

Viktorija Terjaņika

CO₂ VALORISATION IN CIRCULAR ECONOMY

Doctoral Thesis



RIGA TECHNICAL UNIVERSITY
Faculty of Electrical and Environmental Engineering
Institute of Energy Systems and Environment

Viktorija Terjaņika

Doctoral Student of the Study Programme “Environmental Engineering”

CO₂ VALORISATION IN CIRCULAR ECONOMY

Doctoral Thesis

Scientific supervisors:
Dr. sc. ing. JELENA PUBULE
Dr. habil. sc. ing. DAGNIJA BLUMBERGA

Riga 2025

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 (CO₂), 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, CO₂ valorisation is becoming a strategically important area for many countries striving for sustainable development. CO₂ valorisation involves converting CO₂ 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 CO₂ valorisation technologies is a pressing issue. This process is especially important for regions where CO₂ 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 CO₂ 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 CO₂ 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 CO₂ valorisation options for regional development and the study of barriers to sustainable implementation of technologies to the consideration of legal and economic aspects of CO₂ 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 CO₂ 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 CO₂ valorisation routes adapted to Latvian conditions.

The systematisation of these methods allows to create an integrated methodology, that includes sequential steps and recommendations for the implementation of CO₂ 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 CO₂ 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 CO₂ 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 CO₂;
- 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 (CO₂) emisijas – vienu no galvenajiem klimata pārmaiņu cēloņiem.. Viens no iespējamajiem risinājumiem ir valorizācija, proti, pievienot vērtību produktam, kas parasti tiek uzskatīts par blakusproduktu vai atkritumu. Mūsdienās CO₂ valorizācija kļūst par stratēģiski nozīmīgu jomu daudzām valstīm, kuras tiecas uz ilgtspējīgu attīstību. CO₂ 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, CO₂ valorizācijas tehnoloģiju izpēti un ieviešana ir steidzams uzdevums. Šis process ir īpaši svarīgs reģioniem, kuros CO₂ emisijas ievērojami pārsniedz pieļaujamos standartus un/vai kur nepieciešamas inovatīvas pieejas, lai uzlabotu vides situāciju.

Šajā promocijas darbā tiek piedāvāts CO₂ 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 CO₂ 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 CO₂ valorizācijas iespēju analīzes reģionālajai attīstībai un šķēršļu izpēti ilgtspējīgu tehnoloģiju ieviešanai līdz juridisko un ekonomisko aspektu izvērtēšanai CO₂ izmantošanā enerģētikas nozarē. Izmantotās metodes ietver:

- Reģionālās attīstības scenāriju novērtējums oglekļa uztveršanas un izmantošanas tehnoloģiju integrācijai enerģētikas sektorā;
- CO₂ 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 CO₂ valorizācijas ceļu ilgtspējas analīzei, pielāgojot tās Latvijas apstākļiem.

Šo metožu pielietojums un sistematizācija ļauj izstrādāt holistisku ceļvedi, kurā iekļauti secīgi soļi un ieteikumi CO₂ 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 – vēltā 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

CONTENT.....	7
GENERAL CHARACTERISTICS OF THE THESIS.....	9
1. LITERATURE ANALYSIS	16
1.1. Relevance of Key Performance Indicators in CO ₂ Valorisation Context	18
1.2. Geographical Aspects of CO ₂ Valorisation Potential	22
1.3. Strategic Importance of SWOT Analysis for CO ₂ Valorisation	23
1.4. Public and Business Attitudes Towards CO ₂ Utilisation.....	27
1.5. Role of Legislation in Shaping CO ₂ Valorisation Pathways.....	30
1.6. Policy Support of CCUS Technologies Introduction	32
1.7. The Significance of GHG Inventories in Biomass Utilisation and Energy Planning	35
1.8. Motivation for Transition to Biomethane Production	37
1.9. Sustainability Perspective through Life Cycle Assessments	38
2. METHODOLOGY.....	42
2.1. Approach to Evaluating Key Performance Indicators	42
2.2. Data Sources and Tools for Geospatial Mapping	45
2.3. Framework for SWOT Analysis of CO ₂ Utilisation.....	47
2.4. Survey Design and Stakeholder Engagement Methods.....	50
2.5. Legal Review Method for National and International CO ₂ Policies	52
2.6. Assessment Criteria for Supportive Legislative Measures	53
2.7. GHG Inventory Methodology for Logging Residue Scenario.....	56
2.8. Transition Emission Analysis: Switch to Biomethane Production	63
2.9. LCA and S-LCA Methodologies for CO ₂ Valorisation Projects	65
3. RESULTS.....	72
3.1. Findings from KPI Assessment of CO ₂ Valorisation	72
3.2. Spatial Distribution of CO ₂ Valorisation Potential.....	74
3.3. Identified Strengths, Weaknesses, Opportunities and Threats of CO ₂ Valorisation	78
3.4. Survey Outcomes: Perceptions of CO ₂ Emissions Among Stakeholders	87
3.5. Comparative Analysis of CO ₂ Legislation Across Jurisdictions.....	97
3.6. Evaluation of Policy Instruments Supporting CO ₂ Technologies.....	105
3.7. Emissions Data from Biomass-Based Product Scenario	110
3.8. Impact of Energy Shift on GHG Emissions.....	113

3.9. Environmental and Social Impacts Based on LCA and S-LCA	121
4. DISCUSSION	128
5. CONCLUSION	132
REFERENCES	135
DOCTORAL THESIS PUBLICATIONS	164
ANNEX	282

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 CO₂ is becoming especially relevant. CO₂, 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. CO₂ valorisation is a promising direction in which CO₂ 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 CO₂ 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 CO₂ 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 CO₂. The aim is to develop an integrated methodology, that identifies the requirements, drivers and challenges for CO₂ 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 CO₂ in Latvia;
3. To map and analyse major CO₂ 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 CO₂ utilisation initiatives;
6. To explore opportunities for integrating CO₂ 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 CO₂ valorisation technology can be applied to evaluate the possibility of CO₂ 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 CO₂ valorisation pathway development, starting with analysis and till implementation.

Scientific novelty of the thesis

This thesis proposes a novel, interdisciplinary methodology for assessing CO₂ 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 CO₂ 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 CO₂ 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 CO₂ valorisation;
- Social Life Cycle Assessment – to evaluate human and societal impacts linked to CO₂ valorisation.

While many of the applied methods have been applied individually in studies of CO₂ management or circular economy, this research is among the first to combine them into a comprehensive, scenario-based framework for evaluating CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions, finding the optimal solution and technological development of the region.

Structure of the thesis

The thesis is a collection of ten 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 CO₂ 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 CO₂, 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 CO₂, 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.

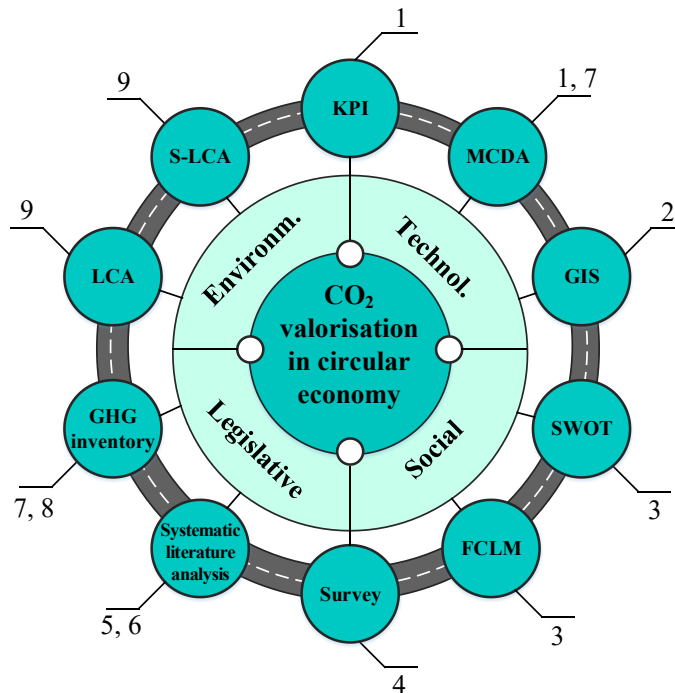


Fig. 1. Scheme of the thesis.

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 CO₂ valorisation in Latvia.

This thesis is based on the following scientific publications:

1. **Terjanika V.**, Pubule J., Gusca J., Blumberga D. Analysis of CO₂ 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 CO₂ Valorisation. *Sustainability* 2022:14(9):5054. doi: 10.3390/su14095054 (Q1)
4. **Terjanika V.**, Vetrinska L., Pubule J. CO₂ 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 CO₂ 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 CO₂ Valorisation Support. *e-Prime - Advances in Electrical Engineering, Electronics and Energy* 2023:4:100181. doi: 10.1016/j.prime.2023.100181 (Q2)
7. Viksne G., Vamza I., **Terjanika V.**, Bezrucko T., Pubule J., Blumberga D. CO₂ 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.**, Pubule J. Sustainability Assessment of CO₂ Valorisation Routes for Latvia: LCA and S-LCA Approach (submitted to *Environmental and Climate Technologies*)
10. **Terjanika V.**, Laktuka K., Vistarte L., Pubule J., Blumberga D. Co-creating low-carbon futures: An open innovation roadmap for regional CO₂. *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:

11. 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

12. Kramens J., Vigants E., Liepins I., **Terjaņika 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
13. Bezrucko T., Lauka D., Laktuka K., Sniega L., Vamza I., Dzalbs A., **Terjaņika 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
14. Valtere M., Kaleja D., Kudurs E., Kalnbalkite A., **Terjaņika 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
15. Kalnbalkite A., Brakovska V., **Terjaņika 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)
16. **Terjaņika 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, Environmental	9	Sustainability Assessment of CO ₂ Valorisation Routes for Latvia: LCA and S-LCA Approach

Approbation of the thesis

1. International Scientific Conference CONECT 2021, 12–14.11.2021, Riga Technical University, Riga, Latvia;
2. 2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTU CON), 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.

This research is funded by the Latvian Council of Science, project CO₂ Deal: Effective Valorisation of CO₂ for Decarbonised Regional Development, project No. lzp-2020/1-0302.

This work has been supported by the European Social Fund within the Project No 8.2.2.0/20/I/008 “Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialisation” of the Specific Objective 8.2.2 “To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialisation Areas” of the Operational Programme “Growth and Employment”.

1. LITERATURE ANALYSIS

The need to address climate change and reduce greenhouse gas emissions brings CO₂ 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. CO₂ 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 CO₂ emissions while creating multiple opportunities to transform carbon into valuable resources. Moreover, CO₂ 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. CO₂ 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 CO₂ valorisation methodology. The analyses are based on various aspects – technical, social, natural and legislative, which allows for a comprehensive assessment of the impact of CO₂ 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 CO₂ 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 CO₂. If not, it is assessed whether CO₂ 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 CO₂ 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 CO₂ valorisation scenario.

In parallel, if CO₂ can be valorised not through CCU technologies but by an alternative way (e.g., by emission avoidance), a calculation of the potential CO₂ emission reduction within such a scenario is carried out. The algorithm of methodology is depicted in Fig. 2.

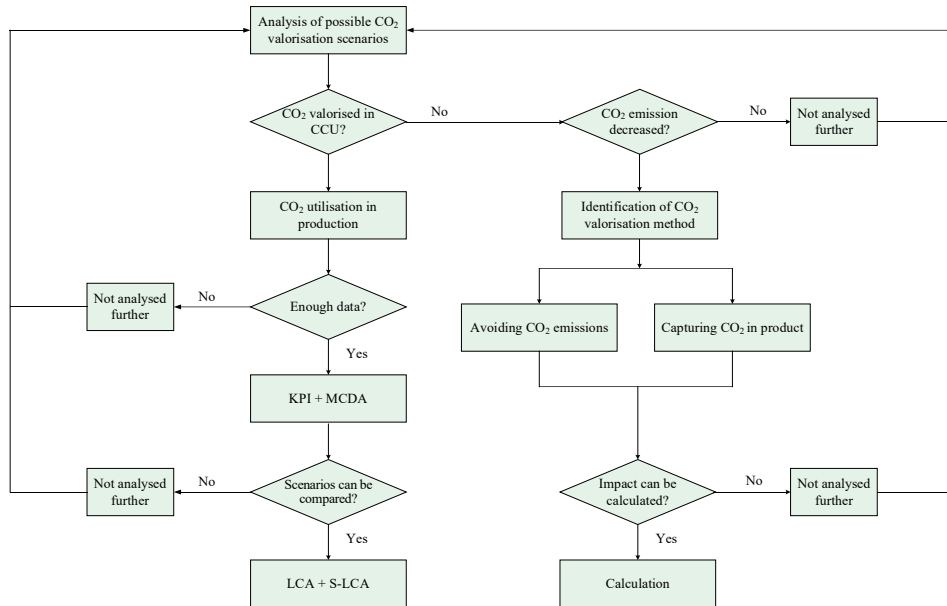


Fig. 2. Algorithm of the scenarios, chosen for specific analysis in the methodology.

In the thesis, offered CO₂ valorisation methodology analyses various CO₂ 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 CO₂ 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 CO₂ 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 CO₂ valorisation possibilities through CCUS technologies. Using this approach, the study aims to answer critical questions about the potential, challenges and implications of different CO₂ valorisation strategies. The selected analytical methods provide a robust basis for the developed CO₂ 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 CO₂ 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 CO₂ Valorisation Context

The growing amount of CO₂ is a serious problem in today's world. The increase in the amount of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ (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 CO₂ emissions, but still amount is too high (European Parliament, 2021; IEA, 2022c) (Fig. 3).

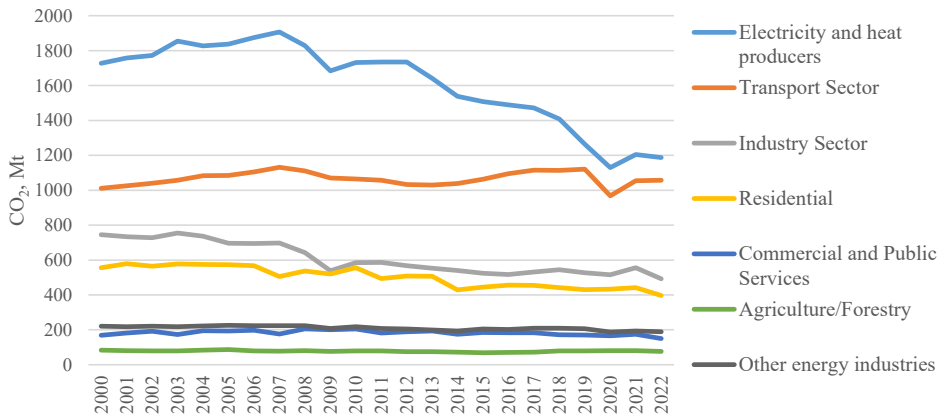


Fig. 3. CO₂ emissions in European Union 2020–2022, by sector (IEA, 2022c).

Despite the fact that in the period 2000 to 2025 the amount of CO₂ emissions in the European energy sector show a decline, this sector is still one of the leaders in terms of CO₂ 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 CO₂ emissions is rising steadily.

The biggest amount of CO₂ 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).

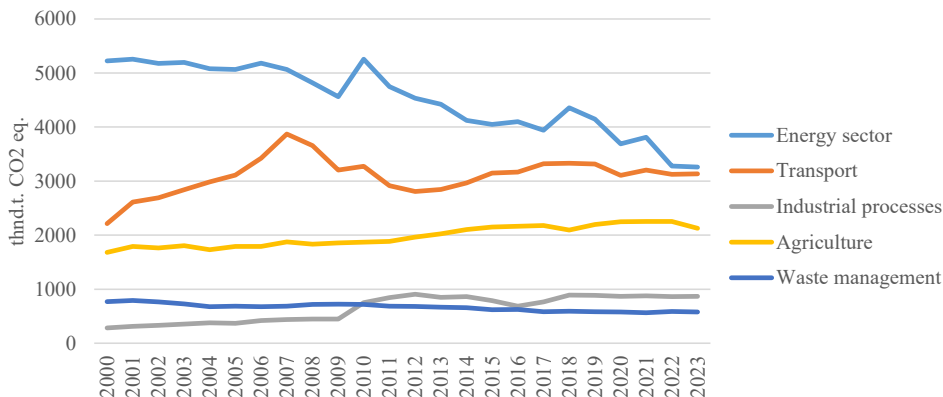


Fig. 4. CO₂ emissions in Latvia sectors in 2000–2023 (Official statistics portal, 2025).

Implementation of new technologies could help to decrease the environmental load – in Latvia energy sector shows decline in CO₂eq emissions, but it is mainly achieved because of biomass combustion (biogenic CO₂ is excluded from total CO₂ 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 CO₂ 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 CO₂ in the country (European Parliament, 2021). It is necessary to systematise the spheres of production and select those sectors that can use CO₂ 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.

CO₂ 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 CO₂ 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 CO₂ in the atmosphere, the introduction of new technologies will create additional jobs, which will have a positive effect on the economy as a whole (LVGMC, 2020).

Within the framework of the H2020 program, many projects are being implemented, the purpose of which is the production of biofuel, using CO₂ as one of the resources. The MefCO₂ projects a good example of this use of CO₂. The project is a working technology that captures and uses CO₂ from a power plant in Germany. The plant uses coal for energy production, the combustion of which emits large amounts of CO₂, thus capturing and then using this CO₂ 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 CO₂ 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 CO₂ is increasingly seen as a resource within the circular economy, its use demands specific capture and purification technologies. CO₂ 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 CO₂ without complex purification process, while others require as pure CO₂ as possible.

In the construction sector, CO₂ can be injected into concrete (carbonation process), where CO₂ 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, CO₂ is being repurposed as a reducing agent in emerging pilot processes. For example, plasma-based CO₂ splitting transforms CO₂ into CO, which can partially replace coke or coal in blast furnaces. Additionally, pilot CO₂ capture units on blast furnaces are being implemented, demonstrating the potential emission decrease in the sector (ArcelorMittal, 2024).

CO₂ 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 CO₂) or a solvent. It can be utilised in production of syngas, methanol and fuel (Phoenix Initiative, 2018). During the fermentation of biomass CO₂ is released, which can be separated from the main stream and utilised in methanol, ethanol or biomethane production. In combustion processes (like boiler houses), CO₂ 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 CO₂ utilisation projects, as well as the demand for CO₂, is growing every year. In 2018, the leaders in the use of CO₂ 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 CO₂ is expected to be 272 MtCO₂ by 2025 (Bellona, 2012; IEA, 2019).

For the successful implementation of CO₂ 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 CO₂ consumed per ton of product or the volume of CO₂ emitted during the production of a new product. Within the framework of the developed methodology, the identification of CO₂ parameters and the determination of the optimal scenario represent the first step.

1.2. Geographical Aspects of CO₂ Valorisation Potential

The second step in the process of implementing CCUS technology is the identification of CO₂ emission sources within the country and the locations where it can potentially be utilised.

The amount of CO₂ emissions is different in every sector of every country. According to statistics, the energy sector is a leader in the production of CO₂ 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 CO₂ 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 % CO₂). 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 CO₂ 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. tCO₂eq 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 CO₂ 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 CO₂ produced. Despite the positive aspects of introducing technologies for capturing and using CO₂ 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 CO₂ is the required level of its purification from impurities. For example, for the use of CO₂ 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 CO₂, 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 CO₂ for biostations as well (Leonzio et al., 2019; Sieborg et al., 2024). Because of this high level of purification required, before using CO₂ as soon as it is produced, it is necessary to first ensure its purity. The main emitter of CO₂ in Latvia is the energy sector, however, combustion of fuel emits not only CO₂, but other elements as well (Murugan et al., 2020), (EPA, 2023). Installation of additional elements is required to ensure the capture of CO₂ 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 CO₂ produced at the enterprise and makes it possible to produce goods with increased added value.

However, CO₂ is not only a waste product of production, but also a potential resource for creating new high value-added products. Potentially, CO₂ 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 CO₂ could be the energy sector. Nowadays CO₂ 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) CO₂ can also be used in algal ponds. According to (G. Li & Yao, 2024), CO₂ 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 CO₂ in the energy sector can significantly diversify this market, which will have a positive effect on the sector.

By identifying the possibilities for CO₂ utilisation and the technologies already available globally, it becomes possible to analyse in greater detail the sectors in Latvia that could potentially capture CO₂, as well as those that could utilise it. Depending on the place where CO₂ is produced (affects the share of possible impurities in the CO₂ flow), volume of CO₂ 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 CO₂ producers and consumers, which may further enhance the effectiveness of CCUS implementation. Thus, the second step of the methodology – identification of CO₂ points – is being completed.

1.3. Strategic Importance of SWOT Analysis for CO₂ 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 CO₂ 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 CO₂ 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.

CO₂ is generated in many sectors (Fig. 4). Although generated amount of CO₂eq emissions is showing a decrease, simultaneously utilisation of biofuels is showing a high incline (Fig. 5) (IEA, 2025).

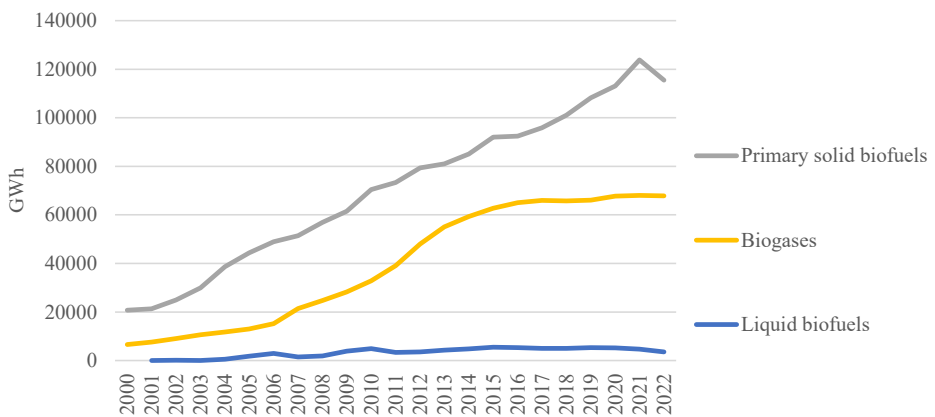


Fig. 5. Energy generation from biofuels in Europe, GWh (IEA, 2025).

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 CO₂ they produce or capture and/or use CO₂.

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 CO₂ 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-empt 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 CO₂ and transporting it to places of further disposal (storage sites) or use for the production of new products.
2. Capture of CO₂ and its use in production right away

CO₂ 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 % CO₂ (Hou et al., 2022), (Gkotsis et al., 2023), and installations using adsorption allow achieving a purity of the main CO₂ stream up to 95 % and recovery of the flow up to 80 % (Hou et al., 2022), (Karimi et al., 2023). CO₂ capture plants separate CO₂ from the overall production gas stream. Such technologies are usually installed in industries with a high content of CO₂ in the exhaust, for example, at heating stations and large industries (Eliasson et al., 2022).

As CO₂ 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 CO₂ 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 CO₂ storage sites (Becattini et al., 2022).

For the analysis of CO₂ 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 CO₂ 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 CO₂ decreasing technologies and to mitigate the amount of CO₂ 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 CO₂ (IPCC, 2022). Even though in Latvia, in comparison with other countries, the amount of CO₂ produced is not so large, even this amount must be taken into account since the consequences caused by CO₂ 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.

CO₂ Utilisation Possibilities

By 2021, 65 commercial CO₂ 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 CO₂ 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 CO₂ emissions both in the manufacturing sector and in the world as a whole. The purpose of these technologies is to prevent CO₂ from being released into the air. Later, this captured CO₂ is transported to certain places intended for long-term storage of CO₂. 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 CO₂, its subsequent purification and liquefaction. The next step is the transportation of liquefied CO₂ to the places of its further storage or use. Usually, special pipes or transport (for example, gas ships) are used for transportation. As for CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.

CO₂ 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 CO₂ (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 CO₂ capture. In the future, the captured CO₂ could be used to produce carbon-negative biofuels (European Commission, 2021h). To determine the possibility of capturing CO₂, it is necessary to analyse the existing legislation of both the European Union and Latvia.

CO₂ Utilisation in Products – CCS / CCU Technologies

Innovative installations for capturing and using CO₂ 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 CO₂ in complex products – chemical compounds, fuels, etc. Since CO₂ 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 CO₂ 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 CO₂ 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 CO₂ capture units with a capture efficiency of up to 1.5 million tons of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ utilisation in production in the European Union cannot be called even. In some countries, technologies allow the use of CO₂ 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 CO₂ utilised by 2050.

Although, measures to reduce the amount of CO₂ 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).

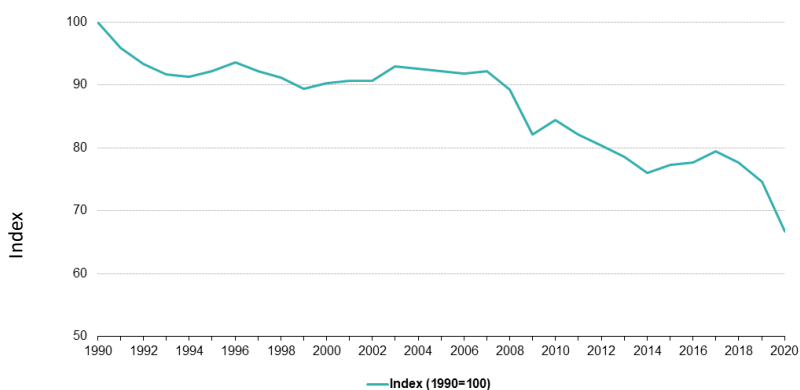


Fig. 6. Total GHG emissions in the European Union, excluding land use, land use change and forestry, but including international aviation (Lyons et al., 2021).

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).

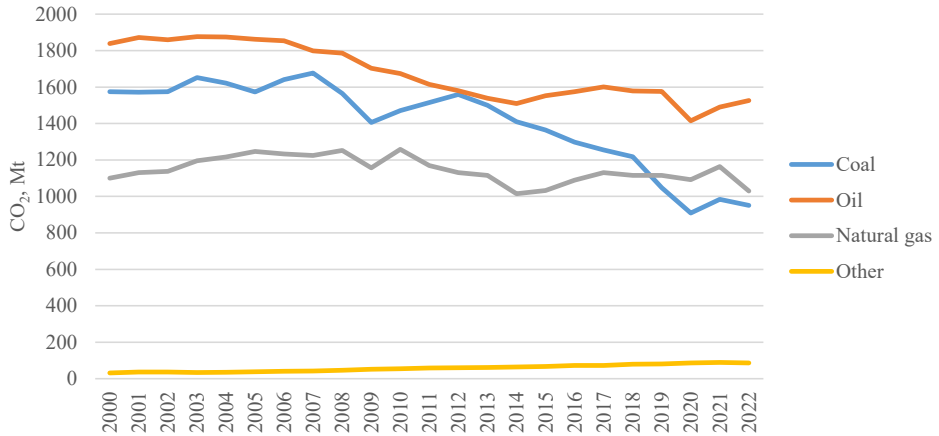


Fig. 7. Annual CO₂ emissions in the world from fossil fuel (excluding land-use)(IEA, 2025).

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions that are otherwise very difficult to reduce (Fig. 8).

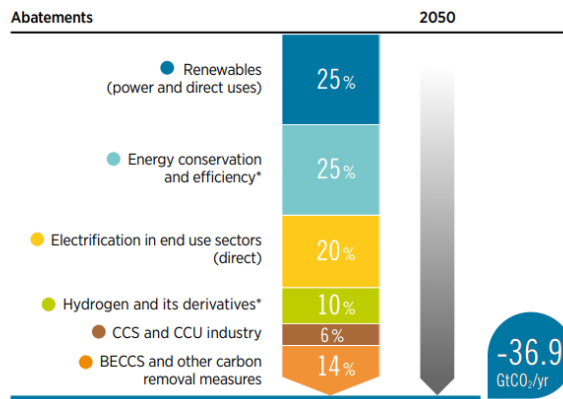


Fig. 8. Carbon emissions abatements, IRENA report (Lyons et al., 2021).

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 analyse the legislative framework of the European Union countries and determine their elaboration regarding the fight against CO₂ emissions. Even though the European Union Regulation 2021/1119 (European Commission, 2021j) indicates countries to the need to reduce CO₂ 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

CO₂ 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 CO₂. Another method involves using what is considered waste in the production of a new product. In this way, the CO₂ 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 CO₂).

This step of the methodology specifically examines the possibility of reducing CO₂ emissions in the forestry sector through their storage in a new product.

Forestry, like other production sectors, is also responsible for a portion of CO₂ 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 CO₂ emissions. On the other hand, wooden products may be a solution for CO₂ 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 m³ of logged wood material removed, 1 m³ 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 CO₂ sequestration. It has been observed that there exists a direct correlation between the amount of CO₂ 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).

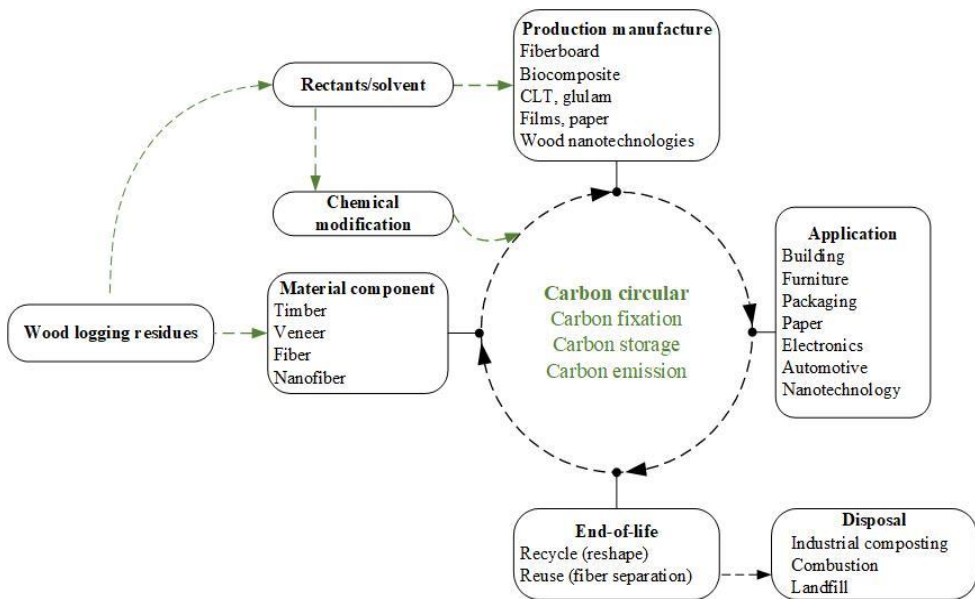


Fig. 9. The sustainable carbon cycle of wood logging residues (Tripathi et al., 2019).

In the wood-based product sector, significant potential for CO₂ 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 CO₂ balance in the atmosphere. It was calculated that 1 m³ of PB and OSB sequester 720 kg of CO₂ each and that a cubic meter of MDF sequesters 820 kg of CO₂, 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 m³ 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 m³ 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 CO₂ 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 CO₂ 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 CO₂ 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 (CH₄), which is classified as low-grade biogas), the remaining 40–50 % are products in the form of CO₂ (Abd et al., 2023; Ayub et al., 2022; IEA Bioenergy, 2020). The purification process involves the removal of CO₂, leaving pure methane. The resulting CO₂ 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 CH₄ content in the mixture raises the calorific value of the gas, making fuel much more valuable. The leading technology for CO₂ 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 CO₂ 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 CO₂ emissions in Latvia highlight the energy production sector as the primary area for the application of CCU technologies. The largest emitter of CO₂ is heat production plants, which in 2022 produced 24.2 % of total CO₂eq 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 CO₂ production and CO₂ utilisation.

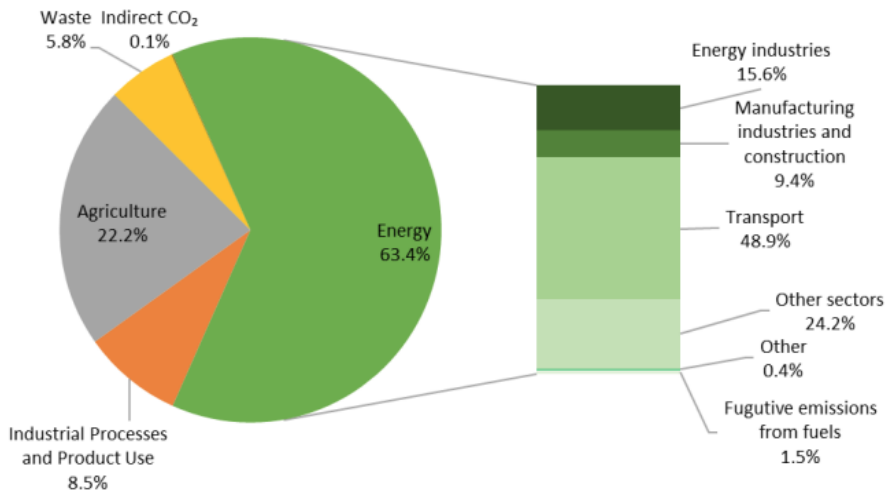


Fig. 10. CO₂ emissions in Latvia, 2022 (Skrebele et al., 2024).

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 CO₂ 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 CO₂ valorisation and the creation of carbon-based materials. It highlights promising advancements in photoelectrochemical conversion of CO₂ 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 CO₂ utilisation scenarios – methanol and sustainable aviation fuel (SAF) ethanol production – in the context of Latvia. The sustainability assessment addresses potential environmental impacts of CO₂ 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 CO₂ 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 CO₂ 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 assess CO₂ 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 CO₂ 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 CO₂ valorisation scenarios. This is necessary to understand the requirements for technologies (for CO₂ 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 CO₂ valorisation: literature review, HORIZON2020 data analysis (H2020) (European Commission, 2021) Key performance indicators analysis and Multi-Criteria Decision analysis.

Literature sources were used to search for methods of utilising CO₂ 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 CO₂ 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 CO₂ utilisation are collected. Next step after H2020 project analysis is to select main CO₂ 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 CO₂ valorisation, which would be applicable in Latvia. An algorithm of the analyses applied in this research is depicted in Fig. 11.

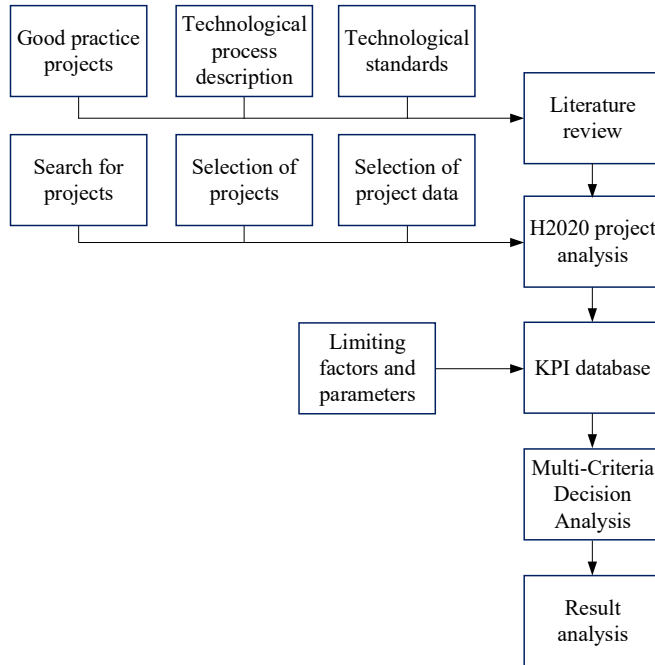


Fig. 11. Methodological scheme.

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 CO₂.

Analysing the H2020 program, out of more than 32,000 projects, it was possible to sort out 242 projects in which CO₂ 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).

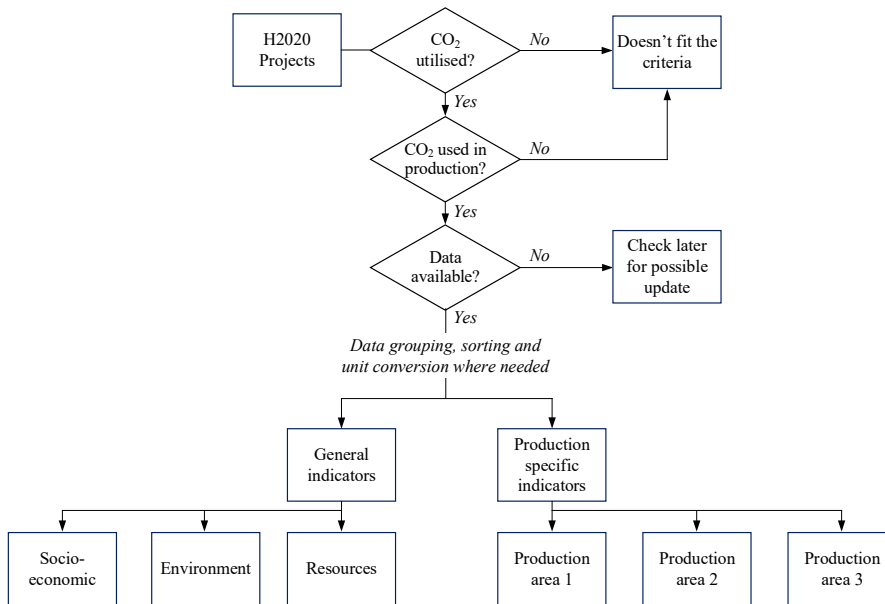


Fig. 12. Algorithm of H2020 project processing and KPI database compiling.

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 CO₂ 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 CO₂. For example, the main indicators are such indicators as electricity consumption per ton of product produced / ton of CO₂ produced (MWh/t and MWh/tCO₂), the amount of CO₂ required to produce a ton of product and the amount of CO₂ created during the production of a ton of the final product (tCO₂ utilised/t product, tCO₂ generated/t product), as well as the ratio of required and generated CO₂ (tCO₂ utilised/tCO₂ generated), etc.

Multi-Criteria Analysis

Multi-Criteria Analysis was carried out to analyse the degree of importance of each CO₂ 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 CO₂, several criteria have been used:

- Amount of permitted additive in CO₂ flow;
- Electricity per 1 tonne of product;
- Amount of CO₂ utilised;
- Amount of CO₂ 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.

	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 CO₂ 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 CO₂ in the production of new goods. The factors limiting the use of CO₂ 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 CO₂ 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 CO₂ emissions were obtained from companies' annual reports.
3. Unfortunately, the mentioned government agencies did not always contain the necessary data on the amount of CO₂ 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 CO₂ – 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 CO₂ 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 CO₂ and its potential use were marked on the maps of Latvia in the *ArcGis* programme.

2.3. Framework for SWOT Analysis of CO₂ 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 CO₂, potential internal and external factors that may affect CO₂ 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.

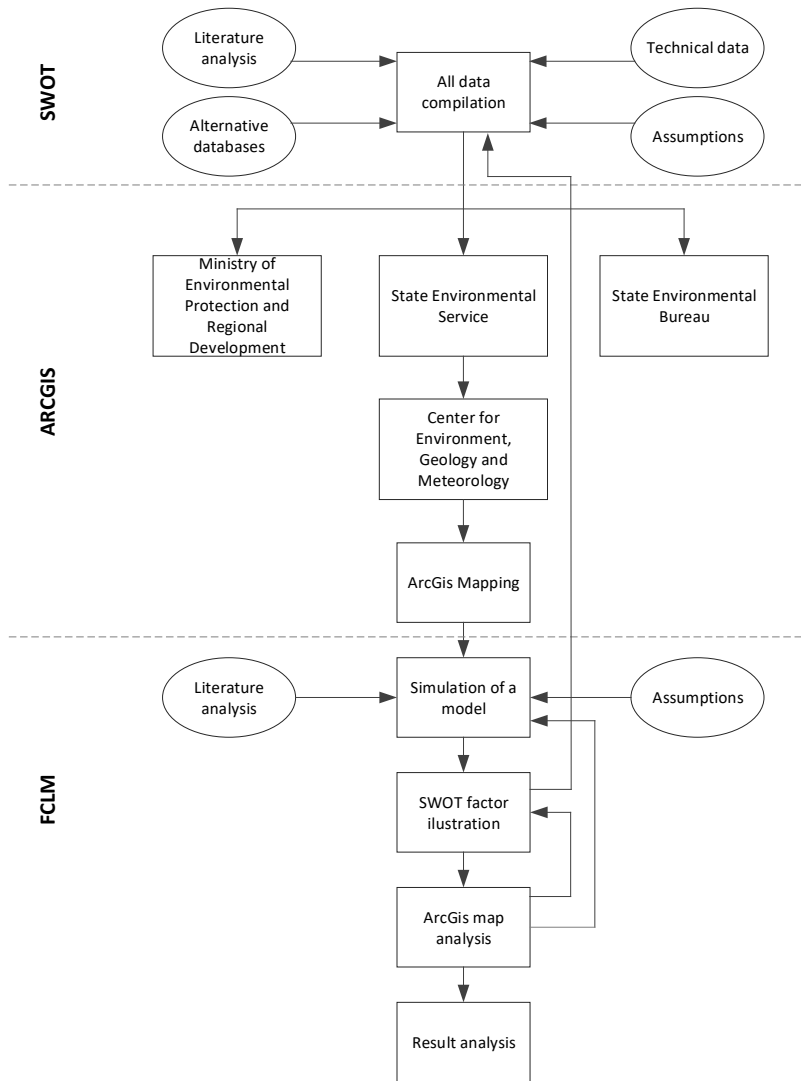


Fig. 13. The algorithm of the performed work.

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 CO₂ valorisation options have been observed: a) CO₂ capture and utilisation in Europe; b) CO₂ capture and utilisation in the case of Latvia; c) CO₂ 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 CO₂ is the distance from the manufacturer to the buyer. Geographical analysis can indicate whether the distance within one country is an obstacle to CO₂ valorisation. This could also potentially define so-called CO₂ production and use clusters based on specific criteria (e.g. required CO₂ 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 CO₂ 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 CO₂ 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):

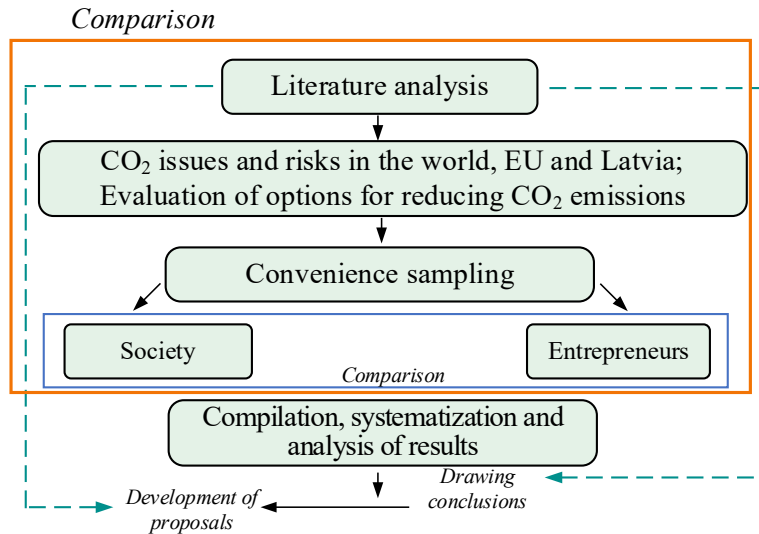


Fig. 14. Algorithm of the survey.

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 CO₂ emissions, possible actions to reduce them, and the willingness of respondents to pay for these emissions.

To determine people's opinions on CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ Policies

Next step of the methodology is a comparative legal review method, which is applied to examine regulatory frameworks governing CO₂ 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 CO₂ emissions. The research included a search and subsequent accounting for CO₂, CCS, CCUS, CCU, carbon/ CO₂ utilisation, carbon/ CO₂ capture, and carbon/ CO₂ storage. The analysis of legislative sources on the opportunities provided for using, capturing, and storing CO₂ was based on the political framework, policy instruments, and CO₂ 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).

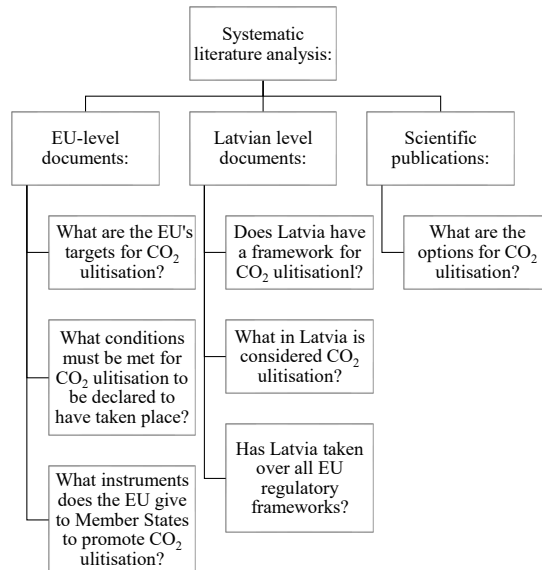


Fig. 15. Systematic literature analysis steps

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 CO₂, 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ recovery?
- What conditions must be met for CO₂ recovery to be recognised?
- What tools does the EU provide the Member States to promote CO₂ recovery?

Scientific papers:

- What are the possibilities for CO₂ utilisation?
- What is the experience of other countries and cases?

A search strategy is developed to identify relevant literature on policy instruments for CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.

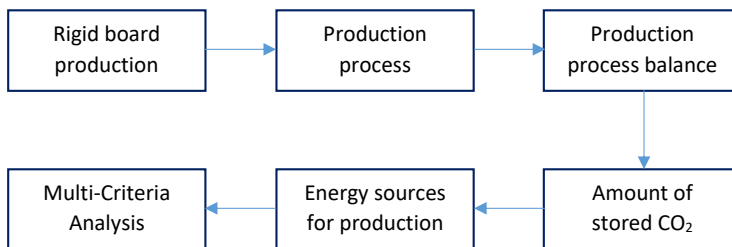


Fig. 16. Algorithm of the methodology.

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/m³. 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).

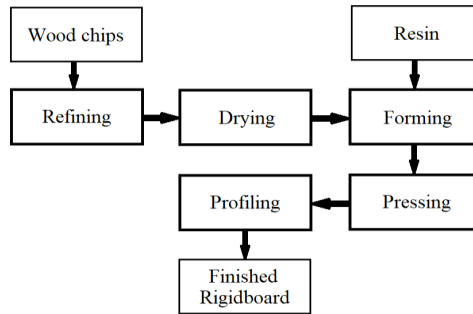


Fig. 17. Simplified rigidboard manufacturing process (Tellnes et al., 2017).

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/m³	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 m³ 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 m³ 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 m³ 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 CO₂ 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 CO₂ stored in the material is assumed to be the same for all standards and is calculated (Latvijas Radio, 2022):

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

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);
$m.mCO_2$	molecular mass of CO ₂ = 44 g/mol;
$m.mC$	atomic mass of carbon = 12 g/mol.

By substituting the masses of carbon and CO₂, 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 CO₂ sequestered in the finished product and $m_{dry}(timber)$ is the dry weight of timber in the finished product.

Only the CO₂ 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 CO₂ 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 CO₂ 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 CO₂.

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 m³ 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 CO₂ 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 km² (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 Nm³ 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:

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

where

E	Total amount of emissions from the biomethane production (before energy conversion), kg CO ₂ eq/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), gCO ₂ eq/MJ final product;
e _{td,feedstock,n}	Amount of emissions from the transport of feedstock n to the digester, CO ₂ eq/MJ final product;
e _{1,n}	Annual emissions from carbon stock changes due to land usage for feedstock type n, gCO ₂ eq/MJ final product;
e _{sca,n}	Emissions savings from improved agricultural management of feedstock type n, gCO ₂ eq/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 ₂ eq/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 ₂ eq/MJ final product;
e _{ccr}	Emission savings from carbon capture and replacement, gCO ₂ eq/MJ final product

Parameters e_{ec}, e_t, e_p, and e_u are calculated according to Eq. (4):

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

Eq. (1) and (2) are the basis for the following calculations. Even though parameter e is calculated in [gCO₂/MJ of the final product (CH₄)], it is also recommended to calculate it per mass of the intermediate product (as [gCO₂/kg product]) and only at the end allocate the parameter to the final product.

2.9. LCA and S-LCA Methodologies for CO₂ 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 CO₂ 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

CO₂ 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 CO₂ 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 CO₂ as a feedstock offers significant advantages, including the potential to reduce the overall carbon footprint of the process.

One approach to CO₂ utilisation involves combining captured CO₂ 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 CO₂, 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/Al₂O₃ 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 CO₂.

The project “*Creating added-value chemicals from bio-industrial CO₂ emissions using integrated catalytic technologies*” (European Commission, 2021d) highlights that converting CO₂ 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 CO₂ conversion to renewable methanol through innovative heterogeneous catalyst systems optimised for advanced hydrogenation technologies (microwave, plasma, and magnetic induction)*” (European Commission, 2021f), aims to develop hydrogenation-based methods for converting CO₂ into renewable methanol.

