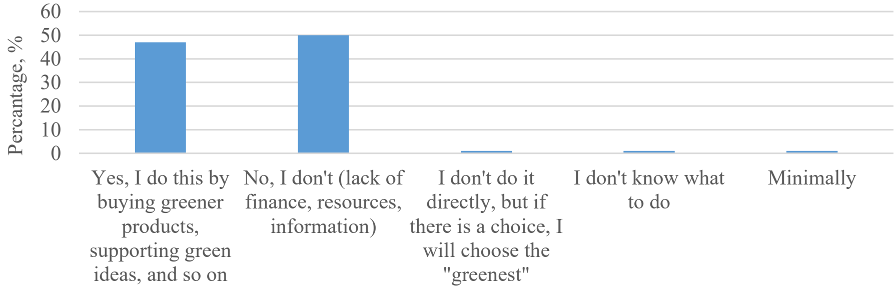

b

Fig. 30. Questions: a) *What actions would You be willing to take to reduce the negative impact of CO_2 emissions?* b) *Are You currently doing anything to reduce CO_2 emissions daily?*.

People are ready to change, but sometimes the inaccessibility or inability to purchase more environmentally friendly products or leave more environmentally friendly destroys the motivation of people to act.

Survey of Entrepreneurs

For a comprehensive analysis, it is important to know the entrepreneurs' opinion. Unfortunately, the feedback was shallow – only 11 % of the questionnaires were completed (10 answered questionnaires from 90 sent). The low response rate impacts the study's effectiveness and only partially reflects entrepreneurs' opinions. This low feedback may be due to entrepreneurs' lack of interest in CO_2 emissions, disinterest in surveys in general, or lack of time to complete the questionnaire.

The respondents were asked to answer questions such as "*Field of activity of the enterprise*" and "*Duration of activity*" in the questionnaire. Thus, 40 % of respondents answered that they work in the agricultural industry and 20 % – in the manufacturing industry; 10 % each received answers "*Extractive industry and energy*", "*Chemical industry*", "*Ship repair industry*", and "*Metalworking*". In turn, when asked about the duration of the activity, 90 % of respondents answered that they had been working for more than 20 years, and 10 % – 8–19 years. However, despite such an extended period, the topic of reducing CO_2 emissions is by no means relevant to all enterprises:

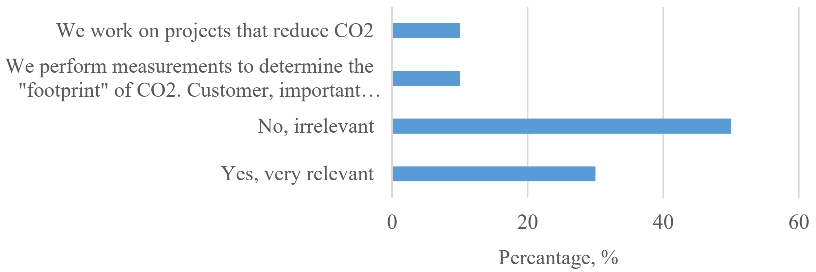

Fig. 31. Entrepreneur's field of activity.

Only half of the respondents stated that the problem of CO_2 emissions is more or less relevant to them. However, since most respondents are involved in the agricultural sector, such a result was expected (Fig. 31). The agricultural industry does not produce large amounts of CO_2 emissions and does not have appliances that require the installation of specialised devices for the purification of produced gases.

The Most Relevant Reasons in the Context of CO_2 Emission Reduction

Answering the question about the reasons that are relevant for the enterprise in the context of CO_2 emission reduction, the option "C*ompliance with the requirements and legislation of the state*" received the most response (50 %), leaving the option "*Impact on human health*" in second place (40 %). This result is quite logical from the companies' point of view since they must comply with all laws adopted by the state. Because the fact that the options "Impact on human health" and "*Impact on climate*" also entered the top three indicates that entrepreneurs are aware of the role of emissions and CO_2 in particular on the environment (Fig. 32).

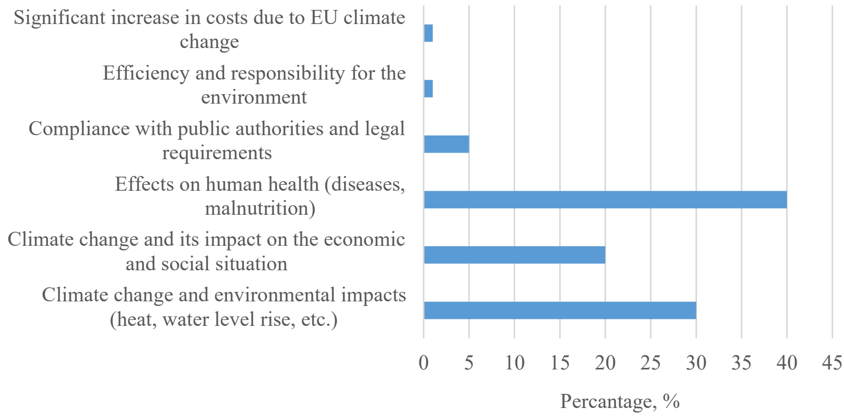

Fig. 32. What reasons are the most relevant in the context of CO_2 emission to entrepreneurs.

Motivates/Reasons to Reduce the Amount of CO_2 Emissions

The next question was aimed at determining the motives of the enterprise and was asked as "*What are Your Motives/Reasons to Reduce the Amount of CO_2 Emissions at Your Company*". This question was open-type, allowing respondents to write their own opinions.

Considering the results of the previous question, it was essential to see personal motives – concern for the environment and human health. Thus, among the answers received were – "*Efficiency and care for the environment*", "*Reducing the consumption of energy resources*", and "*Universal – climate change*".

Is there anything currently being done at Your enterprise to reduce emissions?

According to the answers to this question, enterprises can be divided into three groups:

1. Businesses only realise their role in climate change;
2. Enterprises that actively and comprehensively work to reduce their impact on the environment;
3. Enterprises for which the emissions issue is not (yet) relevant.

Since this question was also open-typed, it was very informative to see the views of entrepreneurs on the need to assess the impact of their enterprises on the environment. So, among the answers were such as "*We do nothing*", "*We carry out internal audit, monitoring, certification of products indicating the created and simultaneously captured CO_2 emissions throughout the entire life cycle of the product*", and "*We try to use energy resources more efficiently*". Some entrepreneurs indicated that they are reviewing the production process to identify areas that could be upgraded to be more efficient and environmentally friendly and optimise logistics. Analysing the answers received, it is sure that most entrepreneurs approach the issue of emissions very carefully and deliberately. However, it is recognised that at times, due to the specificity of production and its complexity and based on the requirements of the legislation, it becomes increasingly difficult for enterprises to comply with increasingly stringent laws. One of the respondents answered that if (when) there is a need, the issue of transferring production to another country with less strict legislation will be considered.

The Entrepreneur's Motives to Reduce CO_2 Emissions

Similar to the previous question, the next question was also about the motives, but specifically for the entrepreneur – "*What could motivate You to reduce Your CO_2 emissions?*", this question was also open type. According to the answers, enterprises, by their motivations, can be divided into three groups:

1. Nothing can motivate them;
2. Support from the state, the European Union. The most frequently cited assistance is financial, as equipment upgrades are often required. State guarantees, the well-being of workers, the ability to participate in the CO_2 trading system, etc. are also needed;
3. Can be motivated by external factors, such as higher cost of resources, lower prices for "green" technologies, etc.

However, one of the answers received stands out – "*I think that the situation with emissions in Latvia is much better than in the rest of the world, and at the moment, it is more important not to "cut off the shoulder", but gradually and slowly move towards the green course. You can't run ahead of everyone – you have to act deliberately from the very beginning*". This answer can be regarded as advice for a wait-and-see policy for enterprises and a more deliberate policy for the state. It is necessary to adopt laws that will be most effective in the context of Latvia but will not cause irreparable damage to the industrial sector.

Willingness and Readiness of Entrepreneurs to Act to Reduce CO_2 Emissions

Analysing the willingness of entrepreneurs to pay, the question was asked – what exactly would entrepreneurs be ready to do to reduce emissions.

According to the responses received, entrepreneurs are ready to install additional equipment (70 %). Companies are not prepared to act globally (for example, participating in improving CO_2 policies) (Fig. 33).

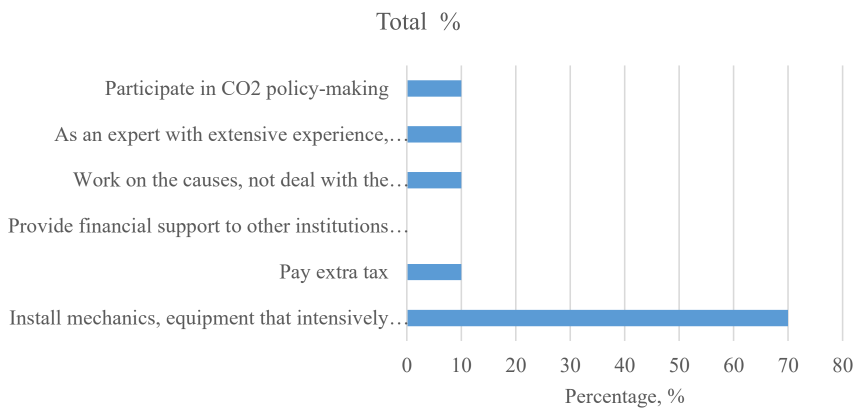

Fig. 33. Possible ways to reduce CO_2 emissions by entrepreneurs.

Willingness to Invest in Green Technologies

The aim of the last question was to determine what part of the monthly income entrepreneurs are ready to invest in the green technologies. This question showed that companies are not ready to invest in green technologies actively. 40 % of respondents answered that they are prepared to invest only 5–10 % of their monthly income. However, such answer options as "*Already invested in green technologies – at least even in heating tariffs*", "*Each situation must be considered separately*" and "*Depending on the return*" received 10 % of the total number of answers. Even though companies are currently not ready to give away most of their income, the answer "*Less than 3 %*" has not become the most popular (Fig. 34).

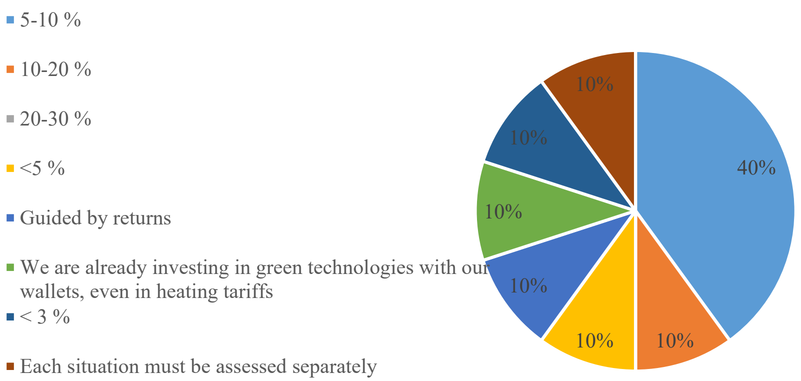

Fig. 34. Part of monthly income entrepreneurs is ready to invest in green technologies.

In general, analysing the results of a survey of entrepreneurs, it can be concluded that in the context of reducing CO_2 emissions, entrepreneurs can be assessed according to the following criteria: interest in a particular issue, the scope of the enterprise (for an agricultural enterprise, the problem of CO_2 emissions is less relevant than for a production workshop). However, 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.

3.5. Comparative Analysis of CO_2 Legislation Across Jurisdictions

International Legal Framework

International legislation regarding the protection of the environment 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 Paris Agreement was adopted in 2015 and signed by 191 countries worldwide. The agreement itself is a good step in the right direction. However, the text of the deal is highly inaccurate. The consequences for the country in case of refusal to follow the document are also not described (United Nations, 2015). Besides, the cooperation of countries within the framework of this agreement is weakly specified – it is indicated as "voluntary" rather than "desirable" or "obligatory" (United Nations, 2015).

Countries are given the freedom to participate. Any country can withdraw from the agreement three years after its signing (United Nations, 2015).

The European Climate Law (also known as Regulation (EU) 2021/1119) is a tool to limit global temperature rise to 1.5 degrees compared to the preindustrial era (European Commission, 2021j). The law implies that using the legislation of the European Union; countries must equally reduce the amount of created emissions so that by 2050 no country in the Union produces GHG. It should be clarified that such a policy requires specific knowledge in science since it sets the methodological recommendations for the European Scientific Advisory Board on Climate Change (European Commission, 2021j).

As an additional tool for controlling and reducing the amount of emissions, the European Union has developed its own emissions trading system, that aims to decrease the amount of emissions created using the economy. All Union countries and EEA members participate in it, making this system the largest in the world (European Commission, 2022d).

Because not all countries of the European Union are technologically advanced in the same way, a special equalisation fund, The Modernisation Fund, was created. It is possible to distribute up to 310 million ETS permits within this fund. However, not in all countries, these funds can be implemented. For Latvia, this fund could be beneficial, as it would help enterprises become more efficient and, if possible, switch to renewable energy sources. The country has already applied for investments for 2021–2030 and received 3,968,834 emissions allowances with a value of about 160 million euros (European Commission, 2021g).

The Investment Fund is the successor to the NER300 program. With a budget of 2 billion euros, this program was created to develop low-carbon technologies with a focus on CCS and innovative technologies for producing renewable energy on an industrial scale (European Commission, 2022b).

The Innovation Fund is the most extensive funding system that aims to stimulate and support the adoption of innovative low-carbon technologies. The fund receives its funding mainly from the sale of emission permits. This fund is designed to help businesses that decide to install greener technologies, including CCS, CCU, and similar carbon capture and utilisation facilities.

Regulatory changes will further benefit early adopters of CCU technologies shortly. The Commission's proposal creates an incentive to capture and utilise emissions to be permanently chemically bound in the product so that they do not enter the atmosphere during everyday use (European Commission, 2021i). Assistance focuses on developing small and large-scale low-carbon technology projects, carbon capture, utilisation, storage technologies, and renewable energy and energy storage methods. Unlike the Modernisation Fund, this fund is available to every country in the European Union (European Commission, 2021e).

CCS Directive assumes that CO_2 will be stored in geological repositories safe for humans and nature. Such storage will allow permanent storage of CO_2, thus releasing the emissions obtained during production, not into the atmosphere but underground holds (European Commission, 2009).

The directive is valid throughout the European Union. However, it does not apply to storage facilities with less than 100 kt storage capacity used in research projects (European Commission, 2009). Even though the directive supports introduction of CCS, countries are free to choose whether to develop such repositories on their territory or not. The government has the right to completely ban the creation of underground CO_2 storage (European Commission, 2009).

The Commission of the European Union intends to promote the development of carbon capture technologies. 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 the Table 15 below.

Table 15.

European laws and funds

Name	For whom	Goal
Paris Agreement	All countries who signed the document (191)	To control and limit global temperature rise
European Climate Law	All EU countries	Tool to limit global temperature rise
ETS	All EU countries + EEA	Tool for controlling and reducing the amount of emissions
Modernisation fund (Kioto protokol)	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

Latvian Legislation on CO_2

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 is a priority for implementation and cannot be ignored in case of any confrontation with local laws (European Commission, 2022c).

The Law on Pollution came into force in 2001. The law aims to prevent and/or reduce the negative impact of pollution on human health, property, and the environment and neutralise the consequences of the damage caused by climate change (Saeima, 2001). It is essential to add that this law characterises GHG. GHG are claimed to be gases of both anthropogenic and natural origin present in the atmosphere and absorb/reflect infrared radiation. A list of these gases is – CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), nitrogen trifluoride (NF_3) (Saeima, 2001).

Like other countries of the European Union, Latvia participates in emissions trading. In this regard, the Cabinet of Ministers has developed a set of rules that came into force in 2012. According to these rules, the institution responsible for the trade process, the Ministry of Environmental Protection and Regional Development, was appointed. The institution's responsibilities include control over the trading process, supervision of the fulfilment of obligations by buyers, summarising and analysing the information on emissions, and informing the European Commission about the income received from the auction (Cabinet of Ministers, 2012).

In 2018, the Cabinet of Ministers developed and launched a methodology for calculating GHG emissions. The primary purpose of the method is to assess the impact of specific planned and/or already implemented climate change measures. The methodology can be successfully used for various calculations. If necessary, if the conditions of the required measures do not fall under the main algorithm of the method, an alternative calculation method is proposed (Paragraph 10) (Cabinet of Ministers, 2018).

This Climate law is still under development. It is supposed to replace the "On Pollution" (Saeima, 2001). The new law aims to limit climate change and ensure adaptation to climate change in the country. This is expected to be achieved by reducing anthropogenic emissions and increasing carbon sequestration by 2050, achieving the primary goal of climate neutrality. This result is planned to be maintained and improved up to harmful emissions in the future.

The focus should be on paragraph 42, which stands for:

- On the territory of Latvia, in its exclusive economic zone and on the continental shelf, storage of CO_2 in geological structures and the vertical water layers is prohibited;
- The Cabinet of Ministers approves the procedure in which the storage of CO_2 is possible in cases not mentioned in the first part of this paragraph (Ministry of Environmental Protection and Regional Development, 2021).

The second point is an essential difference from the previous law, "On Pollution," the difference from which the new one makes it possible to consider specific projects in private by the Cabinet of Ministers. This means that projects aimed at capturing and storing CO_2 are potential in the future. Additionally, the law stipulates that the Cabinet of Ministers is responsible for the procedure for transporting CO_2, as well as for determining the course for its use (Ministry of Environmental Protection and Regional Development, 2021).

In Latvia, GHG emissions are controlled in five sectors: energy (excluding transport), industry, agriculture, land use and forestry, and waste management. The control looks like a multilateral accounting that includes GHG and CO_2 calculations and information from the emissions trading register (Ministry of Environmental Protection and Regional Development, 2020). Data on emissions are publicly available and include detailed information – which company, for which year, how many, and what emissions were produced (Latvian Geological and Meteorological Center, 2022). Additionally, it is possible to analyse emissions based on the category of the enterprise (category – permit for polluting activity). Data for each enterprise is available on the Valsts Vides Dienests website (eng. – State Environmental Service) (State Environmental Service, 2020). The amount of CO_2 in Latvia has increased slightly. However, as the trendline shows, the increase is still observed. In 2019–2020, emissions decreased due to the reduction of production scale due to the quarantine caused by Covid-19. However, emissions are expected to return to or exceed previous levels if high electricity prices force producers to switch to less environmentally friendly resources, such as coal (Alvarez et al., 2021), (Crellin, 20201), (Potter & Jackson, 2021). This means that the amount of CO_2 emissions will increase.

In February 2020, the National Energy and Climate Plan for 2021–2030 was adopted. The document determines the basic principles, goals, and directions of action of the Latvian state energy and climate policy for the next ten years, taking into account the outlined long-term development directions. This plan sets out goals and ways to achieve them in various sectors. These include reducing GHG emissions and increasing the market share of renewable energy. This step will significantly improve the efficiency of the energy sector and promote the introduction of innovative technologies in the manufacturing industry. An additional advantage will be an increase in the competitiveness of enterprises, which, in turn, will have a positive effect on the economy as a whole (Ministry of Economics Republic of Latvia, 2020). This document pays little attention to carbon capture and/or storage systems but, at the same time, states that in the future, cooperation with other countries on innovative technologies (CCU, hydrogen, etc.) will be sought. It is also planned to increase CO_2 capture and storage systems investment up to 2 % (in the previous period, 2014–2018, it was 0 %) (Cabinet of Ministers, 2020b).

Action Plan for Reducing Air Pollution 2020–2030 was developed within the law "On Pollution" (Saeima, 2001). The action plan aimed at reducing the amount of emissions was created in 2020 and is designed for ten years. The main idea of the document is to reduce the negative impact of pollution on the environment. This document differs from other documents in that it aims to reduce costs and loss of working time caused by air pollution due to health problems and visits to the doctor (Cabinet of Ministers, 2020a). The plan is expected to help Latvia meet the emission reduction targets set by the European Union by 2020, 2025, and 2030. Additionally, the program should improve the quality of human life and health and improve the state of the ecosystem and air quality in Latvian cities. Implementing the measures included in the plan will also reduce GHG emissions, promote innovation, and increase the competitiveness of technologies. All listed legislative documents of Latvia are summarised in the Table 16.

Table 16.

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."

Continuation of Table 16.

GHG Monitoring and reporting	Procedures for monitoring, calculating, and reporting the GHG emissions
Air Pollution Reduction Action Plan 2020–2030. year	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

Legislation in Other EU Countries

Great Britain

Under The Climate Change Act (UK Legislation, 2008), adopted in 2019, the UK has to achieve zero emissions by the 2050 and 78% by 2035 (Press Release. Gov.UK, 2021), (UK Legislation, 2019). This law was positively adopted, as it involves the transformation of the energy sector and a significant simplification of the solution to climate change issues (Fankhauser et al., 2018). However, several additional policies and measures have been created to achieve the set climate targets. Specifically, the following points are relevant to emissions: New Emissions Trading Scheme; Contracts for Difference, Climate Change Levy (Black, 2021). In parallel with the legislation, CCS projects are also being developed. In 2015, a competition with a budget of ~1.18 billion euros for CCS development ended (HM Government, 2017). There are plans to build carbon storage facilities in the North Sea, and in the north-eastern part, it is planned to create a network for transporting and storing CO_2. It is assumed that thanks to this network, it will be possible to transport gas from all over Europe (Institution of Civil Engineers (ICE), 2017). The UK government has also announced that it will be phasing out coal burned at stations not equipped with CCS (Department for Business, 2018).

Germany

Germany has raised the percentage of reduction in GHG emissions. However, unlike the UK, not so much – 65 % by 2030 and 88 % by 2040 (IEA, 2022b). Unlike the UK, which introduced the first unified climate law in 2008 (Fankhauser et al., 2018), Germany did not have a similar direction until 2019. In 2021, the German Bundestag introduced reforms to Climate Law. The rules for reducing emissions by 65 % and 88 % by 2035 and 2040, respectively, are written for the LULUCF sector. It is planned that by 2045 the industry will become negative by 35 million tons of CO_2 emissions (i.e. will capture CO_2, not emit). Additionally, the law of permanent storage of CO_2 in holds is prescribed (Bundesministerium der Justiz, 2012). It spells out the rules potentially allowing medium-sized CCS pilot projects. However, not all states are allowed to develop the project, and many forms of Germany have introduced a ban on CCS projects in their territories. The deadline for submitting applications for the development of storage facilities ended in 2016, and at the moment, it is possible to launch only a project approved before the designated year. The

CO_2 Storage Act was planned to ensure the permanent storage of CO_2 in underground storage of earth rocks in the most environmentally friendly and sustainable way. The law regulates the complete analysis of the stones and the CCS project itself. The act would provide annual storage of up to 1.3 Mt CO_2 with a maximum storage capacity of 4 Mt CO_2 per year. Despite the closure of the initiative in 2018, opinions began to be expressed about the resumption of projects in the direction of storage and utilisation of CO_2 (CCS and CCU). Natural storage can be used in cases where production does not use coal or gas energy. It was suggested that these technologies could be used to protect the climate in industrial processes (Wettengel, 2018).

Sweden

In June 2017, the Swedish government decided to introduce amendments to climate policy. The main modification is introducing a framework, as it determines the implementation of the Paris Agreements in the country. Sweden has said it will achieve zero GHG emissions by 2045. An 85 % reduction is planned by modernising equipment, introducing innovative technologies, and abandoning fossil fuels. The remaining 15 % reduction will be completed by accumulating CO_2 in forests and land and the active use of CCS technologies (Swedish Climate Policy Council, 2021). It is planned that carbon capture technologies will be able to reduce emissions associated with both fuel use and various technological processes. The cement industry is currently considered the most natural area for CO_2 capture installations – the combination of CCS installations and bioenergy can significantly reduce GHG emissions in the long term. A guide to implementing carbon capture and storage technologies has also been developed. It should be noted that this policy is aimed not only at large emitters but also at smaller ones (Government Offices of Sweden, 2020), (Ministry of the Environment and Energy, 2017). Additionally, the government has established a National Centre for CO_2 Capture and Storage. Financing is provided to capture and subsequent storage of CO_2 created from renewable energy sources (creation of the so-called biological CCS) (The Swedish Environmental Protection Agency, 2021). Industrial Leap is also a severe document, the development of which began in 2018 and will end in 2040. The main goal of the reform is the transition of the manufacturing sector from old technologies to those that do not produce emissions in the process.

One of the options for such technologies is producing energy using CCS installations. A positive aspect of this document is that the grant is available to manufacturers and researchers in this field (The Swedish Environmental Protection Agency, 2021).

Lithuania

Lithuania is included in the list of countries in the Baltic region in which CO_2 storage systems have been actively developed. In 2011, the country's legislation fully implemented the EU directive on CO_2 storage (Lockwood, 2023; Rutters & CGS Europa partners, 2013). However, in 2020, the Lithuanian government banned any projects to capture and store CO_2. This decision was justified by concerns about the risk of underground water contamination with liquid CO_2 (Shogenova, 2020a). According to (Shogenova, 2020a), this decision is the most negative for the region for 2020, as it prohibits any placement of CO_2 underground in artificial and natural storage and any work and development in this direction. Despite the adopted law, in the country's National Development Plan for 2021–2030, ideas appear for developing systems for capturing, using, and underground storage of CO_2. Such a change of opinion is due to the possibility of using the European Innovation Fund to develop CCS and CCU technologies (Lietuvos Respublikos energetikos ministerija, 2020). In addition, the chances of modernising the production sector are being considered. The technical and economic aspects of CO_2 capture installations and their subsequent utilisation and storage in specialised storage facilities in Lithuania are assessed. The plans also include a detailed analysis of the payback and feasibility of this type of project compared to other countries of the EU Common Economic Space (countries to which the CO_2 captured in Lithuania could be redirected) (Lietuvos Respublikos energetikos ministerija, 2020).

Estonia

The CO_2 utilisation and storage legislation in Estonia is not very developed. There is a law to reduce emissions (Eesti Vabariigi Valitsus, 2022), which refers to the need to modernise the manufacturing and energy sectors. Another document is the government action program (Eelnoude Infosusteneem & Secretary of State, 2019). This document already pays more attention to CCS technologies. It is planned to pay more attention to competitive, low-carbon technologies in the country's future. The following document is already more detailed in this type of question. The NECP 2030 National Plan is a communication drawn up by the requirement of the Parliament of the European Union (No 2018/1999). The plan proposes modernising the manufacturing and energy sectors, motivating producers to utilise CO_2 storage facilities, and using energy obtained from non-fossil sources (European Commission, 2016). The 2021 report of the country's energy sector proposes introducing CCS and CCU systems. This technology would help the government fulfil its emissions reduction plans (Konist et al., 2021). From a financial point of view, the authors of the document admit that at current prices for CO_2 quotas (as of March 2021, the cost was ~40 Euro per ton), it is more profitable to invest in the development and construction of infrastructure for capturing, cleaning, transporting and storing CO_2. And although CCS and CCU technologies are costly and require significant investments, in Estonia, additional funding from European grants for developing CCS / CCUS technologies was not yet attracted. In addition, the document proposes several levers to encourage the introduction and utilisation of CO_2 capture and storage systems – subsidies, capital grants (for the construction phase), investment tax credits/incentives, production subsidies, production tax deductions (for companies producing CCS / CCU), feed-in tariffs for products using CCS/CCU technology, as well as a price surcharge for all products using CCS/CCU (Konist et al., 2021). All listed legislative documents of mentioned EU countries are summarised below.

Table 17.

Legislative documents on CO_2 in EU countries

Country	Document	Goal
Britain	The Climate Change Act	To transform the energy sector, simplify the pollution of climate change issues.
	New Emission Trading scheme	Replaces EU scheme after UK left the EU
	Contracts for Difference	To fixate price on low-carbon energy. To motivate the utilisation of low-carbon energy.
	Climate energy Levy	To motivate companies to increase energy efficiency.
Germany	Federal Climate Change Act	To transform the energy sector, simplify the pollution of climate change issues.
	Climate Law	To unfasten emission reduction; to optimise the LULUCF sector.
	Carbon Dioxide Storage Act	Rules for CCS project construction and utilisation
Sweden	Climate Act	Provisions on the climate policy
	Industrial Leap	Support the production sector's transition to zero-emission technologies
Estonia	Governmental Action Plan	To implement low-carbon technologies.
	National Action Climate Plan (NECP) 2030	To modernise production and energy sectors by implementing innovative emission-control technologies
Lithuania	National Energy and Climate Plan 2021–2030	To modernise production and energy sectors by implementing innovative emission-control technologies.

Despite the poorly developed legislation on CO_2 utilisation in the Baltic States, options for cooperation between Latvia and Estonia are being actively discussed and analysed. During this cooperation, Estonia could potentially supply Latvia with CO_2, where it would be subsequently buried. Latvia has delicious geological layers suitable for storing CO_2 from the Baltic region (Shogenov & Shogenova, 2020), (Shogenova, 2020b).

The onshore CCUS scenario includes capturing CO_2 emissions from the largest emitters in Estonia and Latvia (mainly in the energy sector) and storing these emissions in North Blidene storage (Latvia). The scenario assumes that the project's construction will take about two years and last about 30 years. According to the system, the storage could hold about 204 Mt CO_2 (Shogenova et al., 2021).

3.6. 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 (European Environmental Agency, 2021) provides an opportunity to conclude the diversity and scope of EU Member States' policy instruments (Fig. 35).

As seen in Fig. 35, 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).

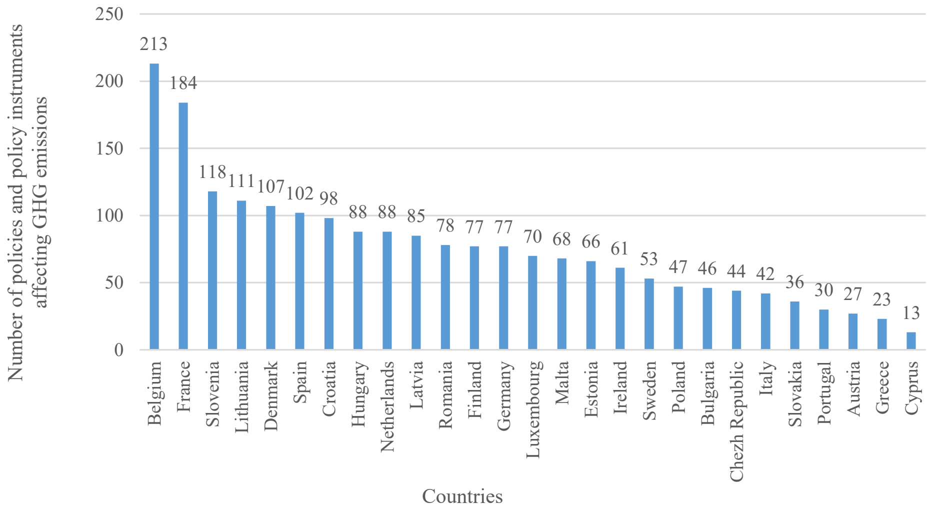

Fig. 35. Number of policies and policy instruments affecting GHG emissions in EU Member States (European Environmental Agency, 2021).

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

A summary of the evaluation results is shown in Table 18.

From Table 18, it can be seen that all EU Member States have also implemented EU Emissions Trading System (EU ETS). All twenty-seven Member States are experiencing an increase in the share of renewable energy in the energy sector and energy efficiency improvements. All EU Member States have regulations that severely restrict or ban GHG emissions into the atmosphere. The possibility of emitting fluorinated gases is significantly limited in most countries. Four Member States (Belgium, Croatia, Romania and Sweden) are implementing or planning to deploy CCS technologies. CCU technology is neither enforced nor planned in any member state.

In many EU countries, there are also different ways to tax CO_2. Still, only a few countries have a tax on CO_2 emissions specifically. According to the (World Bank, 2022), there are currently active carbon taxes in thirteen EU Member States: Sweden, Finland, Estonia, Latvia, Poland, Slovenia, Denmark, the Netherlands, Luxembourg, France, Spain, Portugal and Ireland.

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.

Table 18.

Categorisation of policies and instruments affecting GHG emissions (European Environmental Agency, 2022)

	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	

Developed Legislation System

A systematic literature analysis has shown that countries such as Belgium, Croatia, Lithuania and Sweden have the most detailed legislation on CO_2 emissions. However, other countries of the European Union are also developing and implementing documents aimed at reducing the amount of CO_2 produced in the country.

Belgium. For 2019, about 123 megatons of CO_2-eqv were created in Belgium, which is 17 % lower than in 2005 (European Parliament, 2021). In many respects, this result was achieved by introducing the latest production technologies and modernising the transport sector. A Climate Policy cuts across all industries – transport, taxation, energy, and environment (Stibbe, 2019).

The National Energy and Climate Plan for Belgium (Klimaat.BE, 2019) mentions technologies for storing and using CO_2. In 2030, licenses for many incineration plants will expire, and the issue of extending these licenses has become acute – they will be raised only if the plant meets stringent CO_2 emissions requirements. In addition, the question is being investigated how efficiently these combustion stations can capture the CO_2 they create and whether it can be further valorised in the circular economy. This type of economy implies using not even CCS but more CCU technologies, which is technologically more difficult but brings excellent benefits (Klimaat.BE, 2019). Using these technologies and creating a CCS network, it is possible to achieve CO_2 neutrality for individual regions and the entire country.

According to (Zero Emission Platform, 2022), there are currently four active CCS projects in Belgium (LEILAC, C4U, ArcelorMittal Steelanol Ghent, Antwerp@C) and 3 CCU projects (FLITE, North-CCU-Hub, Power-to-Methanol Antwerp BV). The country's policy is aimed at the circular economy; consequently, the utilisation of the created CO_2 in production will continue further, and there will be more CCS and CCU stations.

Croatia. Croatia has ten large CO_2 production sites, the largest of which are a fertiliser manufacturer in Kutina and a cement plant in the city of Našice. The remaining enterprises of the "big 10" are power stations, oil and gas processing stations, and a glass factory. The region has geological formations suitable for underground CO_2 storage. Therefore, in 2014, the CO_2 EOR Project Croatia was launched in the country, allowing it to obtain more minerals and put waste CO_2 underground simultaneously. This project allows storing more than 400 mln.m^3 CO_2 (MOLGroup, 2014). Another promising project, the Bio-Refinery Project, is an offshoot of the existing INA Downstream 2023 refinery. His new course is CCS technology, and CCU – captured CO_2 will be utilised to produce improved biofuels, biogas and other products. This project fits perfectly into the example of a circular economy when the emission of one industry becomes an essential resource for another industry (INA, 2022). A developed system of CO_2 transportation makes it possible to move gas across the country, thus enabling large contributors of CO_2 not to emit it into the atmosphere but to sell it. Even though the pipeline has already been launched and shows good results, it is planned to expand further, allowing even the country's most remote corners to use this infrastructure (Marsh & Strategy CCUS, 2021).

Lithuania. In 2020 all CO_2 capture and storage projects were frozen due to the government and public's extremely negative mood; not so long ago, the country returned to CCS technologies and the opportunities they bring (Shogenova, 2020a). Lithuania's renewed interest in such projects can be attributed to the opportunity to apply for funding from the Innovation Fund, aimed at developing a national technological platform and strengthening the industrial sector, particularly through innovative approaches to CO_2 capture, storage, and potential subsequent utilisation. The National Development Plan 2021–2030 pays attention to CCS and CCU technologies – the advantages and benefits the country can receive if they are introduced into existing production are considered (Mockevicius, 2011; Shogenova, 2020b).

Sweden. There have been talks about capturing CO_2 in Sweden for a long time. Still, in June 2017, the Swedish government announced a new document – an addition to the already existing act on climate policy. A severe reduction of emissions and the achievement of zero emissions earlier than the deadline set by the Paris Agreement – by 2045, no CO_2 should be created in the country. The main changes will affect the modernisation of the production sector. The focus is on innovative technologies that capture CO_2 from exhaust gases and redirect it to producing other valuable products (thus obtaining both environmental and economic benefits) or putting CO_2 in landfills (Lietuvos Respublikos energetikos ministerija, 2020). It is essential to clarify that the new policies are aimed at large CO_2 emitters and small ones (Swedish Climate Policy Council, 2021).

The state supports CCS projects in every possible way. So, for example, installing Bioenergy with carbon capture and storage (BECCS) technology can significantly reduce the amount of CO_2 emissions created in energy production and even make them harmful. BECCS technologies are a new milestone in developing CO_2 capture and storage technologies. This installation is designed for stations producing energy from biofuels (Government Offices of Sweden, 2020). In achieving the goals of the Paris Agreement, it is planned to install BECCS at the largest power plants in the country.

Legislation System with Some Legislation Acts

This group includes countries that scored at least 10 points in Table 18. In many of these countries, projects are planned that would allow capturing, storing and/or utilisation of CO_2. For example, Latvia and Estonia are actively negotiating the creation of an infrastructure for capturing, transporting and storing CO_2 from Estonia in Latvia. No geological formations in Estonia would allow the storage of CO_2. However, there are such formations in the territory of Latvia (Levihn, 2021), (Shogenova et al., 2021).

In another country, Germany, despite the closure of all CCS / CCU projects in 2018, more and more attention has been paid to these technologies in recent years. At the beginning of 2022, the country announced the creation of two projects with the launch in 2025 (Leilac2) and 2027 (H2morrow), as well as a CO_2 liquefaction project and its temporary storage in Wilhelmshaven (IOGP Europe, 2022) .

According to (IOGP Europe, 2022), as of January 2022, the total number of CCUS plants reaches 65 throughout the European Union (already operating and planned projects together), which will reduce CO_2 emissions by about 65 million tons per year by 2030. This number of stations, although still small, given that just less than two years ago, as of June 2020, there were half as many projects (existing and planned together), it indicates that the actions taken by both the government and the enterprises themselves are going in the right direction (IOGP Europe, 2020).

Insufficiently Developed Legislation System

Ten countries are included in the category of countries with an insufficiently developed legal framework, but more is needed in these countries to more actively capture and store (or utilisation) CO_2. These countries are beginning their transition to greener and more innovative production systems. Many countries from this list actively use the opportunities the European Union – Innovation Fund and Modernisation Fund provides. Both funds are aimed at the country's analysis, development and implementation of CCS systems. According to (European Commission, 2022a), the second call for large-scale projects received 138 applications from all over Europe, in one way or another, aimed at reducing the amount of emissions created. Successful implementation of the announced projects will make it possible to reduce CO_2 emissions by more than 710 million tons. (during the entire operation period within the Innovation Fund framework). In addition, it is worth mentioning that despite the poorly developed legislative framework (compared to countries from the first group, for example, Belgium), applications have been submitted in these countries for creating CCUS stations (or CO_2 transportation). For instance, in Ireland, the experimental installation of a post-combustion CO_2 capturing plant is being planned, with the launch of the project in 2028 (Ervia, 2022).

Future work in enabling policy framework, making investing in all parts of the value chain economically feasible, and continued support and coordination are crucial for implementing CCS/CCU. EU should set a clear role, scope and targets of CCS/CCU, including revision of directive guidance and development of new regulatory frameworks of different aspects of value chains, for example, CO_2 cross-border transportation, certification of carbon removal activities etc.

3.7. Emissions Data from Biomass-Based Product Scenario

In this step of the methodology the amount of stored biogenic CO_2 in the new fiberboard insulation material for the eight different accounting standards is shown in Table 19. The stored amount has been calculated for 1 m^3 of the new fiberboard insulation material.

Table 19.

Stored biogenic CO_2 depending on accounting standard

Technical standard	**Stored CO_2, kg/m^3**	**Source**
EN-15804 (2012)	359	(BRE Global Ltd., 2013)
ISO/DIS-21930 (2015)	251	(Flanagan & Steckel, 2019)
EN-15804 (2012) +A1:2013	359	Global Ltd. 2013)
CEN/TR-16970 (2016)	359	Global Ltd. 2013)
EN-16485 (2014)	359	Global Ltd. 2013)
ISO/TS-14067 (2013)	90	(Wolf et al., 2010)
PEF v2.2 (2016)	90	(Wolf et al., 2010)
PAS-2050 (2011)	291	(BSI, 2011)

For standards EN-15804 (2012), EN-15804 (2012) +A1:2013, CEN/TR-16970 (2016) and EN-16485 (2014) the calculated amount of stored CO_2 is the same, as they are all based om the same standard of EN-15804 (2012) and assume that the amount is calculated with the formula shown in Eq. (2), with no further elaboration. ISO/TS-14067 (2013) and PEF v2.2 (2016) standards are based on the previous ISO-14040/44 standard for LCA, and do not differ in calculating the stored CO_2.

Standards based on the EN-15804 offer the highest amount of CO_2 stored in one cubic meter of the product – 359 kgCO_2/m^3, while the lowest amount of CO_2 stored can be attributed to standards based on the previous ISO-14040/44 LCA standard – 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 multicriteria analysis of three different energy production scenarios are shown in Table 20.

Table 20.

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
NOX 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 multicriteria analysis of three different energy production scenarios are shown in Fig. 36.

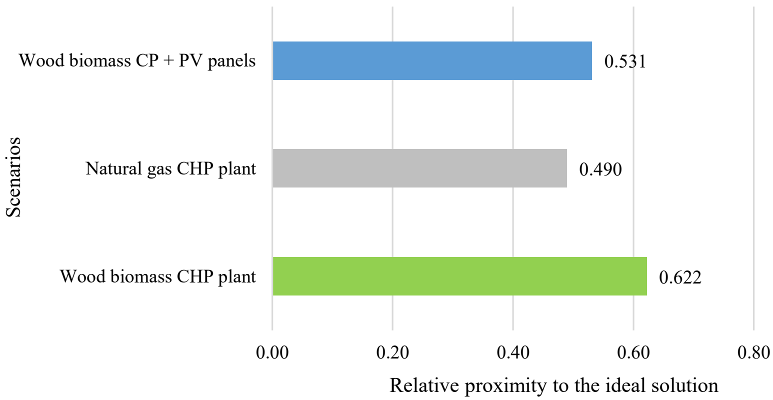

Fig. 36. Multicriteria analysis results.

The results of the multicriteria analysis show that the best scenario for energy production for the manufacturing plant is the wood biomass CHP plant (0.622). In second place are the wood biomass combustion plant and Solar PV panel scenario (0.531), barely beating out the natural gas CHP plant scenario (0.490). While currently, the multicriteria analysis shows that the fossil resource utilisation scenario of natural gas is relatively close in valuation compared to the renewable resource scenarios (wood biomass), it is evident that the evaluation of the natural gas

CHP plant scenario could decrease in the future, as the world moves to use more renewable resources. Nevertheless, the natural gas CHP plant scenario still needs to be reviewed and considered, so it can be clearly shown that there are better renewable resource alternatives, which are the wood biomass CHP and combustion plants. To emphasise this further, 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. This, in turn, could significantly impact the evaluations of the different energy production scenarios, possibly increasing the assessment of the renewable energy source scenarios to mark them as the clear favourite over fossil resource use.

3.8. Impact of Final Product Shift on GHG Emissions

Potentially, this step of the methodology allows for the use of default data from the station. However, to obtain more accurate results (field-based results), it is recommended to use actual production data. In this case, the calculations are based on real data provided by the biogas station. With this data, it is possible to calculate the GHG emissions generated by the station, as well as estimate how much emissions will be saved if, instead of biogas, the station produces methane for its subsequent utilisation in the city's power grid. Based on (European Parliament, 2018), a similar calculation was made for the observed Biogas Plant.

Calculation of Emission Parameters

The $e_{ec,n}$ parameter only applies to maize silage, grass silage and immature grain crops. According to (REDcert GmbH, 2021), the substrate with the least influence on the result may not be considered at this calculation stage, so substrate “spoiled/immature grains” is neglected.

Table 21 lists the values for maize silage that are needed to calculate the parameter e_{ec} (Eq. (2)). Similar calculations should be made for each substrate utilised in production. All values (emission factors, heating values, etc.) are taken from the European Commission schemes (European Commission, 2024b), (Biograce, 2019).

Table 21.

Values for the maize silage (European Commission, 2024b), (Biograce, 2019).

Substrate: Maize Silage	Value	Emission Factor
Seeds	30 kg/ha year	0.32 $kgCO_2eq/kg$
N fertiliser (mineral)	90 kg/ha year	6.41 $kgCO_2eq/kg$
N fertiliser (digestate)	10 kg/ha year	0.0075 $kgCO_2eq/kg$
CaO fertiliser	0 kg/ha year	0.89 $kgCO_2eq/kg$
N_2O field emission	–	5.6 kgN_2O eq/ha year
Pesticides	NA	13.9 $kgCO_2eq/kg$
Diesel (machinery)	11,764.7 L/ha year	3.14 / 2.1 $kgCO_2eq/kg$
Maize yield (fresh matter)	37820 kg/ha year	–

Thus, the three main substrates have the following effect in $kgCO_2eq$ per one kilogram and one ton of fresh matter (FM) (Table 22).

Table 22.

The e_c parameters for the main substrates

Substrate	e_{ec}, $kgCO_2eq/kg$	e_{ec}, $kgCO_2eq/t$ FM
Grass silage	0.104	103.7
Immature grain crops	0.081	81.2
Maize silage	0.067	67.4

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 (European Commission, 2010).

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}, $e_{sca,n}$. During the period under review, no improvements or upgrades were made to the agricultural feedstock management system at the station, and no CO_2 capture and storage system was installed.

In turn, the $e_{td,\ feedstock,n}$ parameter shows the emissions from resource transportation to the digester and is calculated by Eq. (5)

$$e_{td,feedstock,n} = \frac{(d_1 \cdot f_1)+(d_e \cdot f_e) \cdot EF}{Amount\ of\ transported\ substrate} \quad (5)$$

where

d_l Distance traveled while loaded, km;
d_e Distance traveled while empty, km;
f_l Fuel consumption loaded, L/km;
f_e Fuel consumption empty, L/km.

Biogas Plant works with different substrates; therefore, the parameter must be calculated for each. The type of fuel utilised should also be considered since the emission factor (EF) depends on it. For diesel, for example, the EF is 3.14 $kgCO_2eq/l$ (Table 23).

Table 23.

Substrate transport process

	Value	Unit
The volume of transported biomass	5 491.25	t
Distance (loaded)	4	km
Distance (empty)	4	km
Fuel consumption (loaded)	0.41	l/km
Fuel consumption (empty)	0.24	l/km

Having data on logistics and using Eq. (5), we get that the $e_{td,feedstock,n}$ parameter for the station is 0.0015 $kgCO_2eq/t$ for one type of substrate. The total GHG emissions of all 13 substrate types equals 1.96 $kgCO_2eq/t$.

Emissions from Processes 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 (Table 24).

Table 24.

Main processes on the plant and their values

	Value	Unit
Electricity	11 619 000	kWh/year
Process heat	11 325.58	MJ/year
Methane yield	5 621 708	$Nm^3/year$
Methane loss	562 170.8	$Nm^3/year$
Digestate	43 000	t/year

According to RED and ISCC certification systems (European Parliament, 2018), (ISCC, 2017), if a special gas-tight lid for storing digestate is installed at the biogas station, the loss of methane is reduced and can be assumed to be ~1 %. These covers are installed at the observed Biogas Plant, so in further calculations, methane losses will be taken as 1 %.

Each resource utilised – electricity and heat – also has its own emission factor (Table 25):

Table 25.

Emission factor for electricity and heat usage

Input	**Emission Factor**	**Unit**
Electricity mix	0.19	$kgCO_2eq/kWh$
Heat (CHP Unit)	0.61	$kgCO_2eq/MJ$
Methane	23	$kgCO_2eq/kgCH_4$

Using Eq. (6), we can calculate the parameter ep_1:

$$e_{p1} = \frac{(Electricity \cdot EF_E)+(Heat \cdot EF_h)+(Methane\ loss \cdot EF_m)}{Total\ methane\ yield} \tag{6}$$

where

EF_E Emission factor from electricity, kg CO_2eq/kWh;

EF_h Emission factor from heat, kg CO_2eq/MJ;

EF_m Emission factor from methane, kg CO_2eq/kg CH_4.

Substituting the required values from Table 25 shows that 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. Similar to the previous step, emissions from processing biogas to biomethane should take the biomethane yield per year, regardless of the amount of biomethane subject to further certification (European Parliament, 2018).

For the Biogas Plant, the biogas treatment process requires the following investments (Table 26):

Table 26.

Required input for the biogas treatment

	Value	Unit
Methane input	5 621 708	Nm^3/year
Methane slip (in PSA)*	1–5	%
Methene loss	562 170.8	Nm^3/year
Electricity**	994 462.8	kWh/year
Process heat	0	MJ/year
Biomethane output***	4 735 537.2	Nm^3/year

Note: *PSA – Pressure Swing Adsorption, biogas treatment technology
**0.21 kWh/m^3 multiplied by biomethane output;
*** Methane input minus the 1 % of methane loss in the biogas plant

Thus, the parameter ep_2 is calculated by the Eq. (7):

$$e_{p2} = \frac{(Electricity\ for\ PSA \cdot EF_E) + (Heat\ for\ PSA \cdot EF_h) + (Methane\ loss \cdot EF_m)}{Biomethane\ output} \quad (7)$$

Since biomethane will be utilised 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 (Table 27).

Table 27.

