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CLIMATE AND ENERGY MEASURES EVALUATION WITH COMPOSITE SUSTAINABILITY INDEX

Doctoral Thesis

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CLIMATE AND ENERGY MEASURES EVALUATION WITH COMPOSITE SUSTAINABILITY INDEX

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ANNOTATION

Energy and climate policies can be assessed as a set of policies to achieve climate goals. However, the effectiveness of policies is largely determined by how precisely specific measures are established and whether they have clear and measurable indicators.

The Doctoral Thesis aims to comprehensively analyse climate and energy measures, their key drivers and weaknesses, and their impact on sustainable development and progress toward achieving climate targets through the development of a sustainability assessment methodology.

The contribution and originality of the Doctoral Thesis are based on the multidimensional combination of several methods that evaluate climate and energy measures through environmental, technical, economic, and social dimensions. The study uses the composite index method as a framework, but also multicriteria-decision analysis, emissions calculation, techno-economic analysis, sensitivity analysis, regression analysis, and Hirschman index.

The outcome of the Doctoral Thesis is a multi-dimensional evaluation of specific climate and energy measures using an indicator approach.

The Doctoral thesis is based on 8 publications that demonstrate the use of the composite index in different cases.

To achieve the aim of the Doctoral thesis, several tasks were identified:

1) Design a comprehensive sustainability assessment methodology that combines different methods (composite index, techno-economic analysis, emission calculations, etc.) and indicators to obtain a multidimensional assessment.

- Define and select quantitative and qualitative indicators that would allow evaluation of the efficiency and contribution of climate and energy measures to achieving climate goals.
- Classifying and grouping indicators into relevant dimensions, including technical, environmental, economic, and social.
- Normalise indicator values to ensure comparability, weight indicators to assign importance to each dimension,
- Aggregate indicators into a Composite Index that summarises a multi-dimensional assessment of measures.

2) Approbation of the developed methodology, evaluating the sustainability of measures:

- Identify the main drivers and weaknesses in climate and energy measures that affect the sustainability of measures and the achievement of the climate goals.
- Analysis of measures related to **technology change**, focusing on energy transition and sustainability in municipalities.

- Comparison of agriculture and forestry measures, evaluating their importance in achieving climate goals.
- Analysis of **system change** measures, such as organic agriculture in comparison to conventional agriculture, analysis of recultivation strategies and potential use of peatlands
- Analysis of the role of renewable energy in sustainability by comparison of the renewable energy potential across sectors.

2) Development of recommendations for policymakers by addressing key drivers, barriers and solutions based on results.

The research shows a unique approach previously not used in evaluating climate and energy measures using a scientifically approved method combination. The outcome of the Doctoral Thesis is a multi-dimensional evaluation of specific climate and energy measures using an indicator approach.

The Thesis consists of an Introduction, three Chapters, Conclusions, total number of pages is 316, 41 figures, and 48 tables. The Bibliography contains 281 titles.

ANOTĀCIJA

Enerģētikas un klimata politiku var novērtēt kā politiku kopumu, lai sasniegtu klimata mērķus. Taču politikas efektivitāti lielā mērā nosaka tas, cik precīzi ir noteikti konkrēti pasākumi un vai tiem ir skaidri un izmērāmi rādītāji. Promocijas darba mērķis ir vispusīgi analizēt klimata un enerģētikas pasākumus, to galvenos virzītājspēkus un vājās vietas, kā arī to ietekmi uz ilgtspējīgu attīstību un virzību uz klimata mērķu sasniegšanu, izstrādājot ilgtspējības novērtēšanas metodoloģiju.

Promocijas darba mērķis ir vispusīgi analizēt klimata un enerģētikas pasākumus, to galvenos virzītājspēkus un vājās vietas, kā arī to ietekmi uz ilgtspējīgu attīstību un virzību uz klimata mērķu sasniegšanu, izstrādājot ilgtspējības novērtēšanas metodoloģiju.

Promocijas darba devums un oriģinalitāte balstīta vairāku metožu daudzdimensionālā kombinācijā, novērtējot klimata un enerģētikas pasākumus, izmantojot vides, tehnisko, ekonomisko un sociālo dimensiju. Pētījumā izmantota saliktā indeksa metode, kas papildināta ar citām zinātniski pamatotām metodēm, piemēram, daudzkritēriju lēmumu analīze, emisiju aprēķins, tehniski ekonomiskā analīze, jutīguma analīze, regresijas analīze un Hiršmana indekss. Izmantojot salikto ilgtspējas indeksu un nosakot virzošos spēkus un vājās puses, darba izstrādes gaitā izpētīta dažādu klimata un enerģijas pasākumu ietekme uz ilgtspējību. Promocijas darba rezultāts ir daudzdimensionāls konkrētu klimata un enerģētikas pasākumu novērtējums, izmantojot indikatoru pieeju.

Promocijas darba pamatā ir astoņas publikācijas, kurās parādīta saliktā indeksa izmantošana dažādos gadījumos un līmeņos. Darba mērķis ir vispusīgi analizēt klimata un enerģētikas pasākumus, to galvenos virzītājspēkus un vājās puses, kā arī to ietekmi uz ilgtspējīgu attīstību un virzību uz klimata mērķu sasniegšanu, izstrādājot ilgtspējas novērtēšanas metodiku.

Promocijas darba mērķa sasniegšanai tika noteikti vairāki uzdevumi:

1) Izstrādāt visaptverošu ilgtspējības novērtēšanas metodoloģiju, kas apvieno dažādas metodes (salikts indekss, tehnoekonomiskā analīze, emisiju aprēķini utt.) un indikatorus, lai iegūtu daudzdimensionālu novērtējumu.