Currently, Latvia imports all of its fuel, making energy security a critical concern. Establishing domestic methanol production from CO₂ 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

CO₂ 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 CO₂ straight from the atmosphere, making a direct contribution to reducing CO₂ emissions. Sustainable fuel production typically involves the electrolysis of water to produce hydrogen, which is then combined with CO₂ through the Fischer–Tropsch synthesis process. Another approach involves using methanol as an intermediate, starting with the hydrogenation of CO₂ 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 CO₂ 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; Bayazit 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; Bayazit 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 CO₂ through fuel production. The two scenarios are:

- Scenario 1: CO₂ utilisation for the production of methanol;
- Scenario 2: CO₂ utilisation for the production of sustainable aviation fuel (SAF-ethanol).

The Functional Unit (FU) chosen for both scenarios is 1 kg of CO₂ treated in each respective scenario.

Goal and Scope

The goal of conducting E-LCA of CO₂ utilisation in fuel production is to evaluate the social and environmental impacts associated with the production, use, and disposal of CO₂ 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 CO₂ 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 CO₂ utilisation in methanol and SAF-ethanol production scenarios;

- Assessment of potential impacts, both positive and negative, associated with CO₂ utilisation in each scenario;
- Recommendations for improving the social and environmental sustainability of CO₂ utilisation based on the analysis outcomes.

Both assessments adopt a gate-to-gate approach, focusing on the impacts directly associated with the CO₂ 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 CO₂ utilisation in Latvia. However, due to regional similarities in CO₂ 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 ₂ O/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
		NM VOC, 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: CO₂ (supplied externally), enzymes, potassium carbonate, ammonium chloride, electricity, and water.

Production process: SAF is produced from CO₂ and H₂O via chain of reactions – direct synthesis of hydrocarbon from CO₂, purification, conversion, separation, oligomerisation and hydrogenation.

Output products: Ethanol.

System boundaries:

- Excluded from the analysis:
 - S-LCA and E-LCA: prior purification of CO₂, transportation of raw materials and final products to end-users.
 - CO₂ 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 CO₂ valorisation opportunities.

3.1. Findings from KPI Assessment of CO₂ Valorisation

Key Performance Indicator analysis

In the process of analysing the methods of CO₂ valorisation, both existing and on-going projects for the use of CO₂ in production and projects from the H2020 program were researched.

During the analysis of H2020 projects (the purpose of which is to use CO₂ 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 CO₂ and required CO₂ ratio), 12 – environment-related (e.g., Total emission during production process and Possible CO₂ capture system efficiency), 18 – economy-related (e.g., Costs of CO₂ if buying, Total costs for CO₂ if doing nothing). The table (Annex A) also includes 28 indicators specific to the scope of potential CO₂ applications, for example, methanol production (CO₂ conversion rate), cement production (CO₂ emissions per tonne of cementitious materials produced), use of algae and greenhouses (CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ stream (%), the amount of CO₂ 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.

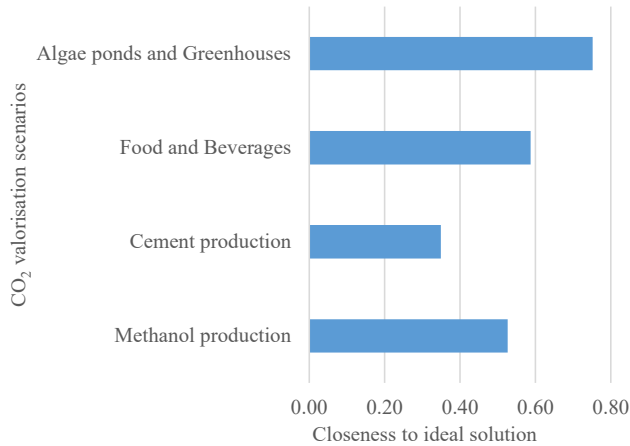


Fig. 19. CO₂ valorisation MCDA results.

The MCDA analysis showed that the optimal scenario for the CO₂ 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 CO₂. According to literary sources, there is no need to supply CO₂ completely purified from impurities, which greatly facilitates the use of this technology. By adding CO₂, 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 CO₂. 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 CO₂ (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 CO₂ 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. CO₂ 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 CO₂ – refrigeration units and as a dry cleaning agent. CO₂ 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 CO₂ 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 CO₂ 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 CO₂ or CO₂ 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 CO₂ Valorisation Potential

CO₂ 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 CO₂ in 2019. Enterprises are located mainly in the Riga region, where the distance to a potential consumer is the smallest (Fig. 20).

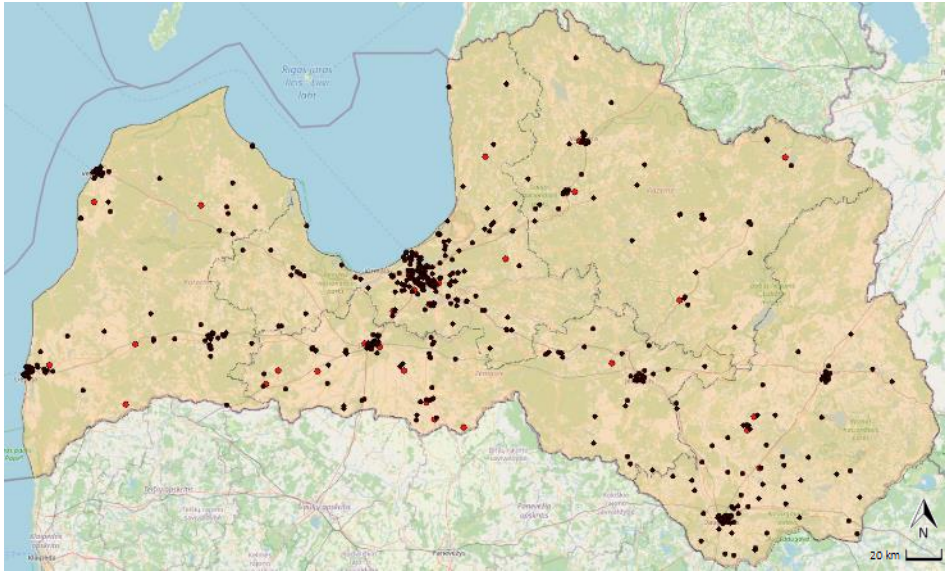


Fig. 20. CO₂ production sites A category companies (red) and B category companies (black).

The territory of the Riga region contains 64 % of all CO₂ 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 CO₂, 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 CO₂ producers and potential utilisers shows how few enterprises from the second category are currently in the country (Fig. 21).

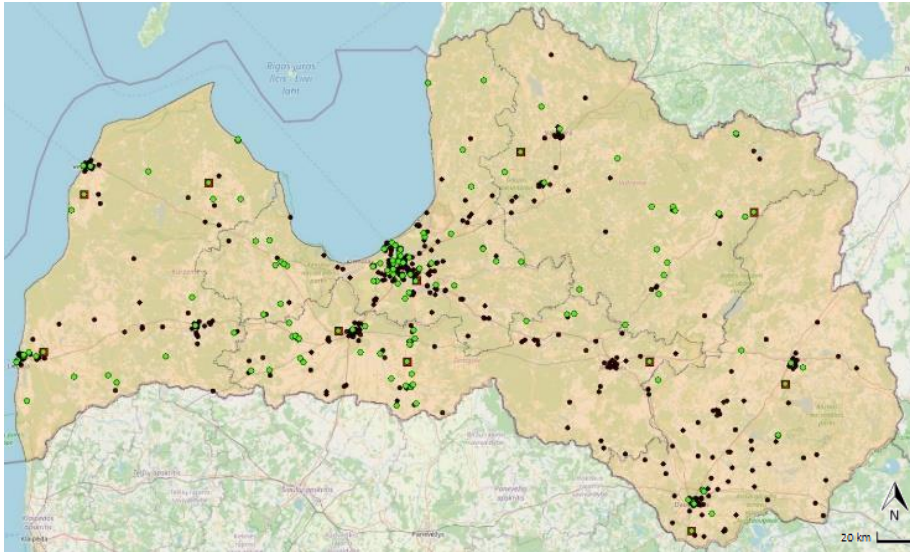


Fig. 21. Sites of CO₂ production (brown) and potential utilisation (green).

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 CO₂ in the country (64.42 % and 25.94 %, respectively), however, the greatest difference in the number of places for the production of CO₂ and its consumption is observed in Latgale, a region with relatively a small share of CO₂ 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 CO₂ 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 CO₂, which is equal to 7.49 % of CO₂ emissions in the region. Other large enterprises with a declared large amount of CO₂ produced are "Putnu fabrika Ķekava" (11100.83 tCO₂, 0.45 %), Olainfarm (10219.42 tCO₂, 0.42 %) and Latvijas Finieris (6828.00 tCO₂, 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 tCO₂ or 80 % of the region's CO₂ emissions. The second place is followed by energy production in Liepāja – Liepājas Enerģija (43632.00 tCO₂, 4.44 %).

According to (Food and Veterinary Service, 2021), there are currently 50 biogas plants in the country that could potentially use CO₂ 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).

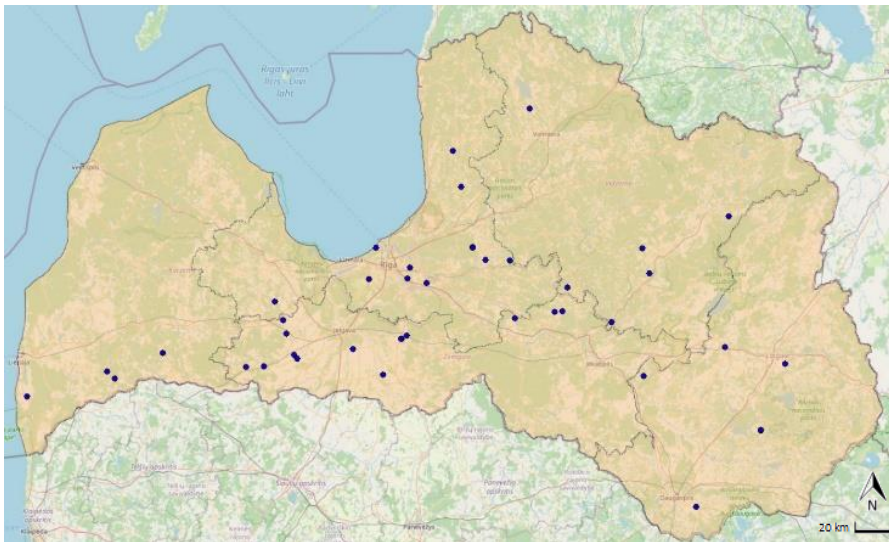


Fig. 22. Sites of biostations in Latvia.

According to the literature sources (Chen et al., 2018; Das et al., 2020), algal ponds can also be used for both CO₂ 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 CO₂ 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 CO₂. For many processes (for example, the chemical and food industries), the CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ to speed up metabolism. According to (Chen et al., 2018; Das et al., 2020), the maximum allowable amount of impurities in the supplied CO₂ can reach 30 %.

3.3. Identified Strengths, Weaknesses, Opportunities and Threats of CO₂ 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 CO₂ 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 CO₂ 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), CO₂ emitters are unlikely to seek to invest in the modernisation of enterprises to reduce the amount of CO₂ generated. If the government introduces new taxes (or

increases existing ones), and increases the cost of CO₂, 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 CO₂ produced, capture, transport and/or reuse (Apeaning et al., 2025; Tello, 2025; Tian et al., 2025).

Detailed analysis of CO₂ valorisation through CCUS technology implementation is presented un subsection below (Tables 12–14).

CO₂ 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 CO₂ 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.

CO₂ 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)

CO₂ Capture and Utilisation in Latvia

The next level of CO₂ 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.

CO₂ 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	

CO₂ Capture and Utilisation in Companies

This group considers all aspects of CO₂ 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 CO₂ capture units, it is possible to

sell the dioxide, thus obtaining additional financial benefits. If CO₂ is used at the company, the captured dioxide can be returned to production (if the quality of CO₂ 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 CO₂ 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.

CO₂ 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 CO₂ (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 CO₂ in production – confidence in the quality of the supplied resource (CO₂) 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 Commission, 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 CO₂ (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 CO₂ production and its potential valorisation points, which allows to analyse the feasibility of using CO₂ 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 CO₂ 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 CO₂ 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), CO₂ 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 CO₂ of a high degree of purity (especially the alcohol industry – yeast emits almost pure CO₂) – it can be used in the chemical industry (Anwar et al., 2020; Umar et al., 2025).

Large amounts of CO₂ 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 CO₂ was supplied to these greenhouses along with heat energy, the yield could be increased (R. Wang et al., 2015). Alternatively to greenhouses, CO₂ can be valorised in algae ponds – in both cases the amount of impurities in CO₂ 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 CO₂ 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).

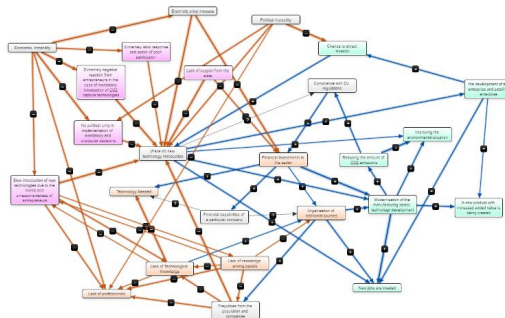
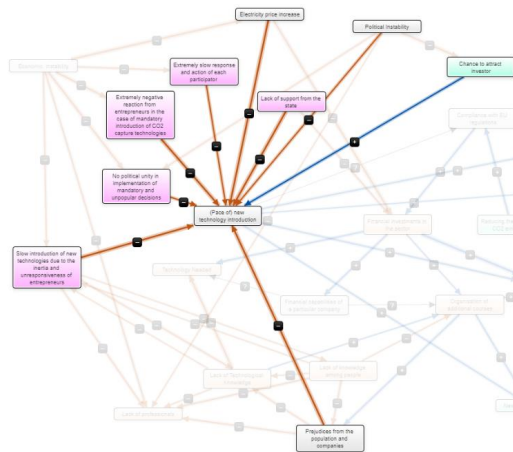


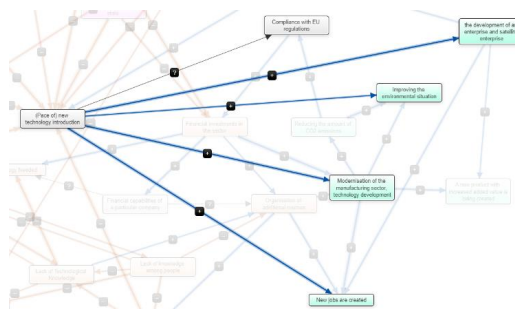
Fig. 23. Results of FCLM analysis (Annex B).

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).



a



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 CO₂ requirements, extremely negative attitude of politicians and influential entrepreneurs to the implementation of mandatory requirements for CO₂ emissions, etc.), and the so-called – public, such as prejudice about the dangers of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ Emission Problem

The first question in the questionnaire was aimed at determining public awareness of the problems of CO₂ emissions and therefore was asked as *“Have You ever heard of the CO₂ emission problem?”* The answer to this question was almost unanimous – 93 % of the respondent answered in the affirmative.

Importance if the CO₂ Problem to the Public

The aim of the next question (*“Does the problem of the CO₂ 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 CO₂ 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 CO₂.

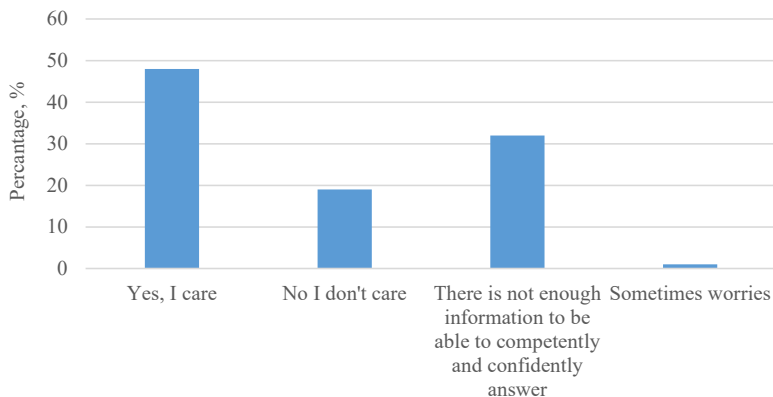


Fig. 25. Answers on does the problem of CO₂ emission bothers respondents.

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 CO₂ emissions or do not consider this problem to be relevant.

The Most Significant and Relevant Impact of CO₂ 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 CO₂ 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 CO₂ 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).

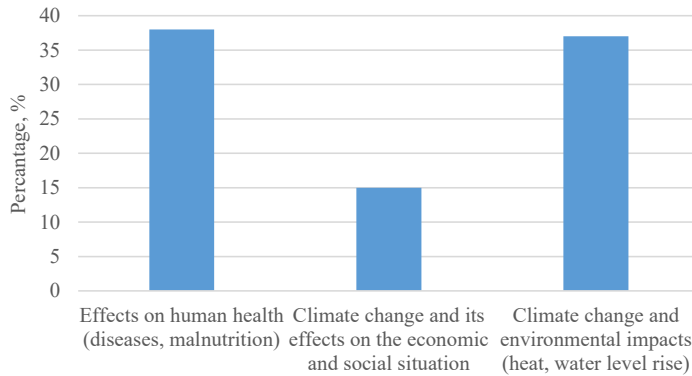


Fig. 26. Reasons why the problem seems relevant.

Reasons why CO₂ 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 CO₂ 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).

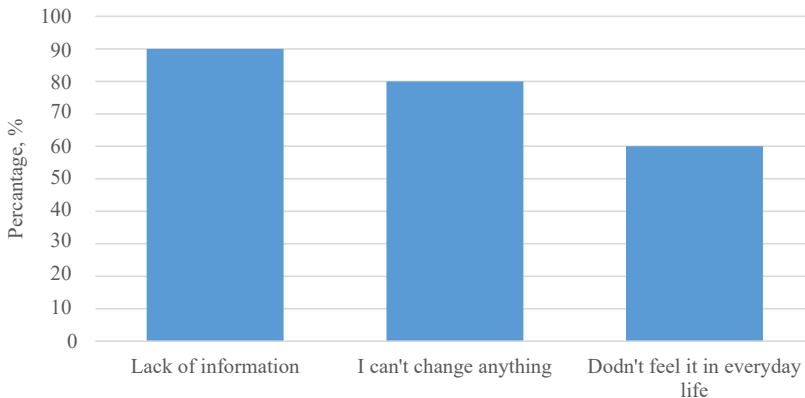


Fig. 27. Reasons why the problem seems irrelevant.

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 CO₂ Emissions for Latvia

The purpose the question *“In Your opinion, is the problem of CO₂ 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 CO₂ 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 CO₂ emissions affect Latvia.

For Whom the Reduction of CO₂ Emissions May Be the Most Important and Relevant

The question *“Mark the Groups of People/Institutions for Whom, in Your Opinion, the Reduction of CO₂ Emissions May Be the Most Important and Relevant”* was aimed to determine who should be most concerned about CO₂ emissions in the public’s opinion. There were several possible answers to this question (Fig. 28).

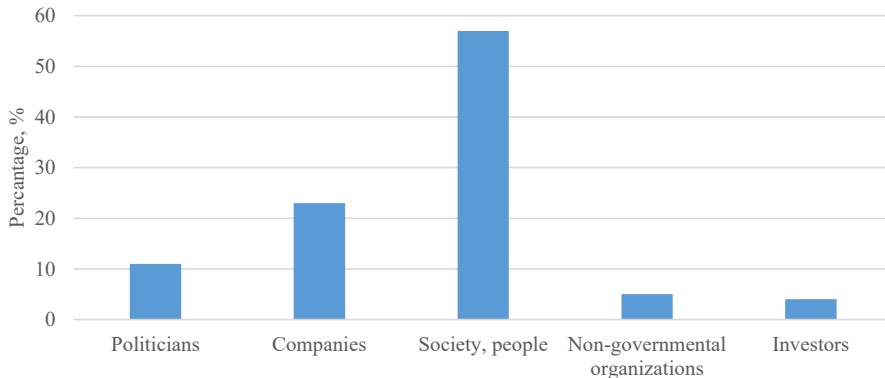


Fig. 28. To whom the reduction of emissions is more critical in Latvia on respondent’s opinion.

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 CO₂ emissions?”, “Are You doing anything now to reduce the amount of CO₂ emissions in Your daily life?” and “What actions would You be willing to take to reduce the negative impact of CO₂ emissions?”

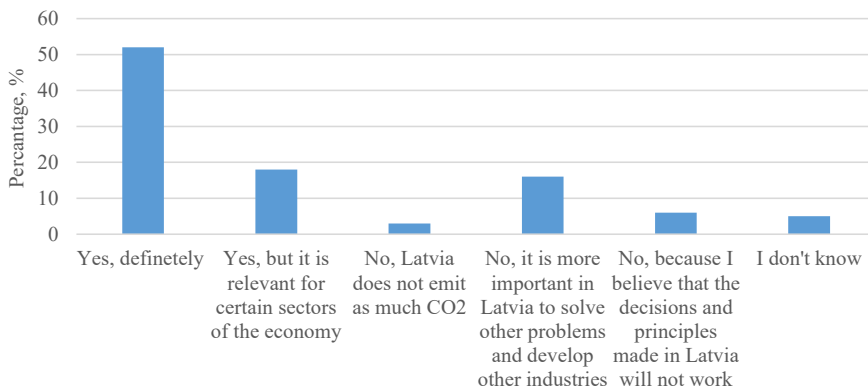


Fig. 29. The necessity to reduce CO₂ emissions on respondent’s opinion.

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 CO₂ 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 CO₂ 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).

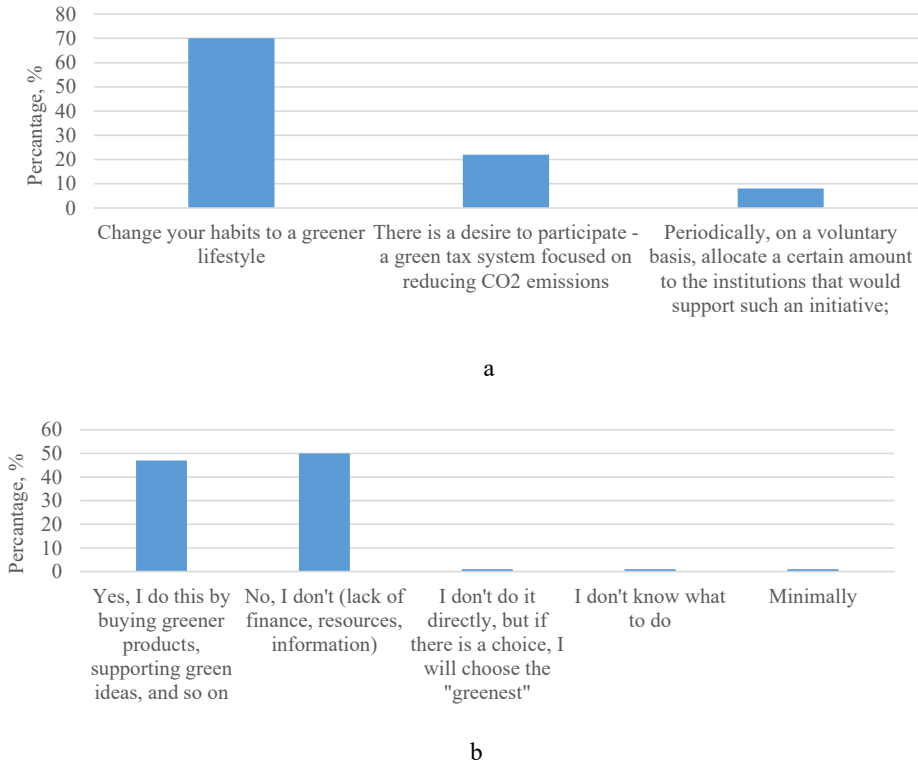


Fig. 30. Questions: a) *What actions would You be willing to take to reduce the negative impact of CO₂ emissions?* b) *Are You currently doing anything to reduce CO₂ emissions daily?*

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 CO₂ 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 CO₂ emissions is by no means relevant to all enterprises:

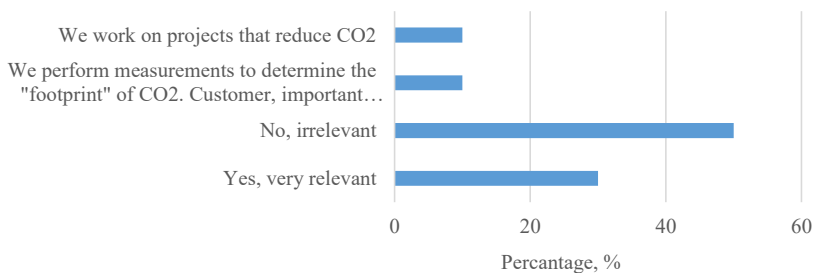


Fig. 31. Entrepreneur’s field of activity.

Only half of the respondents stated that the problem of CO₂ 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 CO₂ 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 CO₂ Emission Reduction

Answering the question about the reasons that are relevant for the enterprise in the context of CO₂ 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 CO₂ in particular on the environment (Fig. 32).

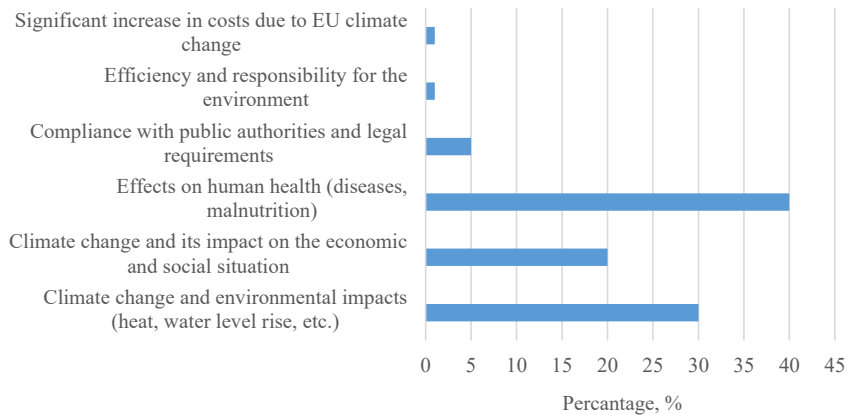


Fig. 32. What reasons are the most relevant in the context of CO₂ emission to entrepreneurs.

Motivates/Reasons to Reduce the Amount of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ policies) (Fig. 33).

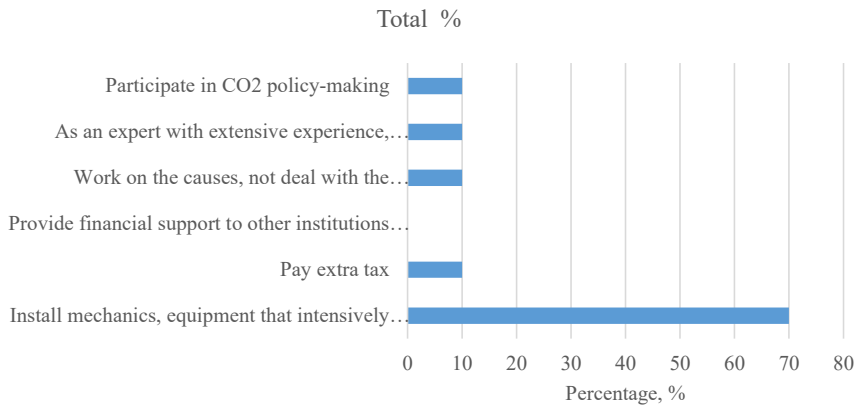


Fig. 33. Possible ways to reduce CO₂ emissions by entrepreneurs.

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).

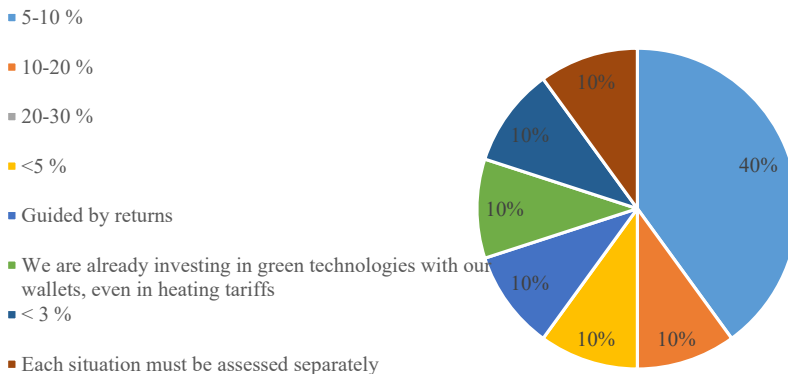


Fig. 34. Part of monthly income entrepreneurs is ready to invest in green technologies.

In general, analysing the results of a survey of entrepreneurs, it can be concluded that in the context of reducing CO₂ 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 CO₂ 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 CO₂ emissions.

3.5. Comparative Analysis of CO₂ 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 CO₂ 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 CO₂ will be stored in geological repositories safe for humans and nature. Such storage will allow permanent storage of CO₂, 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 CO₂ 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 CO₂

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 – CO₂, methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF₆), nitrogen trifluoride (NF₃) (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 CO₂ in geological structures and the vertical water layers is prohibited;
- The Cabinet of Ministers approves the procedure in which the storage of CO₂ 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 CO₂ are potential in the future. Additionally, the law stipulates that the Cabinet of Ministers is responsible for the procedure for transporting CO₂, 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.”

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 CO₂. 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 CO₂ emissions (i.e. will capture CO₂, not emit). Additionally, the law of permanent storage of CO₂ 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

CO₂ Storage Act was planned to ensure the permanent storage of CO₂ 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 CO₂ with a maximum storage capacity of 4 Mt CO₂ 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 CO₂ (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 CO₂ 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 CO₂ 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 CO₂ Capture and Storage. Financing is provided to capture and subsequent storage of CO₂ 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 CO₂ storage systems have been actively developed. In 2011, the country's legislation fully implemented the EU directive on CO₂ storage (Lockwood, 2023; Rutters & CGS Europa partners, 2013). However, in 2020, the Lithuanian government banned any projects to capture and store CO₂. This decision was justified

by concerns about the risk of underground water contamination with liquid CO₂ (Shogenova, 2020a). According to (Shogenova, 2020a), this decision is the most negative for the region for 2020, as it prohibits any placement of CO₂ 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 CO₂. 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 CO₂ 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 CO₂ captured in Lithuania could be redirected) (Lietuvos Respublikos energetikos ministerija, 2020).

Estonia

The CO₂ 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 CO₂ 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 CO₂ 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 CO₂. 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 CO₂ 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.
	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.
Germany	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 CO₂ 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 CO₂, where it would be subsequently buried. Latvia has delicious geological layers suitable for storing CO₂ from the Baltic region (Shogenov & Shogenova, 2020), (Shogenova, 2020b).

The onshore CCUS scenario includes capturing CO₂ 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 CO₂ (Shogenova et al., 2021).

3.6. Evaluation of Policy Instruments Supporting CO₂ 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).

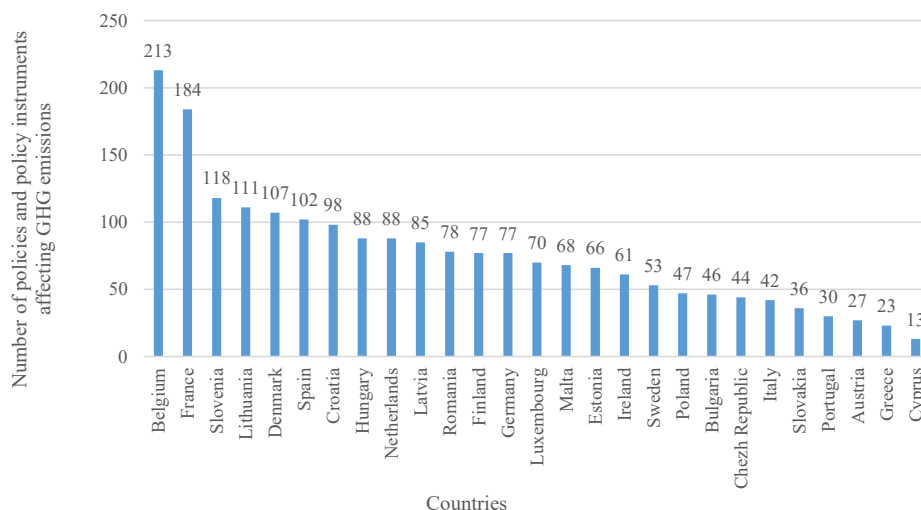


Fig. 35. Number of policies and policy instruments affecting GHG emissions in EU Member States (European Environmental Agency, 2021).

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 CO₂. Still, only a few countries have a tax on CO₂ 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 CO₂ emissions. However, other countries of the European Union are also developing and implementing documents aimed at reducing the amount of CO₂ produced in the country.

Belgium. For 2019, about 123 megatons of CO₂-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 CO₂. 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 CO₂ emissions requirements. In addition, the question is being investigated how efficiently these combustion stations can capture the CO₂ 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 CO₂ 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 CO₂ in production will continue further, and there will be more CCS and CCU stations.

Croatia. Croatia has ten large CO₂ 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 CO₂ storage. Therefore, in 2014, the CO₂ EOR Project Croatia was launched in the country, allowing it to obtain more minerals and put waste CO₂ underground simultaneously. This project allows storing more than 400 mln.m³ CO₂ (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 CO₂ 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 CO₂ transportation makes it possible to move gas across the country, thus enabling large contributors of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ from exhaust gases and redirect it to producing other valuable products (thus obtaining both environmental and economic benefits) or putting CO₂ in landfills (Lietuvos Respublikos energetikos ministerija, 2020). It is essential to clarify that the new policies are aimed at large CO₂ 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 CO₂ emissions created in energy production and even make them harmful. BECCS technologies are a new milestone in developing CO₂ 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 CO₂. For example, Latvia and Estonia are actively negotiating the creation of an infrastructure for capturing, transporting and storing CO₂ from Estonia in Latvia. No geological formations in Estonia would allow the storage of CO₂. 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 CO₂ 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 CO₂ 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) CO₂. 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 CO₂ 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 CO₂ transportation). For instance, in Ireland, the experimental installation of a post-combustion CO₂ 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, CO₂ 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 CO₂ 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 m³ 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 CO₂ is the same, as they are all based on 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 CO₂.

Standards based on the EN-15804 offer the highest amount of CO₂ stored in one cubic meter of the product – 359 kgCO₂/m³, while the lowest amount of CO₂ stored can be attributed to standards based on the previous ISO-14040/44 LCA standard – 90 kgCO₂/m³. Considering all standards, an average value of 270 kgCO₂/m³ 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.

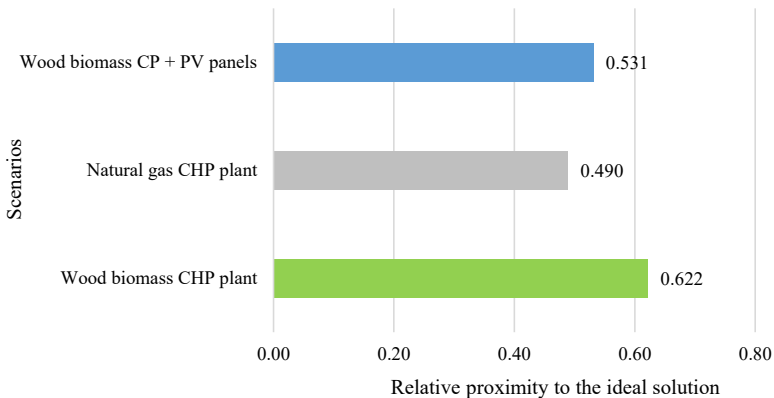


Fig. 36. Multicriteria analysis results.

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 $e_{cc,n}$ 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_{cc} (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 ₂ eq/kg
N fertiliser (mineral)	90 kg/ha year	6.41 kgCO ₂ eq/kg
N fertiliser (digestate)	10 kg/ha year	0.0075 kgCO ₂ eq/kg
CaO fertiliser	0 kg/ha year	0.89 kgCO ₂ eq/kg
N ₂ O field emission	–	5.6 kgN ₂ O eq/ha year
Pesticides	NA	13.9 kgCO ₂ eq/kg
Diesel (machinery)	11,764.7 L/ha year	3.14 / 2.1 kgCO ₂ eq/kg
Maize yield (fresh matter)	37820 kg/ha year	–

Thus, the three main substrates have the following effect in kgCO₂eq 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 ₂ eq/kg	e_{ec} , kgCO ₂ eq/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 CO₂ 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)

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

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 kgCO₂eq/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 kgCO₂eq/t for one type of substrate. The total GHG emissions of all 13 substrate types equals 1.96 kgCO₂eq/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 ₂ eq/kWh
Heat (CHP Unit)	0.61	kgCO ₂ eq/MJ
Methane	23	kgCO ₂ eq/kgCH ₄

Using Eq. (6), we can calculate the parameter e_{p1} :

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

where

EF_E Emission factor from electricity, kg CO₂eq/kWh;

EF_h Emission factor from heat, kg CO₂eq/MJ;

EF_m Emission factor from methane, kg CO₂eq/kg CH₄.

Substituting the required values from Table 25 shows that parameter e_{p1} for the Biogas Plant equals 2.70 kgCO₂eq/m³CH₄.

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 (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/m³ 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. (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
<i>Biomethane distribution, emission factors</i>		
Electricity mix	0.192	kgCO ₂ eq/kWh
Heat process	0.067	kgCO ₂ eq/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/m³;

EF_e Emission factor for electricity for biomethane transport in the natural gas grid, kWh/m³;

HT_{ng} Heat for biomethane transport in the natural gas grid, MJ/m³;

EF_h Emission factor for heat process for biomethane transport in the natural gas grid, kgCO₂eq/kWh;

EC_{st} Electricity for biomethane compression in filling station, kWh/m³;

EF_{st} Emission factor for electricity for biomethane compression in filling station, kWh/m³.

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 kgCO₂eq/m³. If there is no compression, then $e_{td,product} = 0.043$ kgCO₂eq/m³.

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).

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

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):

$$Tot. \text{ usable amount of } CH_4 = \text{Proportion of methane yield} \cdot \text{Tot. biomethane output} \quad (10)$$

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, Nm ³ /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 Nm³ of biomethane:

$$Total\ emissions\ per\ m^3\ CH_4 = \frac{(e_{ec} + e_{td,feedstock,n} + ep_1 + ep_2 + e_{td,product})}{Total\ usable\ amount\ of\ biomethane} \quad (11)$$

Knowing that for the observed Biogas Plant, the sum of all parameters for all substrates is 25 246 762.29 kgCO₂eq/year, and the total amount of biomethane is 4 261 983.48 Nm³/year, using Eq. (11) it has been determined that the total amount of emissions is 5.92 kgCO₂eq/m³.

According to (European Commission, 2021k), GHG emissions from biomass-derived fuels must be expressed in grams of CO₂ equivalent per MJ of biofuel (gCO₂eq/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/m³, resulting in 16.45 gCO₂eq/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 gCO₂eq/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:

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

where

E_B Total emissions from biomethane, gCO₂eq/MJ CH₄;

E_{F(t)} Total emissions from fossil fuel comparator, gCO₂eq/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 CO₂ 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).

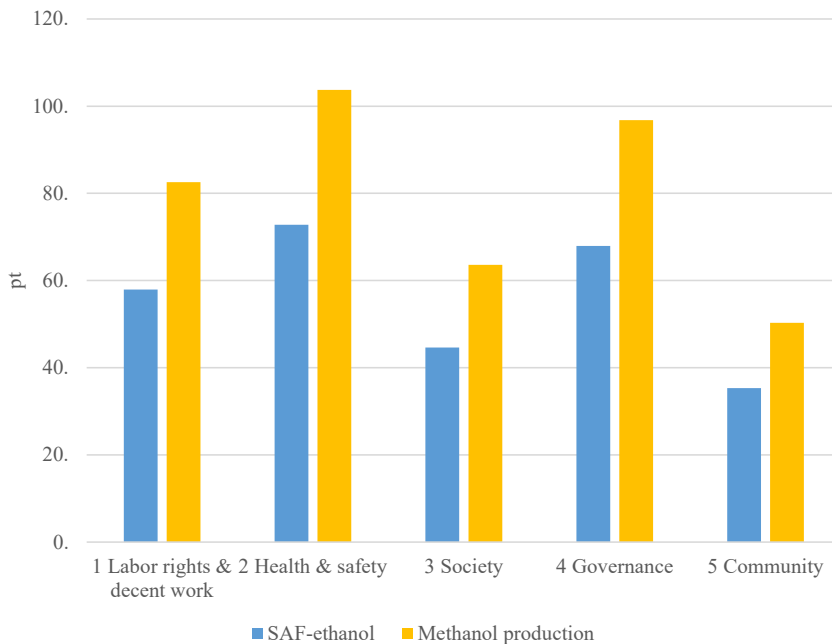


Fig. 37. Assessment by main categories, global annual per capita, weighted.

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.

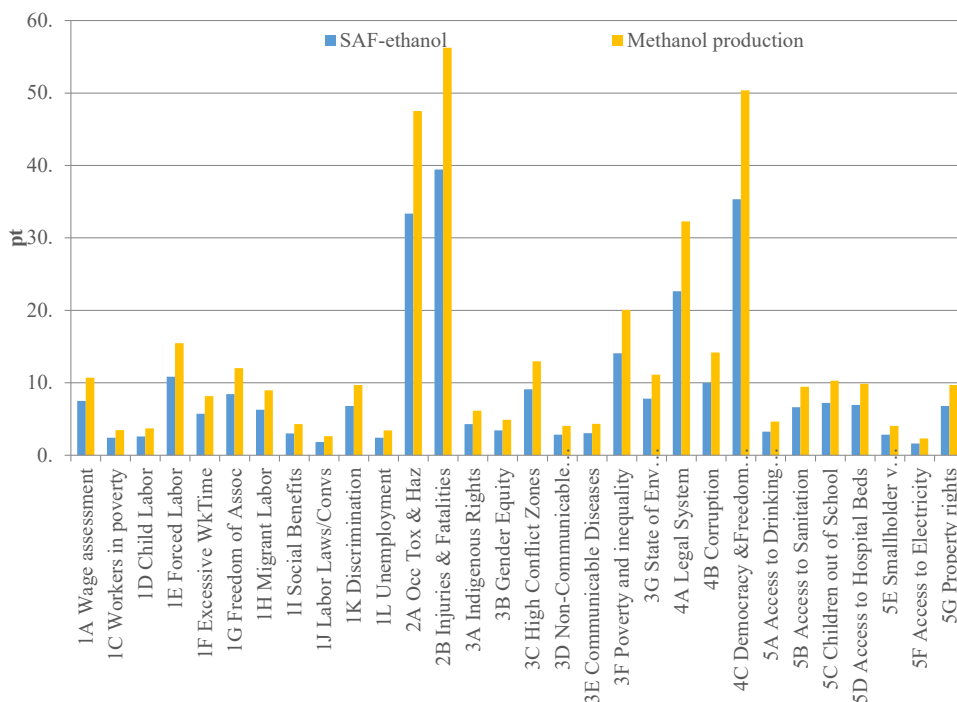


Fig. 38. Assessment by sub-categories, global annual per capita, weighted.

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).

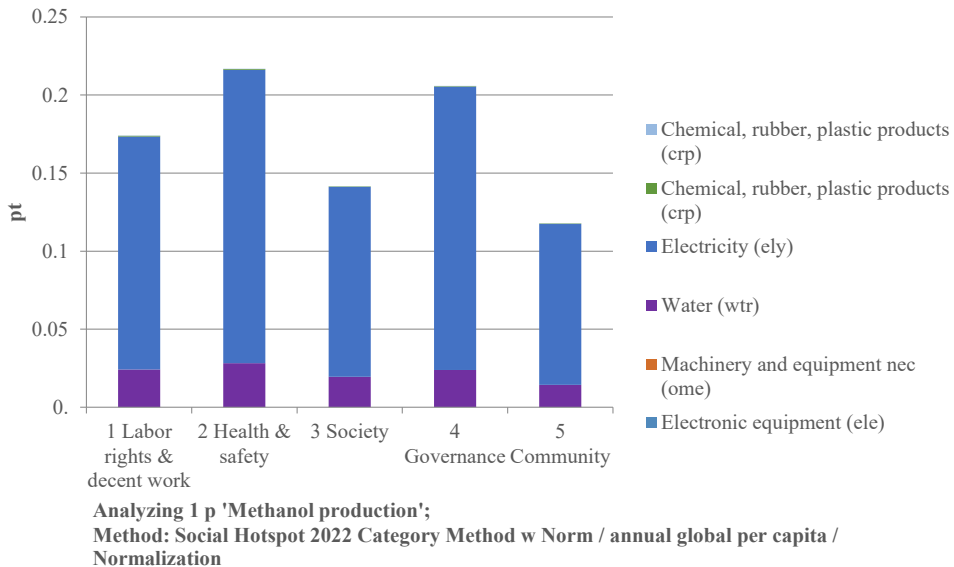


Fig. 39. Methanol production by social categories (without construction), global annual per capita.

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 CO₂ 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.

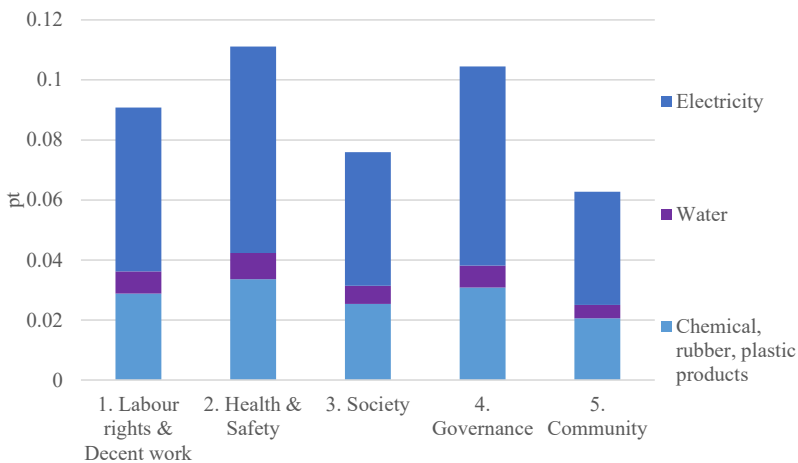


Fig. 40. SAF-ethanol by social categories, global annual per capita.

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 SO₂, 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, SO₂ and NMVOC), which potentially can further oxidise to CO₂ 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).

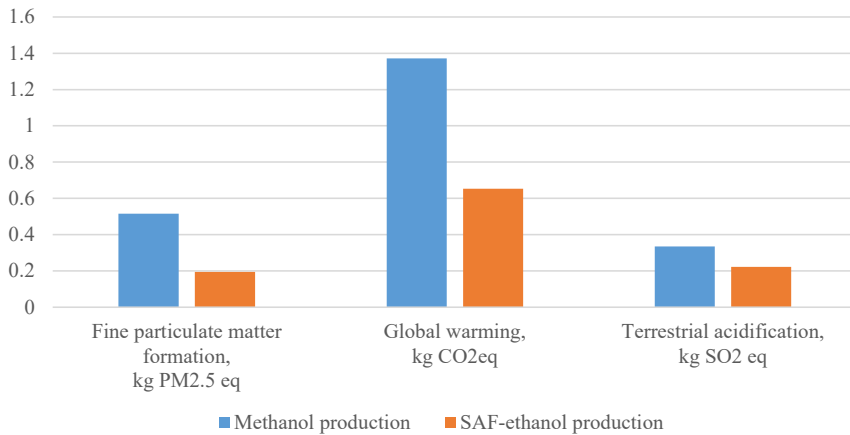


Fig. 41. LCA of Methanol and SAF-ethanol scenarios

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 CO₂ 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 CO₂ valorisation through implementation of CCUS technologies in Latvia, focusing on their application in rural and industrial contexts. The results highlight several viable pathways for CO₂ 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 CO₂ utilisation pathways due to their technological simplicity and high CO₂ consumption. However, their economic and scalability limitations are notable. Algae-based systems, while effective in CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emitters highlights a regional challenge but doesn't take into account lack of necessary infrastructure. For instance, redirecting CO₂ 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* mapping and FLCM analysis methods to analyse the factors influencing the development of CO₂ 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 CO₂ emission problem and their willingness to pay for the reduction of the amount of CO₂ 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 CO₂ 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 CO₂ valorisation by its storing in another product. The proposed wood fiberboard insulation material offers a novel CO₂ storage solution combined with optimal energy source, but environmental benefits of CO₂ 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 CO₂ 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; Srivastava 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 CO₂ 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 CO₂ 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 CO₂ is treated as a feedstock rather than waste. The conversion of CO₂ 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 CO₂ 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 “CO₂ 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 CO₂ emission reduction methods in the biogas-to-biomethane conversion model and in CO₂ 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 CO₂ 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 CO₂ 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).