Required energy input and emission factor from the distribution

Input of energy	**Value**	**Unit**
Electricity (transport in the natural gas grid)	0.003	kWh/m^3
Heat process	0.058	MJ/m^3
Electricity (compression in the filling station)	0.164	kWh/m^3
Biomethane distribution, emission factors		
Electricity mix	0.192	kgCO_2eq/kWh
Heat process	0.067	kgCO_2eq/kWh

Using the data from Table 27, it is possible to calculate the emissions themselves from gas transportation through the network:

$$e_{td,product} = (ET_{ng} \cdot EF_e) + (HT_{ng} \cdot EF_h) + (EC_{st} \cdot EF_{st}) \quad (8)$$

where

ET_{ng} Electricity for biomethane transport in the natural gas grid, kWh/m^3;

EF_e Emission factor for electricity for biomethane transport in the natural gas grid, kWh/m^3;

HT_{ng} Heat for biomethane transport in the natural gas grid, MJ/m^3;

EF_h Emission factor for heat process for biomethane transport in the natural gas grid, kgCO_2eq/kWh;

EC_{st} Electricity for biomethane compression in filling station, kWh/m^3;

EF_{st} Emission factor for electricity for biomethane compression in filling station, kWh/m^3.

Substituting all the data into the formula, we get that the Biogas Plant for the transportation and compression of biomethane at the station produces 0.036 kgCO_2eq/m^3. If there is no compression, then $e_{td.product}$ = 0.043 kgCO_2eq/m^3.

Substrate Allocation

An important calculation step is substrate allocation. Many different substrates are utilised in biomethane production – each of them must be analysed separately for the considered period. It is recommended for biogas producers to write down how much methane can be obtained from each substrate.

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.

At this stage, the first step is to multiply the amount of substrate by the percentage of losses (10 %), thus obtaining the total amount of substrate according to the estimated losses. Further, the proportion of methane in each type of substrate is calculated (European Commission, 2024b), (Biograce, 2019).

$$Share\ of\ CH_4\ yield = \frac{Amount\ of\ substrate\ after\ 10\%\ loss \cdot CH_4\ yield\ of\ the\ substrate}{Total\ CH_4\ yield\ (calculated) in\ the\ biogas\ plant} \cdot 100\% \quad (9)$$

Thus, the following values are typical for the substrates utilised at the Biogas Plant (Table 28):

Table 28.

Methane yield for each kind of utilised substrate (European Commission, 2024b), (Biograce, 2019).

Substrate	**Amount (before losses), t/year**	**Input after losses, t/year**	**Methane yield, Nm^3/t FM** (REDcert GmbH, 2021), (REDcert, 2015)	**Share of methane yield in each substrate, %**
Sediments of floatation milk powder factory	3982.7	3584.4	628.7	36.5
Milk whey	186829.7	15146.7	36.9	9.1
Sludge	8852.2	7966.7	47	6.1
Chicken manure	5491.3	4924.1	55.4	4.4
Beer yeast	169	152.1	505.8	1.3
Immature grain crops sludge	852.4	767.2	54.6	0.7
Maize silage (2019)	15258.3	13732.5	106	23.6
Maize silage (2020)	3602	3241.8	106	5.6
Maize silage (2021)	12.3	11.07	106	0.02
Grass silage (2019)	803.4	723.1	100	1.2
Grass silage (2020)	612	550.8	100	0.9
Grass silage (2021)	513.4	462.1	100	0.7
Spoiled/immature grains	72	64.8	122.2	0.1
Total methane yield calculated, Nm^3		6 179 378.3		

Total amount of Emissions

Now when 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 according to REDcert and ISCC) (European Parliament, 2018; ISCC, 2017; REDcert, 2015):

$$Tot.usable\ amount\ of\ CH_4 = Proportion\ of\ methane\ yield \cdot Tot.biomethane\ ouput \quad (10)$$

For the Biogas Plant, each type of substrate can produce the following amount of biomethane (Table 29):

Table 29.

Total usable amount of biomethane per each substrate

Substrate	**Share of methane yield in each substrate, %**	**Total usable amount of biomethane, Nm³/year**
Sediments of floatation milk powder factory	36.47	1726965.09
Milk whey	9.05	428320.94
Sludge	6.06	286956.36
Chicken manure	4.43	209820.52
Beer yeast	1.25	58956.61
Immature grain crops sludge	0.68	32099.85
Maize silage(2019)	23.56	1 115 525.28
Maize silage (2020)	5.56	26339.83
Maize silage (2021)	0.02	899.25
Grass silage (2019)	1.17	55411.36
Grass silage (2020)	0.89	42210.30
Grass silage (2021)	0.75	35409.75
Spoiled/immature grains	0.13	6068.35

After acquiring the values of the parameters e_{ec}, $e_{td,feedstock,n}$, ep_1, ep_2 and $e_{td,product}$, for each substrate utilised, these values are summed up for use in the following formula to determine the total emissions based on 1 Nm^3 of biomethane:

$$Total\ emissions\ per\ m^3\ CH_4 = \frac{(e_{ec}+e_{td,feedstock,n}+e_{p1}+e_{p2}+e_{td,product})}{Total\ usable\ amount\ of\ biomethane} \quad (11)$$

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. (11) it has been determined that the total amount of emissions is 5.92 kgCO_2eq/m^3.

According to (European Commission, 2021k), GHG emissions from biomass-derived fuels must be expressed in grams of CO_2 equivalent per MJ of biofuel (gCO_2eq/MJ). For recalculation, the lower heating value of biomethane is used:

$$Total\ emissions\ per\ MJ\ CH_4 = \frac{Total\ emissions\ per\ m^3 of\ biomethane}{Heating\ value\ of\ biomethane} \cdot 100 \quad (12)$$

The lower heating value of biomethane is 36 MJ/m^3, resulting in 16.45 gCO_2eq/MJ emissions.

GHG Savings Calculation

The last step is to calculate the directly stored emissions from biomethane. According to the Directive of the European Union 2018/2001 (European Parliament, 2018), the Member States of the European Union have the right to produce only that biomethane, the greenhouse 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 %.

Eq. (13) is used to calculate the stored emissions from biomethane:

$$Saving = \frac{(E_{F(t)} - E_B)}{E_{F(t)}} \cdot 100\% \tag{13}$$

where

E_B Total emissions from biomethane, $gCO_2eq/MJ\ CH_4$;

$E_{F(t)}$ Total emissions from fossil fuel comparator, gCO_2eq/MJ.

In the case of the Biogas Plant, the amount of emissions saved is 80.36 %. However, this value reflects the rate of 1 % loss. According to REDcert, PSA losses can be as high as 5 %. Thus, the smallest amount of saved emissions is 76.34 %.

3.9. Environmental and Social Impacts Based on LCA and S-LCA

This section presents the results of the final step of the methodology – the results of the Social and Environmental Life Cycle Assessment of two scenarios for CO_2 utilisation – methanol and SAF-ethanol production.

Social Life Cycle Assessment

An initial analysis of the key factors revealed that the methanol production scenario has a greater impact across all observed main categories compared to the SAF-ethanol production scenario (Fig. 37).

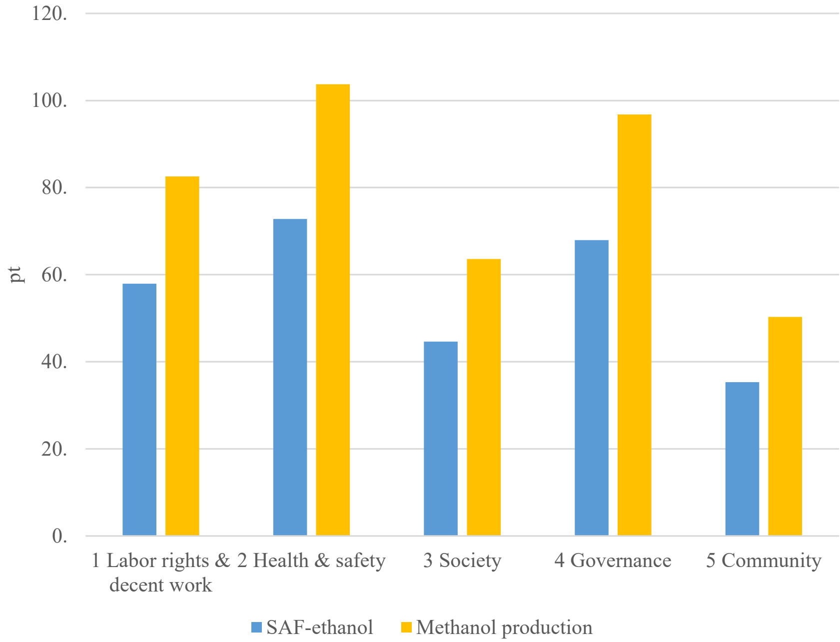

Fig. 37. Assessment by main categories, global annual per capita, weighted.

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.

Since the S-LCA analysis considers not only the production of the target product but also the production of necessary substances, reagents, and equipment (often produced in other countries), it is challenging to precisely determine the impact of categories 3F, 4A, and 4C in the specific context of Latvia. While Latvia maintains relatively high levels of social and gender equality, it is worth noting that, according to Eurostat (Eurostat, 2023), wages in the manufacturing sector in Latvia were among the lowest in the European Union in 2022.

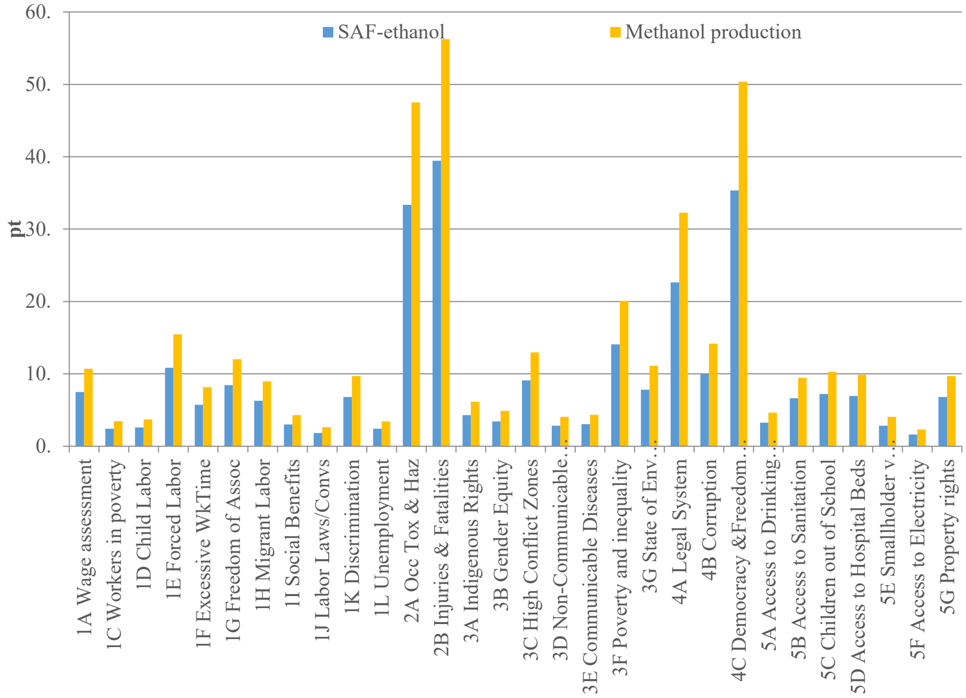

Fig. 38. Assessment by sub-categories, global annual per capita, weighted.

Considering the weighted average indicators of the peak subcategories separately (Fig. 38 and Table 30) according to the scenarios, the following conclusions can be drawn:

- Occupational Toxics & Hazards and Injuries & Fatalities: These indicators include two subcategories: the number of injuries/diseases of various types and the number of deaths. The construction phase is rated high, indicating that workers face significant risks and that injuries are common in this field. According to the Hotspot analysis, occupational hazards are not frequent in other stages of production, either for those producing chemicals or for those directly involved in producing the final product;
- 3F – Poverty and Inequity: This indicator reflects violations of gender and social equality. The SAF-ethanol scenario shows lower violations compared to the Methanol scenario. The indicator is influenced by the fact that the construction phase is physically demanding and traditionally employs more men, thereby affecting the male-to-female ratio in the sector. Additionally, the construction phase is often associated with forced overtime, low-paid migrant labor, and discrimination based on factors such as religion, gender, and social status;
- 4A – Legal System: The scenarios show a medium to very high level of legal system effectiveness, which is a positive indicator. This suggests that the legal system and regulations throughout the production chain are not weak and adequately fulfil their constraints, ensuring compliance with legal requirements (Schwab, 2017);

– 4C – Democracy and Freedom of Speech: This indicator uses data from the (Haghighatjoo et al., 2023), where lower values indicate weaker levels of democracy and higher levels of corruption and bribery, leading to elevated social risks. Both scenarios were rated “low” in the general categories. However, closer analysis reveals that specific stages such as Electricity, Coal, Chemicals, and Machinery show good indicators of democracy. Construction is identified as the stage with the highest risk of corruption and social risks in both scenarios.

Table 30.

Comparison of Methanol and SAF-Ethanol production scenarios

	2A **Occ. Tox & haz**	**2B** **Inj & fat**	**3F** **Pov& ineq**	**4A** **Legal system**	**4C** **Dem & freedom**
Methanol	4.84	5.73 (high)	2.04 (medium)	3.29 (high)	5.12 (low)
SAF-ethanol	3.38	4.00 (medium)	1.43 (low)	2.30 (medium)	3.58 (low)

Methanol Production

As the analysis revealed, the construction stage of the methanol production plant has the most significant impact. This stage is technologically complex, requiring substantial financial investments and the use of expensive, high-tech equipment (Gholizadeh et al., 2025; Haghighatjoo et al., 2023; Pratschner et al., 2023). In comparison to the construction phase, the influence of other factors, such as various chemicals and electricity, becomes less pronounced. The construction process also demands significant human resources and coordination with governance. However, if the construction stage is excluded from the overall analysis, the second most influential factor is electricity consumption, followed by water consumption (Fig. 39).

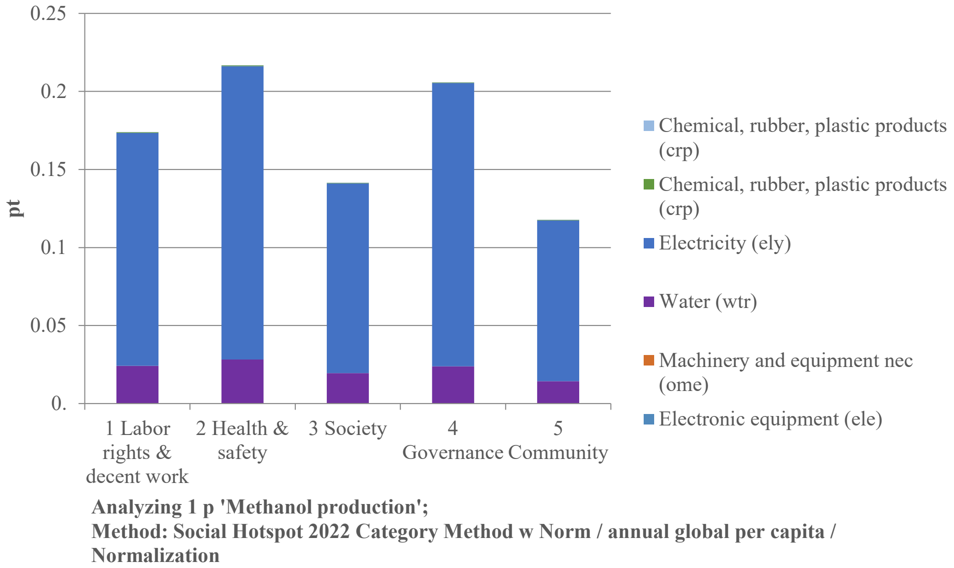

Fig. 39. Methanol production by social categories (without construction), global annual per capita.

SAF-Ethanol Production

The SAF-ethanol production scenario is similar to the methanol production scenario, with the construction phase having the most significant impact across all categories. However, when the construction factor is accounted for separately, other influential factors emerge. As with methanol, electricity consumption is the second most significant factor in ethanol production, as the process also requires high-tech equipment. In this scenario, electricity is sourced from external providers, and CO_2 is supplied rather than extracted from the air. If Direct Air Capture (DAC) technologies were employed, electricity consumption would have a much greater impact on all categories (International Energy Agency, 2024; Ozkan, 2024) Additionally, the production process requires large quantities of various catalysts and other chemical compounds. While these chemicals have a substantial impact on the health and safety of workers and society, as shown in Fig. 40, their effects on other categories remain relatively consistent.

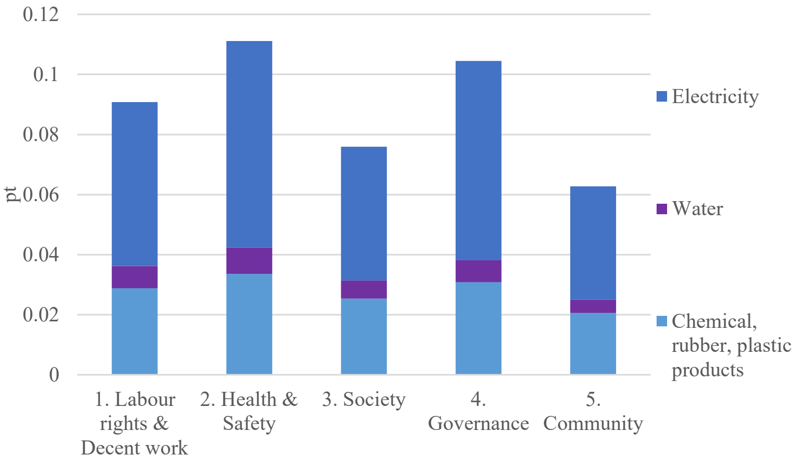

Fig. 40. SAF-ethanol by social categories, global annual per capita.

Life Cycle Assessment

The Life Cycle results for both scenarios show that both have a significant impact on global warming, with methanol production having a greater impact in this category. During the production of methanol and SAF-ethanol, a certain amount of SO_2, NO_x, and other emissions are produced, negatively affecting the environment. The Fine Particulate Matter Formation and Terrestrial Acidification categories are also affected.

Methanol Production

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 air (NO_x, CO, SO_2 and NMVOC), which potentially can further oxidise to CO_2 in the atmosphere (Staniaszek et al., 2022). 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 (Fig. 41)

SAF-Ethanol Production

Ethanol production requires significant amount of energy, as well as chemical reagents. Utilisation of ammonia and sulfuric acid makes negative impact on the categories Fine Particulate Matter, Terrestrial Ecotoxicity and Global Warming (Fig. 41).

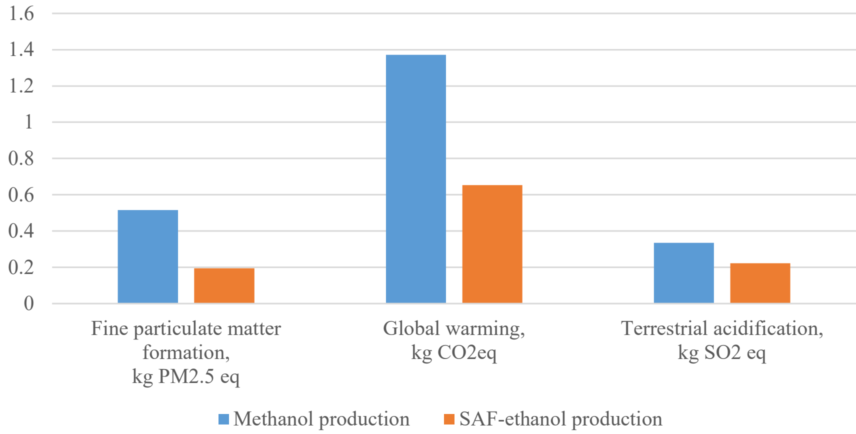

Fig. 41. LCA of Methanol and SAF-ethanol scenarios

As technology advances and the shift towards greener fuels increases, both scenarios have the potential to reduce their environmental impact. Using different types of chemicals and then reclaiming them can reduce the impact. In the case of SAF-ethanol, the transition to DAC technologies could potentially be the optimal solution to the issue of simultaneously reducing CO_2 emissions and fuel production (He et al., 2024; Jiang et al., 2023; U. Lee et al., 2021; Ramos-Fernandez et al., 2025; Suppiah et al., 2021)

4. DISCUSSION

This study evaluates the potential of CO_2 valorisation through 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 algae 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 (X. Wang et al., 2017). Compared to studies in regions like the Netherlands, where algae-based CCU is supported by dense industrial clusters and government subsidies (IEA, 2019; M. A. Khan & Gohari Darabkhani, 2022)**,** Latvia's sparse infrastructure and limited funding pose barriers. The food industry pathway, requiring high CO_2 purity, faces challenges due to the energy-intensive purification processes, which increase costs and emissions if not powered by renewables (Slade et al., 2022) These trade-offs suggest that while these pathways are technically feasible, their economic viability is constrained without robust policy support.

The Key Performance Indicator table developed in this study is a valuable tool for comparing industries, but its current limited data restricts its applicability. Using bigger number of indicators can increase accuracy of the result, making it more appropriate and applicable to the specific conditions (Chauvy et al., 2020; Shokrollahi et al., 2024).

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 (Burgess, 2024; Hong, 2022; Park & Grundmann, 2025) pose a significant barrier. The study's assumption of biomass availability doesn't take into account potential supply chain constraints, such as seasonal variations or competition with food production, which have been critical limitations in other European contexts (IEA, 2019; M. A. Khan & Gohari Darabkhani, 2022). The absence of operational biomass production sites (like, for example, algae ponds) for biofuel production in Latvia further underscores infrastructural gaps compared to countries like Sweden, where such facilities are supported by government (European Commission, 2024a; Tardin-Coelho et al., 2025).

The focus on Riga's boiler houses as major CO_2 emitters highlights a regional challenge but doesn't take into account lack of necessary infrastructure. For instance, redirecting CO_2 to biofuel plants or algae ponds assumes seamless transport and storage infrastructure, which is underdeveloped in Latvia. Other country experience (IEA, 2020a) demonstrates that integrated CCUS networks require significant investment in pipelines and storage sites, which Latvia currently lacks. The economic feasibility of these pathways depends on overcoming these barriers, potentially through EU funding mechanisms like the Innovation Fund (Faber et al., 2022; Maselli et al., 2024; Mohsin et al., 2020; Sheikhtajian et al., 2024).

The third step of the methodology offers the combination of SWOT, *ArcGis* maping and FLCM analysis methods to analyse the factors influencing the development of CO_2 capture technologies and inhibiting their implementation in the territory of Latvia.

The SWOT and FLCM reveal that political and financial barriers dominate CCU adoption in Latvia. These findings align with international studies, such as (Buure et al., 2024; Eberenz et al., 2024; IEA, 2020a), where regulatory uncertainty and funding shortages delay CCUS projects. The human factor, including public and stakeholder resistance, is another critical barrier, as seen in Lithuania's abandoned CCS projects due to public opposition (Buure et al., 2024; IEA, 2020a). While educational campaigns could mitigate this, as suggested, their effectiveness remains uncertain without long-term investment in public engagement, a strategy successfully employed in Sweden (Buure et al., 2024; European Commission, 2024a; IEA, 2020a; Stigson et al., 2016). For more comprehensive results economic analysis should be applied, that would include ETS factor, as carbon pricing significantly influences investment decisions in CCUS (IEA, 2020a; Selim & Jerrad, 2023). Future research should model the impact of ETS price volatility on project viability to provide a more robust economic assessment.

Following step of the methodology offers and assessment of society's and entrepreneurs' understanding of CO_2 emission problem and their willingness to pay for the reduction of the amount of CO_2 emissions. Although the survey was conducted among university staff and students (convenience sampling), the survey results highlight low public awareness and limited entrepreneurial willingness to invest in CCUS, reflecting similar findings in European contexts (Buure et al., 2024; Duetschke, 2024; IEA, 2020a). The low response rate from entrepreneurs (11 %) suggests potential sampling bias, limiting the generalisability of findings. In contrast, Scandinavian countries have leveraged public-private dialogues to align stakeholder interests (Buure et al., 2024; Eberenz et al., 2024; IEA, 2020a). For CCUS implementation Latvian industrial and agricultural sectors suffer from lack of legislative and financial support, a challenge also observed in other European countries' CCUS efforts (Baylin-Stern & Berghout, 2021; IEA, 2020a). Addressing this requires tailored policies, such as tax breaks or subsidies, to bridge the gap between environmental goals and economic realities. To improve the survey, it is recommended to increase the sample size and broaden the scope of the survey. Conducting a preliminary (pilot) survey is advised to enhance response rates and assess the clarity and comprehension of the questions. To reach a larger audience, including both the public and entrepreneurs, it is recommended to conduct the questionnaire electronically, in person, or via telephone.

The fifth and sixth steps of the methodology offer the analysis of legislative system of the European Union and Latvia. 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 (Buure et al., 2024; IEA, 2020b). The lack of public awareness exacerbates resistance to CCUS projects, a situation also observed in Germany (Dütschke & Duscha, 2022). Developing clear, incentive-based legislation, as seen in Sweden's policy, could accelerate adoption. However, the study's focus on legislative analysis doesn't take into account practical implementation challenges, such as enforcement capacity, which has hindered progress in countries like Poland (IEA, 2020a; Pokrzywka, 2025; Wójcicki, 2025).

Sweden's high score in legislative support for CCUS contrasts with Latvia's maturing CCUS framework. The IPCC (Fuss & Johnsson, 2021) 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 CO_2 valorisation by its storing in another product. The proposed wood fiberboard insulation material offers a novel CO_2 storage solution combined with optimal energy source, but environmental benefits of CO_2 storage vary significantly across accounting standards. This variability, also noted in (Bradshaw et al., 2008; Ellen Soldal & Ingunn Saur Modahl, 2022; Van Gulck et al., 2022), introduces uncertainty in claiming contribution to climate neutrality. The preference for wood biomass CHP over fossil-based energy aligns with sustainability goals but assumes stable biomass supply, a limitation not fully addressed. As (M Gustafsson et al., 2021; Park & Grundmann, 2025; Singh et al., 2024) indicate, a stable flow of resources, proper management, a non-saturated market and no or little competition with other sectors are important factors.

The eighth 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 (Ferrari et al., 2024; Lange et al., 2023). 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 (Sadia et al., 2021; Srivastrava et al., 2020).

Scaling this approach requires addressing infrastructure gaps, such as upgrading existing biogas plants (IEA, 2020b).

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 align with (Cordero-Lanzac et al., 2022; Jing et al., 2024), underscoring 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 (Dietrich et al., 2024; Grim et al., 2022; Rojas-Michaga et al., 2023). The lack of sufficient energy infrastructure in Latvia limits scalability (Faber et al., 2022; Maselli et al., 2024; Mohsin et al., 2020; Sheikhtajian et al., 2024). Retrofitting existing biogas plants for methanol production could reduce social and environmental impacts, but public acceptance remains a barrier, as seen in regional CCUS failures (ITUL et al., 2023).

5. CONCLUSION

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 that lacks key concepts such as "CO_2 as a product", "carbon markets", or "carbon neutrality of products". 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. Attention is also given to life cycle assessment and the efficiency of production processes that utilise CO_2 as a raw material, allowing for evaluation not only of environmental benefits but also of energy consumption and resource intensity.

Taken together, the results of the conducted analyses form complementary chapters of a unified scientific framework – from fundamental concepts to practical implementation. They 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 fulfillment 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 carbon capture, utilisation, and storage 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. 42).

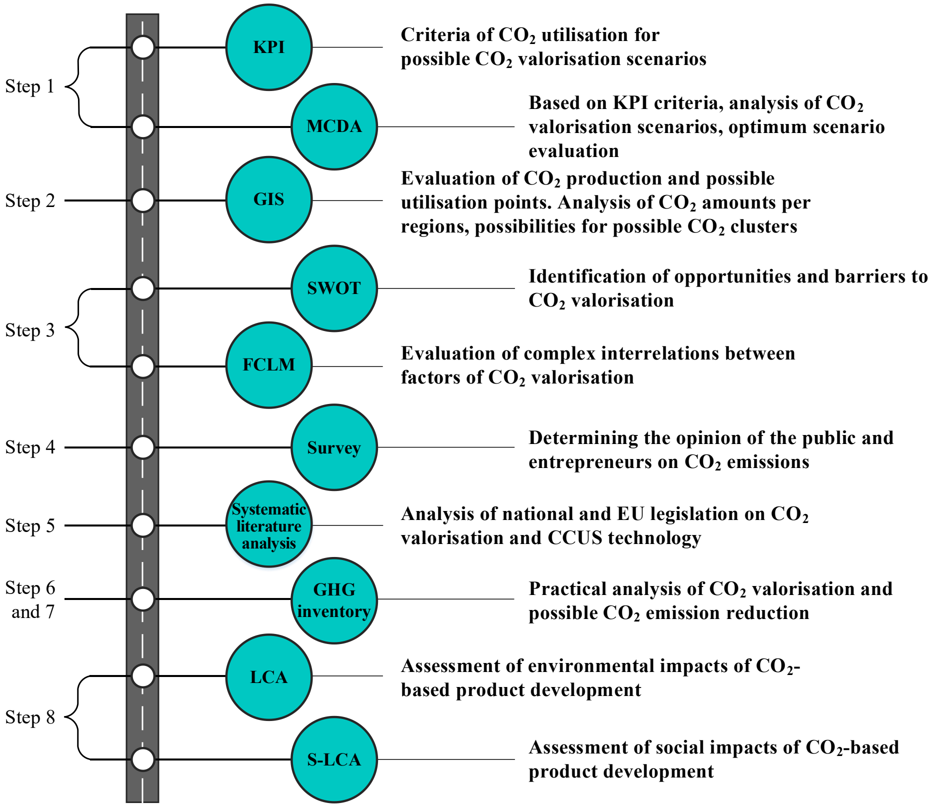

Fig. 42. CO_2 capture and utilisation integrated methodology/roadmap.

As noted in Section 1, due to insufficient data at the time of the study, the analyses presented in the methodology consider different CO_2 valorisation scenarios:

- Step 1 – scenarios of CO_2 valorisation in methanol and cement productions, CO_2 utilisation in the food industry and in greenhouses/algae ponds – other scenarios were not considered due to lack of KPI data (at the time of analysis);
- Step 2 – Spatial analysis of CO_2 emitting and possible valorisation points. No specific CO_2 valorisation scenario considered;

- Step 3 – Combination of GIS, SWOT and FLCM analysis. No specific CO_2 valorisation scenario considered;
- Step 4 – Survey. No specific CO_2 valorisation scenario considered;
- Step 5 – Analysis of legislation. No specific CO_2 valorisation scenario considered;
- Step 6 – Identification of the CO_2 amount, that can be captured in fibrewood material production. Analysis of optimal energy source for fibrewood material production;
- Step 7 – Biomethane production scenario and identification of the amount of avoided CO_2 through changing the manufactured product to one that produces fewer emissions
- Step 8 – Scenarios of CO_2 valorisation in methanol and SAF-ethanol production.

Taken together, 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.

Thesis maps out the complete CO_2 valorisation pathway 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.

Open innovation serves as a leading framework for sustainability transitions across sectors, yet requires evaluation through alternative approaches to CO_2 valorisation. Technocentric models concentrate on technological readiness and economic feasibility, while disregarding social, behavioural, and institutional elements, which are crucial for actual deployment. Market-driven approaches that use carbon pricing, emissions trading, and investment-based models focus on cost efficiency but tend to exclude structurally weaker regions and lack inclusive governance systems. National industrial strategies, such as state-led planning frameworks, provide policy coherence but face challenges with regional stakeholder engagement and limited adaptability. Mission-oriented innovation systems combine public-private resources to achieve common goals, but their rigid top-down structures limit both local experimentation and contextual adaptation. The open innovation ecosystem approach in this Thesis combines scientific evaluation with stakeholder involvement and continuous learning to develop solutions for CO_2 valorisation, which are tailored to specific territories and are both technologically sound and socially acceptable. The CO_2 Deal Roadmap methodological framework in Fig. 43 follows open innovation and co-creation principles. The roadmap follows a nonlinear structure integrating multiple methodological tools into a dynamic ecosystem, enabling knowledge exchange between domains and sectors. The ecosystem approach requires active participation from industry representatives and SMEs, academic institutions, municipalities, and civil society actors who contribute to all phases of the roadmap development. The stakeholders' contributions enable the identification of CO_2 sources and valorisation routes, evaluation criteria prioritisation, and decision-making model refinement. Through open innovation, external ideas and expertise can enter the system, while co-creation ensures solutions are developed with stakeholders instead of for them. The inclusive multi-actor approach connects scientific research to policy and practical implementation, resulting in customised regional strategies that meet technological readiness requirements and community needs. The roadmap 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 multi-criteria 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.

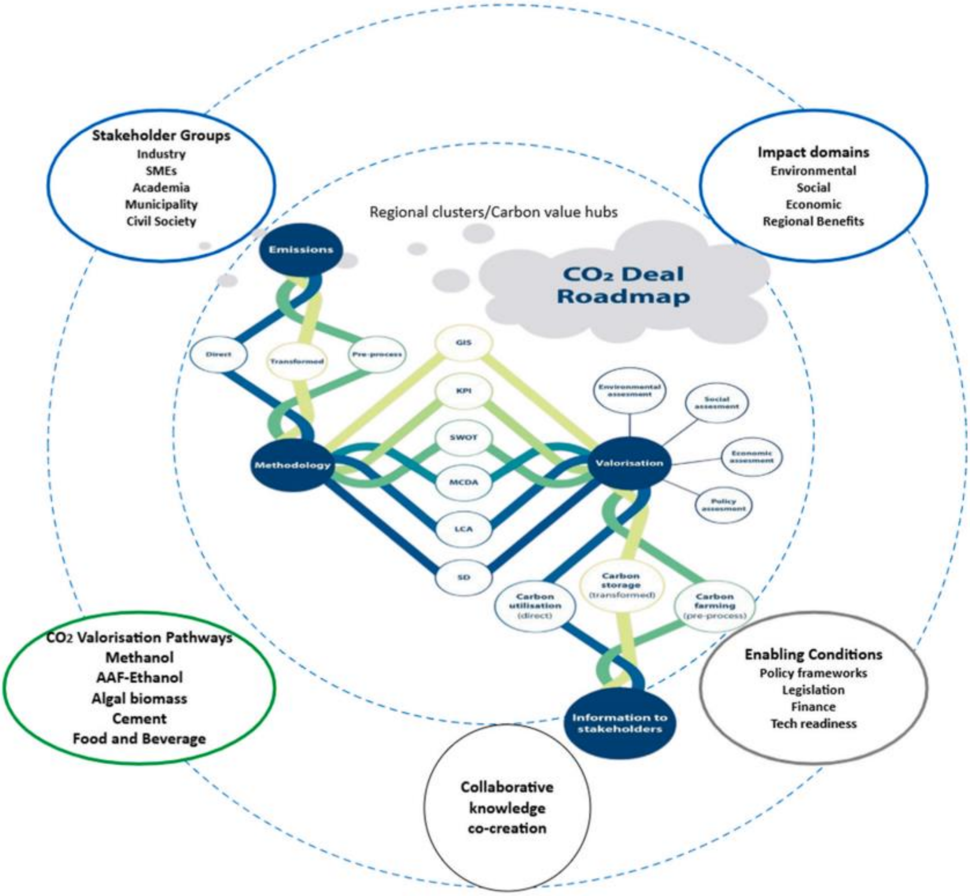

Fig. 43. CO_2 valorisation methodology.

The objectives set to 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.

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DOCTORAL THESIS PUBLICATIONS

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 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).

PAPER 1. ANALYSIS OF CO_2 VALORISATION OPTIONS FOR REGIONAL DEVELOPMENT

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Analysis of CO_2 Valorisation Options for Regional Development

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Abstract **– Mitigation of CO_2 emissions has become a top-question in international and national arenas, likewise on the city level. Existing CO_2 mitigation measures are primarily oriented towards wider deployment of low-carbon technologies of renewable energy sources and energy efficiency measures, focusing on energy production, distribution and energy use sectors, as well as the transport sector. Due to higher CO_2 reduction efficiency and the cost aspect, the direct CO_2 mitigation options currently applied are mostly oriented on large scale CO_2 generators. Meanwhile the rural, sparsely populated regions already suffer from a lack of innovative industrial economic activities, inhabitant's migration to urban areas and mostly involved in agriculture, land use and forestry activities. They are also "saved" by the public authorities from targeted CO_2 emissions mitigation actions, therefore, the understanding of processes within rural CO_2 economy sectors, factors, interconnections and effects to the environment and nature quality and finally guidelines to future actions are crucial. To analyse CO_2 valorisation options for regional development, a multi-modelling approach combining literature review, an indicator analysis method and a multi-criteria decision-making analysis were used. As a result, CO_2 valorisation options and key performance indicators were defined and multi-criteria analysis for regional decarbonization scenarios were performed.**

Keywords **– CO_2 utilisation; decarbonization; key performance indicators; multi-criteria analysis; rural development**

1. INTRODUCTION

The growing amount of CO_2 is a serious problem in today's world. The increase in the amount of carbon dioxide in the atmosphere has dramatic consequences – an increase in the average daily temperature on the planet, which results in the melting of glaciers and a rise in the world ocean level. The concentration of CO_2 rises by 2 ppm annually and has already reached 400 ppm and if the concentration does not stabilize at 450 ppm, the temperature may rise from 2.5 °C to 6.5 °C by 2100 [1], [2].

Seeing the growing amount of harmful emissions, how it affects the environment and people and what serious consequences it can cause in the future, the European Commission launched the Green Deal strategy initiative. The main aims of this strategy are to eliminate greenhouse gas emissions by 2050 (to become carbon neutral) and to decouple the economy from resource use. This leads to the major goal of the initiative – long-term climate neutrality [3].

In December 2020, a new report was published, which focused on greenhouse gas emissions and on carbon emissions particularly and the potential to reduce them in each sector [4].

The European Commission has also revised targets for reducing amounts of CO_2 emissions. An increase in the emission reduction threshold from 40 % (compared to 1990) to 55 % by

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2030 was proposed and subsequently approved. But even this target is not a final decision, since the European Parliament deliberates on lifting this threshold up to 60 % [5].

Emissions of greenhouse gases and especially CO_2 occur in many sectors, the main ones of which are combustion of fossil fuels (oil, coal) in the energy sector and industry, as well as in housing and transport. In the energy and industrial sectors, many sources have high greenhouse emission levels, so they are suitable for adding carbon dioxide capture technology. According to statistical data, in 2020 the energy sector emitted 44.3 % of CO_2 (fossil fuel energy), and the industrial sector – 22.4 %. Land transport is also one of the biggest greenhouse gas producers – 20.6 % of total CO_2 emissions are emitted by this sector [6], [7].

Considering the emissions of carbon dioxide in 2009–2018 in Europe, there is a negative trend in the amount of total CO_2 emissions. If we consider each sector separately, then the largest number of emissions is observed in the energy sector, while emissions in the industrial sector barely exceed 250.000 thousand tons per year [8]. Land utilisation sector shows positive dynamics in CO_2 emissions – the amount is slowly decreasing every year. This may be mostly because of the new, cleaner technology implementation and more sustainable ways of land use (Fig. 1).

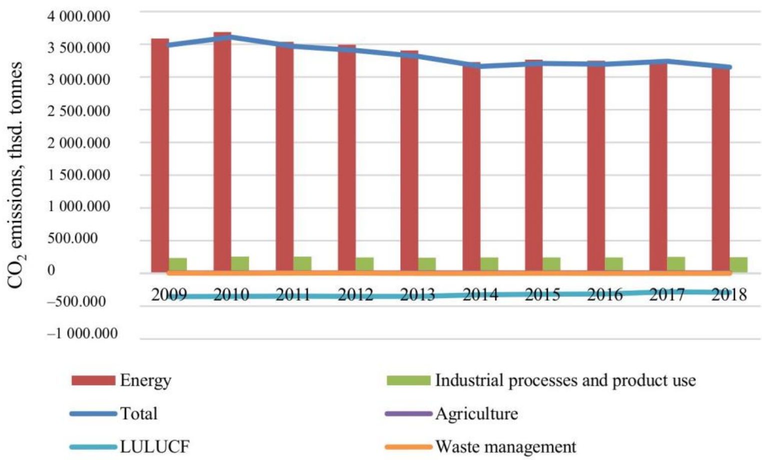

Fig. 1. CO_2 emissions in European Union 2009–2018 [8].

Despite the fact that in the time period from 2010 to 2018 the amount of CO_2 emissions in the European energy sector decreased by 14 %, this sector is still one of the leaders in terms of carbon dioxide emissions [9]. While some countries are actively using the latest energy production technologies, others are experiencing stagnation in this sector, a slow transition to more environmentally friendly fuels and / or slow introduction of innovative technologies [10], [8].

Latvia is one of the countries, where total amount of CO_2 emissions is rising steadily.

The biggest amount of CO_2 emissions was produced in the energy sector, followed by manufacturing sector. Opposite to trend in Europe, in Latvia the difference in amount of emission between these two sectors is not so big (Fig. 2).

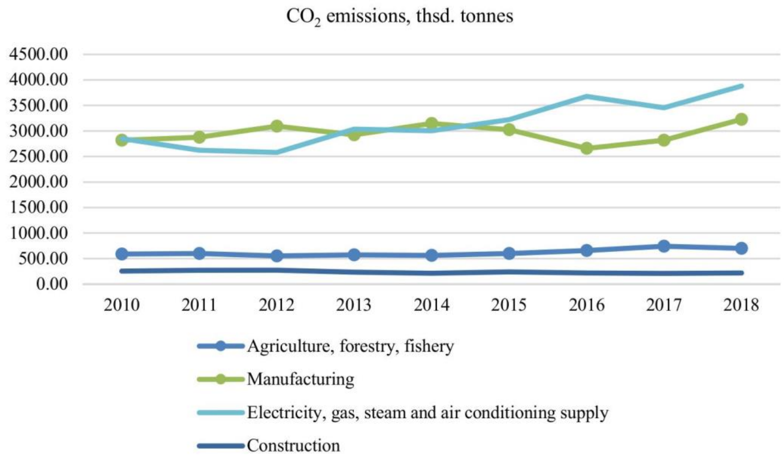

Fig. 2. CO_2 emissions in Latvia sectors in 2010–2018 [11].

Implementation of new technologies could help to decrease the environmental load – in Latvia there was a decline in 2019 in CO_2 emissions in the energy sector for almost 8 % compared to 2018, but it still is not enough to meet new requirements regarding emission control [12]. The slow modernization of production processes and the transition of production to renewable energy sources, the lack of support for the introduction of new technologies, as well as the economic downturn do not contribute to the reduction of carbon dioxide in any country [13].

Despite the introduction of new, stricter standards for production and plans proposed in the European Union for the regulation of greenhouse gases, the number of emissions in some countries is decreasing at an extremely slow rate (and in some sectors it is not decreasing at all), it is necessary to develop an alternative way of using CO_2 in the country [8]. It is necessary to systematize the spheres of production and select those sectors that can use carbon dioxide for the manufacturing of products with increased added value. It is necessary to turn production waste into a valuable product – that is, it needs valorisation.

CO_2 can be used in various fields – as a raw material for the production of innovative fuels, in the chemical industry for the production of chemical substances, as an additional food for algae and as an additive in the cement sector, etc. The use of carbon dioxide in the manufacture of new materials and products is considered to be sustainable production. The production of new types of fuel helps to reduce the amount of emissions, and the use of a "waste product" as a raw material for other manufacturing processes will reduce the amount of CO_2 in the atmosphere, the introduction of new technologies will create additional jobs, which will have a positive effect on the economy as a whole [14].

Within the framework of the H2020 program, many projects are being implemented, the purpose of which is the production of biofuel, using carbon dioxide as one of the resources. The MefCO_2 projects are a good example of this use of carbon dioxide. The project is a working technology that captures and uses carbon dioxide from a power plant in Germany. The plant uses coal for energy production, the combustion of which emits large amounts of CO_2, thus capturing and then using this CO_2 to produce methanol (as well as other valuable chemical compounds) reduces the plant's environmental load. This project demonstrates by its example the possibility of using industrial carbon dioxide for the production of goods with high added value, which has a positive effect on both the environment and the economy of the region [15].

Carbon dioxide is widely used in the chemical and by-chemical industries. It can be used in a 'raw' form, that is, as a working fluid (for example, a refrigerant or supercritical CO_2) or a solvent, or in a processed form as a resource for the production of valuable chemicals, building materials, as well as a product for the production of syngas, methanol and fuel [16].

However, each process of using carbon dioxide requires its own specific technology. Unfortunately, CO_2 cannot be used immediately in all spheres as it is captured. These rare areas, where carbon dioxide can be used without a complex purification process, are the biomethane, ethanol and methanol sectors – during the fermentation of biomass carbon dioxide is released, which can be separated from the main stream and used to produce the corresponding compounds. In the case of biomass combustion (for example, in boiler houses), it is possible to capture CO_2 both before and after combustion and transport it to places for further use, for example, construction and steel refineries. In this case, careful cleaning of carbon dioxide from impurities is required [17].

Despite the seeming complexity of capturing and using carbon dioxide, the number of CO_2 utilization projects, as well as the demand for carbon dioxide, is growing every year. In 2018, the leaders in the use of CO_2 were urea production and enhanced oil recovery, but as technology develops, the share of other sectors (such as the production of methanol and other chemicals) is growing. Annual demand for carbon dioxide is expected to be 272 $MtCO_2$ by 2025 [18], [19].

2. METHODOLOGY

A combination of methodologies was used during the research on the possibility of CO_2 valorisation: literature review, HORIZON2020 data analysis (H2020) [20], key performance indicators analysis and Multi-Criteria Decision analysis.

Literature sources were used to search for methods of utilising carbon dioxide in production, its necessary parameters, quantities and other important data. The analysis included a review of available technologies and their requirements for the use of CO_2 in various production areas, for example, chemical industry, food, construction, energy production, etc. Thanks to these parameters, it became possible to create the key performance indicator (KPI) table – a table in which the most important factors for CO_2 utilisation are collected. After analysing the H2020 projects, it became possible to select the main directions of using carbon dioxide in the new product manufacturing. In turn, quantitative data obtained from these projects serve as benchmarks in the KPI table.

Having all the necessary data, a Multi-Criteria Decision Analysis was carried out, the purpose of which is to determine the optimal area of CO_2 valorisation, which would be applicable in Latvia. An algorithm of the analyses applied in this research is depicted in Fig. 3.

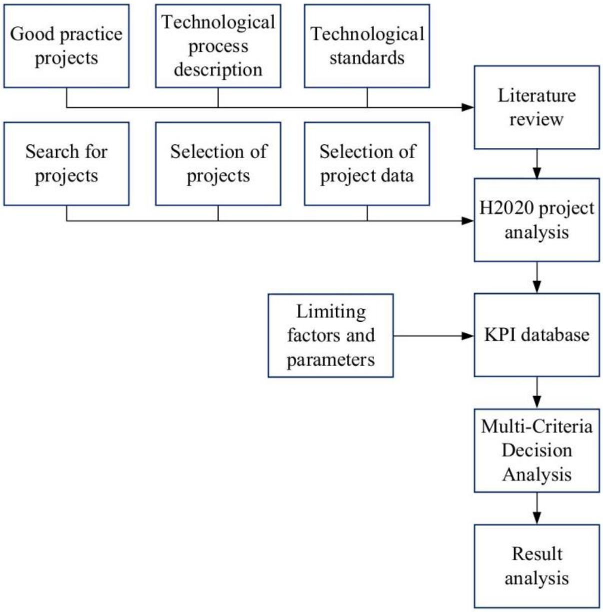

Fig. 3. Methodological scheme.

2.1. Key Performance Indicators

Key Performance Indicators are known to be an efficient way to compare various solutions and technologies in a definite area. They can be slightly changed depending on the field of the observed production [21].

The KPIs are based on parameters that are generally known at the production stage and are aimed at quantifying such parameters as energy consumption and potential savings, economic benefits from the introduction of a particular technology, the impact of production on the environment, etc. used in various production areas. Performance indicators may be specific to a production area or can be common to various areas [21].

One of the tasks in this work was to create a KPI table. During the analysis of literature, technical reports and descriptions, as well as H2020 projects, a KPI table was compiled, consisting 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.

Analysing the H2020 program, out of more than 32 000 projects, it was possible to sort out 242 projects in which CO_2 is planned to be used for the manufacturing of new products. Of the already made sample, only 30 projects had enough data for further work – filling in the created table of Key Performance Indicators (the process of project processing for indicator development is shown in Fig. 4).

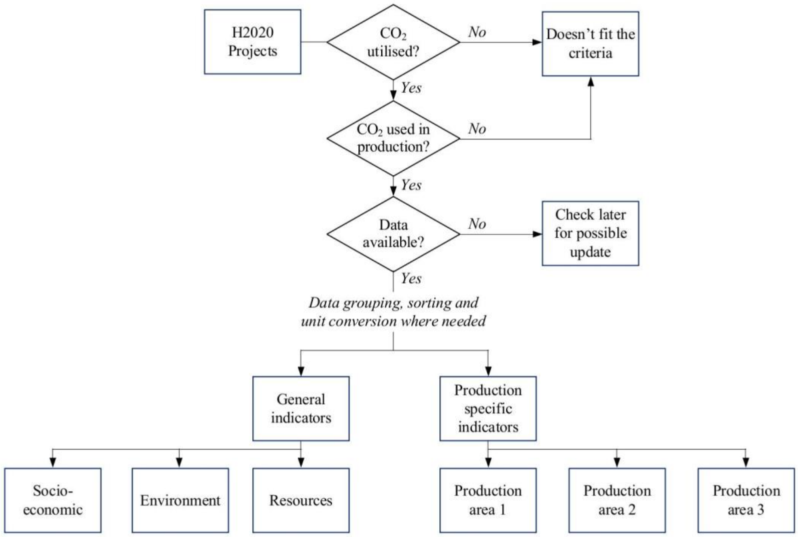

Fig. 4. Algorithm of H2020 project processing and KPI database compiling.