• Definēt un atlasīt kvantitatīvos un kvalitatīvos rādītājus, kas ļautu novērtēt klimata un enerģētikas pasākumu efektivitāti un ieguldījumu klimata mērķu sasniegšanā.

• Rādītāju klasificēšana un grupēšana atbilstošās dimensijās, tostarp tehniskajās, vides, ekonomiskajās un sociālajās dimensijās.

• Normalizēt indikatoru vērtības, lai nodrošinātu salīdzināmību, svara rādītājus, lai piešķirtu nozīmi katrai dimensijai,

• Apkopotos rādītājus saliktā indeksā, kas apkopo pasākumu daudzdimensiju novērtējumu.

2) Izstrādātās metodikas aprobācija, izvērtējot pasākumu ilgtspēju:

• Identificēt galvenos virzītājus un vājās vietas klimata un enerģētikas pasākumos, kas ietekmē pasākumu ilgtspēju un klimata mērķu sasniegšanu.

• veikt ar ar tehnoloģiju izmaiņām saistīto pasākumu analīzi, koncentrējoties uz enerģētikas pāreju un ilgtspējību pašvaldībās.

• veikt lauksaimniecības un zemes izmantošanas pasākumu salīdzinājumu.

• veikt ar sistēmas maiņu saistīto pasākumu analīzi, izvērtējot SEG emisiju samazināšanas potenciālu.

• Salīdzināt salīdzinot atjaunojamās enerģijas potenciālu starp tautsaimniecības nozarēm.

3) Ieteikumu izstrāde politikas veidotājiem, risinot galvenos virzītājspēkus, šķēršļus un risinājumus, pamatojoties uz rezultātiem.

Pētījums parāda unikālu pieeju, kas iepriekš netika izmantota klimata un enerģētikas pasākumu novērtēšanā, izmantojot zinātniski apstiprinātu metožu kombināciju. Promocijas darba rezultāts ir daudzdimensionāls konkrētu klimata un enerģētikas pasākumu novērtējums, izmantojot indikatoru pieeju.

Promocijas darbs ievada, trīs nodaļām, secinājumiem, kopējais lappušu skaits 316, 41 attēls un 48 tabulas. Bibliogrāfijā ir 281 nosaukums.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisors, Prof.Dagnija Blumberga and Assoc. Prof Ieva Pakere for seeing potential in this methodology through the years and also some potential in me. I would like to thank the colleagues with whom I have collaborated in scientific publications and projects, especially my colleagues Ieva Pakere, Kristiāna Dolge, Vladmirs Kirsanovs, Oskars Švedovs, who are brilliant, responsive researchers from whom I learned a lot. I would like to thank my great study companion and colleague Ilze Luksta, for your presence, emotional support and the opportunity to always come to discuss and share ideas.

I am very grateful to my family and friends for their support during these four years.

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TABLE OF CONTENTS

NOMENCLATURE

CO_2 – Carbon dioxide
CSI – Composite sustainability index
CI – Composite index
DH – District heating
EU – European Union
GHG - Greenhouse gas emissions
IH – Individual heating
N_2O – Nitrous oxide
CH_4 – Methane
Mt – Megatons
Eq. – Equivalents
RES – Renewable energy resources
PM – emissions – Particulate matter emissions

INTRODUCTION

Topicality of the Doctoral Thesis

The transition to a low-carbon economy is one of the most pressing challenges on the global policy agenda. Five years after the Paris Agreement came into force, the European Union has committed itself to taking on a leading role in the global fight against climate change [1]. One year after launching the European Green Deal in December 2020, EU leaders have agreed on a common target to decrease GHG emissions by at least 55% by 2030 compared to 1990 levels [1]. Over the last decade, numerous strategies, regulations, and policies have been enforced to drive decarbonisation, increase energy efficiency, and accelerate and advance the adoption of green energy solutions [2].

National regulatory authorities are responsible for launching policy instruments that meet the transition objectives of a low-carbon economy. It is the responsibility of each Member State of the European Union to prepare and define the climate targets to be achieved, as well as meaningful measures and policies to achieve climate neutrality by 2050. The policies pursued and the enforcement mechanisms used are not always highly effective and often fall short of the necessary climate targets set by policymakers [3]. Therefore, one of the most essential cornerstones of policy is understanding the main factors that hinder the achievement of climate goals [4]. Policies can be implemented through a variety of political and economic instruments, but it is not always clear which policies are being pursued and which instruments are particularly effective and efficient. A lack of understanding of all the underlying forces of sustainability creates systematic risks and contradictions of the intended goals, which can lead to costly consequences that affect the entire economy [5]. The ongoing debates among policymakers over the most optimal, cost-efficient, and sustainable energy infrastructure outline a number of controversial issues, such as renewable energy as opposed to fossil fuels and centralised compared to decentralised production of heat supply.

The Latvian National Energy and Climate Plan for 2030 (hereinafter – NECP) [6] provides an overview of policies and measures to achieve the climate targets. According to the NECP and the assessment of the European Commission, the NECP contains a list of planned and existing actions, but the core of the issue is that there is no information on the impact of each measure or which measures are more significant. Therefore, it is hard to assess clearly whether the proposed measures can achieve the objectives set. According to the European Commission's assessment of the NECP [7], the European Commission points out that most of the measures proposed in the plan to achieve the climate targets are existing measures that will continue in the coming years and may not be sufficient to achieve the set climate targets by 2030 [7]. According to the assessment, the description of the measures is general and there is a lack of specific policy measures and measurable results. The Latvian NECP has not conducted an

impact assessment for each proposed measure and does not provide measurable and achievable indicators, so it is difficult to assess whether the measures will be implemented and what factors and barriers will affect the implementation of the measures [8] The European Commission has also indicated in its assessment of the updated 2024 NECP [9] that the plan lacks specific policy measures and instruments, as well as quantifiable results and factors [6].