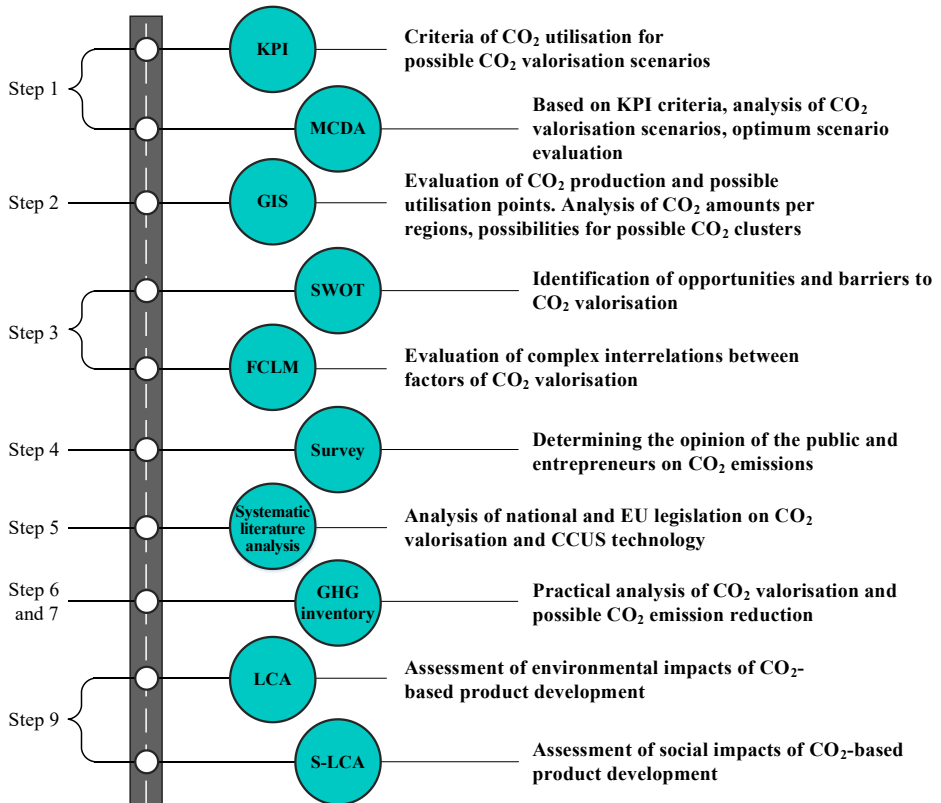


Fig. 42. CO₂ capture and utilisation integrated methodology/roadmap.

As noted in Section 1, due to insufficient data at the time of the study, the analyses presented in the methodology consider different CO₂ valorisation scenarios:

- Step 1 – scenarios of CO₂ valorisation in methanol and cement productions, CO₂ 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 CO₂ emitting and possible valorisation points. No specific CO₂ valorisation scenario considered;

- Step 3 – Combination of GIS, SWOT and FLCM analysis. No specific CO₂ valorisation scenario considered;
- Step 4 – Survey. No specific CO₂ valorisation scenario considered;
- Step 5 – Analysis of legislation. No specific CO₂ valorisation scenario considered;
- Step 6 – Analysis of legislation. No specific CO₂ valorisation scenario considered;
- Step 7 – Identification of the CO₂ amount, that can be captured in fibrewood material production. Analysis of optimal energy source for fibrewood material production;
- Step 8 – Biomethane production scenario and identification of the amount of avoided CO₂ through changing the manufactured product to one that produces fewer emissions
- Step 9 – Scenarios of CO₂ 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.

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 CO₂ 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 CO₂ 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 CO₂, 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.

REFERENCES

- 3D-CCUS. (2016). *DMX Demonstration in Dunkirk*. <https://cordis.europa.eu/project/id/838031>
- Abacus. (2019). *ABACUS project*. <https://www.abacus-bbi.eu/Pages/Welcome.aspx>
- Abbas T., et al. (2020). Biomass Cogeneration Technologies: A Review. *Journal of Sustainable Bioenergy Systems*, 10(1), 1–15. <https://doi.org/10.4236/JSBS.2020.101001>
- Abd A. A., et al. (2023). Green route for biomethane and hydrogen production via integration of biogas upgrading using pressure swing adsorption and steam-methane reforming process. *Renewable Energy*, 210, 64–78. <https://doi.org/10.1016/J.RENENE.2023.04.041>
- AC Group. (2018). *Production of liquefied carbon dioxide*. <https://ac-group.in.ua/en/blog/production-of-liquefied-carbon-dioxide/>
- Advanced Welding Supply Company. (2020). *Welding Gases*.
- Afanasjev S. V., et al. (2016). Технология переработки углекислого газа в метанол. *Himicheskaja Tehnika*, 3.
- Aich A., Ghosh S. K. (2016). Application of SWOT Analysis for the Selection of Technology for Processing and Disposal of MSW. *Procedia Environmental Sciences*, 35, 209–228. <https://doi.org/10.1016/J.PROENV.2016.07.083>
- Akhtar M. S., et al. (2023). Green hydrogen and sustainable development – A social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy. *Journal of Cleaner Production*, 395, 136438. <https://doi.org/10.1016/J.JCLEPRO.2023.136438>
- Akoubeh O. T. (2015). Methane Production from Carbon Dioxide and Increasing Energy Return of Investment (EROI) in Shale Oil. *Proceedings of the TMS Middle East – Mediterranean Materials Congress on Energy and Infrastructure Systems (MEMA 2015)*, 381–393. https://doi.org/10.1007/978-3-319-48766-3_40
- Alamia A., et al. (2024). Optimizing hydrogen and e-methanol production through Power-to-X integration in biogas plants. *Energy Conversion and Management*, 322, 119175. <https://doi.org/10.1016/J.ENCONMAN.2024.119175>
- AlgaePrint. (2014). *Algae Products' Internationalization*. <https://cordis.europa.eu/project/id/650549/reporting>
- Allah F. U. M., et al. (2024). Current status, challenges and future prospects of carbon capture and storage (CCS) for thermal power plants in Brazil. *International Journal of Greenhouse Gas Control*, 136, 104198. <https://doi.org/10.1016/J.IJGGC.2024.104198>
- Allen M., et al. (2018). Summary for Policymakers. In *Aromar Revi*, 1–24.
- Alvarez C., et al. (2021). *What is behind soaring energy prices and what happens next?* <https://www.iea.org/commentaries/what-is-behind-soaring-energy-prices-and-what-happens-next>
- Anto S., et al. (2020). Algae as green energy reserve: Technological outlook on biofuel production. *Chemosphere*, 242, 125079. <https://doi.org/10.1016/J.CHEMOSPHERE.2019.125079>
- Anwar M. N., et al. (2020). CO₂ utilization: Turning greenhouse gas into fuels and valuable products. *Journal of Environmental Management*, 260, 110059. <https://doi.org/10.1016/J.JENVMAN.2019.110059>

- Apeaning R. W., et al. (2025). How effective are climate policy measures in reducing CO2 emissions? Evidence from emerging economies. *Journal of Cleaner Production*, 507, 145395. <https://doi.org/10.1016/J.JCLEPRO.2025.145395>
- Aqua Analytics. (2020). *Измерение растворенного кислорода в пиве*. <https://aquaanalytics-tekhnika.ru/articles/izmerenie-kisloroda-v-pive-s-pomoshhyu-opticheskogo-datchika-orbisphere-m1100/>
- ArcelorMittal. (2024). *World-first trial of new technology to recycle CO2 emissions from steel production begins at ArcelorMittal Gent, Belgium | ArcelorMittal*. <https://corporate.arcelormittal.com/media/news-articles/world-first-trial-of-new-technology-to-recycle-co2-emissions-from-steel-production-begins-at-arcelormittal-gent-belgium>
- ArcGis. (2021). *VZD dati: Pagastu robežas, 2021*. <https://www.arcgis.com/home/item.html?id=b76d9304b3ca467383e462e5dc945d9b>
- Atanu J. (2018). Modified Atmosphere Packaging & Controlled Atmosphere Packaging. In *Food packaging technology*. <https://ebooks.inflibnet.ac.in/ftp08/chapter/modified-atmosphere-packaging-controlled-atmosphere-packaging/>
- Avdiushchenko A., Zajač P. (2019). Circular Economy Indicators as a Supporting Tool for European Regional Development Policies. *Sustainability 2019, Vol. 11, Page 3025, 11(11)*, 3025. <https://doi.org/10.3390/SU11113025>
- Ayub A., et al. (2022). Amine-grafted mesoporous silica materials for single-stage biogas upgrading to biomethane. *Chemical Engineering Journal*, 445, 136497. <https://doi.org/10.1016/J.CEJ.2022.136497>
- Bäcklund K., et al. (2024). Implementing digital innovations: Overcoming organizational challenges. *Developments in the Built Environment*, 18, 100436. <https://doi.org/10.1016/J.DIBE.2024.100436>
- Bakhtavar E., et al. (2020). Fuzzy cognitive maps in systems risk analysis: a comprehensive review. *Complex & Intelligent Systems* 7(2), 621–637. <https://doi.org/10.1007/S40747-020-00228-2>
- Balkan Green Energy News. (2019). *5 MWe biomass cogeneration plant officially opened in the city of Slatina*. <https://balkangreenenergynews.com/5-mwe-biomass-cogeneration-plant-officially-opened-in-the-city-of-slatina/>
- Barbrook-Johnson P., Penn A. S. (2022). Fuzzy Cognitive Mapping. *Systems Mapping*, 79–95. https://doi.org/10.1007/978-3-031-01919-7_6
- Barcelo L., et al. (2014). Cement and carbon emissions. *Materials and Structures/Materiaux et Constructions*, 47(6), 1055–1065. <https://doi.org/10.1617/S11527-013-0114-5>
- Bayazit Subaşı A., et al. (2024). Weighting factors for LCA—a new set from a global survey. *International Journal of Life Cycle Assessment*, 29(11), 2107–2136. <https://doi.org/10.1007/S11367-024-02330-W/FIGURES/8>
- Baylin-Stern A., Berghout N. (2021). *Is carbon capture too expensive?* <https://www.ica.org/commentaries/is-carbon-capture-too-expensive>
- Becattini V., et al. (2022). Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. *International Journal of Greenhouse Gas Control*, 117, 103635. <https://doi.org/10.1016/J.IJGGC.2022.103635>
- Bellona. (2012). *Biomass with CO2 Capture and Storage (Bio-CCS), the way forward for Europe* .1–32.

- Bernal-Torres C. A., et al. (2025). Collaborative work in the implementation of industry 4.0 technologies and its relationship with business sustainability in an emerging economy. *International Journal of Innovation Studies*. <https://doi.org/10.1016/J.IJIS.2025.05.002>
- Bernardi A., et al. (2023). Enviro-economic assessment of sustainable aviation fuel production from direct CO₂ hydrogenation. *Computer Aided Chemical Engineering*, 52, 2345–2350. <https://doi.org/10.1016/B978-0-443-15274-0.50373-5>
- Bhola V., et al. (2014). Overview of the potential of microalgae for CO₂ sequestration. *International Journal of Environmental Science and Technology*, 11(7), 2103–2118. <https://doi.org/10.1007/S13762-013-0487-6/METRICS>
- Bilal H., et al. (2025). Land suitability assessment and self-sufficiency evaluation for fodder crop production in a hyper arid environment coupling GIS-based multi-criteria decision making and optimization. *Ecological Modelling*, 501, 111021. <https://doi.org/10.1016/J.ECOLMODEL.2025.111021>
- BioConCO₂. (2018). *BIOtechnological processes based on microbial platforms for the CONversion of CO₂ from ironsteel industry into commodities for chemicals and plastics*. <https://cordis.europa.eu/project/id/761042>
- Biograce. (2019). *The BioGrace-II GHG calculation tool for electricity, heating and cooling*. Biograce.
- Biographene. (2019). *Producing graphene from biogas: an innovative, renewable and cost-effective value-chain for industrialising the material of the future*. <https://cordis.europa.eu/project/id/877210/reporting>
- BioLyc. (2019). *Biologic Lycopene from Tomatoes*. <https://cordis.europa.eu/project/id/854915/reporting>
- Black R. (2021). How is the UK tackling climate change? *Energy & Climate Intelligence Unit*.
- Borisov V., et al. (2019). The System of Fuzzy Cognitive Analysis and Modeling of System Dynamics. *Proceedings of the IS-2019 Conference*.
- Brad A., et al. (2024). The politics of carbon management in Austria: Emerging fault lines on carbon capture, storage, utilization and removal. *Energy Research & Social Science*, 116, 103697. <https://doi.org/10.1016/J.ERSS.2024.103697>
- Bradshaw J., et al. (2008). CO₂ storage capacity estimation: Issues and development of standards. *International Journal of Greenhouse Gas Control*, 1(1), 62–68. [https://doi.org/10.1016/S1750-5836\(07\)00027-8](https://doi.org/10.1016/S1750-5836(07)00027-8)
- BRE Global Ltd. (2013). *Apache Tomcat Version BRE*. https://www.greenbooklive.com/filelibrary/EN_15804/PN514-BRE-EN-15804-PCR.pdf
- Bruton T., et al. (2009). *A review of the potential of marine algae as a source of biofuel in Ireland*. Sustainable Energy Ireland.
- BSI. (2011). *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services*.
- Budisa N., Schulze-Makuch D. (2014). Supercritical Carbon Dioxide and Its Potential as a Life-Sustaining Solvent in a Planetary Environment. *Life : Open Access Journal*, 4(3), 331. <https://doi.org/10.3390/LIFE4030331>
- Bundesministerium der Justiz. (2012). *Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (Act to demonstrate the permanent storage of carbon dioxide) (Carbon Dioxide*

Storage Act - KSpG). Bundesministerium der Justiz.

- Burgess J. (2024). *UK CCUS deployment costs double, while demand case shrinks: Carbon Tracker | S&P Global*. <https://www.spglobal.com/commodity-insights/en/news-research/latest-news/energy-transition/031324-uk-ccus-deployment-costs-double-while-demand-case-shrinks-carbon-tracker>
- Buure K., et al. (2024). Policy stagnation or reevaluation? Exploring the regulatory dimensions of carbon capture, utilisation and storage in Finland and the Baltic countries. *Energy Research & Social Science*, 118, 103825. <https://doi.org/10.1016/J.ERSS.2024.103825>
- C2Fuel. (2019). *Carbon Captured Fuel and Energy Carriers for an Intensified Steel Off-Gases based Electricity Generation in a Smarter Industrial Ecosystem*. <https://cordis.europa.eu/project/id/838014/reporting>
- C4U. (2020). *Advanced Carbon Capture for steel industries integrated in CCUS Clusters*. <https://cordis.europa.eu/project/id/884418/results>
- Cabinet of Ministers. (2012). Noteikumi Nr. 657. Latvijai piešķirto emisijas kvotu izsolišanas kārtība. *Latvijas Vestnesis*.
- Cabinet of Ministers. (2018). Regulation No. 42. Methodology for Calculating Greenhouse Gas Emissions (Siltumnīcefekta gāzu emisiju aprēķina metodika). *Latvijas Vestnesis*.
- Cabinet of Ministers. (2020a). On the Action Plan for Reducing Air Pollution for 2020-2030 (Par Gaisa piesārņojuma samazināšanas rīcības plānu 2020.–2030. gadam). *Latvijas Vestnesis*, 197.
- Cabinet of Ministers. (2020b). Par Latvijas Nacionālo enerģētikas un klimata plānu 2021.–2030 gadam. *Latvijas Vestnesis*, 29.
- Cadena-Pereda R. O., et al. (2012). Automatic Carbon Dioxide-Methane Gas Sensor Based on the Solubility of Gases in Water. *Sensors (Basel, Switzerland)*, 12(8), 10742. <https://doi.org/10.3390/S120810742>
- Calvillo C., et al. (2025). Regional employment implications of deploying CO2 transport and storage to decarbonise the UK's industry clusters. *Ecological Economics*, 233, 108587. <https://doi.org/10.1016/J.ECOLECON.2025.108587>
- Cannon C., et al. (2021). *Concrete Solutions Guide*. <https://www.rmi.org>
- CAPCO2. (2016). *Intensified Process for CAPturing CO2*. <https://cordis.europa.eu/project/id/827343/reporting/fr>
- Carbon Recycling International. (2022). *World's largest CO2-to-methanol plant starts production*. <https://www.carbonrecycling.is/news-media/worlds-largest-co2-to-methanol-plant-starts-production>
- Carbon8. (2020). *Carbon8 Project*. <https://www.carbon8.co.uk/>
- Cascade-X. (2018). *CO2 to light olefins conversion by cascade reactions over bifunctional nanocatalysts: an 'all X-ray' approach*. <https://cordis.europa.eu/project/id/793423/reporting>
- CATF. (2018). *California's CO2 Reduction Program Opens Doors to CCS*. <https://www.catf.us/2018/11/californias-co2-reduction-program/>
- Celbicon. (2016). *Cost-effective CO2 conversion into chemicals via combination of Capture, Electrochemical and Biochemical Conversion technologies*. <https://cordis.europa.eu/project/id/679050/reporting>

- Central Statistical Bureau Databases. (2020a). *Air emission accounts (NACE Rev. 2)*”, Table ID: VID070. <https://www.csb.gov.lv/lv/statistika/statistikas-temas/vide-energetika/vide/tabulas/vig070/gaisa-emisiju-konti-nace-2red>
- Central Statistical Bureau Databases. (2020b). *Share of global carbon dioxide (CO₂) emissions from fossil fuels and cements as of 2020, by economic sector*. <https://www.statista.com/statistics/1129656/global-share-of-co2-emissions-from-fossil-fuel-and-cement/>
- Certifications Control Union. (2021a). *REDcert - Biomass for Energy - Certifications*. <https://certifications.controlunion.com/en/certification-programs/certification-programs/redcert-biomass-for-energy>
- Certifications Control Union. (2021b). *SURE - verification scheme - Certifications*. <https://certifications.controlunion.com/en/certification-programs/certification-programs/sure-verification-scheme>
- Chakraborty R., et al. (2024). Sustainable fermentable sugar production using a glass fiber supported gallium–molybdenum photocatalyst towards bioethanol production: LCA analysis. *Energy Advances*, 3(10), 2613–2626. <https://doi.org/10.1039/D4YA00226A>
- Chauvy R., et al. (2020). Comparison of multi-criteria decision-analysis methods for selecting carbon dioxide utilization products. *Sustainable Production and Consumption*, 24, 194–210. <https://doi.org/10.1016/J.SPC.2020.07.002>
- Chen C., et al. (2018). Progress toward Commercial Application of Electrochemical Carbon Dioxide Reduction. *Chem*, 4(11), 2571–2586. <https://doi.org/10.1016/j.chempr.2018.08.019>
- CircleEnergy. (2017). *Production of renewable methanol from captured emissions and renewable energy sources, for its utilisation for clean fuel production and green consumer goods*. <https://cordis.europa.eu/project/id/791632/reporting>
- CLEAN. (2019). *Carbon fracturing and storage in shale with wellbore infrastructure monitoring*. <https://cordis.europa.eu/project/id/846775>
- CleanKer. (2017). *CLEAN clinKER production by Calcium looping process*. <https://cordis.europa.eu/project/id/764816/reporting>
- CO₂ Intermediates. (2017). *From CO₂, Water and Sunlight to Valuable Solar Fuels: Tracking Reaction Intermediates in Solar Fuel Generation with Ultrafast Spectroscopy for More Efficient Catalysis*. <https://cordis.europa.eu/project/id/749231>
- Coll C., et al. (2021). *Carbon Capture, Use And Storage (CCUS)*.
- Collis J., et al. (2022). Techno-economic assessment of jet fuel production using the Fischer-Tropsch process from steel mill gas. *Frontiers in Energy Research*, 10, 1049229. <https://doi.org/10.3389/FENRG.2022.1049229/BIBTEX>
- Comino E., Ferretti V. (2016). Indicators-based spatial SWOT analysis: supporting the strategic planning and management of complex territorial systems Article (Accepted version) (Refereed) Indicators-based spatial SWOT analysis: Supporting the strategic planning and management of complex territorial systems. *Ecological Indicators*, 60, 1104–1117. <https://doi.org/10.1016/j.ecolind.2015.09.003>
- Cook D., Pétursson J. G. (2025). The role of GIS mapping in multi-criteria decision analysis in informing the location and design of renewable energy projects - A systematic review. *Energy Strategy*

- Reviews, 59, 101765. <https://doi.org/10.1016/J.ESR.2025.101765>
- Cordero-Lanzac T., et al. (2022). A techno-economic and life cycle assessment for the production of green methanol from CO₂: catalyst and process bottlenecks. *Journal of Energy Chemistry*, 68, 255–266. <https://doi.org/10.1016/J.JECHEM.2021.09.045>
- Cordova S. S., et al. (2022). Potential for the valorization of carbon dioxide from biogas production in Sweden. *Journal of Cleaner Production*, 370. <https://doi.org/10.1016/J.JCLEPRO.2022.133498>
- Cowie P., et al. (2020). Smart rural futures: Will rural areas be left behind in the 4th industrial revolution? *Journal of Rural Studies*, 79, 176. <https://doi.org/10.1016/J.JRURSTUD.2020.08.042>
- Cozmos. (2019). *Efficient CO₂ conversion over multisite Zeolite-Metal nanocatalysts to fuels and OlefinS*. <https://cordis.europa.eu/project/id/837733/reporting>
- Crellin F. (2021). *European gas price surge prompts switch to coal*. Reuters. <https://www.reuters.com/business/energy/european-gas-price-surge-prompts-switch-coal-2021-10-12/>
- CSI. (2005). *CO₂ Accounting and Reporting Standard for the Cement Industry*.
- D’Adamo I., et al. (2023). Biomethane as an energy resource for achieving sustainable production: Economic assessments and policy implications. *Sustainable Production and Consumption*, 35, 13–27. <https://doi.org/10.1016/J.SPC.2022.10.014>
- Danish Energy Agency. (2020). *Technology Data for Generation of Electricity and District Heating*. <https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and>
- Darzi M. A. (2024). Overcoming barriers to integrated management systems via developing guiding principles using G-AHP and F-TOPSIS. *Expert Systems with Applications*, 239, 122305. <https://doi.org/10.1016/J.ESWA.2023.122305>
- Das R., et al. (2020). CO₂ Sequestration Using Algal Biomass and its Application as Bio Energy. *Encyclopedia of Renewable and Sustainable Materials: 1-5*, 372–384. <https://doi.org/10.1016/B978-0-12-803581-8.11030-6>
- de Medeiros Costa H. K., et al. (2021). Sustainable development and its link to Carbon Capture and Storage (CCS) technology: toward an equitable energy transition. *Carbon Capture and Storage in International Energy Policy and Law*, 357–370. <https://doi.org/10.1016/B978-0-323-85250-0.00009-8>
- Decade. (2020). *DistributEd Chemicals And fuels production from CO₂ in photoelectrocatalytic DEvices*. <https://cordis.europa.eu/project/id/862030/reporting>
- Department for Business, E. & I. S. (2018). *IMPLEMENTING THE END OF UNABATED COAL BY 2025*.
- Dieffenbacher GmbH. (2023). *Fiber Insulation Board Lines*. <https://www.environmental-expert.com/products/fiber-insulation-board-lines-190613>
- Dietrich R. U., et al. (2024). Technical, economic and ecological assessment of European sustainable aviation fuels (SAF) production. *CEAS Aeronautical Journal*, 15(2), 161–174. <https://doi.org/10.1007/S13272-024-00714-0/FIGURES/10>
- Dinophyte. (2019). *Dinoflagellate phytotoxins exploitation*. <https://cordis.europa.eu/project/id/866736/reporting/fr>

- Djettene R., et al. (2024). Integrated CO₂ capture and conversion into methanol units: Assessing techno-economic and environmental aspects compared to CO₂ into SNG alternative. *Journal of CO₂ Utilization*, 85, 102879. <https://doi.org/10.1016/J.JCOU.2024.102879>
- Drägerwerk AG. (2017). *Reliable CO₂ monitoring in the beverage industry*.
- Duetschke E. (2024). *Public perception of CCUS* (No. 2). <https://circabc.europa.eu/ui/group/75b4ad48-262d-455d-997a-7d5b1f4cf69c/library/ad3aab68-e28b-4fb6-82ff-524f88b0b8b5/details>
- Durán I., et al. (2022). Modeling a biogas upgrading PSA unit with a sustainable activated carbon derived from pine sawdust. Sensitivity analysis on the adsorption of CO₂ and CH₄ mixtures. *Chemical Engineering Journal*, 428, 132564. <https://doi.org/10.1016/J.CEJ.2021.132564>
- Dütschke E., Duscha V. (2022). Is there a future for CCUS in Europe? An analysis of the policy framework and societal support. *GHGT 16, October*. <https://doi.org/10.2139/ssrn.4286232>
- Eberenz S., et al. (2024). Nine recommendations for engaging with the public and stakeholders for Carbon Capture, Transportation, Utilization, and Storage. *Energy Research & Social Science*, 118, 103804. <https://doi.org/10.1016/J.ERSS.2024.103804>
- eCOCO2. (2019). *Direct electrocatalytic conversion of CO₂ into chemical energy carriers in a co-ionic membrane reactor*. <https://cordis.europa.eu/project/id/838077/results>
- Ecofys, Fraunhofer Institute for Systems and Innovation Research. (2009). *Methodology for the free allocation of emission allowances in the EU ETS*. https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/bm_study-cement_en.pdf
- Ecofys, et al. (2009). *Methodology for the free allocation of emission allowances in the EU ETS post 2012, Sector report for the cement industry*. https://ec.europa.eu/clima/sites/clima/files/ets/allowances/docs/bm_study-cement_en.pdf
- Eeloude Infosusteneem, Secretary of State. (2019). *Vabariigi Valitsuse tegevusprogramm 2019-2023 (Action Program of the Government of the Republic 2019-2023)*.
- Eesti Vabariigi Valitsus. (2022). *Strateegia "Eesti 2035" (Strategy "Estonia 2035")*. <https://valitsus.ee/strateegia-est-2035-arengukavad-ja-planeering/strateegia>
- Electhane. (2015). *Microbiological conversion of renewable electricity and CO₂ to a natural gas quality bio-fuel*. <https://cordis.europa.eu/project/id/673824>
- Eliasson Å., et al. (2022). Efficient heat integration of industrial CO₂ capture and district heating supply. *International Journal of Greenhouse Gas Control*, 118, 103689. <https://doi.org/10.1016/J.IJGGC.2022.103689>
- Ellen MacArthur Foundation, Granta Design. (2015). *Circularity indicators. An approach to measuring Circularity*.
- Ellen S., Ingunn S. M. (2022). *A review of standards and frameworks for reporting of biogenic CO₂*.
- Eloy A., et al. (2020). *EU Demonstration Programme for CO₂ Capture and Storage (CCS)*.
- Emele L., et al. (2021). *Decomposition analysis of CO₂ emissions in the European cement sector*. Oko-Institut.
- ENGICOIN. (2017). *Engineered microbial factories for CO₂ exploitation in an integrated waste treatment platform*. <https://cordis.europa.eu/project/id/760994/reporting>

- Enhance. (2019). *H2020 – ENHAnCE*. <https://h2020-enhanceitn.eu/>
- EPA. (2017). *Catalog of CHP Technologies, Full Report, September 2017*.
- EPA. (2023). *Direct Emissions from Stationary Combustion Sources*.
<http://www.epa.gov/climateleadership/documents/resources/stationarycombustionguidance.pdf>
- EPC Group. (2020). *CO2 Technologies (Purification and Recovery)*. <https://www.epc.com/en/technical-gases/plants-for/co2-purification-and-recovery/>
- Epifanceva D. (2018). Факторы, влияющие на эффективность внедрения инновационных технологий на производстве. *Molodoj Uchenij*, 22(208), 402–403.
- Ervia. (2022). *Carbon Capture and Storage*. <https://www.ervia.ie/who-we-are/carbon-capture-storage/>
- Espada J. J., et al. (2021). Environmental assessment of different technologies for bioethanol production from *Cynara cardunculus*: A Life Cycle Assessment study. *Biomass and Bioenergy*, 144.
<https://doi.org/10.1016/J.BIOMBIOE.2020.105910>
- Esposito E., et al. (2019). Simultaneous production of biomethane and food grade CO2 from biogas: an industrial case study. *Energy & Environmental Science*, 12(1), 281–289.
<https://doi.org/10.1039/C8EE02897D>
- European Commission. (2021). *CORDIS - EU research projects under Horizon 2020 (2014-2020)*.
<https://data.europa.eu/data/datasets/cordis2020projects?locale=en>
- European Commission. (2009). Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Text with EEA relevance). *Official Journal of the European Union*, L140/114.
- European Commission. (2010). Communication from the Commission on the practical implementation of the EU biofuels and bioliquids sustainability scheme and on counting rules for biofuels. *Official Journal of the European Union*, 53, C160.
- European Commission. (2016). *Estonia's 2030 National Energy and Climate Plan (NECP 2030)*.
- European Commission. (2020). *Novel carbon capture and utilisation technologies*.
https://ec.europa.eu/info/research-and-innovation/strategy/support-policy-making/scientific-support-eu-policies/group-chief-scientific-advisors/novel-carbon-capture-and-utilisation-technologies_en
- European Commission. (2021a). *2030 climate & energy framework | Climate Action*.
https://ec.europa.eu/clima/policies/strategies/2030_en
- European Commission. (2021b). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS*.
- European Commission. (2021c). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL. Sustainable Carbon Cycles*.
- European Commission. (2021d). *Creating added-value chemicals from bio-industrial CO2 emissions using integrated catalytic technologies*. <https://cordis.europa.eu/project/id/101000580>
- European Commission. (2021e). *Innovation Fund*. https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund_en

- European Commission. (2021f). *Modernisation Fund*. https://ec.europa.eu/clima/policies/budget/modernisation-fund_en
- European Commission. (2021g). *Modernisation Fund*. https://ec.europa.eu/clima/eu-action/funding-climate-action/modernisation-fund_en
- European Commission. (2021h). *Programm: Horizon Europe - Cluster 5 - Destination 3: Sustainable, secure and competitive energy supply*. https://www.euro-access.eu/programm/horizon_europe_-_cluster_5_-_destination_3_sustainable_secure_and_competitive_energy_supply
- European Commission. (2021i). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport*.
- European Commission. (2021j). Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). *Official Journal of the European Union*, L243/1.
- European Commission. (2021k). *Renewable Energy – Recast to 2030 (RED II)*. https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en
- European Commission. (2021l). *Selective CO₂ conversion to renewable methanol through innovative heterogeneous catalyst systems optimized for advanced hydrogenation technologies (microwave, plasma and magnetic induction)*. <https://cordis.europa.eu/project/id/101022507>
- European Commission. (2022a). *€1.5 billion for clean tech: 138 projects apply to the EU Innovation Fund's second call for large-scale projects*. https://climate.ec.europa.eu/news-your-voice/news/eu15-billion-clean-tech-138-projects-apply-eu-innovation-funds-second-call-large-scale-projects-2022-03-11_en
- European Commission. (2022b). *NER 300 programme*. https://ec.europa.eu/clima/eu-action/funding-climate-action/ner-300-programme_en
- European Commission. (2022c). *Primacy of EU law*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:primacy_of_eu_law
- European Commission. (2022d). *Revision for phase 4 (2021-2030)*. https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/revision-phase-4-2021-2030_en
- European Commission. (2023). *A European Green Deal*. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
- European Commission. (2024a). *€3 billion Swedish State aid*. https://ec.europa.eu/commission/presscorner/detail/lt/ip_24_3583
- European Commission. (2024b). *Voluntary schemes*. https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/voluntary-schemes_en
- European Environmental Agency. (2021). *National greenhouse gas policies and measures in Europe*. EEA. <https://www.eea.europa.eu/themes/climate/national-policies-and-measures/national-policies-and-measures-on-1>
- European Environmental Agency. (2022). *Climate change mitigation policies and measures (greenhouse gas emissions)*. <https://www.eea.europa.eu/data-and-maps/data/climate-change-mitigation-policies-and-measures-1>

- European Parliament. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). *Official Journal of the European Union*, L328/82.
- European Parliament. (2020). *LEGISLATIVE TRAIN 12.2020*.
- European Parliament. (2021). *Climate action in Belgium*.
- European Union. (2019). *Standard Eurobarometer 91 - Spring 2019 - August 2019 - - Eurobarometer survey*. <https://europa.eu/eurobarometer/surveys/detail/2253>
- Eurostat. (2020). *Early estimates of CO2 emissions from energy use*.
- Eurostat. (2023). *Labour cost levels by NACE Rev. 2 activity*. https://ec.europa.eu/eurostat/databrowser/view/LC_LCI_LEV__custom_7490720/default/bar?lang=en
- Faber G., et al. (2022). AssessCCUS: An Integrated Approach for Aggregating Resources to Enable Techno-Economic and Life Cycle Assessment of Carbon Management Technologies. *Frontiers in Climate*, 4. <https://doi.org/10.3389/FCLIM.2022.817211>
- Fabiszewska-Solares J., Laskowski K. (2022). *CCS Regional Cooperation Roadmap for Central and Eastern Europe*. CCS4CCE.
- Fankhauser S., et al. (2018). *10 years of the UK Climate Change Act*. London school of Economics and Political Science. 1–43.
- FAO, et al. (2020). *Forest product conversion factors*. <https://doi.org/10.4060/ca7952en>
- Feiz R., et al. (2015). Improving the CO2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry. *Journal of Cleaner Production*, 98, 272–281. <https://doi.org/10.1016/J.JCLEPRO.2014.01.083>
- Fernandez M. I., et al. (2024). Malaysia’s energy transition and readiness towards attaining net zero: review of the potential, constraints, and enablers. *Renewable Energy Focus*, 51, 100640. <https://doi.org/10.1016/J.REF.2024.100640>
- Ferrari G., et al. (2024). From biogas to biomethane: Comparison of sustainable scenarios for upgrading plant location based on greenhouse gas emissions and cost assessments. *Journal of Cleaner Production*, 478, 143936. <https://doi.org/10.1016/J.JCLEPRO.2024.143936>
- Ferreira Ribero L. M., et al. (2019). Welding Productivity Indicators: A critical analysis. *Journal of Mechanical and Civil Engineering*, 15(5 (I)), 22–32.
- Flanagan B., Steckel D. (2019). *ACLCA Guidance to Calculating Non-LCIA Inventory Metrics in Accordance with ISO 21930:2017*.
- Food and Veterinary Service. (2021). *Section IV - Biogas plants*. <https://registri.pvd.gov.lv/cr/a16a26ff>
- Fornero E. L., et al. (2011). CO2 capture via catalytic hydrogenation to methanol: Thermodynamic limit vs. ‘kinetic limit.’ *Catalysis Today*, 172(1), 158–165. <https://doi.org/10.1016/J.CATTOD.2011.02.036>
- FReSMe. (2020). *FReSMe*. https://cinea.ec.europa.eu/featured-projects/fresme_en
- Fubara T., et al. (2018). Techno-economic assessment of natural gas displacement potential of biomethane: A case study on domestic energy supply in the UK. *Chemical Engineering Research*

- and Design*, 131, 193–213. <https://doi.org/10.1016/J.CHERD.2017.12.022>
- Fuss S., Johnsson F. (2021). The BECCS Implementation Gap—A Swedish Case Study. *Frontiers in Energy Research*, 8, 553400. <https://doi.org/10.3389/FENRG.2020.553400/BIBTEX>
- Galiègue X., Laude A. (2017). Combining Geothermal Energy and CCS: From the Transformation to the Reconfiguration of a Socio-Technical Regime? *Energy Procedia*, 114, 7528–7539. <https://doi.org/10.1016/J.EGYPRO.2017.03.1904>
- GCCA. (2019). *GCCA Sustainability Guidelines for the monitoring and reporting of CO2 emissions from cement manufacturing*.
- GECO. (2018). *Geothermal Emission Control*. <https://cordis.europa.eu/project/id/818169/reporting>
- Ghiat I., et al. (2025). Circularity within carbon capture networks: A review of capture and utilization technologies. *Journal of CO2 Utilization*, 95, 103075. <https://doi.org/10.1016/J.JCOU.2025.103075>
- Ghiat I., et al. (2021). CO2 utilisation in agricultural greenhouses: A novel ‘plant to plant’ approach driven by bioenergy with carbon capture systems within the energy, water and food Nexus. *Energy Conversion and Management*, 228, 113668. <https://doi.org/10.1016/J.ENCONMAN.2020.113668>
- Gholizadeh T., et al. (2025). Sustainable biofuel production through anaerobic digestion, SOEC and carbon-capture-and-utilization (CCU): techno-economic, exergy and Life-cycle analysis. *Energy*, 328, 136458. <https://doi.org/10.1016/J.ENERGY.2025.136458>
- Gkotsis P., et al. (2023). Membrane-Based Technologies for Post-Combustion CO2 Capture from Flue Gases: Recent Progress in Commonly Employed Membrane Materials. *Membranes* 2023, Vol. 13, Page 898, 13(12), 898. <https://doi.org/10.3390/MEMBRANES13120898>
- GLAZER. (2020). *Transforming the glass industry with environmentally clean and energy-efficient laser technology*. <https://cordis.europa.eu/project/id/954932/reporting>
- Global CCS Institute. (2018). *The Global Status of CCs: 2017*.
- Global CCS Institute. (2021a). *Global Status of CCS 2020*. <https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Global-Status-of-CCS-Report-English.pdf>
- Global CCS Institute. (2021b). *Global Status of CCS 2021*.
- Government Offices of Sweden. (2020). *Sweden’s long-term strategy for reducing greenhouse gas emissions*.
- Gramofon. (2016). *New process for efficient CO2 capture by innovative adsorbents based on modified graphene aerogels and MOF materials*. <https://doi.org/10.3030/727619>
- Grasso M. L., et al. (2019). CO2 reutilization for methane production via a catalytic process promoted by hydrides. *Physical Chemistry Chemical Physics*, 21(36), 19825–19834. <https://doi.org/10.1039/C9CP03826D>
- Grim R. G., et al. (2022). Electrifying the production of sustainable aviation fuel: the risks, economics, and environmental benefits of emerging pathways including CO 2. *Energy & Environmental Science*, 15(11), 4798–4812. <https://doi.org/10.1039/D2EE02439J>
- Group of Chief Scientific Advisors. (2018). *Novel Carbon Capture and Utilisation Technologies*. <https://doi.org/10.2777/824461>
- Gullo P., et al. (2017). State-of-the-art technologies for transcritical R744 refrigeration systems - A

- theoretical assessment of energy advantages for European food retail industry. *Energy Procedia*, 123, 46–53. <https://doi.org/10.1016/j.egypro.2017.07.283>
- Guo J., et al. (2025). Integrated system utilizing methanol steam reforming process for hydrogen production combined with methane-hydrogen gas turbine multi-cascade generation. *Applied Thermal Engineering*, 271, 126324. <https://doi.org/10.1016/J.APPLTHERMALENG.2025.126324>
- Gustafsson M., et al. (2021). *IEA Bioenergy Task 37: A perspective on the state of the biogas industry from selected member countries* (Issue September). <https://task37.ieabioenergy.com/country-reports.html>
- Gustafsson M., et al. (2024). Climate performance of liquefied biomethane with carbon dioxide utilization or storage. *Renewable and Sustainable Energy Reviews*, 192, 114239. <https://doi.org/10.1016/J.RSER.2023.114239>
- Haghighatjoo F., et al. (2023). Techno-economic and environmental assessment of CO₂ conversion to methanol: Direct versus indirect conversion routes. *Chemical Engineering and Processing - Process Intensification*, 184, 109264. <https://doi.org/10.1016/J.CEP.2023.109264>
- Halkos G., et al. (2022). Determinants of willingness to pay for urban parks: An empirical analysis in Greece. *Land Use Policy*, 119, 106186. <https://doi.org/10.1016/J.LANDUSEPOL.2022.106186>
- Hamelin L., et al. (2021). Harnessing the full potential of biomethane towards tomorrow's bioeconomy: A national case study coupling sustainable agricultural intensification, emerging biogas technologies and energy system analysis. *Renewable and Sustainable Energy Reviews*, 138, 110506. <https://doi.org/10.1016/J.RSER.2020.110506>
- Harald B., et al. (2002). *Method for the liquefaction of CO₂ from fermentation of alcohol or from other gas sources* (Patent No. EP1308502B1). European Patent Office.
- He S., et al. (2024). Remarkably enhanced catalytic performance of three-dimensional hierarchically porous Mo₂C catalysts for higher alcohols synthesis from syngas. *Molecular Catalysis*, 556, 113941. <https://doi.org/10.1016/J.MCAT.2024.113941>
- Hirunsit P., et al. (2024). From CO₂ to Sustainable Aviation Fuel: Navigating the Technology Landscape. *ACS Sustainable Chemistry and Engineering*, 12(32), 12143–12160. https://doi.org/10.1021/ACSSUSCHEMENG.4C03939/ASSET/IMAGES/LARGE/SC4C03939_0005.JPEG
- HM Government. (2017). *The Clean Growth Strategy Leading the way to a low carbon future*.
- Hofstetter R., et al. (2021). A de-biased direct question approach to measuring consumers' willingness to pay. *International Journal of Research in Marketing*, 38(1), 70–84. <https://doi.org/10.1016/J.IJRESMAR.2020.04.006>
- Hong W. Y. (2022). A techno-economic review on carbon capture, utilisation and storage systems for achieving a net-zero CO₂ emissions future. *Carbon Capture Science & Technology*, 3, 100044. <https://doi.org/10.1016/J.CCST.2022.100044>
- Hosseini S. M., et al. (2023). Life cycle cost and environmental assessment of CO₂ utilization in the beverage industry: A natural gas-fired power plant equipped with post-combustion CO₂ capture. *Energy Reports*, 9, 414–436. <https://doi.org/10.1016/J.EGYR.2022.11.200>
- Hou R., et al. (2022). Current status and advances in membrane technology for carbon capture. *Separation and Purification Technology*, 300, 121863. <https://doi.org/10.1016/J.SEPPUR.2022.121863>

- Hruby M., et al. (2022). *Central and Eastern European CCS Roadmap*. CCS4CCE.
- Hu J., et al. (2025). Technical, economic, and environmental study with ANN-based optimization of a biomass-powered versatile/sustainable polygeneration system with carbon capture/utilization approach. *Energy*, 315, 133935. <https://doi.org/10.1016/J.ENERGY.2024.133935>
- Humphrey S. S., et al. (2023). Supercritical Fluids: Properties, Formation and Applications. *Journal of Engineering in Industrial Research*, 4(3), 176–188.
- HyMap. (2015). *Hybrid Materials for Artificial Photosynthesis*. <https://cordis.europa.eu/project/id/648319/reporting>
- I-PHYC. (2016). *Development of an innovative algae based tertiary wastewater treatment and value recovery system*. <https://cordis.europa.eu/project/id/733718/reporting>
- I-PHYC. (2020). *Broadwindsor*. <https://i-phyc.com/broadwindsor/>
- IEA. (2017). *Tracking Clean Energy Progress 2017*. Paris. 1–116.
- IEA. (2018). *Technology Roadmap - Low-Carbon Transition in the Cement Industry*. www.wbcsdcement.org.
- IEA. (2019). *Putting CO2 to Use*. Paris. 1–86.
- IEA. (2020a). *A new era for CCUS – CCUS in Clean Energy Transitions*. <https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus>
- IEA. (2020b). *Actions for policy makers – The role of CCUS in low-carbon power systems*. <https://www.iea.org/reports/the-role-of-ccus-in-low-carbon-power-systems/actions-for-policy-makers>
- IEA. (2021a). *Global Energy Review: CO2 Emissions in 2021 Global emissions rebound sharply to highest ever level*. Paris. 1–14.
- IEA. (2021b). *Net Zero by 2050 - A Roadmap for the Global Energy Sector*. Paris. 1–224.
- IEA. (2022a). *Carbon capture, utilisation and storage - Fuels & Technologies*. <https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage>
- IEA. (2022b). *Federal Climate Change Act 2021*. <https://www.iea.org/policies/13518-federal-climate-change-act-2021>
- IEA. (2022c). *Total CO2 emissions*. <https://www.iea.org/regions/europe/emissions>
- IEA. (2024). *Direct Air Capture - Energy System - IEA*. <https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture>
- IEA. (2025). *Global Energy Review 2025*. Paris. 1–43.
- IEA Bioenergy. (2020). *Production of food grade sustainable CO2 from a large biogas facility*. Copenhagen. 1–4.
- Ievina B., Romagnoli F. (2020). Potential of chlorella species as feedstock for bioenergy production: A review. *Environmental and Climate Technologies*, 24(2), 203–220. <https://doi.org/10.2478/RTUECT-2020-0067>
- INA. (2022). *Biorafinery Project*. <https://www.ina.hr/biorafinerija/en>

- Institution of Civil Engineers (ICE). (2017). Teesside: creating one of Europe's first clean industrial zones with carbon capture and storage. In *Ice Group*. ICE Group. <https://www.ice.org.uk/engineering-resources/case-studies/teesside-creating-one-of-europe-s-first-clean-industrial-zones-with-carbon-capture-and-storage/>
- International Gas Union. (2021). *Global Renewable & Low-Carbon Gas Report* .
- Ioannis T., et al. (2018). Cost development of low carbon energy technologies - Scenario-based cost trajectories to 2050, 2017 edition. In *JRC Science and Policy Reports*. <https://doi.org/10.2760/23266>
- IOGP. (2019). *The potential for CCS and CCU in Europe REPORT TO THE THIRTY SECOND MEETING OF THE EUROPEAN GAS REGULATORY FORUM 5-6 JUNE 2019 COORDINATED BY IOGP*.
- IOGP Europe. (2020). *CCUS projects in Europe*. IOGP.
- IOGP Europe. (2022). *CO2 storage Projects in Europe*. <https://iogpeurope.org/resource/map-of-eu-ccus-projects/>
- IPCC. (2022). *IPCC Press Release*. IPCC.
- ISCC. (2017). *ISCC 201-3 Guidance for the Certification of Biogas and Biomethane* .
- Ishaq H., Crawford C. (2023). CO₂-based alternative fuel production to support development of CO₂ capture, utilization and storage. *Fuel*, 331, 125684. <https://doi.org/10.1016/J.FUEL.2022.125684>
- ISO. (2006a). *ISO 14040:2006(en), Environmental management — Life cycle assessment — Principles and framework*. ISO. <https://www.iso.org/obp/ui/en/#iso:std:iso:14040:ed-2:v1:en>
- ISO. (2006b). *ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines*.
- Itul A., et al. (2023). *Clean Energy Technology Observatory: Carbon capture storage and utilisation in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets*. <https://doi.org/10.2760/882666>
- Jiang Y., et al. (2023). Recent advances in thermocatalytic hydrogenation of carbon dioxide to light olefins and liquid fuels via modified Fischer-Tropsch pathway. *Journal of CO₂ Utilization*, 67, 102321. <https://doi.org/10.1016/J.JCOU.2022.102321>
- Jing L., et al. (2024). *Comparative life cycle assessment of methanol production processes in China Coal Coking to MeOH Natural Gas to MeOH*. 46.
- Karekar S. C., et al. (2023). Assessing feasible H₂-CO₂ sources in the US as Feedstocks for Sustainable Aviation Fuel Precursors: Acetic Acid and Ethanol Production via Hydrogenotrophic Pathways. *Journal of Environmental Management*, 345(C). <https://doi.org/10.1016/J.JENVMAN.2023.118641>
- Karimi M., et al. (2023). Carbon dioxide separation and capture by adsorption: a review. *Environmental Chemistry Letters* 21(4), 2041–2084. <https://doi.org/10.1007/S10311-023-01589-Z>
- Kazulis V., et al. (2017). Carbon storage in wood products. *Energy Procedia*, 128, 558–563. <https://doi.org/10.1016/J.EGYPRO.2017.09.009>
- Keogh N., et al. (2022). Biogenic renewable gas injection into natural gas grids: A review of technical and economic modelling studies. *Renewable and Sustainable Energy Reviews*, 168. <https://doi.org/10.1016/J.RSER.2022.112818>