Unfortunately, at this stage, the amount of information available does not allow assigning a value to each created indicator. Summarizing all the information and data obtained, only 4 potential directions of CO_2 use can be identified and only 5 indicators can be used for further multi-criteria decision analysis.

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. The table includes general indicators that can be applied in any area and production specific indicators, which, in turn, relate to a specific area of production. Where possible, indicators include CO_2. For example, the main indicators are such indicators as electricity consumption per ton of product produced / ton of CO_2 produced (MWh/t and MWh/tCO_2), the amount of CO_2 required to produce a ton of product and the amount of CO_2 created during the production of a ton of the final product (tCO_2 utilized/t product, tCO_2 generated/t product), as well as the ratio of required and generated CO_2 (tCO_2 utilized/tCO_2 generated), etc.

2.2. Multi-Criteria Analysis

In order to analyse the degree of importance of each CO_2 valorisation option (Methanol production, Cement production, Algae ponds / Greenhouses, Food and Beverage production), a multi-criteria decision analysis was carried out. Choosing the right analysis method, TOPSIS was chosen as the most appropriate [22], [23].

To analyse the options for using CO_2, several criteria have been used:

- amount of permitted additive in 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 existing process.

The criteria and their values were selected based on the available data from H2020. All indicator values that have been used in the analysis are shown in Table 1.

TABLE 1. KEY PERFORMANCE INDICATORS USED IN MCDA

	Methanol Production	**Cement Production**	**Food and Beverages**	**Algae ponds and Greenhouses**
Permitted additive amount in flow %	5	10	1.2	30
Electricity consumption, MWh/t	0.0559	0.819	0.01	0.025
Amount of CO_2 utilised, tCO_2/t	1.4	0.06	1.8	2
Amount of CO_2 produced, tCO_2/t	4	0.4005	0.5	0.257
Simplicity of implementing the technology*	5	5	3	2

*Indicator was measured on a scale 1 to 5, where 1 – simple and 5 – difficult, based on the literature review and H2020 project descriptions.

3. RESULTS AND DISCUSSION

3.1. Key Performance Indicator Analysis

In the process of analysing the methods of CO_2 valorisation, both existing and on-going 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 (e.g., electric energy per one t product, water consumption per one t final product, produced CO_2 and required CO_2 ratio), 12 – environment-related (e.g., total emission during production process and possible CO_2 capture system efficiency), 18 – economy-related (e.g., costs of CO_2 if buying, total costs for CO_2 if doing nothing). The table also includes 28 indicators specific to the scope of potential CO_2 applications, for example, methanol production (CO_2 conversion rate), cement production (CO_2 emissions per tonne of cementitious materials produced), use of algae and greenhouses (CO_2 fixation by plant). Despite the large number of indicators compiled, further analysis is required. It is necessary to fill in as many indicators as possible to enable a better MCDA analysis, which would include more criteria for assessing the scenarios of the potential use of CO_2 as a resource. In the future, when the other indicators receive their benchmark values, they will also be used for analysis.

3.2. Multi-Criteria Decision Analysis Results

Quantitative production data from literature sources, technical descriptions, Good Practice projects and H2020 projects were used for the MCDA analysis. During the analysis of the literature and projects H2020, 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 the use of carbon dioxide in these areas are the most developed and accessible. There are also many examples of good practices available, allowing to learn from the experience and use it in Latvia. Some technologies, such as the carbonisation of beverages, have long been known in the country (the production of alcoholic beverages, for example), while others are still not applied broadly or not used at all (for example, the production of methanol).

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 from 1 to 5). Results of MCDA analysis with the closest to ideal value of each scenario are depicted in Fig. 5.

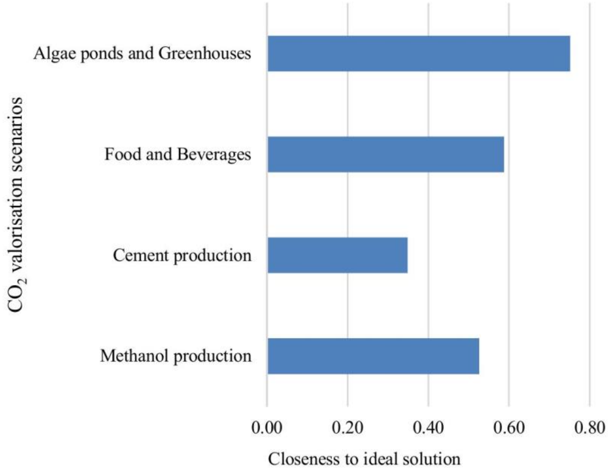

Fig. 5. CO_2 valorisation MCDA results.

The MCDA analysis showed that the optimal scenario for the use of CO_2 could be algae ponds / greenhouses and the food industry (Fig. 5). Algae ponds are an attractive option as algae can absorb large amounts of carbon dioxide. According to literary sources, there is no need to supply CO_2 completely purified from impurities, which greatly facilitates the use of this technology. By adding carbon dioxide, algae grow much faster. When the mass is sufficient, it can be used as biofuel or fertilizer, which is an additional advantage of this scenario [24], [25].

A good example of the use of algal biomass is the H2020 project IPHYC-H2020. In this project, microalgae are used for wastewater treatment. Plants purify water from phosphorus and nitrogen compounds, and to speed up metabolism receive specially introduced carbon dioxide. Once the microalgae have reached a sufficient mass, they are used in energy production. Thus, water purification becomes not only more efficient and environmentally friendly, but also produces much less CO_2 (and with sufficient technology improvement, it can potentially become a carbon-neutral process), but also allows the production of biofuel (biomethane), and from digestate – an environmentally friendly and efficient fertilizer, which also has a positive effect on the number of emissions in the country [26]–[28]. Such algal installations can potentially be installed in regional governments. This would help not only produce valuable goods (like biofuel) and reduce the amount of CO_2 emissions, but also increase the efficiency of the agricultural sector in the region [29], [30].

The second scenario, the food industry, is just as good. Carbon dioxide can be used both as a gas to protect against pests and to extend product shelf-life, and as a substance to carbonate beverages [31]–[33]. As an additional way of using CO_2 – refrigeration units and as a dry cleaning agent. Carbon dioxide 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 %) [31], [32].

Technologies for using carbon dioxide 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 [34]. In turn, considering the scenario of using carbon dioxide in the production of methanol, the advantage of the location of the stations in the regions is the proximity to the direct supplier of biomass. This advantage has the potential to significantly reduce logistics costs. However, the construction of such a biostation requires large expenditures, which are often inaccessible to regional governments. Food and beverage producers also have the potential to use carbon dioxide produced either locally or in neighbouring companies. CO_2 can be used both directly for the carbonization of products, and as a product preservative, a refrigerant in refrigeration units and an environmentally friendly and safe cleaning agent for technical appliances [31], [35], [36].

4. Conclusion

By analysing the available literature as well as the H2020 projects, many potential uses of carbon dioxide have been identified. The optimal ones are the production of methanol, food carbonisation and conservation, additive in the production of cement and additional CO_2 source for the metabolism of plants and algae.

Based on the analysis of literature sources and H2020 projects, as well as the subsequent MCDA analysis, it can be concluded that algae ponds / greenhouses is currently the most available method of CO_2 utilisation. The technologies for this scenario are the simplest (in comparison with other alternative scenarios), and the consumption of carbon dioxide is the highest. The second option for the use of carbon dioxide is its use in the food industry. These technologies have been known for a long time, their implementation in existing production is simple and affordable. However, the disadvantage is the need for a high degree of CO_2 purification. These two scenarios are most suitable for the rural region, since the technologies are the most accessible, easy to maintain, and cheaper, and the consumption of carbon dioxide, from the considered scenarios, is the highest.

In the process of researching ways to valorise carbon dioxide, a table of key indicators was created, which allows comparing various industries, regardless of their scope. Despite the fact that at the moment only a small number of the indicators can be fully used, in the future, when the other indicators get their values, the table will be used on a wider scale. This table will help to identify enterprises with the greatest potential for introducing new technologies for the utilization of CO_2 both at the place of its production and in case if transported from elsewhere.

This work was written with a focus on the possibility of carbon dioxide valorization in Latvia, but the results can be used in other countries as well.

The research carried out in this work has outpaced the level of willingness of enterprises to change, to carry out green transformations in order to comply with the green direction adopted in the European Union. The Green Deal Initiative will promote changes in the manufacturing sector more and more actively and this work proposes a solution to the CO_2 problem in Latvia. The study outlines the way forward for ecological and sustainable production.

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PAPER 2. REGIONAL DEVELOPMENT SCENARIOS AND MODEL BOUNDARIES FOR CCU IN ENERGY SECTOR IN LATVIA

Regional Development Scenarios and Model Boundaries for CCU in Energy Sector in Latvia

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***Abstract*—Despite the measures taken, the amount of carbon dioxide emissions continues to increase every year and energy sector is taking the leading positions. However, with the use of the latest technologies and the experience of existing projects, it is possible to achieve positive results on both fronts. Using technologies for capturing and using CO_2, one can not only reduce the amount of emissions in the country and make the energy sector more environmentally friendly, but also help the development of Latvian regions.**

***Keywords*—CO_2 emissions; CCU technologies; regional development**

I. Introduction

The amount of CO_2 emissions continues to grow every year. It is growing, despite the measures taken and the strictness of control over countries and how they fulfil the set requirements. The consequences of slow measures can reach dramatic levels – melting glaciers, rising sea levels, unstable temperatures and an increase in the number of natural disasters [1], [2].

To stabilize the climate situation, the European Union adopted the Green Deal initiative. The main goal of this initiative is to neutralize carbon dioxide emissions by 2050. To control the achievement of the set goal, the task was divided into stages, one of which is to cut carbon dioxide emissions by half by 2030 [3], [4].

In December 2020, a new report was published focusing on greenhouse gases. In more precise, the report discusses the problem of carbon dioxide and methods to reduce its emissions in various sectors [5].

According to statistics, the energy sector is a leader in the production of carbon dioxide emissions as in the world and the European Union, as in Latvia [1], [6], [7]. According to [1], in 2018 the largest amount of carbon dioxide emissions was recorded in the USA and China (10–50% of the total number of emissions). Germany is the leader in the European Union (2.08% CO_2). The rest of the Union countries, including Latvia, look more optimistic against the general background and the amount of emissions in Latvia did not exceed 0.02% of the total CO_2 emissions in the world (which is better than in Lithuania (0.04%) and Estonia (0.05%)).

According to government statistics, in 2017, the country produced 10161.94 thsnd. tCO_2 (sectors Agriculture, forestry, fishery, Manufacturing, Electricity and Construction), while in 2018 the number of emissions amounted to 8025.64 thousand tCO_2. It is noteworthy that the number of emissions decreased only in the agricultural sector (5.85% decrease compared to a year earlier). Of the above sectors in the period 2017-2018, the manufacturing sector showed the largest increase in emissions – +14.50% (Electricity +12.30%, Construction +4.06%) [6]. Considering emissions by sectors of its production, it becomes obvious that the leader in CO_2 production is the energy and industrial sectors [6]. The worsening of the situation can be explained by the extremely slow introduction of innovative technologies, stagnation of the sector, unwillingness and / or inability of entrepreneurs to change. Installations for capturing and neutralizing CO_2 directly at the site of its production can often be simply inaccessible for the region and / or the entrepreneur, and therefore there is no way to reduce the amount of carbon dioxide produced. Despite the positive aspects of introducing technologies for capturing and using carbon dioxide in industry, there are many factors that limit the use of a particular technology in practice.

The major and, perhaps, the main limiting factor for the use of CO_2 is the required level of its purification from impurities. For example, for the use of carbon dioxide in the food industry, it is necessary to ensure the purity of the gas up to 99.5% [8]–[10]. A similar level of purification can be provided either by an industry already initially aimed at the production of CO_2, or by certain processes of the chemical industry (as well as the food industry itself). In turn, biostations need a level of at least 95%. As in the case of the food sector, the chemical industry and the food industry can also provide CO_2 for biostations as well [11], [12]. Because of this high level of purification required, before using carbon dioxide as soon as it is produced, it is necessary to first ensure its purity. The main producer of CO_2 in Latvia is the energy sector, however, combustion of fuel produces not only CO_2, but other elements as well [13]–[15]. Installation of additional elements is required to ensure the capture of carbon dioxide before, after or during combustion. The installation of such equipment entails additional financial and energy costs, but makes it possible to reduce the amount of carbon dioxide produced at the enterprise and makes it possible to produce goods with increased added value.

However, carbon dioxide is not only a waste product of production, but also a potential resource for creating new high value-added products. Potentially, carbon dioxide can be used as a resource in the chemical industry for extraction of valuable chemical compounds, in the food industry for the carbonization of products, as a refrigerant and energy fluid [8]–[18].

Another important sector for the use of carbon dioxide could be the energy sector. Already, CO_2 is increasingly used in the production of biogas (for example, bioethanol) and biofuels (for example, aviation fuel, dimethyl ether (DME), gasoline) [19]–[23]. CO_2 can also be used in algal ponds. According to [24], carbon dioxide is able to speed up the metabolism of plants, thus increasing the rate of biomass growth significantly. Once the biomass reaches a sufficient amount, it can be used to produce biogas. Using carbon dioxide in the energy sector can significantly diversify this market, which will have a positive effect on the sector.

II. Methodology

To determine the development potential of the regions and analyse the possibilities of using technologies for capturing and using carbon dioxide in the energy sector, the following tasks were completed:

1. The analysis of literary sources was carried out in order to identify the possibilities of using both pure and industrial carbon dioxide in the production of new goods. The factors limiting the use of CO_2 in a particular technology have been identified.
2. Using state databases State Environmental Service and Ministry of Environmental Protection and Regional Development, a database of Latvian A and B category companies emitting carbon dioxide has been compiled [25]–[27]. The base includes data such as the name of the enterprise, its location (address and coordinates), the category of the permit for polluting activity (A or B), the type of activity and the number of emissions produced. This analysis did not consider category C enterprises. In the group of enterprises with a permit A there were the largest producers of the industrial sector (e.g. Schwenk), the energy sector (e.g. Rīgas Siltums) and landfills. The group of companies with a category B permit includes enterprises of various sectors - food and beverage, industrial, energy, chemical and refining. Considering the energy sector, this paper did not consider the type of heating - central or not. Where possible, data on the amount of carbon dioxide produced was taken from the company's annual reports.
3. Unfortunately, the mentioned government agencies did not always contain the necessary data on the amount of CO_2 emitted, or the data were outdated. Because of this, the missing emission data were taken from the Latvian Center for Environment, Geology and Meteorology portal [28]. In this work, there is no separation in the source of the produced CO_2 - either it was the result of the heating of the building or a by-product of the production process. The purpose of the work is to analyze the total amount of produced carbon dioxide and the possibility of its further use.
4. Having filled in the table with all the necessary data, the points of both the production of carbon dioxide and its potential use were marked on the maps of Latvia in the *ArcGis* program.

III. Results

A. CO_2 Producers and Potential Consumers

According to data obtained from State Environmental Service databases, there are 48 A category enterprises and 610 B category enterprises in Latvia that emitted carbon dioxide in 2019. Enterprises are located mainly in the Riga region, where the distance to a potential consumer is the smallest (Fig. 1).

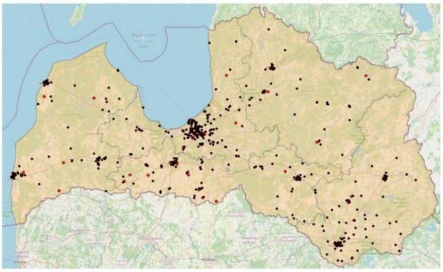

Fig. 1. CO_2 production sites A category companies (red) and B category companies (black)

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

By analysing the list of potential consumers of carbon dioxide, a list of enterprises was compiled. These include those enterprises, the main activity of which is related to the production of energy (bio-stations, landfills), food and beverages, algal pools / greenhouses. Considering the ratio of the number of enterprises producing CO_2 and those enterprises that can potentially use it, it becomes obvious how few enterprises from the second category are currently in the country (Fig. 2).

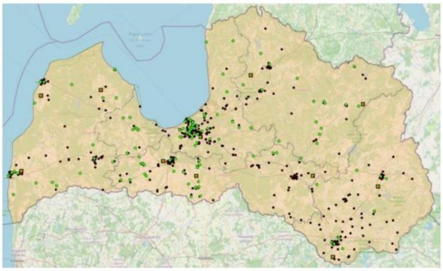

Fig. 2. Sites of CO_2 production (brown) and potential utilisation (green)

Considering the ratio of CO_2 producers and its potential consumers by region, as well as the amount of carbon dioxide produced in each region, it becomes obvious that the consumer / producer ratio, although it can be considered important, is still not decisive in determining the "pollution" of the region (Table 1).

TABLE I. 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

As can be seen in Table 1. Riga region and Kurzeme produce the largest amount of carbon dioxide in the country (64.42% and 25.94%, respectively), however, the greatest difference in the number of places for the production of CO_2 and its consumption is observed in Latgale, a region with relatively a small share of CO_2 in the country. Such a large difference can be explained by the density of industrial institutions, population and the level of development of the regions.

Such a large number of carbon dioxide emissions in the Riga region is explained by the large number of production facilities located closer to the capital, where the main sales market for the manufactured products is located. There are also large producers in the Riga region (often with a category A polluting activity permit). This, for example, is the energy sector – the main stations of Rigas Siltums themselves in 2019 produced more than 180 thousand tons of carbon dioxide, which is equal to 7.49% of CO_2 emissions in the region. Other large enterprises with a declared large amount of CO_2 produced are "Putnu fabrika Ķekava" (11100.83 tCO_2, 0.45%), Olainfarm (10219.42 tCO_2, 0.42%) and Latvijas Finieris (6828.00 tCO_2, 0.28%).

A number of large factories are also located in Kurzeme. However, unlike the Riga region, in Kurzeme the leader is not the energy sector, but the industrial sector – the cement production of Schwenk in 2019 generated 793917.68 tCO_2 or 80% of the region's CO_2 emissions. The second place is followed by energy production in Liepaja – Liepājas Enerģija (43632.00 tCO_2, 4.44%).

According to [29], there are currently 50 biogas plants in the country that could potentially use carbon dioxide to increase the plant's productivity. The stations are located mainly in rural areas of the regions (for example, the southern part of Kurzeme, flat areas of Vidzeme), but there is no region where the station would not exist (Fig. 3).

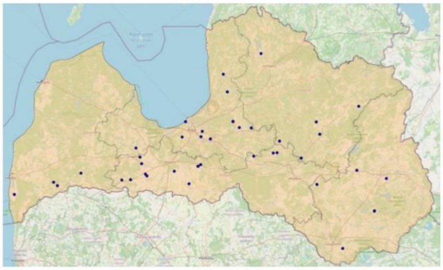

Fig. 3. Sites of biostations

According to the literature sources [24], [30], [31], algal ponds can also be used for both carbon dioxide recovery and energy production. Algae are plants that, under favorable conditions, quickly gain mass, which can be used as biomass in biogas stations. The remaining digestate, in turn, can be used as fertilizer in agricultural areas, increasing the yield of grain and other crops. Plant residues can then also be used in the production of energy in biostations, in this way enclosing the circular economy cycle. Unfortunately, at the moment there is not a single active algal pond in Latvia.

Landfills can also potentially use carbon dioxide for energy production [32], [33].

B. Boundaries of CCU implementation

Unfortunately, a number of restrictions impede the implementation of CSSU technologies. One of the main limitations is the required purity of carbon dioxide. For many processes (for example, the chemical and food industries), the CO_2 purification level must be at least 99.5%. Installations with such a high level of efficiency can often be financially disadvantageous. The economic component of the modernization issue is the second, but not least limiting factor. However, companies aiming to reduce the amount of carbon dioxide generated can count on financial assistance from European funds [34], [35].

Such installations for carbon capture and purification can be installed in various production places and, for example, in boiler houses. The purity of the CO_2 obtained at the outlet directly depends on the efficiency of the technology used [36]. In the ideal case, the percentage of purification can reach 99% and such CO_2 can potentially be used in biogas stations, and, for example, in algal ponds. The advantage of these ponds is the fact that plants do not need perfectly pure CO_2 to speed up metabolism. According to [37], the maximum allowable amount of impurities in the supplied CO_2 can reach 30%.

IV. Conclusions

In this paper, the possibilities of using Carbon Capture and Utilisation (CCU) technologies in various sectors were analysed.

The energy sector – the production of biogas and biofuels – has a high potential to reduce the amount of carbon dioxide not only in the atmosphere, but also in the industrial sector. Potentially, biogas stations could become consumers of the produced CO_2, but this requires the installation of additional equipment, which entails additional financial costs. Many enterprises and regions are currently not ready to invest in the development of CCU technologies, despite all the advantages, since there is no confidence in financial support from both the state and various funds. It is necessary to reconsider the possibilities of financial assistance to enterprises that could potentially use CO_2 in their production. This work did not take into account the ETS system, but this system definitely puts pressure on enterprises and motivates them to modernize production processes.

A large number of enterprises in the country are trying to be closer to their main sales market – the Riga region. As a result, the largest amount of CO_2 emissions, in comparison with other regions of the country, is located in this part of the country. It is necessary to take measures to reduce emissions to make better the environmental situation in this area – to improve and modernize existing production, create new enterprises that could use CO_2 to produce goods with high added value. The largest CO_2 producers in the region are boiler houses. In the case of installing systems for capturing and further purifying carbon dioxide, emissions can be redirected either to biofuel production plants or to ponds to accelerate the metabolism of algae. Unfortunately, at the moment there is not a single active algal pond in the country where biofuel could be produced.

Due to the relatively large number of CO_2 production sites, as well as the high level of development of the agro-industrial sector, technologies on the use of carbon dioxide for energy production can potentially be implemented in Latgale. Production sites can be biogas plants, using biomass as the main resource. Since Latgale is agricultural region, the biggest part of biomass can potentially come as residue from crops and other agricultural plants. The southern territories of Kurzeme are also considered agro-industrial and at the moment there are already 4 biogas stations operating. Potentially, these plants could use technologies to capture and use carbon dioxide to produce improved biogas, biomethanol and other valuable fuels.

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PAPER 3. BARRIERS AND DRIVING FACTORS FOR SUSTAINABLE DEVELOPMENT OF CO_2 VALORISATION

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Barriers and Driving Factors for Sustainable Development of CO_2 Valorisation

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Abstract: Mitigating CO_2 emissions has become a top question in international and national arenas, likewise on the city level. To initiate and maintain transformative policies related to climate neutrality, an evident-based multi-sectoral forecasting model needs to be timely and effectively deployed. Decarbonisation solutions should be considered from the economic, environmental, and social perspectives. The resulting complexity constitutes an essential barrier to implementing CO_2 valorisation projects. This study aims to analyse barriers and driving factors for the sustainable development of CO_2 valorisation options. In order to reach the research goal, a methodological approach based on the combination of strengths, weaknesses, opportunities, and threats analysis, Geographical Information System and Fuzzy Logic Cognitive Analysis method was used. The method has been applied to a case study in Latvia

Keywords: CO_2 technologies; SWOT; FLCA; ArcGis

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1. Introduction

Mitigating CO_2 emissions have become a top question in international and national arenas, likewise on the city level. Existing CO_2 mitigation measures are primarily oriented towards wider deployment of low-carbon technologies of renewable energy sources and energy efficiency measures, focusing on energy production, distribution and energy use sectors, and transport. In 2019, the manufacturing sector emitted more than a fifth of all global emissions in terms of CO_2 and occupied a solid third place after the transport (29%) and energy (25%) sectors [1]. For 2019, the global annual amount of created carbon dioxide emissions exceeded 35 billion tons, pervasive 36% more than in 1990 (22.70 billion tons) and 5.5% more than in 2010 (33.13 billion tons). Such negative dynamics raise concerns for a stable future of the climate. Carbon dioxide is one of the main factors in changing climatic conditions—and an increase in its concentration causes an increase in the harmful temperature on the planet and, as a result, unstable weather and natural disasters [2].

Seeing the potential threats of such development of events and what they may lead to in the future, it was decided to act, and so the Green Deal strategy is being actively developed and applied. The main goal of this initiative is to reduce carbon dioxide emissions and become carbon neutral by 2050. One of the stages towards achieving this goal is an intermediate point—the year 2030, by which each country needs to achieve a reduction of CO_2 emissions by at least 55% in comparison with 1990. It is difficult to say whether the goals will be achieved on time. Thus, the 20-20-20 package created in 2008 set the goal of achieving a 20% reduction in CO_2 emissions compared to 1990 by 2020, increasing the use of renewable energy sources (abandoning non-renewable ones), and increasing the amount of generated energy and its efficiency by 20%. These goals were not achieved, and it is likely that if it were not for the economic crisis of 2009, it is quite possible that the target for the amount of carbon dioxide emissions could not have been achieved either [3,4].

The year 2020 has also proved to be a challenge for many entrepreneurs. The fall in economic activity affected the amount of carbon dioxide emissions in the atmosphere—its concentration decreased by 10% compared to a year earlier [5]. However, as the economy recovers, CO_2 will start to rise again.

Carbon dioxide is generated in many sectors. The switch to renewable energy sources is helping to reduce the amount of this greenhouse gas in the atmosphere, but it is not enough to change the energy sector alone. The manufacturing sector also needs to be modernised and become more environmentally friendly.

Over the past ten years, Latvia's carbon dioxide emissions have remained at the same level. The only sector showing negative dynamics is the power generation sector (Figure 1). Compared to 2018, this sector produced 8% less carbon dioxide in 2019, but this is too little to fulfil the plans set by the Green Deal initiative [6].

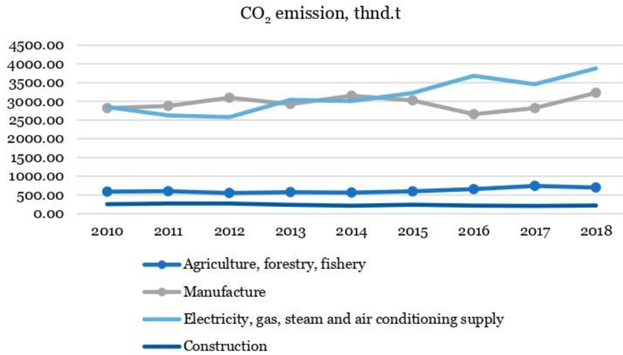


Figure 1. CO_2 emissions in Latvian sectors from 2010 to 2018 [6].

According to [7], the country continues to use coal and oil as fuel, but the number of renewable energy sources in the sector is increasing every year. According to the Investment and Development Agency of Latvia, the share of renewables energy generation is more than 40%, which gives hope for a decrease in the amount of carbon dioxide in the electricity generation sector [8] (Figure 2).

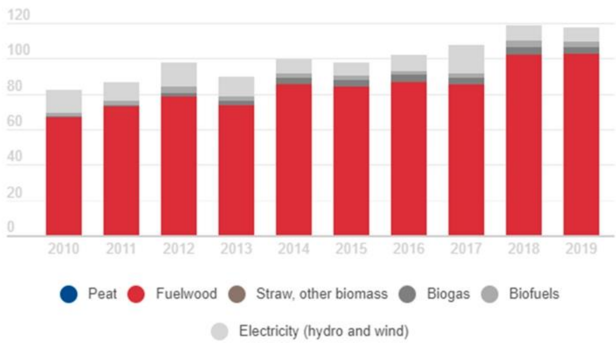


Figure 2. Primary energy generation from renewables, PJ [8].

Unfortunately, it is not enough to improve just the energy sector—changes are needed everywhere. There are many reasons why manufacturers are reluctant to install new technologies that reduce the amount of carbon dioxide they produce or capture and/or use carbon dioxide.

The main reasons for the slow transition to renewable energy sources and the replacement of outdated technologies with new ones could be:

1. The cost of technology and the payback period [9];
2. Complexity of technology and/or difficulty in maintenance [9];
3. Stubbornness and resistance of people—the human factor: people are afraid of losing their jobs. If new technologies are introduced into their lives too quickly, sooner or later, people might begin to grumble and then sabotage the work [10,11];
4. Bureaucracy [10];
5. Competition with existing technologies—due to conservatism, the transition to new technologies is slow. Old technologies have already shown and proven themselves, and the transition to new ones is often associated with the need for additional resources (personnel training, financial investments) [10,11];
6. Competence of decision-makers (lack of information about new technologies, which interferes with making objective decisions) [10,11].

The location of the enterprise could also be mentioned as a factor if the enterprise is aimed at capturing and selling CO_2 too far from a potential buyer. A logical question arises about the practicality of such a decision. Gas capturing and transfer technologies can be too expensive for an acceptable payback period [9,10].

Another reason change is happening so slowly may be the human factor—people are accustomed to a particular lifestyle and habits and therefore do not want to change. In the case of production, there may be two options—either the production itself offers an opportunity that pre-empts its time, or the market is not flexible enough for changes. Even if the manufacturer proposes a new product, the market will not accept it, and the enterprise will suffer significant losses. Technological innovation may be too large-scale (severe or sudden) for the local community. The risks may be so great that society is initially too sceptical about paying attention and/or investing in this technology or development. The third problem in the group of human factors may be the fear caused by little knowledge regarding the technology. Fears that new technologies, built on the basis of old ones, can take away a person's job are often crucial when it comes to adoption and acceptance [10,11].

When deciding whether or not to implement a technology, it is essential to analyse the barriers and driving factors carefully. One of the simplest methods is performing the SWOT analysis (strengths, weaknesses, opportunities, and threats). SWOT analysis allows assessing all the risks and possibilities of using a particular technology or methodology at different levels—starting with the impact of the innovation on the national level and a more local one (for example, the enterprise level). Evaluation provides an opportunity to assess the feasibility of innovation, take corrective actions to minimise potential risks and create a chain of stakeholders in the project [12]. The comprehensive analysis allows for identifying and providing information about external and internal factors that affect the project (or decision) both positively and negatively. With these data, the entrepreneur can determine the best scenario for performing [13].

In order to conduct a SWOT analysis, it is necessary to know what carbon capture technologies exist. These technologies can be divided into two large groups:

1. Capturing CO_2 and transporting it to places of further disposal (storage sites) or use for the production of new products.
2. The capture of CO_2 and its use in production right away

Carbon dioxide capture technologies are pervasive in the manufacturing and energy sectors. Technologies that have already proven themselves are, for instance, adsorption and membrane systems [14]. For example, the efficiency of pilot membrane plants can reach 80% CO_2 [14,15], and installations using adsorption allow achieving purity of the main CO_2 stream up to 95% and recovery of the flow up to 80% [14,16]. Carbon dioxide capture plants separate CO_2 from the overall production gas stream. Such technologies are usually installed in industries with a high content of carbon dioxide in the exhaust, for example, at heating stations and large industries [2].

As carbon dioxide is captured and removed, it must be transported (if it is impossible to use it in the same production). For long distances, it is preferable to use a pipeline, but it is possible to transport CO_2 by transport. In this case, it is necessary to ensure specific conditions (temperature −20–30 °C, pressure 1.5–2.5 MPa), which, due to their technical complexity, are not suitable for sizeable CO_2 storage sites [2].

For the analysis of CO_2 emissions, geographic modelling programs are actively used—the so-called Geographic Information System programs (GIS). The Group of GIS programs appeared relatively recently but has already established itself as a helpful program package in planning and resource management. It is possible to store, analyse, and process large data packages even from different and unrelated sources with such a program. The ability to plan problem-solving processes and make predictions in this program makes it possible to put forward quality solutions to problems [17]. Due to the program's versatility, analyses can be combined with analyses made using other methods, such as Multi-Criteria Analysis, AHP (Analytic Hierarchy Process) or SWOT [18]. Such a combination has the best effect on the quality of the analysis performed and justifies the results obtained. There are many disciplines in which a combination of GIS and an analytical program (Multiple-Criteria Decision Analysis (MCDA), AHP, etc.) could be productively used, such as development planning and modelling of urban and natural systems, the organisation of traffic flow, etc. [18]. For example, a combination of GIS and MCE (Multi-Criteria Evaluation) was used by Elmadi and Kheireldin [19]. This combination made it possible to determine the best scenario for the use of water resources at three levels—the level of direct use of the water resource, the water channel—the level of resource accumulation (and its subsequent withdrawal) and the mixed level. In his work, the author claims that the combined use of both analysis methods (GIS and MCE) is a serious, high-quality and reliable way to assess various scenarios for solving complex problems. Using both techniques simplifies the process of considering multiple options and, as a result, makes decision-making easier [19]. Boroushaki also used the possibility of parallel use of various analysis methods to obtain more accurate results [20]. The author of this study shared a method for integrating MCDA analysis into the ArcGis environment. Nasehi et al. used a combination of SWOT analysis and GIS software in their work to determine the optimal scenario for the development of urbanisation (industrial zones) with the minimum possible impact on the environment [21]. The use of SWOT analysis and cartographic programs allows decision-makers to evaluate the proposed solutions to the problem and prioritise them. When the choice is made at high levels, this combination will help to ensure the transparency of the solution and its comprehensiveness [22].

The combination of various analysis methods makes it possible to neutralise the disadvantages of each method separately. For example, SWOT analysis alone helps in identifying the main influencing factors. By combining SWOT with GIS, these factors already acquire the basis and validity.

2. Methodology

Within the framework of this work, a SWOT analysis was carried out to conduct a comprehensive analysis of the possibility of capturing and/or using carbon dioxide in the territory of Latvia. In parallel, using the data from [23], all places of CO_2 production and potential use places were marked on Latvia's map using the Geographical Information System program via ArcGis software. The use of SWOT analysis, together with cartographic programs, 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 [22].

For a more comprehensive analysis of the problem of technology implementation, an additional analysis was chosen—Fuzzy Logic Cognitive Analysis (FLCA). This analysis can be characterised as a way that displays fuzzy logical connections between various factors. FLCA models are beneficial when modelling complex systems and systems with a large number of factors influencing decision making [24]. The algorithm of the performed work can be seen on Figure 3.

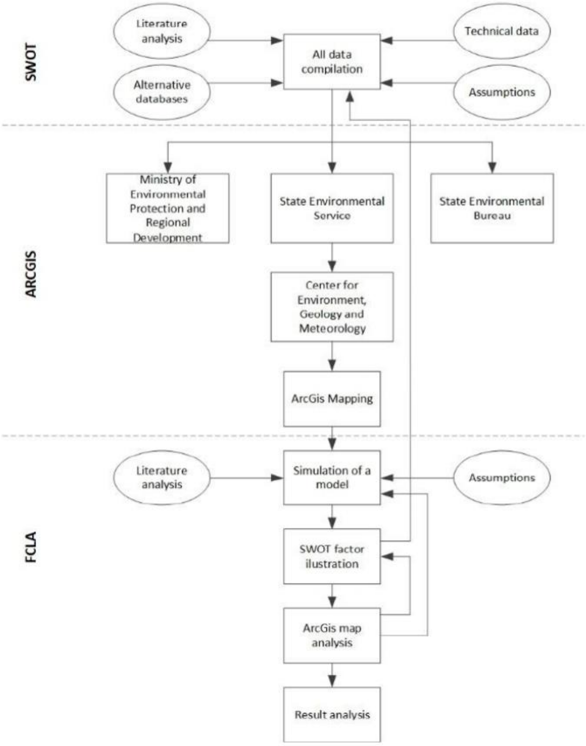


Figure 3. The algorithm of the performed work.

2.1. SWOT Analysis

The purpose of a SWOT (strengths, weaknesses, opportunities, and threats) analysis is to identify key factors, both external and internal, that may influence the process or task under consideration. The analysis groups these factors into four groups and two categories [25–27]:

1. Internal factors—strengths and weaknesses of the problem under consideration
2. External factors—opportunities and threats that can be caused from outside

In this paper, SWOT analysis is used to identify opportunities and threats nationwide and strengths and weaknesses within the enterprise. In order to ensure a qualitative analysis, this study used the opinion of all stakeholders who received a permit for polluting activities of category A (48 enterprises) and B (610 enterprises). Subsequently, all these enterprises were marked on ArcGis maps. Additionally, those enterprises that could potentially use CO2 were marked on the map(Figure 4).

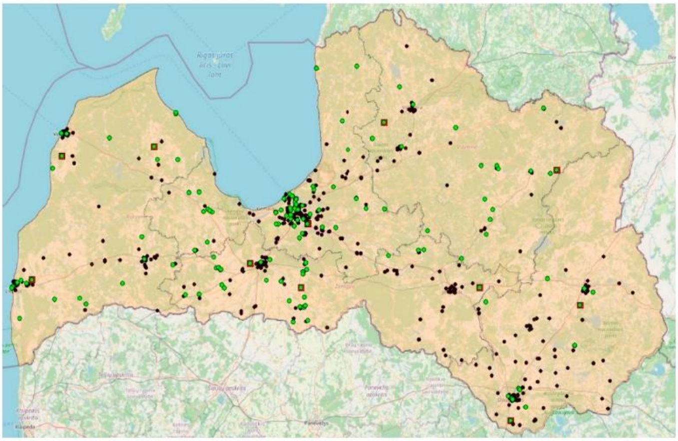


Figure 4. Sites of CO_2 (dark brown) production and (green) potential utilisation [23].

Considering the use of CO_2 following options have been observed: (a) CO_2 capture and utilisation in Europe; (b) CO_2 capture and utilisation in the case of Latvia; (c) CO_2 capture directly at the place of production, processing and transportation/reusing.

2.1.1. CO_2 Capture and Utilisation in Europe

Technologies for carbon capture and storage are called CCS and for storage and/or utilisation—CCSU, respectively. The so-called "major" factors affecting CO_2 capture and utilisation/storage are factors within the European Union—political divisions, bureaucracy, etc. However, at the same time, at this level, a vital factor can be called the influence of other countries on each other and the opportunity to exchange experience and knowledge (Table 1).

Table 1. CO_2 Capture and Utilisation in Europe.

Strength	Weaknesses
Influence of large countries of the Union on small ones, the ability to apply sanctions in case of non-fulfilment of obligations	Prolonged response and action of each participating country separately
Improving the quality of life for residents of the European Union (improving air, environment, health, additional jobs) [28]	No unity in making mandatory and unpopular decisions
Cooperation of countries on the issue of CCSU technologies, the ability to finance technology development and innovation in the sector	Different financial situations of each country [9,28]
Diversified development of CCS and CCSU technologies (applicable in various production sectors)	Different levels of technological development
Support for renewable energy and the phasing out of non-renewable ones	Not all countries have developed a clear-enough regulatory system for CCS and CCSU implementation [29]
Knowledge about energy efficiency and required measures [30]	CCSU technologies are still in the development stage [28]
	In the case of storage—suitable underground storage facilities are required, the imperfection of laws (the ability to find loopholes for default) [31]
	Low level of public awareness of the problem and public acceptance of changes [32]

Table 1. *Cont.*

Opportunities	Threats
The opportunity to change the economic situation in the world for the better	The ecological situation is deteriorating faster than countries react to it and act
Great world experience in the field of CCSU technologies—there is an opportunity to use and share best practices and mistakes (thus stimulating the further development of the sector)	An unstable political situation, epidemics (as well as major disasters and cataclysms) and their consequences (economic decline)
An increase in the CO_2 tax and the price of CO_2 quotas (stimulation of a faster installation of CCSU technologies)	An increase in electricity prices, the development of technologies will increase the technological gap between countries [28]
	The gap in experience and knowledge regarding CCS technologies [29]

2.1.2. CO_2 Capture and Utilisation in Latvia

The next level of carbon dioxide utilisation/storage is the national level. At this level, the main factors are bureaucracy, low awareness and/or inertia of people responsible for innovations, financial problems (for example, high cost of technology) and lack of technology representatives in the country. The problem is also a lack of practical experience in using this type of technology. However, the introduction of new technologies may provide new jobs, contribute to the development of the production sector in Latvia, and attract additional investments in production (Table 2).

Table 2. CO_2 Capture and Utilisation in Latvia.

Strength	Weaknesses
The need for changes	No or too little help from the state [9,33]
Requirements for reducing CO_2 emissions at the legislative level	High cost of technology [33–35]
The ability to attract foreign investors	Lack (or small number) of specialists and or representatives in this field in the country [33,35]
Additional jobs	The slow introduction of technologies due to the inertia and unresponsiveness of entrepreneurs [34]
The development of an enterprise and satellite enterprises	The extremely negative reaction from entrepreneurs in the case of mandatory introduction of CO_2 capture technologies
An extremely positive impact on the environment and human health	Low awareness of investors about CCS and CCSU technologies [9,36]
Knowledge about energy efficiency and required measures	
Opportunities	**Threats**
The opportunity to receive project financing from European funds [37]	Economic instability (caused by instability from the outside—exchange rates, politics, etc.) [34]
The ability to attract specialists from other countries	An increase in the price of electricity
Decrease in the amount of CO_2 emissions in the country	
The development of the production sector	

2.1.3. CO_2 Capture and Utilisation in Companies

This group considers all aspects of CO_2 capture at the place of its direct production, processing (purification and compression) and transportation to places of further use or resale, and the scenario of its use immediately at the same company (Table 3).

Table 3. CO_2 Capture and Utilisation in Companies.

Strength	Weaknesses
Knowledge of technology	The need to acquire new technologies [34,35]
Additional income for production (CO_2 is a by-product that can be sold or utilised)	The high cost of technology may put at risk the existence of the company [33,34]
Variety of technologies	Lack of free space for technology installation
Easy to install CO_2 capture systems	The need to redo an existing production process
Synergy with an existing company (transportation)	Additional financial costs associated with the maintenance of new installations [34]
The technological advantage over competitors (utilisation)	The need to create a logistics network (transportation)
No dependence on CO_2 suppliers (utilisation)	
Confidence in the quality and purity of captured CO_2 (utilisation)	
Opportunities	**Threats**
Additional jobs	Increasing requirements for CO_2 quality
Possibility to attract funding from the EU and the state	Too long technology payback time
Chance to get foreign investment	Absence of a representative of the technology manufacturer in the country [33]
Possibility to reduce the number of generated emissions	
Sustainable development	
The ability to reduce the price of the final product, which will attract additional buyers (utilisation)	Distance from a potential buyer (transportation)
	Dependence on the CO_2 buyer(transportation)
	Conservatism and unwillingness to change (utilisation)
	Alternative resources to carbon dioxide (utilisation)

At this level, the main positive factors can be called the development of the sector the chance to attract funds for the company's development. By installing CO_2 capture units, it is possible to sell the dioxide, thus obtaining additional financial benefits. If CO_2 is used at the company, the captured dioxide can be returned to production (if the quality of CO_2 meets production requirements). However, financial problems are serious obstacles—high prices for the acquisition, installation and maintenance of technology can jeopardise the entire production as such, and the payback time of the purchase can be too long. If the company itself does not use CO_2 and there is no one nearby who could buy it, then the purchase of the unit also does not seem to be a profitable solution.

According to Table 3, it becomes evident that in both cases—both for the producer-supplier of CO_2 (produced and sold) and for the producer-consumer (at the same company), the main problems are financial difficulties—new equipment requires significant financial investments and the company is not always ready to take risks for the sake of possible profit. Another problem, which is unlikely to be solved shortly, is the technological issue. There are no representatives of enterprises producing such complex equipment in Latvia, and if this equipment fails, the company risks downtime and financial costs. Fears of this particular plan, the lack of confidence that they will be supported at the state level (funds and subsidies)—this is what do not allow modernising the often-outdated production sector at a sufficiently fast pace.

However, despite such serious barriers, for both parties, there are also excellent reasons for taking risks and acquiring new technologies for using CO_2 in production—confidence in the quality of the supplied resource (carbon dioxide) and that these supplies will be continuous, the ability to save on resource (which, most likely, will only become more expensive every year). In order to modernise an existing production, it is possible to attract funds and/or participate in international projects, such as H2020 [38].

2.2. ArcGis Analysis

In order to mark all points of carbon dioxide production and places of its potential use on the map of Latvia, it is necessary to collect relevant information. Production data were collected from government databases such as State Environmental Service, Latvian Center for Environment, Geology and Meteorology [39,40]. The results of such mapping have already been thoroughly discussed and analysed in [23]. The places of carbon dioxide production in 2019 were marked on the map of Latvia, indicating both the category of the enterprise (A or B permit) and the type of activity itself. Enterprises with the C-type permission were not included in this work. Companies with the A-type permission are landfills, energy sector, and the industrial sector's largest producers. The B-type group consists of companies in different working areas—food production, energy, chemical, industrial, refining, etc. The energy sector was not divided into central and autonomous heating systems. To analyse the producer-consumer relationship on the map, we marked the places of carbon dioxide production and its potential use (Figure 3). All CO_2 production and potential utilisation point coordinates were taken from the Latvian Center for Environment, Geology and Meteorology database [40].

According to Figure 4. it becomes apparent that the production locations and potential use of carbon dioxide very often coincide. The main clusters of points can be observed in large cities of the country—Riga, Daugavpils, Liepaja, Jelgava and Ventspils, as well as Rezekne and Valmiera. More and more industries will appear closer to cities—places of potential sales of manufactured products. However, even outside the city—in the countryside, there is a possibility of using the created carbon dioxide and converting it into products with high added value.

2.3. Combination of ArcGis and SWOT

One of the factors influencing the decision to implement the use/transportation of carbon dioxide is the distance from the manufacturer to the buyer (the results of the SWOT analysis). Maps created in ArcGis indicate that the distance within one country is not an obstacle to using technologies of this type. Another factor was the quality (in other words, purity) of carbon dioxide. This criterion is decisive in using CO_2 in production since, often, the permissible amount of impurities should not exceed 0.5–5%. If carbon dioxide is used in greenhouses or algal ponds as a catalyst for plant metabolism, the number of impurities can be up to 30% [41,42]. Unfortunately, in Latvia, large enough greenhouses are not widespread, and there are no industrial-scale algal ponds. This means that all carbon dioxide produced and liquefied (in the case of transportation) for further utilisation must be processed with a high degree of purification, which undoubtedly entails additional costs.

2.4. Fuzzy Logic Cognitive Analysis

Fuzzy Logic Cognitive Analysis can be used as an effective decision-making tool in a complex risk assessment analysis and management. Tools such as the FLCA can save much time, especially when analysing complex systems of interdependent factors is needed. FLCA tools make it possible to analyse and simulate the possible scenarios of the proposed decision and its development and visualise it [43]. By identifying key factors or analysing the likely future of scenarios, it is possible to see its weak points at the beginning of project development and make the necessary decisions and corrections in advance. Identifying key factors and their relationships is the main aspect of this analysis. This allows to explore possible scenarios and helps collect the necessary information already at the decision-making stage [43,44].

The FLCA has proven to be an excellent tool for analysis. Many factors do not have formulated quantitative and/or qualitative data, as well as for discussions, negotiations and finding consensus among many parties [44].

Based on the results of the SWOT analysis and using ArcGis maps, an FLCA analysis was carried out using a free-access program called Mental Modeler. This paper investigated the connections and factors affecting the rate of introduction of new technologies at the entrepreneurial level within the country. Factors of a political nature and public were considered. Using the factors specified in the SWOT analysis, the ArcGis results, and personal opinion of the authors, flows affecting the new technology introduction have been depicted.

3. Results and Discussion

3.1. SWOT Analysis

The results of the SWOT analysis show that at the level of entrepreneurs, fears for financial stability in the case of using technologies for capturing and using/transporting carbon dioxide are a severe factor. Since every year, the requirements for "cleanliness" of the production process will only grow, sooner or later. Still, entrepreneurs will face the need to either completely redesign the production line to reduce the amount of CO_2 already at this stage or modify the existing lines so that the produced gas would be used further—either in the same production or in some other. At the moment, if an entrepreneur decides to improve production, he can apply for financial assistance from European projects and funds [36,37]; however, to receive more severe support, it is necessary to provide a truly innovative project [37,45]. If no measures by the state are taken (both at the national level and the level of the European Union), producers are unlikely to seek to invest in the modernisation of enterprises to reduce the amount of carbon dioxide generated. If the government introduces new taxes (or increases existing ones) and increases the cost of CO_2, entrepreneurs, sooner or later, will have no choice but to improve production lines [46]. However, in parallel with the introduction of new taxes, the government should subsidise measures aimed at decarbonisation of the industrial and energy sectors, compensate electricity costs and/or give financial help in the acquisition of the necessary installations to reduce the amount of CO_2 produced, capture, transport and/or reuse [47].

Facilitate financial aid for demonstration projects of varying readiness levels. However, most of the funds work either with projects already in the final stage of development and at the stage of popularisation, or with an enterprise of a certain size, with a certain annual turnover, or work in a particular sector [47,48]. Even if it is possible to attract sufficient funding already at the stage of project development, in the future, only demonstration projects will not be able to interest potential investors. Another possibility to make CCS and CCS technologies more attractive is to change the taxation system as it was made in the United States. Every company can attain a tax credit for every captured metric ton of CO_2 [49,50]. To really contribute to the introduction and active use of CCS and CCSU installations, it is necessary to pay great attention to the research and development of appropriate technologies; the enterprise must be able to invest in projects that are still based mainly on the research of various institutes and organisations, as well as large companies [2].

3.2. ArcGis and SWOT Analysis

Thanks to mapping—the creation of maps with marked points of carbon dioxide production and its potential use, it became possible to analyse the feasibility of using CO_2 on a national scale. Since most enterprises are in the area of large cities, the cost of transporting carbon dioxide will not be high. In each „cluster" of production points, there are several potential consumers—if the purity of carbon dioxide meets the necessary requirements. In the presence of demand from the potential consumer, the produced CO_2 will not be emitted into the atmosphere but will be used to create new products with a high added value. According to literature sources [51,52], carbon dioxide can have many applications that relatively little financial investment can be realised. This is, for example, the food industry—in large cities, there is a production or processing of various food products, as well as cleaning safe cleaning agents. The food industry, in the course of its activity, produces carbon dioxide of a high degree of purity (especially the alcohol industry—yeast emits almost pure CO_2)—it can be used in the chemical industry [51,52].