In policy action assessment, the aspects of sustainability and tools for making more sustainable decisions are increasingly important [10]. Policy action assessment refers to a systematic evaluation of both policy implementation and outcomes, aimed at determining whether policy actions taken are appropriate and whether the objectives of policies are on track to achieve the targets set. Assessment of policy actions can result in more reasonable and sustainable decision-making. Using key performance indicators (KPIs), it is possible to measure the outcome and monitor progress towards the achievement of goals set [11], [12].

A data-based climate and energy policy actions assessment is more relevant and necessary than ever before to achieve climate targets by 2030 and 2050. Data-based and scientifically justified politics can serve as an instrument to identify successful policies and practices. In sustainability assessment, different aspects, including environmental, economic, and social, should be evaluated if possible [13], [14]. Various composite indicators can be aggregated into sub-indexes and dimensions into the composite index, which can show comprehensive information and ranking among other alternatives [10]. When the indicators' values are identified, the composite index can be used to provide a comprehensive review of specific aspects. Composite indices have been used in designing policies, identifying and forecasting possible risks regarding policy implementation, and monitoring progress [10].

Evaluating climate and energy policy actions through numerical national-scale models is time-consuming and cannot be fully used by modellers. It is more advantageous and easier for decision makers to use CSI for evaluating climate and energy measures [15]. This research used the CI and a combination of other science-based methods to evaluate the sustainability of different climate and energy policy actions.

Hypothesis

By developing a comprehensive sustainability assessment methodology that integrates a combination of methods and data-based indicators in dimensions, it becomes possible to evaluate the drivers and weaknesses of climate and energy measures and their contribution to achieving climate goals.

Objectives of the Doctoral Thesis

The Doctoral Thesis aims to comprehensively analyse climate and energy measures, identifying measurable indicators to analyse key drivers and weaknesses and their impact on sustainable development towards achieving climate targets through the development of a sustainability assessment methodology.

Tasks to Achieve the Goal of the Study

3) Designing a comprehensive sustainability assessment methodology that combines different methods (composite index, techno-economic analysis, emission calculations, etc.) and indicators to obtain a multidimensional assessment:

- define and select quantitative and qualitative indicators that would allow evaluation of the efficiency and contribution of climate and energy measures to achieving climate goals;
- classify and group indicators into relevant technical, environmental, economic, and social dimensions;
- normalise indicator values to ensure comparability;
- weight indicators to assign importance to each dimension;
- aggregate indicators into a composite index that summarises a multi-dimensional assessment of measures.

2. Approbation of the developed methodology, evaluating the sustainability of measures:

- identification of the main drivers and weaknesses in climate and energy measures that affect the sustainability of measures and the achievement of the climate goals;
- analysis of measures related to **technology change**, focusing on energy transition and sustainability in municipalities;
- comparison of agriculture and forestry measures, evaluating their importance in achieving climate goals, considering the connection to other sectors;
- analysis of **system change** measures, evaluating their impact on energy transitions and GHG emission reduction potential;
- analysis of the role of renewable energy in sustainability by comparison of the renewable energy potential across sectors.

3. Development of recommendations for policymakers by addressing key drivers, barriers and solutions based on results.

Research Methodology

The methodological algorithm developed in the Doctoral Thesis is shown in Fig. 1.

1. Sector analysis

This research focuses on the energy sector, agriculture, and land use, which must undertake a set of activities to reduce GHG emissions and sequester carbon to achieve climate goals. Policy activities in this research are related to specific measures in the energy sector, renewable energy use, agriculture and land use. In the energy sector, part of heating is related to the use of

fossil energy, which should be reduced to move closer to climate goals. Topics that are investigated in the Doctoral Thesis are shown in Fig. 1. To provide direction for policy activities, clear signs should indicate direction towards the achievement of the climate goals with measurable outcomes.
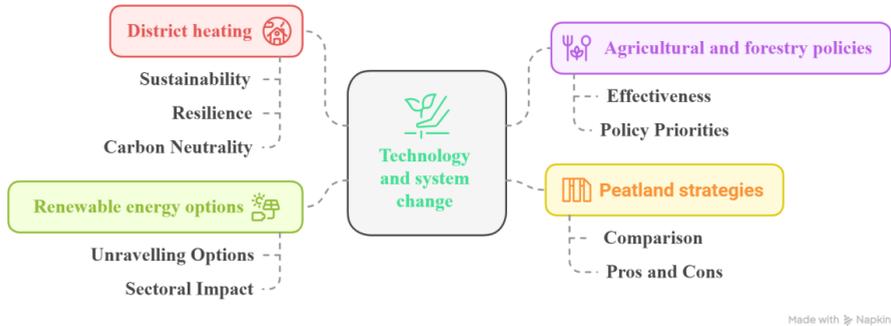
Fig. 1. Climate alternatives regarding technology and system change.

4) Defining climate neutrality alternatives

Further in the Thesis the sequence of publications is presented investigating climate alternatives regarding technology and system change.