- KeroGreen. (2018). *Production of Sustainable aircraft grade Kerosene from water and air powered by Renewable Electricity, through the splitting of CO₂, syngas formation and Fischer-Tropsch synthesis*. <https://cordis.europa.eu/project/id/763909/reporting>
- Ketipi M. K., et al. (2020). Multi-Criteria Decision Making using Fuzzy Cognitive Maps – Preliminary Results. *Procedia Manufacturing*, 51, 1305–1310. <https://doi.org/10.1016/J.PROMFG.2020.10.182>
- Khan M. A., Gohari Darabkhani H. (2022). Technoeconomic Analysis and Risk Assessment of Deploying Micro-Combined Heat and Power (M-Chp) Systems for Domestic Applications. In *SSRN Electronic Journal*. Elsevier BV. <https://doi.org/10.2139/SSRN.4044506>
- Khan M. I. (2018). Evaluating the strategies of compressed natural gas industry using an integrated SWOT and MCDM approach. *Journal of Cleaner Production*, 172, 1035–1052. <https://doi.org/10.1016/J.JCLEPRO.2017.10.231>
- Khojasteh-Salkuyeh Y., et al. (2021). CO₂ utilization for methanol production; Part I: Process design and life cycle GHG assessment of different pathways. *Journal of CO₂ Utilization*, 50, 101608. <https://doi.org/10.1016/J.JCOU.2021.101608>
- Kiselev D., et al. (2017). Problems of ineffective modernization at industrial enterprises and ways of their solution. *MATEC Web of Conferences*, 129, 01029. <https://doi.org/10.1051/mateconf/201712901029>
- Kiss A. A., et al. (2016). Novel efficient process for methanol synthesis by CO₂ hydrogenation. *Chemical Engineering Journal*, 284, 260–269. <https://doi.org/10.1016/j.cej.2015.08.101>
- Klimaat.BE. (2019). *Nationaal Energie- en Klimaatplan 2021-2030*. <https://klimaat.be/klimaatbeleid/belgisch/nationaal/nationaal-energie-en-klimaatplan-2021-2030>
- Knight D., et al. (2024). FreeTxt: A corpus-based bilingual free-text survey and questionnaire data analysis toolkit. *Applied Corpus Linguistics*, 4(3), 100103. <https://doi.org/10.1016/J.ACORP.2024.100103>
- Konist A., et al. (2021). *KLIIMAMUUTUSTE LEEVENDAMINE LÄBI CCS JA CCU TEHNOLOOGIATE (ClimMit) (CLIMATE CHANGE MITIGATION THROUGH CCS AND CCU TECHNOLOGIES (ClimMit))*.
- Körner O., et al. (2007). Design and performance of a measuring system for CO₂ exchange of a greenhouse crop at different light levels. *Biosystems Engineering*, 97(2), 219–228. <https://doi.org/10.1016/J.BIOSYSTEMSENG.2007.02.018>
- Kosonen P. (2020). *Techno-Economic Study of Bio-Ethanol Production as a Carbon Capture and Utilization Process*. Tampere University.
- Krajnc D., Glavic P. (2003). Indicators of sustainable production. *Clean Technologies and Environmental Policy*, 5(3–4), 279–288. <https://doi.org/10.1007/s10098-003-0221-z>
- KUBBI. (2019). *Cost- and Climate-Efficient Milk Cooling Using Slurry Ice and Natural CO₂*. <https://cordis.europa.eu/project/id/856130/reporting/es>
- Kudurs E., et al. (2020). Are Industries Open for Renewable Energy? *Environmental and Climate Technologies*, 24(3), 447–456. <https://doi.org/10.2478/RTUECT-2020-0115>
- Lange N., et al. (2023). *Assessment of Greenhouse Gas Emission Reduction from Biogas Supply Chains in Germany in Context of a Newly Implemented Sustainability Certification*. 85–101. https://doi.org/10.1007/978-3-031-29294-1_6

- Langley N. M., et al. (2012). A critical evaluation of CO₂ supplementation to algal systems by direct injection. *Biochemical Engineering Journal*, 68, 70–75. <https://doi.org/10.1016/J.BEJ.2012.07.013>
- Larsen V. G., et al. (2022). What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. *Journal of Building Engineering*, 50, 104203. <https://doi.org/10.1016/J.JOBE.2022.104203>
- LASERCUT. (2016). *Valorising small diameter trees by cutting them with laser*. <https://cordis.europa.eu/project/id/735812>
- Latvian Geological and Meteorological Center. (2022). *Pollutant Release and Transfer Register*. <https://prtr.lvghmc.lv/>
- Latvijas Gaze. (2022a). *Energy of the future – biomethane*. <https://lg.lv/en/news/energy-of-the-future-biomethane>
- Latvijas Gaze. (2022b). *Latvijas Gāze includes initiatives for the development of biomethane production in the environmental policy of the company*. <https://lg.lv/en/news/latvijas-gaze-includes-initiatives-for-the-development-of-biomethane-production-in-the-environmental-policy-of-the-company>
- Latvijas Radio. (2022). *Pieaug koksnes šķeldas cena, apkure ar šķeldu ir 5 reizes lētāka nekā dabasgāzi*. <https://lr1.lsm.lv/lv/raksts/eiro-fokusa/pieaug-koksnes-skeldas-cena-apkure-ar-skeldu-ir-5-reizes-letaka-.a155970/>
- Lavrenchenko G. K., Kopitin A. V. (2011). New Technologies For Extraction of CO₂ from Smoke Gases of Heat Stations. *Technical Gases*, 2, 32–42. <https://doi.org/10.18198/j.ind.gases.2011.0548>
- Lee B., et al. (2025). Clustered carbon capture as a technologically and economically viable concept for industrial post-combustion CO₂ capture. *Energy Conversion and Management*, 330, 119608. <https://doi.org/10.1016/J.ENCONMAN.2025.119608>
- Lee U., et al. (2021). Using waste CO₂ from corn ethanol biorefineries for additional ethanol production: life-cycle analysis. *Biofuels, Bioproducts and Biorefining*, 15(2), 468–480. <https://doi.org/10.1002/BBB.2175>
- Leeson D., et al. (2017). A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *International Journal of Greenhouse Gas Control*, 61, 71–84. <https://doi.org/10.1016/J.IJGGC.2017.03.020>
- Lefvert A., et al. (2022). What are the potential paths for carbon capture and storage in Sweden? A multi-level assessment of historical and current developments. *Energy Research & Social Science*, 87, 102452. <https://doi.org/10.1016/J.ERSS.2021.102452>
- LEILAC. (2016). *Low Emissions Intensity Lime and Cement*. <https://cordis.europa.eu/project/id/654465/reporting>
- Leonzio G., et al. (2019). Methanol production by CO₂ hydrogenation: Analysis and simulation of reactor performance. *International Journal of Hydrogen Energy*, 44(16), 7915–7933. <https://doi.org/10.1016/J.IJHYDENE.2019.02.056>
- Levihn F. (2021). *Bio-CCS kan bli en konkurrensfördel för svensk industri*. Stockholm Exergi.
- Li G., Yao J. (2024). A Review of Algae-Based Carbon Capture, Utilization, and Storage (Algae-Based CCUS). *Gases 2024, Vol. 4, Pages 468-503*, 4(4), 468–503. <https://doi.org/10.3390/GASES4040024>

- Li H., et al. (2025). Selecting proper technologies for capturing CO₂ from bioenergy conversion. *Renewable and Sustainable Energy Reviews*, 218, 115747. <https://doi.org/10.1016/J.RSER.2025.115747>
- Lietuvos Respublikos energetikos ministerija. (2020). *LIETUVOS RESPUBLIKOS NACIONALINIS ENERGETIKOS IR KLIMATO SRITIES VEIKSMŲ PLANAS 2021-2030 m. (NATIONAL ENERGY AND CLIMATE ACTION PLAN OF THE REPUBLIC OF LITHUANIA for 2021-2030)*.
- Life Cycle Initiative. (2023). *Environmental LCA*. <https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/environmental-lca/>
- Liu Y., et al. (2025). Connection, deviation, patterns, and trends: Visualizing the interplay of sustainability science and social–ecological system research. *Journal of Cleaner Production*, 504, 145431. <https://doi.org/10.1016/J.JCLEPRO.2025.145431>
- Lo Cascio E., et al. (2018). Key performance indicators for integrated natural gas pressure reduction stations with energy recovery. *Energy Conversion and Management*, 164, 219–229. <https://doi.org/10.1016/j.enconman.2018.02.089>
- Lockwood T. (2023). *Where will Europe store its CO₂?* <https://www.catf.us/2023/07/where-will-europe-store-its-co2/>
- López Fernández D., Oliver M. (2025). Methodology, strategies, and factors for business innovation in large companies. *International Journal of Innovation Studies*, 9(2), 91–115. <https://doi.org/10.1016/J.IJIS.2025.02.002>
- LOTER.CO2M. (2018). *CRM-free Low Temperature Electrochemical Reduction of CO₂ to Methanol*. <https://cordis.europa.eu/project/id/761093/reporting>
- LSM.lv. (2022). «Latvijas gāze» brīdina par dabasgāzes biržas cenas trīskāršu pieaugumu aprīlī. <https://www.lsm.lv/raksts/zinas/ekonomika/latvijas-gaze-bridina-par-dabaszgazes-birzas-cenas-triskarsu-pieaugumu-aprili.a446800/>
- Luo L., et al. (2023). Environmental and economic analysis of renewable heating and cooling technologies coupled with biomethane utilization: A case study in Chongqing. *Sustainable Energy Technologies and Assessments*, 56, 102992. <https://doi.org/10.1016/J.SETA.2022.102992>
- LVGMC. (2020). *Pollutant Emission and Transfer Register*. <https://prtr.lvgmc.lv/>
- LVGMC. (2020). *2020.gadā iesniegtās siltumnīcefekta gāzu inventarizācijas kopsavilkums*.
- Lyons M., et al. (2021). *Reaching Zero with Renewables: Capturing carbon*.
- MacroFuels. (2016). *Developing the next generation Macro-Algae based biofuels for transportation via advanced bio-refinery processes*. <https://cordis.europa.eu/project/id/654010/reporting>
- Madsen J., et al. (2010). Methane and carbon dioxide ratio in excreted air for quantification of the methane production from ruminants. *Livestock Science*, 129(1–3), 223–227. <https://doi.org/10.1016/J.LIVSCI.2010.01.001>
- Manganaro J. L., Lawal A. (2016). CO₂ Life-Cycle Assessment of the Production of Algae-Based Liquid Fuel Compared to Crude Oil to Diesel. *Energy and Fuels*, 30(4), 3130–3139. <https://doi.org/10.1021/ACS.ENERGYFUELS.6B00207>
- Marchi M., et al. (2018). CO₂ recovery from wine production: Possible implications on the carbon balance at territorial level. *Journal of CO₂ Utilization*, 28, 137–144. <https://doi.org/10.1016/j.jcou.2018.09.021>

- Marmier A. (2023). Decarbonisation options for the Cement Industry. In *Publications Office of the European Union* (Issue EUR 31378 EN). <https://doi.org/10.2760/174037>
- Marsh V., Strategy CCUS. (2021). *Regions in focus: Spotlight on industry in Northern Croatia and Romania*.
- Maselli G., et al. (2024). Carbon capture and utilisation (CCU) solutions: Assessing environmental, economic, and social impacts using a new integrated methodology. *Science of The Total Environment*, 948, 174873. <https://doi.org/10.1016/J.SCITOTENV.2024.174873>
- MefCO₂. (2014). *Synthesis of methanol from captured carbon dioxide using surplus electricity*. <https://cordis.europa.eu/project/id/637016/reporting>
- MEFCO₂. (2019). *MefCO₂ project*. <http://www.mefco2.eu/>
- MEMBER. (2016). *Advanced MEMBranes and membrane assisted procEses for pre- and post-combustion CO₂ captuRe*. <https://member-co2.com/>
- Mendas A., et al. (2024). Group Decision-Making Based on GIS and MultiCriteria Analysis for Assessing Land Suitability for Agriculture. *Revue Internationale de Geomatique*, 33(0), 383–398. <https://doi.org/10.32604/RIG.2024.055321>
- Meng F., et al. (2022). Effects of hydroxyethyl group on monoethanolamine (MEA) derivatives for biomethane from biogas upgrading. *Fuel*, 325, 124874. <https://doi.org/10.1016/J.FUEL.2022.124874>
- Merkle W., et al. (2017). High-pressure anaerobic digestion up to 100 bar: influence of initial pressure on production kinetics and specific methane yields. *Environmental Technology*, 38(3), 337–344. <https://doi.org/10.1080/09593330.2016.1192691>
- MetaFuel. (2015). *High Temperature Methanol Fuel Cell*. <https://cordis.europa.eu/project/id/674137/results>
- Mikhelkis L., Govindarajan V. (2020). Techno-economic and partial environmental analysis of carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCU/S): Case study from proposed waste-fed district-heating incinerator in Sweden. *Sustainability (Switzerland)*, 12(15), 5922. <https://doi.org/10.3390/SU12155922>
- Ministry of Economics Republic of Latvia. (2020). *Latvia's National Energy and Climate Plan 2021-2030*.
- Ministry of Environmental Protection and Regional Development. (2020). *Siltumnīcefekta gāzu monitorings un ziņošana*. <https://www.varam.gov.lv/lv/siltumnicefekta-gazu-monitorings-un-zinosana>
- Ministry of Environmental Protection and Regional Development. (2021). *Climate Law*. <https://www.varam.gov.lv/lv/klimata-likums>
- Ministry of Environmental Protection and Regional Development Republic of Latvia. (2020). *Waste management regions and landfills in Latvia*.
- Ministry of the Environment and Energy. (2017). *The Swedish climate policy framework*.
- Mishra A. K., et al. (2020). Defects in nanosilica catalytically convert CO₂ to methane without any metal and ligand. *Proceedings of the National Academy of Sciences of the United States of America*, 117(12), 6383–6390. <https://doi.org/10.1073/pnas.1917237117>

- Mockevicius, J. (2011). *CCS LEGISLATION FRAMEWORK IN LITHUANIA*. LGT.
- Modeler, M. (2024). *Fuzzy Logic Cognitive Mapping*. <https://www.mentalmodeler.com/>
- Modern Brewhouse. (2018). *CO2 Purity and Why It's Important*. <https://www.themodernbrewhouse.com/carbon-dioxide-purity/>
- Moestedt J., et al. (2015). Determination of Methane and Carbon Dioxide Formation Rate Constants for Semi-Continuously Fed Anaerobic Digesters. *Energies* 2015, Vol. 8, Pages 645-655, 8(1), 645–655. <https://doi.org/10.3390/EN8010645>
- Mohsin I., et al. (2020). Economic and Environmental Assessment of Integrated Carbon Capture and Utilization. *Cell Reports Physical Science*, 1(7), 100104. <https://doi.org/10.1016/J.XCRP.2020.100104>
- MOLGroup. (2014). *CO2 EOR Project Croatia*.
- Morimoto S., et al. (2021). Scenario assessment for producing methanol through carbon capture and utilization technologies considering regional characteristics. *Journal of CO2 Utilization*, 45, 101452. <https://doi.org/10.1016/J.JCOU.2021.101452>
- Muhammad Rashed A. M., Shuichi T. (2017). Enrichment of Methane Concentration by Removing Contaminant Gases from Biogas Mixtures Based on Chemical Purification Processes. *International Journal of Transport Phenomena*, 14, 171–182.
- Muizniece I., Blumberga D. (2018). Methodology for determining potential of forest bioproduct commercialization. *Environmental Development*. <https://doi.org/10.1016/J.ENVDEV.2018.02.004>
- Mukeshimana M. C., et al. (2021). Evaluating strategies for renewable energy development in Rwanda: An integrated SWOT – ISM analysis. *Renewable Energy*, 176, 402–414. <https://doi.org/10.1016/J.RENENE.2021.05.104>
- Murugan A., et al. (2020). Performing Quality Assurance of Carbon Dioxide for Carbon Capture and Storage. *C 2020*, 6(4), 76. <https://doi.org/10.3390/C6040076>
- NASA. (2021). *Emissions from Fossil Fuels Continue to Rise*. <https://earthobservatory.nasa.gov/images/152519/emissions-from-fossil-fuels-continue-to-rise>
- Nasehi S., et al. (2019). Strategic planning, based on environmental spatial assessment, using SWOT and GIS to locate sustainable industrial areas (case study: Tehran province). *Pollution*, 5(3), 569–583. <https://doi.org/10.22059/POLL.2018.260564.464>
- NETL. (2023). *Point Source Carbon Capture from Industrial Sources*. <https://www.netl.doe.gov/carbon-capture/industrial>
- NOCO2. (2019). *Novel CO2 condensation and separation in supersonic flows contributing to carbon capture and storage (CCS)*. <https://cordis.europa.eu/project/id/792876>
- Nordic Electrofuel. (2023). *Clean at scale. Decarbonizing aviation*. <https://nordicelectrofuel.no/>
- Nouri A., et al. (2025). Integration of biomass gasification and MEA-based CO2 capture for sustainable power and methanol production: Energy, exergy, and economic analysis and optimization. *Energy*, 319, 135062. <https://doi.org/10.1016/J.ENERGY.2025.135062>
- NTPleasure. (2018). *Non-Thermal Plasma Enabled Catalysis-Separation system for Upgrading biogas to methane-NTPleasure*. <https://cordis.europa.eu/project/id/748196/reporting>

- O'Mahony T. (2021). Cost-Benefit Analysis and the environment: The time horizon is of the essence. *Environmental Impact Assessment Review*, 89, 106587. <https://doi.org/10.1016/J.EIAR.2021.106587>
- OCEAN. (2020). *Oxalic acid from CO2 using Electrochemistry At demonstration scale*. <https://cordis.europa.eu/project/id/767798/reporting>
- OECD (Ed.). (2020). *Rural Well-being: Geography of Opportunities*. OECD. <https://doi.org/10.1787/D25CEF80-EN>
- Office of the Law Revision Counsel United States Code. (2021). 26 USC 45Q: Credit for carbon oxide sequestration. In *Internal revenue Code, 135(80402(f))*, 1334.
- Official statistics portal. (2025). *Siltumņīcefekta gāzu emisijas 1990–2023, tūkst. tonnas CO2 ekvivalentos*. https://data.stat.gov.lv/pxweb/lv/OSP_PUB/START__ENV__GP__GPE/GPE030/table/tableViewLayout1/
- Onofre A., et al. (2020). Eco-innovation in the cleaning process: An application of dry ice blasting in automotive painting industry. *Journal of Cleaner Production*, 272, 122987. <https://doi.org/10.1016/j.jclepro.2020.122987>
- Ontario.ca. (2002). *Supplemental carbon dioxide in greenhouses*. <https://www.ontario.ca/page/supplemental-carbon-dioxide-greenhouses>
- OpenLCA. (2025). *openLCA Nexus: The source for LCA data sets*. <https://nexus.openlca.org/>
- Osipova I., Menschikova V. (2017). Идентификация рисков технического перевооружения промышленных предприятий и ключевые направления управления ими. *Socialjno-Ekonomicheskie Javlenija i Processi*, 12(2), 91–97. <https://doi.org/10.20310/1819-8813-2017-12-2-91-97>
- Ozkan M. (2024). Atmospheric alchemy: The energy and cost dynamics of direct air carbon capture. *MRS Energy and Sustainability*, 1–16. <https://doi.org/10.1557/S43581-024-00091-5/FIGURES/3>
- Pacheco K. A., et al. (2021). Multi criteria decision analysis for screening carbon dioxide conversion products. *Journal of CO2 Utilization*, 43, 101391. <https://doi.org/10.1016/j.jcou.2020.101391>
- Pallado P. (2001). Dry-cleaning with liquid carbon dioxide. *Industrial Chemistry Library*, 9(C), 641–649. [https://doi.org/10.1016/S0926-9614\(01\)80037-X](https://doi.org/10.1016/S0926-9614(01)80037-X)
- Park H., Grundmann P. (2025). Institutional work after hype: The case of biogas in Germany. *Energy Research & Social Science*, 119, 103820. <https://doi.org/10.1016/J.ERSS.2024.103820>
- Parliamentary Advisory Group on CCS. (2016). *LOWEST COST DECARBONISATION FOR THE UK: THE CRITICAL ROLE OF CCS*.
- Pastare L., Romagnoli F. (2019). Life Cycle Cost Analysis of Biogas Production from Ceratophyllum demersum, Fucus vesiculosus and Ulva intestinalis in Latvian Conditions. *Environmental and Climate Technologies*, 23(2), 258–271. <https://doi.org/10.2478/rtuect-2019-0067>
- Pérez-Fortes M., et al. (2016). Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment. *Applied Energy*, 161, 718–732. <https://doi.org/10.1016/j.apenergy.2015.07.067>
- Pérez-Fortes M., et al. (2016). Techno-economic and environmental evaluation of CO2 utilisation for fuel production. Synthesis of methanol and formic acid. *Publications Office of the European Union*. <https://doi.org/10.2790/89238>

- Phoenix Initiative. (2018). *A European Integrated Approach to CO2 Valorisation*.
- Pio D. T., et al. (2023). Decarbonizing the aviation sector with Electro Sustainable Aviation Fuel (eSAF) from biogenic CO2 captured at pulp mills. *Chemical Engineering Journal*, 463, 142317. <https://doi.org/10.1016/J.CEJ.2023.142317>
- Poczeta K., et al. (2020). Fuzzy Cognitive Maps Optimization for Decision Making and Prediction. *Mathematics*, 8(11), 2059. <https://doi.org/10.3390/MATH8112059>
- Pogonyi T., et al. (2018). Arc welding of zinc coated high strength steels. *Lecture Notes in Mechanical Engineering*, 0(9783319756769), 768–778. https://doi.org/10.1007/978-3-319-75677-6_65
- Pokrzywka G. (2025). *CCUS in the updated National Energy and Climate Plan (NECP)*. Chambers and Partners. <https://chambers.com/articles/poland-ccus-in-the-updated-national-energy-and-climate-plan-necp>
- Potter E., Jackson V. (2021). *High natural gas prices lead to increased coal generation, 2021 carbon emissions: ELA*. S&P Global Commodity Insights. <https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/natural-gas/081021-high-natural-gas-prices-lead-to-increased-coal-generation-2021-carbon-emissions-eia>
- Prakash G. K. S. (2015). *The Methanol Economy*. University of Southern California.
- Pratschner S., et al. (2023). Techno-economic assessment of a power-to-green methanol plant. *Journal of CO2 Utilization*, 75, 102563. <https://doi.org/10.1016/J.JCOU.2023.102563>
- Pré. (2024a). *ecoinvent | High-quality LCI database integrated in SimaPro*. <https://simapro.com/products/ecoinvent/>
- Pré. (2024b). *SimaPro | LCA software for informed changemakers*. <https://simapro.com/>
- Press Release. Gov.UK. (2021). UK enshrines new target in law to slash emissions by 78% by 2035. *Gov.UK*.
- ProGeo. (2016). *ProGeo*. <https://cordis.europa.eu/project/id/717957/results>
- Ramos-Fernandez E. V., et al. (2025). Potential pathways for CO2 utilization in sustainable aviation fuel synthesis. *Chemical Science*, 16(2), 530–551. <https://doi.org/10.1039/D4SC06164K>
- Rassool D. (2020). *Overview of Organisations and Policies Supporting the Deployment of Large-Scale CCS Facilities*.
- Stubdrup R., et al. (2016). Best Available Techniques (BAT) Reference Document for the Production of Wood-based Panels. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). <https://doi.org/10.2791/21807>
- Ravikumar D., et al. (2021). Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit. *Nature Communications*, 12(1), 1–13. <https://doi.org/10.1038/S41467-021-21148-W>;SUBJMETA=172,4057,4077,4081,639,704;KWRD=CARBON+CAPTURE+AND+STORAGE, ENVIRONMENTAL+IMPACT
- Ravn S. (2020). *Topsoe to build demonstration plant to produce cost-competitive CO2-neutral methanol from biogas and green electricity*. <https://www.topsoe.com/blog/topsoe-to-build-demonstration-plant-to-produce-cost-competitive-co2-neutral-methanol-from-biogas-and-green-electricity>
- Recharge & Collins, L. (2021). *The amount of energy required by direct air carbon capture proves it is*

- an exercise in futility*. <https://www.rechargenews.com/energy-transition/the-amount-of-energy-required-by-direct-air-carbon-capture-proves-it-is-an-exercise-in-futility/2-1-1067588>
- REDcert. (2015). *REDcert Version 07 System principles for interfaces and suppliers of waste and residual materials*.
- REDcert GmbH. (2021). *Scheme principles for GHG calculation. Scheme principles for GHG calculation consent*.
- Natural Refrigerants. (2021). *Natural Refrigerants Cooling & Heating News*. <https://naturalrefrigerants.com/>
- Ren B. P., et al. (2023). Methanol production from natural gas reforming and CO₂ capturing process, simulation, design, and technical-economic analysis. *Energy*, 263, 125879. <https://doi.org/10.1016/J.ENERGY.2022.125879>
- Ren J., et al. (2023). Analysis of coordinated development of “society-ecology-policy” and spatio-temporal variation of people’s livelihoods and well-being in the Yellow River basin, China. *Ecological Indicators*, 148, 110137. <https://doi.org/10.1016/J.ECOLIND.2023.110137>
- rePLAY. (2019). *REPLAY Project*. <https://www.replay-eit.eu/>
- Rezaei E., Catalan L. J. J. (2020). Evaluation of CO₂ utilization for methanol production via tri-reforming of methane. *Journal of CO₂ Utilization*, 42, 101272. <https://doi.org/10.1016/J.JCOU.2020.101272>
- Rezaei E., Catalan L. J. J. (2024). Reformation of CO₂ to dimethyl ether using hydrogen produced by methane pyrolysis in molten metals: Lifecycle and technoeconomic analyses. *International Journal of Hydrogen Energy*, 66, 458–467. <https://doi.org/10.1016/J.IJHYDENE.2024.03.286>
- Richards S. J., Al Zaili J. (2020). Contribution of encouraging the future use of biomethane to resolving sustainability and energy security challenges: The case of the UK. *Energy for Sustainable Development*, 55, 48–55. <https://doi.org/10.1016/J.ESD.2019.12.003>
- Rigamonti L., Brivio E. (2022). Life cycle assessment of methanol production by a carbon capture and utilization technology applied to steel mill gases. *International Journal of Greenhouse Gas Control*, 115, 103616. <https://doi.org/10.1016/J.IJGGC.2022.103616>
- Rissman J., Orvis R. (2017). Carbon Capture And Storage: An Expensive Option For Reducing U.S. CO₂ Emissions. *Forbes*. <https://www.forbes.com/sites/energyinnovation/2017/05/03/carbon-capture-and-storage-an-expensive-option-for-reducing-u-s-co2-emissions/#61c1c43c6482>
- Roche L., et al. (2025). Primary data share indicator for social life cycle assessment. *Journal of Cleaner Production*, 497, 145051. <https://doi.org/10.1016/J.JCLEPRO.2025.145051>
- Rojas-Michaga M. F., et al. (2023). Sustainable aviation fuel (SAF) production through power-to-liquid (PtL): A combined techno-economic and life cycle assessment. *Energy Conversion and Management*, 292, 117427. <https://doi.org/10.1016/J.ENCONMAN.2023.117427>
- ROLINCAP. (2016, October 1). *Systematic Design and Testing of Advanced Rotating Packed Bed Processes and Phase-Change Solvents for Intensified Post-Combustion CO₂ Capture*. <https://doi.org/10.3030/727503>
- Romagnoli F., et al. (2020). Novel stacked modular open raceway ponds for microalgae biomass cultivation in biogas plants: Preliminary design and modelling. *Environmental and Climate Technologies*, 24(2), 1–19. <https://doi.org/10.2478/RTUECT-2020-0050>
- Royo C. M. (2017). *Field Measurements and Modelling Analysis of CO₂ Refrigeration Systems with*

- Integrated Geothermal Storage*. KTH School of Industrial Engineering and Management.
- Rutters H., CGS Europa partners. (2013). *State of play on CO₂ geological storage in 28 European countries*. Report No. D2.10 .
- Sadia S., et al. (2021). *Role of Substrate to Improve Biomass to Biofuel Production Technologies*. 127–156. https://doi.org/10.1007/978-981-15-7070-4_6
- Saeima. (2001). Law "On Pollution" (Likums "Par piesārņojumu"), accepted 15.03.2021. *Latvijas Vestnesis*, 51.
- Saito A., et al. (2019). Those who care about CCS—Results from a Japanese survey on public understanding of CCS-. *International Journal of Greenhouse Gas Control*, 84, 121–130. <https://doi.org/10.1016/J.IJGGC.2019.02.014>
- Salaria A., Panjagari R. N. (2018). Controlled atmosphere Storage and Modified atmosphere Storage Packaging. In *Principles of the food processing & preservation*. Inflibnet Centre.
- Sánchez-Ortiz J., et al. (2020). Indicators to Measure Efficiency in Circular Economies. *Sustainability*, 12(11), 4483. <https://doi.org/10.3390/su12114483>
- Sangannavar P. A., et al. (2022). Biomethane: a sustainable bioenergy source from potential waste effluents. In *Microbial Resource Technologies for Sustainable Development*. Elsevier. <https://doi.org/10.1016/B978-0-323-90590-9.00004-3>
- SCARABEUS. (2019). *Supercritical CARbon dioxide/Alternative fluids Blends for Efficiency Upgrade of Solar power plants*. <https://cordis.europa.eu/project/id/814985/reporting>
- Schakel W., et al. (2017). New indicator for comparing the energy performance of CO₂ utilization concepts. *Journal of CO₂ Utilization*, 22, 278–288. <https://doi.org/10.1016/j.jcou.2017.10.001>
- Schlaggermann P., et al. (2012). Composition of Algal Oil and Its Potential as Biofuel. *Journal of Combustion*, 2012(1), 285185. <https://doi.org/10.1155/2012/285185>
- Schwab, K. (2017). *The Global Competitiveness Report*.
- sCO₂-HeRo. (2015). *The supercritical CO₂ Heat Removal System*. <https://cordis.europa.eu/project/id/662116/reporting>
- Seber G., et al. (2022). Uncertainty in life cycle greenhouse gas emissions of sustainable aviation fuels from vegetable oils. *Renewable and Sustainable Energy Reviews*, 170, 112945. <https://doi.org/10.1016/J.RSER.2022.112945>
- SelectCO₂. (2019). *Selective Electrochemical Reduction of CO₂ to High Value Chemicals*. <https://cordis.europa.eu/project/id/851441/reporting>
- Selim C., Jerrad T. (2023). *The Investment Case for CCS: Policy Drive and Case Studies* . <https://www.globaleccsinstitute.com/resources/publications-reports-research/the-investment-case-for-ccs/>
- Seo S. N. (2017). The Theory of Public Goods and Their Efficient Provisions. In *The Behavioral Economics of Climate Change* (pp. 33–64). Academic Press. <https://doi.org/10.1016/B978-0-12-811874-0.00002-7>
- SHDB. (2024). *SHDB - Home*. <http://www.socialhotspot.org/>
- Sheikhtajian S., et al. (2024). Investment in CCUS under technical uncertainty considering investor's risk

- aversion: An exotic compound real-options approach. *International Journal of Greenhouse Gas Control*, 138, 104241. <https://doi.org/10.1016/J.IJGGC.2024.104241>
- Shirizadeh B., Quirion P. (2022). The importance of renewable gas in achieving carbon-neutrality: Insights from an energy system optimization model. *Energy*, 255, 124503. <https://doi.org/10.1016/J.ENERGY.2022.124503>
- Shogenov K., Shogenova A. (2020). Cost-Competitive and Self-Supporting Geothermal Energy, CO₂-EOR and CO₂ Storage Concept: Case Study of the E6 Structure in the Baltic Sea. *SSRN Electronic Journal*. <https://doi.org/10.2139/SSRN.3366151>
- Shogenova A. (2020a). *CARBON NEUTRAL BALTIC STATES: DO WE HAVE CCUS AMONG ACCEPTED OPTIONS?*
- Shogenova A. (2020b). *CARBON NEUTRAL BALTIC STATES: DO WE HAVE CCUS AMONG ACCEPTED OPTIONS?* TalTech.
- Shogenova A., et al. (2021). Techno-economic Modelling of the Baltic CCUS Onshore Scenario for the Cement Industry Supported by CLEANKER Project. *SSRN Electronic Journal*. <https://doi.org/10.2139/SSRN.3817710>
- Shokrollahi M., et al. (2024). Identification and evaluation of most promising CO₂ utilization technologies: Multi criteria decision analysis and techno-economic assessment. *Journal of Cleaner Production*, 434, 139620. <https://doi.org/10.1016/J.JCLEPRO.2023.139620>
- Sieborg M. U., et al. (2024). Bio-integrated carbon capture and utilization: at the interface between capture chemistry and archaeal CO₂ reduction. *Nature Communications* 2024 15:1, 15(1), 1–11. <https://doi.org/10.1038/s41467-024-51700-3>
- Singh D., et al. (2024). Technical and operational challenges in setting up a decentralized biogas plant: Opportunities and future perspective toward sustainable nation. *Process Safety and Environmental Protection*, 185, 392–407. <https://doi.org/10.1016/J.PSEP.2024.02.079>
- Sinha R. K., Chaturvedi N. D. (2019). A review on carbon emission reduction in industries and planning emission limits. *Renewable and Sustainable Energy Reviews*, 114, 109304. <https://doi.org/10.1016/J.RSER.2019.109304>
- Sirwan K. A. (2024). How to choose a sampling technique and determine sample size for research: A simplified guide for researchers. *Oral Oncology Reports*, 12, 100662.
- Skrebele A., et al. (2024). *Latvia` s National Inventory Document under the UNFCCC*.
- Slade R., et al. (2022). *Climate Change 2022 Mitigation of Climate Change*.
- Snyder H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333–339. <https://doi.org/10.1016/J.JBUSRES.2019.07.039>
- SOCRATES. (2016). *SOcial Cognitive Robotics in The European Society*. <https://cordis.europa.eu/project/id/721619/results>
- SOLPART. (2016). *High Temperature Solar-Heated Reactors for Industrial Production of Reactive Particulates*. <https://cordis.europa.eu/project/id/654663/reporting>
- Srivastava N., et al. (2020). *Substrate Analysis for Effective Biofuels Production*. <https://doi.org/10.1007/978-981-32-9607-7>
- Standal K., et al. (2023). Can renewable energy communities enable a just energy transition? Exploring

- alignment between stakeholder motivations and needs and EU policy in Latvia, Norway, Portugal and Spain. *Energy Research & Social Science*, 106, 103326.
<https://doi.org/10.1016/J.ERSS.2023.103326>
- Staniaszek Z., et al. (2022). The role of future anthropogenic methane emissions in air quality and climate. *Npj Climate and Atmospheric Science*, 5(1), 1–8. <https://doi.org/10.1038/S41612-022-00247-5>;SUBJMETA=106,1108,35,682,694,704,824;KWRD=ATMOSPHERIC+CHEMISTRY,CLIMATE+AND+EARTH+SYSTEM+MODELLING,CLIMATE-CHANGE+MITIGATION
- Stantcheva S. (2023). How to Run Surveys: A Guide to Creating Your Own Identifying Variation and Revealing the Invisible. *Annual Review of Economics*, 15, 205–234.
<https://doi.org/10.1146/annurev-economics-091622-010157>
- State Environmental Service. (2020). *Maps*. <https://registri.vvd.gov.lv/piesarnojoso-darbibu-vietu-karte/>
- State Environmental Service. (2022). *Atļauja B kategorijas piesārņojošai darbībai Nr. RE10IB0013*.
- Stibbe. (2019). *Belgium's Energy & Climate Plan -What is the legislative framework for legislative framework for climate policy in Belgium?* <https://www.stibbe.com/publications-and-insights/belgiums-energy-climate-plan-what-is-the-legislative-framework-for>
- Stigson P., et al. (2016). Prospects for Swedish acceptance of carbon dioxide storage in the Baltic Sea: Learning from other energy projects. *Greenhouse Gases: Science and Technology*, 6(2), 188–196.
<https://doi.org/10.1002/GHG.1585>
- Stokke R., et al. (2022). The role of green public procurement in enabling low-carbon cement with CCS: An innovation ecosystem perspective. *Journal of Cleaner Production*, 363, 132451.
<https://doi.org/10.1016/J.JCLEPRO.2022.132451>
- SUN-to-LIQUID. (2015). *SUNlight-to-LIQUID: Integrated solar-thermochemical synthesis of liquid hydrocarbon fuels*. <https://cordis.europa.eu/project/id/654408/reporting>
- SUNRISE. (2019). *Solar Energy for a Circular Economy*. <https://cordis.europa.eu/project/id/816336>
- Suppiah D. D., et al. (2021). Supported metal oxide catalysts for CO₂ Fischer–Tropsch conversion to liquid fuels - A review. *Energy and Fuels*, 35(21), 17261–17278.
<https://doi.org/10.1021/ACS.ENERGYFUELS.1C02406>/ASSET/IMAGES/MEDIUM/EF1C02406_0007.GIF
- Suzuki K., et al. (2022). An international comparative study on driving attitudes and behaviors based on questionnaire surveys. *IATSS Research*, 46(1), 26–35.
<https://doi.org/10.1016/J.IATSSR.2021.10.002>
- Swedish Climate Policy Council. (2021). *Report of the Swedish Climate Policy Council 2021*.
- Syed M., McLean K. C. (2022). Who gets to live the good life? Master Narratives, identity, and well-being within a marginalizing society. *Journal of Research in Personality*, 100, 104285.
<https://doi.org/10.1016/J.JRP.2022.104285>
- Takeshita T. (2011). Competitiveness, role, and impact of microalgal biodiesel in the global energy future. *Applied Energy*, 88(10), 3481–3491. <https://doi.org/10.1016/J.APENERGY.2011.02.009>
- Tam V. W., et al. (2023). Optimal BIM and LCA integration approach for embodied environmental impact assessment. *Journal of Cleaner Production*, 385, 135605.
<https://doi.org/10.1016/J.JCLEPRO.2022.135605>

- Tardin-Coelho R., et al. (2025). Carbon capture utilisation and storage (CCUS) and public perceptions: A systematic literature review. *International Journal of Greenhouse Gas Control*, 145, 104393. <https://doi.org/10.1016/J.IJGGC.2025.104393>
- Tariq G., et al. (2025). Techno-economic and life cycle assessment of integrated bio- and e-methanol production from biomass with carbon capture and utilization. *Chemical Engineering Journal*, 515, 163850. <https://doi.org/10.1016/J.CEJ.2025.163850>
- Tellnes L. G., et al. (2017). Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: a review study for construction materials based on forest products. *IForest - Biogeosciences and Forestry*, 10(5), 815. <https://doi.org/10.3832/IFOR2386-010>
- Tello W. P. (2025). Policy interactions and electricity generation sector CO₂ emissions: A quasi-experimental analysis. *Energy Policy*, 198, 114434. <https://doi.org/10.1016/J.ENPOL.2024.114434>
- The Swedish Environmental Protection Agency. (2021). *Report for Sweden on climate policies and measures and projections*.
- Thomas M., et al. (2022). Great expectations: Public opinion about energy transition. *Energy Policy*, 162, 112777. <https://doi.org/10.1016/J.ENPOL.2022.112777>
- Tian Z., et al. (2025). Strategies for reducing CO₂ emissions under the framework of Sustainable Development Goals. *Energy Strategy Reviews*, 59, 101745. <https://doi.org/10.1016/J.ESR.2025.101745>
- Timmons D., Terwel R. (2022). Economics of aviation fuel decarbonization: A preliminary assessment. *Journal of Cleaner Production*, 369, 133097. <https://doi.org/10.1016/J.JCLEPRO.2022.133097>
- Transitions to low carbon electricity systems: Key economic and investment trends*. (2019).
- Treves A., et al. (2020). The reintroduction of Castor fiber in Piedmont (Italy): An integrated SWOT-spatial multicriteria based approach for the analysis of suitability scenarios. *Ecological Indicators*, 118, 106748. <https://doi.org/10.1016/J.ECOLIND.2020.106748>
- Tri-HP. (2019). *Trigeneration systems based on heat pumps with natural refrigerants and multiple renewable sources*. <https://cordis.europa.eu/project/id/814888/results>
- Tripathi N., et al. (2019). Biomass waste utilisation in low-carbon products: harnessing a major potential resource. *Npj Climate and Atmospheric Science* 2019 2:1, 2(1), 1–10. <https://doi.org/10.1038/s41612-019-0093-5>
- Trobiani Di Canto J. A., et. al. (2023). Turning waste into insulation – A new sustainable thermal insulation board based on wheat bran and banana peels. *Building and Environment*, 244, 110740. <https://doi.org/10.1016/J.BUILDENV.2023.110740>
- U.S. Department of Energy. (2016). *Gas Turbines Combined Heat and Power Technology Fact Sheet Series*.
- Ugwu A., et al. (2022). Carbon Capture Utilization and Storage in Methanol Production Using a Dry Reforming-Based Chemical Looping Technology. *Energy and Fuels*, 36(17), 9719–9735. https://doi.org/10.1021/ACS.ENERGYFUELS.2C00620/ASSET/IMAGES/LARGE/EF2C00620_0015.JPEG
- UK Legislation. (2008). *Climate Change Act 2008*. 7. <https://www.legislation.gov.uk/ukpga/2008/27/contents>
- UK Legislation. (2019). *The Climate Change Act 2008 (2050 Target Amendment) Order 2019*. 1056.

- Umar M., et al. (2025). Advancing frontiers in CO₂ capture: The renaissance of biomass-derived carbon materials. *Coordination Chemistry Reviews*, 526, 216380. <https://doi.org/10.1016/J.CCR.2024.216380>
- UNCTAD. (2018). *Technology and Innovation Report 2018: Harnessing Frontier Technologies for Sustainable Development*.
- UNCTAD. (2019). *THE IMPACT OF RAPID TECHNOLOGICAL CHANGE ON SUSTAINABLE DEVELOPMENT*.
- United Nations. (2015). *Paris Agreement* .
- US Department of Energy. (2017). *Algae Cultivation for Carbon Capture and Utilization Workshop Summary Report*.
- US4GREENCHEM. (2015). *Combined Ultrasonic and Enzyme treatment of Lignocellulosic Feedstock as Substrate for Sugar Based Biotechnological Applications*. <https://cordis.europa.eu/project/id/669055>
- ValueMag. (2017). *Valuable Products from Algae Using New Magnetic Cultivation and Extraction Techniques*. <https://cordis.europa.eu/project/id/745695/reporting>
- Van Gulck L., et al. (2022). How to evaluate circularity through an LCA study based on the standards EN 15804 and EN 15978. *International Journal of Life Cycle Assessment*, 27(12), 1249–1266. <https://doi.org/10.1007/S11367-022-02099-W/TABLES/6>
- Veitmans K., Grinfelds U. (2016). Wood Fiber Insulation Material. *Research for Rural Development*, 2, 91–98.
- Vermeulen P. (2015). Alternative sources of CO₂ for the greenhouse horticulture. *Journal of Energy Challenges & Mechanics*. https://www.researchgate.net/publication/282006970_Alternative_sources_of_CO2_for_the_greenhouse_horticulture#fullTextFileContent
- Vidya K. M., et al. (2024). Combination of remote sensing, GIS, AHP techniques and geophysical data to delineate groundwater potential zones in the Shiriya River Basin, South India. *Geosystems and Geoenvironment*, 3(4), 100294. <https://doi.org/10.1016/J.GEOGEO.2024.100294>
- von Rothkirch J., Ejderyan O. (2021). Anticipating the social fit of CCS projects by looking at place factors. *International Journal of Greenhouse Gas Control*, 110, 103399. <https://doi.org/10.1016/J.IJGGC.2021.103399>
- VVD. (2022). *AB atlaujas*. <https://registri.vvd.gov.lv/izsniegtas-atlaujas-un-licences/a-un-b-atlaujas/>
- Wang G., et al. (2025). Technical progress and application of global carbon dioxide capture, utilization and storage cluster. *Petroleum Exploration and Development*, 52(2), 536–547. [https://doi.org/10.1016/S1876-3804\(25\)60585-4](https://doi.org/10.1016/S1876-3804(25)60585-4)
- Wang M., Yu X. (2024). An Overview of the Sustainable Aviation Fuel: LCA, TEA, and the Sustainability Analysis. *Engineering Proceedings 2024*, 80(1), 3. <https://doi.org/10.3390/ENGPROC2024080003>
- Wang N., et al. (2023). MEA-based CO₂ capture: a study focuses on MEA concentrations and process parameters. *Frontiers in Energy Research*, 11, 1230743. <https://doi.org/10.3389/FENRG.2023.1230743/BIBTEX>
- Wang R., et al. (2015). The research progress of CO₂ sequestration by algal bio-fertilizer in China. *Journal of CO₂ Utilization*, 11, 67–70. <https://doi.org/10.1016/J.JCOU.2015.01.007>

- Wang X., et al. (2017). Food-energy-environment trilemma: Policy impacts on farmland use and biofuel industry development. *Energy Economics*, 67, 35–48.
<https://doi.org/10.1016/J.ENERCO.2017.05.021>
- Wei J., et al. (2017). Directly converting CO₂ into a gasoline fuel. *Nature Communications*, 8(1), 1–9.
<https://doi.org/10.1038/ncomms15174>
- Wei K., et al. (2022). Recent advances in CO₂ capture and reduction. *Nanoscale*, 14(33), 11869–11891.
<https://doi.org/10.1039/D2NR02894H>
- Wettengel J. (2018). Call for open debate on CCU and CCS to save industry emissions. *Clean Energy Wire*.
- Witte K. (2021). *Social Acceptance of Carbon Capture and Storage (CCS) from Industrial Applications*.
- Wójcicki A. (2025). Development of CCUS value chain scenarios in northern Poland. *Advances in Carbon Capture Utilization and Storage*, 1. <https://doi.org/10.21595/ACCUS.2025.24676>
- Wolf M.-A., et al. (2010). *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance*. <https://doi.org/10.2788/38479>
- World Bank. (2022). *State and Trends of Carbon Pricing 2022*. Washington, DC: World Bank.
<https://doi.org/10.1596/978-1-4648-1895-0>
- Wyns T., et al. (2019). *Industrial Transformation 2050*.
- Xie J., et al. (2025). Life cycle carbon footprint and cost assessment of modern coal chemical industry coupled with carbon capture utilization and storage technology. *Fuel*, 401, 135788.
<https://doi.org/10.1016/J.FUEL.2025.135788>
- Xiong K., Kong F. (2017). The Analysis of Farmers' Willingness to Accept and Its Influencing Factors for Ecological Compensation of Poyang Lake Wetland. *Procedia Engineering*, 174, 835–842.
<https://doi.org/10.1016/J.PROENG.2017.01.230>
- Xu M., et al. (2021). Assessment of potential, cost, and environmental benefits of CCS-EWR technology for coal-fired power plants in Yellow River Basin of China. *Journal of Environmental Management*, 292, 112717. <https://doi.org/10.1016/J.JENVMAN.2021.112717>
- Yamada K., et al. (2020). Low-temperature Conversion of Carbon Dioxide to Methane in an Electric Field. *Chemistry Letters*, 49(3), 303–306. <https://doi.org/10.1246/cl.190930>
- Yan B., et al. (2021). Spatial distribution of biogas potential, utilization ratio and development potential of biogas from agricultural waste in China. *Journal of Cleaner Production*, 292, 126077.
<https://doi.org/10.1016/J.JCLEPRO.2021.126077>
- Yao B., et al. (2020). Transforming carbon dioxide into jet fuel using an organic combustion-synthesized Fe-Mn-K catalyst. *Nature Communications*, 11(1), 1–12. <https://doi.org/10.1038/s41467-020-20214-z>
- Yaqoob H., et al. (2021). The potential of sustainable biogas production from biomass waste for power generation in Pakistan. *Journal of Cleaner Production*, 307, 127250.
<https://doi.org/10.1016/J.JCLEPRO.2021.127250>
- Yusuf N., Almomani F. (2023). Highly effective hydrogenation of CO₂ to methanol over Cu/ZnO/Al₂O₃ catalyst: A process economy & environmental aspects. *Fuel*, 332, 126027.
<https://doi.org/10.1016/J.FUEL.2022.126027>

- Zabranska J., Pokorna D. (2018). Bioconversion of carbon dioxide to methane using hydrogen and hydrogenotrophic methanogens. *Biotechnology Advances*, 36(3), 707–720. <https://doi.org/10.1016/J.BIOTECHADV.2017.12.003>
- Zagashvili J. V., et al. (2018). Малотоннажная установка получения метанола (Patent No. RU183172U1).
- Zapantis A., et al. (2019). *Policy Priorities to Incentivise Large Scale Deployment of CCS*.
- Zarauz I., et al. (2025). Social sustainability in a good bioeconomy paradigm: A systematic review of social life cycle assessment (S-LCA). *Journal of Cleaner Production*, 486, 144570. <https://doi.org/10.1016/J.JCLEPRO.2024.144570>
- Zauchá J., et al. (2025). Implementing the EU MSP Directive: Current status and lessons learned in 22 EU Member States. *Marine Policy*, 171, 106425. <https://doi.org/10.1016/J.MARPOL.2024.106425>
- Zero Emission Platform. (2022). *CCS/CCU projects*. <https://zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/>
- Zhang C., et al. (2024). Analysis of integrated CO₂ capture and utilization via calcium-looping in-situ dry reforming of methane and Fischer-Tropsch for synthetic fuels production. *Separation and Purification Technology*, 329, 125109. <https://doi.org/10.1016/J.SEPPUR.2023.125109>
- Zhang F., et al. (2020). Thermodynamic and exergoeconomic analysis of a novel CO₂ based combined cooling, heating and power system. *Energy Conversion and Management*, 222, 113251. <https://doi.org/10.1016/j.enconman.2020.113251>
- Zhang X., et al. (2019). CFD Modelling of Finned-tube CO₂ Gas Cooler for Refrigeration Systems. *Energy Procedia*, 161, 275–282. <https://doi.org/10.1016/J.EGYPRO.2019.02.092>
- Zhang Y., et al. (2021). Exploring cooling pattern of low-income households in urban China based on a large-scale questionnaire survey: A case study in Beijing. *Energy and Buildings*, 236, 110783. <https://doi.org/10.1016/J.ENBUILD.2021.110783>
- Zhang Z., et al. (2021). Simulation and techno-economic assessment of bio-methanol production from pine biomass, biochar and pyrolysis oil. *Sustainable Energy Technologies and Assessments*, 44, 101002. <https://doi.org/10.1016/J.SETA.2021.101002>

DOCTORAL THESIS PUBLICATIONS

This thesis is based on the following scientific publications:

1. Terjanika V., Pubule J., Gusca J., Blumberga D. Analysis of CO₂ 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 CO₂ Valorisation. *Sustainability* 2022:14(9):5054. doi: 10.3390/su14095054 (Q1)
4. Terjanika V., Vetrinska L., Pubule J. CO₂ 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 CO₂ 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 CO₂ Valorisation Support. *e-Prime - Advances in Electrical Engineering, Electronics and Energy* 2023:4:100181. doi: 10.1016/j.prime.2023.100181 (Q2)
7. Viksne G., Vamza I., Terjanika V., Bezrucko T., Pubule J., Blumberga D. CO₂ 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., Pubule J. Sustainability Assessment of CO₂ Valorisation Routes for Latvia: LCA and S-LCA Approach (submitted to *Environmental and Climate Technologies*)

PAPER 1. ANALYSIS OF CO₂ VALORISATION
OPTIONS FOR REGIONAL DEVELOPMENT

Analysis of CO₂ Valorisation Options for Regional Development

Viktorija TERJANIKA¹, Julija GUSCA², Jelena PUBULE^{3*}, Dagnija BLUMBERGA⁴

¹⁻⁴*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, Latvia*

Abstract – Mitigation of CO₂ emissions has become a top-question in international and national arenas, likewise on the city level. Existing CO₂ 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 CO₂ reduction efficiency and the cost aspect, the direct CO₂ mitigation options currently applied are mostly oriented on large scale CO₂ 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 CO₂ emissions mitigation actions, therefore, the understanding of processes within rural CO₂ economy sectors, factors, interconnections and effects to the environment and nature quality and finally guidelines to future actions are crucial. To analyse CO₂ 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, CO₂ valorisation options and key performance indicators were defined and multi-criteria analysis for regional decarbonization scenarios were performed.