Large amounts of carbon dioxide are generated in boiler houses located throughout the country. This gas contains many impurities, making it unsuitable for chemical or food industry use. However, if there are greenhouses nearby, this gas, albeit in small quantities, can be used as a catalyst for plant growth [53]. Large greenhouses, for example, are located at SIA Getlini and SIA Ziedi landfills. The heat generated during the decomposition of garbage is sent to greenhouses, allowing the harvesting of vegetables and flowers even at an atypical time for this. If carbon dioxide was supplied to these greenhouses along with heat energy, the yield could be increased [41].

As mentioned above, one of the factors affecting the speed of introduction of new technology also depends on the human factor. 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—a place where due to the dense population, changes occur more often. People react more quickly to what is happening in the neighbouring production and also modernise theirs [54–56]. In turn, regional enterprises can supply the produced carbon dioxide 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. In an urban environment, such skills are also easier to acquire than if production is located in rural areas [55,57]. Competition with existing classical technologies plays a vital role in developing innovative technologies. The urban environment is also a more conducive environment for introducing new technologies since people are less conservative than residents of rural areas [54–56].

3.3. FLCA and SWOT Analysis

Having received the results of the previous two analyses—SWOT and ArcGis, the FLCA analysis was performed. When considering all the data obtained, a picture of the influence of various factors on each other and the relationship between them was obtained. In this case, the picture of the relationship at the national level was taken observed—the influence of politics and entrepreneurs within the country (Figure 5).

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

The main factor most influenced by others is the speed of implementing new technologies (Figure 6).

The speed of technology implementation is influenced by political factors (inertia of political forces, lack of unity in the adoption of critical CO_2 requirements, extremely negative attitude of politicians and influential entrepreneurs to the implementation of mandatory requirements for CO_2 emissions, etc.), and the so-called—public, such as prejudice about the dangers of CO_2 and the need for change. An important role is also played by the lack of educational events where people would receive information about the seriousness of the problem and the need for modernisation. Since the introduction of technologies and the organisation of additional training and educational courses for citizens and workers require financial investments, this factor may be key in fulfilling the obligations undertaken to reduce the amount of carbon dioxide produced in the production sector.

All the threats and weaknesses, advantages and opportunities listed in the SWOT analysis appear in the FLCA analysis. However, the FLCA analysis allows seeing the entire chain visually and assessing what the primary factor (political factor and funding) is and what is secondary (lack of awareness of the population and lack of skill in working with new technologies).

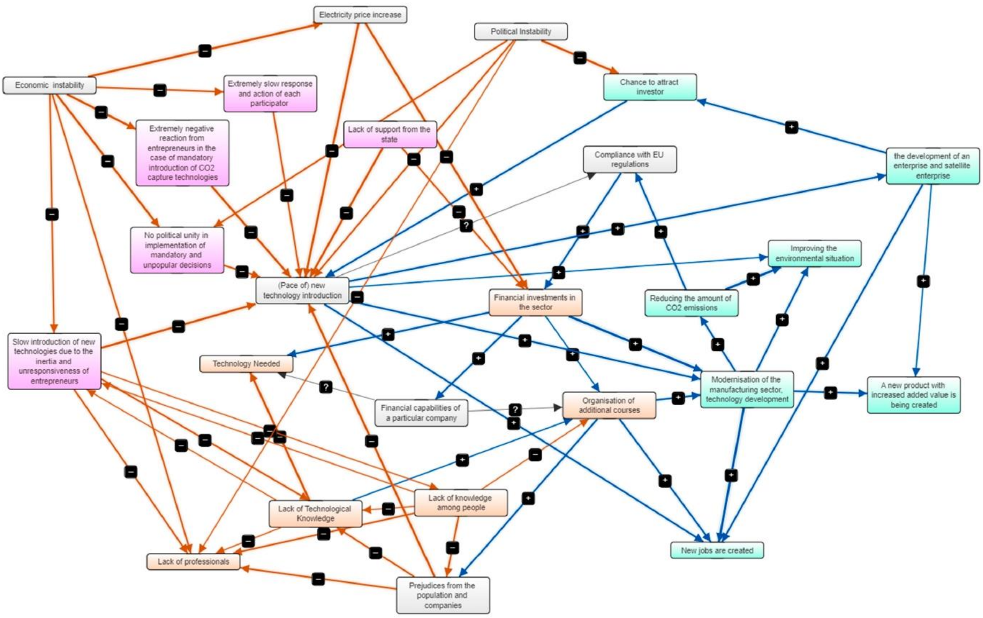
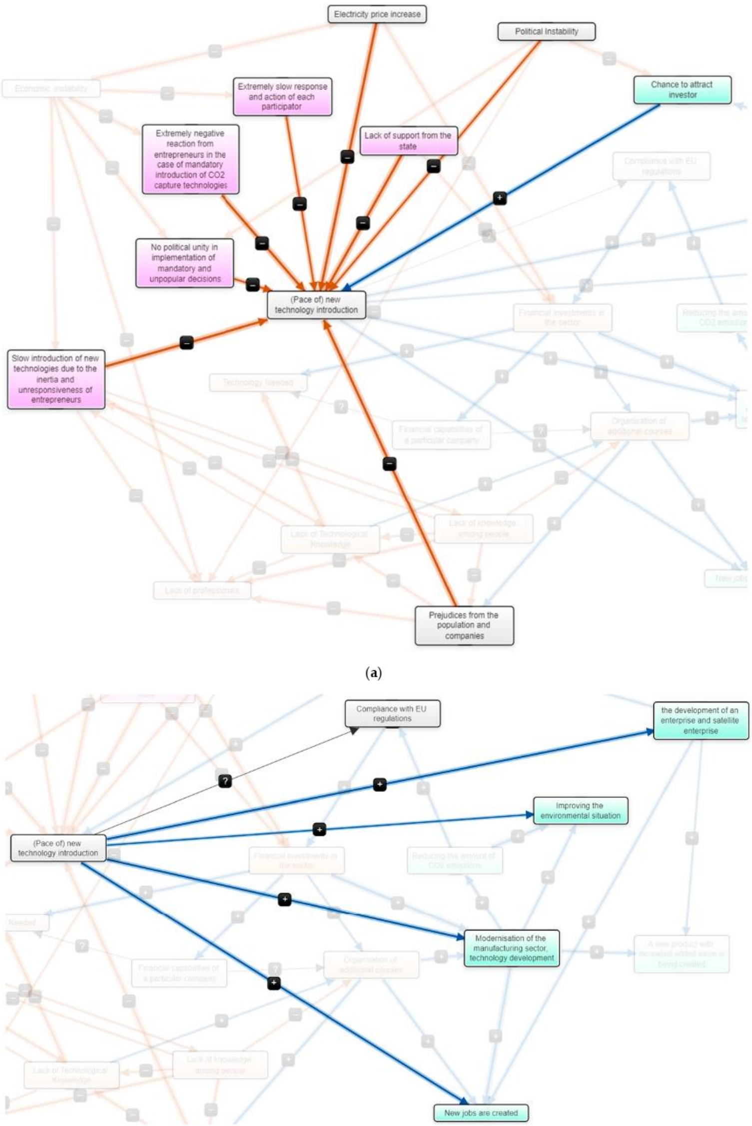


Figure 5. Results of FLCA analysis.



(**a**)

(**b**)

Figure 6. Factors (**a**) influencing the rate of introduction of technologies, (**b**) which are influenced by the rate of introduction of new technologies.

4. Conclusions

In this paper, using the SWOT, ArcGis and FLCA analysis methods, the factors influencing the development of CO_2 capture technologies and inhibiting their implementation in the territory of Latvia were analysed.

The SWOT analysis showed that the main factors influencing the implementation of CCU technologies are political and financial. The political aspect plays a vital role at all levels—both at the entrepreneurial level and at the national and European levels. The ambiguity of the adopted laws and financial instability prevent entrepreneurs from taking significant and serious steps in the modernisation of existing production. It is often difficult for entrepreneurs to follow the latest requirements of new laws—they can no longer act in advance due to the lack of financial support from the state.

The following analysis of the FLCA visually showed the dependence of the factors indicated in the SWOT and made it possible to determine which of them directly affect the introduction of new technologies and which ones affect indirectly. Similar to the SWOT analysis, political and economic factors have a direct and maximum impact on the speed of adoption of new technologies. However, the FLCA analysis showed that the human factor plays an equally important role. The rejection of new products by the population can slow down the speed of new technology implementation. However, in contrast to the political aspect, the negative impact of the human factor can be reduced by conducting educational and awareness-raising courses for both workers and the public. People need to know why changes are being made in the usual production process and what advantages are brought by the modernisation of technologies (for example, the creation of new jobs). Even though this modernisation often requires serious financial investments, in the future, the enterprise can start producing a product with high added value, enter a new market and, as a result, recoup the investments made. In this case, the company becomes attractive to investors.

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Institutional Review Board Statement: In accordance with CODE OF ETHICS FOR SCIENTISTS, approved by Latvian Academy of Sciences and the Latvian Council of Science, prior to the commencement of the research, the field's research ethics committee or the researcher must evaluate whether the anticipated benefit from the research results will justify the possible risks to the person subject to the research and to society. As in this particular research was not research on "Human Subjects or Animals" and participants were informed about the aim of the research, we as researcher group (Scientific and ethical committee of Institute of Energy Systems and Environment, Protocol No 26/11/2021) evaluated risks and agreed on an approval of the research.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available data from free databases were used.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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PAPER 4. CO_2 AS A RESOURCE. SOCIETY'S WILLINGNESS TO PAY ANALYSIS

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CO_2 as Resource. Society's Willingness to Pay Analysis

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Abstract **– Climate change, including the efficient management of CO_2 emissions, is considered a significant environmental challenge today. Carbon dioxide is still considered an undesirable by-product that must be eliminated. However, it can be turned into a source of income. By using the latest technologies of CO_2 capturing and/or utilization, valuable products with high added value can be created. For more effective analysis of the opportunities to use CO_2 in Latvia, it is necessary to find out the opinion of both the public and the industrial sector. The prospects of such technologies in the local market soon depend on the desire and opportunities of the market to turn waste into a profitable resource. This paper aims to determine the Latvian manufacturer's and society's willingness to pay and make changes in CO_2 utilization. The analysis of the conducted survey will give an insight into the opinion of these significant market players in Latvian case.**

Keywords **– Carbon dioxide emissions; CCS; CO_2; Latvia; willingness to pay**

1. Introduction

Climate change is one of the main challenges of our time. It influences and will influence every country and every person, regardless of the place of residence, social status, and beliefs [1].

The climate has changed, proven by historical and geographical evidence [2]. However, at the end of the 20th century, the problem of climate change was officially recognized at the international level during the first climate conference in Geneva [3]. It is recognized that human activity destroys the balance of carbon dioxide. Over the past 50 years, intensive use of fossil resources (coal, oil, gas) has increased the amount of CO_2 emissions in the atmosphere. And although some carbon dioxide is trapped in plants and oceans, a considerable amount of CO_2 remains in the atmosphere and, being one of the greenhouse gases, contributes to climate change [1].

Approximately one-third of the total carbon dioxide created is generated in China (27 % of the total as of 2020), 18 % in the United States of America, and 17 % in the European Union [4]. However, it should be pointed out that even though the EU is the third-largest emitter of CO_2 in the world, each country of the Union creates a different amount of carbon dioxide (Fig. 1).

Even though in Latvia, in comparison with other countries, the amount of CO_2 produced is not so large, even this amount must be considered since the consequences caused by CO_2 emissions will affect every inhabitant of the planet. The average world temperature in 2018, compared to the 1980s, was 1.1 °C higher, and in Latvia, this difference was 1.5 °C, and this

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value is certainly not the last. The amount of precipitation, the maximum recorded temperature, the number of storms, and strength only increase [6].

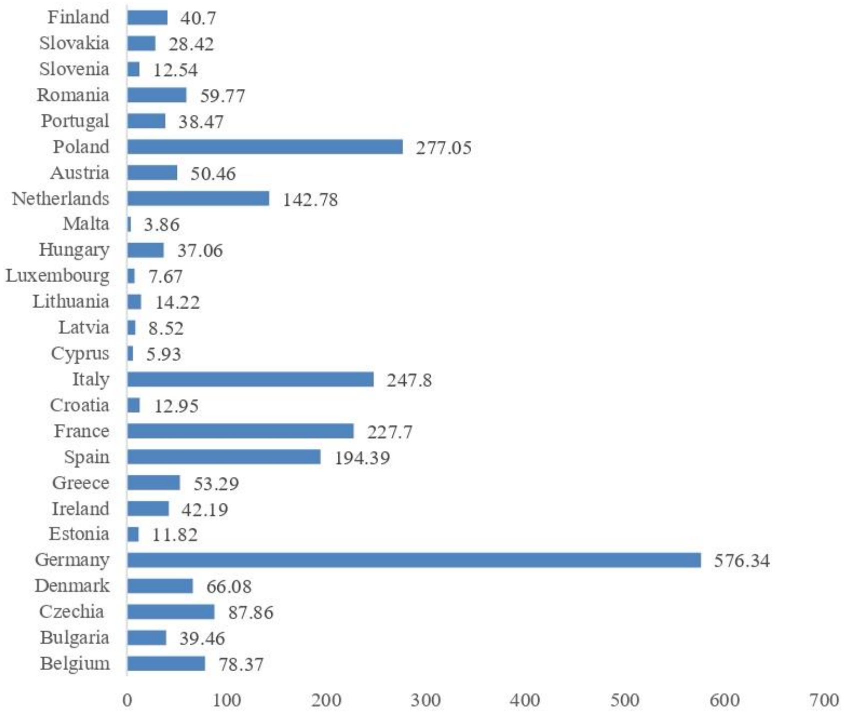


Fig. 1. CO_2 emissions in million metric tons in EU by country, year 2019 [5].

1.1. CO_2 Utilisation Possibilities

The introduction of technologies to reduce the amount of greenhouse gases is becoming increasingly important. By 2021, 65 commercial CO_2 capture and storage (CCS) installations have been installed worldwide. In 2021, 102 more stations were under construction [7]. In turn, 27 installations allow capturing and using carbon dioxide in the world for 2021. However, another 71 are in varying construction degrees, and another 97 have been announced for construction [8].

CCS is considered a technology that has the potential to significantly reduce CO_2 emissions both in the manufacturing sector and in the world as a whole. The purpose of these technologies is to prevent carbon dioxide from being released into the air. Basically, CCS technologies are used to capture carbon dioxide from static sources of CO_2. Later, this captured carbon dioxide is transported to certain places intended for long-term storage of CO_2. An alternative to storing gas can also be its utilisation in other industries [9].

The principle of operation of the CCS technology can be described as follows - the capture of carbon dioxide, its subsequent purification and liquefaction. The next step is the transportation of liquefied CO_2 to the places of its further storage or use. Usually, special pipes or transport (for example, gas ships) are used for transportation. As for CO_2 storing – for these purposes geological formations (for example, which previously contained oil or gas) or suitable underwater deposits are usually used [10].

Many technologies allow the use of carbon dioxide in production. According to Rodin *et al.* [11], carbon dioxide can be processed in many different, unrelated processes (for instance, reduction processes, bioconversion, hydrogenation, etc.), resulting in many valuable products of various groups – chemicals (for instance methanol and organic acids), fuels (methane, ethanol), minerals (aggregates, cured concrete) [11].

According to the European Commission [12], both CCS and CCU technologies have great potential to reduce the amount of CO_2 in the atmosphere significantly.

However, it should be borne in mind that one cannot rush and act thoughtlessly in this matter despite the seriousness of the situation. Such behaviour can cause significant financial losses [13]. The installation of CCU units is a large-scale process that requires a substantial investment of both resources and finances. Such technologies indicate that they are sufficiently developed for their more active use. The technologies are also long-term enough to be beneficial in the long run. According to the UNECE report [13], the Zero-Net plan will require significant changes to the economy. Technology development needs, commercialization, and public acceptance will need to be considered.

It is also necessary to balance two scenarios – which technology to use – CCS or CCU? Which option a country chooses depends on how actively it will be able to reduce the number of emissions produced in the long term [12]–[14].

Lack of public awareness of the possibilities of using CO_2 is also a problem. Each resident can contribute to reducing the number of generated emissions. Lifestyle, decisions made in everyday life – all this can leave its mark on ecology. And although studies indicate that climate change is the second most important issue for EU residents [15] (in the case of Latvia, this issue ranks 11^{th} out of 13), in Latvia, residents have become shown more concern and responsibility for climate change.

1.2. Willingness to Pay

Before introducing any changes in the country's legal system, it is essential to know the public's opinion on these changes [16].

According to [17], general well-being consists of three main factors – the national economy (production), the environment, and the public. With this in mind, when analysing people's opinions and their desire to promote change, it is worth interviewing the production sector (i.e., manufacturers) and people (i.e., the public). Such an analysis can provide a practical insight into the opinion of residents about the problem of CO_2 emissions and their desire to implement carbon capture/use systems. This is especially important given people's concerns about the environmental risks allegedly associated with such installations [18].

It is believed that the calculation of the cost of installing and maintaining CCS and CCSU technologies is a complex and costly process. The technologies are also expensive due to their relatively low prevalence [18]. According to [19], the high cost of capture processes and high energy costs are severe barriers to acquiring these installations. Additionally, when evaluating the entire life cycle of a CCS, it is necessary to consider social, natural, and economic aspects – how they change under the influence of CCS. Financial flows are also significant and closely related to these aspects [20]. The longer CCS remains financially unaffordable to entrepreneurs, the longer it is more profitable to pay carbon emissions quotas than to modernize production and install CCS and/or CCU. The more extended public opinion uncertainty (technology adoption) remains, the longer the government will procrastinate with climate change [18], [21], [22].

For a more efficient and faster implementation of CCS and CCU systems, it is necessary to consider the public's opinion and whether it is ready to 'pay' for environmental improvement.

There are several assessment methods. For example, *Stated preferences methods* – involves asking a person directly how much he evaluates a particular aspect (technology, thing, service, etc.). The purpose of this type of survey is to create a hypothetical market in which respondents make decisions about certain products [23]. It can be found out not only the maximum price that a person is willing to pay (*willingness to pay*) but also whether he agrees to receive compensation for not using the technology (*willingness-to-accept compensation*) [24]–[26]. This type of study is carried out in cases where there is no connection between the ecosystem and services, or these links are not strong enough to be valued monetarily.

This type of research is based on a questionnaire survey of the target audience. Suggested answers usually represent non-market values, such as quality of life, environment, certain characteristics, etc.

These analysis methods are especially useful when it is necessary to determine the impact on non-market goods associated with significant values if these values can be expressed by sampling [27].

The purpose of this work was to determine the opinion of two groups – the public and entrepreneurs – on the problem of CO_2 emissions and the willingness to pay for reducing the consequences caused by emissions.

2. METHODOLOGY

The survey of respondents was chosen as the primary research tool. According to the literature analysis conducted, conducting a survey is a great way to get the opinion of a large number of people [28]–[30]. A survey can be conducted in various areas. Still, the goal is often similar – to find out the opinion of a person or a group of people on a particular topic [31]. The method is suitable because it is cheap, fast, and accurate to collect the correct information [30]. An additional advantage of this method is its versatility – the survey can be conducted both face-to-face and remotely – by phone or via the Internet. As part of this work, the survey was conducted electronically, as there were still several restrictions due to COVID-19 that prevented the face-to-face survey of respondents.

The main instrument of the survey is a questionnaire. Its quality is the main factor. The success and accuracy of the study depend on its structure, the formulation of questions, and the correctness of the chosen audience [30].

In this work, the study was carried out according to the following algorithm, see Fig. 2.

Literature analysis and identification of the main factors influencing the implementation of CCS and CCSU units form the basis of the work. Without this information, it is impossible to formulate accurate questions for the respondents qualitatively. 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 questions (in addition to the main ones about age, education received and profession currently occupied). All questions were closed-ended. Using a questionnaire, 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.

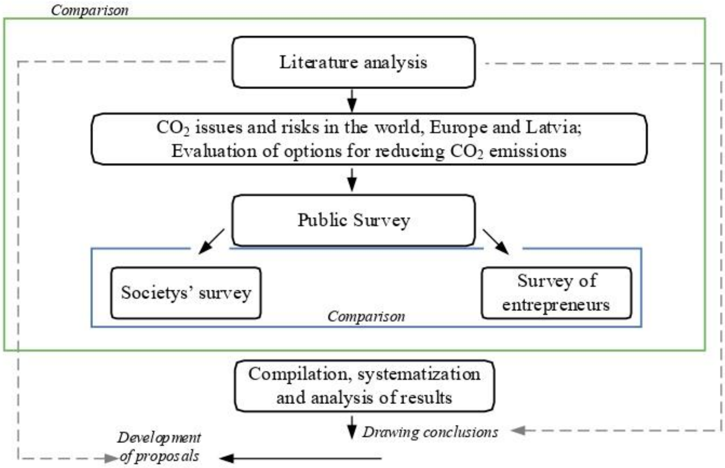


Fig. 2. Algorithm of the survey.

In turn, the questionnaire for entrepreneurs consisted of five questions (in addition to the main questions about the scope of the enterprise, its 'age' and the degree of importance of the issue of CO_2 emissions for their particular enterprise). Respondents were asked to indicate particularly important reasons for making changes to upgrades in their enterprise in the context of carbon dioxide emissions, as well as what could motivate them to change (for example, too high energy bills, favourable conditions for obtaining subsidies for upgrades, etc.). Questions 2 and 3 were open-ended and entrepreneurs were asked to indicate the motives/reasons for reducing the amount of CO_2 emissions in their enterprise, as well as measures that could motivate them to change. Also, entrepreneurs were asked to indicate what part of their income they are ready to give to combat CO_2 emissions.

The information obtained makes it possible to judge the public's opinion about the problem objectively.

3. Results

3.1. Public's Opinion

To achieve this goal, an anonymous survey was organized. The survey was conducted electronically on the Internet. For the convenience of the respondents, the questionnaire was compiled both for Latvian-speaking and non-Latvian-speakers. One hundred eighty-nine people received the questionnaire, but only 82 respondents sent answers. The division into groups turned out to be approximately the same – 42 answers from Latvian-speaking respondents and 40 from non-Latvian-language speakers.

According to the results, most of the respondents are women (77 %), and summing up the age of the respondent; the leading group is in the range of 19–25 years (42 %) and 26–40 years (40 %). This questionnaire allowed getting the opinions of people of different ages. Of the respondents, 17 % noted that they were in the group of 41–60 years. Of the respondents, 28 % of respondents have higher professional education, and 60 % of respondents have degrees – bachelor's (22 %), secondary vocational (16 %), secondary (18 %), and master's (4 %). Of all the responses received, 11 % of respondents indicated that they had not yet received higher education and 1 % had a doctorate degree. In general, it can be concluded that the respondents' level of education is reasonable. It should also be taken into account that many educational institutions strive to inform students about environmental problems and how to solve them. Therefore, it can be assumed that the other answers of the respondents are the answers of competent people.

3.1.1. Public Awareness of the CO_2 Emission Problem

The first question in the questionnaire was aimed at determining public awareness of the problems of CO_2 emissions and therefore was asked as '*Have You ever heard of the CO_2 emission problem?*' The answer to this question was almost unanimous – 93 % of the respondent answered in the affirmative.

3.1.2. Importance of the CO_2 Problem to the Public

The aim of the next question ('*Does the problem of the CO_2 emission bother You and seem urgent*') was to find out the public opinion on this problem and what do they think about it. The answers to this question were divided – 48 % of respondents answered that they were concerned about CO_2 emissions, but 32 % responded that they had too little information to answer this question competently and confidently (Fig. 3). This means that educational institutions should pay more attention to environmental issues and CO_2.

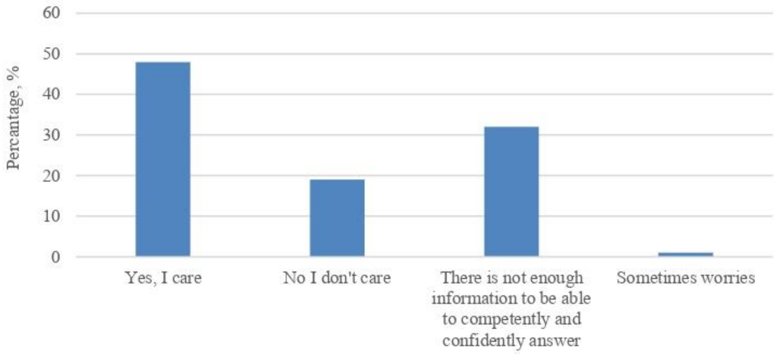


Fig. 3. Answers on the question if the problem of CO_2 emission bothers respondents.

However, it should be noted that 19 % of respondents marked the option '*No, I don't care.*' Considering that 32 % of those who answered about the lack of information also cannot give precise details on emissions, in total, this is 51 % of people who do not see a problem in CO_2 emissions or do not consider this problem to be relevant.

3.1.3. The Most Significant and Relevant Impact of CO_2 Problem in Public's Opinion

The question '*Indicate the reasons that seem to You the most significant and relevant*' is more in-depth, and its main task was to find out what precisely the respondent considers the most important in the problem of CO_2 emissions – the impact on human health, the impact on the environment, and the problems caused by changes in the socio-economic sphere of life or caused by changes in 'behaviour nature' – an increase in the average annual temperature, an increase in the water level, climate instability, and so on. It is assumed that this question was answered by those who answered 'yes' to the previous question, '*Do You care about the CO_2 problem*'. The question allowed selecting of multiple answers. The response options '*Effects on human health*' and '*Climate change and environmental impacts*' were marked by the respondents almost the same number of times – 38 and 37 times, respectively. According to this question and the results obtained, the impact of climate change on the economy is the least of public concern (Fig. 4).

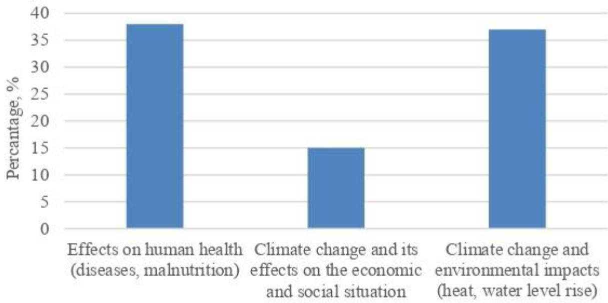


Fig. 4. Reasons why the problem seems relevant.

3.1.4. Reasons why CO_2 Problem Seem Irrelevant

Since one of the previous questions had the option to answer '*No, I don't care*', the next question – '*Why does the CO_2 problem seem irrelevant to You?*' – was designed to determine the reason for this position. Similar to the previous question, the responses of the two groups differed (Fig. 5).

Based on the answers provided, it can be assumed that the main reason for not realizing the problem is the lack of information among people. If more people talked about how much the climate has changed in the last few years (a period that is easier to observe), it would be easier to understand the magnitude of the emissions problem and the consequences of inaction. Also, Latvian speakers noted the option 'I can't change anything'. This answer is similar to psychology – 'I can't change anything, and therefore I won't do anything'. This inspires specific fears that the public will not do anything to reduce the number of emissions created by them shortly. There is a need for educational events that tell what the average person can do to improve the climate.

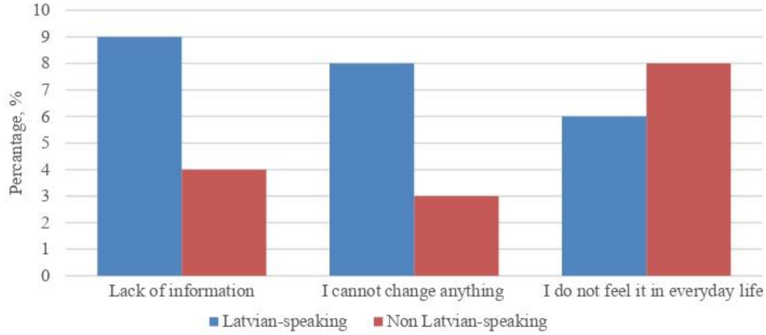


Fig. 5. Reasons why the problem seems irrelevant.

3.1.5. How relevant Is the Problem of CO_2 Emissions for Latvia?

The purpose of the question '*In Your opinion, is the problem of CO_2 emission relevant for Latvia?*' was to determine the attitude of the inhabitants of Latvia to the problem – how relevant it is in the context of the country.

As follows from the results obtained, most of the respondents answered that the problem of CO_2 emissions is relevant to Latvia. However, 18 % responded that there are more critical problems in the country. It is oppressive that almost a quarter of the respondents could not answer this question. As a result, the votes were divided almost equally – 58 % against 42 %. However, even though only 16 % more people recognize the relevance of the problem for Latvia, it is necessary to conduct educational activities that would tell and show how CO_2 emissions affect Latvia.

3.1.6. For Whom the Reduction of CO_2 Emissions May Be the Most Important and Relevant

The question 'Mark the Groups of People/Institutions for Whom, in Your Opinion, the Reduction of CO_2 Emissions May Be the Most Important and Relevant' was aimed to determine who should be most concerned about CO_2 emissions in the public's opinion. There were several possible answers to this question (Fig. 6).

The answers to this question were distributed according to expectations – the public believes that the issue of emissions is essential to the public itself. And only then do companies (entrepreneurs) follow. Non-government organizations and investors received the least number of points, which means that the public is confident that such changes are not critical for these organizations. According to the results of this issue, the public is confident that climate change and the consequences they cause will primarily affect ordinary people, and not investors. Companies can suffer due to the introduction of new laws that complicate the work of the enterprise.

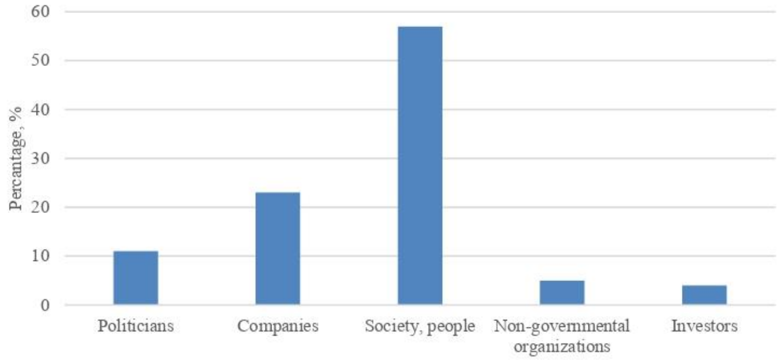


Fig. 6. To whom the reduction of emissions is more critical in Latvia on respondent's opinion.

In general, the result of the question indicates that the public understands that there is a problem, and it is essential for every person.

3.1.7. The Need for Action

To assess the readiness of people to act, several questions were asked about the need to reduce the number of emissions. Thus, the questions were asked: '*Do You think it is necessary to reduce the amount of CO_2 emissions?*', '*Are You doing anything now to reduce the amount of CO_2 emissions in Your daily life?*' and '*What actions would You be willing to take to reduce the negative impact of CO_2 emissions?*'

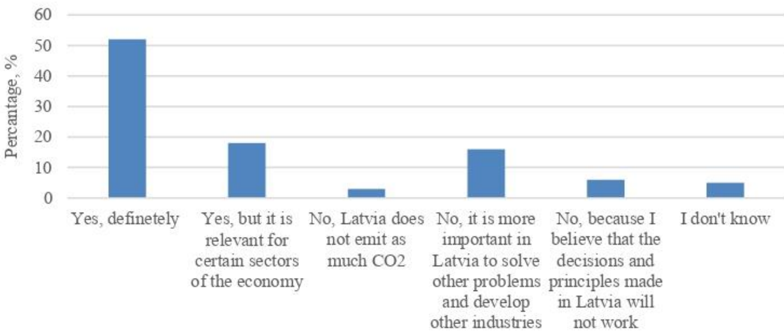
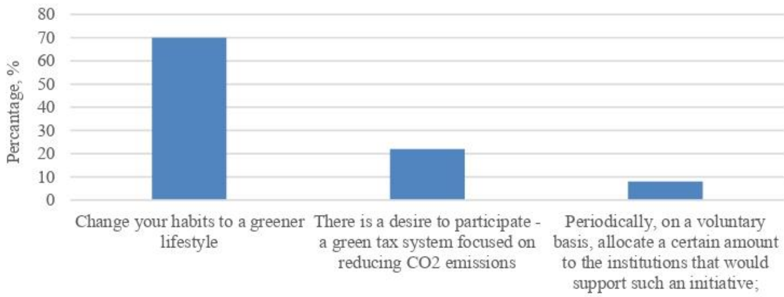


Fig. 7. The necessity to reduce CO_2 emissions on respondent's opinion.

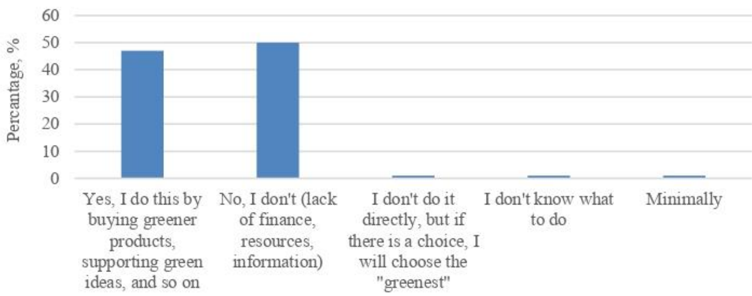
The questionnaire showed that it is necessary to reduce the number of emissions and the option that the reduction is relevant for specific sectors (Fig. 8). However, in contrast to the non-Latvian-speaking group, in the Latvian-speaking group, the option '*No, because I believe that the decisions and principles made in Latvia will not work*' scored 11.9 %, while in the non-Latvian-speaking group, no one ticked this answer. But even this result raises questions about the people's trust in the system of laws in the country and their effectiveness in practice.

The authorities should be told what measures were planned, how they were implemented, and what results were obtained. This would allow residents to have confidence in the system. Also, many people are sure that there are more pressing problems than CO_2 emissions (16 % of the total responses). Considering the questionnaires separately, this answer option was chosen by 11.9 % in the Latvian-speaking group and 20 % in the non-Latvian-speaking group, respectively, which is the second and third answer to this question in both groups (Fig. 7).

According to the results (Fig. 8(a)), 70 % of respondents are ready to change their habits if it helps to reduce CO_2 emissions. At the same time, almost a quarter of the respondents answered that they were prepared to participate in the 'green tax system' (22 %). In turn, answering the question of what they are doing now in everyday life (Fig. 8(b)), the answers were divided almost evenly – 47 % of respondents believe that they buy more environmentally friendly products, but 50 % answered that they do nothing due to certain factors (for example, lack of finances to buy more expensive, but more 'green' products).



(a)



(b)

Fig. 8. Questions: a) What actions would You be willing to take to reduce the negative impact of CO_2 emissions? b) Are You currently doing anything to reduce CO_2 emissions daily?

People are ready to change, but sometimes the inaccessibility or inability to purchase more environmentally friendly products or leave more environmentally friendly destroys the motivation of people to act.

3.2. Survey of Entrepreneurs

Considering that for a better analysis of willingness to pay, it is necessary to know the public's opinion, but a survey of entrepreneurs was also conducted. Unfortunately, the feedback was shallow – only 11 % of the questionnaires were completed.

The respondents were asked to answer questions such as '*Field of activity of the enterprise*' and '*Duration of activity*' in the questionnaire. Thus, 40 % of respondents answered that they work in the agricultural industry and 20 % – in the manufacturing industry. 10 % each received such answers as 'Extractive industry and energy,' 'Chemical industry,' 'Ship repair industry,' and 'Metalworking'. In turn, when asked about the duration of the activity, 90 % of respondents answered that they had been working for more than 20 years, and 10 % – 8–19 years. However, despite such an extended period, the topic of reducing CO_2 emissions is by no means relevant to all enterprises:

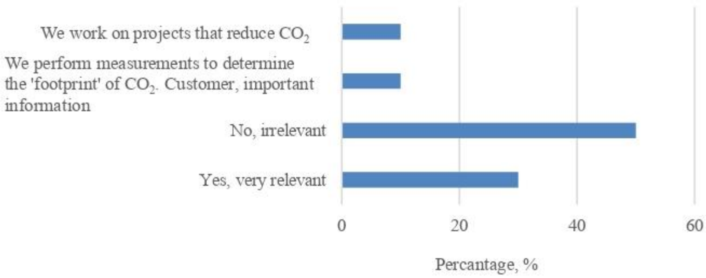


Fig. 9. Entrepreneur's field of activity.

Only half of the respondents stated that the problem of CO_2 emissions is more or less relevant to them. However, since most respondents are involved in the agricultural sector, such a result was expected (Fig. 9). The agricultural industry does not produce large amounts of CO_2 emissions and does not have appliances that require the installation of specialized devices for the purification of produced gases.

3.2.1. The Most Relevant Reasons in the Context of CO_2 Emission Reduction

Answering the question about the reasons that are relevant for the enterprise in the context of CO_2 emission reduction, the option '*Compliance with the requirements and legislation of the state*' received the most response (50 %), leaving the option 'Impact on human health' in second place (40 %). This result is quite logical from the companies' point of view since they must comply with all laws adopted by the state. Because the fact that the options '*Impact on human health*' and '*Impact on climate'* also entered the top three indicates that entrepreneurs are aware of the role of emissions and CO_2 in particular on the environment (Fig. 10).

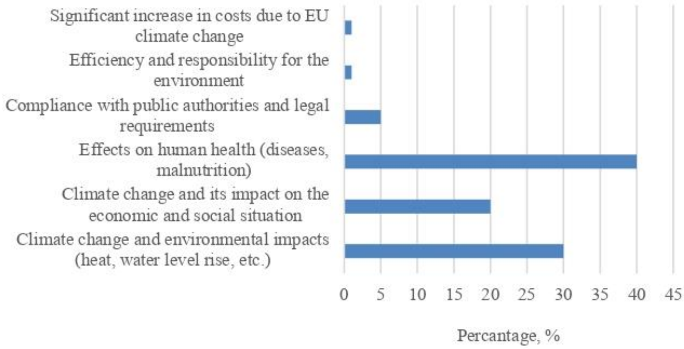


Fig. 10. What reasons are the most relevant in the context of CO_2 emission to entrepreneurs.

3.2.2. Motives/Reasons to Reduce the Amount of CO_2 Emissions

The next question was aimed at determining the motives of the enterprise and was asked as '*What are Your Motives/Reasons to Reduce the Amount of CO_2 Emissions at Your Company*'. This question was open-type, allowing respondents to write their own opinions.

Considering the results of the previous question, it was essential to see personal motives – concern for the environment and human health. Thus, among the answers received were – '*Efficiency and care for the environment*', '*Reducing the consumption of energy resources'*, and '*Universal – climate change*'.

Is there anything currently being done at Your enterprise to reduce emissions?

According to the answers to this question, enterprises can be divided into three groups:

1. Businesses only realize their role in climate change,
2. Enterprises that actively and comprehensively work to reduce their impact on the environment,
3. Enterprises for which the emissions issue is not (yet) relevant.

Since this question was also open-typed, it was very informative to see the views of entrepreneurs on the need to assess the impact of their enterprises on the environment. So, among the answers were such as '*We do nothing*', '*We carry out internal audit, monitoring, certification of products indicating the created and simultaneously captured CO_2 emissions throughout the entire life cycle of the product*', and '*We try to use energy resources more efficiently*'. Some entrepreneurs indicated that they are reviewing the production process to identify areas that could be upgraded to be more efficient and environmentally friendly and optimize logistics. Analyzing the answers received, it is sure that most entrepreneurs approach the issue of emissions very carefully and deliberately. However, it is recognized that at times, due to the specificity of production and its complexity and based on the requirements of the legislation, it becomes increasingly difficult for enterprises to comply with increasingly stringent laws. One of the respondents answered that if (when) there is a need, the issue of transferring production to another country with less strict legislation will be considered.

3.2.3. The Entrepreneur's Motives to Reduce CO_2 Emissions

Similar to the previous question, the next question was also about the motives, but specifically for the entrepreneur – '*What could motivate You to reduce Your CO_2 emissions?*', this question was also open type. According to the answers, enterprises, by their motivations, can be divided into three groups:

1. Nothing can motivate them,
2. Support from the state, the European Union. The most frequently cited assistance is financial, as equipment upgrades are often required. State guarantees, the well-being of workers, the ability to participate in the CO_2 trading system, etc. are also needed,
3. Can be motivated by external factors, such as higher cost of resources, lower prices for 'green' technologies, etc.

However, one of the answers received stands out – 'I think that the situation with emissions in Latvia is much better than in the rest of the world, and at the moment, it is more important not to 'cut off the shoulder', but gradually and slowly move towards the green course. You can't run ahead of everyone – you have to act deliberately from the very beginning'. This answer can be regarded as advice for a wait-and-see policy for enterprises and a more deliberate policy for the state. It is necessary to adopt laws that will be most effective in the context of Latvia but will not cause irreparable damage to the industrial sector.

3.2.4. Willingness and Readiness of Entrepreneurs to Act to Reduce CO_2 Emissions

Analysing the willingness of entrepreneurs to pay, the question was asked – what exactly would entrepreneurs be ready to do to reduce emissions.

According to the responses received, entrepreneurs are ready to install additional equipment (70 %). Companies are not prepared to act globally (for example, participating in improving CO_2 policies) (Fig. 11).

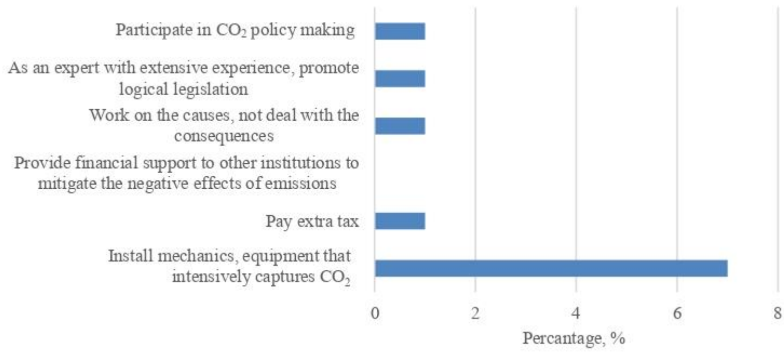


Fig. 11. Possible ways to reduce CO_2 emissions by entrepreneurs.

3.2.5. Willingness to Invest in Green Technologies

The aim of the last question was to determine what part of the monthly income entrepreneurs are ready to invest in the green technologies. This question showed that companies are not ready to invest in green technologies actively. 40 % of respondents answered that they are prepared to invest only 5–10 % of their monthly income. However, such answer options as '*Already invested in green technologies – at least even in heating tariffs*', '*Each situation must be considered separately*' and '*Depending on the return*' received 10 % of the total number of answers. Even though companies are currently not ready to give away most of their income, the answer '*Less than 3 %*' has not become the most popular (Fig. 12).

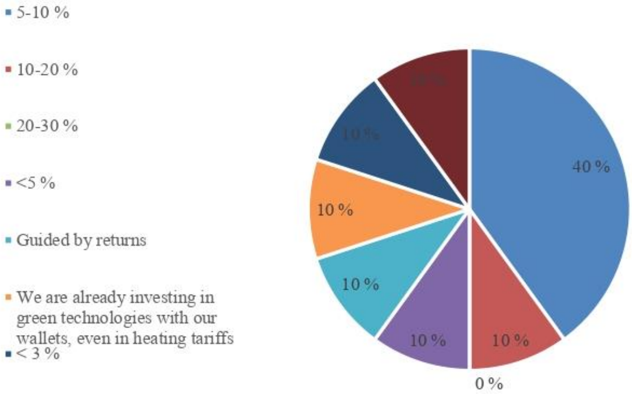


Fig. 12. Part of monthly income entrepreneurs is ready to invest in green technologies.

In general, analysing the results of a survey of entrepreneurs, it can be concluded that in the context of reducing CO_2 emissions, entrepreneurs can be assessed according to the following criteria: interest in a particular issue, the scope of the enterprise (for an agricultural enterprise, the problem of CO_2 emissions is less relevant than for a production workshop). However, all interviewed companies recognized the importance and necessity of modernization 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.

4. CONCLUSIONS

Considering climate change, entrepreneurs worldwide and in Latvia need to assess their impact on the environment and the activities they can carry out in their enterprise. Even though in comparison with other countries, Latvia cannot be called a 'big producer' of CO_2 emissions, the problem of emissions is not local. Every government and enterprise needs to think about ways to reduce and/or prevent the deterioration of the environment and human health.

Many CO_2 capture plants of various types of operation have been developed and already put into operation. Many of them are still at the stage of pilot projects. However, according to literature analysis, the level of carbon dioxide has reached the point where it is necessary to use all available technologies in as many production processes as possible. It is required to use both CO_2 capture and storage systems and carbon dioxide utilization systems.

Because the problem of carbon dioxide is a problem that concerns us all, it is also necessary to solve it together. For more collaborative work, both the opinion of the public and the opinion of entrepreneurs should be taken into account. Desynchronization can cause delays and/or increase the cost of optimization.

A survey of relevant groups was conducted to determine the public and entrepreneurs to pay. The purpose of the survey was to find out people's opinions about the problem of CO_2 emissions, their level of information about this problem, their willingness to change, and their willingness to pay for a reduction in carbon dioxide emissions.

82 questionnaires were received from the public group (64 % of the total number of questionnaires sent out). The survey involved people of different gender, ages, level of education, and field of activity. Based on the results obtained, it can be concluded that people do not have enough information about CO_2 emissions for a more objective judgment about the problem. People also have little idea of what, for their part, they could do to reduce emissions.

A group of entrepreneurs received ten questionnaires (11 % of the total number of questionnaires sent out). They were representatives of various areas. However, a more significant number were from the agricultural sector. This fact can explain why the generalized results of the responses indicate that, at the moment, the modernization of production processes is not so relevant. However, entrepreneurs do not deny the existence of the problem of CO_2 emissions and are ready to pay 5–10 % of their income every month to reduce the number of emissions and climate change caused. The survey results indicate that to modernize production, entrepreneurs need softer and more loyal legislation, as well as financial assistance from public services.

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PAPER 5. LEGAL FRAMEWORK ANALYSIS FOR CO_2 UTILISATION

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Legal Framework Analysis for CO_2 Utilisation in Latvia

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Abstract – **The ever-increasing amount of greenhouse gas emissions are forcing countries and the industrial sector in particular to develop ways to improve the manufacturing industry and reduce the amount of emissions created in compliance with the requirements of the European Green Deal initiative. However, all modifications must be under local laws and European directives. The purpose of this work is to analyse existing laws, regulations, and directives, both local and European, to identify limiting factors and factors that contribute to a more active introduction of systems for capturing, using, and reducing the amount of carbon dioxide created in production processes. The results of this analysis will determine the strengths and weaknesses of the local manufacturing sector and its ability to meet ever-tightening requirements.**

Keywords – **CO_2; CCS; CCU; policy; legislation**

1. INTRODUCTION

1.1. CO_2 Utilisation / Valorisation Concept

In times of fighting climate change and increasing CO_2 emissions, every possible means must be used to achieve the goal of reducing emissions by 55 % by 2030 and zero emissions by 2050. Switching to a Circular economy can undoubtedly help accomplish these goals. Use of carbon captured from waste streams as a substitute for fossil carbon. Circular economy and sustainable manufacturing sectors can use this solution and thus promote carbon capture and use (CCU) technologies in producing high-value-added goods (e.g., synthetic fuels).

According to the European Parliament and the Council [1], it is necessary to expand the scope of technologies to capture and subsequently store carbon dioxide (either in special storage facilities or in ecosystems).

The European Union actively supports the development and launch of CCU (Carbon Capture and Utilisation) and CCS technologies. Horizon Europe has also been actively calling for integrating carbon capture and/or use systems (CCUS) into industrial centres. This would help significantly reduce the number of carbon emissions created and, in the long term, reduce the cost of CO_2 capture. In the future, the captured carbon dioxide could be used to produce carbon-negative biofuels [2].

The concept of capturing and using carbon dioxide is to capture it during the production of some product (in which CO_2 is a by-product) and return it to the output of some other product as a necessary resource. Such valuable new products can be, for example, chemicals [3] and aviation fuel [4].

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Carbon dioxide utilisation aims to turn waste into a valuable product. And although CO_2 can be converted into valuable products, these conversions are usually very energy-intensive, making it difficult to achieve the desired result in reducing the number of emissions created. To determine the possibility of capturing carbon dioxide, it is necessary to analyse the existing legislation of both the European Union and Latvia.

1.2. CO_2 Utilisation in Products – CCS / CCU Technologies

Innovative installations for capturing and using carbon dioxide are actively discussed at the national and European levels and global levels. When talking about such technologies, the European Commission group asks two critical questions:

- How do we make CCS and CCSU plants efficient but, at the same time, environmentally friendly enough? What are the actual climate benefits of these technologies?
- How to consider climate mitigation of carbon dioxide in complex products – chemical compounds, fuels, etc. Since carbon dioxide will remain bound in the product for a different period and then be released into the atmosphere [5].

Considering that the captured carbon can be further used to produce chemicals and fuels, the question of environmental friendliness and, no less critical, the cost-effectiveness of such technologies is often raised. Studies on the long-term benefits of both CCS and CCSU installations are being conducted in different parts of the world [6]–[9].

Undoubtedly, the environmental friendliness of installations is a vast field for discussion. Considering that such plants allow the use of CO_2 that would otherwise be emitted into the atmosphere (and sometimes will enable removing this CO_2 directly from the air), CCSU plants are beneficial in the long term from an environmental point of view.