Technology alternative

Analysis of measures related to technology change, focusing on sustainability in DH heating systems, resilience of DH systems and carbon neutrality options.

1. Comparison of individual heating and district heating technology sustainability.

2. Case study assessing the sustainability of individual and district heating technologies for municipal buildings.

3. Comparison of the resilience of municipal district heating across different municipalities in Latvia.

Evaluation of the sustainability of climate policies

Analysis of agriculture and forestry measures, evaluating their importance in achieving climate goals and policy priorities.

4. Identification of agriculture and forestry policies and their priorities based on description in NECP and expert survey.

System change

Analysis of system change measures, such as organic agriculture in comparison to conventional agriculture, and analysis of recultivation strategies and potential use of peatlands

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5. Comparison of organic and conventional dairy farming sustainability.

6. Investigation of peatland restoration strategies and alternative use of peatlands in order to sequester carbon.

7. Comparison of economic and environmental sustainability for different peatland restoration strategies and alternative uses.

8. Analysis of the role of renewable energy in sustainability by comparison of the renewable energy potential across sectors [6]. The detailed structure of the Doctoral Thesis is shown in Fig. 2.

5) **Defining dimensions –** economic, environmental, social, and technical.

6) **Selection of indicators. Based on scientific literature, indicators are determined, which are then used to construct the composite index.**

7) **Determining values of indicators**

Methods: literature analysis, expert survey; techno-economic analysis on climate and energy measures; emission calculation regarding GHG emission calculation; HHI index for assessment of diversification of resources.

8) **Weighting dimensions.**

9) **Normalisation indicator values.** For each dimension, each indicator has a positive or negative meaning (a balance of positive and negative effects is created), which is taken into account when normalising each indicator with the Min-max method.

10) **Aggregation of indicators into a composite index. The quantitative assessment of** each dimension in the overall index is determined by summing up the indicators.

11) **Uncertainty assessment, regression analysis regarding adaptive and inherent DH resilience.**

12) **Recommendations development.**

Methodology can be seen in Fig. 2.

Fig. 2 Detailed structure of the Doctoral thesis.

Scientific Novelty

The Doctoral Thesis provides a comprehensive, novel methodology for the multidimensional assessment of climate and energy measures towards climate goals, integrating a combination of sciencec-based methods in evaluation. The multidimensional approach, compared to the single indicator assessment, provides a more comprehensive picture of the indicators that affect sustainability.

The study uses the composite index method as a framework for analysis, integrating other methods like techno-economic analysis and emissions calculation to determine values of the indicators. Expert survey and multicriteria analysis were performed to determine indicator weight. In the Doctoral Thesis, methods such as sensitivity analysis, regression analysis, and the Hirschman index were also used in the research (see Fig. 3). The composite index summarises different indicators into one index comprising different aspects of sustainability.

Indicators were determined for defining climate neutrality policy in the Doctoral Thesis. These indicators made it possible to evaluate sustainability in various cases and different sectors using a scientifically based combination of methods. The methodology incorporates both quantitative and qualitative indicators across several dimensions, allowing analysis of how measures contribute to climate goals.

The research's novel contribution is its focus on evaluating system change and technology change measures in the context of climate and energy transitions. The Thesis focused on how these changes impact sustainability at the municipal level, contributing to a better understanding of energy transitions and the potential for GHG reduction.
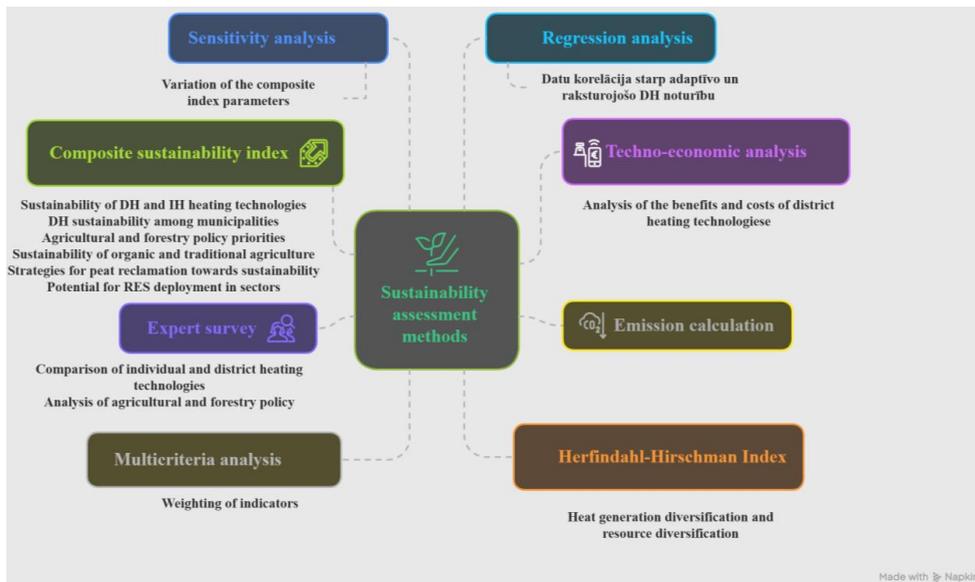
Fig. 3 Methods used in the Doctoral thesis [16].

Practical Relevance

The Thesis results offer a valuable tool, validated by real-life case studies, for policymakers, municipalities, and businesses to evaluate sustainability and improve climate and energy measures, ensuring that they are effective, sustainable, and aligned with climate goals.

Methodology and indicators can be used to initially review and assess existing climate and energy measures and develop new climate and energy policies.