Keywords – CO₂ utilisation; decarbonization; key performance indicators; multi-criteria analysis; rural development

1. INTRODUCTION

The growing amount of CO₂ 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 CO₂ 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 CO₂ emissions. An increase in the emission reduction threshold from 40 % (compared to 1990) to 55 % by

* Corresponding author.
E-mail address: jelena.pubule@rtu.lv

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 CO₂ 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 CO₂ (fossil fuel energy), and the industrial sector – 22.4 %. Land transport is also one of the biggest greenhouse gas producers – 20.6 % of total CO₂ 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 CO₂ 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 CO₂ 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).

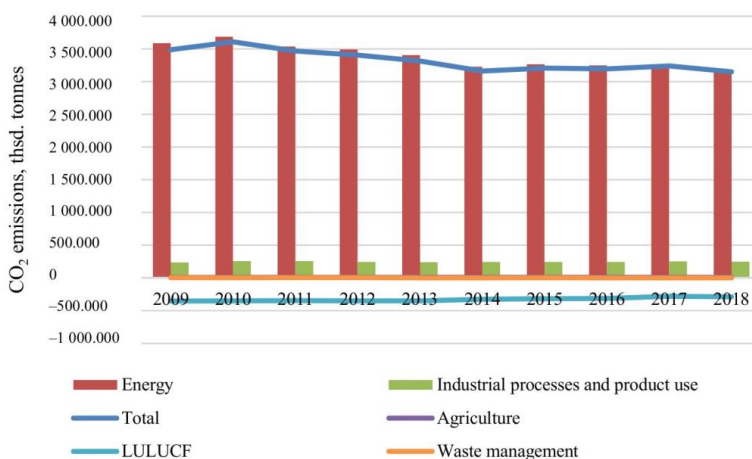


Fig. 1. CO₂ emissions in European Union 2009–2018 [8].

Despite the fact that in the time period from 2010 to 2018 the amount of CO₂ 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 CO₂ emissions is rising steadily.

The biggest amount of CO₂ 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).

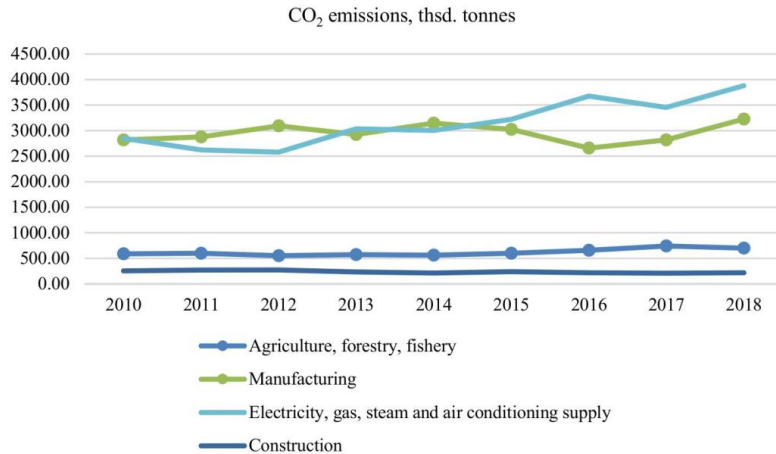


Fig. 2. CO₂ emissions in Latvia sectors in 2010–2018 [11].

Implementation of new technologies could help to decrease the environmental load – in Latvia there was a decline in 2019 in CO₂ 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 CO₂ 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.

CO₂ 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 CO₂ 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 MefCO₂ 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 CO₂, thus capturing and then using this CO₂ 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 CO₂) 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, CO₂ 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 CO₂ 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 CO₂ utilization projects, as well as the demand for carbon dioxide, is growing every year. In 2018, the leaders in the use of CO₂ 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 MtCO₂ by 2025 [18], [19].

2. METHODOLOGY

A combination of methodologies was used during the research on the possibility of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ valorisation, which would be applicable in Latvia. An algorithm of the analyses applied in this research is depicted in Fig. 3.

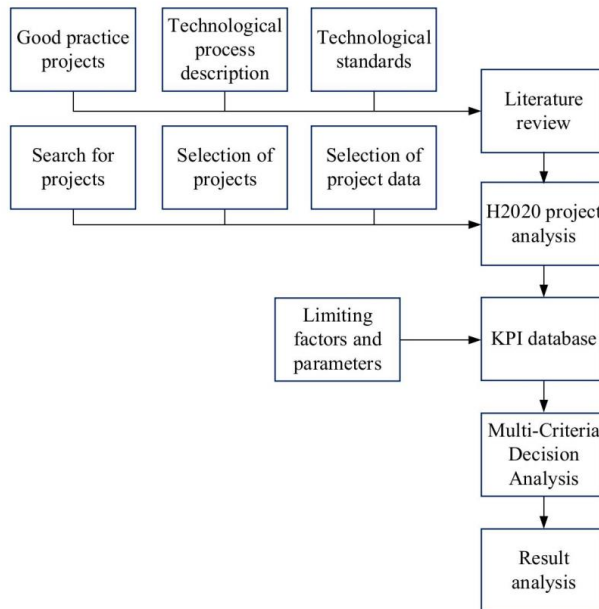


Fig. 3. Methodological scheme.

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 CO₂.

Analysing the H2020 program, out of more than 32 000 projects, it was possible to sort out 242 projects in which CO₂ 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).

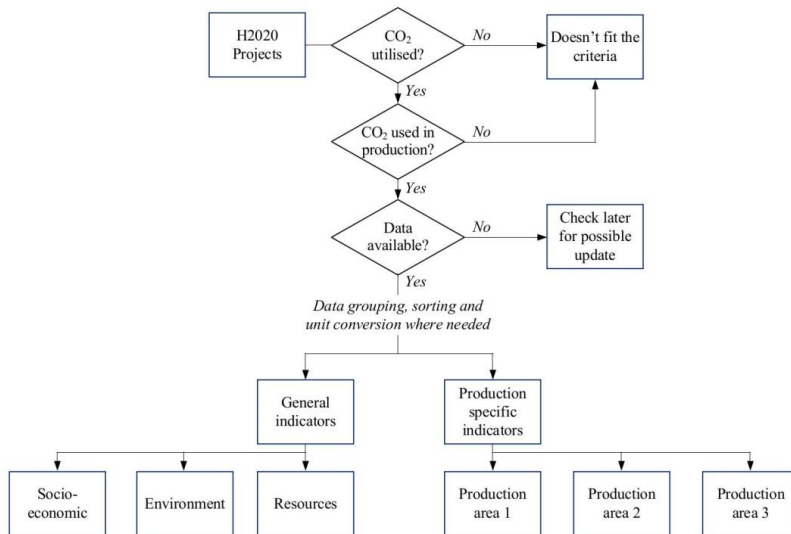


Fig. 4. Algorithm of H2020 project processing and KPI database compiling.

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 CO₂ 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 CO₂. For example, the main indicators are such indicators as electricity consumption per ton of product produced / ton of CO₂ produced (MWh/t and MWh/tCO₂), the amount of CO₂ required to produce a ton of product and the amount of CO₂ created during the production of a ton of the final product (tCO₂ utilized/t product, tCO₂ generated/t product), as well as the ratio of required and generated CO₂ (tCO₂ utilized/tCO₂ generated), etc.

2.2. Multi-Criteria Analysis

In order to analyse the degree of importance of each CO₂ 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 CO₂, several criteria have been used:

- amount of permitted additive in CO₂ flow;
- electricity per 1 tonne of product;
- amount of CO₂ utilised;
- amount of CO₂ 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 CO₂ valorisation, both existing and on-going projects for the use of CO₂ in production and projects from the H2020 program were researched.

During the analysis of H2020 projects (the purpose of which is to use CO₂ 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 CO₂ and required CO₂ ratio), 12 – environment-related (e.g., total emission during production process and possible CO₂ capture system efficiency), 18 – economy-related (e.g., costs of CO₂ if buying, total costs for CO₂ if doing nothing). The table also includes 28 indicators specific to the scope of potential CO₂ applications, for example, methanol production (CO₂ conversion rate), cement production (CO₂ emissions per tonne of cementitious materials produced), use of algae and greenhouses (CO₂ 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 CO₂ 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 CO₂ 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 CO₂ stream (%), the amount of CO₂ 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.

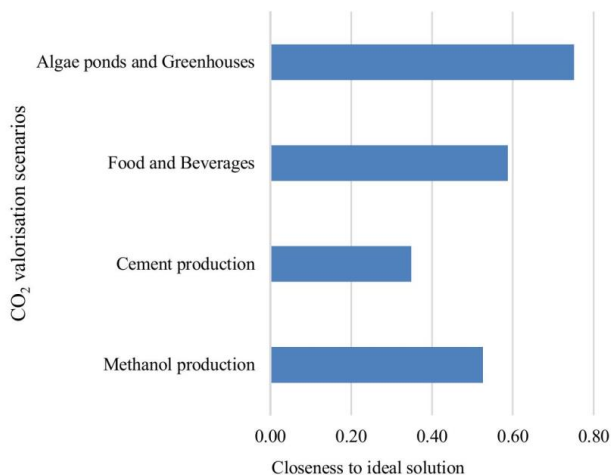


Fig. 5. CO₂ valorisation MCDA results.

The MCDA analysis showed that the optimal scenario for the use of CO₂ 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 CO₂ 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 CO₂ (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 CO₂ 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 CO₂ – 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. CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ problem in Latvia. The study outlines the way forward for ecological and sustainable production.

ACKNOWLEDGEMENT

This research is funded by the Latvian Council of Science, project CO₂ Deal: Effective Valorisation of CO₂ for Decarbonised Regional Development, project No. lzp-2020/1-0302.

REFERENCES

- [1] Chery D., Lair V., Cassir M. Overview on CO₂ valorization: challenge of molten carbonates. *Frontiers in Energy Research* 2015;3:43. <https://doi.org/10.3389/fenrg.2015.00043>
- [2] Alvarez E., et al. EU Demonstration Programme for CO₂ Capture and Storage (CCS). ZEP's Proposal. 2008.
- [3] European Commission. A European Green Deal [Online]. [Accessed 16.10.2020]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
- [4] European Parliament. Legislative Train 12.2020. 1A European Green Deal. Strasbourg: EP, 2020.
- [5] European Commission. 2030 climate and energy framework [Online]. [Accessed 10.01.2021]. Available: https://ec.europa.eu/clima/policies/strategies/2030_en
- [6] Statista. Share of global carbon dioxide (CO₂) emissions from fossil fuels and cements as of 2020, by economic sector [Online]. [Accessed 18.09.2020]. Available: <https://www.statista.com/statistics/1129656/global-share-of-co2-emissions-from-fossil-fuel-and-cement/>
- [7] Our World Data. CO₂ emissions [Online]. [Accessed 18.09.2020]. Available: <https://ourworldindata.org/co2-emissions>
- [8] Eurostat. Greenhouse emissions by source sector [Online]. [Accessed 19.05.2021]. Available: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_air_gge&lang=en
- [9] Ritchie H. Sector by sector: where do global greenhouse gas emissions come from? Our World in data. 2020.
- [10] International Atomic Energy Agency. Transitions to low carbon electricity systems: Key economic and investment trends. Vienna: IAEA, 2019.
- [11] Central Statistical Bureau Databases. Air emissions accounts [Online]. [Accessed 7.09.2020]. Available: https://data1.csb.gov.lv/pxweb/lv/vide/vide_vide_ikgad/VIG070.px/table/tableViewLayout1/ (in Latvian)
- [12] Eurostat News release. Early estimates of CO₂ emissions from energy use. Luxembourg: Eurostat Press Office, 2020.
- [13] Kudurs E., et al. Are Industries Open for Renewable Energy? *Environmental and Climate Technologies* 2020;24(3):447–456. <https://doi.org/10.2478/rtuect-2020-0115>
- [14] Latvian Center for Environment, Geology and Meteorology. 2020. gadā iesniegtās siltumnīcefekta gāzu inventarizācijas kopsavilkums (Greenhouse gases inventory summary, submitted in 2020.) Riga: LVGMC, 2020. (in Latvian)
- [15] MefCO₂ project [Online]. [Accessed 15.11.2020]. Available: <http://www.mefco2.eu/>
- [16] Phoenix Initiative. A European Integrated Approach to CO₂ Valorisation [Online]. [Accessed 06.03.2021]. Available: https://www.phoenix-co2-valorisation.eu/lw_resource/datapool/systemfiles/cbox/56/live/lw_datei/flyer-phoenix_180215_v6.pdf
- [17] Olajire A. A. Valorization of greenhouse carbon dioxide emissions into value-added products by catalytic processes. *Journal of CO₂ Utilization* 2013;3–4:74–92. <https://doi.org/10.1016/j.jcou.2013.10.004>
- [18] European Biofuels Technology Platform. Biomass with CO₂ Capture and Storage (Bio-CCS). The way forward for Europe. Oslo: Bellona, 2012.
- [19] IEA. Putting CO₂ to Use. Creating value from emissions. Paris: International Energy Agency, 2019.
- [20] EU Open Data Portal. CORDIS - EU research projects under Horizon 2020 (2014-2020) [Online]. [Accessed 15.10.2020]. Available: <https://data.europa.eu/euodp/en/data/dataset/cordisH2020projects>
- [21] Cascio E. L., et al. Key performance indicators for integrated natural gas pressure reduction stations with energy recovery. *Energy Conversion and Management* 2018;164:219–229. <https://doi.org/10.1016/j.enconman.2018.02.089>
- [22] Pacheco K. A., et al. Multi criteria decision analysis for screening carbon dioxide conversion products. *Journal of CO₂ Utilization* 2021;43:101391. <https://doi.org/10.1016/j.jcou.2020.101391>
- [23] Chauvy R., et al. Comparison of multi-criteria decision-analysis methods for selecting carbon dioxide utilization products. *Sustainable Production and Consumption* 2020;24:194–210. <https://doi.org/10.1016/j.spc.2020.07.002>
- [24] Styring P., et al. Carbon Capture and Utilisation in the green economy. Using CO₂ to manufacture fuel, chemicals and materials. United Kingdom: CO₂Chem Publishing, 2012.
- [25] Wang R., Peng B., Huang K. The research progress of CO₂ sequestration by algal bio-fertilizer in China. *Journal of CO₂ Utilization* 2015;11:67–70. <https://doi.org/10.1016/j.jcou.2015.01.007>

- [26] I-PHYC project [Online]. [Accessed 16.11.2020]. Available: <https://i-phyc.com/>
- [27] Anto S., *et al.* Algae as green energy reserve: Technological outlook on biofuel production. *Chemosphere* 2020;242:125079. <https://doi.org/10.1016/j.chemosphere.2019.125079>
- [28] Romagnoli F., *et al.* Novel Stacked Modular Open Raceway Ponds for Microalgae Biomass Cultivation in Biogas Plants: Preliminary Design and Modelling. *Environmental and Climate Technologies* 2020;24(2):1–19. <https://doi.org/10.2478/rtuect-2020-0050>
- [29] Pastare L., Romagnoli F. Life Cycle Cost Analysis of Biogas Production from *Cerathophyllum demersum*, *Fucus vesiculosus* and *Ulva intestinalis* in Latvian Conditions. *Environmental and Climate Technologies* 2019;23(2):258–271. <https://doi.org/10.2478/rtuect-2019-0067>
- [30] Ievina B., Romagnoli F. Potential of Chlorella Species as Feedstock for Bioenergy Production: A Review. *Environmental and Climate Technologies* 2020;24(2):203–220. <https://doi.org/10.2478/rtuect-2020-0067>
- [31] Drägerwerk AG & Co KGaA. Reliable CO₂ monitoring in the beverage industry. Technical Paper. Germany: Drägerwerk AG & Co KGaA.
- [32] Nerantzis E., *et al.* Winemaking process engineering: On line fermentation monitoring - Sensors and equipment. *e-Journal of Science & Technology* 2007;29–36.
- [33] Sanjeev K., Ramesh M. N. Low Oxygen and Inert Gas Processing of Foods. *Critical Reviews in Food Science and Nutrition* 2007;46(5):423–451. <https://doi.org/10.1080/10408390500215670>
- [34] Ghiat I., *et al.* CO₂ utilisation in agricultural greenhouses: A novel ‘plant to plant’ approach driven by bioenergy with carbon capture systems within the energy, water and food Nexus. *Environmental Conversion and Management* 2021;228:1136668. <https://doi.org/10.1016/j.enconman.2020.113668>
- [35] Zhang X., *et al.* CFD Modelling of Finned-tube CO₂ Gas Cooler for Refrigeration Systems. *Energy Procedia* 2019;161:275–282. <https://doi.org/10.1016/j.egypro.2019.02.092>
- [36] Zhang Z., *et al.* Simulation and techno-economic assessment of bio-methanol production from pine biomass, biochar and pyrolysis oil. *Sustainable Energy Technologies and Assessments* 2021;44:101002. <https://doi.org/10.1016/j.seta.2021.101002>

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

Viktorija Terjanika
Institute of Energy Systems and Environment
Riga Technical University
Azenes 12/1, Riga, Latvia
Viktorija.terjanika@rtu.lv

Dagnija Blumberga
Institute of Energy Systems and Environment
Riga Technical University
Azenes 12/1, Riga, Latvia

Jeļena Pubule
Institute of Energy Systems and Environment
Riga Technical University
Azenes 12/1, Riga, Latvia
Jelena.pubule@rtu.lv

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 CO₂, 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—CO₂ emissions; CCU technologies; regional development

I. INTRODUCTION

The amount of CO₂ 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% CO₂). 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 CO₂ 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. tCO₂ (sectors Agriculture, forestry, fishery, Manufacturing, Electricity and Construction), while in 2018 the number of emissions amounted to 8025.64 thousand tCO₂. 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂, 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 CO₂ 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 CO₂ in Latvia is the energy sector, however, combustion of fuel produces not only CO₂, 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, CO₂ is increasingly used in the production of biogas (for example, bioethanol) and biofuels (for example, aviation fuel, dimethyl ether (DME), gasoline) [19]–[23]. CO₂ 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 CO₂ 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 CO₂ 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 CO₂ - 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. CO₂ 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).

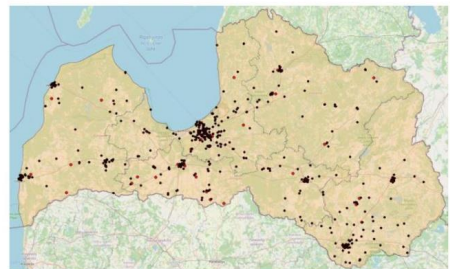


Fig. 1. CO₂ production sites A category companies (red) and B category companies (black)

The territory of the Riga region contains 64% of all CO₂ 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 CO₂ 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).

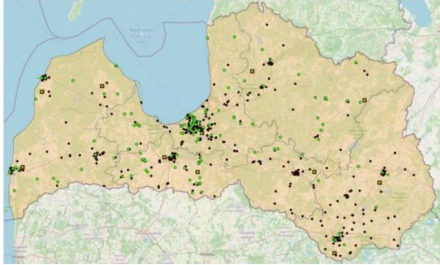


Fig. 2. Sites of CO₂ production (brown) and potential utilisation (green)

Considering the ratio of CO₂ 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. CO₂ 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 CO₂ and its consumption is observed in Latgale, a region with relatively a small share of CO₂ 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 Rīgas Siltums themselves in 2019 produced more than 180 thousand tons of carbon dioxide, which is equal to 7.49% of CO₂ emissions in the region. Other large enterprises with a declared large amount of CO₂ produced are "Putnu fabrika Ķekava" (11100.83 tCO₂, 0.45%), Olainfarm

(10219.42 tCO₂, 0.42%) and Latvijas Finieris (6828.00 tCO₂, 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 tCO₂ or 80% of the region's CO₂ emissions. The second place is followed by energy production in Liepāja – Liepājas Enerģija (43632.00 tCO₂, 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).

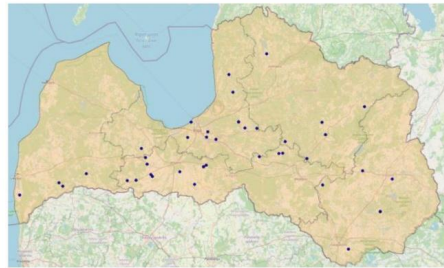


Fig. 3. Sites of biostations

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ to speed up metabolism. According to [37], the maximum allowable amount of impurities in the supplied CO₂ 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 CO₂, 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 CO₂ 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 CO₂ 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 CO₂ to produce goods with high added value. The largest CO₂ 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 CO₂ 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.

REFERENCES

[1] Statista, "Share of global carbon dioxide (CO₂) emissions from fossil fuels and cements as of 2020, by economic sector" [Online]. Available: <https://www.statista.com/statistics/1129656/global-share-of-co2-emissions-from-fossil-fuel-and-cement/> (Accessed 18.09.2020)

[2] D. Chery, V. Liar, M. Cassir, "Overview on CO₂ valorization: challenge of molten carbonates", *Fron. En. Res.* Vol. 3, pp. 43, 2015.

[3] European Commission, "A European Green Deal" [Online]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (Accessed 16.10.2020)

[4] European Parliament, Legislative Train 12.2020. 1A European Green Deal, Strasbourg: EP, 2020.

[5] European Commission, "2030 climate and energy framework" [Online]. Available: https://ec.europa.eu/clima/policies/strategies/2030_en (Accessed 10.01.2021)

[6] Central Statistical Bureau Republic of Latvia, "Air emission accounts (NACE Rev. 2)", Table ID: VID070 [Online]. Available: <https://www.csb.gov.lv/lv/statistika/statistikas-temas/vide-energetika/vide/tabulas/vig070/gaisa-emisiju-konti-nace-2red> (Accessed 7.09.2020) (in Latvian)

[7] Eurostat News release, Early estimates of CO₂ emissions from energy use, Luxembourg: Eurostat Press Office, 2020.

[8] Drägerwerk AG, Reliable CO₂ monitoring in the beverage industry, Lubeck: Drägerwerk AG.

[9] M. Marchi, et al., "CO₂ recovery from wine production: Possible implications on the carbon balance at territorial level", *J. CO₂ Util.* Vol. 28, pp. 137–144, 2018.

[10] N. Kaliyan, et al., "Applications of Carbon Dioxide in Food and Processing Industries: Current Status and Future Thrusts", *Am. Soc. Ag. Bio. Eng. (ASABE)*, 2013.

[11] G. Leonzio, E. Zondervan, P. U. Foscolo, "Methanol production by CO₂ hydrogenation: Analysis and simulation of reactor performance", *Int. J. Hyd. En.* Vol. 44, Iss. 16, pp. 7915–7933, 2019.

[12] E. L. Fornero, et al., "CO₂ capture via catalytic hydrogenation to methanol: Thermodynamic limit vs. 'kinetic limit'", *Cat. Tod.* Vol. 172, Iss. 1, pp. 158–165, 2011.

[13] A. Murugan, et al., "Performing Quality Assurance of Carbon Dioxide for Carbon Capture and Storage", *J. Carb. Res.* Vol. 6, Iss. 76, pp. 1–15, 2020.

[14] K. Goto, et al., "Effect of CO₂ purity on energy requirement of CO₂ capture processes", *En. Proc.* Vol. 37, pp. 806–812, 2013.

[15] R. T. J. Porter, et al., "The range and level of impurities in CO₂ streams from different carbon capture sources", *Int. J. Green. Gas Con.* Vol. 36, pp. 161–174.

[16] A. M. Muhammad Rashed, T. Shuichi, "Enrichment of Methane Concentration by Removing Contaminant Gases from Biogas Mixtures Based on Chemical Purification Processes", *Int. J. Tran. Phen.* Vol. 14, pp. 171–182, 2016.

[17] F. Zhang, et al., "Thermodynamic and exergoeconomic analysis of a novel CO₂ based combined cooling, heating and power system", *En. Con. Man.* Vol. 222, p. 113251, 2020.

[18] P. Gullo, et al., "State-of-the-art technologies for transcritical R744 refrigeration systems - A theoretical assessment of energy advantages for European food retail industry", *En. Proc.*, Vol. 123, pp. 46–53, 2017.

[19] S. V. Afanasyev, D. I. Trofimov, S. P. Sergeev, "Technology for processing carbon dioxide into methanol", *Chim. Tech.* Vol. 3, pp. 41–73, 2016. (in Russian)

[20] A. K. Mishra, et al., "Defects in nanosilica catalytically convert CO₂ to methane without any metal and ligand", *Proc. Nat. Ac. Sci. Un. St. Am.* Vol. 117, Iss. 12, pp. 6383–6390, 2020.

[21] I. V. Savenkova, Y. Y. Mikhailova, "Technology of one-stage synthesis of dimethyl ether from natural gas", *Vest. AGTU* Vol. 6, Iss. 47, pp. 145–147, 2018. (in Russian)

[22] J. Wei, et al., "Directly converting CO₂ into a gasoline fuel", *Nat. Com.* Vol. 8, Iss. 1, pp. 1–9, 2017.

[23] B. Yao, et al., "Transforming carbon dioxide into jet fuel using an organic combustion-synthesized Fe-Mn-K catalyst", *Nat. Com.* Vol. 11, Iss 1, pp. 1–12, 2020.

[24] R. Wang, B. Peng, K. Huang, "The research progress of CO₂ sequestration by algal bio-fertilizer in China", *J. CO₂ Util.* Vol. 11, pp. 67–70, 2015

- [25] State Environmental Service, "A and B permits for polluting activities" [Online]. Available: <https://registri.vvd.gov.lv/zsniestas-atlaujas-un-licences/a-un-b-atlaujas/> (Accessed 18.10.2020) (in Latvian)
- [26] State Environmental Service, "Maps" [Online]. Available: <https://registri.vvd.gov.lv/piesamojoso-darbibu-vietu-karte/> (Accessed 18.10.2020) (in Latvian)
- [27] Ministry of Environmental Protection and Regional Development Republic of Latvia, "Waste management regions and landfills in Latvia" [Online]. Available: https://www.varam.gov.lv/sites/varam/files/content/files/atkritumu_poligoni_lv_karte.pdf (Accessed 25.03.2020) (in Latvian)
- [28] Latvian Center for Environment, Geology and Meteorology, "Pollutant Emission and Transfer Register" [Online]. Available: <https://prtr.lvymc.lv/> (Accessed 27.11.2020) (in Latvian)
- [29] Food and Veterinary Service, "Section VI – Biogas plants" [Online]. Available: <https://registri.pvd.gov.lv/cr/a16a26ff> (Accessed 12.03.2021)
- [30] C. Chen, J. F. Khosrowabadi Kotyk, S. W. Sheehan, "Progress toward Commercial Application of Electrochemical Carbon Dioxide Reduction", Chem. Vol. 4, Iss. 11, pp. 2571–2586, 2018.
- [31] J. L. Fan, et al., "Efficiency evaluation of CO₂ utilization technologies in China: A super-efficiency DEA analysis based on expert survey", J. CO₂ Util. Vol. 11, pp. 54–62, 2015.
- [32] B. Yan, et al., "Spatial distribution of biogas potential, utilization ratio and development potential of biogas from agricultural waste in China", J. Clean. Prod. Vol. 292, pp. 126077, 2021.
- [33] H. Yacoub, et al., "The potential of sustainable biogas production from biomass waste for power generation in Pakistan", J. Clean. Prod. Vol. 307, pp. 127250, 2021.
- [34] European Commission, "Modernisation Fund" [Online]. Available: https://ec.europa.eu/clima/policies/budget/modernisation-fund_en (Accessed 15.09.2021)
- [35] European Commission, "Innovation Fund" [Online]. Available: https://ec.europa.eu/clima/policies/innovation-fund_en (Accessed 15.09.2021)
- [36] EPC Group, "CO₂ Technologies (Purification and Recovery)" [Online]. Available at: <https://www.epc.com/en/technical-gases/plants-for/co2-purification-and-recovery/> (Accessed: 24.11.2020).
- [37] N. M. Langley, T. L. Harrison, R. Hille, "A critical evaluation of CO₂ supplementation to algal systems by direct injection", Bio. Eng. J. Vol. 68, pp. 70–75, 2012.

PAPER 3. BARRIERS AND DRIVING FACTORS FOR
SUSTAINABLE DEVELOPMENT OF CO₂
VALORISATION

Article

Barriers and Driving Factors for Sustainable Development of CO₂ Valorisation

Viktorija Terjanika * and Jelena Pubule

Institute of Energy Systems and Environment, Riga Technical University, Azenes Street 12/1, 1048 Riga, Latvia; jelena.pubule@rtu.lv

* Correspondence: viktorija.terjanika@rtu.lv

Abstract: Mitigating CO₂ 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 CO₂ valorisation projects. This study aims to analyse barriers and driving factors for the sustainable development of CO₂ 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: CO₂ technologies; SWOT; FLCA; ArcGis



Citation: Terjanika, V.; Pubule, J. Barriers and Driving Factors for Sustainable Development of CO₂ Valorisation. *Sustainability* **2022**, *14*, 5054. <https://doi.org/10.3390/su14095054>

Academic Editor:
Antonio Caggiano

Received: 25 March 2022
Accepted: 21 April 2022
Published: 22 April 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Mitigating CO₂ emissions have become a top question in international and national arenas, likewise on the city level. Existing CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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, CO₂ 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].

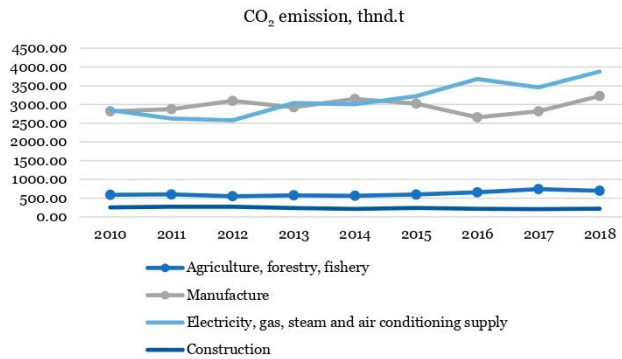


Figure 1. CO₂ emissions in Latvian sectors from 2010 to 2018 [6].

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).

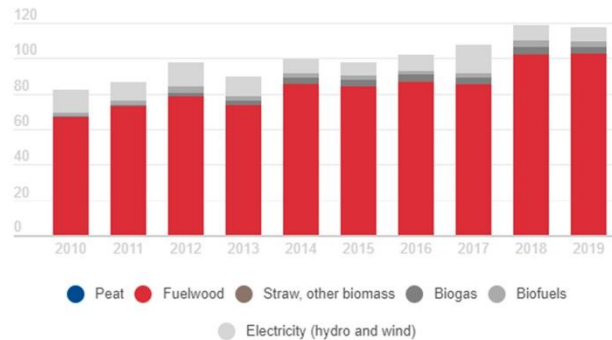


Figure 2. Primary energy generation from renewables, PJ [8].

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 CO₂ 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 CO₂ and transporting it to places of further disposal (storage sites) or use for the production of new products.
2. The capture of CO₂ 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% CO₂ [14,15], and installations using adsorption allow achieving purity of the main CO₂ stream up to 95% and recovery of the flow up to 80% [14,16]. Carbon dioxide capture plants separate CO₂ 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 CO₂ 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 CO₂ storage sites [2].

For the analysis of CO₂ 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 CO₂ 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.

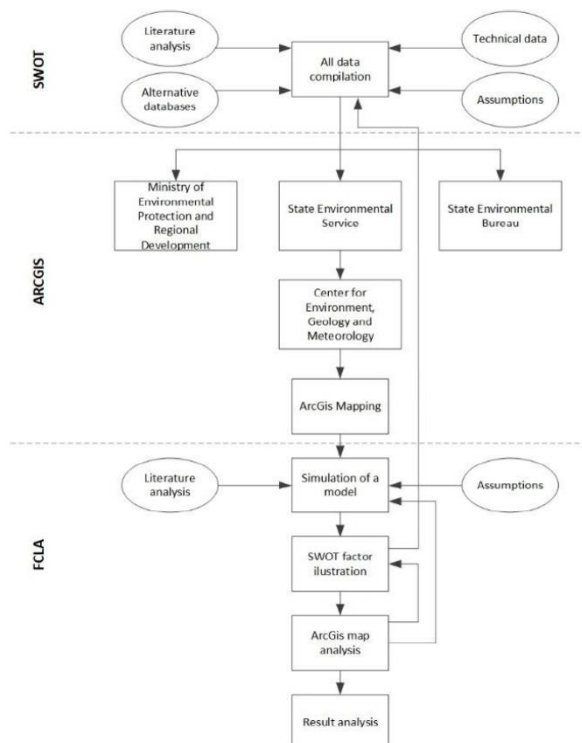


Figure 3. The algorithm of the performed work.

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).

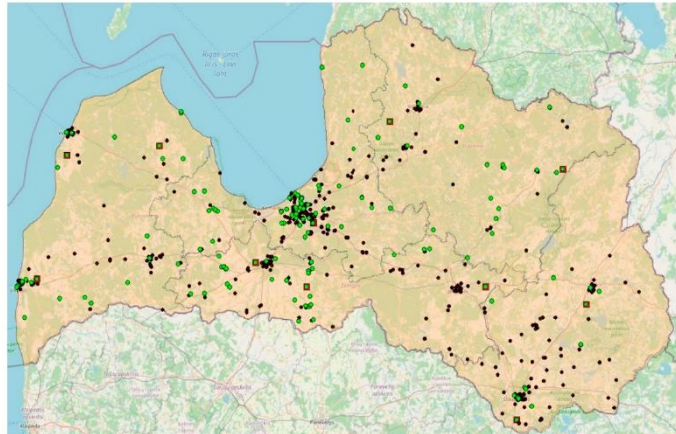


Figure 4. Sites of CO₂ (dark brown) production and (green) potential utilisation [23].

Considering the use of CO₂ following options have been observed: (a) CO₂ capture and utilisation in Europe; (b) CO₂ capture and utilisation in the case of Latvia; (c) CO₂ capture directly at the place of production, processing and transportation/reusing.

2.1.1. CO₂ 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 CO₂ 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. CO₂ 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. CO₂ 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. CO₂ 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. CO₂ Capture and Utilisation in Companies

This group considers all aspects of CO₂ 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. CO₂ 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 CO₂ capture units, it is possible to sell the dioxide, thus obtaining additional financial benefits. If CO₂ is used at the company, the captured dioxide can be returned to production (if the quality of CO₂ 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 CO₂ 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 CO₂ (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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂, 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 CO₂ 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 CO₂ [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 CO₂ 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 CO₂ 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 CO₂)—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 CO₂ requirements, extremely negative attitude of politicians and influential entrepreneurs to the implementation of mandatory requirements for CO₂ emissions, etc.), and the so-called—public, such as prejudice about the dangers of CO₂ 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).

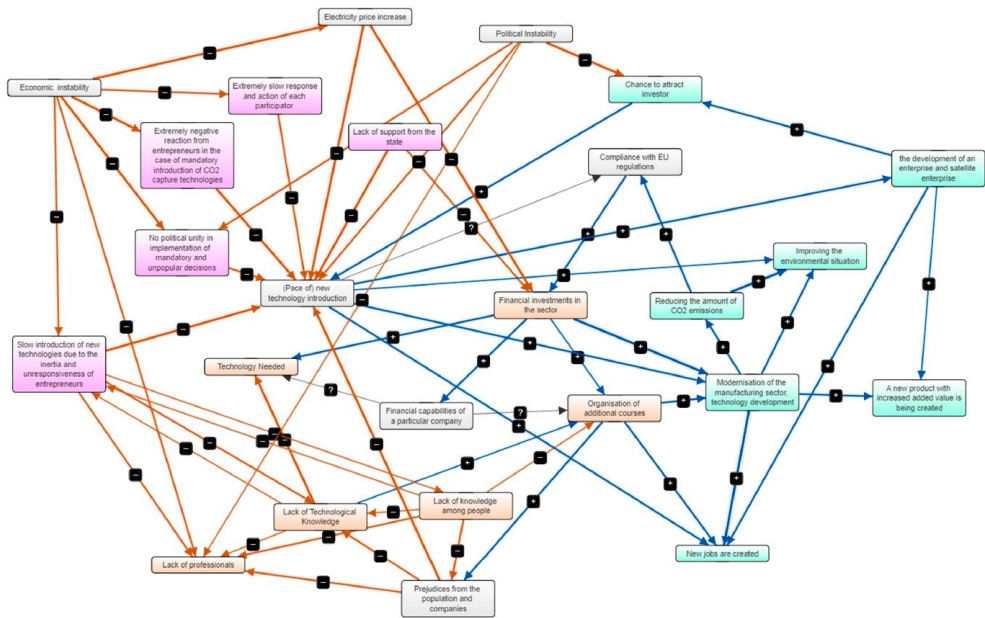


Figure 5. Results of FLCA analysis.

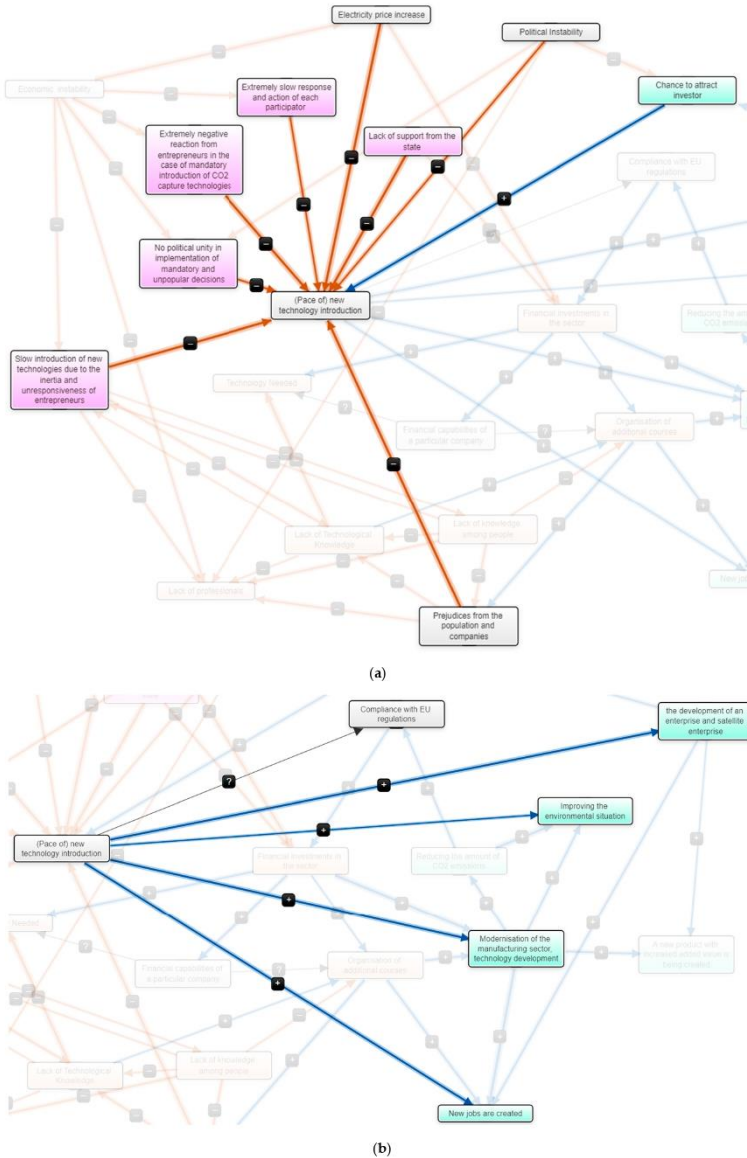


Figure 6. Factors (a) influencing the rate of introduction of technologies, (b) which are influenced by the rate of introduction of new technologies.

4. Conclusions

In this paper, using the SWOT, ArcGis and FLCA analysis methods, the factors influencing the development of CO₂ 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.

Author Contributions: J.P. analysed the publicly available information regarding the CO₂ emission data. V.T. analysed the publicly available data regarding the CO₂ emission data, performed data visualisation. All authors have read and agreed to the published version of the manuscript.

Funding: This research is funded by the Latvian Council of Science, project CO₂ Deal: Effective Valorisation of CO₂ for Decarbonised Regional Development, project No. lzp-2020/1-0302.

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.

References

1. EPA. Sources of Greenhouse Gas Emissions. Available online: <https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions> (accessed on 26 November 2021).
2. Ming, Z.; Shaojie, O.; Yingjie, Z.; Hui, S. CCS technology development in China: Status, problems and countermeasures—Based on SWOT analysis. *Renew. Sustain. Energy Rev.* **2014**, *39*, 604–616. [CrossRef]
3. European Commission. *Proposal for a Regulation of the European Parliament and of the Council Establishing the Framework for Achieving Climate Neutrality and Amending Regulation (EU) 2018/1999 (European Climate Law)*; EC: Brussels, Belgium, 2020.
4. Keating, D. Businesses and Consumers Will Decide whether the EU Green Deal Works. Euractiv.com. Available online: <https://www.euractiv.com/section/energy-environment/news/businesses-and-consumers-will-decide-whether-the-eu-green-deal-works/> (accessed on 26 November 2021).

5. Thys, J. A European Green Deal Under Pressure. Institut Montaigne. Available online: <https://www.institutmontaigne.org/en/blog/european-green-deal-under-pressure> (accessed on 26 November 2021).
6. Central Statistical Bureau Republic of Latvia. Gaisa Emisiju Konti (NACE 2. Red.). 2020. Available online: <https://www.csb.gov.lv/lv/statistika/statistikas-temas/vide-energetika/vide/tabulas/vig070/gaisa-emisiju-konti-nace-2red> (accessed on 9 July 2020).
7. Ritchie, H.; Roser, M. Our World in Data. Latvia: CO₂ Country Profile. 2020. Available online: <https://ourworldindata.org/co2/country/latvia> (accessed on 26 November 2021).
8. Investment and Development Agency of Latvia. Environment and Renewable Energy Industry. 2020. Available online: <https://www.liaa.gov.lv/en/trade/industries/environment-and-renewable-energy> (accessed on 26 November 2021).
9. International Energy Agency. *A Policy Strategy for Carbon Capture and Storage*; IEA: Paris, France, 2012.
10. Epifanceva, D. Factors affecting the effectiveness of the introduction of innovative technologies in production. *Molod. Uchenij* **2018**, *22*, 402–403.
11. Osipova, I.; Menschikova, V. Identification of risks of technical re-equipment of industrial enterprises and key areas of their management. *Soc. Javlenija Process.* **2017**, *12*, 91–97.
12. Aich, A.; Ghosh, S.K. Application of SWOT Analysis for the Selection of Technology for Processing and Disposal of MSW. *Procedia Environ. Sci.* **2016**, *35*, 209–228. [[CrossRef](#)]
13. Khan, M.I. Evaluating the strategies of compressed natural gas industry using an integrated SWOT and MCDM approach. *J. Clean. Prod.* **2018**, *172*, 1035–1052. [[CrossRef](#)]
14. Leung, D.Y.C.; Caramanna, G.; Maroto-Valer, M.M. An overview of current status of carbon dioxide capture and storage technologies. *Renew. Sustain. Energy Rev.* **2014**, *39*, 426–443. [[CrossRef](#)]
15. Brunetti, A.; Scura, F.; Barbieri, G.; Drioli, E. Membrane technologies for CO₂ separation. *J. Memb. Sci.* **2010**, *359*, 115–125. [[CrossRef](#)]
16. Clausse, M.; Merel, J.; Meunier, F. Numerical parametric study on CO₂ capture by indirect thermal swing adsorption. *Int. J. Greenh. Gas Control* **2011**, *5*, 1206–1213. [[CrossRef](#)]
17. Al Fareed, A.; Kamla, A.A.-B. The Role of GIS on the Decision Making Process at Muscat Municipality: A SWOT analysis. In Proceedings of the 10th IBIMA Conference, Kuala Lumpur, Malaysia, 30 June–2 July 2008.
18. Andreas, M.; Allan, A. Incorporating geology and geomorphology in land management decisions in developing countries: A case study in Southern Costa Rica. *Geomorphology* **2007**, *87*, 68–89. [[CrossRef](#)]
19. Elmahdi, A.; Kheireldin, K. GIS and Multi-Criteria Evaluation for Integrated Water Resources. In Proceedings of the ISCO 2004—13th International Soil Conservation Organisation Conference, Brisbane, Australia, 4–8 July 2004.
20. Boroushaki, S.; Malczewski, J. Using the fuzzy majority approach for GIS-based multicriteria group decision-making. *Comput. Geosci.* **2010**, *36*, 302–312. [[CrossRef](#)]
21. Nasehi, S.; Hoveidi, H.; Imanpour Namin, A.; Nohegar, A. Strategic planning, based on environmental spatial assessment, using SWOT and GIS to locate sustainable industrial areas (case study: Tehran province). *Pollution* **2019**, *5*, 569–583.
22. Comino, E.; Ferretti, V. Indicators-based spatial SWOT analysis: Supporting the strategic planning and management of complex territorial systems. *Ecol. Indic.* **2016**, *60*, 1104–1117. [[CrossRef](#)]
23. Terjanika, V.; Gusca, J.; Pubule, J.; Blumberga, D. Analysis of CO₂ Valorisation Options for Regional Development. *Environ. Clim. Technol.* **2021**, *25*, 243–253. [[CrossRef](#)]
24. Poczeta, K.; Papageorgiou, E.I.; Gerogiannis, V.C. Fuzzy Cognitive Maps Optimization for Decision Making and Prediction. *Math.* **2020**, *8*, 2059. [[CrossRef](#)]
25. Shinno, H.; Yoshioka, H.; Marpaung, S.; Hachiga, S. Quantitative SWOT analysis on global competitiveness of machine tool industry. *J. Eng. Des.* **2006**, *17*, 251–258. [[CrossRef](#)]
26. Gürel, E. Swot Analysis: A Theoretical Review. *J. Int. Soc. Res.* **2017**, *10*, 994–1006. [[CrossRef](#)]
27. Matteo Mazziotta, A.P. Methods for Constructing Composite Indices: One for All or All for One? *Riv. Ital. Econ. Demogr. Stat.* **2016**, *82*, 394–411.
28. UNCTAD. *The Impact of Rapid Technological Change on Sustainable Development*; UNCTAD: Geneva, Switzerland, 2019.
29. Metz, B.; Davidson, O.; de Coninck, H.; Loos, M.; Meyer, L. *Carbon Dioxide Capture and Storage*; Cambridge University Press: Cambridge, MA, USA, 2005.
30. Mukeshimana, M.C.; Zhao, Z.Y.; Nshimiyanana, J.P. Evaluating strategies for renewable energy development in Rwanda: An integrated SWOT-ISM analysis. *Renew. Energy* **2021**, *176*, 402–414. [[CrossRef](#)]
31. Rassool, D. *Overview of Organisations and Policies Supporting the Deployment of Large-Scale CCS Facilities*; Global CCS Institute: Washington, DC, USA, 2020.
32. Witte, K. Social Acceptance of Carbon Capture and Storage (CCS) from Industrial Applications. *Sustainability* **2021**, *13*, 12278. [[CrossRef](#)]
33. Lendel, V.; Varmus, M. Identification of the main problems of implementing the innovation strategy in Slovak businesses. *Acta Univ. Agric. Silv. Mendel. Brun.* **2012**, *60*, 221–234. [[CrossRef](#)]
34. Kiselev, D.; Popov, Y.; Kanygina, O. Problems of ineffective modernization at industrial enterprises and ways of their solution. *MATEC Web Conf.* **2017**, *129*, 01029. [[CrossRef](#)]
35. Klein, K.J.; Knight, A.P. Innovation Implementation Overcoming the Challenge. *Am. Psychol. Soc.* **2005**, *14*, 243–246.