Currently, it is CCS installations that can effectively work with large enterprises. This technology can be upgraded to BECCS – Bioenergy Carbon Capture and Storage, and then CCS can generate so-called 'negative emissions' by using carbon dioxide from the atmosphere. Innovative methods could help complete the Paris Agreement [10].

According to the International Energy Agency, to achieve these goals, it is necessary to increase the capacity of such installations tenfold [11]. According to the Global CCS Institute, to achieve this goal, at least 2.5 thousand more carbon dioxide capture units with a capture efficiency of up to 1.5 million tons of CO_2 per year must be installed worldwide by 2040 [12].

At the end of 2020, CCS units were capturing 73 million tons per year, while by the end of 2021, productivity increased to 111 million tons per year [13]. Even though CCS does not directly use carbon dioxide but only allows it to be placed in storage (rather than emitted into the atmosphere), according to [14], net-zero emissions cannot be achieved without such technologies.

Analysing the CCS and CCSU installations, we can conclude that both technologies are still quite expensive due to their high energy consumption [15]. Production with CCS installed uses much more energy than production without it to extract, for example, oil [16]. According to the statements of [13], the cost of installing a CCS depends on many factors – the scope of production, the type and quality of the resource, the extraction of CO_2 immediately from the stream, or whether it needs to be isolated from concentrated stream gas, etc. However, as technology advances, the price of such plants is falling, and plants are becoming more and more the subject of discussions about cheap methods of decarbonisation [17].

Currently, the situation with carbon dioxide in production in the European Union cannot be called even. In some countries, technologies allow the use of CO_2 now, while in others, the economic and technological base requires additional investments. It is needed to attract extra political leverage and possible funding [18].

The main aim of CCU technologies is to allow 'fossil carbon to be left in the ground'. The [18] also argues that CCU technologies can benefit areas such as cement (carbon enrichment) and energy. CO_2 captured in other processes as a by-product can be redirected to other methods already as a resource. According to a report from the European Commission, products such as urea, methanol, etc., can already be produced using CCU. Using carbon dioxide in the production of fertilisers can be a profitable investment since, in this case, carbon dioxide is embedded in the soil [19], [20].

2. METHODOLOGY

The study consists of descriptive and systematic literature analysis of both international and national legal law regarding the issue of CO_2 emissions. 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 carbon dioxide 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 questions (see Fig. 1).

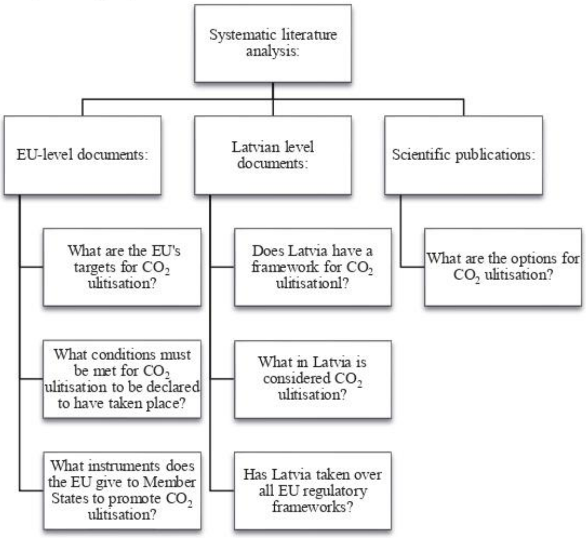

Fig. 1. Systematic literature analysis steps.

Before governing structures make decisions, they must familiarise themselves with the legislation. Each country of the European Union is obliged to comply with the laws of its own country and the laws of the European Union [21]. In parallel, when developing specific steps, the responsible structures should pay attention to similar solutions and their implementation experience in other countries. Exploring the extent to which the country's government is aimed at capturing/recycling carbon dioxide, this paper analysed the national laws of Latvia and the European Union. Additionally, a study was made on the laws of several countries of the European Union – Great Britain (EU member until 2020), Germany, Sweden, Lithuania, and Estonia. The first three countries are selected based on their technological development. In turn, the analysis of the legislation of Lithuania and Estonia is based on the fact that these two countries are Latvia's neighbours, and laws in these countries are often adopted with an eye to each other. In the case of a positive experience in one country, this decision will likely be made in a neighbouring country.

3. RESULTS

3.1. International Legal Framework

International legislation regarding the protection of the environment 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 carbon dioxide emissions.

The Paris Agreement was adopted in 2015 and signed by 191 countries worldwide. The agreement itself is a good step in the right direction. However, the text of the deal is highly inaccurate. The consequences for the country in case of refusal to follow the document are also not described [21]. Besides, the cooperation of countries within the framework of this agreement is weakly specified – it is indicated as 'voluntary' rather than 'desirable' or 'obligatory' [21].

Countries are given the freedom to participate. Any country can withdraw from the agreement three years after its signing [21].

The European Climate Law (also known as Regulation (EU) 2021/1119) is a tool to limit global temperature rise to 1.5 degrees compared to the preindustrial era [22]. The law implies that using the legislation of the European Union; countries must equally reduce the number of created emissions so that by 2050 no EU country produces greenhouse gases. It should be clarified that such a policy requires specific knowledge in science since it sets the methodological recommendations for the European Scientific Advisory Board on Climate Change [22].

As an additional tool for controlling and reducing the number of emissions, the European Union has developed its own emissions trading system. This system aims to reduce the number of emissions created using the economy. All Union countries and EEA members participate in it, making this system the largest in the world [23].

Because not all countries of the European Union are technologically advanced in the same way, a special equalization fund, The Modernization Fund, was created. It is possible to distribute up to 310 million ETS permits within this fund. However, not in all countries, these funds can be implemented. For Latvia, this fund could be beneficial, as it would help enterprises become more efficient and, if possible, switch to renewable energy sources. The country has already applied for investments for 2021–2030 and received 3 968 834 emissions allowances with a value of about 160 million euros [24].

The Investment Fund is the successor to the NER300 program. With a budget of 2 billion euros, this program was created to develop low-carbon technologies with a focus on CCS and innovative technologies for producing renewable energy on an industrial scale [25].

The Innovation Fund is the most extensive funding system that aims to stimulate and support the adoption of innovative low-carbon technologies. The fund receives its funding mainly from the sale of emission permits. This fund is designed to help businesses that decide to install greener technologies, including CCS, CCU, and similar carbon capture and utilization facilities.

Regulatory changes will further benefit early adopters of CCU technologies shortly. The Commission's proposal creates an incentive to capture and utilize emissions to be permanently chemically bound in the product so that they do not enter the atmosphere during everyday use [26]. Assistance focuses on developing small and large-scale low-carbon technology projects, carbon capture, use, storage technologies, and renewable energy and energy storage methods. Unlike the Modernization Fund, this fund is available to every country in the European Union [27].

CCS Directive assumes that CO_2 will be stored in geological repositories safe for humans and nature. Such storage will allow permanent storage of carbon dioxide, thus releasing the emissions obtained during production, not into the atmosphere but underground holds [28].

The directive is valid throughout the European Union. However, it does not apply to storage facilities with less than 100 kt storage capacity used in research projects [28]. Even though the directive supports the use of CCS, countries are free to choose whether to develop such repositories on their territory or not. The government has the right to completely ban the creation of underground CO_2 storage [28].

The Commission of the European Union intends to promote the development of carbon capture technologies. 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 the table below.

TABLE 1. EUROPEAN LAWS AND FUNDS

Name	**For whom**	**Goal**
Paris Agreement	All countries who signed the document (191)	To control and limit global temperature rise
European Climate Law	All EU countries	Tool to limit global temperature rise
ETS	All EU countries + EEA	Tool for controlling and reducing the number of emissions
Modernization 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. EUR
CCS Directive	All EU countries	To help implement CCS technologies

3.2. Latvian Legislation on CO_2

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 is a priority for implementation and cannot be ignored in case of any confrontation with local laws [29].

The Law on Pollution came into force in 2001. The law aims to prevent and/or reduce the negative impact of pollution on human health, property, and the environment and neutralise the consequences of the damage caused by climate change [30]. It is essential to add that this law characterises greenhouse gases. GHGs are claimed to be gases of both anthropogenic and natural origin present in the atmosphere and absorb/reflect infrared radiation. A list of these gases is – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), nitrogen trifluoride (NF_3) [30].

Like other countries of the European Union, Latvia participates in emissions trading. In this regard, the Cabinet of Ministers has developed a set of rules that came into force in 2012. According to these rules, the institution responsible for the trade process, the Ministry of Environmental Protection and Regional Development, was appointed. The institution's responsibilities include control over the trading process, supervision of the fulfilment of obligations by buyers, summarising and analysing the information on emissions, and informing the European Commission about the income received from the auction [31].

In 2018, the Cabinet of Ministers developed and launched a methodology for calculating greenhouse gas emissions. The primary purpose of the method is to assess the impact of specific planned and/or already implemented climate change measures. The methodology can be successfully used for various calculations. If necessary, if the conditions of the required measures do not fall under the main algorithm of the method, an alternative calculation method is proposed (Paragraph 10) [32].

This Climate law is still under development. It is supposed to replace the 'On Pollution' [30]. The new law aims to limit climate change and ensure adaptation to climate change in the country. This is expected to be achieved by reducing anthropogenic emissions and increasing carbon sequestration by 2050, achieving the primary goal of climate neutrality. This result is planned to be maintained and improved up to harmful emissions in the future.

The focus should be on paragraph 42, which stands for:

- On the territory of Latvia, in its exclusive economic zone and on the continental shelf, storage of carbon dioxide in geological structures and the vertical water layers is prohibited;
- The Cabinet of Ministers approves the procedure in which the storage of carbon dioxide is possible in cases not mentioned in the first part of this paragraph [33].

The second point is an essential difference from the previous law, 'On Pollution,' the difference from which the new one makes it possible to consider specific projects in private by the Cabinet of Ministers. This means that projects aimed at capturing and storing CO_2 are potential in the future. Additionally, the law stipulates that the Cabinet of Ministers is responsible for the procedure for transporting carbon dioxide, as well as for determining the course for its use [33].

In Latvia, greenhouse gas emissions are controlled in five sectors: energy (excluding transport), industry, agriculture, land use and forestry, and waste management. The control looks like a multilateral accounting that includes greenhouse gas and CO_2 calculations and information from the emissions trading register [34]. Data on emissions are publicly available and include detailed information – which company, for which year, how many, and what emissions were produced [35]. Additionally, it is possible to analyse emissions based on the category of the enterprise (category – permit for polluting activity). Data for each enterprise is available on the Valsts Vides Dienests website (eng. – State Environmental Service) [36]. The amount of CO_2 in Latvia has increased slightly. However, as the trendline shows, the increase is still observed. In 2019–2020, emissions decreased due to the reduction of production scale due to the quarantine caused by Covid-19 [37]. However, emissions are expected to return to or exceed previous levels if high electricity prices force producers to switch to less environmentally friendly resources, such as coal [38]–[40]. This means that the amount of CO_2 emissions will increase.

In February 2020, the National Energy and Climate Plan for 2021–2030 was adopted. The document determines the basic principles, goals, and directions of action of the Latvian state energy and climate policy for the next ten years, taking into account the outlined long-term development directions. This plan sets out goals and ways to achieve them in various sectors. These include reducing greenhouse gas emissions and increasing the market share of renewable energy. This step will significantly improve the efficiency of the energy sector and promote the introduction of innovative technologies in the manufacturing industry. An additional advantage will be an increase in the competitiveness of enterprises, which, in turn, will have a positive effect on the economy as a whole [41]. This document pays little attention to carbon capture and/or storage systems but, at the same time, states that in the future, cooperation with other countries on innovative technologies (CCU, hydrogen, etc.) will be sought. It is also planned to increase CO_2 capture and storage systems investment up to 2 % (in the previous period, 2014–2018, it was 0 %) [42].

Action Plan for Reducing Air Pollution 2020–2030 was developed within the law 'On Pollution' [30]. The action plan aimed at reducing the number of emissions was created in 2020 and is designed for ten years. The main idea of the document is to reduce the negative impact of pollution on the environment. This document differs from other documents in that it aims to reduce costs and loss of working time caused by air pollution due to health problems and visits to the doctor [43]. The plan is expected to help Latvia meet the emission reduction targets set by the European Union by 2020, 2025, and 2030. Additionally, the program should improve the quality of human life and health and improve the state of the ecosystem and air quality in Latvian cities. Implementing the measures included in the plan will also reduce greenhouse gas emissions, promote innovation, and increase the competitiveness of technologies. All listed legislative documents of Latvia are summarised in the table below.

TABLE 3. 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. year	Developed within the law 'On Pollution' Aimed at reducing the number 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

3.3. Legislation in Other EU Countries

3.3.1. Great Britain

Under The Climate Change Act [44], adopted in 2019, the UK has to achieve zero emissions by the 2050 and 78 % by 2035 [45], [46]. This law was positively adopted, as it involves the transformation of the energy sector and a significant simplification of the solution to climate change issues [47]. However, several additional policies and measures have been created to achieve the set climate targets. Specifically, the following points are relevant to emissions:

New Emissions Trading Scheme; Contracts for Difference, Climate Change Levy [48] In parallel with the legislation, CCS projects are also being developed. In 2015, a competition with a budget of ~1.18 billion euros for CCS development ended [49]. There are plans to build carbon storage facilities in the North Sea, and in the north-eastern part, it is planned to create a network for transporting and storing carbon dioxide. It is assumed that thanks to this network, it will be possible to transport gas from all over Europe [50]. The UK government has also announced that it will be phasing out coal burned at stations not equipped with CCS [51].

3.3.2. Germany

Germany has raised the percentage of reduction in greenhouse gas emissions. However, unlike the UK, not so much – 65 % by 2030 and 88 % by 2040 [52]. Unlike the UK, which introduced the first unified climate law in 2008 [47], Germany did not have a similar direction until 2019. In 2021, the German Bundestag introduced reforms to Climate Law. The rules for reducing emissions by 65 % and 88 % by 2035 and 2040, respectively, are written for the LULUCF sector. It is planned that by 2045 the industry will become negative by 35 million tons of CO_2 emissions. Additionally, the law of permanent storage of CO_2 in holds is prescribed [53]. It spells out the rules potentially allowing medium-sized CCS pilot projects. However, not all states are allowed to develop the project, and many forms of Germany have introduced a ban on CCS projects in their territories. The deadline for submitting applications for the development of storage facilities ended in 2016, and at the moment, it is possible to launch only a project approved before the designated year. The CO_2 Storage Act was planned to ensure the permanent storage of CO_2 in underground storage of earth rocks in the most environmentally friendly and sustainable way. The law regulates the complete analysis of the stones and the CCS project itself. The act would provide annual storage of up to 1.3 Mt CO_2 with a maximum storage capacity of 4 Mt CO_2 per year. Despite the closure of the initiative in 2018, opinions began to be expressed about the resumption of projects in the direction of storage and utilization of CO_2 (CCS and CCU). The idea of natural storage can be used in cases where production does not use coal or gas energy. It was suggested that these technologies could be used to protect the climate in industrial processes [54].

3.3.3. Sweden

In June 2017, the Swedish government decided to introduce amendments to climate policy. The main modification is introducing a framework, as it determines the implementation of the Paris Agreements in the country. Sweden has said it will achieve zero greenhouse gas emissions by 2045. An 85 % reduction is planned by modernising equipment, introducing innovative technologies, and abandoning fossil fuels. The remaining 15 % reduction will be completed by accumulating CO_2 in forests and land and the active use of CCS technologies [55]. It is planned that carbon capture technologies will be able to reduce emissions associated with both fuel use and various technological processes. The cement industry is currently considered the most natural area for CO_2 capture installations – the combination of CCS installations and bioenergy can significantly reduce greenhouse gas emissions in the long term. A guide to implementing carbon capture and storage technologies has also been developed. It should be noted that this policy is aimed not only at large producers of emissions but also at smaller ones [56], [57]. Additionally, the government has established a National Center for CO_2 Capture and Storage. Financing is provided to capture and subsequent storage of CO_2 created from renewable energy sources (creation of the so-called biological CCS) [58]. Industrial Leap is also a severe document, the development of which began in 2018 and will end in 2040. The main goal of the reform is the transition of the manufacturing sector from old technologies to those that do not produce emissions in the process. One of the options for such technologies is producing energy using CCS installations. A positive aspect of this document is that the grant is available to manufacturers and researchers in this field [58].

3.3.4. Lithuania

Lithuania is included in the list of countries in the Baltic region in which carbon dioxide storage systems have been actively developed. In 2011, the country's legislation fully implemented the EU directive on CO_2 storage [59]. However, in 2020, the Lithuanian government banned any projects to capture and store CO_2. This decision was justified by concerns about the risk of underground water contamination with liquid carbon dioxide [60], [61]. According to [60], this decision is the most negative for the region for 2020, as it prohibits any placement of carbon dioxide underground in artificial and natural storage and any work and development in this direction. Despite the adopted law, in the country's National Development Plan for 2021–2030, ideas appear for developing systems for capturing, using, and underground storage of carbon dioxide. Such a change of opinion is due to the possibility of using the European Innovation Fund to develop CCS and CCU technologies [62]. In addition, the chances of modernizing the production sector are being considered. The technical and economic aspects of carbon dioxide capture installations and their subsequent use and storage in specialized storage facilities in Lithuania are assessed. The plans also include a detailed analysis of the payback and feasibility of this type of project compared to other countries of the EU Common Economic Space (countries to which the carbon dioxide captured in Lithuania could be redirected) [62].

3.3.5. Estonia

The carbon dioxide use and storage legislation in Estonia is not very developed. There is a law to reduce emissions [63], which refers to the need to modernize the manufacturing and energy sectors. Another document is the government action program [64]. This document already pays more attention to CCS technologies. It is planned to pay more attention to competitive, low-carbon technologies in the country's future. The following document is already more detailed in this type of question. The NECP 2030 National Plan is a communication drawn up by the requirement of the Parliament of the European Union (No 2018/1999). The plan proposes modernizing the manufacturing and energy sectors, motivating producers to use CO_2 storage facilities, and using energy obtained from non-fossil sources [65]. The 2021 report of the country's energy sector proposes introducing CCS and CCU systems. This technology would help the government fulfil its emissions reduction plans [66]. From a financial point of view, the authors of the document admit that at current prices for CO_2 quotas (as of March 2021, the cost was ~40 EUR per ton), it is more profitable to invest in the development and construction of infrastructure for capturing, cleaning, transporting and storing carbon dioxide. And although CCS and CCU technologies are costly and require significant investments, in Estonia, additional funding from European grants for developing CCS/CCSU technologies was not yet attracted. In addition, the document proposes several levers to encourage the introduction and use of CO_2 capture and storage systems – subsidies, capital grants (for the construction phase), investment tax credits/incentives, production subsidies, production tax deductions (for companies producing CCS/CCU), feed-in tariffs for products using CCS/CCU technology, as well as a price surcharge for all products using CCS/CCU [66]. All listed legislative documents of mentioned EU countries are summarised in Table 4.

TABLE 4. LEGISLATIVE DOCUMENTS ON CO_2 IN EU COUNTRIES

Country	Document	Goal
Britain	The Climate Change Act	To transform the energy sector, simplify the pollution of climate change issues.
	New Emission Trading scheme	Replaces EU scheme after UK left the EU
	Contracts for Difference	To fixate price on low-carbon energy. To motivate the utilization of low-carbon energy.
	Climate energy Levy	To motivate companies to increase energy efficiency.
Germany	Federal Climate Change Act	To transform the energy sector, simplify the pollution of climate change issues.
	Climate Law	To unfasten emission reduction; to optimize the LULUCF sector.
	Carbon Dioxide Storage Act	Rules for CCS project construction and utilization
Sweden	Climate Act	Provisions on the climate policy
	Industrial Leap	Support the production sector's transition to zero-emission technologies
Estonia	Governmental Action Plan	To implement low-carbon technologies.
	National Action Climate Plan (NECP) 2030	To modernize production and energy sectors by implementing innovative emission-control technologies
Lithuania	National Energy and Climate Plan 2021–2030	To modernize production and energy sectors by implementing innovative emission-control technologies.

Despite the poorly developed legislation on CO_2 use in the Baltic States, options for cooperation between Latvia and Estonia are being actively discussed and analysed. During this cooperation, Estonia could potentially supply Latvia with CO_2, where it would be subsequently buried. Latvia has delicious geological layers suitable for storing CO_2 from the Baltic region [60], [67].

The onshore CCUS scenario includes capturing CO_2 emissions from the largest emitters in Estonia and Latvia (mainly in the energy sector) and storing these emissions in North Blidene storage (Latvia). The scenario assumes that the project's construction will take about two years and last about 30 years. According to the system, the storage could hold about 204 Mt CO_2 [8].

4. CONCLUSION

To achieve the goals to reduce carbon dioxide emissions, countries must optimize production processes and change the legal framework. The possibility of using sustainable carbon cycles can be a solution to the problem of emissions in the world and boost economic and technological development. However, these technologies must be specified in the legislation.

This work analyses the legislative framework for capturing and using carbon dioxide in the European Union, many of its countries, and Latvia. Currently, the use of CO_2 capture and storage technologies is poorly specified both in the laws of the European Union and in the rules of individual countries. Despite this, the EU motivates and stimulates the active development of such technologies throughout the Union by offering financial assistance to projects. In some countries, the government is also actively involved in technology transfer to be more ecological and environmentally friendly.

The disadvantage of the issue of CCS and CCU technologies is the too low level of public awareness (and sometimes the political sector) about these technologies – what they are, what they are for, and what advantages they bring. As the analysis showed, such countries as Lithuania and Germany abandoned CCS projects precisely under pressure from the public/politicians. Recently, however, people's opinions have begun to change. Additional research is needed for a more active introduction of innovative technologies and to determine the public's view. An analysis of the willingness to pay could undoubtedly help determine the education and awareness of people in matters of CO_2 emissions and their attitude to this topic.

Developing legislation that motivates entrepreneurs to use low-carbon technologies, including CCS and CCU, is necessary. It is essential to indicate all the benefits that an entrepreneur, as a direct 'producer' of emissions, will receive from acquiring innovative technologies and what disadvantages an adverse decision may have. Society – the public, entrepreneurs, and politicians must realize the need to change since only through change can success be achieved in preserving the climate and the environment.

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PAPER 6. POLICY INSTRUMENTS FOR CO_2 VALORISATION SUPPORT

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Policy instruments for CO_2 valorisation support

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ABSTRACT

Mitigation of CO_2 emissions has become a top question in international and national arenas, likewise on the city level. Existing CO_2 mitigation measures are primarily orientated toward wider deployment of low-carbon technologies of renewable energy sources and energy efficiency measures, focusing on energy production, distribution, and energy use sectors, transport. In the recently announced European Green Deal strategy, response action on climate and environmental protection challenges for Europe 2050 is set. The strategy targets "to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use." Rapid and intelligent solutions are needed to reach this ambitious target, which requires converting to profoundly transformative policies beyond others. An evident-based multi-sectoral forecasting model must be timely and effectively deployed to initiate and maintain such transformative policies. This work aims to analyse existing laws, regulations, and directives, both local and European, to identify limiting factors and factors that contribute to a more active introduction of systems for capturing, using, and/or reducing the amount of carbon dioxide created in production processes. The work results show how developed countries' laws regarding carbon dioxide emissions - its capture, storage, and/or utilisation. At the time of writing, the most extensive legislative framework is represented in Sweden, followed by Belgium, Croatia, and Lithuania. The results show that Sweden has the most developed legislation and measures on CO_2 issues and stimulates producers in various sectors to reduce emissions. The country with the most policies implemented is Belgium (213), while the country with the minor policies is Cyprus (13). Analysing the legislation of the countries of the European Union, it was concluded that Sweden's most extensive issue of CO_2 emissions, storage, and utilisation had been worked out. The results emphasise the need for coherence between legislative frameworks in Member states. Therefore the role of CCS/CCU should be determined in national climate and energy strategies, ensuring compliance with CO_2 export within the EU member states.

1. Introduction

The European Union's (EU) target of achieving climate neutrality and reducing greenhouse gas (GHG) emissions by 2050 require all Member States to weigh their emissions and potential to reduce them.

EU countries could achieve the EU's goals and climate settings by enabling the private sector and the scientific community to make technological advances in carbon capture and utilisation (CCU). CCU include capturing and transforming carbon dioxide (CO_2) into more valuable products, thus ensuring the meaningful use of CO_2 and reducing its concentration in the atmosphere. However, for this to be possible, the legislator would need to develop a clear strategic and regulatory framework for using CCU technology.

The European Commission stated in its report of 15 December 2021 that "in 2018, the EU economy consumed around one billion tonnes of biogenic (45%) and fossil (54%) carbon and only a tiny proportion of the carbon currently used is recycled carbon (1%)" [1]. The EU is definitely in demand for carbon in its various production processes. In the same document, the European Commission also sets a target of 300 to 500 Mt CO_2 utilised by 2050.

Despite the fact that multiple research is made [2–4], the largest emitters of CO_2 in the EU are still energy producers (coal reactors, natural gas reactors) and the transport sector (Fig. 1), but the industrial and agricultural sectors are also essential emitters.

The fact that CO_2 is considered a GHG is linked to the impact of CO_2 on climate change. One of the indicators of climate change is the change in global temperature, where there is a correlation between its increase and the amount of CO_2 stored in the atmosphere [6]. CO_2 is responsible

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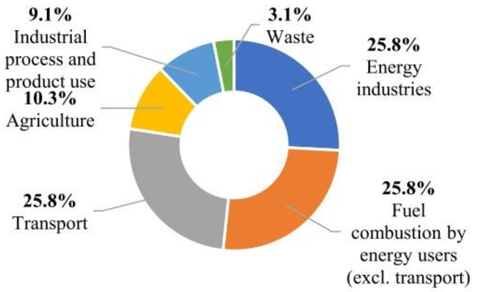

Fig. 1. Greenhouse gas emitters in the European Union [5].

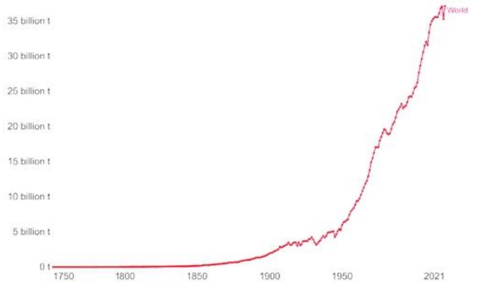

Fig. 3. Annual CO_2 emissions in the world from fossil fuel burning and cement production (excluding land-use) [10].

for around 20% of the Earth's greenhouse effect [7]. Since the beginning of industrialisation, the amount of CO_2 in the atmosphere has risen from 280 ppm to 410 ppm today. It is projected that by the year 2100, the concentration of CO_2 in the atmosphere could reach 540–970 ppm [8].

However, measures to reduce the amount of carbon dioxide are being taken – new regulations and laws are being adopted. The European Union has reduced its GHG emissions, so it only makes sense to review the EU's common policy, which has led Member States to reduce GHG emissions by up to 24% since 1990 (Fig. 2) [9].

According to [10], the number of emissions only from the combustion of fossil fuels (oil, coal) is growing every year. A slight drop in 2020–2021 was due to stagnation due to COVID-19, but this reduction is expected to be reversed in the coming years (Fig. 3).

As stated by IPCC 2022 [11], the number of emissions should be reduced – activities aimed at modernising several sectors (manufacturing, transport, energy, etc.) should start now and be implemented as soon as possible. Emissions reduction is a global measure. Each country will have to do its part to achieve the result; otherwise, the consequences will affect everyone. The basis of the changes in each country's legislative framework is a well-developed system of laws that allows the country to move towards a more environmentally friendly development.

One way to mitigate the impact of CO_2 emissions is through carbon capture and utilisation (CCU) or CO_2 valorisation. This involves capturing CO_2 emissions from industrial processes and converting them into valuable products such as fuels, chemicals, and building materials. CO_2 valorisation has the potential to not only reduce emissions but also create economic opportunities and contribute to sustainable development.

Despite the potential benefits of CO_2 valorisation, there currently needs to be more policy instruments in place to support its development and implementation. This is partly due to the fact that CO_2 valorisation technologies are still in the early stages of development and commercialisation, and there needs to be more awareness and understanding of the potential benefits of these technologies. Therefore, policy instruments that can incentivise the development and adoption of CO_2 valorisation technologies are crucially needed. Such instruments can include carbon pricing mechanisms, tax incentives, and research and development funding. These policy instruments can play a critical role in accelerating the development and deployment of CO_2 valorisation technologies while also contributing to achieving climate change goals and sustainable development objectives. The research of the CCS4CEE project also points to the need for more elaboration of policies regarding carbon capture and storage (CCS) technologies. If national strategies (i.e. NECP and Long-Term Support) concern such technologies, then only superficially. However, regarding the role of CCS, policies should be clear and consistent and allow regional collaboration in this area [12]. As [13] indicates, in Central and Eastern Europe, fiscal and public finance policies are only available for the CCS pilot projects. The lack of financial support and favourable conditions for maintaining CCS projects is a crucial drawback for such high-class technologies. The absence of sufficient supportive policies is also indicated by [14–16]. Nonetheless, according to the IRENA report [17], carbon capture technologies are essential, especially in sectors with high CO_2 emissions that are otherwise very difficult to reduce (Fig. 4).

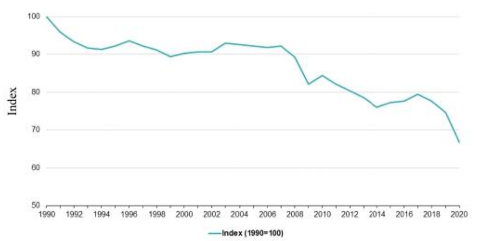

Fig. 2. Total GHG emissions in the European Union, excluding land use, land use change and forestry, but including international aviation [9].

However, for the countries of Europe to achieve energy and climate targets, national governments should reconsider the role of CCS and include it in national strategies.

The purpose of this work was to analyse the legislative framework of the European Union countries and determine their elaboration regarding the fight against carbon dioxide emissions. Even though the European Union Regulation 2021/1119 [18] indicates countries to the need to reduce CO_2 emissions, the document does not define technologies and ways in which these reductions could be achieved optimally. Each country has the right to determine which technologies and/or measures to use to complete the task. In this regard, in this paper, particular attention was paid to legislation system aimed at innovative technologies that capture carbon and either put it in underground storage (CCS) or use it in producing a new product (Carbon capture and utilisation, CCU), thereby using the principles of the circular economy, as since the awareness and availability of this information can contribute to the promotion of similar technologies in other countries.

Innovative technologies such as Carbon Capture, Storage and/or Utilization, according to [19–22], could be the solution necessary to achieve zero and even negative emissions. Yet, few policies have been published so far. International regulations are one of the main obstacles to the successful evolution of CCS/CCU technologies. Acceleration and development of CCS/CCU technologies are possible with the predictable regulatory environment. Therefore, it is essential to determine how ready the countries' legislation is for technologies of this level.

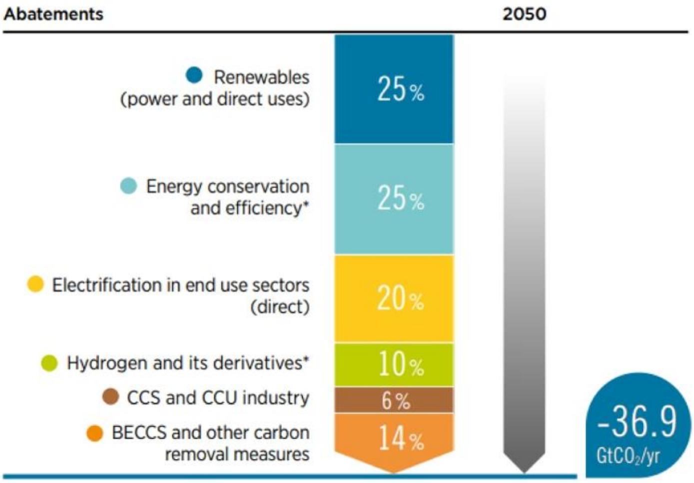

Fig. 4. Carbon emissions abatements, IRENA report [17].

2. Methods

2.1. Systematic literature analysis

Literature analysis is necessary to get a complete picture of the legislation system and to build a knowledge base on the research topic. 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:

- World-class documents, such as the Paris Climate Agreement.
- Documents at the EU level, such as Regulation (EU) 2021/1119 [18] of the European Parliament and the Council.
- 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 [23].

For the systematic analysis of the literature, two groups of documents were selected, and each of them raised its questions:

EU-level documents:

- What are the EU's targets for CO_2 recovery?
- What conditions must be met for CO_2 recovery to be recognised?
- What tools does the EU provide the Member States to promote CO_2 recovery?

Scientific papers:

- What are the possibilities for CO_2 utilisation?
- What is the experience of other countries and cases?

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, which included technologies and/ or measures for carbon dioxide 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. Only official documents (such as policies, scientific documents and reports) were included in the research. The same criteria were implemented to all scientific research papers. Only those papers were observed that are not older than five years. Older document was used only in case if no recent paper was found.

This method used two types of keywords: direct and general or indirect. Keywords were selected through literature and systematic literature analysis (Table 1).

The information gathered by the EEA on the climate policies of the EU Member States was analysed [24].

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 work were selected:

® P1 – country uses the EU ETS;
® P2 – GHG emissions mark-ups in the country are taxed;
® P3 – the country has tax rebates to meet climate targets;

Table 1
Keywords.

Direct keywords	Indirect keywords
CO_2 / carbon dioxide utilisation/CCU	CO_2 / carbon dioxide capture
CO_2 / carbon dioxide utilisation	CO_2 / carbon dioxide storage
	CO_2 / carbon dioxide storage / CCS
	CO_2 / carbon dioxide binding
	CCS

® P4 – the country is increasing the number of renewable energy resources in the field of energy;
® P5 – energy efficiency works are being carried out in the country;
® P6 – the country has restrictions or prohibitions on GHG emissions;
® P7 – the country uses the LULUCF sector to reduce emissions;
® P8 – the state provides funding for research into GHG emission reduction technologies;
® P9 – GHG capture is taking place in the country;
® P10 – the use of CCS technologies is taking place or is planned in the country;
® P11 – the use of CCU technology is taking place or is planned in the country.

These categories were then assigned values according to their relevance to the aims and objectives of the work:

® If the country has at least one policy instrument or the policy falls into categories P1, P2, P3 or P5, one point is awarded;
® If the country has at least one policy instrument or the policy falls into categories P4, P6 or P7, two points were awarded;
® If the country has at least one policy instrument or the policy falls into categories P8, P9, P10 or P11, three points were awarded.

The difference in the number of points is explained by the complexity (financial, legislative, technical) of the policy's adoption and/or implementation.

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.

3. Results and discussion

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 [24] provides an opportunity to conclude the diversity and scope of EU Member States' policy instruments (Fig. 5).

As seen in Fig. 4, 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).

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

A summary of the evaluation results is shown in Table 2.

From Table 2, it can be seen that all EU Member States are also users of the EU ETS. All twenty-seven Member States are experiencing an increase in the share of renewable energy in the energy sector and energy efficiency improvements. All EU Member States have regulations that severely restrict or ban GHG emissions into the atmosphere. The possibility of emitting fluorinated gases is significantly limited in most countries. Four Member States (Belgium, Croatia, Romania and Sweden) are implementing or planning to deploy CCS technologies. CCU technology is neither enforced nor planned in any member state.

In many EU countries, there are also different ways to tax CO_2. Still, only a few countries have a tax on CO_2 emissions specifically. According to the [25] World Bank, there are currently active carbon taxes in thirteen EU Member States: Sweden, Finland, Estonia, Latvia, Poland, Slovenia, Denmark, the Netherlands, Luxembourg, France, Spain, Portugal and Ireland.

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.

3.1. Developed legislation system

A systematic literature analysis has shown that countries such as Belgium, Croatia, Lithuania and Sweden have the most detailed legislation on CO_2 emissions. However, other countries of the European Union are also developing and implementing documents aimed at reducing the amount of carbon dioxide produced in the country.

Belgium. For 2019, about 123 megatons of CO_2eqv were created in Belgium, which is 17% lower than in 2005 [27]. In many respects, this result was achieved by introducing the latest production technologies and modernising the transport sector. A Climate Policy cuts across all industries – transport, taxation, energy, and environment [28].

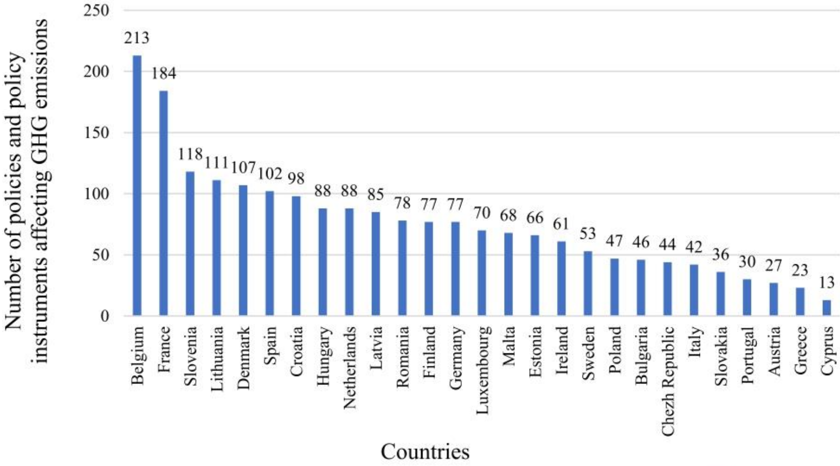

Fig. 5. Number of policies and policy instruments affecting GHG emissions in EU Member States [24].

Table 2
Categorisation of policies and instruments affecting GHG emissions [26].

	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	

The National Energy and Climate Plan for Belgium [29] mentions technologies for storing and using carbon dioxide. In 2030, licenses for many incineration plants will expire, and the issue of extending these licenses has become acute - they will be raised only if the plant meets stringent CO_2 emissions requirements. In addition, the question is being investigated how efficiently these combustion stations can capture the carbon dioxide they create and whether it can be further used in the circular economy. This type of economy implies using not even CCS but more CCU technologies, which is technologically more difficult but brings excellent benefits [29]. Using these technologies and creating a CCS network, it is possible to achieve CO_2 neutrality for individual regions and the entire country.

According to [30], there are currently four active CCS projects in Belgium (LEILAC, C4U, ArcelorMittal Steelanol Ghent, Antwerp@C) and 3 CCU projects (FLITE, North-CCU-Hub, Power-to-Methanol Antwerp BV). The country's policy is aimed at the circular economy; consequently, the use of the created CO_2 in production will continue further, and there will be more CCS and CCU stations.

Croatia. Croatia has ten large CO_2 production sites, the largest of which are a fertiliser manufacturer in Kutina and a cement plant in the city of Našice. The remaining enterprises of the "big 10" are power stations, oil and gas processing stations, and a glass factory. The region has geological formations suitable for underground carbon dioxide storage. Therefore, in 2014, the CO_2 EOR Project Croatia was launched in the country, allowing it to obtain more minerals and put waste CO_2 underground simultaneously. This project allows storing more than 400 mln.m^3 CO_2 [31]. Another promising project, the Bio-Refinery Project, is an offshoot of the existing INA Downstream 2023 refinery. His-new course is CCS technology, and CCU – captured carbon dioxide will be used to produce improved biofuels, biogas and other products. This project fits perfectly into the example of a circular economy when the emission of one industry becomes an essential resource for another industry [32]. A developed system of CO_2 transportation makes it possible to move gas across the country, thus enabling large producers of carbon dioxide not to emit it into the atmosphere but to sell it. Even though the pipeline has already been launched and shows good results, it is planned to expand further, allowing even the country's most remote corners to use this infrastructure [33].

Lithuania. In 2020 all CO_2 capture and storage projects were frozen due to the government and public's extremely negative mood; not so long ago, the country returned to CCS technologies and the opportunities they bring [34]. The reason why Lithuania returned to projects can be considered the opportunity to use the Innovation Fund for the development of the national technological platform and the development of the industrial sector as such, linking it to innovative developments in the field of capture and disposal and, possibly, the subsequent use of carbon dioxide. The National Development Plan 2021–2030 pays attention to CCS and CCU technologies - the advantages and benefits the country can receive if they are introduced into existing production are considered [35].

Sweden. There have been talks about capturing carbon dioxide in Sweden for a long time. Still, in June 2017, the Swedish government announced a new document - an addition to the already existing act on climate policy. A severe reduction of emissions and the achievement of zero emissions earlier than the deadline set by the Paris Agreement – by 2045, no CO_2 should be created in the country. The main changes will affect the modernisation of the production sector. The focus is on innovative technologies that capture carbon dioxide from exhaust gases and redirect it to producing other valuable products (thus obtaining both environmental and economic benefits) or putting CO_2 in landfills [36]. It is essential to clarify that the new policies are aimed at large producers of carbon dioxide and small ones [37].

The state supports CCS projects in every possible way. So, for example, installing Bioenergy with carbon capture and storage (BECCS) technology can significantly reduce the number of CO_2 emissions created in energy production and even make them harmful. BECCS technologies are a new milestone in developing carbon dioxide capture and storage technologies. This installation is designed for stations producing energy from biofuels [38]. In achieving the goals of the Paris Agreement, it is planned to install BECCS at the largest power plants in the country.

3.2. Legislation system with some legislation acts

This group includes countries that scored at least 10 points in Table 2. In many of these countries, projects are planned that would allow capturing, storing and/or utilisation of carbon dioxide. For example, Latvia and Estonia are actively negotiating the creation of an infrastructure for capturing, transporting and storing carbon dioxide from Estonia in Latvia. No geological formations in Estonia would allow the storage of CO_2. However, there are such formations in the territory of Latvia [39,40].

In another country, Germany, despite the closure of all CCS / CCU projects in 2018, more and more attention has been paid to these technologies in recent years. At the beginning of 2022, the country announced the creation of two projects with the launch in 2025 (Leilac2) and 2027 (H2morrow), as well as a carbon dioxide liquefaction project and its temporary storage in Wilhelmshaven [41].

According to [41], as of January 2022, the total number of CCUS plants reaches 65 throughout the European Union (already operating and planned projects together), which will reduce carbon dioxide emissions by about 65 million tons per year by 2030. This number of stations, although still small, given that just less than two years ago, as of June 2020, there were half as many projects (existing and planned together), it indicates that the actions taken by both the government and the enterprises themselves are going in the right direction [42].

3.3. Insufficiently developed legislation system

Ten countries are included in the category of countries with an insufficiently developed legal framework, but more is needed in these countries to more actively capture and store (or use) carbon dioxide. These countries are beginning their transition to greener and more innovative production systems. Many countries from this list actively use the opportunities the European Union – Innovation Fund and Modernization Fund provides. Both funds are aimed at the country's analysis, development and implementation of CCS systems. According to [43], the second call for large-scale projects received 138 applications from all over Europe, in one way or another, aimed at reducing the number of emissions created. Successful implementation of the announced projects will make it possible to reduce CO_2 emissions by more than 710 million tons. (during the entire operation period within the Innovation Fund framework). In addition, it is worth mentioning that despite the poorly developed legislative framework (compared to countries from the first group, for example, Belgium), applications have been submitted in these countries for creating CCUS stations (or carbon dioxide transportation). For instance, in Ireland, the experimental installation of a post-combustion carbon dioxide capturing plant is being planned, with the launch of the project in 2028 [44].

The results of the study emphasise the need for coherence between legislative frameworks in Member states. Therefore the role of CCS/CCU should be determined in national climate and energy strategies, ensuring compliance with CO_2 export within the EU member states.

Future work in enabling policy framework, making investing in all parts of the value chain economically feasible, and continued support and coordination are crucial for implementing CCS/CCU. EU should set a clear role, scope and targets of CCS/CCU, including revision of directive guidance and development of new regulatory frameworks of different aspects of value chains, for example, CO_2 cross-border transportation, certification of carbon removal activities etc.

4. Conclusion

This work aimed to study the legislative framework of the countries of the European Union. The work results show how developed countries' laws regarding carbon dioxide emissions - its capture, storage and/or utilisation. At the time of writing, the most extensive legislative framework is represented in Sweden (19 pin total), Croatia (18), Belgium (16), and Lithuania (16) – these countries marked GHG emissions for further taxing excessive emissions and push industries to use more ecological equipment and production methodologies. All these countries aim to use renewable energy sources, thus lowering the share of coal, oil and other fuel types with high emissions. But taxing and pushing are not the only measures taken – countries provide research funding and help implement new technology. Financial and technology helps make the transition of the sectors much faster and easier.

On the other hand, the least points got such countries as Ireland (7 points in total), Cyprus (8) and Greece (8). Unlike the mentioned leading countries, in this trio, the taxation system does not encourage producers to reduce emissions. However, the countries are still trying to improve energy efficiency and use the opportunities of the agriculture and forestry sectors to reduce the number of already created emissions.

The analysis of the published policies on CO_2 emissions showed that Belgium has the most policies – 213, followed by France (184) and Slovenia (118). Rounding out the list are Austria (27), Greece (23) and Cyprus (13). And if the situation looks logical in Greece and Cyprus - the smallest number of laws and points received- then the situation with the top three looks different. Sweden, which received the most points (i.e., the country is actively promoting the topic of reducing emissions, motivating the transition to cleaner technologies and using renewable energy sources), has only 53 laws in its asset. This result suggests that these laws are elaborated with particular care and detail, eliminating the need to issue new laws.

Analysing the legislation of the countries of the European Union, it was concluded that Sweden's most extensive issue of CO_2 emissions, its storage and utilisation, has been worked out. In this regard, the country can be called a leader in innovative CCUS technologies. When developing documents and activities supporting CO_2-emitting sectors, the EU countries should first familiarise themselves with Sweden's experience. However, no specific law will immediately change the situation in the country - the adopted laws work together - one law complements the other. This allows the system to move forward and for entrepreneurs to clarify what needs to be done. Misunderstanding hinders the development of the technological process.

The IPCC 2022 report [15] states that emissions should be reduced. The sooner actions are started, the fewer emissions should be reduced annually. But if measures to reduce greenhouse gases are slowed down or postponed, then, with each subsequent year, the amount of reduction will only increase, and at one moment, it will become too big to accomplish. Quick and timely actions of entrepreneurs and, first of all, legislators are necessary to implement the tasks set to reduce CO_2 emissions successfully.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jelena Pubule reports financial support was provided by Latvian Council of Sciences.

Data availability

No data was used for the research described in the article.

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PAPER 7. CO_2 STORAGE IN LOGGING RESIDUE PRODUCTS WITH ANALYSIS OF ENERGY PRODUCTION SCENARIOS

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CO_2 Storage in Logging Residue Products with Analysis of Energy Production Scenarios

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Abstract **– Woody logging residues produced by logging activities are currently an underutilised resource that is mainly burned for energy production or left in the forest to decay, thus releasing CO_2 into the atmosphere. This resource could be used to manufacture long-lasting products and store a significant amount of CO_2, promoting CO_2 valorisation in rural areas. In this study, potential use for logging residues is proposed – the production of low-density wood fibreboard insulation panels. The new material's potential properties, manufacturing method and combined heat and power (CHP) plant parameters were proposed. The potential climate benefits of the new product were analysed using various biogenic carbon accounting methods. As energy production for manufacturing can be a significant source of emissions, possible energy production scenarios were analysed for manufacturing the product. However, an economically and environmentally viable energy production scenario should be chosen. By conducting a multi-criteria analysis, three possible energy production scenarios were analysed – wood biomass CHP plant, a natural gas CHP plant and a standalone wood biomass combustion plant combined with Solar photo-voltaic (PV) panels. The scenarios were analysed in terms of technological, economic, and environmental performance to determine the best strategy in this case.**

Keywords **– CO_2 storage; energy production; logging residues; wood products.**

1. INTRODUCTION

Forestry practices produce large amounts of waste and residues from the harvestable yield. This can present significant management problems, as the discarded biomass can hurt the environment. Meanwhile, sustainable energy sources and raw material feedstock are required with increasing global population and rising demand for construction products and materials. Forestry waste and logging residues are under-utilized resources for energy and material production. To date, there has been little activity to utilise these resources in a 'low carbon' way. It is estimated that for every cubic meter of logged wood material removed, a cubic meter of wastes and residues (e.g., stumps, branches, greenery) is left in the forest. Currently, of all wood-derived biomass produced globally, 20 % can be accounted as primary production loss left in the woods to decay, which could instead be used as a feedstock for a variety of products, including the production of fuels, polymers and building materials and products [1].

Wood, like products made from it, has a significant advantage over other building materials – they are an essential source of CO_2 sequestration. It has been observed that there exists a direct correlation between the amount of CO_2 sequestered and the amount of wood-derived

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biomass harvested to produce high-added value products – with increasing amounts of wood harvested or rising efficiency of timber used, the amount of carbon sequestration is also increased [2]. The overall decarbonisation solutions can be achieved if sustainable carbon cycles, including using Carbon Capture and Utilisation technologies, are implemented (see Fig. 1) [3]–[6].

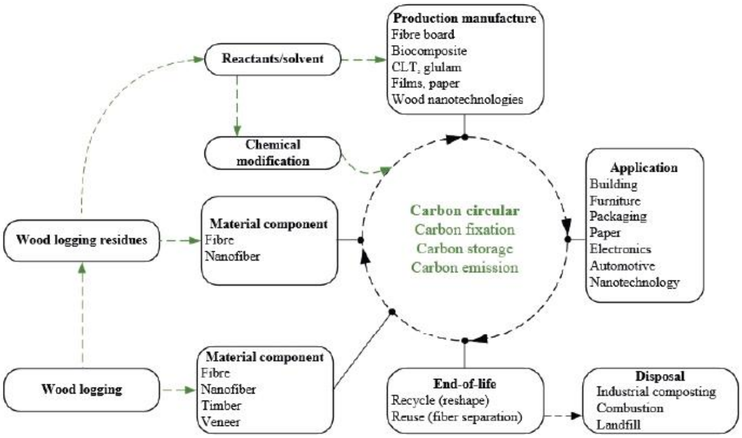

Fig 1. The sustainable carbon cycle of wood logging residues [1].