The Doctoral Thesis obtained indicators to evaluate the sustainability of various climate and energy measures. These indicators can be used in decision-making, defining driving forces and possible weaknesses. Indicators and their values can be used as a database in various climate and energy measure analyses. The set of indicators can help policy-makers make more effective and understandable decisions.

Approbation of the Thesis

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

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1. CONECT 2021: XVI International Scientific Conference of Environmental and Climate Technologies. POSTER SESSION: *From multicriteria decision analysis to composite sustainability index for policy impact assessment in national energy and climate plans.*

2. CONECT 2022: XVI International Scientific Conference of Environmental and Climate Technologies. PANEL SESSION V: Renewable Energy Technologies. *The comparison of RES sustainable development in the main sectors of the Economy*.

3. CONECT 2022: XVI International Scientific Conference of Environmental and Climate Technologies. POSTER SESSION: *Assessing the effectiveness of forestry and agricultural policies in national energy and climate plans*.

4. CONECT 2023: XVI International Scientific Conference of Environmental and Climate Technologies. POSTER SESSION: Carbon Farming in the New Common Agriculture Policy: analysis of Measures and identification of the blind spots.

5. CONECT 2023: XVI International Scientific Conference of Environmental and Climate Technologies. POSTER SESSION: Evaluating the effectiveness of agricultural and forestry policies in achieving environmental goals through environmental policy documents.

6. CONECT 2024: XVII International Scientific Conference of Environmental and Climate Technologies. POSTER SESSION: Organic or Non-organic Agriculture: Comparison of Organic and Conventional Farming Sustainability.

The results of the Doctoral Thesis are approved in 8 connected scientific publications. Scientific publications are indexed in Scopus.

1. Balode, L.; Dolge, K.; Blumberga, D. The Contradictions between District and Individual Heating towards Green Deal Targets. Sustainability 2021, 13, 3370. https://doi.org/10.3390/su13063370

2. Balode, L.; Zlaugotne, B.; Gravelsins, A.; Svedovs, O.; Pakere, I.; Kirsanovs, V.; Blumberga, D. Carbon Neutrality in Municipalities: *Balancing Individual and District Heating Renewable Energy Solutions*. Sustainability 2023, 15, 8415. https://doi.org/10.3390/su15108415

3. Balode, L; Blumberga, D. *Evaluating the Effectiveness of Agricultural and Forestry Policies in Achieving Environmental Goals Through Policy Documents* Environmental and Climate Technologies, vol. 27, no. 1, 2023, pp. 195–211. https://doi.org/10.2478/rtuect-2023-0015

4. Balode, L.; Dolge, K.; Blumberga, D. *Sector-Specific Pathways to Sustainability: Unravelling the Most Promising Renewable Energy Options.* Sustainability 2023, 15, 12636. https://doi.org/10.3390/su151612636

5. Balode, L.; Bumbiere, K.; Sosars, V.; Valters, K.; Blumberga, D. *Pros and Cons of Strategies to Reduce Greenhouse Gas Emissions from Peatlands: Review of Possibilities.* Appl. Sci. 2024, 14, 2260. https://doi.org/10.3390/app14062260

6. Balode, L.; Blumberga, D. *Comparison of the Economic and Environmental Sustainability for Different Peatland Strategies.* Land, 2024, vol. 13, no. 4, pp. 1–19. e-ISSN 2073-445X, doi:10.3390/land13040518

7. Balode, L.; Pakere, I.; Luksta, I.; Blumberga, D. *Organic versus conventional agriculture: comparison of economic and environmental sustainability* , Environmental and Climate Technologies, vol. 29, no. 1, Riga Technical University, 2025, pp. 1-20. Pieejams: https://doi.org/10.2478/rtuect-2025-0001

8. Pakere, I.; Balode, L. (corresponding author); Krīgers, G.; Blumberga, D. District heating resilience under high energy price shocks, Energy, vol 323, 2025, 135855, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2025.135855.

Other Related Publications

1. Balode, L.; Dolge, K.; Lund, P. D., & Blumberga, D. *How to assess policy impact in national energy and climate plans*, Environmental and Climate Technologies, vol. 25, no. 1, pp. 405–421, Jan. 2021, doi: 10.2478/rtuect-2021-0030.

2. Balode, L.; Dolge, K.; Lund, P. D., & Blumberga, D. *How to assess policy impact in national energy and climate plans*, Environmental and Climate Technologies, vol. 25, no. 1, pp. 405–421. 2021, doi: 10.2478/rtuect-2021-0030.

3. Dolge, K.; Balode, L.; Laktuka, K., et al. A Comparative Analysis of Bioeconomy Development in European Union Countries. Environmental Management 71, pp. 215–233 (2023). https://doi.org/10.1007/s00267-022-01751-3

4. Pubule, J; Vištarte L.; Balode, L. *Agricultural Sector Towards Climate Neutrality: an Analysis of Common Agricultural Policy. Case of Latvia,* Agriculture, Ecosystems and Environment., vol. 27, no. 1, Riga Technical University, 2023, pp. 683-695. https://doi.org/10.2478/rtuect-2023-0050

5. Terjanika, V. et al. Legal Framework Analysis for CO_2 Utilisation in Latvia, Environmental and Climate Technologies, vol. 26, no. 1, Riga Technical University, 2022, pp. 917–929. https://doi.org/10.2478/rtuect-2022-0069

6.   Zlaugotne, B.; Zihare, L.; Balode, L, et al. Multi-Criteria Decision Analysis Methods Comparison, Environmental and Climate Technologies, vol. 24, no. 1, Riga Technical University, 2020, pp. 454–471. https://doi.org/10.2478/rtuect-2020-0028

Monographs

1. Blumberga, D.; Balode, L.; Bumbiere, K.; Dzalbs, A.; Indzere, Z.; Kalnbaļķīte, A.; Priedniece, V.; Pubule, J.; Vamža, I.; Zlaugotne, B.; Žihare, L. Bioresources for Sustainable Development. Riga, RTU Press, 2021. 483 p. ISBN 978-9934-22-701-1. Available from: doi:10.7250/9789934227035

2. Blumberga, D.; Balode, L; Bumbiere, K.; Indzere, Z., et al. Zivju apstrādes efektivitātes ceļvedis. Rīga: RTU Izdevniecība, 2021.