36. Zapantis, A.; Townsend, A.; Rassool, D. *Policy Priorities to Incentivise Large Scale Deployment of CCS*; Global CCS Institute: Washington, DC, USA, 2019.
37. European Commission. Innovation Fund. Available online: https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund_en (accessed on 29 November 2021).
38. European Commission. CORDIS—EU Research Projects under Horizon 2020 (2014–2020). Available online: <https://data.europa.eu/data/datasets/cordis2020projects?locale=en> (accessed on 29 November 2021).
39. VVD. AB Atļaujas (AB Permissions). Available online: <https://registri.vvd.gov.lv/izsniegta-atlaujas-un-licences/a-un-b-atlaujas/> (accessed on 13 January 2022).
40. LVGMC. Pollutant Release and Transfer Register. Available online: <https://prtr.lvgmc.lv/> (accessed on 13 January 2022).
41. Wang, R.; Peng, B.; Huang, K. The research progress of CO₂ sequestration by algal bio-fertilizer in China. *J. CO₂ Util.* **2015**, *11*, 67–70. [CrossRef]
42. Styring, P.; Jansen, D.; de Coninck, H.; Reith, H.; Armstrong, K. *Carbon Capture and Utilisation in the Green Economy Using CO₂ to Manufacture Fuel, Chemicals and Materials*; Centre for Low Carbon Futures: Sheffield, UK, 2011.
43. Bakhtavar, E.; Valipour, M.; Yousefi, S.; Sadiq, R.; Hewage, K. Fuzzy cognitive maps in systems risk analysis: A comprehensive review. *Complex Intell. Syst.* **2020**, *7*, 621–637. [CrossRef]
44. Borisov, V.; Stefanov, A.; Bobryakov, A.; Luferov, V. The System of Fuzzy Cognitive Analysis and Modeling of System Dynamics. In Proceedings of the IS-2019 Conference, Ulyanovsk, Russia, 24–27 September 2019; Volume 2475, pp. 72–81.
45. European Commission. Modernisation Fund. Available online: https://ec.europa.eu/clima/eu-action/funding-climate-action/modernisation-fund_en (accessed on 29 November 2021).
46. Goulder, L.H.; Parry, I.W.H. Chapter 1. What is the Best Policy Instrument for Reducing CO₂ Emission? In *Fiscal Policy to Mitigate Climate Change*; Oxford University Press: Oxford, UK, 2008; Volume 2, pp. 152–174.
47. Scott, V. What can we expect from Europe’s carbon capture and storage demonstrations? *Energy Policy* **2013**, *54*, 66–71. [CrossRef]
48. Wyns, T.; Khandekar, G.; Axelson, M.; Sartor, O.; Neuhoff, K. *Industrial Transformation 2050. Towards an Industrial Strategy for a Climate Neutral Europe*; IES: Brussels, Belgium, 2019.
49. CATF. California’s CO₂ Reduction Program Opens Doors to CCS. Available online: <https://www.catf.us/2018/11/californias-co2-reduction-program/> (accessed on 29 November 2021).
50. International Revenue Service, Treasury. 26 USC 45Q: Credit for Carbon Oxide Sequestration. *Intern. Revenue Serv.* **2021**, *86*, 4728–4773.
51. Bellona. *Biomass with CO₂ Capture and Storage (Bio-CCS), the Way Forward for Europe*; Bellona: Oslo, Norway, 2012.
52. Olajire, A.A. Valorization of greenhouse carbon dioxide emissions into value-added products by catalytic processes. *J. CO₂ Util.* **2013**, *3–4*, 74–92. [CrossRef]
53. Blom, T.J.; Straver, W.A.; Ingratta, F.J. *Carbon Dioxide in Greenhouses*; OMAFRA: Guelph, ON, Canada, 2012.
54. Gale, H.F. Is There a Rural-Urban Technology Gap? Results of the ERS Rural Manufacturing Survey. *Agric. Inf. Bull.* **1997**, *736*, 736.
55. UNCTAD. *Technology and Innovation Report 2018: Harnessing Frontier Technologies for Sustainable Development*; UNCTAD: New York, NY, USA; Geneva, Switzerland, 2018.
56. Cowie, P.; Townsend, L.; Salemink, K. Smart rural futures: Will rural areas be left behind in the 4th industrial revolution? *J. Rural Stud.* **2020**, *79*, 176. [CrossRef]
57. OECD. *Rural Well-Being: Geography of Opportunities*; OECD: Paris, France, 2020.

PAPER 4. CO₂ AS A RESOURCE. SOCIETY'S
WILLINGNESS TO PAY ANALYSIS

CO₂ as Resource. Society's Willingness to Pay Analysis

Viktorija TERJANIKA^{1*}, Liana VETRINSKA², Jelena PUBULE³

¹⁻³*Institute of Energy Systems and Environment, Riga Technical University, Azenes st. 12/1, Riga, LV-1048, Latvia*

Abstract – Climate change, including the efficient management of CO₂ 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 CO₂ capturing and/or utilization, valuable products with high added value can be created. For more effective analysis of the opportunities to use CO₂ 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 CO₂ 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; CO₂; 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 CO₂ emissions in the atmosphere. And although some carbon dioxide is trapped in plants and oceans, a considerable amount of CO₂ 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 CO₂ 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 CO₂ produced is not so large, even this amount must be considered since the consequences caused by CO₂ 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

* Corresponding author.
E-mail address: Viktorija.Terjanika@rtu.lv

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

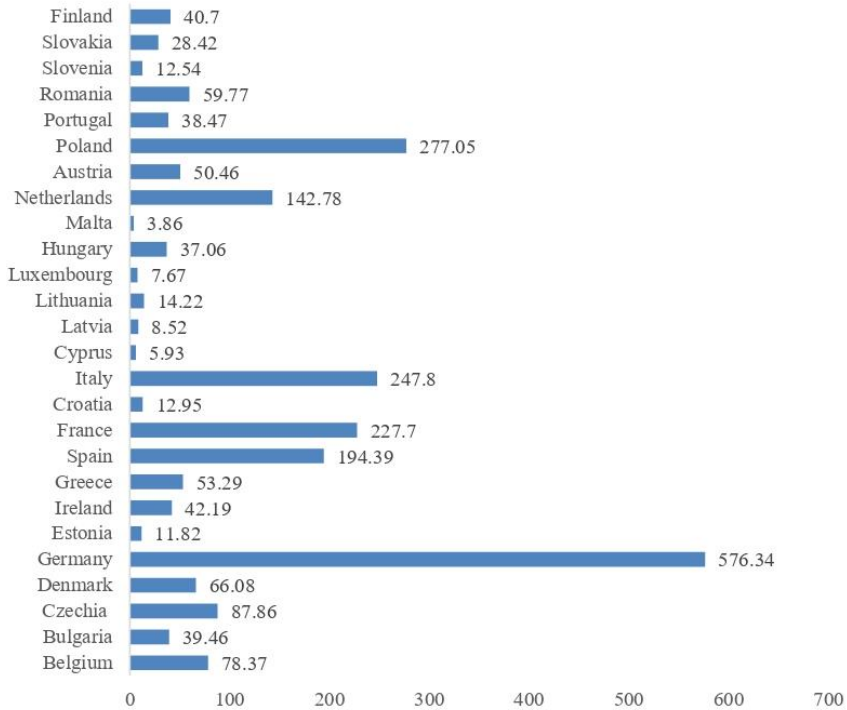


Fig. 1. CO₂ emissions in million metric tons in EU by country, year 2019 [5].

1.1. CO₂ Utilisation Possibilities

The introduction of technologies to reduce the amount of greenhouse gases is becoming increasingly important. By 2021, 65 commercial CO₂ 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 CO₂ 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 CO₂. Later, this captured carbon dioxide is transported to certain places intended for long-term storage of CO₂. 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 CO₂ to the places of its further storage or use. Usually, special pipes or transport (for example, gas ships) are used for transportation. As for CO₂ 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 CO₂ 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 CO₂ 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 11th 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 CO₂ 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 CCU 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 CO₂ 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 CO₂ 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 CO₂ 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.

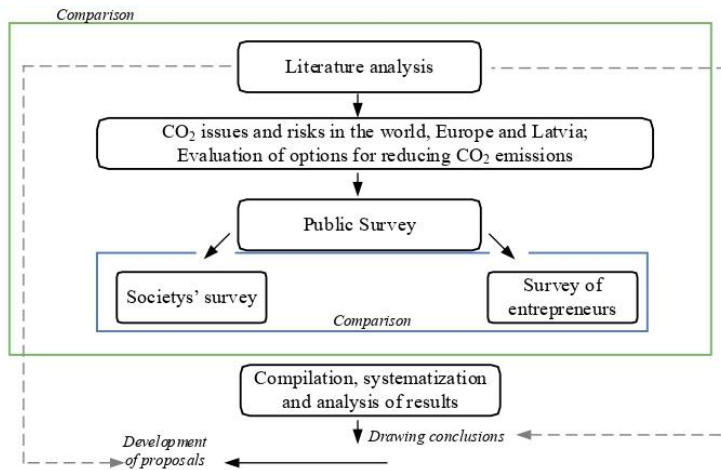


Fig. 2. Algorithm of the survey.

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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ Emission Problem

The first question in the questionnaire was aimed at determining public awareness of the problems of CO₂ emissions and therefore was asked as 'Have You ever heard of the CO₂ emission problem?' The answer to this question was almost unanimous – 93 % of the respondent answered in the affirmative.

3.1.2. Importance of the CO₂ Problem to the Public

The aim of the next question ('Does the problem of the CO₂ 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 CO₂ 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 CO₂.

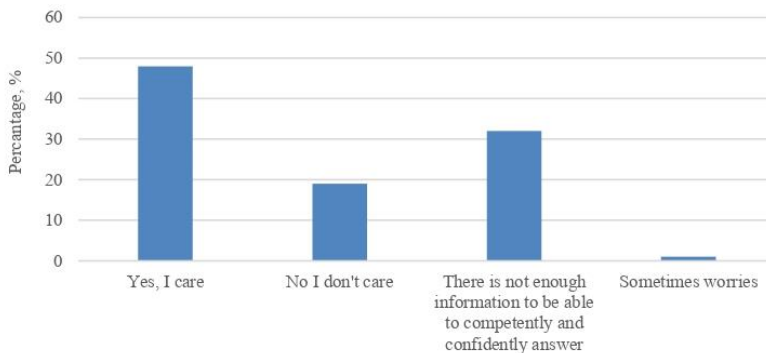


Fig. 3. Answers on the question if the problem of CO₂ emission bothers respondents.

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 CO₂ emissions or do not consider this problem to be relevant.

3.1.3. The Most Significant and Relevant Impact of CO₂ 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 CO₂ 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 CO₂ 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).

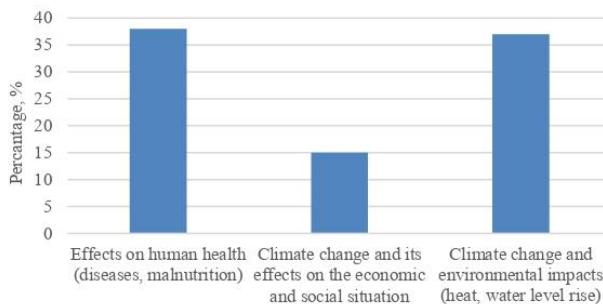


Fig. 4. Reasons why the problem seems relevant.

3.1.4. Reasons why CO₂ 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 CO₂ 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.

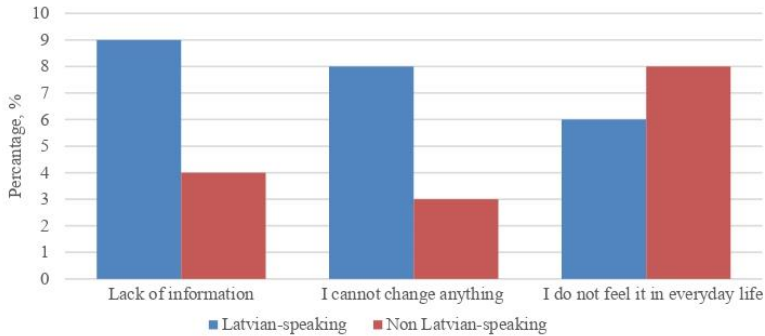


Fig. 5. Reasons why the problem seems irrelevant.

3.1.5. How relevant Is the Problem of CO₂ Emissions for Latvia?

The purpose of the question 'In Your opinion, is the problem of CO₂ 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 CO₂ 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 CO₂ emissions affect Latvia.

3.1.6. For Whom the Reduction of CO₂ Emissions May Be the Most Important and Relevant

The question 'Mark the Groups of People/Institutions for Whom, in Your Opinion, the Reduction of CO₂ Emissions May Be the Most Important and Relevant' was aimed to determine who should be most concerned about CO₂ 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.

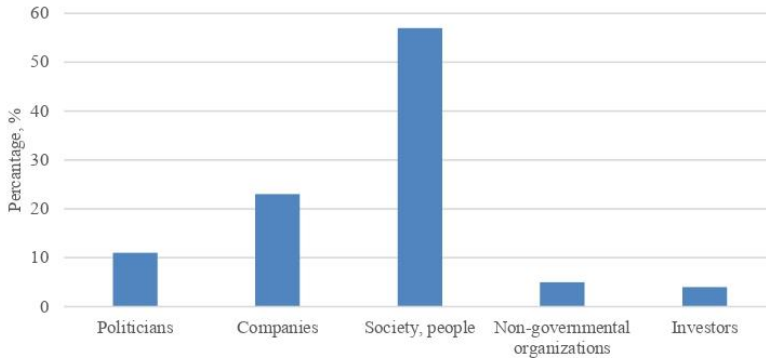


Fig. 6. To whom the reduction of emissions is more critical in Latvia on respondent's opinion.

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 CO₂ emissions?', 'Are You doing anything now to reduce the amount of CO₂ emissions in Your daily life?' and 'What actions would You be willing to take to reduce the negative impact of CO₂ emissions?'

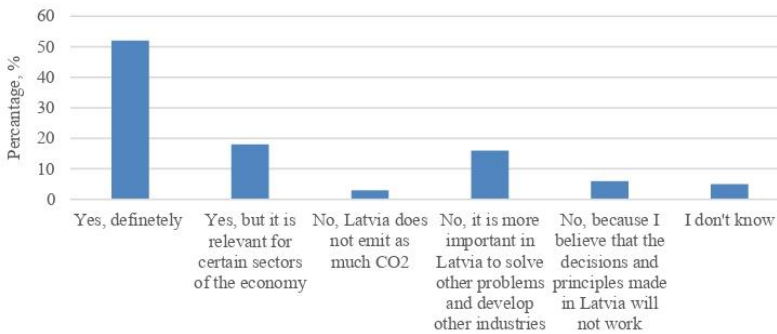
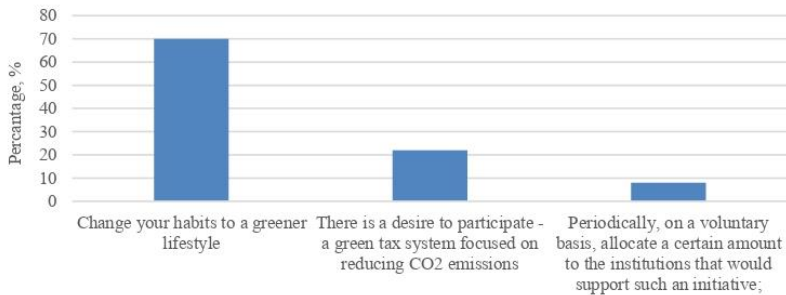


Fig. 7. The necessity to reduce CO₂ emissions on respondent's opinion.

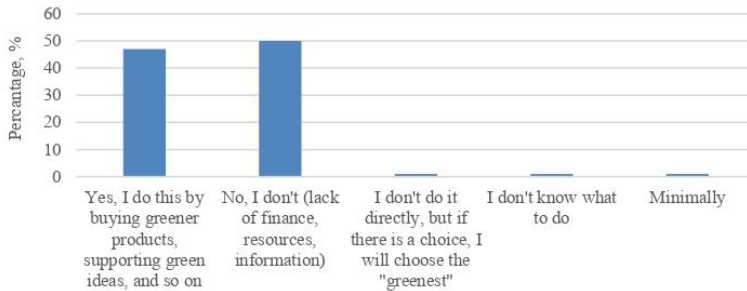
The questionnaire showed that it is necessary to reduce the number of emissions and the option that the reduction is relevant for specific sectors (Fig. 8). However, in contrast to the non-Latvian-speaking group, in the Latvian-speaking group, the option 'No, because I believe that the decisions and 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 CO₂ 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 CO₂ 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 CO₂ emissions? b) Are You currently doing anything to reduce CO₂ 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 CO₂ emissions is by no means relevant to all enterprises:

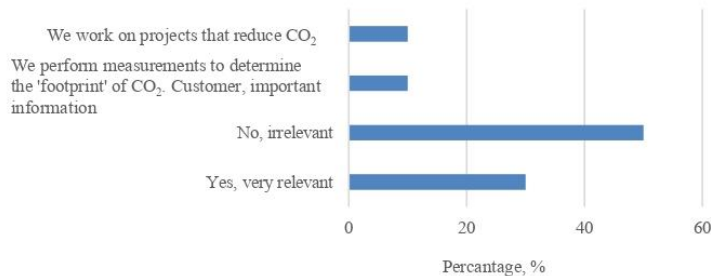


Fig. 9. Entrepreneur's field of activity.

Only half of the respondents stated that the problem of CO₂ 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 CO₂ 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 CO₂ Emission Reduction

Answering the question about the reasons that are relevant for the enterprise in the context of CO₂ 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 CO₂ in particular on the environment (Fig. 10).

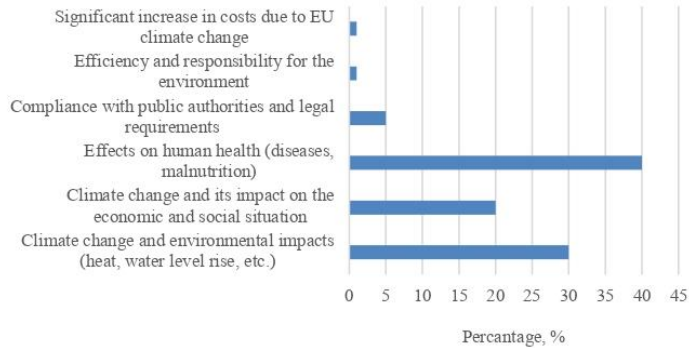


Fig. 10. What reasons are the most relevant in the context of CO₂ emission to entrepreneurs.

3.2.2. Motives/Reasons to Reduce the Amount of CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ policies) (Fig. 11).

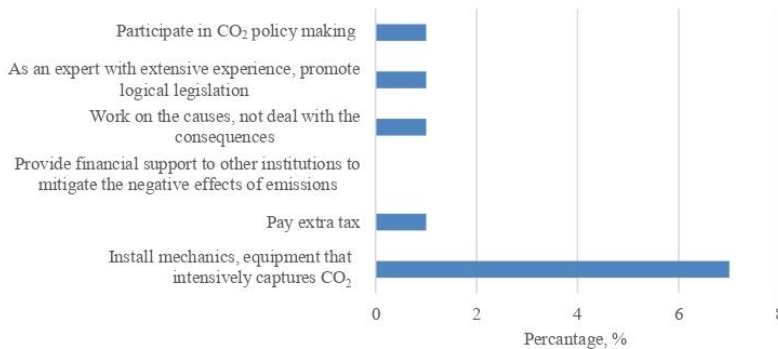


Fig. 11. Possible ways to reduce CO₂ emissions by entrepreneurs.

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).

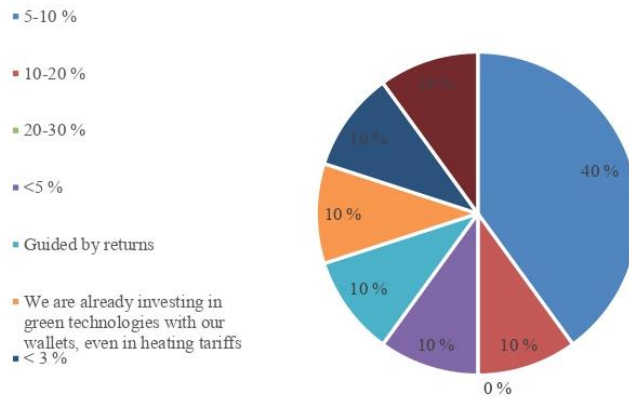


Fig. 12. Part of monthly income entrepreneurs is ready to invest in green technologies.

In general, analysing the results of a survey of entrepreneurs, it can be concluded that in the context of reducing CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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.

ACKNOWLEDGEMENT

This research is funded by the Latvian Council of Science, project CO₂ Deal: Effective Valorisation of CO₂ for Decarbonised Regional Development, project No. lzp-2020/1-0302.

REFERENCES

- [1] IPCC. IPCC Press Release. Geneva: IPCC, 2022.
- [2] Pei Q., *et al.* Climate change, state capacity and nomad–agriculturalist conflicts in Chinese history. *Quaternary International* 2019:508–36–42. <https://doi.org/10.1016/j.quaint.2018.10.022>
- [3] World Meteorological Organization. Proceedings of the World Climate Conference. Geneva: WMO, 1979.
- [4] Ritchie H., Roser M. CO₂ emissions, 2020. <https://ourworldindata.org/co2-emissions> (accessed Apr. 11, 2022).
- [5] Statista. CO₂: total emissions by EU country 2019, 2020 [Online]. [Accessed 12.04.2022]. Available: <https://www.statista.com/statistics/789024/emissions-co2-dioxide-of-carbon-by-country-eu/>
- [6] World Meteorological Organization. WMO Statement on the State of the Global Climate in 2019. Geneva: WMO, 2020.
- [7] Global CCS Institute. Global Status of CCS 2020. Melbourne: Global CCS Institute, 2021.
- [8] IEA. Carbon capture, utilisation and storage - Fuels & Technologies [Online]. [Accessed 11.04.2022]. Available: <https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage>
- [9] Xu M., *et al.* Assessment of potential, cost, and environmental benefits of CCS-EWR technology for coal-fired power plants in Yellow River Basin of China. *Journal of Environmental Management* 2021:292:112717. <https://doi.org/10.1016/j.jenvman.2021.112717>
- [10] Stokke R., *et al.* The role of green public procurement in enabling low-carbon cement with CCS: An innovation ecosystem perspective. *Journal of Cleaner Production* 2022:363:132451. <https://doi.org/10.1016/j.jclepro.2022.132451>
- [11] Rodin V., *et al.* Assessing Biogenic Carbon Dioxide Potentials in Europe for Valorisation. *Journal of CO₂ Utilization* 2020:41:101219. <https://doi.org/10.1016/j.jcou.2020.101219>
- [12] IOGP. The potential for CCS and CCU in Europe Report To The Thirty Second Meeting Of The European Gas Regulatory Forum 5-6 June 2019 Coordinated By IOGP. Madrid: IOGP, 2019.
- [13] Coll C., *et al.* Carbon Capture, Use And Storage (CCUS). New York, 2021.
- [14] Allen M., *et al.* Summary for Policymakers. Geneva, 2018.
- [15] European Union. Standard Eurobarometer 91. Europeans' views on the priorities of the European Union. European Union, 2019.

- [16] Thomas M., *et al.* Great expectations: Public opinion about energy transition. *Energy Policy* 2022:162:112777. <https://doi.org/10.1016/j.enpol.2022.112777>
- [17] Bejere G., *et al.* Samaziniet klimata izmaiņas: lietojiet koksnī! (Reduce climate change: Use wood!). Ceļ-Bois, 2006.
- [18] Galiegue S., Laude A. Combining Geothermal Energy and CCS: From the Transformation to the Reconfiguration of a Socio-Technical Regime? *Energy Procedia* 2017:114:7528–7539. <https://doi.org/10.1016/j.egypro.2017.03.1904>
- [19] Von Rothkirch J., Ejderyan O. Anticipating the social fit of CCS projects by looking at place factors. *International Journal of Greenhouse Gas Control* 2021:110:103399. <https://doi.org/10.1016/j.ijggc.2021.103399>
- [20] Hardisty P. E., Sivapalan M., Brooks P. The Environmental and Economic Sustainability of Carbon Capture and Storage. *Int. J. Environ. Res. Public Health* 2011:8(5):1460. <https://doi.org/10.3390/IJERPH8051460>
- [21] Bäckstrand K., Meadowcroft J., Oppenheimer M. The politics and policy of carbon capture and storage: Framing an emergent technology. *Global Environmental Change* 2011:21(2):275–281. <https://doi.org/10.1016/J.GLOENVCHA.2011.03.008>
- [22] Pubule J., *et al.* Analysis of the environmental impact assessment of power energy projects in Latvia. *Management of Environmental Quality* 2012:23(2):190–203. <https://doi.org/10.1108/14777831211204930>
- [23] Seo S. N. The Theory of Public Goods and Their Efficient Provisions. *The Behavioral Economics of Climate Change*. Academic Press, 2017:33–64. <https://doi.org/10.1016/B978-0-12-811874-0.00002-7>
- [24] Haloks G., *et al.* Determinants of willingness to pay for urban parks: An empirical analysis in Greece. *Land Use Policy* 2022:119:106186. <https://doi.org/10.1016/j.landusepol.2022.106186>
- [25] Hofstetter R., *et al.* A de-biased direct question approach to measuring consumers' willingness to pay. *International Journal of Research in Marketing* 2021:38(1):70–84. <https://doi.org/10.1016/J.IJRESMAR.2020.04.006>
- [26] Xiong K., Kong F. The Analysis of Farmers' Willingness to Accept and Its Influencing Factors for Ecological Compensation of Poyang Lake Wetland. *Procedia Engineering* 2017:174:835–842. <https://doi.org/10.1016/J.PROENG.2017.01.230>
- [27] O'Mahony T. Cost-Benefit Analysis and the environment: The time horizon is of the essence. *Environmental Impact Assessment Review* 2021:89:106587. <https://doi.org/10.1016/j.eiar.2021.106587>
- [28] Suzuki K., *et al.* An international comparative study on driving attitudes and behaviors based on questionnaire surveys. *LATSS Research* 2022:46(1):26–35. <https://doi.org/10.1016/j.latssr.2021.10.002>
- [29] Balagué C., de Valck K. Using Blogs to Solicit Consumer Feedback: The Role of Directive Questioning Versus No Questioning. *J. Interact. Mark.* 2013:27(1):62–73. <https://doi.org/10.1016/J.INTMAR.2012.06.002>
- [30] Jones T. L., Baxter M., Khanduja V. A quick guide to survey research. *Ann. R. Coll. Surg. Engl.* 2013:95(1):5–7. <https://doi.org/10.1308/003588413X13511609956372>
- [31] Zhang Y., *et al.* Exploring cooling pattern of low-income households in urban China based on a large-scale questionnaire survey: A case study in Beijing. *Energy in Buildings* 2021:236:110783. <https://doi.org/10.1016/j.enbuild.2021.110783>

PAPER 5. LEGAL FRAMEWORK ANALYSIS FOR
CO₂ UTILISATION

Legal Framework Analysis for CO₂ Utilisation in Latvia

Viktorija TERJANIKA^{1*}, Emils ZARINS², Lauma BALODE³, Jelena PUBULE⁴

¹⁻⁴*Institute of Energy Systems and Environment, Riga Technical University, Azenes st. 12/1, Riga, LV-1048, Latvia*

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 – CO₂; CCS; CCU; policy; legislation

1. INTRODUCTION

1.1. CO₂ Utilisation / Valorisation Concept

In times of fighting climate change and increasing CO₂ 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 CO₂ 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 CO₂ 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].

* Corresponding author.
E-mail address: viktorija.terjanika@rtu.lv

Carbon dioxide utilisation aims to turn waste into a valuable product. And although CO₂ 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. CO₂ 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 CO₂ that would otherwise be emitted into the atmosphere (and sometimes will enable removing this CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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. CO₂ 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 CO₂ emissions. The study included a search and subsequent accounting for CO₂, CCS, CCUS, CCU, carbon/ CO₂ utilisation, carbon/ CO₂ capture, and carbon/ CO₂ 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 CO₂ 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).

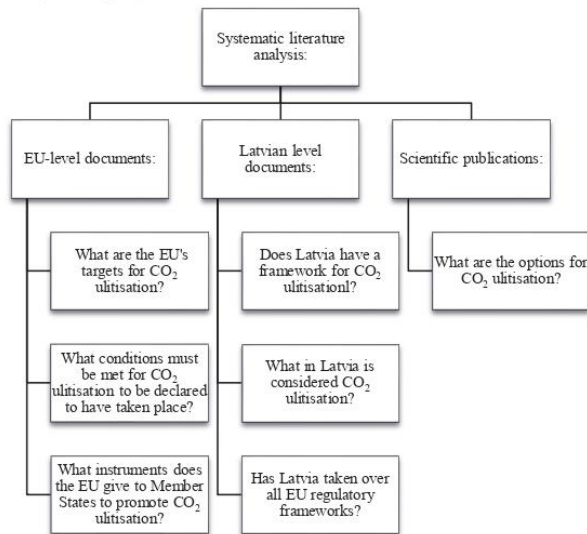


Fig. 1. Systematic literature analysis steps.

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 CO₂ 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 CO₂ 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 CO₂

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 (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF₆), nitrogen trifluoride (NF₃) [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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions. Additionally, the law of permanent storage of CO₂ 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 CO₂ Storage Act was planned to ensure the permanent storage of CO₂ 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 CO₂ with a maximum storage capacity of 4 Mt CO₂ 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 CO₂ (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 CO₂ 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 CO₂ 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 CO₂ Capture and Storage. Financing is provided to capture and subsequent storage of CO₂ 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 CO₂ storage [59]. However, in 2020, the Lithuanian government banned any projects to capture and store CO₂. 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂, where it would be subsequently buried. Latvia has delicious geological layers suitable for storing CO₂ from the Baltic region [60], [67].

The onshore CCUS scenario includes capturing CO₂ 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 CO₂ [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 CO₂ 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 CO₂ 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.

ACKNOWLEDGEMENT

This work has been supported by the European Social Fund within the Project No 8.2.2.0/20/I/008 "Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization" of the Specific Objective 8.2.2 "To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas" of the Operational Programme "Growth and Employment".

REFERENCES

- [1] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee Of The Regions. Brussels: EC, 2021.
- [2] European Commission. Programm: Horizon Europe - Cluster 5 – Destination 3: Sustainable, secure and competitive energy supply [Online]. [Accessed 13.04.2022]. Available: https://www.euro-access.eu/programm/horizon_europe_-_cluster_5_-_destination_3_sustainable_secure_and_competitive_energy_supply
- [3] Sahoo P. K., Zhang Y., Das S. CO₂-promoted reactions: An emerging concept for the synthesis of fine chemicals and pharmaceuticals. *ACS Catal.* 2021;11(6):3414–3442. <https://doi.org/10.1021/acscatal.0c05681>
- [4] Yao B., et al. Transforming carbon dioxide into jet fuel using an organic combustion-synthesized Fe-Mn-K catalyst. *Nat. Commun.* 2020;11(1):6395. <https://doi.org/10.1038/s41467-020-20214-z>
- [5] European Commission. Novel carbon capture and utilisation technologies [Online]. [Accessed 13.04.2022]. Available: https://ec.europa.eu/info/research-and-innovation/strategy/support-policy-making/scientific-support-eu-policies/group-chief-scientific-advisors/novel-carbon-capture-and-utilisation-technologies_en
- [6] WorleyParsons Inc. Economic Assessment of Carbon Capture and Storage Technologies. Canberra: WorleyParsons, 2011.
- [7] Leeson D., et al. A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources. *Int. J. Greenh. Gas Control* 2017;61:71–84. <https://doi.org/10.1016/j.ijggc.2017.03.020>
- [8] Shogenova A., et al. Techno-economic Modelling of the Baltic CCUS Onshore Scenario for the Cement Industry Supported by CLEANKER Project. *Proceedings of the 15th Greenhouse Gas Control Technologies Conference 2021*. <https://doi.org/10.2139/SSRN.3817710>
- [9] Mikhelkis L., Govindarajan V. Techno-economic and partial environmental analysis of carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCU/S): Case study from proposed waste-fed district-heating incinerator in Sweden. *Sustain.* 2020;12(15):5922. <https://doi.org/10.3390/SU12155922>
- [10] Edenhofer O., et al. Climate Change 2014 Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press, 2014.
- [11] International Energy Agency. Tracking Clean Energy Progress 2017. Paris: IEA, 2017.
- [12] Global CCS Institute. The Global Status of CCs: 2017. Melbourne: Global CCS Institute, 2018.

- [13] Global CCS Institute. Global Status of CCS 2021. Melbourne: Global CCS Institute, 2021.
- [14] International Energy Agency. Net Zero by 2050 - A Roadmap for the Global Energy Sector. Paris: IEA, 2021.
- [15] Kuckshinrichs W., Vögele S. Economic Analysis of Carbon Capture in the Energy Sector. *Carbon Capture, Storage and Use* 2015:147–171. https://doi.org/10.1007/978-3-319-11943-4_7
- [16] Rissman J., Orvis R. Carbon Capture And Storage: An Expensive Option For Reducing U.S. CO2 Emissions. *Forbes* 2017.
- [17] Parliamentary Advisory Group on CCS. Lowest Cost Decarbonisation for the UK: the Critical Role of CCS. Oxburgh: SCCS, 2016.
- [18] Group of Chief Scientific Advisors. Novel Carbon Capture and Utilisation Technologies. Luxembourg: Publications Office of the European Union, 2018.
- [19] Koizumi H., et al. One-pot catalytic synthesis of urea derivatives from alkyl ammonium carbamates using low concentrations of CO₂. *Commun. Chem.* 2021:4:66. <https://doi.org/10.1038/s42004-021-00505-2>
- [20] Styring P., et al. Carbon Capture and Utilisation in the green economy Using CO₂ to manufacture fuel, chemicals and materials. York: The Centre for Low Carbon Futures, 2012.
- [21] United Nations. Paris Agreement. New York: UN, 2015.
- [22] European Commission. Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). *Off. J. Eur. union* 2021:L243/1.
- [23] European Commission. Revision for phase 4 (2021-2030) [Online]. [Accessed 13.04.2022]. Available: https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/revision-phase-4-2021-2030_en
- [24] European Commission. Modernisation Fund [Online]. [Accessed 13.04.2022]. Available: https://ec.europa.eu/clima/eu-action/funding-climate-action/modernisation-fund_en
- [25] European Commission. NER 300 programme [Online]. [Accessed 13.04.2022]. Available: https://ec.europa.eu/clima/eu-action/funding-climate-action/ner-300-programme_en
- [26] European Commission. Proposal for a Regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport. Brussels: EC, 2021.
- [27] European Commission. Innovation Fund [Online]. [Accessed 29.11.2021]. Available: https://ec.europa.eu/clima/eu-action/funding-climate-action/innovation-fund_en
- [28] European Commission. Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Text with EEA relevance). *Off. J. Eur. Union* 2009:L140/114.
- [29] European Commission. Primacy of EU law [Online]. [Accessed 13.04.2022]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:primacy_of_eu_law
- [30] Saeimi. On Pollution. *Latv. Vestn.* 2001:51.
- [31] Cabinet of Ministers. Latvījai piešķirto emisijas kvotu izsolišanas kārtība (Procedure for auctioning emission quotas allocated to Latvia.). *Latv. Vestn.* 2012:157. (in Latvian)
- [32] Cabinet of Ministers. Methodology for Calculating Greenhouse Gas Emissions. *Latv. Vestn.* 2018:18.
- [33] Ministry of Environmental Protection and Regional Development. Klimata Likums (Climate Law) [Online]. [Accessed 14.04.2022] Available: <https://www.varam.gov.lv/lv/klimata-likums> (in Latvian)
- [34] Ministry of Environmental Protection and Regional Development. Siltumnīcefekta gāzu monitorings un ziņošana (Monitoring and reporting of greenhouse gases) [Online]. [Accessed 14.04.2022] Available: <https://www.varam.gov.lv/lv/siltumnicefakta-gazu-monitorings-un-zinosana>
- [35] Latvian Geological and Meteorological Center. Pollutant Release and Transfer Register [Online]. [Accessed 14.04.2022]. Available: <https://prtr.lv/gmc.lv/>
- [36] State Environmental Service. Maps [Online]. [Accessed 14.04.2022]. Available: <https://registri.vvd.gov.lv/piesarnojoso-darbibu-vietu-karte/> (in Latvian)
- [37] Official Statistics Portal. Gaisa emisiju konti (NACE 2.red.) 2000 – 2020 [Online]. [Accessed 14.04.2022]. Available: https://data.stat.gov.lv/pxweb/en/OSP_PUB/START_ENV_GP_GPE/GPE010/
- [38] Alvarez C., Molnar G., IEA. What is behind soaring energy prices and what happens next? [Online]. [Accessed 14.04.2022]. Available: <https://www.iea.org/commentaries/what-is-behind-soaring-energy-prices-and-what-happens-next>
- [39] Crellin F. European gas price surge prompts switch to coal [Online]. [Accessed 14.04.2022]. Available: <https://www.reuters.com/business/energy/european-gas-price-surge-prompts-switch-coal-2021-10-12/>
- [40] Potter E., Jackson V. High natural gas prices lead to increased coal generation, 2021 carbon emissions: EIA. *S&P Global Commodity Insights* 2021.
- [41] Ministry of Economics Republic of Latvia. Latvia's National Energy and Climate Plan 2021-2030. Riga: MoE, 2020.
- [42] Cabinet of Ministers. Par Latvijas Nacionālo enerģētikas un klimata plānu 2021.-2030 gadam (About Latvia's National Energy and Climate Plan for 2021-2030.). *Latv. Vestn.* 2020:29. (in Latvian)
- [43] Cabinet of Ministers. On the Action Plan for Reducing Air Pollution for 2020-2030. *Latv. Vestn.* 2020:197.

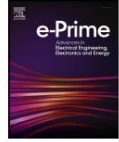
- [44] UK Legislation. Climate Change Act 2008. London: The Stationery Office, 2008:27.
- [45] Press Release. UK enshrines new target in law to slash emissions by 78 % by 2035. London: BEIS, 2021.
- [46] UK Legislation. The Climate Change Act 2008 (2050 Target Amendment) Order 2019. London: London: The Stationery Office, 2019:1056.
- [47] Fankhauser S., Averkhenkova A., Finnegan J. 10 years of the UK Climate Change Act. London: LSE, 2018.
- [48] Black R. How is the UK tackling climate change? [Online]. [Accessed 14.04.2022]. Available: <https://eciu.net/analysis/briefings/uk-energy-policies-and-prices/how-is-the-uk-tackling-climate-change>
- [49] HM Government. The Clean Growth Strategy - Leading the way to a low carbon future. London: BEIS, 2017.
- [50] Institution of Civil Engineers (ICE). Teesside: creating one of Europe's first clean industrial zones with carbon capture and storage. London: ICE Group, 2017.
- [51] Department for Business, Energy & Industrial Strategy. Implementing the end of Unabated Coal by 2025. London: BEIS, 2018.
- [52] IEA. Federal Climate Change Act 2021 [Online]. [Accessed 14.04.2022]. Available: <https://www.iea.org/policies/13518-federal-climate-change-act-2021>
- [53] Bundesministerium der Justiz. Gesetz zur Demonstration der dauerhaften Speicherung von Kohlendioxid (Act to demonstrate the permanent storage of carbon dioxide) (Carbon Dioxide Storage Act - KSpG). Berlin: Bundesministerium der Justiz, 2012. (in German)
- [54] Wettengel J. Call for open debate on CCU and CCS to save industry emissions. *Clean Energy Wire*, 2018.
- [55] Kuylenstierna, J., *et al.* Report of the Swedish Climate Policy Council 2021. Stockholm: Swedish Climate Policy Council, 2021.
- [56] Government Offices of Sweden Ministry of the Environment. Sweden's long-term strategy for reducing greenhouse gas emissions. Stockholm: MoE, 2020.
- [57] Government Offices of Sweden Ministry of the Environment and Energy. The Swedish climate policy framework. Stockholm: MoEE.
- [58] The Swedish Environmental Protection Agency. Report for Sweden on climate policies and measures and projections. Stockholm: SEPA, 2021.
- [59] Rutters H., CGS Europa partners. State of play on CO₂ geological storage in 28 European countries. Report No. D2.10. CO₂ GeoNET, 2013.
- [60] Shogenova A. Carbon Neutral Baltic States: Do We Have Ccus Among Accepted Options? Tallin: TalTech, 2020.
- [61] Mockevicius J. CCS Legislation Framework in Lithuania CCS Legislation Framework in Lithuania in Lithuania. Vilnius: LGT, 2011.
- [62] Lietuvos Respublikos Energetikos Ministerija. Lietuvos Respublikos Nacionalinis Energetikos ir Klimato Srities Veiksmų Planas 2021-2030 M (National Energy and Climate Action Plan of the Republic of Lithuania for 2021-2030.). Vilnius: EM, 2020. (in Lithuanian)
- [63] Eesti Vabariigi Valitsus. Strateegia 'Eesti 2035' (Strategy 'Estonia 2035') [Online]. [Accessed 14.04.2022]. Available: <https://valitsus.ee/strateegia-estni-2035-arengukavad-ja-planeering/strateegia> (in Estonian)
- [64] Secretary of State. Vabariigi Valitsuse tegevusprogramm 2019-2023 (Action Program of the Government of the Republic 2019-2023). Tallin: Eelnõude infosüsteem, 2019. (in Estonian)
- [65] European Commission. Estonia's 2030 National Energy and Climate Plan (NECP 2030). Luxembourg: EC, 2016.
- [66] Konist A., *et al.* Kliimamuutuste Leevendamise Läbi CCS Ja CCU Tehnoloogiate (ClimMit) (Climate Change Mitigation Through Ccs And Ccu Technologies (ClimMit)). Tallin: TalTech, 2021. (in Estonian)
- [67] Shogenov K., Shogenova A. Cost-Competitive and Self-Supporting Geothermal Energy, CO₂-EOR and CO₂ Storage Concept: Case Study of the E6 Structure in the Baltic Sea. *Proceedings of the 14th Greenhouse Gas Control Technologies Conference* 2018. <https://doi.org/10.2139/SSRN.3366151>

PAPER 6. POLICY INSTRUMENTS FOR CO₂
VALORISATION SUPPORT



Contents lists available at ScienceDirect

e-Prime - Advances in Electrical Engineering, Electronics and Energy

journal homepage: www.elsevier.com/locate/prime

Policy instruments for CO₂ valorisation support

Viktorija Terjanika, Jelena Pubule^{*}, Dagnija Blumberga, Emils Zarins

Institute of Energy Systems and Environment, Riga Technical University, Riga, Latvia

ARTICLE INFO

Keywords:

Legislation framework
European union
CO₂
CCS
CCU

ABSTRACT

Mitigation of CO₂ emissions has become a top question in international and national arenas, likewise on the city level. Existing CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 (CO₂) into more valuable products, thus ensuring the meaningful use of CO₂ 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 CO₂ utilised by 2050.

Despite the fact that multiple research is made [2–4], the largest emitters of CO₂ 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 CO₂ is considered a GHG is linked to the impact of CO₂ 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 CO₂ stored in the atmosphere [6]. CO₂ is responsible

^{*} Corresponding author.

E-mail address: jelena.pubule@rtu.lv (J. Pubule).

<https://doi.org/10.1016/j.prime.2023.100181>

Received 9 January 2023; Received in revised form 10 May 2023; Accepted 27 May 2023

Available online 28 May 2023

2772-6711/© 2023 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

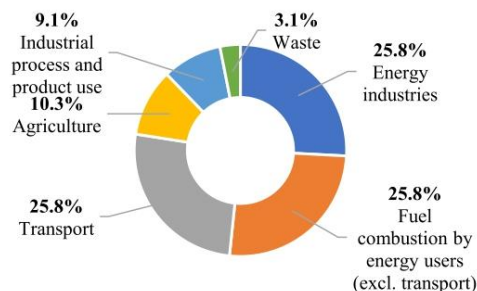


Fig. 1. Greenhouse gas emitters in the European Union [5].

for around 20% of the Earth's greenhouse effect [7]. Since the beginning of industrialisation, the amount of CO₂ in the atmosphere has risen from 280 ppm to 410 ppm today. It is projected that by the year 2100, the concentration of CO₂ 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 CO₂ emissions is through carbon capture and utilisation (CCU) or CO₂ valorisation. This involves capturing CO₂ emissions from industrial processes and converting them into valuable products such as fuels, chemicals, and building materials. CO₂ valorisation has the potential to not only reduce emissions but also create economic opportunities and contribute to sustainable development.

Despite the potential benefits of CO₂ 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 CO₂ valorisation technologies are still in the early stages of development and

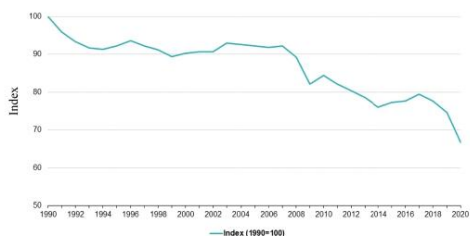


Fig. 2. Total GHG emissions in the European Union, excluding land use, land use change and forestry, but including international aviation [9].

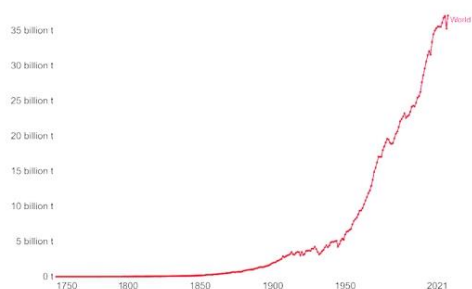


Fig. 3. Annual CO₂ emissions in the world from fossil fuel burning and cement production (excluding land-use) [10].

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 CO₂ 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 CO₂ 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 CO₂ emissions that are otherwise very difficult to reduce (Fig. 4).

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 CO₂ 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.

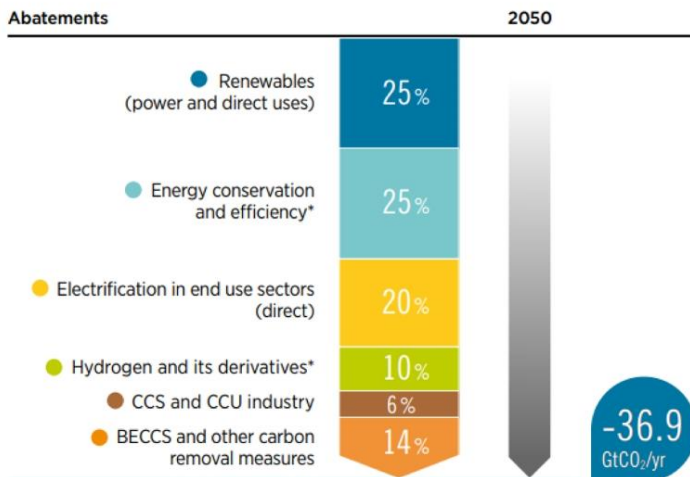


Fig. 4. Carbon emissions abatements, IRENA report [17].