In the wood-based product sector, significant potential for CO_2 sequestration can be attributed to the production of wood-based panels and engineered wood products [7], [8]. In a 2017 study about carbon storage in wood products, the carbon sequestration potential of three different wood-based panels was reviewed – oriented strand board (OSB), particleboard (PB) and medium density fibreboard (MDF). According to the IPCC methodology, all three of these products are included in the national inventory reports as harvested wood products that store carbon, thus decreasing the overall CO_2 balance in the atmosphere. It was calculated that a cubic meter of PB and OSB sequester 720 kg of CO_2 each and that a cubic meter of MDF sequesters 820 kg of CO_2, considering the number of emissions from material production [9].

However, despite this advantage, producing such panels is quite an energy-intensive process. The Best Available Techniques (BAT) Reference Document to produce Wood-based Panels states that the average amount of thermal energy required to produce one cubic meter of the material is 0.955 MWh for PB, 0.4 MWh for OSB and 1.65 MWh for MDF panels. The average amount of electrical energy required to produce one cubic meter of the material is 0.155 MWh for PB, 0.115 MWh for OSB and 0.505 MWh for MDF panels [9], [10]. In turn, producing such thermal insulation materials as Ecowool and mineral wool requires 0.00416 MWh and 0.200 MWh of electricity per cubic meter of product. Although rigidboards are popular insulation material, they are mostly produced from expanded polystyrene or polyurethane foam – both are produced from fossil resources eliminating the opportunity to store CO_2 in such products. Nevertheless, rigid and flexiboards from wood fibres are becoming more popular. Production technology of such materials is similar to other wood fibre materials, in detail described further in this paper.

Although the CO_2 sequestration benefits of one cubic meter of rigid board insulation material will be lower than that of OSB, PB and MDF panels, considering the lower density of wood in the material, it will require less energy and raw materials to manufacture. The low-efficiency and uninsulated buildings in Latvia and many other countries are still tall, meaning that building insulation materials will remain a high-demand product for the foreseeable future. There is a wide range of insulation materials available today, each with its advantages and disadvantages. However, modern consumers care not only about the physical and mechanical properties of the material but also about the environmental impact. Manufacturing insulation materials could become one of the future opportunities of the forestry industry of Latvia. Generating by-products and residues in the harvesting and manufacturing processes is inevitable. Currently, forestry companies mainly use these by-products to produce energy or sell them to other companies. Exporting these by-products is still inefficient since they are now sold as low-added value products. As companies in the forestry sector move to increase the efficiency and productivity of their production, the utilisation of wastes and residues previously considered low value is becoming an increasingly attractive option. Using these by-products to manufacture thermal insulation is one of the potential solutions for increasing their value [11], [12].

Mitigation of CO_2 emissions has become a top question in the last decades. Therefore, understanding processes within rural CO_2 economy sectors, factors, interconnections and effects on the environment and nature quality and guidelines for future activities are crucial. Valorisation of CO_2, including direct capture and utilization, transformed CO_2 utilization or pre-processed CO_2 utilization, can positively affect the reduction of CO_2 emission and the development of rural areas [3]–[6]. The changes in wood waste treatment practices and production of the rigid board from wood logging residues can have a positive effect on mitigating CO_2 emissions, providing its storage in the products. This work aims to analyse the environmental impact of this insulating material. Using an underestimated resource to produce thermal insulation material can be viable from economic and technological perspective. The practice could be favourable from product demand, and raw material supply perspective by adding value to wood value-chain.

2. METHODS AND METHODOLOGY

For this study, the production of rigid board wood insulation material was chosen. The production methodology consists of steps like a description of the production process and needed feedstock calculation of the amount of CO_2 that can be stored in the final product. As for the energy sources for the rigid board production. Three different scenarios have been compared using the multicriteria analysis method. All steps of the methodology are seen in Fig. 2.

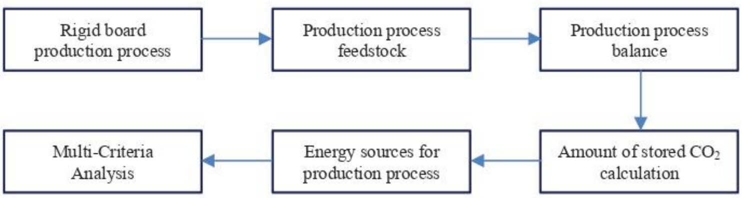

Fig. 2. Algorithm of the methodology.

The rigid board is produced similarly to other wood fibre boards e.g., MDF and LDF. The same dry process is used for refining the dried wood fibres derived from wood chips. After drying, the material goes through forming, pressing and profiling. A simplified manufacturing process of rigid board insulation panels is shown in Fig. 3. The refined and dried wood fibres are mixed with resin, formed into a mat, and then pressed and cured. Curing occurs by passing steam through the mat to heat it slightly. In comparison to general MDF production, the working pressure is lower and process does not require heated press. The slight temperature increase and the small amount of water cure the resin. The resin used for rigid board production is exclusively pMDI (polymeric methylene diphenyl diisocyanate). Rigid board is produced in various thicknesses ranging 18–244 mm and in densities ranging 100–220 kg/m^3. It is mainly used for insulation purposes, and the raw boards are passed through a profiler to produce a tongue-and-groove finish [10].

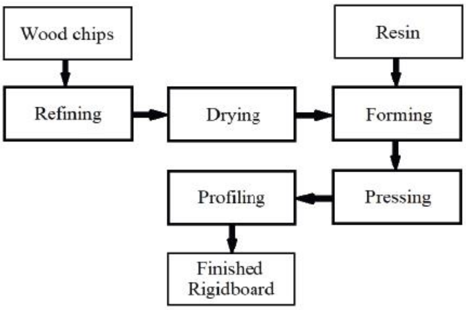

Fig. 3. Simplified rigidboard manufacturing process [10].

The primary feedstock for manufacturing the new rigidboard is logging residues, mainly from coniferous trees, the dominant tree group harvested in Latvia. The logging residues used for the production of chips will especially be branches, smaller logs and possibly stumps that are not used in conventional production. It is assumed that all needles and other greenery will fall off or be removed from the feedstock while in storage and manufacturing. To produce fibreboard insulation panels, wood fibres of strong and uniform quality must be obtained. Although MDF and other fibreboard producers traditionally use roundwood as a raw feedstock, novel methods of cleaning and sorting waste wood or production residues from other woodworking industries have enabled alternative sources of wood materials on dedicated production lines [10]. A 2013 study about the chase characteristics of wood chips produced from logging residues concluded that wood chips produced from logging residues have a moisture content of 50 % and are suitable for use in small and medium size boilers [13]. It is assumed that the wood chips obtained from logging residue feedstock will be of sufficient quality to produce fibreboard panels.

The material balance of the new fibreboard insulation panel is shown in Table 1. Material density is assumed maximum for rigid board production from the BAT Reference Document for Wood-based Panels [10]. Material balance was chosen based on fibreboard and insulation board data from the Forest Product Conversion Factors document [14], assuming an increased bark and decreased wood content. The weight content of bark, binders and fillers, moisture and wood in one cubic meter of the finished insulation panel were calculated based on the chosen material density and material balance.

For the new fibreboard insulation material manufacturing process, the standard dry manufacturing process was chosen from the BAT Reference Document for the Production of Wood-based Panels [10], modified for rigid board production (Fig. 2).

TABLE 1. FIBREBOARD INSULATION MATERIAL BALANCE

	Content, kg/m^3	Balance, %	Source
Density	220	100	[10]
Bark	6.6	3	[14]
Binders and fillers	11	5	[14]
Moisture	13.2	6	[14]
Wood	189.2	86	[14]

It is assumed that the new plant would produce 300 000 m^3 of fibreboard insulation material annually, based on average plant capacities in the industry [10]. To calculate the specific amounts of heat and electric energy needed to produce one cubic meter of the material, existing insulation material manufacturing plant data was used. Assuming that an existing plant has an electrical capacity of 5 MW and a heat capacity of 10 MW [15] and operates for 8000 hours annually, the manufacturing plant would require 0.13 MWh of electricity and 0.26 MWh of thermal energy to produce one cubic meter of fibreboard insulation material. Energy consumption for the most energy-intensive manufacturing processes is shown in Table 2. The drying of the wood fibres consumes the most energy, mainly in the form of thermal energy, as the fibres need to be dried from a moisture content nearing 100 % to 5 %. The dryers also need to be ventilated, using mechanical ventilators that consume electricity. The second most energy-intensive process is refining the fibres, which requires powerful motors that consume the most electricity. Thermal energy is also needed for refining to supply hot steam for cooking and washing wood chips. The pressing of the fibreboard mat requires thermal energy in the form of steam and electricity for the press rollers; however, for the production of rigid board insulation, the energy consumption is minimised, as the temperature required is relatively low. Lastly, all other processes requiring electricity are grouped, such as chipping, sawing and profiling [10].

TABLE 2. ENERGY CONSUMPTION FOR PRODUCTION

Manufacturing process	Electricity, MWh/m^3	Thermal energy, MWh/m^3
Drying	0.03	0.16
Refining	0.08	0.08
Pressing	0.01	0.02
Chipping, sawing, profiling	0.01	–
Total	0.13	0.26

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. Many different technical standards for Life Cycle Analysis (LCA) with other methods and approaches for carbon accounting. Still, in this case, only standards relevant to forest-based building materials and biogenic carbon were used. The standards used can be grouped into those that deal only with building materials (ISO-21930, EN-15804, CEN/TR-16970, EN-16485) and those which cover all products (PAS-2050, ISO/TS-14067, PEF). The standards can also be distinguished by geographical coverage, as some are international standards (ISO-21930, PAS-2050, ISO/TS-14067), and others are specific to Europe (EN-15804, CEN/TR-16970, EN-16485, PEF) and have stronger links to government regulation [16]–[18]. 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 [17]:

$$mCO_2 = \mathrm{m_{dry}}(\mathrm{timber}) \cdot \mathrm{C}_f \cdot \frac{m.mCO_2}{m.m_\mathrm{C}}, \tag{1}$$

where

mCO_2	mass of CO_2 sequestered, $kgCO_2$;
$m_{dry}(\mathrm{timber})$	dry weight of timber in the finished product, kg;
C_f	percentage of carbon in dry matter (for timber = 0.5);
$m.mCO_2$	molecular mass of CO_2 = 44 g/mol;
$m.m_C$	atomic mass of carbon = 12 g/mol.

By substituting the masses of carbon and CO_2, Eq. (1) becomes:

$$mCO_2 = m_{dry}(\mathrm{timber}) \cdot 0.5 \cdot \frac{44}{12} = m_{dry}(\mathrm{timber}) \cdot 1.833\,, \tag{2}$$

where mCO_2 is the mass of CO_2 sequestered in the finished product and $m_{dry}(\mathrm{timber})$ is the dry weight of timber in the finished product.

Only the CO_2 sequestered from the wood and bark content for 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 fibreboard 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. Indeed, producing heat and power from the most environmentally friendly renewable sources would be the best way to minimise emissions from manufacturing. However, this may not always be the most technologically and economically viable option. Thus, energy production for product manufacturing needs to be assessed from an environmental point of view while considering the technological and economic aspects. Three energy production scenarios were evaluated based on the proposed manufacturing plant capacity of 5 MW electrical capacity and 10 MW heat capacity [16], current trends in the sector and possible future technologies. Technological, economic and environmental data for the three proposed scenarios are shown in Table 3. The capacities of the energy production plants were chosen according to the required minimum heat capacity of the manufacturing plant of 10 MW, as all the process heat needs to be produced on-site to meet heat and steam requirements. The electrical power of the energy production plant can be lower than the electrical demand of the manufacturing plant, as electricity can also be supplied from the grid. The first proposed scenario is to produce heat and power with a biomass combined heat and power (CHP) plant, which would use wood chips as fuel. The chosen CHP technology is a wood chip boiler combined with a steam turbine. The second proposed scenario is a natural gas CHP plant with a gas turbine technology well suited for industrial processes. The third proposed scenario is a wood biomass combustion plant (CP) producing only thermal energy, using wood chips as fuel, combined with Solar Photo-voltaic (PV) panels for electricity production.

To evaluate environmental impacts, five different emission values were considered for each scenario: NO_X (nitrogen oxides), CO (carbon monoxide), VOC (volatile organic compounds), PM (particulate matter) and CO_2 (carbon dioxide).

TABLE 3. TECHNOLOGICAL, ECONOMIC AND ENVIRONMENTAL PARAMETERS OF PROPOSED ENERGY PRODUCTION SCENARIOS

Parameter	Wood biomass CHP	Natural gas CHP	Wood biomass CP + PV panels	Sources
Electrical capacity, MWe	5	7.5	4	[19], [20], [21]
Thermal capacity, MWth	12	10.7	12	[19], [20]
Electrical efficiency, %	25	29.2	–	[20], [22]
Thermal efficiency, %	60	41.4	85	[20], [22]
Total efficiency, %	85	70.6	85	[20], [22]
Capital costs, EUR/kW[a]	3310	1510	965[b]	[23]
O&M costs, $\%_{CAPEX}$	2	2.5	2[b]	[23]
Fuel cost, EUR/MWh	25	81.2	25	[24], [25]
NO_X emissions, g/MWh[c]	29	27	9.1	[20], [26]
CO emissions, g/MWh[c]	8	31.5	2.5	[20], [26]
VOC emissions, g/MWh[c]	0	27	0	[20], [26]
PM emissions, g/MWh[c]	44	0	13.6	[20], [26]
CO_2 emissions, kg/MWh[d]	0	202	0	[27]

[a] Based on the electrical capacity for CHP and thermal capacity for CP

[b] Does not include the cost of PV panels

[c] Applies to electricity produced for CHP and thermal energy for CP

[d] Applies to both electrical and thermal energy produced

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. Still, they are recalculated according to the thermal capacity of the combustion 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.

The capital costs and O&M costs for the Solar PV panels are chosen according to the peak capacity of Solar PV panel installation. 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 [21].

A multicriteria analysis using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method compares the three energy production scenarios. Using the TOPSIS method, the proposed scenarios or alternatives are evaluated for the ideal possible solution. The alternative that is the closest to the ideal solution is considered to be the best scenario [28]. 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 chosen for the analysis are shown in Table 4. The values of the criteria were calculated using data from Table 3 and applied to the manufacturing plant's selected electrical and thermal energy demand parameters, with the annual plant production capacity of 300 000 m^3 of fibreboard insulation material. The criteria values were calculated relative to one cubic meter of the finished product.

To perform the multicriteria analysis, the criteria weights need to be determined. The criteria weights were determined using the Analytical Hierarchy Process (AHP) method [28]. The criteria were first ranked in importance, prioritising economic and technological criteria, and then ranking the environmental criteria by their global warming potential. The weights of each criteria were then determined according to their rank, consequently comparing them to each other.

TABLE 4. CHOSEN CRITERIA FOR THE MULTICRITERIA ANALYSIS

Technological criteria	Economic criteria	Environmental criteria
Fuel energy content, GJ/m^3	Capital costs, EUR/m^3	NO_X emissions, g/m^3
	Fuel costs, EUR/m^3	CO emissions, g/m^3
	O&M costs, EUR/m^3	VOC emissions, g/m^3
	Bought/sold electricity, EUR/m^3	PM emissions, g/m^3
		CO_2 emissions, kg/m^3

With the obtained criteria weights, the results of the multicriteria analysis were calculated. The result is shown as a relative closeness coefficient to the ideal solution. The results can have a value ranging from 0 to 1, with the ideal solution being a value of 1. The closer the coefficient of a proposed alternative is to the maximum value of 1, the closer it is to the ideal solution.

3. RESULTS

The amount of stored biogenic CO_2 in the new fibreboard insulation material for the eight different accounting standards is shown in Table 5. The stored amount has been calculated for one cubic meter of the new fibreboard insulation material.

TABLE 5. STORED BIOGENIC CO_2 DEPENDING ON ACCOUNTING STANDARD

Technical standard	Stored CO_2, kg/m^3	Source
EN-15804 (2012)	359	[18]
ISO/DIS-21930 (2015)	251	[29]
EN-15804 (2012) +A1:2013	359	[18]
CEN/TR-16970 (2016)	359	[18]
EN-16485 (2014)	359	[18]
ISO/TS-14067 (2013)	90	[30]
PEF v2.2 (2016)	90	[30]
PAS-2050 (2011)	291	[31]

For standards EN-15804 (2012), EN-15804 (2012) +A1:2013, CEN/TR-16970 (2016) and EN-16485 (2014) the calculated amount of stored CO_2 is the same, as they are all based om the same standard of EN-15804 (2012) and assume that the amount is calculated with the formula shown in Eq. (2), with no further elaboration. ISO/TS-14067 (2013) and PEF v2.2 (2016) standards are based on the previous ISO-14040/44 standard for LCA, and do not differ in calculating the stored CO_2.

Standards-based on the EN-15804 standard offer the highest amount of CO_2 stored in one cubic meter of the product – 359 $kgCO_2/m^3$, while the lowest amount of CO_2 stored can be attributed to standards based on the previous ISO-14040/44 LCA standard – 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 multicriteria analysis 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 multicriteria analysis of three different energy production scenarios are shown in Fig. 4.

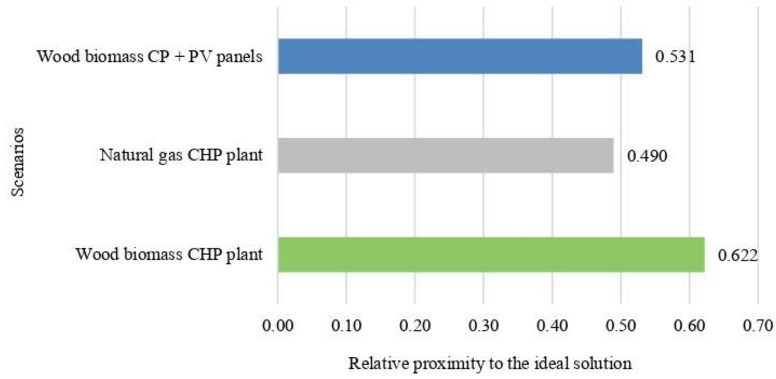

Fig. 4. Multicriteria analysis results.

The results of the multicriteria analysis show that the best scenario for energy production for the manufacturing plant is the wood biomass CHP plant (0.622). In second place are the wood biomass combustion plant and Solar PV panel scenario (0.531), barely beating out the natural gas CHP plant scenario (0.490). While currently, the multicriteria analysis shows that the fossil resource use scenario of natural gas is relatively close in valuation compared to the renewable resource use scenarios of wood biomass, it is evident that the evaluation of the natural gas CHP plant scenario could decrease in the future, as the world moves to use more renewable resources. Nevertheless, the natural gas CHP plant scenario still needs to be reviewed and considered, so it can be clearly shown that there are better renewable resource alternatives, which are the wood biomass CHP and combustion plants. To emphasise this further, 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. This, in turn, could significantly impact the evaluations of the different energy production scenarios, possibly increasing the assessment of the renewable energy source scenarios to mark them as the clear favourite over fossil resource use.

4. Conclusion

This study proposed a new possible wood fibreboard insulation material product made from a currently underutilised wood resource – logging residues. The material balance of the new product was presented, along with the manufacturing technology, manufacturing plant capacity and energy resource demands. The possible amount of CO_2 stored in the new product was calculated and reviewed using eight standards and their methods for biogenic carbon accounting.

The amount of stored CO_2 in the material varies considerably depending on the accounting method. Ideally, one of the eight possible standards should be chosen and prioritised. If no standard can be selected, an average value of stored CO_2 calculated from all eight standards could be proposed.

As the single largest source of emissions for the manufacturing of the new product is energy production, different energy production scenarios were analysed based on current trends in the industry. The scenarios were analysed regarding technological, economic, and environmental performance. Renewable energy scenarios should be considered a priority. However, fossil resource use was also considered, as the technical and financial benefits might outweigh the environmental disadvantages.

Three energy production scenarios were analysed: wood biomass combined heat and power (CHP) plant, a natural gas CHP plant and a standalone wood biomass combustion plant combined with solar photo-voltaic (PV) panels. The analysis results show the wood biomass CHP plant as the best scenario for energy production for the new manufacturing plant. However, the other scenarios are relatively close in evaluation.

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PAPER 8. CALCULATION OF GREENHOUSE GAS SAVINGS: SWITCH FROM ELECTRICITY PRODUCTION TO BIOMETHANE. CASE STUDY

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Calculation of Greenhouse Gas Savings: Switch from Electricity Production to Biomethane. Case Study

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Abstract **– Greenhouse gases are mainly comprised of carbon dioxide. In 2021, anthropogenic CO_2 emissions in the atmosphere have risen to 37.9 Gt, a 60 % increase from the levels observed in 1990. The production of high-value products using CO_2 can contribute to decreasing atmospheric CO_2 levels and advancing the objectives of the Green Deal. In Latvia, biofuel–biomethane production may also present a viable solution. Diversifying the energy sector, which can benefit the country's economy, is another advantage of this scenario. The study examines the transformation of a Latvian biogas production facility, which shifts towards producing biomethane as its final product. The study also involves the computation of greenhouse gas emission reductions resulting from utilizing biomethane instead of biogas in the network.**

Keywords **– Biogas; biomethane; GHG; GHG calculation; fuel; Latvia.**

1. Introduction

Global warming and climate change are caused by greenhouse gases (GHGs). This problem is one of the most severe problems of our time. Greenhouse gases are a range of gases such as carbon dioxide (CO_2), methane (CH_4), nitric oxide (N_2O), as well as hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride (SF_6). Among them, carbon dioxide is the major. Adding to the complexity is the fact that CO_2 is an integral part of almost any technological process due to the use of fossil fuels [1]–[3].

In 2015, an agreement was adopted, the purpose of which is to fight climate change [4]. The main goal of the European Union is to become ultimately carbon neutral by 2050, with an intermediate goal of reducing greenhouse gases by at least 55 % by 2030 [5]. Such a task requires changes in many sectors, including the energy sector. According to the IEA report [6], in 2021, CO_2 emissions accounted for 89 % of total greenhouse gas emissions in the energy sector. Switching from fossil energy sources to renewable ones can reduce the share of carbon dioxide. Implementing CO_2 capture and/or use systems in the industry could also potentially benefit total emissions [7], [8]. As stated [8], CCS and CCU technologies can reduce carbon emissions by 20 %.

Two main ways of using carbon dioxide can be distinguished – its conversion into various products (for example, plastic [9], [10], and its use directly without modification [3]. Unlike using carbon dioxide directly, converting it is a more attractive option, as it allows getting valuable products, such as new chemical compounds (like carbon monoxide), as well as fuel

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[11], [12]. However, despite the opportunity to obtain a valuable product, converting carbon dioxide requires energy, which already creates CO_2 in itself [3].

Biomethane is a renewable gas that can be obtained from biogas purification (depending on the system, biogas can contain ~50 % methane (CH_4), which is classified as low-grade biogas) [13]. The purification process involves the removal of carbon dioxide, leaving pure methane. The resulting CO_2 is of sufficient purity to be sold or redirected to other industries (e.g., greenhouses, pharmacy, etc.), thus promoting CCU technologies. At the same time, increasing the CH_4 content in the mixture raises the calorific value of the gas, making fuel much more valuable. The leading technology for CO_2 removal is Pressure Swing Adsorption (PSA), which working principle is based on adsorption differences of components and reagents [13], [14]. Biomethane has characteristics similar to fossil natural gas, making it a potential substitute for this fuel. An additional plus is the ability to use the same equipment and infrastructure, as well as the 'compatibility' of these two gases – they can be safely mixed [15]–[18].

Latvia already has everything necessary for the development and further production of biomethane. The first biogas stations appeared in the country in the 1990s, and their main resource is biomass and agricultural waste. As of 2019, 53 biogas production stations were registered in the country; however, several stations were closed due to several financial and political decisions [19].

1.1. Advantages of Biomethane

Even though, at the moment, natural gas occupies up to a quarter of the world energy resource market [20], it has the lowest carbon footprint. The importance and necessity of other low-carbon gases are also increasingly recognized. Such gases can be biomethane produced in anaerobic processes, syngas, and even low-carbon hydrogen. The current production rate and the prices for the mentioned types of gas show the importance of their production in the future. Although the benefits of biomethane production often come down to financial considerations, it is essential to remember that biomethane production is also beneficial from an environmental and sustainability point of view, as the carbon footprint that is left behind the biomethane is much lower than it is for more conventional types of fuel [16], [21, [22].

Biogas and biomethane are both renewable gases that have the potential to help reduce greenhouse gases. Using biomethane in a network created for natural gas and its subsequent replacement does not require additional financial investments or the development of new and/or other infrastructure. The existing gas transport network in Latvia can already be used for biomethane. This fact is a critical condition in the fight against the reduction of emissions and decarbonization of the gas sector, which, in addition, can provide an affordable price for the consumer and bring diversification into the energy sector. Another advantage of biomethane is that it can be stored and produced permanently and constantly. This fact will balance intermittent energy from other renewable energy sources, such as windmills [23]–[26]. As a renewable energy source, biomethane can positively contribute to dealing with climate change. Reducing anthropogenic emissions is a complex task; therefore, every decision to reduce our impact on the climate is significant and tangible in the long term [3].

1.2. Carbon Cycle

Sustainable agriculture and methane production are closely linked to the carbon cycle and sustainable resource and energy management. During biogas production, digestate is created – a by-product of production- a valuable organic substrate rich in nutrients [27], [28]. Unlike the raw materials used in biogas production, digestate can be used immediately as an organic fertilizer in the agricultural industry. Additionally, using such a fertilizer promotes the reuse of nutrients, returning them to the soil for enrichment and restoration and, thus, the replacement of mineral fertilizers [29].

Depending on the resource used, the biogas produced at the plant can contain up to 60 % biomethane. The remaining 40 % are products in the form of carbon dioxide [30].

Setting up the process correctly is essential to purify biogas completely of impurities like water and sulfides. These measures help achieve biomethane's highest quality and performance [31]. The use of carbon dioxide is the last step in the carbon cycle – a process that starts with the use of CO_2 in plants, which then becomes a resource for biogas production and is released to become a resource for the growth of new plants.

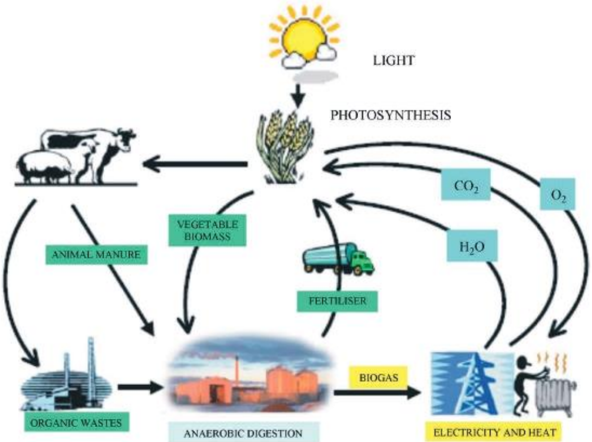

Fig. 1. Carbon cycle principle [32].

The European Union initiative [33] indicates the need for sustainable use of natural resources to increase efficiency in transitioning to a cyclical economic system through cooperation (synergy) of various sectors. Facilitating the policies and levers of the sectors involved can also positively impact the effectiveness of the implementation of a low-carbon economy, the use of renewable energy, efficiency measures, etc. Because biogas is produced from organic waste, this production complies with the basic principles of the circular economy (and the economy of circular energy) [34]. Biogas can be produced not only from waste from the agricultural sector but also from household and industrial waste. Additionally, wastewater can also be used as a resource, increasing its added value [35].

2. METHODOLOGY

The purpose of this paper is to analyse the Biogas plant's transition from biogas to the production of biomethane and its further implementation in the natural gas grid. The study contains calculations of this transition – GHG savings, considering the resource heterogeneity. This work did not account for the distance to the grid injection point. It is also assumed that the plant uses the Pressure Swing Adsorption (PSA) method for the transition process, as it is effective and suitable for working with gas mixtures generated by non-homogenous feedstock [36].

2.1. Biogas Plant Case Study

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 (Fig. 2).

Fig. 2. Region of the location of the Biogas Plant [37].

According to [38] and a personal interview with the biogas station manager, in 2021, the station used just over 57 thousand tons of substrates. In total, 13 substrates were involved in the production – milk whey, sludge, chicken manure, beer yeast, grass silage, immature grain crops silage, maize silage, and spoiled grains (Table 1). 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.

TABLE 1. SUBSTRATES AND THEIR QUANTITIES USED IN THE BIOGAS PLANT CASE STUDY IN 2021

Substrate	Amount, t/year	Methane yield, Nm^3/t [38]
Sediments of flotation from milk powder factory	3982.7	682.7
Milk whey	16 829.78	36.9
Sludge	8852.2	47
Chicken manure	5419.3	55.4
Beer yeast	169	505.8
Immature grain crops silage	852.4	54.6
Maize silage (2021)	15 258.3	106
Maize silage (2020)	3 602	106
Maize silage (2019)	12.3	106
Grass silage (2021)	803.4	100
Grass silage (2020)	612	100
Grass silage (2019)	513.4	100
Spoiled/immature grains	72	122.2
TOTAL	57 050.6	

2.2. GHG Savings Calculation

The calculation of greenhouse gases was carried out based on Directive 2018/2001/EU (REDII) [39], [40]. This directive is a continuation of REDI 2009, which sets out methods for controlling the sustainable and ecological production of biofuels. Additionally, a network of stakeholders, such as producers and consumers, has been established within REDI. To participate in such a network, each participant must obtain certification from REDcert and ISCC [41]. REDcert, in turn, is a quality assurance and assessment scheme for indicators such as sustainable production, traceability of documentation, etc. REDcert is accepted throughout Europe [42].

There are two ways to calculate the amount of greenhouse gases saved – actual value and default value-based [43]. 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 work.

Eq. (1) shows the calculation of emissions in case of co-digestion of various substrates in biomethane production from biogas:

$$E = \sum_{1}^{n} S_n \cdot (e_{ec,n} + e_{td,\text{feedstock},n} + e_{l,n} - e_{sca,n}) + e_p + e_{td,\text{product}} + e_u - e_{ccs} - e_{ccr} \,, \tag{1}$$

where

- E Total amount of emissions from the biomethane production (before energy conversion), kg CO_2eq/ton;
- S_n 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), g CO_2eq/MJ final product;
- $e_{td,\text{feedstock},n}$ Amount of emissions from the transport of feedstock n to the digester, g CO_2eq/MJ final product;
- $e_{l,n}$ Annual emissions from carbon stock changes due to land usage for feedstock type n, g CO_2eq/MJ final product;
- $e_{sca,n}$ Emissions savings from improved agricultural management of feedstock type n, g CO_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, g CO_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, g CO_2eq/MJ final product;
- e_{ccr} Emission savings from carbon capture and replacement, g CO_2eq/MJ final product

Parameters e_{ec}, e_t, e_p, and e_u are calculated according to Eq. (2):

$$e_{ec}, e_{td}, e_p, e_u = \frac{\sum \text{amount of material input} \cdot \text{Emissions Factor of the material}}{\text{Yield or quantity of the material}} \tag{2}$$

Eqs. (1) and (2) are the basis for the following calculations. Even though parameter e is calculated in [g CO_2/MJ of the final product (CH_4)], it is also recommended to calculate it per mass of the intermediate product (as [g CO_2/kg V_{product}]) and only at the end allocate the parameter to the final product.

3. RESULTS

Having the necessary data from a biogas production station, it is possible to calculate the greenhouse gas emissions generated by the station, as well as how much emissions will be saved if, instead of biogas, the station produces methane for its subsequent use in the city's power grid. Based on [43], a similar calculation was made for the observed Biogas Plant.

3.1. Calculation of Emissions Parameters

The $e_{ec,n}$ parameter only applies to maize silage, grass silage and immature grain crops. According to [44], the substrate with the least influence on the result may not be considered at this calculation stage, so substrate 'spoiled/immature grains' is neglected.

Table 2 lists the values for maize silage [45] that are needed to calculate the parameter e_{ec} (Eq. (2)). Similar calculations should be made for each substrate used in production. All values (emission factors, heating values, etc.) are taken from the European Commission schemes [45], [46].

TABLE 2. VALUES FOR THE MAIZE SILAGE [45], [46]

Substrate: Maize Silage	Value	Emission Factor
Seeds	30 kg/ha year	0.32 $kgCO_2eq/kg$
N fertiliser (mineral)	90 kg/ha year	6.41 $kgCO_2eq/kg$
N fertiliser (digestate)	10 kg/ha year	0.0075 $kgCO_2eq/kg$
CaO fertiliser	0 kg/ha year	0.89 $kgCO_2eq/kg$
M2O field emission	–	5.6 kgN_2O eq/ha year
Pesticides	NA	13.9 $kgCO_2eq/kg$
Diesel (machinery)	11 764.7 L/ha year	3.14 / 2.1 $kgCO_2eq/kg$
Maize yield (fresh matter)	37 820 kg/ha year	–

Thus, the three main substrates have the following effect in $kgCO_2eq$ per one kilogram and one ton of fresh matter (FM):

TABLE 3. THE E_C PARAMETERS FOR THE MAIN SUBSTRATES

Substrate	e_{ec}, $kgCO_2eq/kg$	e_{ec}, $kgCO_2eq/t$ FM
Grass silage	0.104	103.7
Immature grain crops	0.081	81.2
Maize silage	0.067	67.4

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 [47].

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}, $e_{sca,n}$. During the period under review, no improvements or upgrades were made to the agricultural feedstock management system at the station, and no CO_2 capture and storage system was installed.

In turn, the $e_{td,\text{ feedstock},n}$ parameter shows the emissions from resource transportation to the digester and is calculated by Eq. (3):

$$e_{td,\text{feedstock},n} = \frac{(d_1 \cdot f_1) + (d_e \cdot f_e) \cdot EF}{\text{Amount of transported substrate}} \tag{3}$$

where

d_1 Distance travelled while loaded, km;

d_e Distance travelled while empty, km;

f_1 Fuel consumption loaded, L/km;

f_e Fuel consumption empty, L/km.

Biogas Plant works with different substrates; therefore, the parameter must be calculated for each. The type of fuel used should also be considered since the emission factor (EF) depends on it. For diesel, for example, the EF is 3.14 $kgCO_2eq/l$ (Table 4).

TABLE 4. SUBSTRATE TRANSPORT PROCESS

	Value	Unit
The volume of transported biomass	5491.25	t
Distance (loaded)	4	km
Distance (empty)	4	km
Fuel consumption (loaded)	0.41	L/km
Fuel consumption (empty)	0.24	L/km

Having data on logistics and using Eq. (3), 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 equals 1.96 $kgCO_2eq/t$.

3.2. Emissions from Processes 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 – e_{p1}, it is required to know the amount of energy spent on biogas production, as well as the loss of methane (Table 5).

TABLE 5. MAIN PROCESSES ON THE PLANT AND THEIR VALUES

	Value	Unit
Electricity	11 619 000	kWh/year
Process heat	11 325.58	MJ/year
Methane yield	5 621 708	Nm^3/year
Methane loss	562 170.8	Nm^3/year
Digestate	43 000	t/year

According to RED and ISCC certification systems [43], [48], if a special gas-tight lid for storing digestate is installed at the biogas station, the loss of methane is reduced and can be assumed to be ~1 %. These covers are installed at the observed Biogas Plant, so in further calculations, methane losses will be taken as 1 %.

Each resource used – electricity and heat – also has its own emission factor (Table 6):

TABLE 6. EMISSION FACTOR FOR ELECTRICITY AND HEAT USAGE

Input	Emission Factor	Unit
Electricity mix	0.19	$kgCO_2eq/kWh$
Heat (CHP Unit)	0.61	$kgCO_2eq/MJ$
Methane	23	$kgCO_2eq/kgCH_4$

Using Eq. (4), we can calculate the parameter e_{p1}:

$$e_{p1} = \frac{(\text{Electricity} \cdot EF_E) + (\text{Heat} \cdot EF_h) + (\text{Methane loss} \cdot EF_m)}{\text{Total methane yield}}, \tag{4}$$

where

EF_E Emission factor from electricity, kg CO_2eq/kWh;
EF_h Emission factor from heat, kg CO_2eq/MJ;
EF_m Emission factor from methane, kg CO_2eq/kg CH_4.

Substituting the required values from Table 6 shows that 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 (e_{p2}). Biogas processing is the last stage of its production. It is this stage that includes the transfer of biogas to biomethane. Similar to the previous step, emissions from processing biogas to biomethane should take the biomethane yield per year, regardless of the amount of biomethane subject to further certification [43].

For the Biogas Plant, the biogas treatment process requires the following investments (Table 7):

TABLE 7. REQUIRED INPUT FOR THE BIOGAS TREATMENT

	Value	Unit
Methane input	5 621 708	Nm^3/year
Methane slip (in PSA)*	1–5	%
Methene loss	562 170.8	Nm^3/year
Electricity**	994 462.8	kWh/year
Process heat	0	MJ/year
Biomethane output***	4 735 537.2	Nm^3/year

Note: *PSA – Pressure Swing Adsorption, biogas treatment technology
**0.21 kWh/m^3 multiplied by biomethane output;
*** Methane input minus the 1 % of methane loss in the biogas plant

Thus, the parameter e_{p2} is calculated by the Eq. (5):

$$e_{p2} = \frac{(\text{Electricity for } PSA \cdot EF_E) + (\text{Heat for } PSA \cdot EF_h) + (\text{Methane loss} \cdot EF_m)}{\text{Biomethane output}} \tag{5}$$

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 (Table 8).

TABLE 8. REQUIRED ENERGY INPUT AND EMISSION FACTOR FROM THE DISTRIBUTION

Input of energy	**Value**	**Unit**
Electricity (transport in the natural gas grid)	0.003	kWh/m^3
Heat process	0.058	MJ/m^3
Electricity (compression in the filling station)	0.164	kWh/m^3
Biomethane distribution, emission factors		
Electricity mix	0.192	kgCO$_2$eq/kWh
Heat process	0.067	kgCO$_2$eq/kWh

Using the data from Table 8, it is possible to calculate the emissions themselves from gas transportation through the network:

$$e_{td,\text{product}} = (ET_{\text{ng}} \cdot EF_{\text{e}}) + (HT_{\text{ng}} \cdot EF_{\text{h}}) + (EC_{\text{st}} \cdot EF_{\text{st}}), \quad (6)$$

where

ET_{ng} Electricity for biomethane transport in the natural gas grid, kWh/m^3;

EF_{e} Emission factor for electricity for biomethane transport in the natural gas grid, kWh/m^3;

HT_{ng} Heat for biomethane transport in the natural gas grid, MJ/m^3;

EF_{h} Emission factor for heat process for biomethane transport in the natural gas grid, kgCO$_2$eq/kWh;

EC_{st} Electricity for biomethane compression in filling station, kWh/m^3;

EF_{st} Emission factor for electricity for biomethane compression in filling station, kWh/m^3.

Substituting all the data into the formula, we get that the Biogas Plant for the transportation and compression of biomethane at the station produces 0.036 kgCO$_2$eq/m^3. If there is no compression, then $e_{td.\text{product}}$ = 0.043 kgCO$_2$eq/m^3.

3.3. Substrate Allocation

An important calculation step is substrate allocation. Many different substrates are used in biomethane production – each of them must be analysed separately for the considered period. It is recommended for biogas producers to write down how much methane can be obtained from each substrate.

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.

At this stage, the first step is to multiply the amount of substrate by the percentage of losses (10 %), thus obtaining the total amount of substrate according to the estimated losses. Further, using Eq. (7), the proportion of methane in each type of substrate is calculated [45], [46]:

$$\text{Share of CH}_4\text{ yield} = \frac{\text{Amount of substrate after 10\% loss} \cdot \text{CH}_4 \text{ yield of the substrate}}{\text{Total CH}_4 \text{ yield (calculated) in the biogas plant}} \cdot 100\% \quad (6)$$

Thus, the following values are typical for the substrates used at the Biogas Plant (Table 9):

TABLE 9. METHANE YIELD FOR EACH KIND OF USED SUBSTRATE [45], [46]

Substrate	Amount (before losses), t/year	Input after losses, t/year	Methane yield, Nm^3/t FM [44], [49]	Share of methane yield in each substrate, %
Sediments of floatation milk powder factory	3982.7	3584.4	628.7	36.5
Milk whey	186 829.7	15 146.7	36.9	9.1
Sludge	8852.2	7966.7	47	6.1
Chicken manure	5491.3	4924.1	55.4	4.4
Beer yeast	169	152.1	505.8	1.3
Immature grain crops sludge	852.4	767.2	54.6	0.7
Maize silage (2019)	15 258.3	13 732.5	106	23.6
Maize silage (2020)	3602	3241.8	106	5.6
Maize silage (2021)	12.3	11.07	106	0.02
Grass silage (2019)	803.4	723.1	100	1.2
Grass silage (2020)	612	550.8	100	0.9
Grass silage (2021)	513.4	462.1	100	0.7
Spoiled/immature grains	72	64.8	122.2	0.1
Total methane yield calculated, Nm^3		6 179 378.3		

3.4. 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 according to REDcert and ISCC) [43], [48], [50]:

$$\text{Total usable amount of biomethane} = \text{Proportion of methane yield} \times \text{Total biomethane output} \qquad (7)$$

For the Biogas Plant, each type of substrate can produce the following amount of biomethane (Table 10):

TABLE 10. TOTAL USABLE AMOUNT OF BIOMETHANE PER EACH SUBSTRATE

Substrate	Share of methane yield in each substrate, %	Total usable amount of biomethane, Nm^3/year
Sediments of floatation milk powder factory	36.47	1 726 965.09
Milk whey	9.05	428 320.94
Sludge	6.06	286 956.36
Chicken manure	4.43	209 820.52
Beer yeast	1.25	58 956.61
Immature grain crops sludge	0.68	32 099.85
Maize silage (2019)	23.56	1 115 525.28
Maize silage (2020)	5.56	26 339.83
Maize silage (2021)	0.02	899.25
Grass silage (2019)	1.17	55 411.36

Grass silage (2020)	0.89	42 210.30
Grass silage (2021)	0.75	35 409.75
Spoiled/immature grains	0.13	6068.35

After acquiring the values of the parameters e_{ec}, $e_{td,\text{feedstock},n}$, $e_{\text{p}1}$, $e_{\text{p}2}$ 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:

$$\text{Total emissions per m}^3\text{ biomethane} = \frac{(e_{ec} + e_{td,\text{feedstock},n} + e_{\text{p}1} + e_{\text{p}2} + e_{td,\text{product}})}{\text{Total usable amount of biomethane}} \tag{8}$$

Knowing that for the observed Biogas Plant, the sum of all parameters for all substrates is 25 246 762.29 $\text{kgCO}_2\text{eq/year}$, and the total amount of biomethane is 4 261 983.48 $\text{Nm}^3\text{/year}$, using Eq. (8) it has been determined that the total number of emissions is 5.92 $\text{kgCO}_2\text{eq/m}^3$.

According to REDII [40], greenhouse gas emissions from biomass-derived fuels must be expressed in grams of CO_2 equivalent per MJ of biofuel ($\text{gCO}_2\text{eq/MJ}$). For recalculation, the lower heating value of biomethane is used:

$$\text{Total emissions per MJ biomethane} = \frac{\text{Total emissions per m}^3\text{ of biomethane}}{\text{Heating value of biomethane}} \times 100 \tag{9}$$

The lower heating value of biomethane is 36 MJ/m^3, resulting in 16.45 $\text{gCO}_2\text{eq/MJ}$ emissions.

3.5. GHG Savings Calculation

The last step is to calculate the directly stored emissions from biomethane. According to the Directive of the European Union 2018/2001 [43], the Member States of the European Union have the right to produce only that biomethane, the greenhouse emissions of which do not exceed the established value of 24 $\text{gCO}_2\text{eq/MJ}$. This value is based on a fossil fuel comparator, E, as well as a minimum allowable emission retention value of 35 %.

Eq. (10) is used to calculate the stored emissions from biomethane:

$$\text{Saving} = \frac{(E_{\text{F}(t)} - E_{\text{B}})}{E_{\text{F}(t)}} \cdot 100\% \tag{10}$$

where

E_{B} Total emissions from biomethane, $\text{gCO}_2\text{eq/MJ CH}_4$;

$E_{\text{F}(t)}$ Total emissions from fossil fuel comparator, $\text{gCO}_2\text{eq/MJ}$.

In the case of the Biogas Plant, the number of emissions saved is 80.36 %. However, this value reflects the rate of 1 % loss. According to REDcert, PSA losses can be as high as 5 %. Thus, the smallest number of saved emissions is 76.34 %.

4. Conclusion and Discussion

In this paper, a Latvian Biogas Plant case study was carried out to determine the amount of emissions saved from biomethane production. The actual value method offered by REDcert was used for calculations. These calculations help determine the potential environmental benefits of switching from biogas production to biomethane.

All calculations were performed based on the rules of the method and took into account all the substrates used at the station, the main ones being maize silage, grass silage, sludge, milk whey, and manure. The calculations were based on standard resource data (i.e., emission factor), and therefore the technique is suitable not only for analysis

The calculations also considered the recommended assumption of 1–5 % losses in the PSA technology from using biomethane. At the minimum value, the losses of emissions savings for the plant amounted to 80.34 %, while the worst-case scenario (5 %) showed 76.34 % of GHG savings.

This method of calculation can be time-consuming since it is necessary to calculate the number of emissions for each substrate used. It is also required to strictly follow each step because skipping them can distort the final result.

According to the requirements of the European Union, specified in REDcert, starting from 2017, the conservation of emissions for biogas plants using a mixture of different substrates for production should not be less than 50 %. Otherwise, this project will not be considered successful. However, the Biogas Plant is an excellent example of a successful transition from biogas to biomethane. Thus, the station can become a carbon neutral project and part of the Decarbonized Regional Development projects aimed at reducing greenhouse emissions in Latvia.

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PAPER 9. CO-CREATING LOW-CARBON FUTURES: AN OPEN INNOVATION ROADMAP FOR REGIONAL CO_2.

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Co-creating low-carbon futures: An open innovation roadmap for regional CO_2

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ABSTRACT

The research develops an open innovation roadmap which enables Latvian regions to use carbon dioxide. The research combines stakeholder collaboration with spatial analysis and performance evaluation, environmental impact assessment, and economic feasibility studies. The roadmap evaluates several pathways to convert carbon dioxide into useful products. The research combines co-creative methods with multiple approaches, which the authors describe as a “tangle of threads” to integrate academic, industrial, governmental and civil society perspectives. The process allows for ongoing feedback while developing scenarios and strategic alignment to national and European sustainability goals. The assessment of five pathways revealed algal biomass, methanol, and ethanol production as the most sustainable options for carbon conversion, location flexibility, and economic viability. The roadmap functions as a regional planning instrument and a theoretical addition to open innovation principles. The research shows how collaborative governance combined with knowledge exchange enables the transformation of emissions into entrepreneurship through innovation clusters and carbon valorisation hubs. The model provides a transferable circular economy framework which can be scaled up for other regional contexts while establishing foundations for future living labs and policy experimentation platforms.

1. Introduction

The increasing pressure to fight climate change and meet strict decarbonisation objectives has pushed carbon capture, utilisation, and storage (CCUS) technologies into the core of worldwide sustainability approaches (Ding et al., 2023; Esiri et al., 2024; Gupta et al., 2023). The scientific community considers CCUS essential for carbon-neutral transitions because it minimises industrial CO_2 emissions while creating multiple opportunities to transform carbon into valuable resources (Daneshvar et al., 2021; Kim et al., 2019; Mon et al., 2024; Zheng et al., 2022). Effective CCUS technology deployment at scale needs more than technological solutions because it requires active collaborative ecosystems which unite scientific advancements with business requirements and societal goals (Storrs et al., 2023). Open innovation is fundamental to achieving this goal (Jiutian et al., 2022). This paradigm encourages organisations to look for ideas, technological solutions, and knowledge outside their internal boundaries, thus promoting sectoral collaboration and fast-tracking sustainable technology transfer while engaging diverse stakeholders (Fu, 2020; Oliveira-Duarte et al., 2021). Open-innovation ecosystems combine data and technologies to support the collaborative development of advanced CCUS solutions and to improve operational efficiency and market competitiveness. Through open innovation initiatives, academia, industry, and policy actors can collaborate to develop location-specific strategies for carbon management and utilisation, which helps bridge the gap between research and application (Marchesani and Ceci, 2025; Argente-Garcia et al., 2024). Open innovation is a directional tool for sustainable CCUS technology implementation in the local and global markets. Through open innovation platforms, knowledge spreads among disciplines, whereas developers create region-specific solutions that support circular economy-based carbon value chain development (Parker et al., 2024). Open innovation platforms allow rural actors, including local communities, farmers, and SMEs, to participate in decarbonisation initiatives by adapting current technologies or jointly developing new solutions. This approach accelerates innovation while simultaneously building better social approval and policy compatibility.

Current EU strategies demonstrate expanding awareness of the necessity of collective innovation networks between different stakeholders to fulfil the 2030 and 2050 carbon neutrality targets through documents such as the Sustainable Carbon Cycles Communication and the Net Zero

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Industry Act and Industrial Carbon Management Strategy (European Commission, 2021, 2024a, 2024b; European Union, 2024). Open innovation is essential for moving CCUS technology from isolated implementation to a comprehensive system-wide transformation by combining technology with social and market-based aspects. CO_2 transitioned from a wasteful resource to a beneficial feedstock for climate-smart manufacturing industries, supporting sustainable growth, regional resilience, and long-term climate commitment.