Thesis Outline

The Doctoral Thesis is based on 8 thematically connected publications. It consists of an introduction and three chapters:

- Literature review;
- Methodology;
- Results, conclusions and recommendations.

The introduction justifies the topicality and the aim of the Doctoral Thesis. The literature review shows insights on individual and district heating, energy security, agriculture and land use, renewable energy, and issues in these areas towards climate goal achievement.

The methodology part summarises all the methods and indicators used to conduct the research. The Methodology focuses on a composite index, which is supplemented by other methods to determine the values of the indicators, assign weights to the indicators, or calculate uncertainty. Results reveal the use of composite indeces in investigating different climate and energy measures and policy actions, discovering driving forces and weaknesses in sustainability.

1. LITERATURE REVIEW

According to the European Green Deal, achieving the climate targets set for 2030 and beyond by 2050 requires active promotion and development of measures to decarbonise the energy system. Energy consumption in different sectors is currently responsible for 75% of total EU GHG emissions. With the European Green Deal, the EU plans to review all current energy and climate policies to meet the targets for 2030 [17].

Many EU environmental policies have been developed and integrated simultaneously to strengthen the European Green Deal and achieve its goals. The energy sector must be prioritised to achieve the climate targets and the set level of GHG emissions. The Green Deal anticipates the need to use renewable energy sources while rapidly moving away from fossil fuels [17].

1.1. Comparison of individual and district heating

Various factors determine the difference between DH and IH [18], [19], [20], [21]. Decentralised energy can be more expensive than centralised energy in some cases, so it is not available to everyone for financial reasons; statistically, decentralised energy supply to residential buildings is chosen by more financially stable residents [22]. Decentralised heating solutions include a variety of different technologies, such as gas/oil boilers, air/ground source heat pumps, solar thermal, wood pellet boilers [21], [23].

Heat pumps are electrically powered thermal technologies that generate heat by using solar energy stored in natural heat sources such as air, water, or soil. They are increasingly used in residential heating and cooling, influenced by their high energy efficiency [24], [25]. Heat pump technologies can be used in commercial buildings and factories, as well as in households. They are considered environmentally friendly and highly energy efficient and can be integrated into existing systems [26].

With the increasing use of solar collectors, it is possible to significantly reduce the demand for fossil energy resources and use solar energy instead. In recent years, solar collectors have been increasingly used in the construction of buildings to reduce carbon emissions. By using solar collectors, it is possible not only to provide space heating but also to meet the demand for hot water [27] efficiently. Solar collectors' disadvantages relate to solar energy's periodicity and the need to combine solar collectors with other heat supply solutions in case of insufficient heat energy [21].

Wood pellet boilers are individual technological devices for producing thermal energy. The heating system of pellet boilers consists of elements such as a heat accumulator, boiler, and building, which is a unit of energy consumption [28].

District heating

Several countries have implemented various policies to promote district heating infrastructure, which is an essential element of a low-carbon energy system [29]. It is recognised as one of the solutions to mitigate climate change [30]. District heating will become more profitable and cost-effective in the future, and district heating using renewable energy sources is estimated to be one of the most important solutions for decarbonising the energy sector [31]. It is estimated that district heating systems can reduce emissions by 113 million tonnes of CO_2 per year in Europe, which is 2.6% of total CO_2 emissions [32]. New district heating system is the most cost-efficient and competitive solution compared to different individual heating technologies [13], [14] due to its ability to diversify heat sources, use cheaper fuels, and use high-tech efficiency [13], [14].

DH provides continuous heating through heating networks from heat generators (e.g., boilers, cogeneration plants, etc.) located away from the consumer [33], [34], [35]. Heat losses in heating networks only exist in the case of DH and affect the need for a higher-power boiler. This is certainly reflected in costs [36], [37]. Transitioning to a fourth-generation DH can reduce heat loss in networks [33], [38]. In this respect, 4th generation means reducing the temperature regime in the heating networks (low-temperature network) by considering the specific thermal energy consumption of each connected building, which impacts the heat loss and fuel consumption reduction [38], [39].

A sustainable heat supply is characterised by the efficient use of renewable energy sources for heat supply, both through the use of renewable energy sources in individual heat supply and through their integration into district heating systems [18].

1.1.   Energy system resilience

The energy sector DH and cooling industry currently account for 50% of final energy consumption and are the largest energy consumers in Europe, ahead of transport and electricity. A large part of the energy is used for residential heating, where 79% of energy is used for space heating, water heating, and space cooling [40], [41].