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 CO₂ 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 CO₂ 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 CO₂ recovery?
- What conditions must be met for CO₂ recovery to be recognised?
- What tools does the EU provide the Member States to promote CO₂ recovery?

Scientific papers:

- What are the possibilities for CO₂ utilisation?
- What is the experience of other countries and cases?

A search strategy is developed to identify relevant literature on policy instruments for CO₂ 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 CO₂. Still, only a few countries have a tax on CO₂ 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 CO₂ 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 CO₂eqv 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].

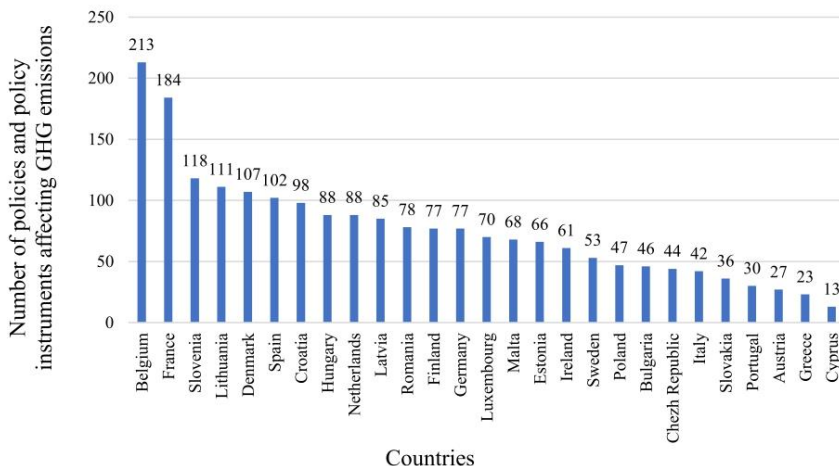


Fig. 5. Number of policies and policy instruments affecting GHG emissions in EU Member States [24].

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 CO₂ 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 CO₂ 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 CO₂ in production will continue further, and there will be more CCS and CCU stations.

Croatia. Croatia has ten large CO₂ 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 CO₂ EOR Project Croatia was launched in the country, allowing it to obtain more minerals and put waste CO₂ underground simultaneously. This project allows storing more than 400 mln.m³ CO₂ [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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂. 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 CO₂ 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 CO₂ 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, CO₂ 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 CO₂ 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 CO₂ 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 CO₂-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 CO₂ 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.

Acknowledgement

This research is funded by the Latvian Council of Science, project CO2 Deal: Effective Valorisation of CO2 for Decarbonised Regional Development, project No. Izp-2020/1-0302.

References

- European Commission. Communication from the commission to the european parliament and the council sustainable carbon cycles, Brussels, EC, 2021.
- J. Kang, Y. Yang, Energy carbon emission structure and reduction potential focused on the supply-side and demand-side, *PLoS ONE* 15 (10) (2020), e0239634, <https://doi.org/10.1371/journal.pone.0239634>.
- S.A. Mansouri, et al., Energy hub design in the presence of p2g system considering the variable efficiencies of gas-fired converters, in: Proceedings of the International Conference on Smart Energy Systems and Technologies (SEST), 2021, pp. 1–6, <https://doi.org/10.1109/SEST50973.2021.9543179>.
- Q.-L. Jing, et al., The impact of public transportation on carbon emissions—from the perspective of energy consumption, *Sustainability* 14 (2022) 6248, <https://doi.org/10.3390/su14106248>.
- Eurostat, European Commission, 2018. How are emissions of greenhouse gases by the EU evolving? <https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-4a.html?lang=en> (accessed 07 March 2022).
- R. Lindsey, If carbon dioxide hits a new high every year, why isn't every year hotter than the last? NOAA Climate.Gov., 2021 <https://www.climate.gov/news-feature/s/climate-qa-if-carbon-dioxide-hits-new-high-every-year-why-isn%E2%60%99t-every-year-hotter-last> (accessed 06 March 2022).
- Nasa Earth Observatory. The carbon cycle, 2011 <https://earthobservatory.nasa.gov/features/CarbonCycle/page5.php> (accessed 06 March 2022).
- B. Song, A. Qin, B.Z. Tang, Syntheses, properties, and applications of CO2-based functional polymers, *Cell Rep. Phys. Sci.* 3 (2) (2022), 100719, <https://doi.org/10.1016/j.xcrp.2021.100719>.
- Eurostat. Greenhouse gas emission statistics - emission inventories, 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Greenhouse_gas_emission_statistics_-_emission_inventories (accessed 2 March 2022).
- H. Ritchie, M. Roser, CO2 emissions, 2020. <https://ourworldindata.org/co2-emissions> (accessed 4 March 2022).
- H.O. Pörtner, et al., Climate Change 2022: impacts, adaptation and vulnerability. summary for policymakers. IPCC, Geneva, 2022.
- K. Laskowski, J. Fabiszewska-Solares, CCS regional cooperation roadmap for central and eastern Europe. CCS4CEE, 2022.
- M. Hrubý, A. Visnerova, V. Bartovic, Central and Eastern European CCS Roadmap, CCS4CEE (2022).
- S.S. Cordova, M. Gustafsson, M. Eklund, N. Svensson, Potential for the valorization of carbon dioxide from biogas production in Sweden, *J. Clean. Prod.* 370 (2022), 133498, <https://doi.org/10.1016/j.jclepro.2022.133498>.
- S. Fuss, F. Johnson, The BECCS implementation gap – a swedish case study, *Frontiers (Boulder)* 8 (2020), 553400, <https://doi.org/10.3389/fenv.2020.553400>.
- A. Lefvert, E. Rodriguez, M. Fridahl, S. Gronkvist, S. Haikola, A. Hansson, What are the potential paths for carbon capture and storage in Sweden? A multi-level assessment of historical and current developments, *Energy Res. Soc. Sci.* 87 (2022), 102452, <https://doi.org/10.1016/j.erss.2021.102452>.
- M. Lyons, P. Durrant, K. Kochhar, Reaching Zero With Renewables Capturing Carbon, IRENA, Abu Dhabi, 2021.
- Regulation (EU), 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), Official J. Eur. Union (2021), L243/1.
- O. Geden, F. Schenuit, Unconventional mitigation. carbon dioxide removal as a new approach in EU climate policy, SWP Research Paper, Berlin, 2020.
- E. Rodriguez, A. Lefvert, M. Fridahl, Stefan Gronkvist, S. Haikola, A. Hansson, Tensions in the energy transition: Swedish and Finnish company perspectives on bioenergy with carbon capture and capture, *J. Clean. Product.* 280 (2021), 124527, <https://doi.org/10.1016/j.jclepro.2020.124527>.
- R. Bellamy, J. Lezaun, J. Palmer, Perceptions of bioenergy with carbon capture and storage in different policy scenarios, *Nat. Commun.* 10 (2019) 743, <https://doi.org/10.1038/s41467-019-08592-5>.
- R. Bellamy, M. Fridahl, J. Lezaun, J. Palmer, E. Rodriguez, A. Lefvert, A. Hansson, S. Gronkvist, S. Haikola, Incentivising bioenergy with carbon capture and storage (BECCS) responsibly: comparing stakeholder policy preferences in the United Kingdom and Sweden, *Environ. Sci. Pol.* 116 (2021) 47–55, <https://doi.org/10.1016/j.envsci.2020.09.022>.
- H. Snyder, Literature review as a research methodology: an overview and guidelines, *J. Bus. Res.* 104 (2019) 333–339, <https://doi.org/10.1016/j.jbusres.2019.07.039>.
- European Environmental Agency, National Greenhouse Gas Policies and Measures in Europe, 2021. <https://www.eea.europa.eu/themes/climate/national-policies-and-measures/national-policies-and-measures-on-1> (accessed 26 February 2022).
- The World Bank, State and Trends of Carbon Pricing, The World Bank, Washington, 2022.
- European Environmental Agency, Climate change mitigation policies and measures (greenhouse gas emissions), 2021. <https://www.eea.europa.eu/data-and-maps/data/climate-change-mitigation-policies-and-measures-1> (accessed 26 February 2022).
- European Parliament, Climate action in Belgium, EP, Brussels, 2021.
- O. Giacomo, Belgium's energy & climate plan - what is the legislative framework for climate policy in Belgium? Stribe, Amsterdam, 2019.
- European Commission, Belgisch geïntegreerd Nationaal Energie- en Klimaatplan 2021-2030, EC, Brussels, 2019.
- Zero Emission Platform, CCS/CCU projects. <https://zeroemissionsplatform.eu/ab-out-ccs-ccu/ccs-ccu-projects> (accessed 15 April 2022).
- MOLGroup, CO2 EOR Project Croatia, MOLGroup, Budapest, 2013.
- Bioraffinery Project 2022. <https://www.ina.hr/bioraffinerija/en/> (accessed 15 May 2022).
- V. Marsh, Regions in focus: spotlight on industry in Northern Croatia and Romania, Strategy CCUS, Orleans, 2021.
- A. Shogenova, Carbon neutral baltic states: do we have CCUS among accepted options? TalTech, Tallin, 2020.
- J. Mockevicius, CCS legislation framework in Lithuania, LGT, Vilnius, 2011.
- Lietuvos Respublikos Energetikos Ministerija, Lietuvos Respublikos Nacionalinis Energetikos ir Klimato Srities Veiksmų Planas 2021-2030 M.(National Energy And Climate Action Plan Of The Republic Of Lithuania For 2021-2030), Vilnius, 2020.
- Swedish Climate Policy Council, Report of the Swedish Climate Policy Council 2021, SCP, Stockholm, 2021.
- Ministry of the Environment, Sweden's long-term strategy for reducing greenhouse gas emissions, MoE, Stockholm, 2020.
- F. Levihn, Bio-CCS: giving Swedish industry a competitive advantage, Stockholm Exergi, Stockholm, 2021.
- A. Shogenova, K. Shogenov, M. Uibu, R. Kuusik, K. Simmer, F. Canonico, Techno-economic Modelling of the Baltic CCUS Onshore Scenario for the Cement Industry Supported by CLEANER Project, SSRN Electron. J. (2021) 1–13.
- International Association of Oil & Gas Producers, CCUS projects in Europe, IOGP, London, 2022.
- International Association of Oil & Gas Producers, CCUS projects in Europe, IOGP, London, 2020.
- European Commission, €1.5 billion for clean tech: 138 projects apply to the EU Innovation Fund's second call for large-scale projects, 2022. https://ec.europa.eu/clima/news-your-voice/news/eu15-billion-clean-tech-138-projects-apply-eu-innovation-funds-second-call-large-scale-projects-2022-03-11_en (accessed 19 May 2022).
- Ervia project. <https://www.ervia.ie/who-we-are/carbon-capture-storage> (accessed 01 January 2022).

PAPER 7. CO₂ STORAGE IN LOGGING RESIDUE
PRODUCTS WITH ANALYSIS OF ENERGY
PRODUCTION SCENARIOS

CO₂ Storage in Logging Residue Products with Analysis of Energy Production Scenarios

Gustavs VIKSNE¹, Ilze VAMŽA², Viktorija TERJANIKA^{3*}, Tereza BEZRUCKO⁴,
Jelena PUBULE⁵, Dagnija BLUMBERGA⁶

¹⁻⁶Riga Technical University, Institute of Energy Systems and Environment, Azenes iela 12/1, Riga,
LV 1048, Latvia

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 CO₂ into the atmosphere. This resource could be used to manufacture long-lasting products and store a significant amount of CO₂, promoting CO₂ 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 – CO₂ 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 CO₂ sequestration. It has been observed that there exists a direct correlation between the amount of CO₂ sequestered and the amount of wood-derived

* Corresponding author.
E-mail address: viktorija.terjanika@rtu.lv

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].

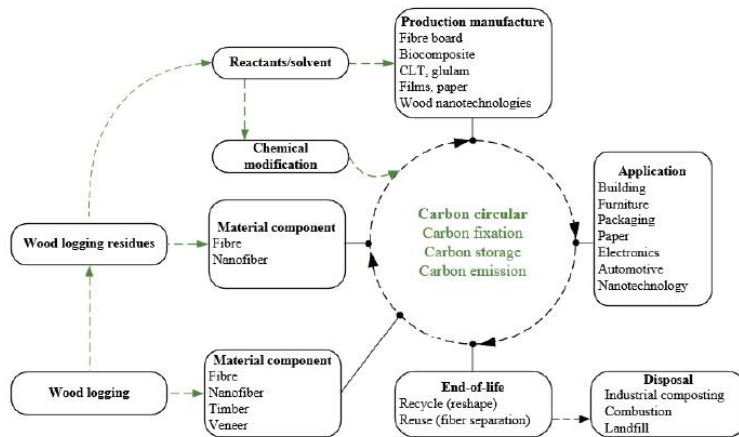


Fig 1. The sustainable carbon cycle of wood logging residues [1].

In the wood-based product sector, significant potential for CO₂ 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 CO₂ balance in the atmosphere. It was calculated that a cubic meter of PB and OSB sequester 720 kg of CO₂ each and that a cubic meter of MDF sequesters 820 kg of CO₂, 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 CO₂ 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 CO₂ 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 CO₂ emissions has become a top question in the last decades. Therefore, understanding processes within rural CO₂ economy sectors, factors, interconnections and effects on the environment and nature quality and guidelines for future activities are crucial. Valorisation of CO₂, including direct capture and utilization, transformed CO₂ utilization or pre-processed CO₂ utilization, can positively affect the reduction of CO₂ 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 CO₂ 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 CO₂ 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.

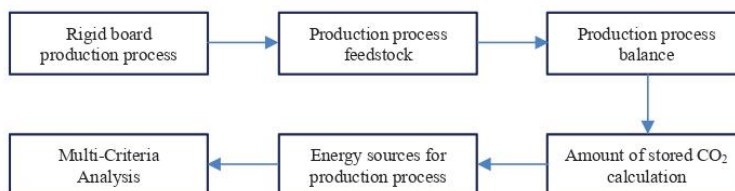


Fig. 2. Algorithm of the methodology.

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/m³. It is mainly used for insulation purposes, and the raw boards are passed through a profiler to produce a tongue-and-groove finish [10].

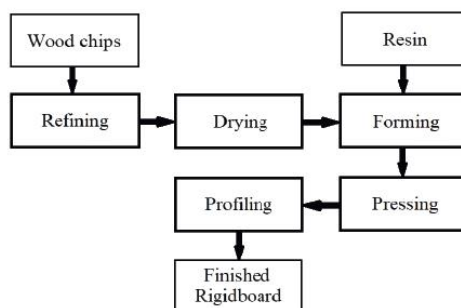


Fig. 3. Simplified rigidboard manufacturing process [10].

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 m³ 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 CO₂ 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 CO₂ stored in the material is assumed to be the same for all standards and is calculated [17]:

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

where

mCO_2	mass of CO ₂ sequestered, kgCO ₂ ;
$m_{\text{dry}}(\text{timber})$	dry weight of timber in the finished product, kg;
C_f	percentage of carbon in dry matter (for timber = 0.5);
$m \cdot mCO_2$	molecular mass of CO ₂ = 44 g/mol;
$m \cdot m_C$	atomic mass of carbon = 12 g/mol.

By substituting the masses of carbon and CO₂, Eq. (1) becomes:

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

where mCO_2 is the mass of CO₂ sequestered in the finished product and $m_{\text{dry}}(\text{timber})$ is the dry weight of timber in the finished product.

Only the CO₂ 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 CO₂ 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 CO₂ 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 CO₂ (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, MW _{th}	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 m³ 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 CO₂ 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 CO₂ 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 CO₂ is the same, as they are all based on 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 CO₂.

Standards-based on the EN-15804 standard offer the highest amount of CO₂ stored in one cubic meter of the product – 359 kgCO₂/m³, while the lowest amount of CO₂ stored can be attributed to standards based on the previous ISO-14040/44 LCA standard – 90 kgCO₂/m³. Considering all standards, an average value of 270 kgCO₂/m³ 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.

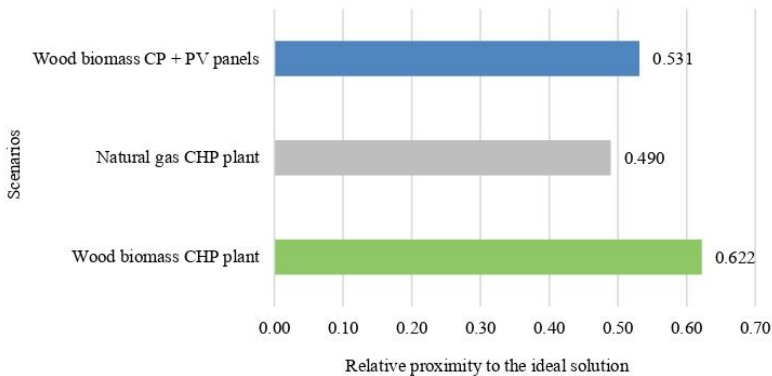


Fig. 4. Multicriteria analysis results.

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 CO₂ stored in the new product was calculated and reviewed using eight standards and their methods for biogenic carbon accounting.

The amount of stored CO₂ 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 CO₂ 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.

ACKNOWLEDGEMENT

This research is funded by the Latvian Council of Science, project CO2 Deal: Effective Valorisation of CO₂ for Decarbonised Regional Development, project No. lzp-2020/1-0302.

REFERENCES

- [1] Montanari C., Olsén P., Berglund L. A. Sustainable Wood Nanotechnologies for Wood Composites Processed by In-Situ Polymerization. *Front. Chem.* 2021;9:1–12. <https://doi.org/10.3389/fchem.2021.682883>
- [2] Blumberga D., et al. Forest biomass – new products and technologies. Riga: Riga Technical University, Institute of Energy Systems and Environment, 2016.
- [3] Terjanika V., Pubule J. Barriers and Driving Factors for Sustainable Development of CO₂ Valorisation. *Sustainability* 2022;14(9):5054. <https://doi.org/10.3390/su14095054>

- [4] Terjanika V., et al. Analysis of CO₂ Valorisation Options for Regional Development. *Environmental and Climate Technologies* 2021.25(1):243–253. <https://doi.org/10.2478/rtuct-2021-0017>.
- [5] Terjanika V., Blumberga D., Pubule J. Regional Development Scenarios and Model Boundaries for CCU in Energy Sector in Latvia. *Proceedings of the IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University, RTUCON* 2021. <https://doi.org/10.1109/RTUCON53541.2021.9711727>.
- [6] Singh T., et al. Emerging technologies for the development of wood products towards extended carbon storage and CO₂ capture. *Carbon Capture Science & Technology* 2022:4:100057. <https://doi.org/10.1016/j.cscst.2022.100057>.
- [7] Xu X., et al. Bamboo construction materials: Carbon storage and potential to reduce associated CO₂ emissions. *Science of the Total Environment* 2022:814:152697. <https://doi.org/10.1016/j.scitotenv.2021.152697>.
- [8] Tripathi N., et al. Biomass waste utilisation in low-carbon products: harnessing a significant potential resource. *Npj Climate and Atmospheric Science* 2019:2:35. <https://doi.org/10.1038/s41612-019-0093-5>.
- [9] Kazulis V., et al. Carbon storage in wood products. *Energy Procedia* 2017:128:558–563. <https://doi.org/10.1016/j.egypro.2017.09.009>.
- [10] Raunkjaer Stubbdrup K., et al. Best Available Techniques (BAT) Reference Document for the Production of Wood-based Panels. Seville: JRC, 2016.
- [11] Veitmans K., Grinfelds U. Wood fibre insulation material. *Research for Rural Development* 2016:2:91–98.
- [12] Vamza I., et al. Bioresource utilization index – A way to quantify and compare resource efficiency in production. *Journal of Cleaner Production* 2021:320:128791. <https://doi.org/10.1016/j.jclepro.2021.128791>.
- [13] Grudulis K., et al. 2013. Characteristics of wood chips from logging residues and quality influencing factors. *Research for Rural Development* 2013:2:49–54.
- [14] FAO, ITTO, United Nations. Forest product conversion factors. Rome: FAO, 2020.
- [15] Dieffenbacher GmbH. Fibre Insulation Board lines [Online]. [Accessed 20.04.2022]. Available: <https://www.environmental-expert.com/products/fibre-insulation-board-lines-190613>
- [16] Tellnes L. G. F., et al. Comparative assessment for biogenic carbon accounting methods in carbon footprint of products: A review study for construction materials based on forest products. *ISEF – Italian Society of Silviculture and Forest Ecology* 2017:10(5):815–823. <https://doi.org/10.3832/ifor2386-010>.
- [17] Pubule J., et al. Analysis of the environmental impact assessment of power energy projects in Latvia. *Management of Environmental Quality* 2012:23(2):190–203. <https://doi.org/10.1108/14777831211204930>.
- [18] BRE Ltd. BRE Global Product Category Rules for Type III environmental product declaration of construction products to EN 15804:2012+A1:2013. Watford: BRE Group, 2014.
- [19] Balkan Green Energy News. 5 MWe biomass cogeneration plant officially opened in the city of Slatina. 2019 [Online]. [Accessed 20.04.2022]. Available: <https://balkangreenenergynews.com/5-mwe-biomass-cogeneration-plant-officially-opened-in-the-city-of-slatina/>
- [20] U.S. Department of Energy. Combined Heat and Power Technology Fact Sheet Series: Gas turbines. Washington: DoE, 2016.
- [21] Danish Energy Agency. Technology Data for Energy Plants for Electricity and District Heating generation. Copenhagen: DEA, 2019.
- [22] Abbas T., Issa M., Ilinca A. Biomass Cogeneration Technologies: A Review. *Journal of Sustainable Bioenergy Systems* 2020:10(1):1–15. <https://doi.org/10.4236/jsbs.2020.101001>
- [23] Tsiropoulos I., Tarvydas D., Zucker A. Cost development of low carbon energy technologies. Luxembourg: Publication Office of European Union, 2018.
- [24] Zalamane D. Pieaug koksnes šķeldas cena, apkure ar šķeldu ir 5 reizes lētāka nekā ar dabasgāzi (The price of wood chips is rising, heating with wood chips is 5 times cheaper than with natural gas.). 2022 [Online]. [Accessed 20.04.2022]. Available: <https://lr1.lsm.lv/lv/raksts/eiro-fokusa/pieaug-koksnes-skeldas-cena-apkure-ar-skeldu-ir-5-reizes-letaka.-a155970/> (in Latvian)
- [25] 'Latvijas gaze' brīdina par dabasgāzes biržas cenas trīskāršu pieaugumu aprīlī ('Latvian gas' warns of a threefold increase in natural gas exchange prices in April). 2022 [Online]. [Accessed 20.04.2022]. Available: <https://www.lsm.lv/raksts/zinas/ekonomika/latvijas-gaze-bridina-par-dabasgazes-birzas-cenas-triskarsu-pieaugumu-aprili.a446800/> (in Latvian)
- [26] Darrow K., et al. Catalogue of CHP technologies. Boston: EPA, ICF International, 2017.
- [27] Cabinet of Ministers. Methodology for calculating greenhouse gas emissions. *Latvijas Vestnesis* 2018:18.
- [28] Ishizaka A., Nemery P. Multi-criteria Decision Analysis: Methods and Software. USA: Wiley, 2013.
- [29] American Center for Life Cycle Assessment. ACLCA Guidance to Calculating Non-LCIA Inventory Metrics in Accordance with ISO 21930:2017. Washington: ACLCA, 2019.
- [30] European Commission, Joint Research Centre, Institute for Environment and Sustainability. International Reference Life Cycle Data System (ILCD) Handbook. General guide for Life Cycle Assessment. Detailed guidance. Luxembourg: Publications Office of the European Union, 2010.
- [31] British Standards Institution. 2011. PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.

PAPER 8. CALCULATION OF GREENHOUSE GAS
SAVINGS: SWITCH FROM ELECTRICITY
PRODUCTION TO BIOMETHANE. CASE STUDY

Calculation of Greenhouse Gas Savings: Switch from Electricity Production to Biomethane. Case Study

Viktorija TERJANIKA^{1*}, Angelica Araceli SANCHEZ VALDESPINO², Jelena PUBULE³

^{1–3}*Institute of Energy Systems and Environment, Riga Technical University, Āzēnes street 12/1, Riga, LV-1048, Latvia*

Received 29.03.2023; accepted 29.09.2023

Abstract – Greenhouse gases are mainly comprised of carbon dioxide. In 2021, anthropogenic CO₂ 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 CO₂ can contribute to decreasing atmospheric CO₂ 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 (CO₂), methane (CH₄), nitric oxide (N₂O), as well as hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride (SF₆). Among them, carbon dioxide is the major. Adding to the complexity is the fact that CO₂ 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, CO₂ 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 CO₂ 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

* Corresponding author.
E-mail address: Viktorija.terjanika@rtu.lv

[11], [12]. However, despite the opportunity to obtain a valuable product, converting carbon dioxide requires energy, which already creates CO₂ in itself [3].

Biomethane is a renewable gas that can be obtained from biogas purification (depending on the system, biogas can contain ~50 % methane (CH₄), which is classified as low-grade biogas) [13]. The purification process involves the removal of carbon dioxide, leaving pure methane. The resulting CO₂ 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 CH₄ content in the mixture raises the calorific value of the gas, making fuel much more valuable. The leading technology for CO₂ 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 CO₂ in plants, which then becomes a resource for biogas production and is released to become a resource for the growth of new plants.

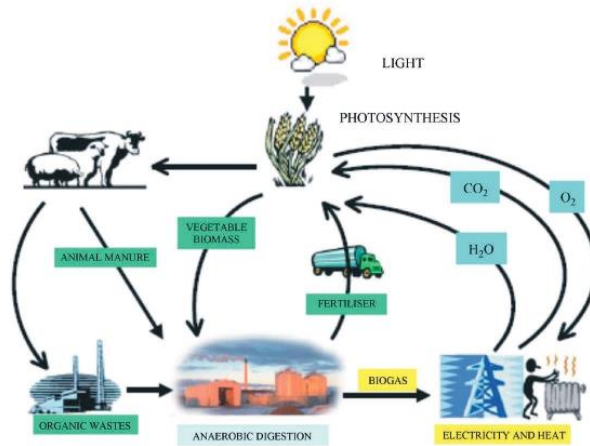


Fig. 1. Carbon cycle principle [32].

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 km² (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 Nm³ 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:

$$E = \sum_{n=1}^n S_n \cdot (e_{ec,n} + e_{td,feedstock,n} + e_{l,n} - e_{sca,n}) + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr}, \quad (1)$$

where

- E Total amount of emissions from the biomethane production (before energy conversion), kg CO₂eq/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 CO₂eq/MJ final product;
- $e_{td,feedstock,n}$ Amount of emissions from the transport of feedstock n to the digester, g CO₂eq/MJ final product;
- $e_{l,n}$ Annual emissions from carbon stock changes due to land usage for feedstock type n , g CO₂eq/MJ final product;
- $e_{sca,n}$ Emissions savings from improved agricultural management of feedstock type n , g CO₂eq/MJ final product;
- e_p Emissions from processing, g CO₂/MJ final product;
- $e_{td,product}$ Emissions from transport and distribution of biomethane, g CO₂eq/MJ final product;
- e_u Emissions from the fuel in use, g CO₂/MJ final product;
- e_{ccs} Emissions savings from carbon capture and geological storage, g CO₂eq/MJ final product;
- e_{ccr} Emission savings from carbon capture and replacement, g CO₂eq/MJ final product

Parameters e_{ec} , e_{td} , e_p , and e_u are calculated according to Eq. (2):

$$e_{ec}, e_{td}, e_p, e_u = \frac{\sum \text{amount of material input} \cdot \text{Emissions Factor of the material}}{\text{Yield or quantity of the material}} \quad (2)$$

Eqs. (1) and (2) are the basis for the following calculations. Even though parameter e is calculated in [g CO₂/MJ of the final product (CH₄)], it is also recommended to calculate it per mass of the intermediate product (as [g CO₂/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 ₂ eq/kg
N fertiliser (mineral)	90 kg/ha year	6.41 kgCO ₂ eq/kg
N fertiliser (digestate)	10 kg/ha year	0.0075 kgCO ₂ eq/kg
CaO fertiliser	0 kg/ha year	0.89 kgCO ₂ eq/kg
M2O field emission	–	5.6 kgN ₂ O eq/ha year
Pesticides	NA	13.9 kgCO ₂ eq/kg
Diesel (machinery)	11 764.7 L/ha year	3.14 / 2.1 kgCO ₂ eq/kg
Maize yield (fresh matter)	37 820 kg/ha year	–

Thus, the three main substrates have the following effect in kgCO₂eq per one kilogram and one ton of fresh matter (FM):

TABLE 3. THE e_c PARAMETERS FOR THE MAIN SUBSTRATES

Substrate	e_{ec} , kgCO ₂ eq/kg	e_{ec} , kgCO ₂ eq/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 CO₂ 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. (3):

$$e_{td,feedstock,n} = \frac{(d_l \cdot f_l) + (d_e \cdot f_e) \cdot EF}{\text{Amount of transported substrate}} \quad (3)$$

where

d_l	Distance travelled while loaded, km;
d_e	Distance travelled 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 used should also be considered since the emission factor (EF) depends on it. For diesel, for example, the EF is 3.14 kgCO₂eq/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 $e_{td,feedstock,n}$ parameter for the station is 0.0015 kgCO₂eq/t for one type of substrate. The total GHG emissions of all 13 substrate types equals 1.96 kgCO₂eq/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 ₂ eq/kWh
Heat (CHP Unit)	0.61	kgCO ₂ eq/MJ
Methane	23	kgCO ₂ eq/kgCH ₄

Using Eq. (4), we can calculate the parameter e_{p1} :

$$e_{p1} = \frac{(\text{Electricity} \cdot EF_E) + (\text{Heat} \cdot EF_h) + (\text{Methane loss} \cdot EF_m)}{\text{Total methane yield}}, \quad (4)$$

where

EF_E Emission factor from electricity, kg CO₂eq/kWh;

EF_h Emission factor from heat, kg CO₂eq/MJ;

EF_m Emission factor from methane, kg CO₂eq/kg CH₄.

Substituting the required values from Table 6 shows that parameter e_{p1} for the Biogas Plant equals 2.70 kgCO₂eq/m³CH₄.

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	%
Methane 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/m³ 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):

$$e_{p2} = \frac{(\text{Electricity for PSA} \cdot EF_E) + (\text{Heat for PSA} \cdot EF_h) + (\text{Methane loss} \cdot EF_m)}{\text{Biomethane output}} \quad (5)$$

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:

$$e_{id,product} = (ET_{ng} \cdot EF_e) + (HT_{ng} \cdot EF_h) + (EC_{st} \cdot EF_{st}), \quad (6)$$

where

- ET_{ng} Electricity for biomethane transport in the natural gas grid, kWh/m³;
 EF_e Emission factor for electricity for biomethane transport in the natural gas grid, kWh/m³;
 HT_{ng} Heat for biomethane transport in the natural gas grid, MJ/m³;
 EF_h Emission factor for heat process for biomethane transport in the natural gas grid, kgCO₂eq/kWh;
 EC_{st} Electricity for biomethane compression in filling station, kWh/m³;
 EF_{st} Emission factor for electricity for biomethane compression in filling station, kWh/m³.

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 kgCO₂eq/m³. If there is no compression, then $e_{id,product} = 0.043$ kgCO₂eq/m³.

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]:

$$\text{Total usable amount of biomethane} = \text{Proportion of methane yield} \times \text{Total biomethane output} \quad (7)$$

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} , $e_{td,feedstock,n}$, e_{p1} , e_{p2} and $e_{td,product}$, for each substrate used, these values are summed up for use in the following formula to determine the total emissions based on 1 Nm³ of biomethane:

$$\text{Total emissions per m}^3 \text{ biomethane} = \frac{(e_{ec} + e_{td,feedstock,n} + e_{p1} + e_{p2} + e_{td,product})}{\text{Total usable amount of biomethane}} \quad (8)$$

Knowing that for the observed Biogas Plant, the sum of all parameters for all substrates is 25 246 762.29 kgCO₂eq/year, and the total amount of biomethane is 4 261 983.48 Nm³/year, using Eq. (8) it has been determined that the total number of emissions is 5.92 kgCO₂eq/m³.

According to REDII [40], greenhouse gas emissions from biomass-derived fuels must be expressed in grams of CO₂ equivalent per MJ of biofuel (gCO₂eq/MJ). For recalculation, the lower heating value of biomethane is used:

$$\text{Total emissions per MJ biomethane} = \frac{\text{Total emissions per m}^3 \text{ of biomethane}}{\text{Heating value of biomethane}} \times 100 \quad (9)$$

The lower heating value of biomethane is 36 MJ/m³, resulting in 16.45 gCO₂eq/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 gCO₂eq/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:

$$\text{Saving} = \frac{(E_{F(t)} - E_B)}{E_{F(t)}} \cdot 100\% \quad (10)$$

where

E_B Total emissions from biomethane, gCO₂eq/MJ CH₄;

$E_{F(t)}$ Total emissions from fossil fuel comparator, gCO₂eq/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.

ACKNOWLEDGEMENT

This work has been supported by the European Social Fund within the Project No 8.2.2.0/201/008 “Strengthening of PhD students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization” of the Specific Objective 8.2.2 “To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas” of the Operational Programme “Growth and Employment”.

REFERENCES

- [1] Statista. Annual CO₂ emissions worldwide 1940-2021 [Online]. [Accessed 19.01.2023]. Available: <https://www.statista.com/statistics/276629/global-co2-emissions>
- [2] European Commission. Global CO₂ emissions rebound in 2021 after temporary reduction during COVID19 lockdown [Online]. [Accessed 19.01.2023]. Available: https://joint-research-centre.ec.europa.eu/jrc-news/global-co2-emissions-rebound-2021-after-temporary-reduction-during-covid19-lockdown-2022-10-14_en
- [3] Esposito E., et al. Simultaneous production of biomethane and food grade CO₂ from biogas: an industrial case study. *Energy Environ. Sci.* 2019;12(1):281–289. <https://doi.org/10.1039/C8EE02897D>
- [4] UNFCCC. Adoption of the Paris Agreement. Bonn: UNFCCC, 2015.
- [5] European Commission. A European Green Deal [Online]. [Accessed 15.02.2023]. Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
- [6] International Energy Agency. Global Energy Review: CO₂ Emissions in 2021 Global emissions rebound sharply to highest ever level. Paris: IEA, 2021.
- [7] Han J., et al. Coal-fired power plant CCUS project comprehensive benefit evaluation and forecasting model study. *J. Clean. Prod.* 2023;385:135657. <https://doi.org/10.1016/J.JCLEPRO.2022.135657>
- [8] Guerrero-Lemus R., Martinez-Duart J. M. Renewable Energies and CO₂: Cost Analysis, Environmental Impacts and Technological Trends. London: Springer, 2013.
- [9] Zhang X., et al. Synthesis and characterization of siloxane functionalized CO₂-based polycarbonate. *Polymer (Guildf)*. 2023;266:125623. <https://doi.org/10.1016/J.POLYMER.2022.125623>
- [10] Wang M., et al. Aldehyde end-capped CO₂-based polycarbonates: a green synthetic platform for site-specific functionalization. *Polym. Chem.* 2022;13(12):1731–1738. <https://doi.org/10.1039/D2PY00129B>
- [11] Chen Q., et al. Opportunities of integrated systems with CO₂ utilization technologies for green fuel & chemicals production in a carbon-constrained society. *J. CO₂ Util.* 2016;14:1–9. <https://doi.org/10.1016/J.JCOU.2016.01.004>
- [12] Zang G., et al. Performance and cost analysis of liquid fuel production from H₂ and CO₂ based on the Fischer-Tropsch process. *J. CO₂ Util.* 2021;46:101459. <https://doi.org/10.1016/J.JCOU.2021.101459>

- [13] Abd A. A., et al. Green route for biomethane and hydrogen production via integration of biogas upgrading using pressure swing adsorption and steam-methane reforming process. *Renewable Energy* 2023:210:64–78. <https://doi.org/10.1016/j.renene.2023.04.041>
- [14] Meng F., et al. Effects of hydroxyethyl group on monoethanolamine (MEA) derivatives for biomethane from biogas upgrading. *Fuel* 2022:325:124874. <https://doi.org/10.1016/j.fuel.2022.124874>
- [15] Luo L., et al. Environmental and economic analysis of renewable heating and cooling technologies coupled with biomethane utilization: A case study in Chongqing. *Sustain. Energy Technol. Assessments* 2023:56:102992. <https://doi.org/10.1016/J.SETA.2022.102992>
- [16] D'Adamo I., Ribichini M., Tsagarakis K. P. Biomethane as an energy resource for achieving sustainable production: Economic assessments and policy implications. *Sustain. Prod. Consum.* 2023:35:13–27. <https://doi.org/10.1016/J.SPC.2022.10.014>
- [17] Fubara T., Ceceļja F., Yang A. Techno-economic assessment of natural gas displacement potential of biomethane: A case study on domestic energy supply in the UK. *Chem. Eng. Res. Des.* 2018:131:193–213. <https://doi.org/10.1016/J.CHERD.2017.12.022>
- [18] Ghai L., et al. CO₂ utilisation in agricultural greenhouses: A novel 'plant to plant' approach driven by bioenergy with carbon capture systems within the energy, water and food Nexus. *Energy Convers. Manag.* 2021:228:113668. <https://doi.org/10.1016/J.ENCONMAN.2020.113668>
- [19] Latvijas Gāze. Energy of the future – biomethane [Online]. [Accessed 19.01.2023]. Available: <https://lg.lv/en/news/energy-of-the-future-biomethane>
- [20] International Gas Union. Global Renewable & Low-Carbon Gas Report. London: IGU, 2021.
- [21] Shirzadeh B., Quirion P. The importance of renewable gas in achieving carbon-neutrality: Insights from an energy system optimization model. *Energy* 2022:255:124503. <https://doi.org/10.1016/J.ENERGY.2022.124503>
- [22] Keogh N., Corr D., Monaghan R. F. D. Biogenic renewable gas injection into natural gas grids: A review of technical and economic modelling studies. *Renew. Sustain. Energy Rev.* 2022:168:112818. <https://doi.org/10.1016/J.RSER.2022.112818>
- [23] Richards S. J., Al Zaili J. Contribution of encouraging the future use of biomethane to resolving sustainability and energy security challenges: The case of the UK. *Energy Sustain. Dev.* 2020:55:48–55. <https://doi.org/10.1016/J.ESD.2019.12.003>
- [24] Hamelin L., Møller H. B., Jørgensen U. Harnessing the full potential of biomethane towards tomorrow's bioeconomy: A national case study coupling sustainable agricultural intensification, emerging biogas technologies and energy system analysis. *Renew. Sustain. Energy Rev.* 2021:138:110506. <https://doi.org/10.1016/J.RSER.2020.110506>
- [25] Sangannavar P. A., et al. Biomethane: a sustainable bioenergy source from potential waste effluents. *Microbial Resource Technologies for Sustainable Development*. Elsevier, 2022:195–212.
- [26] Latvijas Gāze. Latvijas Gāze includes initiatives for the development of biomethane production in the environmental policy of the company [Online]. [Accessed 18.01.2023]. Available: <https://lg.lv/en/news/latvijas-gaze-includes-initiatives-for-the-development-of-biomethane-production-in-the-environmental-policy-of-the-company>
- [27] Weinrich S., et al. Value of Batch Tests for Biogas Potential Analysis – Method comparison and challenges of substrate and efficiency evaluation of biogas plants. Paris: IEA Bioenergy, 2018.
- [28] Liebetrau J., Pfeiffer D., Thran D. Collection of Methods for Biogas. Methods to determine parameters for analysis purposes and Parameters that describe processes in the biogas sector. Leipzig, 2016.
- [29] Gulayn F., et al. Valorization of digestates from urban or centralized biogas plants: a critical review. *Rev. Environ. Sci. Bio/Technology* 2020:19(2):419–462. <https://doi.org/10.1007/S11157-020-09531-3>
- [30] IEA Bioenergy. Production of food grade sustainable CO₂ from a large biogas facility. Paris: IEA Bioenergy, 2020.
- [31] Ayub A., et al. Amine-grafted mesoporous silica materials for single-stage biogas upgrading to biomethane. *Chem. Eng. J.* 2022:445:136497. <https://doi.org/10.1016/J.CEJ.2022.136497>
- [32] Panwar N. L., Kaushik S. C., Kothari S. Role of renewable energy sources in environmental protection: A review. *Renew. Sustain. Energy Rev.* 2011:15(3):1513–1524. <https://doi.org/10.1016/J.RSER.2010.11.037>
- [33] European Commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy. Brussels: EC, 2011.
- [34] van Hoof J., et al. Taking on tomorrow: The rise of circularity in energy, utilities and resources. London: PWC, 2020.
- [35] Periyasamy S., et al. Wastewater to biogas recovery. *Clean Energy and Resource Recovery*. Elsevier, 2022:301–314.
- [36] Duan I., Rubiera F., Pevida C. Modeling a biogas upgrading PSA unit with a sustainable activated carbon derived from pine sawdust. Sensitivity analysis on the adsorption of CO₂ and CH₄ mixtures. *Chemical Engineering Journal* 2022:428:132564. <https://doi.org/10.1016/j.cej.2021.132564>
- [37] ArcGis. Valsts Zemes Dienesta dati: Pagastu robežas, 2021 (State land service data data: Parish borders, 2021) [Online]. Accessed 19.01.2023]. Available: <https://www.arcgis.com/home/item.html?id=b76d9304b3ca467383e462e5dc945d9b>
- [38] State Environmental Service. Atļauja B kategorijas piesārņojošai darbībai Nr. RE10IB0013 (Permit for category B polluting activity No. RE10IB0013). Rīga: VVD, 2022.

-
- [39] Oehmichen K., *et al.* Technical principles and methodology for calculating GHG balances of Biomethane Guidance document Content. Leipzig: DBFZ, 2016.
- [40] European Commission. Renewable Energy – Recast to 2030 (RED II) [Online]. [Accessed 15.01.2023]. Available: https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en
- [41] Certifications Control Union. SURE - verification scheme – Certifications [Online]. [Accessed 17.01.2023]. Available: <https://certifications.controlunion.com/en/certification-programs/certification-programs/sure-verification-scheme>
- [42] Certifications Control Union. REDcert - Biomass for Energy - Certifications [Online]. [Accessed 17.01.2023]. Available: <https://certifications.controlunion.com/en/certification-programs/certification-programs/redcert-biomass-for-energy>
- [43] Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). *Off. J. Eur. Union* 2018:L328/82.
- [44] REDcert GmbH. Scheme principles for GHG calculation. Scheme principles for GHG calculation consent. Bonn: REDCert, 2021.
- [45] European Commission. Voluntary Schemes [Online]. [Accessed 18.02.2023]. Available: https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/voluntary-schemes_en
- [46] Biograce. The BioGrace-II GHG calculation tool for electricity, heating and cooling. Maryland: Biograce, 2019.
- [47] Communication from the Commission on the practical implementation of the EU biofuels and bioliquids sustainability scheme and on counting rules for biofuels. *Off. J. Eur. Union* 2010:C160/53.
- [48] ISCC. ISCC 201-3 Guidance for the Certification of Biogas and Biomethane. Koln: ISCC, 2017.
- [49] REDcert. REDcert Version 07 System principles for interfaces and suppliers of waste and residual materials. Bonn: REDCert, 2015.

PAPER 9. SUSTAINABILITY ASSESSMENT OF CO₂
VALORISATION ROUTES FOR LATVIA: LCA AND
S-LCA APPROACH

Sustainability Assessment of CO₂ Valorisation Routes for Latvia: LCA and S-LCA Approach

Viktorija TERJANIKA^{1*}, Jelena PUBULE²

^{1,2} *Institute of Energy Systems and Environment, Riga Technical University, Azenes st. 12/1, Riga, LV-1048, Latvia*

Abstract – Current climate change and sustainability challenges require developing innovative methods to reduce carbon dioxide emissions and optimise production processes. Modern technologies make it possible to use CO₂ and life cycle analysis is widely used to evaluate such technologies. Environmental life cycle analysis can show the impact of processes on the environment, while social life cycle analysis evaluates social and economic impacts. Within the framework of this work, two scenarios for using CO₂ were analysed – production of methanol and sustainable fuel (SAF). The analysis aims to assess the potential environmental impacts of CO₂ utilisation and considers the impact on the environment, human health, labour rights, working conditions, social equity, and other social factors, as well as costs and economic sustainability. The scenarios were selected according to the conditions and capabilities of Latvia, as well as to identify the optimal solution for the country to achieve the Green Deal objectives.

Keywords – Carbon Capture and Storage; Carbon Capture and Utilisation; Latvia; Environmental Life Cycle Assessment; Social Life Cycle Assessment; Sustainability

1. INTRODUCTION

The environmental problem of increasing carbon emissions is a serious issue that significantly impacts the planet. Manufacturing processes are producing growing amounts of anthropogenic (i.e., human-made) carbon dioxide, contributing to global warming and other environmental changes, such as unstable temperatures and flooding. According to the IPCC report, it is critical to limit the temperature increase to below 1.5 °C, as the resulting natural changes will otherwise become more severe [1–3]. The need to reduce these emissions is urgent, and effective measures must be taken to mitigate the adverse effects of climate change.

One promising approach is the use of carbon capture and storage (CCS) or, alternatively, carbon capture and utilization (CCU) technologies. These systems capture the carbon dioxide produced by industrial processes before it is released into the atmosphere. In the case of CCS, the captured CO₂ is stored in underground facilities for extended periods, offering a long-term solution [4, 5].

Capturing CO₂ opens a wide range of opportunities – the captured carbon dioxide can be used for enhanced oil recovery, water treatment, or the production of valuable chemicals like urea [6, 7]. Implementing these systems is crucial for reducing greenhouse gas emissions. Furthermore, CCU technologies can support the sustainable development of the economy and industrial sectors [8]. United Nations Framework Convention on Climate Change emphasised the transition away from fossil fuels and the acceleration of carbon capture, utilisation, and storage (CCUS) technologies [9].

However, as Tam et al. [10] 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

* Corresponding author.
E-mail address: Viktorija.terjanika@edu.rtu.lv

The header is left blank

of a product or process provides valuable insights into the environmental effects of planned activities. Life Cycle Assessment (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 [11].

Social Life Cycle Assessment (S-LCA), a complementary method to LCA, focuses on the social dimension – 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 [12]. 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. As noted by Larsen et al. [13], 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. Latvia has reduced its total emissions by 60 % since 1990. However, in 2021, removals decreased by 119 % compared to 1990, highlighting a concerning trend. Therefore, solutions such as CCU must be further explored and assessed in order to achieve climate neutrality goals.

The source and composition of CO₂ emissions in Latvia highlight the energy production sector as the primary area for the application of CCU technologies. The largest emitter of CO₂ is heat production plants, which in 2022 produced 24.2 % of total CO₂eq emissions in Energy sector [14] (Fig. 1).

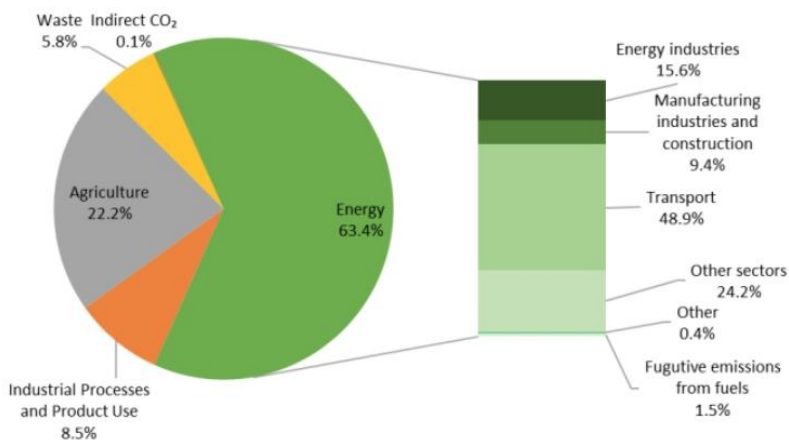


Fig. 1. CO₂ emissions in Latvia, 2022 [14]

In line with climate neutrality goals, decarbonisation strategies have been developed and assessed for Latvia. These include identifying regional CO₂ “value spots” – areas where carbon dioxide can be directly utilised (e.g., in CO₂-based product development) to create high-added-value outputs. This approach supports the decarbonisation of rural areas while simultaneously promoting regional economic growth [15, 16]. Two scenarios for CO₂ 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 research 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 [17] emphasises the need to establish new pathways for CO₂ valorisation and the creation of carbon-based materials. It highlights promising advancements in photoelectrochemical conversion of CO₂ into selective gaseous products (such as methane) and liquid fuels (such as methanol and ethanol). The report also stresses the importance of conducting Life Cycle Assessments (LCA) of CCUS options to evaluate their overall impacts. Currently, there is a lack of comprehensive sustainability assessments – especially those based on LCA and Social LCA (S-LCA) – that compare various decarbonisation scenarios at national or regional levels.