Reducing CO_2 emissions is an important issue that affects all regional and international levels. Existing measures to reduce CO_2 emissions primarily focus on actively using low-carbon technologies and renewable energy sources. Emission reduction measures in specific sectors, such as electricity and heat production and distribution and transport, are also widely used (Bilgili et al., 2024; Pata et al., 2024). Owing to higher CO_2 reduction efficiencies and costs, current direct CO_2 reduction options focus primarily on large CO_2 emitters, leaving out small and medium enterprises. This difference is especially evident in regions not covered by various national emission-reduction initiatives (Yu et al., 2023).

This research implements an open innovation framework, but other CO_2 valorization models exist in the academic literature (Huang and Zhou, 2025). Technology-push models focus on centralised research and development, in which innovation is led by scientific breakthroughs with limited stakeholder involvement (Nuñez-Jimenez et al., 2022; Mon et al., 2024; Kim et al., 2019). Closed innovation approaches focus on developing internal solutions while protecting intellectual property, resulting in delayed regional adaptation (Felin and Zenger, 2013; Andrade-Rojas et al., 2024). Market-based models that use carbon pricing and emissions trading systems create financial incentives, but do not include planning instruments or local community participation mechanisms (Saqib and Satar, 2021). Such approaches stimulate innovation but fail to recognize the fundamental characteristics of regional sustainability transitions. The open innovation framework used in this research includes diverse actor perspectives and co-creation processes to develop CO_2 valorisation pathways that are both technically feasible and socially grounded. This evaluation demonstrates how open innovation delivers superior benefits for regional carbon governance.

The increasing importance of CO_2 valorisation has emerged as a vital strategy to decrease emissions while advancing technological development across national and regional jurisdictions. CO_2 has transitioned from an unwanted industrial by-product to a valuable resource utilised by multiple industries (Kondaveeti et al., 2020). The conversion of CO_2 into synthetic fuels, polymers, and fertilisers creates new possibilities for decreasing carbon emissions while promoting technological innovation alongside economic expansion (Nwabueze and Leggett, 2024). Organisations can exchange knowledge beyond their usual limits through open innovation and bring in external concepts, technological solutions, and business approaches (Jekabsone and Anohina-Naumeca, 2024). The collaborative environment enables the fast testing of sustainable CO_2 valorisation pathways while promoting quick deployment (Miranda et al., 2023). Implementing CO_2 reuse models depends on multiple essential factors, including emission source location, characteristics, emission purity and volume, industrial site availability, regional economic and environmental factors, and market requirements. Adopting new technologies and existing process optimisation creates substantial opportunities to expand CO_2 usage in various industries (Ekemezie and Digitemie, 2024). Evaluating CO_2 usage potential requires interdisciplinary collaboration between established experts, practitioners, society, and scientists who bring new advances in the field (Aagaard-Hansen, 2007). The initial, unfamiliar stages of pre-treatment and processing rely on traditional practices, which scientists have enhanced through collaborative research and innovative developments made possible by open sectoral partnerships.

To address these possibilities, this study examines different scenarios for CO_2 valorisation by integrating methodologies such as Multi-Criteria Decision Analysis (MCDA), Social Life Cycle Analysis (S-LCA), Environmental Life Cycle Analysis (E-LCA), and Cost Effectiveness Analysis (CEA). It considers the essential stages for successful valorisation: Strengths, Weaknesses, Opportunities, and Threats Analysis (SWOT), society, entrepreneurs' willingness to pay (WTP), and establishing a supportive regulatory framework.

Applying open innovation principles, which combine efforts between academia, industry, policymakers and civil society, resulted in developing an innovative "tangle of threads" approach to identify optimal solutions for CO_2 valorisation, focusing on Latvia's primary CO_2 sources and their composition. This study explores the potential use of CO_2 as a resource, evaluated through multidisciplinary indicators encompassing geographical, technological, environmental, social, and economic dimensions. The method allows for joint knowledge creation between experts and external contributors while bringing fresh perspectives and practical solutions to the proposed solutions. Open innovation speeds up the deployment of effective CO_2 valorisation strategies through adaptive and inclusive decision-making processes. The novelty of this study is the development of a roadmap for decision-makers on how to use CO_2 in the regions of Latvia in the context of an open innovation ecosystem. The framework functions as a collaborative system that unites enterprises with policymakers, academic institutions, and civil society to support regional CO_2 valorisation pathway development from creation to testing to implementation. The roadmap enables sectoral knowledge sharing and participatory decision-making to validate solutions that work technically and socially.

2. Methodology

The authors of this study mapped out the complete CO_2 valorisation pathway 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.

Open innovation serves as a leading framework for sustainability transitions across sectors, yet requires evaluation through alternative approaches to CO_2 valorisation. Technocentric models concentrate on technological readiness and economic feasibility, while disregarding social, behavioural, and institutional elements, which are crucial for actual deployment. Market-driven approaches that use carbon pricing, emissions trading, and investment-based models focus on cost efficiency but tend to exclude structurally weaker regions and lack inclusive governance systems. National industrial strategies, such as state-led planning frameworks, provide policy coherence but face challenges with regional stakeholder engagement and limited adaptability. Mission-oriented innovation systems combine public-private resources to achieve common goals, but their rigid top-down structures limit both local experimentation and contextual adaptation. The open innovation ecosystem approach in this study combines scientific evaluation with stakeholder involvement and continuous learning to develop solutions for CO_2 valorisation, which are tailored to specific territories and are both technologically sound and socially acceptable.

The CO_2 Deal Roadmap methodological framework in Fig. 1 follows open innovation and co-creation principles. The roadmap follows a non-linear structure integrating multiple methodological tools into a dynamic ecosystem, enabling knowledge exchange between domains and sectors.

The ecosystem approach requires active participation from industry representatives and SMEs, academic institutions, municipalities, and civil society actors who contribute to all phases of the roadmap development. The stakeholders' contributions enable the identification of CO_2 sources and valorisation routes, evaluation criteria prioritisation, and

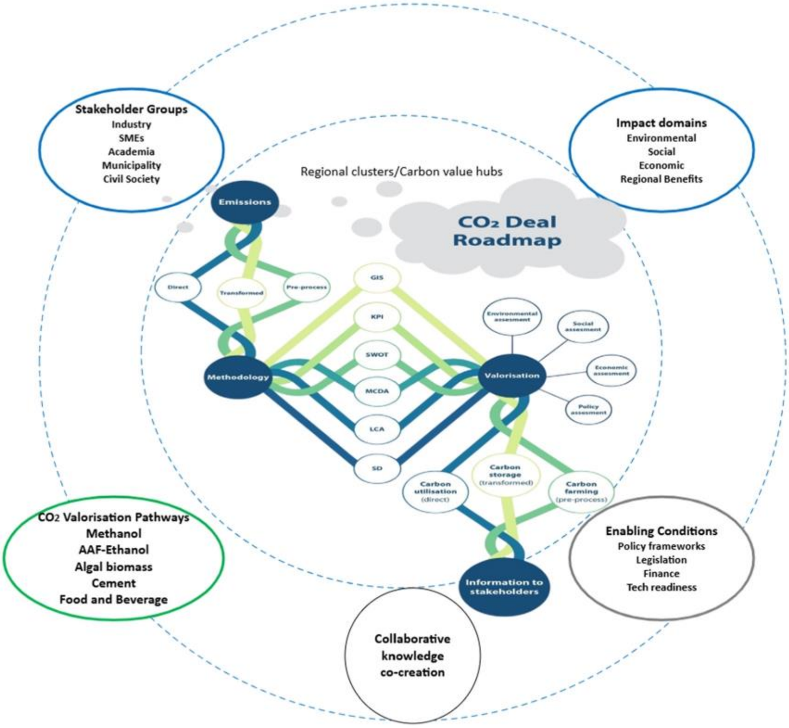

Fig. 1. Regional CO_2 valorization methodology.

decision-making model refinement. Through open innovation, external ideas and expertise can enter the system, while co-creation ensures solutions are developed with stakeholders instead of for them. The inclusive multi-actor approach connects scientific research to policy and practical implementation, resulting in customised regional strategies that meet technological readiness requirements and community needs. The roadmap 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 multi-criteria 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.

The qualitative coding method based on thematic analysis served to analyse data collected from participatory workshops and stakeholder consultations. Transcripts were imported into NVivo 14 and systematically coded using inductive and deductive approaches. The initial codebook consisted of predefined categories, which included technological feasibility alongside social acceptance, economic implications, and policy gaps. The initial categories were expanded through multiple readings to include new themes that stakeholders introduced. Two researchers conducted independent coding, which they later validated against each other to achieve intersubjective consistency and transparency. The researchers grouped the codes into larger thematic domains, which showed both common priorities and opposing viewpoints between different actor groups. The subsequent SWOT and Fuzzy Cognitive Logic Analysis (FCLA) analyses incorporated these codes to maintain stakeholder voices throughout decision-making models through quantitative and qualitative integration. The systematic coding method maintained stakeholder input throughout the modelling stages, which enhanced both analytical coherence and social relevance of the roadmap. The combination of methods strengthened the co-creation aspect of the roadmap while providing deeper insights into stakeholder priorities.

The development of an open innovation ecosystem is grounded in a consecutive multi-modelling approach that integrates (1) literature review, (2) Geographic Information Systems (GIS), (3) Key Performance Indicator (KPI) analysis, (4) MCDA, (5) SWOT analysis, (6) FCLA, (7) E-LCA, (8) S-LCA, (9) CEA, and (10) System Dynamics Modelling (SD). The open innovation ecosystem informed each step of this modelling sequence by incorporating stakeholder perspectives, enabling iterative roadmap refinement, and ensuring relevance to real-world needs. As a result, the outcome is a technically robust framework and a socially responsive tool to support informed decision-making on regional CO_2 valorisation in Latvia.

The selection process for CO_2 conversion pathways began with an evaluation of more than 20 options, which were identified through literature research and stakeholder workshops. The evaluation process reduced pathways through their regional applicability, technological maturity, and available data. The evaluation of shortlisted options, algal biomass, methanol, ethanol, urea, and synthetic methane, used a combined MCDA and E-LCA and S-LCA framework. The framework used economic indicators (CAPEX, OPEX) together with environmental indicators (GHG reduction potential, land/water use) and social indicators (job creation, public acceptance). The stakeholder scoring process helped to finalise the ranking, which resulted in the selection of algae, methanol, and ethanol as the top three pathways based on technical feasibility and sustainability impact.

The integration of co-creative methods with spatial and environmental analyses played a central role in translating abstract scenarios into practical planning tools. GIS supported the identification of high-potential siting zones based on CO_2 emission densities, infrastructure proximity, and land-use compatibility. Simultaneously, environmental assessments such as E-LCA and S-LCA evaluated trade-offs between ecological impacts and social acceptability. The roadmap delivers regionally tailored outputs through the integration of stakeholder feedback into spatial modelling layers and sustainability criteria. The roadmap provides location-specific deployment options together with sustainability-ranked valorisation pathways and actionable recommendations that match technical feasibility with community preferences.

The assessment methods operated within an open innovation system, bringing together researchers with industry partners, policymakers, and local communities. This systemic, participatory framework facilitated collaborative knowledge exchange, cross-sectoral sustainability evaluation, and co-creating adaptive CO_2 valorisation strategies aligned with environmental and socio-economic objectives. The open innovation approach also enables iterative feedback loops, enhances transparency in scenario selection, and promotes the co-development of technologies and policies.

The study's first phase included several activities, including a literature review on possible ways to valorise CO_2 and an analysis of global experiences and trends. In addition, European Member States' regional and national development plans were analysed to identify best practices in policy planning for CO_2 valorisation. The literature review was supplemented with data from statistical and national databases, and a map of CO_2 sources and potential consumers was created using ArcGIS (Oymatov et al., 2021). An analysis of the ratio of producers to consumers by region and possible options for CO_2 valorisation was carried out (Usmani et al., 2020), taking into account the geographical location of the sites (Park and Yang, 2020).

Research on projects funded by the Horizon 2020 program has served to establish KPIs (Angelakoglou et al., 2023; Wang et al., 2020). These indicators were established by analysing existing CO_2 application technologies and pilot projects. Different technologies and scenario evaluations depend on KPI as an effective tool (Lindig et al., 2024). These indicators can be adapted to a particular production area of interest and are based on parameters familiar to the start of the production phase. These factors aim to control and compare the energy consumption, potential savings, economic benefits of adopting certain technologies, and environmental impact of production. KPI development and analysis followed open innovation ecosystem principles by incorporating research institutions' active engagement with technology start-ups, industrial stakeholders, and regional public authorities (Choi et al., 2020; Urasova et al., 2024). The indicators gained relevance and applicability in real-world scenarios through this cross-sectoral collaboration, combining technical knowledge with entrepreneurial agility, market relevance, and policy considerations (Liu, 2021; Zulganef et al., 2022).

The SWOT analysis was the next phase to assess the CO_2 capture and utilisation possibilities within the Latvian territory. SWOT analysis sought to determine the evaluated development options' strengths, weaknesses, opportunities, and threats (Zhang et al., 2024). The FLCA, SWOT, and ArcGIS analyses were used to obtain more comprehensive results. FLCA, as an additional tool, helps identify the relationships and interdependencies between the factors, which makes it especially useful for analysing large and complex systems with multiple decision-making variables (Buah et al., 2021; Lo Cascio et al., 2018; Poczeta et al., 2020).

In a collaborative multi-stakeholder analysis, the MCDA method was used to determine the most suitable CO_2 usage scenario based on the available input data and key performance indicators to develop sustainable CO_2 utilisation pathways.

E-LCA examines human health, ecosystems, and resource utilisation, whereas S-LCA extends to social justice, legal compliance, affordability, and safety (Choe et al., 2023; Duval-Dachary et al., 2024; Larsen et al., 2022). This study assessed the environmental and social effects of methanol and SAF-ethanol production (referred to as ethanol in this study) using E-LCA and S-LCA. In parallel, other decision-making tools, such as MCDA and KPI, were used to assess CO_2 utilisation scenarios in food and beverage production, cement production, and algal biomass generation. The Life Cycle Assessment (LCA) framework did not include these three valorisation routes because of their non-comparability with bioenergy production scenarios. The E-LCA used a gate-to-gate approach, SimaPro Ecoinvent database, and ReCiPe Endpoint methodology (Huijbregts et al., 2016). This allows for a spatially sensitive assessment of specific production processes and their related CO_2 use. Similarly, S-LCA enabled a targeted comparison of social indicators, such as health, safety, accident rates, wages, and overall social value, using the SimaPro HotSpot database with the same methodological and boundary choices (Dekker et al., 2019; Rahmah et al., 2024; Dos Reis et al., 2024).

CEA also assessed the economic feasibility of CO_2 valorisation, which depends on technological maturity, electricity and fuel costs, the price and demand of the final product, and CO_2 capture costs. The capture cost can be between 14 and 23 EUR/t CO2 to 37–110 EUR/t CO_2 based on the enterprise and process type, whereas transportation costs by truck or pipeline can range from 110 to 138 EUR/t CO_2. CEA, such as LCA and S-LCA, has focused on methanol, ethanol, and algal biomass scenarios based on extensive literature (Azhari et al., 2022; Chiou et al., 2023; Pérez-Fortes and Tzimas, 2016; Sarwer et al., 2022).

A pre-process carbon utilisation case study in the agricultural sector was conducted to bridge theory with practice. Using system dynamics modelling, a scenario analysis was performed on a Latvian dairy farm that produces 4736 tons of milk annually. This case exemplifies how real-life operations can inform future carbon farming strategies and serve as a platform for multi-actor experimentation and living lab-style collaboration (Atzori et al., 2023; Bumbiere et al., 2023; Van Boxmeer et al., 2021; Van der Linden et al., 2020).

3. Results

3.1. Identification of regional CO_2 valorization hubs through ecosystem mapping

The first result of this open-innovation approach leads to the discovery of regional CO_2 "carbon value hubs." The CO_2 "carbon value hubs" represent areas where CO_2 sources and users operate together to enable direct CO_2 utilisation for new product creation or process optimisation. The approach combines industry and local planner input to create a strategy for rural area decarbonisation alongside regional economic development through innovation. Networked management of small-scale CO_2 emissions produces valuable resources that generate environmental and social advantages instead of creating obstacles. The analysis of Latvian CO_2 sources (e.g. energy plants and landfills) against CO_2 utilisation points (e.g. greenhouses and fish farms) showed potential "value spots" in north-east Kurzeme and north Riga near a boiler house and fish processing plant as well as western Zemgale with its biogas plant near a greenhouse. Developing hubs show how open innovation ecosystems link different types of actors because a landfill provides biogas to the energy sector, and greenhouses utilise biogas plant CO_2 emissions to increase their crop yields by 25–35 % (Ghiat et al., 2020; Sanjeev and Ramesh, 2006). The roadmap promotes a collaborative approach through cross-industry symbiosis, transforming single CO_2 sources into connected members of a regional CO_2 network.

3.2. Key performance indicators and scenario selection

Developing a complete set of KPIs is crucial for assessing CO_2 valorisation options from an open innovation perspective. The team created 47 general and 28 sector-specific KPIs that included technical efficiency, resource use, environmental impact, and socioeconomic factors based on Horizon 2020 project reports, literature research, and industry stakeholder input. The KPI development process was collaborative and included practical insights from companies and policymakers that reflected knowledge exchange within the ecosystem. Multiple CO_2 utilisation scenarios were evaluated using these KPIs to determine the ones that showed the most significant potential. Multiple CO_2 utilisation scenarios included established uses and new opportunities, which balanced established solutions and innovative approaches. Five core scenarios were evaluated for energy, fuel, industrial, and agricultural uses: (a) algal biomass cultivation in ponds and greenhouses depends on CO_2 for growth enhancement, (b) food and beverage applications (e.g. carbonation and refrigeration), (c) methanol production (fuel/feedstock via CO_2 hydrogenation or biogas conversion), (4) ethanol production (sustainable aviation fuel from CO_2-derived ethanol), and (5) cement curing enhancement (CO_2 mineralisation in cement production).

The scenarios were selected based on the literature, technology readiness, and stakeholder discussions to represent the sectors of regional interest. Combining bio-based (algae and agriculture) with industrial (cement and fuels) options follows an open innovation principle that enables knowledge from various industries to guide the roadmap. This approach supports immediate feasible solutions, such as established food industry applications and future-oriented transformative solutions, such as synthetic fuel manufacturing.

3.3. SWOT analysis and guiding insights

A SWOT analysis was carried out with inputs from regional stakeholders to identify the enablers and challenges for each CO_2 utilisation option. This exercise offered important information from business and policy perspectives and revealed several ecosystem insights. In a positive light, SWOT revealed some strengths, such as existing expertise in energy efficiency and the potential to create employment in rural areas and promote sustainable entrepreneurship through new CO_2 based industries. They mentioned that companies currently using CO_2 can decrease their dependency on external suppliers, which could translate into cost savings and local supply chain development. These points support the idea that a CO_2 valorisation ecosystem can promote regional innovation-driven growth (new companies, services, and skills around CO_2 reuse). Nevertheless, SWOT also revealed several weaknesses and threats that the open innovation approach should be able to address. The low awareness or inertia of those responsible for innovation, limited practical experience with CCUS technologies, and high up-front costs act as barriers to innovation. Industry stakeholders identified financial risks from unproven, expensive technologies as major obstacles because they create development expenses that exceed available funding possibilities. The research results guide additional studies about cost-effectiveness and demonstrate the need for collaborative solutions through co-investment models or public-private partnerships to share costs. The deployment process faces challenges because government support remains limited while funding is fragmented. This indicates a policy gap and implies that a better coherence of national policies or incentives with CO_2 innovation goals must be established (a theme discussed later in the policy discussion). Also, the SWOT's mention of "low awareness" shows the importance of knowledge dissemination and stakeholder engagement in the ecosystem – essentially, outreach and training so businesses and local authorities are more aware of CO_2 valorisation opportunities. In an open innovation ecosystem, this can be mitigated by workshops, demonstration projects, and knowledge-sharing platforms that connect innovators and end users. Fig. 2 illustrates the main findings from the SWOT analysis.

3.4. Policy and legislative landscape

The research also evaluated the EU country-specific and Latvian legislative frameworks for CO_2 utilisation because a supportive policy environment is essential for innovation adoption. This analysis examined which countries have progressed CCU-related laws and how simple it is for enterprises to implement CO_2 capture/utilisation under current regulations. The research shows that all EU member states have some emission reduction policy through EU ETS membership and renewable energy targets. However, CCU-supporting legislative documents are in different numbers and scopes. Some countries have more streamlined permit processes or incentives for CCUS projects, while others have lagged, creating an uneven field for innovation diffusion. For Latvia, aligning regional efforts with European policy frameworks was vital. The EU's sustainable carbon cycle strategy and Net-Zero Industry Act demonstrate how collaborative innovation networks and industrial carbon management should be implemented. The roadmap implements these principles through policy recommendations, including clearer regulations and subsidies or carbon pricing mechanisms to motivate businesses towards CO_2 valorisation adoption. The European Green Deal's competitive low-carbon economy vision can be achieved through simplified permitting procedures and financial incentives which reduce SWOT barriers. The legislative review provides essential regulatory support for the open innovation ecosystem through policy recommendations. This study enhances policy-innovation relationships by encouraging policymakers to establish an environment which combines regulations with funding programs and carbon markets to expedite CO_2 utilisation projects.

3.5. MCDA outcomes

With the KPIs and case study data collaboratively defined, the TOPSIS MCDA was carried out to rank the CO_2 utilisation scenarios. The MCDA has explicitly incorporated the weights assigned to different criteria by stakeholders based on technical, economic, environmental, and social aspects, which is the hallmark of the inclusive approach. The TOPSIS results show that the most favourable scenarios for CO_2 utilisation at the regional level are: (1) application of CO_2 in algal biomass cultivation (algae ponds and greenhouses) and (2) application in the food and beverage industry. These options surpassed the (3) methanol, (4) ethanol, and (5) cement scenarios regarding the overall sustainability score (Fig. 3).

The algae/greenhouse scenario has a synergistic advantage in the agricultural sector: algae and plants are sound absorbers of CO_2 with little or no purification, thereby converting waste gas into biomass for fertilisers or biofuels (Leflay et al., 2021; Caia et al., 2018). This not only reduces the cost (no expensive gas scrubbing needed) but also illustrates a cross-sector innovation – energy (CO_2 source) and agriculture (CO_2 user)–for mutual advantage. Such integration is precisely what an open innovation ecosystem facilitates by connecting emitters with biotechnology innovators. The food and beverage industry scenario was ranked high because of the existing experience and the possibility of its implementation; many Latvian companies already use CO_2 for carbonation, packaging, or refrigeration. Familiarity means fewer unknowns in implementation and quicker uptake. However, it also poses a challenge: high CO_2 purity requirements ($>$ 98 % for food-grade CO_2) mean extra expenses, which points to a technological need that collaboration could address (e.g. R&D partnerships for cheaper purification technologies).

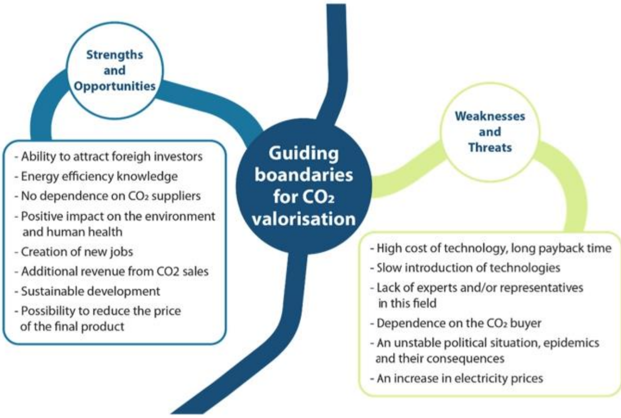

Fig. 2. Substantial benefits and barriers to the development of CO_2 *valorisation* options.

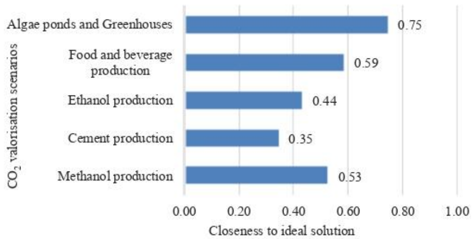

Fig. 3. Results of TOPSIS analysis.

The methanol and ethanol scenarios were placed in the middle. Methanol production has been identified as a promising route because of its relatively low technological complexity and because methanol is a versatile chemical feedstock and fuel. It leverages existing assets (e.g. combining captured CO_2 with biogas via known processes such as reverse water-gas shift) and could capitalise on the growing demand for low-carbon fuels, and thus could be attractive to investors if economic barriers can be addressed (Khojasteh-Salkuyeh et al., 2021; Borisut and Nuchitprasittichai, 2019; Ugwu et al., 2022; Anwar et al., 2020). Ethanol (specifically SAF-ethanol as aviation fuel) is technically feasible. This is in line with the efforts to decarbonise transport, but its energy consumption and the fact that it is still in the early stages of development make it less appealing (Pio et al., 2023; Collis et al., 2022). Fuel pathways may become more favourable as technologies advance, and open innovation partnerships (e.g. demonstration projects such as CO_2-to--fuels consortiums) can share learning to reduce costs. Cement utilisation, on the other hand, ranked lowest. This is because current cement processes are energy-intensive, and the CO_2 uptake is low; even advanced carbonation can only mineralise a small proportion of the emissions (e.g. ~ 15 kg CO_2 per ton of cement). Although cement is a construction material, the analysis indicates that using CO_2 in biofuel or industrial feedstock is a more efficient way of reusing CO_2 than the cement industry, at least with current technologies (Winnefeld et al., 2022; Ravikumar et al., 2021). This finding is essential at the ecosystem level as it directs regional efforts towards more rewarding options, such as algae and fuels, and away from spending much on the less rewarding ones. It also signals policymakers and industry that innovation should improve cement CCUS technology or consider other sectors for a more immediate impact. Finally, the MCDA revealed that logistics and quality factors are essential across all scenarios: the distance between CO_2 producers and users (our GIS mapping showed that it is generally manageable within Latvia) and the purity needed for each use. These practical considerations show how the ecosystem approach, linking sources to use efficiently, is critical for CO_2 valorisation to be successful at the regional level. In other words, the TOPSIS results not only rank the options but also determine the network design of the CO_2 ecosystem, indicating where the infrastructure (such as pipelines or transport) and innovation (such as impurity-tolerant processes) should be directed.

3.6. Environmental and social impact evaluation

An open innovation system assesses success through environmental and social sustainability metrics and technical practicality. The evaluation included LCA of methanol and ethanol production scenarios, including E-LCA and S-LCA. The research focused on these two processes because they provided a helpful comparison between chemical and biofuel production methods. At the same time, other options, such as food and cement production and algae usage, were too complex for comparison. The E-LCA results, in summary, indicate that methanol and ethanol production methods produce substantial reductions in net CO_2 emissions relative to standard procedures while creating distinct environmental trade-offs between energy consumption and resource depletion. The S-LCA study generated more compelling results by analysing how stakeholders, including workers and local communities, and the broader society would be affected. Fig. 4 presents the social impact assessment.

Both methanol and ethanol production paths generated similar results in various performance categories, yet the "Health & Safety" evaluation demonstrated higher risks associated with methanol production than ethanol production. The reason behind this finding stems from methanol's requirement for dangerous substances and its intricate manufacturing process, which creates elevated occupational dangers and potential accidents. The production of ethanol results in lower social risks because it typically occurs in nations with strong safety regulations and demands fewer dangerous substances. From an open innovation standpoint, these findings stress that technology adoption should consider social acceptance and worker well-being. An open innovation ecosystem enables early collaboration between labour representatives, local communities, and safety regulators to minimise risks when

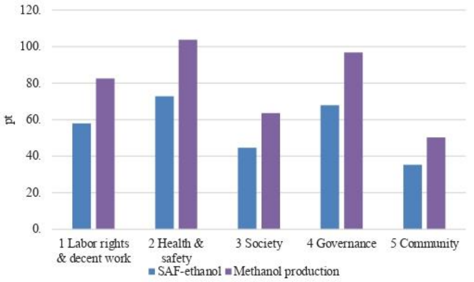

Fig. 4. Assessment by main categories: global annual per capita.

developing CO_2 projects. The ecosystem approach could produce knowledge exchanges about methanol plant safety best practices through international partnerships or industry consortia to help Latvia develop safer production methods. Ethanol currently demonstrates superior social performance; thus, policymakers who want to advance pilot projects should focus on promoting CO_2-to-ethanol initiatives because they might receive less public opposition. The LCA results show that sustainability is not only a single dimension but multiple dimensions. The recommended solutions (algae and fuels) have to meet the environmental standards and social requirements for sustainable implementation through stakeholder-informed processes.

3.7. Economic feasibility and business model implications

To translate these scenarios into practice, their economic viability was evaluated through a CEA. This analysis included the capital and operating costs, revenues, and market conditions of four scenarios (algal biomass, methanol, ethanol, and cement) based on the literature and current market data. Economic results present a way to develop business models, and investment needs that link the technical roadmap to the market. A key finding is that CO_2 valorisation can generate substantial economic value, but profitability depends on effective integration with existing infrastructure and market support instruments. For instance, in the methanol production scenario, using Latvia's existing biogas plants as a basis for CO_2-to-methanol conversion can significantly reduce capital costs because core facilities are already built.

Modern methanol plants can consume up to 180 tons of CO_2 annually to generate 130,000 tons of low-carbon methanol. At current prices (approximately €300/ton in early 2024), it can generate over €140 million in annual revenue. This means that there is a feasible business model that conventional biogas companies can adopt by venturing into liquid fuel production while using open innovation through collaboration with chemical engineers and exploring EU funding (the analysis, as well as EU financial support and the drive for alternative fuels under policies such as the Green Deal, may enhance methanol's prospects). Such projects have a favourable net present value provided that product prices are constant, which means that market foresight and policy incentives play a role in de-risking investment. This exemplifies how policy and entrepreneurship must align, achieved through stable carbon prices or contracts for differences recommended in the EU industrial policy.

For ethanol production, the CEA points to the fact that the market is still in its infancy; ethanol prices rose in 2022 and then eased to €497/ton in 2024. Producing ethanol from CO_2 is costly (3.5 tons of CO_2 per ton of ethanol), and a large plant can consume more than 3.6 million tons of CO_2 in 30 years (Tanzil et al., 2021; Karekar et al., 2023). The economic viability of this case may be based on the premium price of sustainable aviation fuel and the regulatory requirements that compel airlines to use e-fuel. A possible business model for this is a public-private partnership where aviation companies, fuel producers, and the government bear some of the investment costs since the social impact (reduction in emissions in aviation) is high. This analysis indicates that such a plant would require long-term policy support through blending mandates or offtake agreements to be financially viable, again stressing the relationship between policy and business innovation.

The cement enhancement scenario is the least favourable regarding technology but has economic challenges. The costs of a carbon-cured cement plant are mainly the costs of constructing new kilns and equipment, and the revenue from cement is low, at €50–90/ton. Nevertheless, if such a plant could mineralise some CO_2 (up to ~ 390,000 tons over 25 years if optimised), the return on investment is low given the current cement prices and the limited carbon credits it can earn (Stefaniuk et al., 2023). This shows that unless there are creative business models that include selling carbon credits or marketing low-carbon cement at a premium, companies are unlikely to invest in CO_2 valorisation in cement on a large scale. It is a warning that some pathways may require technological advancements or market changes (e.g. increased carbon prices) to be economically viable.

Among the scenarios considered, algal biomass was one of the most economically viable for small-scale applications. Algal farms have lower capital costs and shorter project durations (approximately 10 years). Importantly, because algae do not need purified CO_2, operational costs are lower, so the process is more cost-efficient when CO_2 is used. Algal biomass can be sold at 90–135/ton (Zabochnicka et al., 2022; Klein et al., 2023). In that case, a facility can generate tens of thousands of euros per year, which is not too high and may be quite profitable if the farm is used with other sources of income (such as waste management or biofuel production). This scenario suggests opportunities for SMEs and cooperatives. For instance, several farmers and energy producers could collaborate to set up an algal cultivation unit to convert emissions into marketable bio-products, splitting costs and profits. This co-op model is a perfect example of open innovation at work, which brings together knowledge from agriculture, energy, and biotechnology. Although algae may not be as profitable as large methanol plants, it offers a way for local businesses to start with CO_2 valorisation, which may be helpful in rural areas interested in innovation. Fig. 5 compares the scenario economics, showing revenue potentials and CO_2 usage over the project lifetimes.

It also shows that cement produces the highest product volume but uses the least CO_2. In contrast, because of their longer duration, methanol projects will be able to use the most CO_2, and algae will use CO_2 efficiently but at a smaller scale. In general, an economic analysis makes the roadmap more relevant. This links the technical results to the market environment. It guides the innovation diffusion process, for instance, by utilising available facilities (biogas-to-methanol) or by targeting specific market segments (algae bio fertilisers) in the first instance and preparing for future growth in new markets, such as ethanol. The paper also shows where business model innovation is needed, for instance, to create value from CO_2 credits, form industrial clusters to share resources or secure policy backed contracts to overcome the identified financial barriers. These insights make the roadmap technically correct and realistic in terms of economic feasibility, thus improving stakeholder engagement

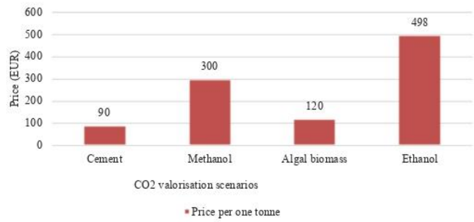

Fig. 5. Comparison of prices (EUR/t) for the scenarios analysed.

in the implementation process, including investors, entrepreneurs, and companies.

3.8. System dynamic model

The roadmap investigates pre-process CO_2 utilisation through carbon farming and industrial applications, as reducing emissions at their source, particularly in agriculture, remains essential for regional CO_2 strategies. A system dynamics model analysed this sector using agricultural expert cooperation while incorporating real farm data to evaluate Latvia's agricultural sector. Latvia's agricultural CO_2 reduction strategy became the preferred option because of its alignment with the Common Agricultural Policy Strategic Plan and the National Energy and Climate Plan. The roadmap includes farming practice recommendations that directly fit within the established policy framework and stakeholder environment, where farmers, their advisors, and policymakers actively participate in the model development process. Carbon farming practices include activities that enhance carbon capture, minimise CO_2 emissions from farms through no-till farming, and cover cropping and manure management improvements. The model revealed that agricultural emissions reductions primarily stem from enhancing land and waste management practices. Soil cultivation combined with suitable crop choices enables substantial CO_2 absorption from soils and plants because crop cultivation generates 55 % of agricultural emissions. The importance of transferring carbon capture techniques to farmers becomes clear from these findings because an innovative ecosystem can facilitate this connection between agricultural scientists and farming communities. A detailed analysis of a large dairy farm included three scenarios: no new investments alongside investments in enhanced manure management and investments in a comprehensive set of improvements that included manure management, barn climate control, and feeding enhancements. When implementing several innovation measures, the dairy farm managed a 60 % decrease in CO_2 emissions per production unit, leading to a 69 % increase in milk production per cow compared to the baseline conditions. The emission reduction in the scenario with manure management only exceeded that of the no-investment scenario, but not as much. This research demonstrates that system-wide emission reduction requires coordinated change because focusing on waste reduction alone produces minimal benefits. However, implementing changes across multiple system elements, such as waste, energy efficiency, and animal diets, has a substantial overall impact.

The open innovation ecosystem concept functions at the same level as the farm model because numerous evidence-based interventions developed for practical implementation result in better sustainability and increased productivity. The business outcome of this case demonstrates that sustainability investments generate financial returns through efficiency improvements that allow farmers to maintain milk production with the same number of cows, thus motivating other farmers to implement similar innovations. The spread of successful farm practices through agricultural extension services represents knowledge spillover in the ecosystem because it converts individual farm data into standards for other operations. The farm case study analysis included stakeholder co-development because model builders worked with real operational data that farm owners/managers were likely to use to refine the model to produce realistic outcomes and practical recommendations. Through participatory modelling, stakeholders become more invested in the outcomes because they contribute to developing recommendations, thus making them more likely to adopt the proposed changes. The agricultural-focused analysis extends the roadmap by introducing complex ecosystem patterns of different sectors. The example demonstrates that open innovation applies to farming and other traditional sectors, where farmers, researchers, and policymakers collaborate to develop new carbon farming techniques for CO_2 reduction. The proposed ecosystem builds regional capability because its successful implementation depends on training programs, advisory services, and potential incentive schemes for farmers who require multi-actor coordination.

4. Discussion

The research outcomes present definitive evidence for establishing an open innovation system to manage regional CO_2 valorisation activities. The analysis reveals that no individual actor, along with their technology, provides the solution because successful CO_2 utilisation depends on stakeholder collaboration and interaction to develop viable utilisation roadmaps. The process used perspectives from academia (LCA and GIS analysis tools), industry (emissions and cost data), government (policy alignment) and community members (social and environmental considerations) to define KPIs, select scenarios and evaluate them. The roadmap demonstrates open innovation principles through co-development because it was created by ecosystem participants (see Fig. 6). The ongoing feedback from stakeholders played a crucial role in developing the first roadmap while also helping to modify evaluation criteria and adjust scenarios according to changing regional priorities and capacity limitations. The development process maintained flexibility and context-awareness through structured feedback mechanisms, which allowed for responsiveness.

The SWOT analysis included business and policy stakeholder perceptions, combining industrial data and local knowledge to obtain socially strong and real results. Knowledge Exchange and Spillovers: Through the implementation of a multidisciplinary "tangle of threads" methodology (GIS, MCDA, LCA, etc.), a stakeholder-inclusive framework allowed expertise to flow between different domains. Technical carbon capture information is merged with practical business knowledge, which combines carbon capture methods with renewable energy integration and farm management strategies with market trend data. The participating companies and institutions gain capacity-building benefits through the study, whereas the broader region receives a documented knowledge base presented in the roadmap. The innovation ecosystem relies heavily on knowledge spillovers to create new business opportunities because an energy company might discover algal cultivation techniques. At the same time, agriculture experts gain knowledge of the carbon market, which can result in collaborative projects and business concepts outside this study.

The results revealed that the ecosystem creates benefits which lead to entrepreneurship and capacity development. New business opportunities emerge through high-potential scenarios, such as algal biomass production and CO_2-derived fuels, which enable startup ventures and fresh market sectors throughout the region (e.g. algae farming ventures, biofuel refineries, CO_2 capture services). Open innovation enables the discovery of new opportunities that would otherwise remain hidden during traditional analyses in the absence of sectoral dialogue. Conventional analysis would likely fail to identify opportunities that require sectoral cooperation, such as combining waste CO_2 with agricultural production.

Carbon value hubs enable innovation clusters to form by creating a framework for companies, researchers, and local authorities to execute pilot projects. The clusters drive enhanced entrepreneurship through spin-offs and new suppliers while developing permanent regional expertise for CO_2 management and monetisation. Through this process, the region establishes itself as an industry leader for CO_2 valorisation, thus drawing in investors and skilled personnel who create a positive feedback loop from the open ecosystem model.

The main finding of our research demonstrates how business models and policy frameworks merge with technology. The roadmap presents a complete solution because it considers the economic, legislative, environmental, and technical aspects. Technical feasibility, market viability, and policy support are essential for success in real-world innovation ecosystems. The financial obstacles and price factors identified in SWOT and CEA directly specify which business model innovations must be developed, such as consortium formation for cost-sharing and EU funding utilisation. The roadmap's recommendations show institutional

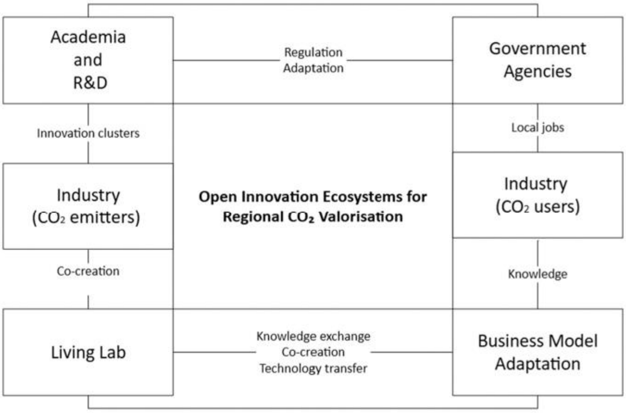

Fig. 6. Open innovation ecosystems for regional CO_2 valorisation.

readiness because of the legislative analysis and the EU Green Deal target alignment. The open innovation ecosystem enables policymakers to participate at the beginning of the process (as they did in this research), which leads to strategy implementation through specific programs, incentives, or regulatory adaptations.

The regional CO_2 roadmap functions as a policy-informing instrument while embodying the ecosystem principle which connects science with market and governance. The development of "CO_2 valorisation clusters' presents itself as an operational structure of the ecosystem. The clusters or hubs promote physical closeness and network development through shared pipelines, joint facilities, and communal R&D labs, which reduce new project barriers through resource sharing and support company-wide problem-solving through cluster associations and innovation hubs. The results provide specific locations and industrial sectors for cluster development, providing instant value for regional planning and economic development agencies. The cluster arrangement enables better resource and knowledge sharing between members, representing an open innovation achievement.

The thematic consistency of open innovation is shown through analysis and interpretation by demonstrating how collaborative engagement and integrated perspectives produce more robust conclusions in each results segment. The "tangle of threads" approach analysed technical results while examining their effects on the innovation ecosystem (e.g., it examined how top-ranked scenarios might create new partnerships and how joint action could address identified barriers). The established pathway enables conclusions to link the roadmap back to both open innovation framework principles and the broader policy framework, thus creating a cohesive narrative about how sustainable CO_2 conversion into regional assets requires an innovative ecosystem of cooperation.

The research results need interpretation through specific study restrictions. The roadmap implementation success in different regions depends on how well local data exists, how capable institutions are, and how much stakeholders participate. The accuracy of cost predictions and life cycle assessments depends on certain assumptions requiring verification through pilot project implementation.

The study makes significant methodological and conceptual contributions despite its limitations. The research develops open innovation applications through a multi-model framework which connects separate knowledge domains for information exchange. The proposed model demonstrates transferability to assist small and mid-sized economies in the transition to low-carbon and circular economies.

Future studies must evaluate the roadmap's effectiveness in different regional settings while monitoring CO_2 valorisation cluster performance and identifying the behavioural and institutional factors that lead to successful co-creation. The roadmap requires implementation through living labs and innovation clusters as the following steps to validate its effectiveness in real-world scenarios.

The research adds theoretical value to open innovation science by showing how multi-actor ecosystem models can be used for sustainability transitions. Open innovation has mainly been used in high-tech or corporate settings. Still, this study demonstrates its application for regional policy formation and cross-sectoral strategy alignment and co-creation among government agencies, SMEs and civil society. The "tangle of threads" methodology introduces a systems-based method which connects technical assessments to institutional social and market feedback loops to bridge technology with governance and entrepreneurial practice.

The open innovation approach provided several benefits to the research, but several limitations were apparent during the participatory process. The process of uniting various stakeholder interests requires extensive time and specialized facilitation skills, which not all regions possess. The full participation of smaller actors, including SMEs and rural municipalities, is sometimes limited because they lack sufficient capacity and resources, which reduces their representativeness. The ecosystem enables idea sharing but creates decision-making challenges when stakeholders fail to achieve consensus. The practical implementation of open innovation requires structured facilitation, capacity-building measures and contingency mechanisms to address these issues. Identifying these limitations will improve the framework's future use by identifying areas that require additional support and adaptive governance.

This study identified several barriers to its implementation. Regulatory fragmentation at the regional level creates inconsistencies in permitting CO_2 capture and reuse projects. Financial risks related to high upfront investments and uncertain carbon pricing deter SME participation. Technological challenges include low technology readiness levels for some valorisation options and integration difficulties with existing infrastructure. To overcome these issues, the roadmap proposes policy recommendations, such as the creation of a regional CO_2 valorisation fund to de-risk pilot projects, harmonisation of permitting procedures across municipalities, and targeted R&D incentives for bio-based CO_2 pathways. Involving regional authorities early in the planning phase is essential to ensure that the outputs are aligned with practical policy tools and ongoing climate strategies.

5. Conclusions

The industrial sectors benefit from CCUS technologies to lower CO_2 emissions. Successfully deploying these technologies depends on the interaction between legislative, technological, economic, social, and environmental factors. Sustainability performance, return on investment, and system adaptability must be holistically evaluated to ensure impact and longevity. The ecosystem consists of multiple institutional layers and stakeholder types, where public and private actors jointly identify, test, and scale valorisation solutions facilitated by shared infrastructure, collaborative data, and adaptive governance.

This study developed a geographical framework for the valorisation of CO_2 in Latvia, which evaluated five scenarios for CO_2 utilisation (methanol, ethanol, cement, algal biomass, and food industry) using an integrated methodological framework. The proposed 'tangle of threads' framework combined GIS, KPI co-development, TOPSIS, E-LCA, S-LCA, and CEA. The application of this hybrid method reflects the complexity of innovation adoption in sustainability transitions and supports decision-making from multiple perspectives.

Methanol, ethanol, and algal biomass production were determined to be the most sustainable CO_2 utilisation pathways due to their high CO_2 conversion potential and low environmental footprint. The algal biomass scenario was the most sustainable option, as it required the least purification, had the highest flexibility of location, and had the lowest capital and operational costs. The process is also more socially and environmentally acceptable than chemical conversion pathways because it has lower health and safety risks. SAF ethanol production is not yet cost-effective because of its high energy requirements. Still, it remains a promising future option as technologies evolve and regulatory incentives for low-carbon fuels expand.

Cement and food industry scenarios were not assessed through LCA and CEA because of technological heterogeneity or a mismatch with energy-based valuation metrics. However, they are still relevant for niche applications and require further investigation. At the regional level, algae-based CO_2 utilisation provides a low-barrier entry point that could strengthen Latvia's renewable energy sector and decentralised energy resilience. However, limitations in infrastructure can hinder its rapid implementation. However, retrofitting existing biogas plants for methanol production is an economically viable short-term strategy that requires less capital expenditure and produces market-ready outputs. The economic assessment of the roadmap evaluated both short-term sustainability through retrofit readiness and capital efficiency and long-term scalability by examining market trends, policy support, and infrastructure expansion potential in decentralised. The roadmap's modular structure, policy alignment, and participatory co-creation methods ensure its transferability to diverse regional contexts, provided that essential enabling conditions—such as stakeholder engagement, emissions data availability, and institutional capacity—are in place regions.

The findings may be limited by the representativeness of the stakeholder group. Despite efforts to include diverse actors, some sectors—particularly small rural enterprises or marginalised communities—may have been underrepresented due to capacity, awareness, or logistical constraints. The transferability of the roadmap to other regions depends on local governance structures, institutional maturity, and data availability. As such, while the model offers a strong conceptual foundation, its replication should be adapted contextually and accompanied by targeted stakeholder mapping and engagement strategies.

The study makes a significant contribution by going beyond technical evaluation. The roadmap implementation within an open innovation ecosystem demonstrates how stakeholders, including industry, government, researchers and local communities, can guide sustainable emissions conversion into value through collaborative efforts. The model promotes innovation, adoption, entrepreneurial activity and policy alignment, and regional capacity-building. The roadmap established in this research serves as a versatile and expandable framework with applications inside Latvia and outside its borders. The research enhances open innovation theory through its application of ecosystem models to regional sustainability transitions while showing how systems-based co-creation frameworks can develop practical strategies that unite technical aspects with institutional and social elements. The framework connects technology assessments to institutional and market integration, thus enabling a wider transition towards circular and low-carbon economies. The roadmap adaptability received support from ongoing stakeholder feedback loops, which allowed for scenario refinement and produced outputs that matched local implementation constraints and institutional realities. The feedback-based design approach makes the roadmap more relevant for long-term use and easier to replicate.

The roadmap supports EU Green Deal objectives and Latvian national climate and energy strategies through its direct integration of policy-relevant indicators. The assessment used KPIs, MCDA, and E-LSA and S-LCA to select pathways that met environmental, economic, and social sustainability criteria, which align with EU-wide targets. The evaluation of scenarios included governmental actors who validated both institutional applicability and regulatory compliance.

Further research should include additional technologies, expand stakeholder engagement, and deepen economic modelling to assess scalability under diverse regional conditions. Innovation clusters and living labs could also be established to validate the proposed solutions in real-world settings and accelerate their implementation.

The roadmap provides a transferable framework which can be used as a basic template for other regions that want to implement sustainable CO_2 valorisation. The successful adaptation of the approach requires early involvement of regional stakeholders, access to relevant emissions and infrastructure data, and institutional support for cross-sectoral collaboration. The open innovation ecosystem is particularly suited for regions with emerging circular economy policies and a need to activate synergies between industry, research, and local governance. The modular structure of the methodology (e.g., GIS, MCDA, LCA) allows for contextual tailoring while preserving the roadmap's core co-creative logic. Future applications should prioritise capacity building and policy alignment to replicate the Latvian case in other EU and global regions. The roadmap's modular structure, policy alignment, and participatory co-creation methods ensure its transferability to diverse regional contexts, provided that essential enabling conditions—such as stakeholder engagement, emissions data availability, and institutional capacity—are in place.

Future research needs to conduct longitudinal studies to track the development of stakeholder engagement and technology adoption throughout carbon valorisation ecosystems. The evaluation of the roadmap's adaptability in different socio-economic and regulatory contexts requires cross-regional comparative studies, especially in EU regions with varying levels of institutional capacity or carbon intensity. These studies can help determine the critical enablers of successful transferability, such as data infrastructure, policy alignment, and innovation culture.