Maintaining sustainable heating price levels is a crucial aspect of the future development of DH systems to provide a low-carbon and affordable heat supply. The recent extreme increase in resource prices during the energy crisis in 2022/2023 has raised an important question of how to increase the overall resilience of energy systems. In Baltic countries, DH systems are crucial to energy infrastructure and the main source of heating in residential buildings. Improving DH systems is vital to achieving city climate neutrality targets [42], [43]. DH energy systems can integrate RES into the energy supply to reduce the impact of fossil fuel use and move toward decarbonisation goals in the energy sector [44].

Energy systems are subject to major disruptions when affected by hazards that can be natural or human-caused. If an energy system, including the DH system, is disturbed, its failure to operate impacts infrastructure, economic activities, and society. Energy systems, including DH systems, are critical infrastructure. All energy services depend on the efficient functionality of the respective energy networks, so their protection against external factors is essential for consumer safety and usability [45].

The meaning of energy security is to provide a stable and uninterrupted energy supply to all energy consumers at a reasonable price [7]. Although geopolitical conflicts on a smaller or larger scale have always been on, the daily ongoing war in Ukraine, triggered by Russia's invasion in 2021, is a stark reminder of the potential threats to global energy security; energy resource dependence. If a country's energy system is dependent on one type of resource, such as imported resources, then it may cause an out-of-control situation.

Resilience characterises the system's ability and reaction to natural or human-caused stressors and disturbances. The resilience of an energy system could be defined as the capacity of an engineered system to resist, absorb, buffer, and recover from stressors [47], [48] and the effects of various hazards [43], [49]. Systems with low resilience to threats and disturbances cannot be sustainable [48]. Natural hazards or cyber-attacks affect system resilience [49]. Resilient energy systems can recover to their initial state more easily after disruptions and disturbances. On the contrary, systems with low resilience will be more vulnerable to unexpected threats, and recovery to a normal state might be longer [41].

The timely assessment of DH energy systems' vulnerability is a crucial part of well-thought-out decision-making. Therefore, improving the resilience of the DH system becomes a more important issue for a stable and sustainable energy system [50], [51].

The fulfilment of the energy security condition is best characterised by how much energy resources and energy Latvia is able to produce itself and how much needs to be imported, as well as by how many different sources of energy resources are imported from. The energy sector is particularly sensitive to climate risks, which means planning and implementing appropriate measures to strengthen the sector against the risks and extremes caused by climate change [6].

1.2. DH in Latvia and price fluctuations

DH plays a significant role in the energy supply in Latvia, and it is the primary type of heat supply in cities. Due to the importance of DH to Latvian citizens, these heat prices are regulated by the state, but municipalities organise DH energy availability in their territory. Latvia's consumer price of heat or final heat tariff consists of three components: production, distribution and realisation rate. The highest role of these components is for the production component, but realisation costs are the lowest [52]. DH heating tariffs vary based on several factors like taxes, fuel prices, investments and operational parameters [52].

The heat supply in Latvia has faced a recent switch to solid biomass. However, some DH systems still use natural gas as a main heat source. In 2018, 61.2% of the heat was produced in boiler houses using biomass, and 37.6% was made using natural gas [53]. Therefore, the increase in gas prices after Russia invaded Ukraine significantly impacted the price of the final energy product. Also, the cost of wood chips and pellets increased due to the ban on wood imports from Russia and Belarus and increased demand for solid biomass [53]. Fig. 1.2.1 indicates the fuel price changes from January 2020 to March 2024 in Latvia, which is further assessed.
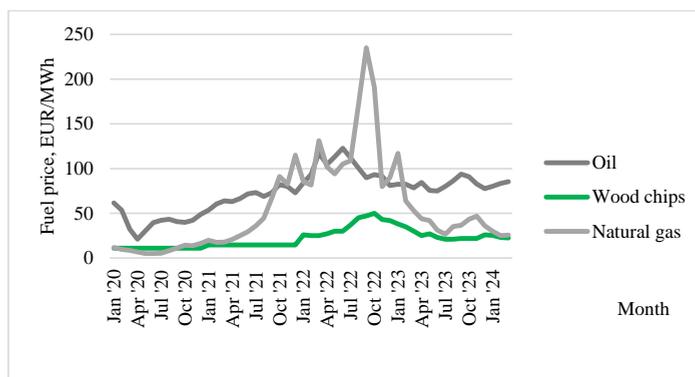
Fig. 1.2.1. Fuel price changes [53].

1.3.   Carbon-neutral municipalities

Carbon-neutrality in municipalities can be achieved by combining DH and individual heating solutions involving the use of renewable energy sources [54], [55], [56]. Each approach has advantages and disadvantages, but the best solution depends on the specific circumstances of each municipality. As an environmentally friendly and efficient energy use, a decentralised heat supply contributes to achieving energy conservation and emissions reduction goals. Decentralised energy use, such as solar collectors with thermal energy storage or biomass as a resource, reduces dependence on centralised heat generation and transmission. Often, the appropriate infrastructure for connection to district heating networks has not yet been built [36]. On the other hand, it is easier to make investments to construct proper infrastructure [57] in the case of large-scale centralised heat supply [39], [54].

Municipalities are competent in achieving the energy transition objectives locally, including increasing the RES share in the energy mix [42], [65]. To move optimally towards carbon neutrality, it is necessary to balance DH and individual heating support [20], [21], [36].

1.4.   Agriculture

Reducing the level of GHG emissions from agriculture is one of the most serious issues in the EU [58]. The dairy industry generates significant emissions from enteric fermentation, manure, and long-term storage [62], [63]. The emissions produced depend greatly on factors such as livestock feeding [59], manure management systems, feed content, and quality [59], [60]. The European Green Deal incorporates the achievable goals in the agricultural sector set in the European Common Agricultural Policy Plan (CAP) [61]. CAP is one of the key policies designed to promote sustainable agriculture and reduce GHG emissions in the agricultural sector [61], [62], [63], [64].