Based on the conclusions of the literature review, this research aims to evaluate the sustainability aspects of two CO₂ utilisation scenarios – methanol and sustainable aviation fuel (SAF) ethanol production – in the context of Latvia. The sustainability assessment will address potential environmental impacts of CO₂ use, as well as effects on human health, labour rights, working conditions, social equity, economic viability, and other key social and economic factors.

2. METHODOLOGY

2.1. Description of Scenarios

– Scenario 1 – Methanol production

CO₂ 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 [18]. The use of CO₂ in methanol production (as a CCU application) represents a relatively mature technology [19–21]. While methanol has traditionally been produced from natural gas, using CO₂ as a feedstock offers significant advantages, including the potential to reduce the overall carbon footprint of the process.

One approach to CO₂ utilisation involves combining captured CO₂ 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 CO₂, which, after capture, is converted into syngas via the reverse water-gas shift (RWGS) reaction [18, 22, 23]. The resulting syngas is then reacted with additional hydrogen to produce methanol.

Several catalytic technologies exist for this conversion. These include systems such as the Cu/ZnO/Al₂O₃ catalyst and the Haldor Topsoe catalyst, both of which have been successfully demonstrated at pilot and commercial scales [24–26]. In the context of this work, the focus is on methanol production from a combination of biogas and CO₂.

The project “*Creating added-value chemicals from bio-industrial CO₂ emissions using integrated catalytic technologies*” [27] highlights that converting CO₂ 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 CO₂ conversion to renewable methanol through innovative heterogeneous catalyst systems optimised for advanced hydrogenation technologies (microwave, plasma, and magnetic induction)*” [28] aims to develop hydrogenation-based methods for converting CO₂ into renewable methanol.

Currently, Latvia imports all of its fuel, making energy security a critical concern. Establishing domestic methanol production from CO₂ could enhance the country’s energy independence,

The header is left blank

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

CO₂ can be utilised to produce sustainable fuels like ethanol, which can significantly reduce emissions from the transport sector [29]. 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 CO₂ straight from the atmosphere, making a direct contribution to reducing carbon dioxide emissions. Sustainable fuel production typically involves the electrolysis of water to produce hydrogen, which is then combined with CO₂ through the Fischer–Tropsch synthesis process. Another approach involves using methanol as an intermediate, starting with the hydrogenation of CO₂ 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 [30–38]. Although the conversion of CO₂ into ethanol offers environmental advantages, the process is energy-intensive [34, 39].

2.2. Sustainability Assessment

Environmental Life Cycle Assessment (LCA) 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 (S-LCA) 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 [13].

S-LCA observes 25 sub-indicators within five main categories, following the UNEP/SETAC Guidelines [12, 40–43]:

1. Labor rights & Decent work – Working hours, child labor, forced labor, etc;
2. Health & Safety – Occupational injuries, exposure to hazards;
3. Society – Contribution to economic development, local employment;
4. Governance – Corruption prevention, transparency, and legal compliance;
5. 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 [41–43].

For each sub-indicator, we applied weighting factors from the SHDB and aggregated the results at the category and scenario level using the ReCiPe Endpoint method [41–43].

Normalization 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 [44, 45]. This methodology includes four key phases:

- Goal and Scope Definition;
- Life Cycle Inventory (LCI) Analysis;
- Life Cycle Impact Assessment (LCIA);

The header is left blank

- Interpretation.

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

- Scenario 1: CO₂ utilisation for the production of methanol;
- Scenario 2: CO₂ utilisation for the production of sustainable aviation fuel (SAF-ethanol).

The Functional Unit (FU) chosen for both scenarios is 1kg of CO₂ treated in each respective scenario.

2.2.1. Goal and Scope

The goal of conducting a Life Cycle Assessment (LCA) of CO₂ utilisation in fuel production is to evaluate the social and environmental impacts associated with the production, use, and disposal of CO₂ in two scenarios: methanol production in biogas facilities and Sustainable Aviation Fuel (SAF-ethanol) production. Both the Environmental LCA (E-LCA) and Social LCA (S-LCA) aim to analyse all life cycle stages of CO₂ 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:

1. Identification of relevant social and environmental issues related to CO₂ utilisation in methanol and SAF-ethanol production scenarios;
2. Assessment of potential impacts, both positive and negative, associated with CO₂ utilisation in each scenario;
3. Recommendations for improving the social and environmental sustainability of CO₂ utilisation based on the analysis outcomes.

Both assessments adopt a gate-to-gate approach, focusing on the impacts directly associated with the CO₂ 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 [46–50].

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 CO₂ utilisation in Latvia. However, due to regional similarities in CO₂ 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.

2.2.2. Inventory and Boundary Analysis

- 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.

The header is left blank

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 1.

TABLE 1. AVERAGE TOTAL COSTS AND INVENTORY OF METHANOL PRODUCTION

Average Total Costs (S-LCA) [51]		Inventory (E-LCA) [30, 52–56]	
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 ₂ O/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

The boundaries of methanol production scenario are shown below:

The header is left blank

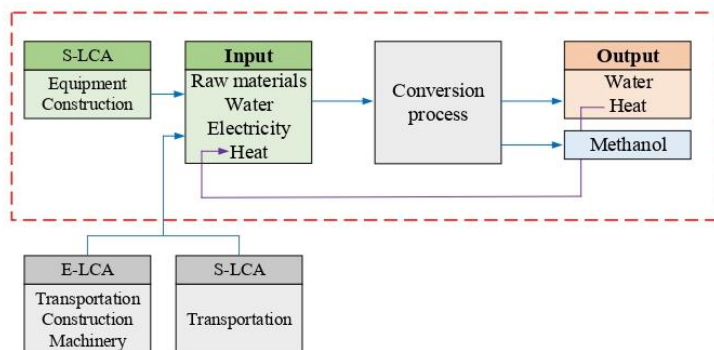


Fig. 2. Boundaries of methanol production scenario

- Scenario 2 – SAF-ethanol production:

Input materials:

- S-LCA: construction materials, mechanical and electrical equipment.
- E-LCA: CO₂ (supplied externally), enzymes, potassium carbonate, ammonium chloride, electricity, and water.

Production process: SAF is produced from CO₂ and H₂O via chain of reactions – direct synthesis of hydrocarbon from CO₂, purification, conversion, separation, oligomerisation and hydrogenation.

Output products: Ethanol.

System boundaries:

- Excluded from the analysis:
 - S-LCA and E-LCA: prior purification of CO₂, transportation of raw materials and final products to end-users.
 - CO₂ 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 2.

TABLE 2. AVERAGE TOTAL COSTS AND INVENTORY OF SAF-ETHANOL PLANT CONSTRUCTION

Inventory of SAF-ethanol (S-LCA) [57]		Inventory (E-LCA) [30–33, 58–61]	
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	0.447
Utilities and materials		Catalyst, kg	0.114
Electricity, M €/y	24.3		

The header is left blank

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
Deionized water, M €/y	0.9
Ammonium chloride, M €/y	2.05
SAF_ethanol production, t/y	34393
Plant lifetime, y	30
Working days	360

The boundaries of SAF-ethanol production scenario are shown below:

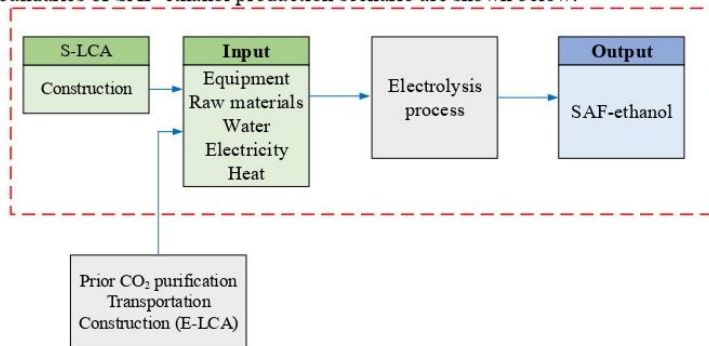


Fig. 3. Boundaries of SAF-ethanol production scenario

3. RESULTS

This study carried out a Social and Environmental Life Cycle Analysis (S-LCA and LCA) of two scenarios for carbon dioxide utilisation: methanol production and SAF-ethanol production.

3.1. Social Life Cycle Analysis

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. 4).

The header is left blank

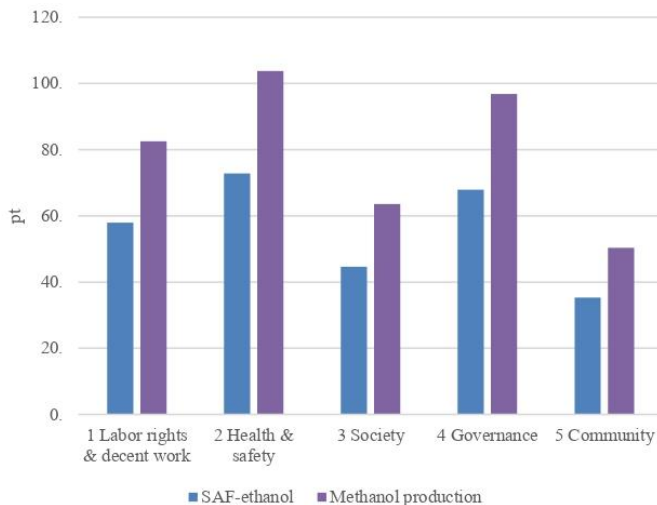


Fig. 4. Assessment by main categories, global annual per capita, weighted

Both methanol and ethanol production processes require the use of 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 [62], wages in the manufacturing sector in Latvia were among the lowest in the European Union in 2022.

The header is left blank

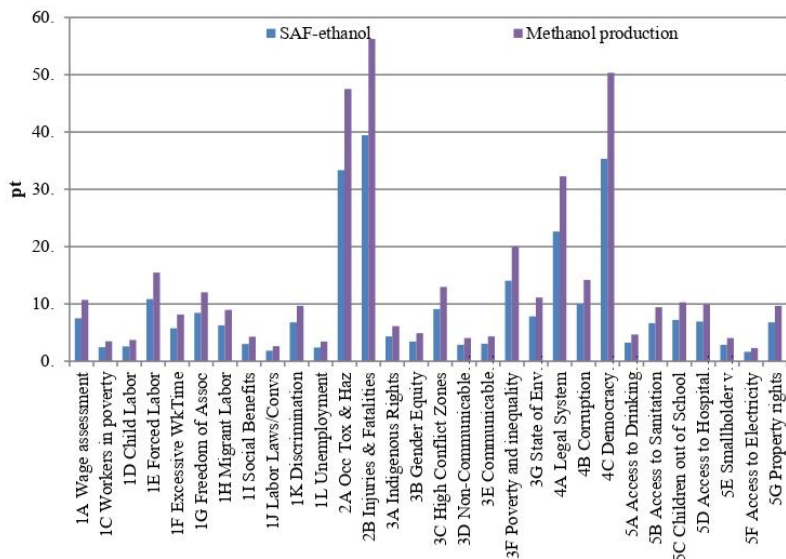


Fig. 5. Assessment by sub-categories, global annual per capita, weighted

Considering the weighted average indicators of the peak subcategories separately (Fig. 5 and Table 3) according to the scenarios, the following conclusions can be drawn:

- 2A and 2B – 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 [63].
- 4C – Democracy and Freedom of Speech: This indicator uses data from the World Economic Forum [64], 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.

The header is left blank

TABLE 3. COMPARISON OF 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)

3.1.1. 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 [52, 64, 65]. 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 usage (Fig. 6).

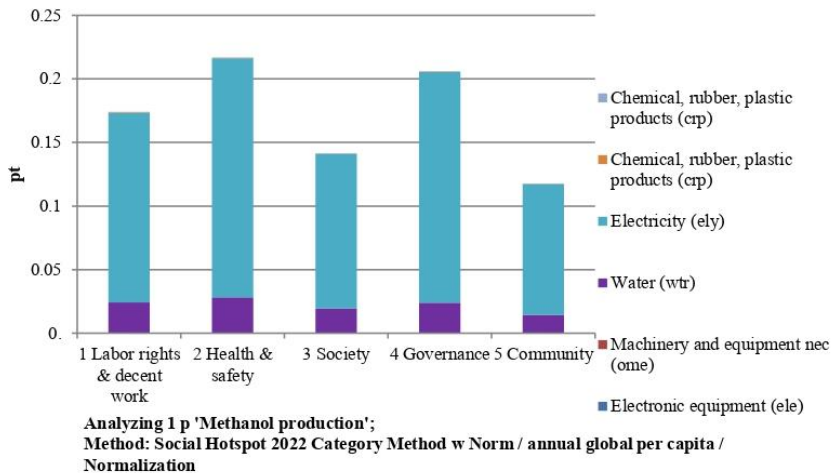


Fig. 6. Methanol production by social categories (without construction), global annual per capita

3.1.2. 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

The header is left blank

external providers, and CO₂ 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 [66, 67]. 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. 7, their effects on other categories remain relatively consistent.

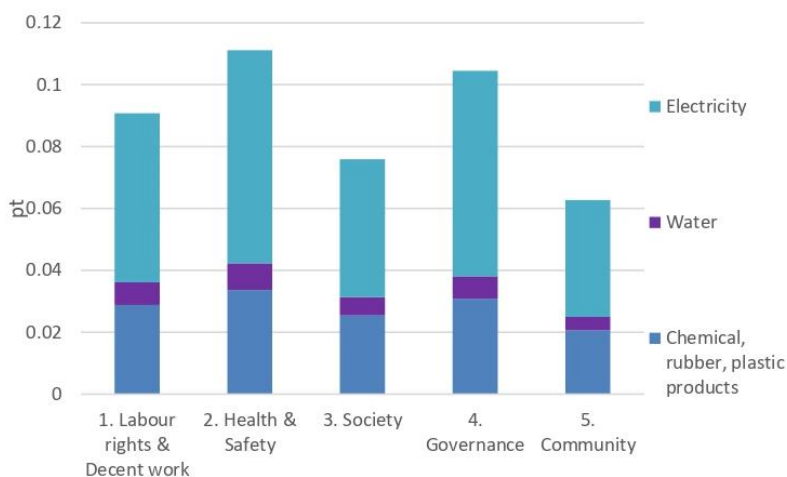


Fig. 7. SAF-ethanol by social categories, global annual per capita

3.2. Environmental Life Cycle Analysis

The Environmental Life Cycle results for both scenarios show that both have a significant impact on global warming, with methanol production having a greater effect in this category. During the production of methanol and SAF-ethanol, a certain amount of SO₂, NO_x, and other emissions are produced, negatively affecting the environment. The Fine Particulate Matter Formation and Terrestrial Acidification categories are also affected.

3.2.1. 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, SO₂ and NMVOC), which potentially can further oxidise to CO₂ in the atmosphere [68]. Additionally, the production and use 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. 8).

3.2.2. 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. 8).

The header is left blank

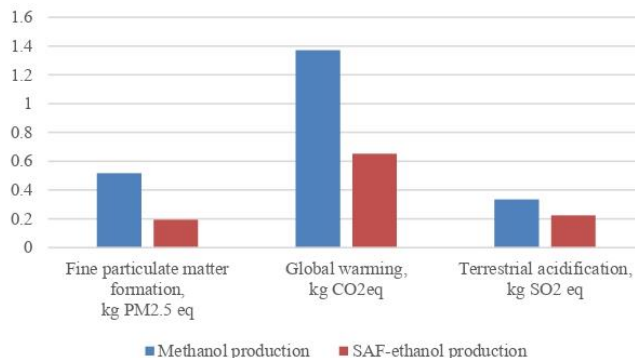


Fig. 8. E-LCA of Methanol and SAF-ethanol scenarios

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 CO₂ emissions and fuel production [30–33, 60].

4. DISCUSSION AND CONCLUSION

CCUS (Carbon Capture, Utilisation, and Storage) holds significant potential for mitigating CO₂ emissions in the industrial sector. However, the number of studies addressing the sustainability, environmental, and social impacts of CCUS remains limited. This is primarily due to the relatively small number of CCUS installations on an industrial scale. Failures to deliver full-scale projects have often been attributed to a lack of public acceptance [17]. The development of CCU projects is complex and influenced by various factors, including financial resources, local community acceptance, stakeholder engagement, economic feasibility, and sustainability considerations.

This study presents an Environmental and Social Life Cycle Analysis of two CO₂ utilisation scenarios: methanol production and ethanol production. This is the first research of its kind in Latvia or its neighbouring countries, such as Estonia or Lithuania.

The methanol production scenario yielded the higher environmental impact in the Life Cycle Analysis, which can be attributed to the volatile emissions produced during the process. Both methanol and ethanol production rely on high-tech equipment, with renewable biomass and emissions from other industries being their primary resources. At this stage, SAF-ethanol production is energy-intensive, but with advancements in technology, energy consumption will decrease, making production more sustainable across all categories. New catalyst and reagents development will promote development of the technology and decrease negative impact on the environmental indicators.

Currently, Latvia does not produce enough energy to support uninterrupted production of SAF-ethanol and methanol directly from CO₂ or with a significant CO₂ resource content. Building a CO₂-utilising SAF-ethanol or methanol production facility from scratch would also present significant challenges. However, Latvia already operates several biogas stations that could be converted to methanol production and CO₂ utilisation if properly equipped and modernised. These existing biogas stations would bypass the "Construction" stage, which

would significantly reduce the overall social impact, resulting in better social outcomes. Introduction of CCU technologies into energy sector would create new jobs, improve the technological capacity of the sector, diversify the national energy mix, and contribute to achieving the Green Deal's CO₂ reduction goals.

Applying Environmental and Social Life Cycle Analyses in the Latvian context helps strike a balance between the social and environmental aspects of the two scenarios. However, further analysis is needed, considering a wider range of technologies, their availability, and the practical feasibility of their implementation in Latvia.

REFERENCES

- [1] Ameer B. H., et al. When did global warming start? A new baseline for carbon budgeting. *Economic Modelling* 2022;116:106005. <https://doi.org/10.1016/j.econmod.2022.106005>
- [2] COP26. The Glasgow Climate Pact. UN Climate Change Conference, United Kingdom, 2021.
- [3] McKinsey & Company. Global Energy Perspective 2023: CCUS outlook. [Online]. [Accessed 17.09.2024]. Available: <https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-ccus-outlook/>
- [4] European Commission. Carbon Capture, utilisation and storage [Online]. [Accessed 15.04.2025]. Available: https://joint-research-centre.ec.europa.eu/projects-and-activities/carbon-capture-utilisation-and-storage_en
- [5] Dahl C. A., Wang J., Sun C. Economic enablement of carbon capture and storage for the low carbon energy transition. Chapter 2. Geophysics and the Energy Transition. Elsevier, 2025:15–83.
- [6] Hu Y., Wu W. Can fossil energy make a soft landing – the carbon-neutral pathway in China accompanying CCS. *Energy Policy* 2023;174:113440. <https://doi.org/10.1016/j.enpol.2023.113440>
- [7] Peres C. B., et al. Advances in Carbon Capture and use (CCU) Technologies: A Comprehensive Review and CO₂ Mitigation Potential Analysis. *Cleaner Technology* 2022;4:1193–1207. <https://doi.org/10.3390/cleantechnol4040073>
- [8] Jarnefelt V. The potential of the CCU technologies in mitigating the climate change. [Online]. [Accessed 13.11.2024]. Available: <https://www.vtresearch.com/en/news-and-ideas/potential-ccu-technologies-mitigating-climate-change>
- [9] UN Climate Change Conference – United Arab Emirates. [Online]. [Accessed 20.12.2024]. Available: [UN Climate Change Conference - United Arab Emirates | UNFCCC](https://unfccc.int/news/un-climate-change-conference-united-arab-emirates)
- [10] Tam V. W. Y., et al. Optimal BIM and LCA integration approach for embodied environmental impact assessment. *Journal of Cleaner Production* 2023;385:135605. <https://doi.org/10.1016/j.jclepro.2022.135605>
- [11] Life Cycle Initiative. Environmental LCA. [Online]. [Accessed 13.11.2024]. Available: <https://www.lifecycleinitiative.org/starting-life-cycle-thinking/life-cycle-approaches/environmental-lca/#:~:text=E%2DLCA%20is%20a%20time,are%20quantified%20throughout%20all%20stages>
- [12] Liu Y., et al. Connection, deviation, patterns, and trends: Visualizing the interplay of sustainability science and social–ecological system research. *Journal of Cleaner Production* 2025;504:145431. <https://doi.org/10.1016/j.jclepro.2025.145431>
- [13] Larsen V. G., et al. What are the challenges in assessing circular economy for the built environment? A literature review on integrating LCA, LCC and S-LCA in life cycle sustainability assessment, LCSA. *Journal of Building Engineering* 2022;50:104203. <https://doi.org/10.1016/j.jobe.2022.104203>
- [14] Skrebele A., et al. Latvia's National Inventory Report under the UNFCCC. Riga: MCaE, 2024.
- [15] Terjanika V., et al. Analysis of CO₂ Valorisation Options for Regional Development. *Environmental and Climate Technologies* 2021;25:243–253. <https://doi.org/10.2478/rtuct-2021-0017>
- [16] Terjanika V., Pubule J. Barriers and Driving Factors for Sustainable Development of CO₂ Valorisation. *Sustainability* 2022;14:5054. <https://doi.org/10.3390/su14095054>
- [17] Itul A., et al. Clean Energy Technology Observatory: Carbon capture utilisation and storage in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets. Publications Office of the European Union, Luxembourg, 2023.
- [18] Khojasteh-Salkuyeh Y., et al. CO₂ utilization for methanol production; Part I: Process design and life cycle GHG assessment of different pathways. *Journal of CO₂ Utilization* 2021;50:101608. <https://doi.org/10.1016/j.jcou.2021.101608>
- [19] Morimoto S., et al. Scenario assessment for producing methanol through carbon capture and utilization technologies considering regional characteristics. *Journal of CO₂ Utilization* 2021;45:101452. <https://doi.org/10.1016/j.jcou.2021.101452>
- [20] Guo J., et al. Integrated system utilizing methanol steam reforming process for hydrogen production combined with methane-hydrogen gas turbine multi-cascade generation. *Applied Thermal Engineering* 2025;271:126324. <https://doi.org/10.1016/j.applthermaleng.2025.126324>
- [21] Ren B. P., et al. Methanol production from natural gas reforming and CO₂ capturing process, simulation, design, and technical-economic analysis. *Energy* 2023;263(C):125879. <https://doi.org/10.1016/j.energy.2022.125879>

The header is left blank

- [22] Nouri A., Tohidi F., Chitsaz A. Integration of biomass gasification and MEA-based CO₂ capture for sustainable power and methanol production: Energy, exergy, and economic analysis and optimization. *Energy* 2025:319:135062. <https://doi.org/10.1016/j.energy.2025.135062>
- [23] Ugwu A., et al. Carbon Capture Utilization and Storage in Methanol Production Using a Dry Reforming-Based Chemical Looping Technology. *Energy & Fuels* 2022:36(17):9719–9735. <https://doi.org/10.1021/acs.energyfuels.2c00620>
- [24] Yusuf N., Almomani F. Highly effective hydrogenation of CO₂ to methanol over Cu/ZnO/Al₂O₃ catalyst: A process economy & environmental aspects. *Fuel* 2023:332(1):126027. <https://doi.org/10.1016/j.fuel.2022.126027>
- [25] Carbon Recycling. World's largest CO₂-to-methanol plant starts production. [Online]. [Accessed 13.11.2024]. Available: <https://www.carbonrecycling.is/news-media/worlds-largest-co2-to-methanol-plant-starts-production>
- [26] TOPSOE. TOPSOE to build demonstration plant to produce cost-competitive CO₂-neutral methanol from biogas and green electricity. [Online]. [Accessed 13.11.2023]. Available: <https://www.topsoe.com/blog/topsoe-to-build-demonstration-plant-to-produce-cost-competitive-co2-neutral-methanol-from-biogas-and-green-electricity>
- [27] Cordis. EU bio-based industry catalysed for zero carbon emissions. [Online]. [Accessed 13.11.2024]. Available: <https://cordis.europa.eu/project/id/101000580>
- [28] Cordis. CO₂ hydrogenation for methanol as a renewable fuel. [Online]. [Accessed 13.11.2024]. Available: <https://cordis.europa.eu/project/id/101022507>
- [29] Seber G., et al. Uncertainty in life cycle greenhouse gas emissions of sustainable aviation fuels from vegetable oils. *Renewable and Sustainable Energy Reviews* 2022:170:112945. <https://doi.org/10.1016/j.rser.2022.112945>
- [30] Ramos-Fernandez E., et al. Potential pathways for CO₂ utilization in sustainable aviation fuel synthesis. *Chemical Science* 2025:2. <https://doi.org/10.1039/D4SC06164K>
- [31] Jiang Y., et al. Recent advances in thermocatalytic hydrogenation of carbon dioxide to light olefins and liquid fuels via modified Fischer-Tropsch pathway. *Journal of CO₂ Utilization* 2023:67:102321. <https://doi.org/10.1016/j.jcou.2022.102321>
- [32] He S., et al. Remarkably enhanced catalytic performance of three-dimensional hierarchically porous Mo₂C catalysts for higher alcohols synthesis from syngas. *Molecular Catalysis* 2024:556:113941. <https://doi.org/10.1016/j.mcat.2024.113941>
- [33] Suppiah D. D. Supported Metal Oxide Catalysts for CO₂ Fischer-Tropsch Conversion to Liquid Fuels-A Review. *Energy & Fuels* 2021:35(21):17261–17278. <https://doi.org/10.1021/acs.energyfuels.1c02406>
- [34] Nordic Electrofuel. Clean at scale. Decarbonizing aviation – making flying sustainable. [Online]. [Accessed 13.11.2024]. Available: <https://nordicelectrofuel.no/>
- [35] Karekar S. C., et al. Assessing feasible H₂-CO₂ sources in the US as Feedstocks for Sustainable Aviation Fuel Precursors: Acetic Acid and Ethanol Production via Hydrogenotrophic Pathways. *Journal of Environmental Management* 2023:345:118641. <https://doi.org/10.1016/j.jenvman.2023.118641>
- [36] Pio D. T., et al. Decarbonizing the aviation sector with Electro Sustainable Aviation Fuel (eSAF) from biogenic CO₂ captured at pulp mills. *Chemical Engineering Journal* 2023:463:142317. <https://doi.org/10.1016/j.cej.2023.142317>
- [37] Collis J., Duch K., Schomäcker R. Techno-economic assessment of jet fuel production using the Fischer-Tropsch process from steel mill gas. *Frontiers in Energy Research* 2022:10:1049229. <https://doi.org/10.3389/fenrg.2022.1049229>
- [38] Bernardi A., et al. Enviro-economic assessment of sustainable aviation fuel production from direct CO₂ hydrogenation. *Computer Aided Chemical Engineering*. Elsevier, 2023:52:2345–2350.
- [39] Collins L. The amount of energy required by direct air carbon capture proves it is an exercise in futility. [Online]. [Accessed 13.11.2024]. Available: <https://www.rechargenews.com/energy-transition/the-amount-of-energy-required-by-direct-air-carbon-capture-proves-it-is-an-exercise-in-futility/2-1-1067588>
- [40] Sala S., et al. Social Life Cycle Assessment – State of the art and challenges; for supporting product policies. Publications Office of the European Union, Luxembourg, 2016.
- [41] Akhtar M. S., et al. Green hydrogen and sustainable development – A social LCA perspective highlighting social hotspots and geopolitical implications of the future hydrogen economy. *Journal of Cleaner Production* 2023:395:136438. <https://doi.org/10.1016/j.jclepro.2023.136438>
- [42] Roche L., Holzapfel P., Finkbeiner M. Primary data share indicator for social life cycle assessment. *Journal of Cleaner Production* 2025:497:145051. <https://doi.org/10.1016/j.jclepro.2025.145051>
- [43] Subasi A., et al. Weighting factors for LCA—a new set from a global survey. *LCI Methodology and Databases* 2024:29:2107-2136. <https://doi.org/10.1007/s11367-024-02330-w>
- [44] International Organization for Standardization. ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines. Geneva: ISO, 2006.
- [45] International Organization for Standardization. ISO 14040 Environmental management – Life cycle assessment – Principles and framework. Geneva: ISO, 2006.
- [46] OpenLCA Nexus [Online]. [Accessed 01.05.2025]. Available: <https://hexus.openlca.org/>
- [47] SimaPro database. [Online]. [Accessed 01.10.2024]. Available: <https://simapro.com/>
- [48] SimaPro Ecoinvent database. [Online]. [Accessed 01.10.2024]. Available: <https://simapro.com/products/ecoinvent/>
- [49] Social Hotspot database. [Online]. [Accessed 01.10.2024]. Available: <http://www.socialhotspot.org/>
- [50] Database & Support team at PRÉ Sustainability. SimaPro database manual. PRÉ Sustainability, 2024.

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 (<i>5-stage preheater+Precliner = Best Available Technology</i>) (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 CO ₂	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	–	

Continuation of Table 1A

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)	tCO ₂ 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	

Continuation of Table 1A

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 <u>recycle</u> 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 ₂ eq/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 ₂ eq/1t of final product	92.2 tCO ₂ /MWh 4tCO ₂ /t Methanol Closed photobioreactor: 21 kgCO ₂ /m ² /a Raceway pond: 6 kgCO ₂ /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 ₂ eq/MBTU =29.28 tCO ₂ eq/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 ₂ eq 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), (Avidiushchenko & 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 <u>capture and treat</u> 1 tonne of CO ₂ EUR/tCO ₂	–
31	Total costs of CO ₂ utilisation	Money spent to <u>utilise</u> 1 tonne of CO ₂ EUR/tCO ₂ utilised	–

Continuation of Table 3A

32	Total costs for CO ₂ if doing nothing	Costs for 1 tonne produced CO ₂ in case if <u>no capture and treatment</u> 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 ₂ converted/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 ₂ conv.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

Continuation of Table 4A

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 ₂ O	-
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)

Continuation of Table 4A

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 % – Pozzolan 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 <i>Cluster West portfolio cement</i> (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 ₂ FeH ₆ (Grasso et al., 2019)
Biomethane		H ₂ :CO ₂ = 4:1	<p>Biogas: 5.82 Pa CO₂ pressure</p> <p>Biogas to biomethane by modifying anaerobic fermentation: 100 bar (Merkle et al., 2017) CO₂ conversion to methane: H₂:CO₂=4:1 If ex-situ: 800 rpm (agitation rate); 37–55 °C (55 - optimal); recirculation input flow 1.75-2.25 (Zabranska & Pokorna, 2018)</p>	<p>Biogas: Methanogenic algae; Acetotrophic methanogens; Methylotrophic methanogens; Homoacetogenic microorganisms; catalysts</p> <p>Biogas to biomethane by CO₂ conversion: H₂ (Zabranska & Pokorna, 2018)</p>

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 ₃ OH unit; 0.1892 kg pure H ₂ per CH ₃ OH unit; 0.2126 kg wet H ₂ per CH ₃ OH unit (Kiss et al., 2016)	Working conditions 200–300 °C; 15–55 bar	99.83 % CH ₄ ; Cl+H ₂ ; Cu/ZnO/Al ₂ O 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

CO₂ production technology

Technology	CO ₂	Process description	Advantages	Disadvantages																				
Beverage carbonation	<p>5g CO₂ per 1 beer litre The required purity of food CO₂ – 98.8 %</p> <p>The output of CO₂ is 95.5 % by weight of alcohol, 51.3 % by weight of sucrose and 54.2 % by weight of starch.</p> <p>Standard parameters of CO₂ content for brands: for stout: 30 % CO₂; for lager with N₂: 50 % CO₂; for regular lager: 60 % CO₂; for heavily carbonated products: 70 % CO₂. (1L of beer ≈ 1.056 kg)</p>	<p>Saturation with CO₂ under high pressure</p> <p>Forced carbonation is carried out at the final stage of industrial production. CO₂ is passed through the containers with the finished beer several times under pressure..</p> <p>The optimum carbonation content is 2.2–2.6 volumes. This is ~5g CO₂/L of beer; it takes ~100g CO₂ for 20-liter keg.</p>	<p>The purer CO₂ is injected, the less O₂ is needed (CO₂:O₂), (Aqua Analytics, 2020)(Modern Brewhouse, 2018)</p> <table border="1"> <thead> <tr> <th></th> <th colspan="3">O₂ concentration, %</th> </tr> </thead> <tbody> <tr> <td>V/V CO₂</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> </tbody> </table> <p>Breweries are sources from which pure CO₂ can be produced without special equipment to increase its concentration:</p> <ul style="list-style-type: none"> gases of alcoholic fermentation at breweries, alcohol and hydrolysis plants with 98-99% CO₂ output <p>depending on the type of raw material used, different CO₂ output per ton (potatoes – 62 kg CO₂ per 1 ton of raw materials, molasses – 117 kg, grain – 171 kg)</p>		O ₂ concentration, %			V/V CO ₂	0.001	0.005	0.02	0.5	7 ppb	35 ppb	142 ppb	1.0	14 ppb	71 ppb	284 ppb	2.0	28 ppb	142 ppb	567 ppb	<p>No equilibrium in this process, since the total gas pressure must exceed the pressure at which the desired CO₂ concentration is provided, and as the bubbles of CO₂ dissolve, the partial pressure of oxygen can reach high levels.</p>
				O ₂ concentration, %																				
V/V CO ₂	0.001	0.005	0.02																					
0.5	7 ppb	35 ppb	142 ppb																					
1.0	14 ppb	71 ppb	284 ppb																					
2.0	28 ppb	142 ppb	567 ppb																					

Continuation of Table 6A

<p>Liquid CO₂ production (AC Group, 2018), (Harald et al., 2002)</p>		<p>In distilleries, liquid CO₂ is produced according to the principle of gas liquefaction using moderate cold.</p> <p>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 CO₂ 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.</p> <p>To generate 1t liquid CO₂ from fermentation gases, 190 kWh of electricity is consumed, and at specialized CO₂ plants - 175 kWh of electricity, 750–850 kg of anthracite and 7 kg of scarce monoethanolamine.</p>		<p>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 CO₂.</p>
---	--	--	--	---

Continuation of Table 6A

<p>Solid CO₂ production (K. Wei et al., 2022), (NETL, 2023)</p>	<p>The production of 1 kg of dry ice requires 1.6–2.0 kg of liquid CO₂</p>	<p>Liquid CO₂ 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 CO₂ is extracted via a heat exchanger by a high-pressure compressor.</p> <p>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 CO₂ is extracted via a heat exchanger by the compressor, while subcooled liquid CO₂ enters the ice makers.</p> <p>Liquid CO₂ loses pressure, reaching the triple point (0.528 MPa) and solidifying. Solid CO₂ 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.</p>	<p>When liquefied, it gives CO₂ of 100 % purity Does not require high pressure containers when transporting, therefore, the cost of transportation is much lower</p>	<p>Steel cylinders for liquid CO₂ require constant technical supervision and systematic repairs to maintain them in a working and safe condition.</p> <p>for storing dry ice, need to create hermetically sealed, buried storage facilities with solid reliable insulation up to 300 mm thick.</p>
--	---	---	---	---

Continuation of Table 6A

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 CO ₂ 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 disinfection, 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 CO₂ utilisation

Acronym	Field	CO ₂ role	Data
GRAMOFON (Gramofon, 2016)	Carbon capture / Gas purification	CO ₂ capture 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 ₂ S – 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 ₂ purity 40 ppm – H ₂ S 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 ₂ laser	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

Continuation of Table 7A

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 – Furfic 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

<p>VALUEMAG (ValueMag, 2017)</p>	<p>Biorafinery</p>	<p>Parameter for algae; supercritical CO₂ extraction</p>	<p>35t algae/year – alga cultivation rate 0.3 EUR/kg biomass – price (4.9–6 EUR/kg – conventional price) 0.1 L/kg – water consumption 750 kW/day – energy consumption 7954 kg B-carotene / 9087 t biomass – Bcarotene yield from biomass 3158 kg B-carotene / 4358 t carrots – B-carotene yield from carrots 1096 kg B-carotene / 4095 t peaches – B-carotene 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-carotene cost (growth and extraction) 400 EUR/kg – w3 cost (G.+ex) PILOT SCALE: (b-carotene for D.salina biomass) 0.308 kgCO₂/min – CO₂ flow rate 1528.0 gCO₂/gr biomass – CO₂ and biomass ratio PILOT SCALE: (b-carotene for N.gaditiana biomass) 0.35 kg CO₂/min – CO₂ flow rate 2228.8 g CO₂/gr biomass – CO₂ and biomass ratio ESTIMATED COST: (based on energetical calculation for extraction b-carotene from microalgae biomass) 6.75 EUR/kg dry – Lyophilization (pre-treatment stage) 29.86 EUR/kg dry – CO₂-SFE extraction stage 36.61 EUR/kg dry – Total cost</p>
--------------------------------------	--------------------	---	--

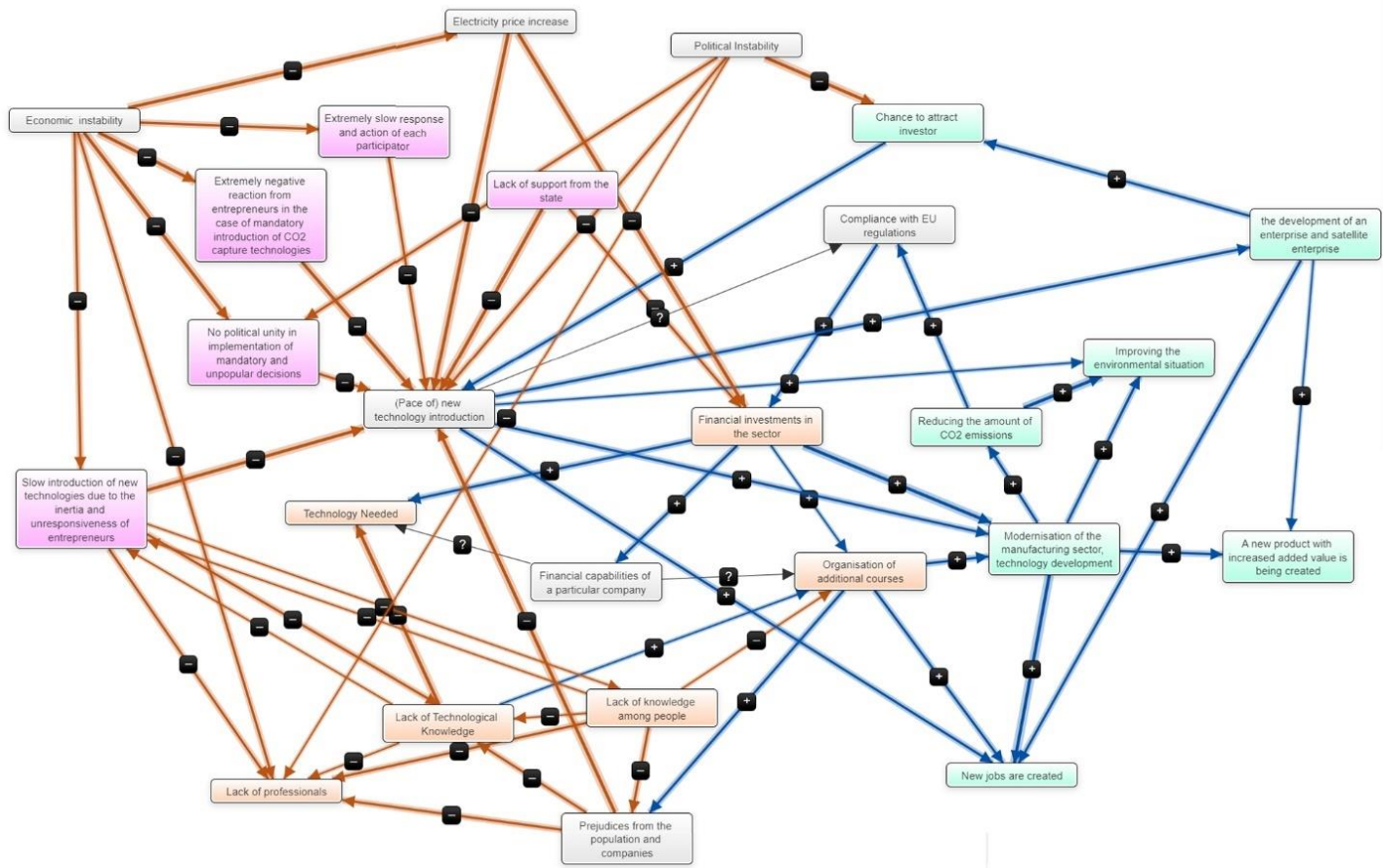
Continuation of Table 7A

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 – biobutanol 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
MefCO ₂ (MefCO ₂ , 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

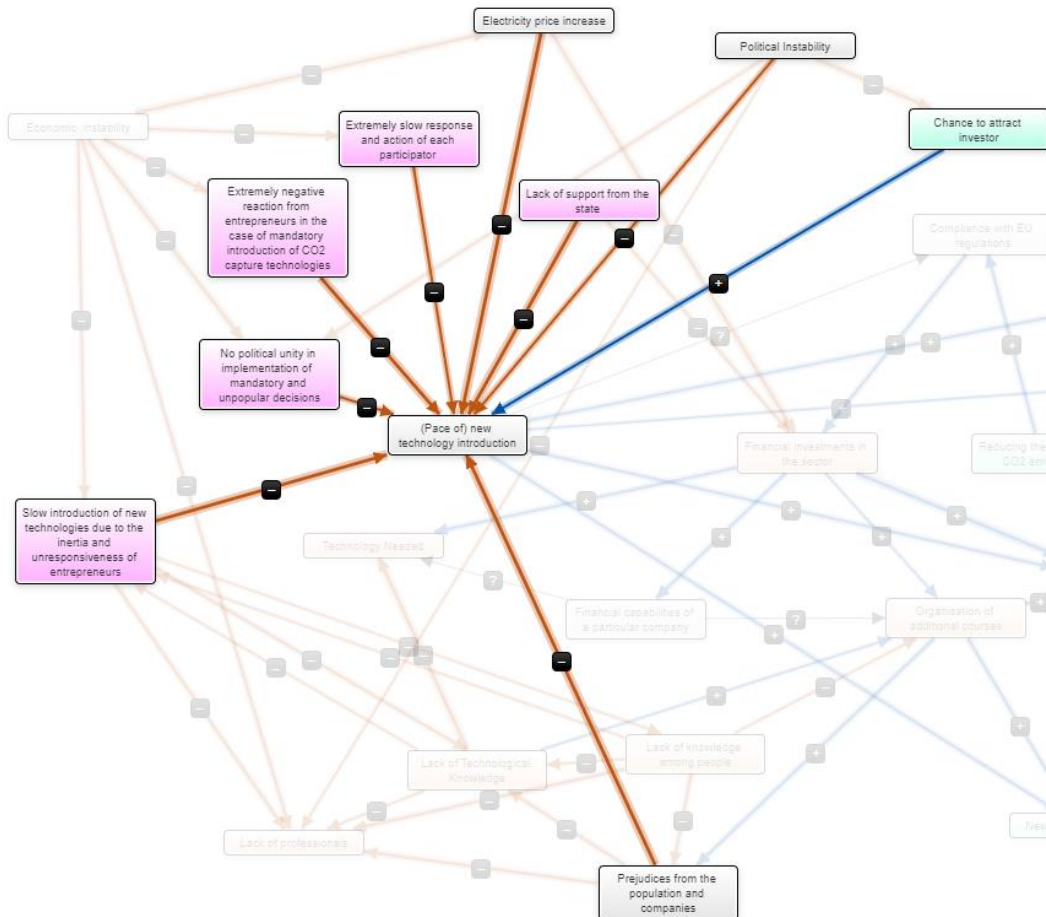
Continuation of Table 7A

MetaFuel (MetaFuel, 2015)	Fuel industry	Feedstock for methanol production	5 tCO ₂ /year – emission
ELECTHANE (Electthane, 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
CIRCLEENERGY (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

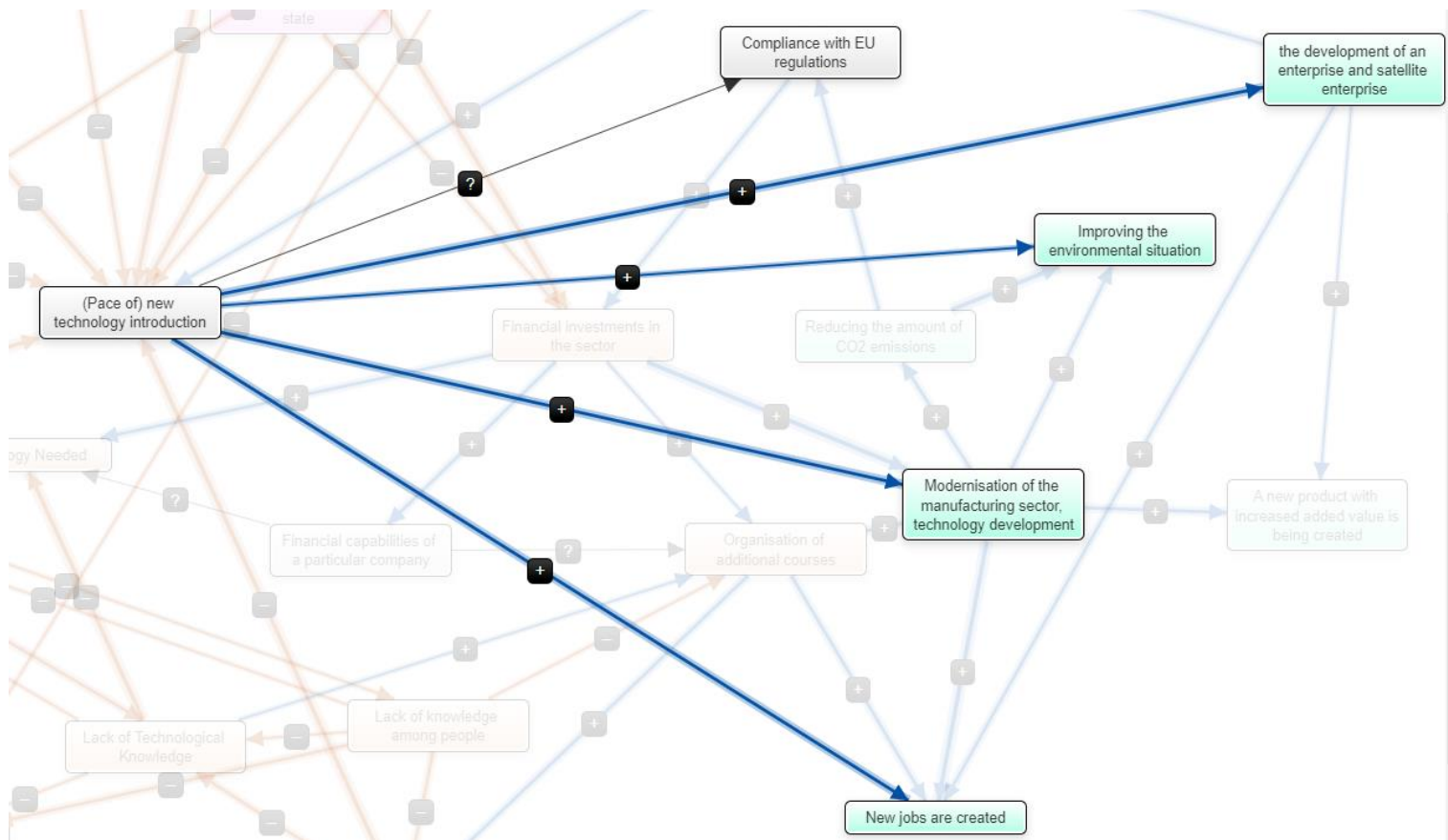
			<p>TO PRODUCE 1 t OF HYDROTALCITE:</p> <p>1.4 MWh/1 t product – electricity consumption</p> <p>3.56 /1t product – Natural gas consumption</p> <p>46 m³/1t product – water consumption</p> <p>0.66 t/1t product – MgCl₂</p> <p>2.92 t/1t product – Al(SO₄)₃</p> <p>0.49 t/1t product – Na₂CO₃</p> <p>0.52 t/1t product – NaOH</p> <p>0.30 t/1t product – HCl</p> <p>0.40 t/1t product – K₂CO₃</p> <p>46 m³/t sorbent – water</p>
--	--	--	--



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.



Viktorija Terņānika was born in Ventspils in 1994. She obtained a Bachelor's degree in Environmental Sciences (2019) and a Master's degree in Environmental Sciences (2021) from Riga Technical University. From 2018 to 2024, she worked at the Riga Technical University's Institute of Energy Systems and Environment. She is currently an Environmental Management Specialist at Geo Consultants Ltd. Her scientific interests are related to environmental issues, sustainability, production processes and emissions.