CRediT authorship contribution statement

Viktorija Terjanika: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Krista Laktuka:** Visualization, Supervision, Data curation, Conceptualization. **Lelde Vistarte:** Resources, Investigation, Data curation. **Jelena Pubule:** Writing – review & editing, Validation, Project administration, Methodology, Conceptualization. **Dagnija Blumberga:** Validation, Methodology, Conceptualization.

Ethical approval

Ethical approval does not apply to this article.

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Declaration of Competing Interest

The authors declared no potential conflict of interest with respect to the research authorship and/or publication in this article.

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Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jelena Pubule reports financial support was provided by Latvian Council of Sciences. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ANNEX

Annex A

RESOURCES

Table 1A

Energy Indicators

No.	Indicator	Description		
ENERGY			**Methanol production**	**Cement production**
1	Electric energy per 1t product	Energy consumption to produce 1 tonne final product MWh/t	Helical tube reactor: 0.00253 MWh/t --- 1.4g/L*day (productivity) Bubble column: 0.0862 MWh/t --- 0.4g/L*day (~10 days) Flat panel airlift: 0.0791-0.158 --- ~0.76g/L*day (Schlagermann et al., 2012) 0.020 MWh/ha – energy demand 0.72 MJ el + 1.7 MJ therm / kg oil	0.833-8.611 MWh/t clinker (*5-stage preheater+Precalciner = Best Available Technology*) (Barcelo et al., 2014) For the calcination process: 0.472 MWh/clinker (theoretical minimum) 0.819 MWh/t clinker – realistic (Ecofys & Fraunhofer Institute for Systems and Innovation Research, 2009)
2	Electric Energy per produced CO2	Energy consumption (production) to produce 1 tonne CO_2 MWh/tCO_2	385gCO_2/kWh electricity produced 107 gCO_2/MJ – CO_2 emission of electricity 72 gCO_2/MJ – CO_2 emission of heat (Schlagermann et al., 2012)	
3	Energy self-sufficient from renewable energies	Amount of renewable energy in total energy consumption MWh/MWh (renewable energy/ total energy demand)	–	
4	Energy required for pre-treatment	Energy consumption to treat 1 tonne of CO_2 MWh/tCO_2 treated	–	
5	Energy required for pre-treatment	Energy consumption to utilise 1 tonne of CO_2 MWh/tCO_2 utilised	–	

6	SPECFER indicator	Specific Primary Energy Consumption per unit of Fossil feedstock Replaced (SPECFER) indicator combines information on the additional energy use of CO_2 utilization with the fossil feedstock that is replaced.(Schakel et al., 2017),	–	
WATER				
7	Water consumption	Tonnes of water consumed per 1 tonne of CO_2 generated during production process t/CO_2	–	
8	Water consumption	Tonnes of water consumed per 1 tonne of CO_2 utilised during production process t/CO_2	–	
9	Water consumption	Tonnes of water consumed per 1 tonne final product t/t product	–	
10	Recycled water	Tonnes of water recycled per 1 tonne CO_2 utilised t/CO_2	–	
MATERIAL				
11	tCO_2 in-/outflow during production process (Use of CO_2 as raw material in production process)	tCO2 used for production / tCO_2 produced in the production process per 1 tonne of final product tCO_2 utilised/t product tCO_2 generated/t product	~1.4t CO_2 utilised / 1t Methanol 4t CO_2 produced / 1t Methanol	0.060 tCO_2/t – concrete 0.010 tCO_2/t – aluminium
12	Produced CO_2 and required CO_2 ratio	Shows the need to buy extra CO_2 for production process or the possibility to sell one tCO_2/tCO_2	4t CO_2 produced / 1.4t CO_2 needed	
13	Raw material	Amount of raw material needed to produce 1 tonne CO_2 t/tCO_2	3.89 t Algae (resource) / tCO_2 emitted in process	

14	Material Supply Chain Risk (Ellen Macarthur Foundation & Granta Design, 2015) Herfindahl-Hirschman Index (HHI)	Risks concerning the continuity of supply of a material for a product are related to the availability of that material for purchase by the product's manufacturer An indicator of monopoly of supply for an element. It is defined by the sum of the squares of the market share for the producers of that element	–	
15	Produced CO_2 and CO_2 available for recycle ratio	Ratio of CO_2 produced during production process and CO_2 amount that is available for returning into production process (without intensive treatment) tCO_2/tCO_2	–	
16	Purification rate of pre-treated stream and needed rate ratio (Ellen Macarthur Foundation & Granta Design, 2015)	Amount of additives in pre-treated exhaust gas stream and needed purification rate for production tCO_2eq/tCO_2	–	
17	Produced / utilised amount of CO_2	Tonnes of CO_2 generated per capita	–	
		Tonnes of CO_2 utilised per capita	–	

Table 2A

Environmental Indicators

No	Indicator	Description	Methanol production	Cement production
18	Total emission during production process	Total emissions in CO_2 equivalent to produce 1 tonne of final product $tCO_2eq/1t$ of final product	92.2 tCO_2/MWh 4tCO_2/t Methanol Closed photobioreactor: 21 $kgCO_2/m^2/a$ Raceway pond: 6 $kgCO2/m^2/a$	526 $kgCO_2$/1.2 t clinker (Barcelo et al., 2014)
19	Direct emissions, total (Gross + Net)	Total <u>direct</u> emissions in CO_2 equivalent to produce 1 tonne of final product tCO_2/t final product	214 $kgCO_2/MBTU$ =62.92 tCO_2/MWh (Manganaro & Lawal, 2016)	
20	Indirect emissions, total (Gross + Net)	Total <u>indirect</u> emissions in CO_2 equivalent to produce 1 tonne of final product tCO_2/t final product	99.9 $kgCO_2eq/MBTU$ =29.28 tCO_2eq/MWh (GCCA, 2019), (CSI, 2005)	
21	Possible CO_2 capture system efficiency	Ratio of captured CO_2 by available capture system and total produced emission amount in CO_2 equivalent tCO_2 captured/tCO_2eq exhaust gases produced	97.8 % - CO_2 capture efficiency 3.91t CO_2 captured / 4t CO_2 produced	
22	Share of CO_2 in total flow	Share of CO_2 in total exhaust gases before capturing tCO_2/t Total emissions	–	
23	Waste generation	Tonnes of waste produced to utilise 1 tonne of CO_2 t/tCO_2	–	
		Tonnes of waste produced to generate 1 tonne of CO_2 t/tCO_2	–	

Continuation of Table 2A

24	Wastes for unit process	Tonnes of waste generated to produce 1 tonne of final product t waste/t final product	–	
25	Waste generation per capita	Municipal waste generated per inhabitant in a company (including and excluding major mineral wastes per GDP unit)	–	
26	Recycling rate	Recycling rate per inhabitant in a company (all waste, biowaste in kg per capita)	–	
27	Rate of reuse	Rate of reuse, rate of remanufacturing, refurbishment, wastewater reuse, wastewater treatment (Sánchez-Ortiz et al., 2020), (Avdiushchenko & Zajaç, 2019)	–	
28	CO_2 avoidance	CO_2 avoided (because there is a certain amount of CO_2 that enters to the CCU-plant to be used as raw material) (Pérez-Fortes et al., 2016)	Closed photobioreactor: 17 $kgCO_2/m^2/a$ Raceway pond: 5 $kgCO_2/m^2/a$ (Schlagermann et al., 2012)	
		CO_2 avoided because some CO_2 is not produced if compared to the conventional process	–	
29	Fuel mix	Fossil fuel / alternative fuel / biomass ratio (CSI, 2005)	–	

Table 3A

Economic Indicators (Socio-economic Indicators)

No	Indicator	Description	
30	Total costs of CO_2 capture and pre-treatment	EUR needed to capture and treat 1 tonne of CO_2 EUR/tCO_2	–
31	Total costs of CO_2 utilisation	Money spent to utilise 1 tonne of CO_2 EUR/tCO_2 utilised	–

32	Total costs for CO_2 if doing nothing	Costs for 1 tonne produced CO_2 in case if no capture and treatment measures are taken EUR/tCO_2	–
33	Costs of CO_2 if buying	Costs of 1 tonne of CO_2 on the market EUR/tCO_2	–
34	Spent on CO_2 avoidance and spent on CO_2 production ratio	Money spent to avoid 1 tonne of CO_2 emissions and money spent to produce 1 tonne of CO_2 ratio EUR per 1 tCO_2 avoided /EUR per 1 tCO_2 produced	–
35	Turnover	Money spent to produce 1 tonne of final product EUR/t produced final product	~0.5$/kg Methanol (Prakash, 2015)
36		Money spent to produce 1 tonne of CO_2 EUR/tCO_2 produced	–
37	Employment rate	Salary EUR per 1 tCO_2 utilised EUR/tCO_2 utilised	–
38		Salary EUR per 1 tCO_2 produced EUR/tCO_2 produced	–
39	Amount of investments in sustainable development	Investments in the sustainable Research and Development (R&D) as fraction of the expenses of the company (per produced 1 tonne of CO_2) EUR/tCO_2	–
40	Value of investment in environmental protection (Avdiushchenko & Zajaç, 2019), (Sánchez-Ortiz et al., 2020)	Investments of company in environmental protection (per produced 1 tonne of CO_2) EUR/tCO_2	–
41	Costs of employee	Costs of employee per 1 tonne output EUR/t output	–
42	Investments in employee development	Investments in employee’s education and professional development EUR/empl. (Krajnc & Glavic, 2003)	–
43	Material circularity indicator (Ellen Macarthur Foundation & Granta Design, 2015)	measures how restorative the material flows of a product or company are (tonnes of resource needed / tonnes of outflow)	–

Continuation of Table 3A

44	Benefit	Benefit/cost ratio. Provides information about how much of the costs to make a product is covered by the benefit of selling this product EURselling/EURspent	–
45	Capital costs	EUR/t final product/year	67.3 US\$2000 per GJ of biodiesel (Takeshita, 2011)
46	Variable costs	EUR/t final product	–
47	Fixed costs	EUR/t final product (Pérez-Fortes et al., 2016)	–

Table 4A

Production specific indicators

1	Methanol production specific	CO_2 that is converted in the reactor of the synthesis process CO_2converted/total CO_2 inlet	70-90% conversion 1.4 tCO_2 used/1.95 tCO_2 injected
2		CO_2 that is transformed into MeOH through the whole process taking into account the recycling streams (Pérez-Fortes et al., 2016) CO_2conv.proc/total CO_2 inlet	–
		Specific energy demand	7.000 MJ/m^2*year – solar radiation 1W/m^2 – raceway pond 100 W/m^3 (= 5 W/m^2) – closed photobioreactors
3		CO_2 used. defined as the net amount of CO_2 that is converted into product, in gate-to-gate approach. It takes into account the difference between the amount of CO_2 that enters the process as raw material and the direct and indirect emissions of CO_2, these last due to electricity and/or steam consumptions	71.7 % - utilisation efficiency 1.95 tCO_2 – used in process (injected) 1.4t CO_2 used – not indicator

4	Methane production(Moestedt et al., 2015)	Organic loading rate	-
5		Methane production rate	1 t of fresh Laminaria gives 22 m^3 of methane. (Bruton et al., 2009)
6		CO_2 formation speed (after feeding and during release)	–
7		Composition of produced biogas (Cadena-Pereda et al., 2012) CO_2/CH_4	–
8		CO_2 dissolvent ratio to obtain needed CO_2 saturation L CO_2/L H_2O	–
9	Methane / Agriculture	CO_2 produced by animals (Madsen et al., 2010) t CO_2/animal feedstock	–
10		Heat production from animal metabolism per t CO_2 (from different nutrients). The more heat is produced by the animal, the more CO_2 is made kJ/tCO_2 (Madsen et al., 2010)	–
11	Cement production (Feiz et al., 2015)	CO_2 emissions from production of 1 tonne of clinker due to calcination – Specific emissions kg CO_2-eq/t-clinker	–
12		CO_2 emissions from combustion of fuels which is represented by the amount of thermal energy required to produce 1 tonne of clinker - Specific heat consumption MJ/t-clinker	1700 MJ/clinker (theoretical minimum) 2950 MJ/t clinker – realistic (Emele et al., 2021), (Ecofys et al., 2009)

13		The share of clinker substitutes in an average cement product, called the Cluster West portfolio cement *(*Clinker to cement ratio) t Clinker/t Cement	Share of clinker: 65–94 % – Portland Composite Cement 95 % – Ordinary Portland Cement 5–64 % – Blast Furnace Cement 45–89 % – Pozzolanic Cement 20–64 % – Composite Cement (Emele et al., 2021), (Ecofys et al., 2009)
14		CO_2 emissions due to production of electricity, which is represented by the amount of electricity used for production of 1 tonne of the *Cluster West portfolio cement* (the average cement product) – Specific electricity consumption kWh/t	0.267–0.534 tCO_2/t clinker – fuel-derived emissions (depending on the fuel used) → 89kgCO_2/MJ for bituminous coal (Emele et al., 2021), (Ecofys et al., 2009)
15		Specific CO_2 emissions (gross). Gross CO_2 emissions per tonne of cementitious materials produced tCO_2/t cementitious material	793–1060 kgCO_2/t clinker – direct emissions in Modern Dry Process and Old Wet Process (Barcelo et al., 2014)
16		Specific CO_2 emissions (net). Net CO_2 emissions per tonne of cementitious materials produced tCO_2/t cementitious material (GCCA, 2019)	–
17		Specific energy consumption for 1 tonne clinker MJ/t clinker (CSI, 2005)	1.75 GJ/t clinker – theoretical energy consumption for the chem.reactions in the kiln (3-6 MJ if inefficiencies taken into account) (Barcelo et al., 2014)
		Embodied CO_2 t CO_2/t clinker	0.866 t CO_2/t clinker (Barcelo et al., 2014)
18		CO_2 captured and stored tCO_2/year (IEA, 2018)	90 % – CO_2 capture

Continuation of Table 4A

19	Refrigeration system (R744 system), supercritical CO_2	Coefficient Of Performance (COP) Seasonal Energy Efficiency Ratios (SEERs)(Refrigerants, 2021)(Royo, 2017) CO_2 flow rate - $kgCO_2$/min CO_2 and biomass ratio – tCO_2/t Biomass	0.3-39 $kgCO_2$/min 1878 tCO_2/t Biomass (shelf-life)
20		Cooling capacity Refrigerant and media temperature ratio	10.000 l/day – Cooling Capacity
21	Algal ponds, (US Department of Energy, 2017)(Bhola et al., 2014),	BOD (Biochemical Oxygen Demand) concentration g/m^3	–
22		CO_2 fixation (consumed by algae) tCO_2/tAlgae	2 tCO_2/t Algae
23		CO_2 flow rate gCO_2/min	0.385-5390 gCO_2/min
24		Sequestration rate tCO_2/m^2 (pond area)	200 tCO_2/ha*year (CO_2 capture)
25	Greenhouses (Körner et al., 2007)	Mean net CO_2 exchange µmolCO_2/s	–
26	Welding (Ferreira Ribero et al., 2019)	Weld volume in cm^3 produced by the quantity of Man-Hours of the team engaged in the welding MH/cm^3	–
27		Quantity in kg produced by the quantity of men hour of the team engaged in the welding. MH/kg	–
28		Velocity of Shielding gas l/min (Pogonyi et al., 2018)	–

Table 5A

Limiting factors

Area	Needed CO_2 pureness	Needed CO_2 amount	Needed temperature / pressure	Other factors
Methane production		H_2:CO_2 = 4:1	200–550 ˚C	Reaction of H_2 and CO_2 and Ni catalyst (Akoubeh, 2015), (Grasso et al., 2019)
		H_2:CO_2 = 4:1	100 ˚C	CeO_2 and CO_2 reaction, catalyst, electric field (Yamada et al., 2020)
		H_2:CO_2 = 4:1	400 ˚C	Mg_2FeH_6 (Grasso et al., 2019)
Biomethane		H_2:CO_2 = 4:1	Biogas: 5.82 Pa CO_2 pressure Biogas to biomethane by modifying anaerobic fermentation: 100 bar (Merkle et al., 2017) CO_2 conversion to methane: H_2:CO_2=4:1 If ex-situ: 800 rpm (agitation rate); 37–55 ˚C (55 - optimal); recirculation input flow 1.75-2.25 (Zabranska & Pokorna, 2018)	**Biogas:** Methanogenic algae; Acetotrophic methanogens; Methylotrophic methanogens; Homoacetogenic microorganisms; catalysts Biogas to biomethane by CO_2 conversion: H_2 (Zabranska & Pokorna, 2018)

Continuation of Table 5A

Methanol production		3–12 vol%	Depending on the reaction, 1.0–1.5MPa, 160–300 °C (Pérez-Fortes et al., 2016), (Zagashvili et al., 2018), (Afanasjev et al., 2016)	Depending on the reaction, different reactants (e.g. H_2)
		H_2:CO_2 = 40:60 (Fornero et al., 2011) H_2:CO_2 = 3:1 (molar ratio) (Leonzio et al., 2019) 1.3756 kg pure CO_2 per CH_3OH unit; 0.1892 kg pure H_2 per CH_3OH unit; 0.2126 kg wet H_2 per CH_3OH unit (Kiss et al., 2016)	Working conditions 200-300 ˚C; 15–55 bar	99.83 % CH_4; Cl+H_2; Cu/ZnO/Al_2O_3 (catalyst, active in 473 K, reaction conditions are limited by kinetic constraints.)
Greenhouses	Pure CO_2	340–1.000 ppm CO_2 (Marcus Gustafsson et al., 2024), (Ontario.ca, 2002)		If gaseous CO_2: S content <0.02 % (by weight); moisture and heat control if gas mixture derived from fuel burning (Vermeulen, 2015)

Continuation of Table 5A

Algae	30 % CO_2	10 m^3/h flow rate	P_{CO2}=0.0012 atm (Langley et al., 2012)	

Urea / fertiliser			15MPa	Reaction in aquas solution of potash. In case of CO_2 shortage, MEA is advised (Lavrenchenko & Kopitin, 2011)
Food and beverages	Purif. rate <98.8 %			Gasous CO_2; Liquid CO_2; Solid CO_2
Welding	99.5 %	Ar:CO_2 = 95:5 %; 90:10 85:15 80:20 75:25 Ar:He:CO_2 90:7.5:2.5 66:26.5:7.5 66.1:33:0.9 (Advanced Welding Supply Company, 2020)		higher purity CO_2 produces better welds; Lower levels of CO_2 can be used for pulsed arc or spray arc welding, while higher levels > 20% are used for short arc welding and the shielding of some flux-cored wires.
Dry cleaning (Onofre et al., 2020)	>99 %		4.5–7.5 MPa; <18 ˚C	ScCO_2 Gaseous CO_2 (Pallado, 2001)

Table 6A

CO_2 production technology

<table>
<tr><th>Technology</th><th>CO_2</th><th>Process description</th><th>Advantages</th><th>Disadvantages</th></tr>
<tr>
<td>Beverage carbonation</td>
<td>5g CO_2 per 1 beer litre
The required purity of food CO_2 – 98.8 %

The output of CO_2 is 95.5 % by weight of alcohol, 51.3 % by weight of sucrose and 54.2 % by weight of starch.

Standard parameters of CO_2 content for brands:
for stout: 30 % CO_2;
for lager with N_2: 50 % CO_2;
for regular lager: 60 % CO_2;
for heavily carbonated products: 70 % CO_2. (1L of beer =~1.056 kg)</td>
<td>Saturation with CO_2 under high pressure

Forced carbonation is carried out at the final stage of industrial production. CO_2 is passed through the containers with the finished beer several times under pressure..

The optimum carbonation content is 2.2–2.6 volumes. This is ~5g CO_2/L of beer; it takes ~100g CO_2 for 20-liter keg.</td>
<td>The purer CO_2 is injected, the less O_2 is needed (CO_2:O_2), (Aqua Analytics, 2020)(Modern Brewhouse, 2018)
<table>
<tr><td></td><td colspan="3">O_2 concentration, %</td></tr>
<tr><td>V/V CO_2</td><td>0.001</td><td>0.005</td><td>0.02</td></tr>
<tr><td>0.5</td><td>7 ppb</td><td>35 ppb</td><td>142 ppb</td></tr>
<tr><td>1.0</td><td>14 ppb</td><td>71 ppb</td><td>284 ppb</td></tr>
<tr><td>2.0</td><td>28 ppb</td><td>142 ppb</td><td>567 ppb</td></tr>
</table>
Breweries are sources from which pure CO_2 can be produced without special equipment to increase its concentration:
• gases of alcoholic fermentation at breweries, alcohol and hydrolysis plants with 98-99% CO2 output

depending on the type of raw material used, different CO_2 output per ton (potatoes – 62 kg CO_2 per 1 ton of raw materials, molasses – 117 kg, grain – 171 kg)</td>
<td>No equilibrium in this process, since the total gas pressure must exceed the pressure at which the desired CO_2 concentration is provided, and as the bubbles of CO_2 dissolve, the partial pressure of oxygen can reach high levels.</td>
</tr>
</table>

Continuation of Table 6A

Liquid CO_2 production (AC Group, 2018), (Harald et al., 2002)		In distilleries, liquid CO_2 is produced according to the principle of gas liquefaction using moderate cold. Fermentation gases pass through traps, a scrubber, and a liquid ring compressor for cleaning and cooling. Compressed to 0.5 MPa, they move through a refrigerator and oil separators. Adsorbers with active carbon purify CO_2 before further compression (2.4–2.5 MPa). After the final stage (7 MPa), the gas is dried and purified in adsorbers with silica gel and zeolite. To generate 1t liquid CO_2 from fermentation gases, 190 kWh of electricity is consumed, and at specialized CO_2 plants - 175 kWh of electricity, 750–850 kg of anthracite and 7 kg of scarce monoethanolamine.		The organization and maintenance of numerous and complex storage tanks requires a lot of labor – the expense for it is over 30 % of the total amount of capital investments for the commissioning of new capacities for the production of liquid CO_2.

Continuation of Table 6A

Solid CO_2 production (K. Wei et al., 2022), (NETL, 2023)	The production of 1 kg of dry ice requires 1.6–2.0 kg of liquid CO_2	Liquid CO_2 from the third-stage condenser is purified and sent at 6–7 MPa to storage receivers, passes through a heat exchanger, cooling to –12 to –8 °C as it throttles to 2.4–2.8 MPa. The liquid and its vapors move to an intermediate vessel, where gaseous CO_2 is extracted via a heat exchanger by a high-pressure compressor. The 2nd control valve lowers the liquid pressure to 0.8 MPa, directing the vapor-liquid mixture to the 2nd vessel, where it cools to –44 °C. Gaseous CO_2 is extracted via a heat exchanger by the compressor, while subcooled liquid CO_2 enters the ice makers. Liquid CO_2 loses pressure, reaching the triple point (0.528 MPa) and solidifying. Solid CO_2 is stored at 0.8 MPa, with filling monitored by a light indicator. Vapors at –78.9 °C enter the jacket, are extracted by the compressor, cooled, filtered, and sent for reuse.	When liquefied, it gives CO_2 of 100 % purity Does not require high pressure containers when transporting, therefore, the cost of transportation is much lower	Steel cylinders for liquid CO_2 require constant technical supervision and systematic repairs to maintain them in a working and safe condition. for storing dry ice, need to create hermetically sealed, buried storage facilities with solid reliable insulation up to 300 mm thick.

Supercritical CO_2 production (Budisa & Schulze-Makuch, 2014), (Humphrey et al., 2023)		During the technological process, a mixture of liquid and gaseous CO_2 is heated, and the phase boundary between liquid and gaseous substances dissolves under the influence of certain conditions - at a critical temperature of 31.1 °C and a pressure of 72.9 atm (7.39 MPa).	Used in petrochemical, food, perfume, pharmaceutical, and other industries, it penetrates materials better than traditional solvents. Widely applied in extracting organic compounds like caffeine, its dissolving ability changes with slight temperature and pressure shifts, enabling fractionation and solvent recovery without extra energy costs.	
To prolong shelf life (Salaria & Panjagari, 2018), (Atanu, 2018)	>20–60 %	Filling the storage with gaseous CO_2 to create a special inert bacteriostatic and fungistatic atmosphere (at a concentration over 20 %) CO_2 atmosphere creation for pest control (>60 %)	widely used as a preservative for Widely used as a preservative: – Extends cut flower storage to 20+ days in a CO2 atmosphere. – Protects cereals, grains, and dried fruits from pests. – Prevents fungal and bacterial rot in stored fruits and berries. – Enhances flavor and shelf life of vegetables under high-pressure CO_2. Also ensures safe disinfestation, as over 60% CO_2 in 1–10 days kills insects, larvae, and eggs.	An atmosphere containing more than 60 % CO_2 for 1–10 days (depending on temperature) – the technology is applicable to products with a bound water content of up to 20 %, such as grain, rice, mushrooms, dried fruits, nuts and cocoa, mixed feed and much other.

Table 7A

H2020 projects for CO_2 utilisation

Acronym	Field	CO_2 role	Data
GRAMOFON (Gramofon, 2016)	Carbon capture / Gas purification	CO_2capture Post-combustion	95 % – CO_2 absorption rate
ROLINCAP (ROLINCAP, 2016)	Carbon capture / Gas purification	CO_2 capture Post-combustion	<2.0 GJ/ton CO_2 – regeneration energy requirement
MEMBER (MEMBER, 2016)	Carbon capture / Gas purification	CO_2 capture, H_2 production and CO_2 utilisation	33 EUR/t CO_2 – CO_2 avoidance cost (CO_2 capture) 90.9 % – CO_2 capture rate (Pre-/post combustion / H_2) 0.3 gCO_2 / g sorbent – sorption capacity 50–100 kg/day – production target
3D (3D-CCUS, 2016)	Carbon capture	carbon capture	1.5 Mt CO_2/year – storage capacity
CapCO2 (CAPCO2, 2016)	Carbon capture	carbon capture	10 tCO_2/day – captured 25 EUR/ton – CO_2 capture cost (new. Old – 75 EUR/ton)
C4U (C4U, 2020)	Carbon capture	CO_2 capture	10 MtCO_2/year – storage capacity
GECO (GECO, 2018)	Carbon capture / Gas purification	CO_2 capture (for further utilisation)	FOR ALGAE: 90 % CO_2+ 2 % H_2S – blend for algae FOR METHANOL: 1.7 mln L/year – produced now 5 mln L/year – planned to produce 6000 tCO_2/year – planned to use for methanol production 83.3 tCO_2/year/L of methanol – planned to utilise per 1 Litre of methanol GREENHOUSES: 99.997 % – CO_2purity 40 ppm – H_2S concentration in CO_2

Continuation of Table 7A

CLEAN (CLEAN, 2019)	Carbon storage	Carbon storage	15000 t CO_2 embedded
NOCO2 (NOCO2, 2019)	Chemical industry	Carbon capture and Storage	90 % – fuel conversion 90 % – gas conversion ~100 % CO_2 capture 20 EUR/t CO_2 – cost avoided
Carbon8 (Carbon8, 2020)	Waste stream processing / cleaning	CO_2 to treat waste	60 000 t CO_2/year captured (in 2019) 3.5 Mt CO_2/year – potential capture capacity
SCARABEUS (SCARABEUS, 2019)	Chemical industry	Feedstock for CO_2 blends	>96 UER/MWh – electricity cost
IPHYC-H2020 (I-PHYC, 2016)	Wastewater treatment	Parameter for microbiota	
HyMAP (HyMap, 2015)	Energetics / Photoreduction	CO_2 photoreduction	12–35 t CO_2/year*ha – conversion rate 0.94 t Final product/year*ha
SUNRISE (SUNRISE, 2019)	Fuel production	CO_2 photoconversion	2500 tCO_2/year*ha conversion rate 100 t of Final product / year*ha 0.4 EUR/L – renewable fuel production cost 90 tH_2/year*ha 300 t ethanol / year*ha OR 500 t ammonia /year*ha 0.2 EUR/L – liquid fuel production cost 40 t Jet Fuel /year*ha
GLAZER (GLAZER, 2020)	Glass processing	CO_2laser	controlling light transmission in the range from 0 up to 98 % by smart glass coatings current glass cutting technology destroys these soft and thin smart coatings, leading to processing rejects levels of up to 80 % pulse frequency of 10–60 kHz and a pulse duration of 200–400 ns

Continuation of Table 7A

LASERCUT (LASERCUT, 2016)	Wood material treatment	CO_2 laser	400 EUR/m^3 – product selling price 2 tCO_2/t of wood – avoided
LEILAC (LEILAC, 2016)	Carbon capture / Gas purification	CO_2 capture	4800t raw material/day – typical cement plant 240 t raw material/day – project cement plant 200 t limestone – feed rate CALCINATION AT: 10.000 kg/hr – cement meal 8.000 kg/hr – limestone 5 % – CO_2 capture
SOCRATCES (SOCRATES, 2016)	Carbon capture / Cement industries	Carbon capture	<12 EUR/kWh – cost storage 3.2 GJ/m^3 – storage energy density
SOLPART (SOLPART, 2016)	Carbon capture / Cement industries	Cement production	300 t/day – Lime production 0.13 MW per 1t lime 300 t/day – Dolomite production 0.083 MW per 1t dolomite 1400 t/day – Phosphate production 0.032 MW per 1t phosphate 0.077 MW/day/1 tonne – solar heat required 3500 t/day – production capacity 30 kg/h CaO (30 kW reactor) 20 kg/h $CaCO_3$ treatment (50 kW reactor) >50 % CO_2 concentration

Continuation of Table 7A

CLEANKER (CleanKer, 2017)	CO_2 capture / Cement production	Feedstock for cement production	90 % – CO_2 capture efficiency
ENHANCE (Enhance, 2019)	Chemical industry	Feedstock for ectoine production	14.000 $ / kg – final product price
CASCADE-X (Cascade-X, 2018)	Chemical industry	Feedstock for ectoine production	40 % CO_2 conversion
US4GREENCHEM (US4GREENCHEM, 2015)	Biorafinery	Feedstock for ectoine production	50 kg biomass/day
BIOGRAPHENE (Biographene, 2019)	Chemical industry	Feedstock for graphene production	28 – new employees
COZMOS (Cozmos, 2019)	Energy sector	Feedstock for chemical and fuel production	1.7 M EUR – net profit
OCEAN (OCEAN, 2020)	Chemical industry	Feedstock for chemical products	250 g CO_2/h – CO_2 conversion rate
C2FUEL (C2Fuel, 2019)	Energy sector	CO_2 conversion to carbon-captured energy carriers	2.4 Mt CO_2 / year – CO_2 avoided 1Nm^3 H_2/h – H_2 production 1.2 Mt DME/year – DME production rate 2.4 mln t FA/ year – Formic Acid production rate 29.1 t H_2/TWh – green H_2 produced
ENGICOIN (ENGICOIN, 2017)	Microbial factory; chemical industry	Feedstock for chemical and plastic product production	Selling price 1.45 EUR/kg – lactic acid 3.5 EUR/kg – PHA 1 EUR/kg – acetone

BIOCONCO2 (BioConCO2, 2018)	Chemical industry	Feedstock for chemical and plastic product production	1.4 Mtonnes CO_2/year – capture at midterm 3.5 Mtonnes CO_2/year – capture at long term
CELBICON (Celbicon, 2016)	Chemical industry	Feedstock for chemical production	0.05 EUR/kWh – Electricity price 50 EUR/t - CO_2 price 1200–2500 EUR/t – Furic acid price 3500 EUR/t – Green H_2 price 1017 EUR/t – CO price 700–1500 EUR/t – Furfural price 290 EUR/t – Surfuric acid 96 % price 600 EUR/t – KOH 95 % price
RePLAy (RePLAy, 2019)	Chemical / Plastic industry	Feedstock for chemical product production	1.6 t CO_2 captured / 1 t product (lactic acid)
DECADE (Decade, 2020)	Chemical industry	Feedstock for chemical product production	1 g Final product (EA) /h – productivity
SELECTCO2 (SelectCO2, 2019)	Chemical industry	Feedstock for chemical production (ethanol or ethylene)	CO_2 Conversion efficiency: 90 % – CO 80 % – ethanol 90 % – ethylene
CO2 Intermediates (CO2 Intermediates, 2017)	Fuel industry	Feedstock for fuel production	5 kt/year – final product production rate (600 kg/h) 1.5 kg CO_2/kg Final product – glycerol production carbon footprint 0.4 kg CO_2/kg Final product – glycerol production carbon footprint incl. biogenic CO_2 allocation 4.7 EUR/kg – product overall expenses

Continuation of Table 7A

SUN-to-LIQUID (SUN-to-LIQUID, 2015)	Fuel industry	Feedstock for fuel production	2.0 EUR/L – production cost (baseline cond.) 1.2 EUR/L – production cost (favourable cond.) >100 kt CO_2/year/1 solar plant – CO_2 demand
KEROGREEN (KeroGreen, 2018)	Fuel industry	Feedstock for fuel production (kerosine)	0.1 kg/h – kerosine production rate 0.2 kg/kWh – CO production yield
eCOCO2 (eCOCO2, 2019)	Fuel industry	Feedstock for jet fuel production	250g Jet fuel / day
TRI-HP (Tri-HP, 2019)	Cooling	Refrigerant	2.2 kg CO_2/min – CO_2 mass flow rate
sCO2-HeRo (sCO2-HeRo, 2015)	Cooling	Refrigerant / Supercritical CO_2	650 g/s – mass flow rate of s CO_2
KUBBI (KUBBI, 2019)	Food processing	Refrigerant / Supercritical CO_2	Cooling capacity 10.000 litres/day

Continuation of Table 7A

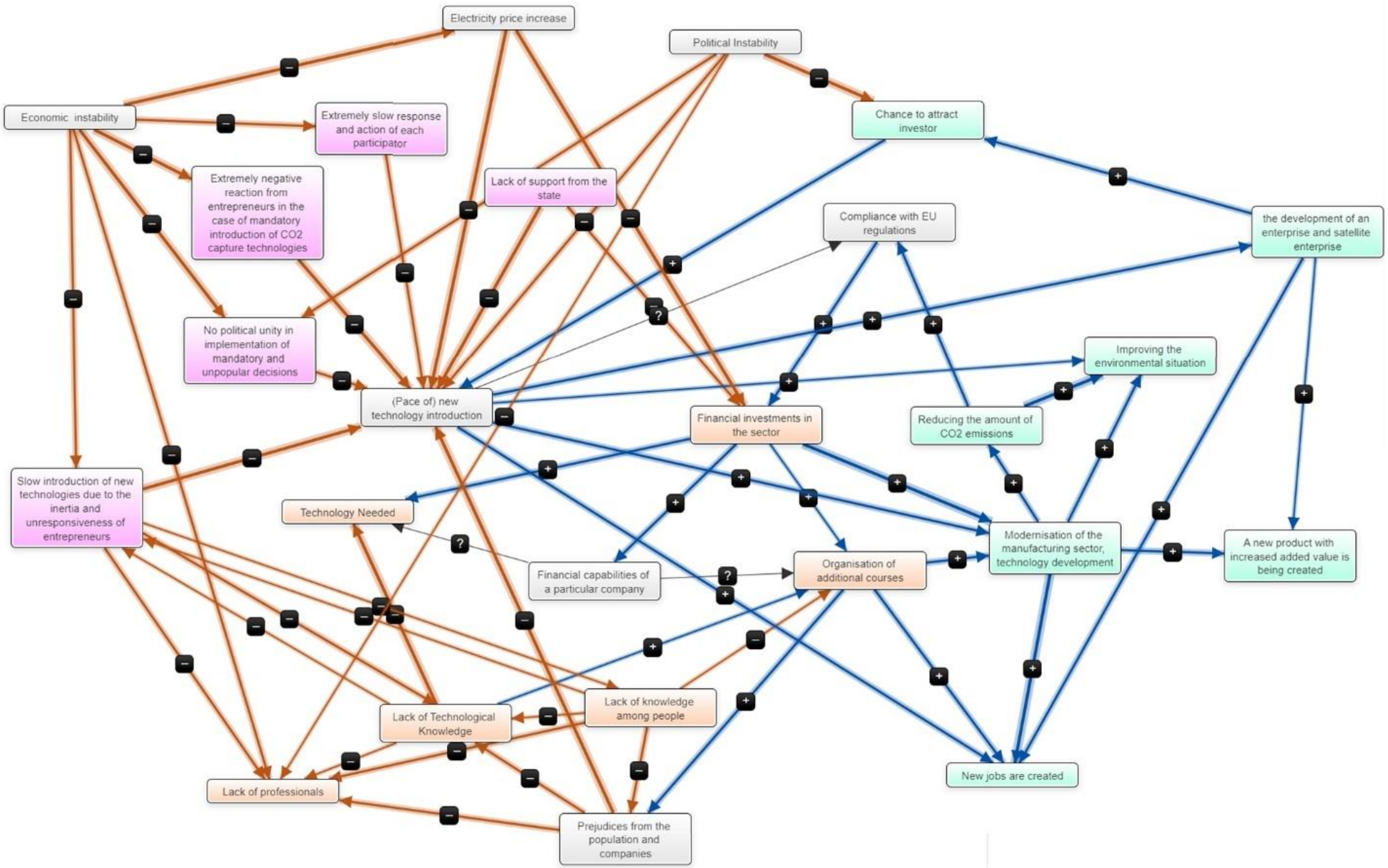
VALUEMAG (ValueMag, 2017)	Biorafinery	Parameter for algae; supercritical CO_2 extraction	35t algae/year – alga cultivation rate 0.3 EUR/kg biomas – price (4.9–6 EUR/kg – conventional price) 0.1 L/kg – water consumption 750 kW/day – energy consumption 7954 kg B-carotine / 9087 t biomass – Bcarotine yield from biomass 3158 kg B-carotine / 4358 t carrots – B-carotine yield form carrots 1096 kg B-carotine / 4095 t peaches – B-carotine yield from peaches 417 t w3 fatty acids / 29078 t biomass – w3 fatty acid yield 36.61 EUR/kg dry – lyophilization and extraction cost 600 EUR/kg – B-carotine cost (growth and extraction) 400 EUR/kg – w3 cost (G.+ex) PILOT SCALE: (b-carotine for D.salina biomass) 0.308 kgCO_2/min – CO_2 flow rate 1528.0 gCO_2/gr biomass – CO_2 and biomass ratio PILOT SCALE: (b-carotine for N.gaditiana biomass) 0.35 kg CO_2/min – CO_2 flow rate 2228.8 g CO_2/gr biomass – CO_2 and biomass ratio ESTIMATED COST: (based on energetical calculation for extraction b-carotine from microalgae biomass) 6.75 EUR/kg dry – Lyophilization (pre-treatment stage) 29.86 EUR/kg dry – CO_2-SFE extraction stage 36.61 EUR/kg dry – Total cost

BioLyco (BioLyco, 2019)	Food processing / medicine	Supercritical CO_2	10 t Final product/year 8 M EUR/year – revenue (40M EUR in 5 years) 16 new employees NPV – 14M EUR 0.82 M EUR/year – in 2018 1.3 M EUR/year – in 2019 1 kg CO_2/1kg of extraction matrix
ALGAEPRINT (AlgaePrint, 2014)	Chemical industry / Algae farms	Feedstock for chemical production	200 tCO_2/ha*year – CO_2 capture 600 tCO_2/ha*year – CO_2 capture by 3 ha plant 1800 tCO_2/ha*year – CO_2 capture by 9 ha plant
MacroFuels (MacroFuels, 2016)	Fuel production / Carbon capture	Feedstock for algae (ethanol, butanol, biogas production)	25 kg ww/m^2/year – seaweed yield (wet weight) per 1000 m^2/ha >4 %/l – bioethanol concentration 15 g./l – biobuthanol yield
ABACUS (Abacus, 2019)	Biorafinery	Parameter for algae	132.8 mg Final product/g resource 0.5–7000 mlCO_2/min – s CO_2 flow rate 6.6-19 % – extraction yield 70 % – goal yield
Dinophyte (Dinophyte, 2019)	Toxin production	Feedstock for algae	3–24 g Final Product (3 toxins)/year – production yield (for 200 L reactor) 2400 mg/Litre / D – biomass production capacity 1 g / year /200 L – Toxin Production yield 15 000 EUR /g – cost of production
MefCO2 (MefCO2, 2014)	Fuel industry	Feedstock for methanol production	1.5 CO_2 captured/ 1t of methanol 1 t Final product /day = 120 m^3/h – methanol production rate 55 kg MEOH/h – conversion efficiency 97 % – conversion efficiency 750–1200 – new employees

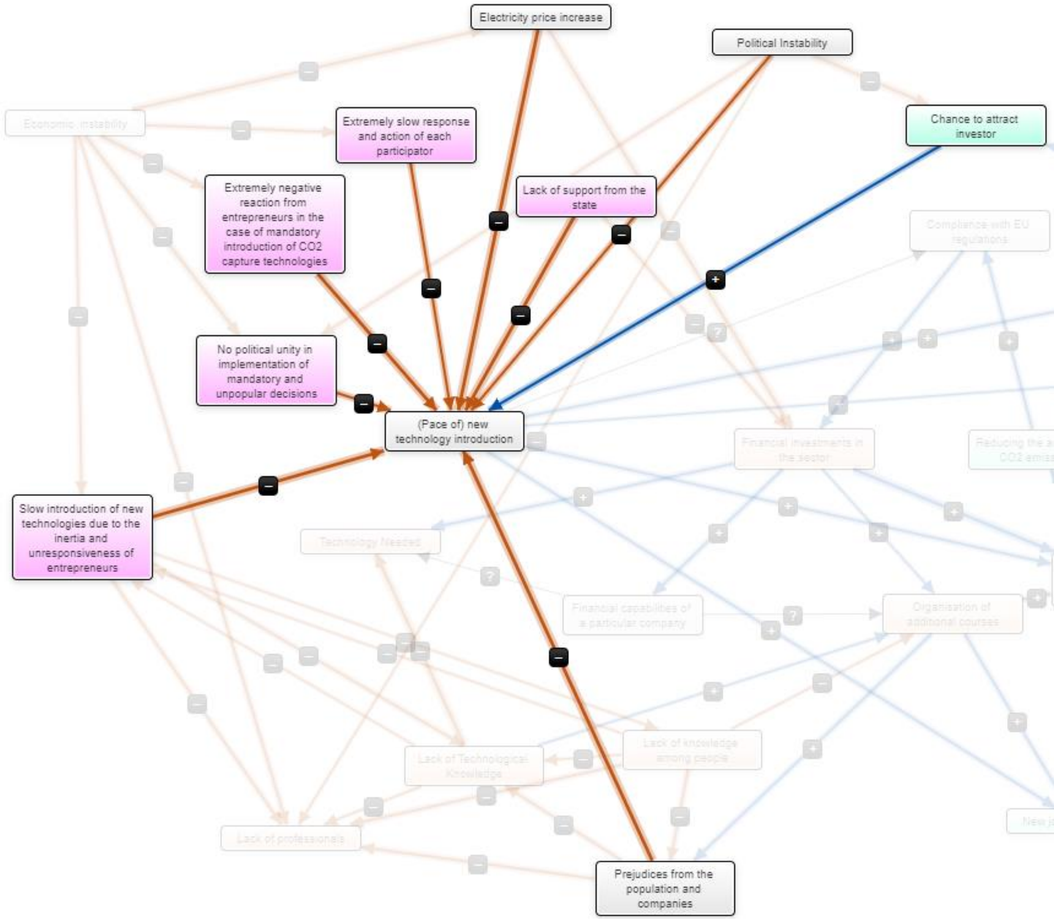
Continuation of Table 7A

MetaFuel (MetaFuel, 2015)	Fuel industry	Feedstock for methanol production	5 tCO_2/year – emission
ELECTHANE (Electhane, 2015)	Fuel industry	Feedstock for methanol production	4000 hr/year – working time
ProGeo (ProGeo, 2016)	Fuel industry	Feedstock for methanol production	25 Nm^3/h – methane production rate 25 EUR/MWh – electricity selling price 4.5–18 EUR/tCO_2 – CO_2 emission tax (before – 5–20 eur/tCO_2) 1 MEUR/year – turnover
CIRCLENERGY (CircleEnergy, 2017)	Fuel industry	Feedstock for methanol production	4 kt/year – methanol production rate 4 t CO_2/t methanol – emission during production 1.4 t CO_2/t methanol – CO_2 utilisation (consumption) 95.4 MEUR/year – annual profit
LOTER.CO2M (LOTER.CO2M, 2018)	Fuel industry	Feedstock for methanol production	>60 % – CO_2 conversion rate
NTPleasure (NTPleasure, 2018)	Fuel industry	Feedstock for methanol production	91.8 % – CO_2 capture efficiency 71.7 % – CO_2 utilisation efficiency 85 % – CO_2 conversion rate 84 % – CH_4 yield
FReSMe (FReSMe, 2020)	Fuel industry	Feedstock for methanol production	800 m^3/hr – input 50 kg/hr – production rate INVENTORY DATA FOR SEWGS UNIT: 0.6 mil steam/mol CO_2 – SEWGS steam consumption 6300 t sorbent/tCO_2 /y – Sorbent 0.013 t cat/tCO_2 / d – WGS Catalyst 0.54 t steel/ tCO_2 /d – Steel installed

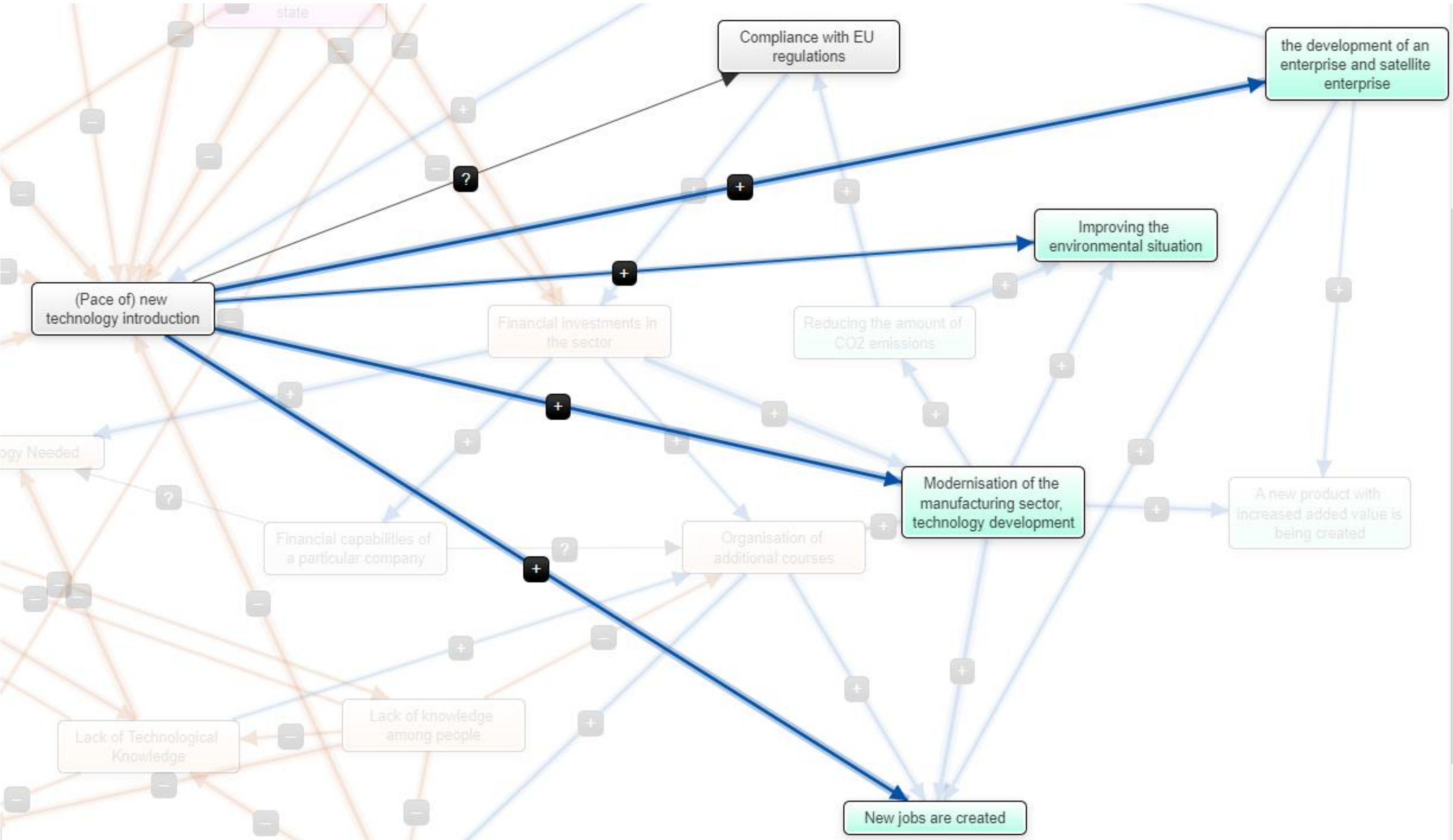
			TO PRODUCE 1 t OF HYDROTALCITE: 1.4 MWh/1 t product – electricity consumption 3.56 /1t product – Natural gas consumption 46 m^3/1t product – water consumption 0.66 t/1t product – MgC_{l2} 2.92 t/1t product – $Al(SO_4)_3$ 0.49 t/1t product – Na_2CO_3 0.52 t/1t product – NaOH 0.30 t/1t product – HCl 0.40 t/1t product – K_2CO_3 46 m^3/t sorbent – water



Annex B. Results of FLCM analysis.



Annex C. Factors, influencing the rate of introduction of technologies.



Annex D. Factors, which are influenced by the rate of introduction of new technologies.

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