The European Green Deal and the Farm to Fork strategy [65] established by the CAP promote organic farming [61], [62], [66]. Similar to the national energy and climate plans, each EU member state must develop national CAPs [61] to set priorities and achievable goals in the agricultural sector [61], [63]. The Farm to Fork strategy aims to reduce pesticide use in the EU by 50% by 2030 and fertiliser use by 20% [65], [67]. In the EU, more than ~54 % of GHG emissions from agriculture are methane (CH_4) emissions from agricultural processes [59].

Several factors influence agriculture, including subsidies, technological capabilities, and knowledge of sustainable agricultural development [68]. Livestock nutrition and changes in living conditions [61], [69] have a positive impact on CH_4 emissions [70]. Forage quality has a significant impact on methane production; if forage is low digestible, the amount of methane gas emissions increases [60], [71]. The optimal digestibility index is 67 %; if it is 50 % and below, there is an increased risk of methane emissions and a decrease in productivity [60], [72].

According to 2022 data, the agricultural sector in Latvia accounted for 2253.8 kt CO_2 eq. [60] or more than 22 % of the total national emissions that year, ranking just behind the energy sector [60]. Data from 2022 shows that GHG emissions related to agriculture have increased by 26% compared to 2005 [6]. Emissions from agricultural soils were the largest contributor to agricultural emissions in this period, creating about 46.5 % of the sector's GHG emissions [60]. In 2022, CH_4 emissions from cattle intestinal fermentation accounted for about 42 % of the total emissions in the agriculture sector or ~946 kt CO_2 eq. [60]. Emissions depend on the feeding tactics and feed content quality [59]. The increased GHG emissions in intensive agriculture are partially explained by the fact that as the production yield increases, the milking of cows also increases, and the amount of manure produced causes higher CH_4 emissions [59].

Dairy farming and emissions from agricultural soils, including wheat production, which accounts for a large part of the harvested grain, are important sources of emissions [65], and alternative solutions for increasing sustainability in these sectors must be evaluated [58].

1.4.1.   Organic farming

The importance of organic farming is emphasised in the EU agro-environmental policy and strategies, which stipulate that by 2030, at least 25 % of agricultural land should be farmed with organic farming methods [62], [65]. The Farm to Fork strategy and action plan encourage an increase in organic farming, intending to convert 25 % of agricultural land to organic farming by 2030 [62], [65]. Also NECP of Latvia states to promote organic dairy farming (low-emission dairy farming) [6]. The main goal of the policy measure is to promote the transition of small and medium-sized conventional dairy farms to the organic farming system, promoting low-emission dairy farming [6].

Organic farming has been assessed for its potential for carbon sequestration, increasing the organic matter content in the soil, and reducing GHG emissions [73].

Dairy cows feed on pastures, and in organic dairy farming, most of the feed must be home-grown. Forage available on pasture contains more fibre, which can reduce methane emissions. Legumes in the composition of pasture are an essential element for obtaining higher-value forage, increasing the protein content in the feed [74]. Factors such as the species composition of dairy cow forage influence the quality of forage; the inclusion of legumes can improve the quality of feed.

In organic farming, the use of chemical fertilisers and pesticides is prohibited, reducing nitrogen oxide emissions formed from chemical fertilisers in conventional agriculture [75]. Switching to organic farming from conventional farming is considered a promising alternative for reducing GHG emissions by reducing the use of synthetic fertilisers [76].

In Latvia, it is estimated that more than 304,000 ha of the land used for agriculture is certified organic farming areas [77]. Grain areas are increasing, and the amount of organic grain produced in the total organic farming system has also increased from 70,000 tons in 2018 to 111,000 tons in 2022 [78]. Grain cultivation in Latvia is estimated to account for ~ 60 % of the production of agricultural products [79]. Cereals occupy more than three-quarters of the organic crop cultivation area, and organic cereals have increased more than twice compared to 2015 [77]. The number of organic farming operators also increased, reaching 4439 in 2021 (in comparison to 3587 operators in 2012) [77], [80].

In 2022, the number of cows in dairy farming in Latvia was 127759, but in 2023, 119042 cows [81]. In 2022, 15,800 cows were in organic dairy farming (Fig. 1.4.1) [82]. In 2020–2021, the produced cow's milk was 988,000, of which 87,000 was organic milk [83]. Although the number of dairy cows continued to decrease, the average milk yield per dairy cow increased by 1.8 %, reaching 7,492 kg per year [84]. Less than half of the organic milk produced is processed as organic milk products due to logistical problems in collecting organic milk, high retail prices and low consumer demand [81], [84].
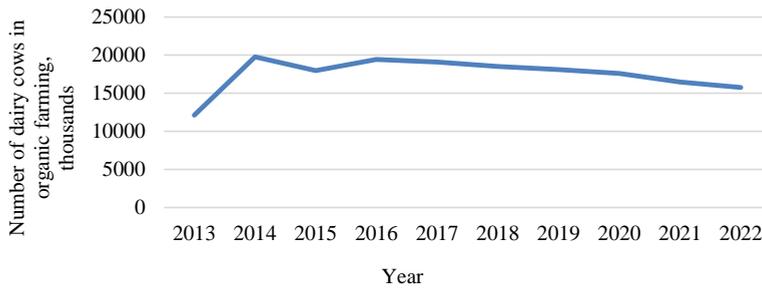
Fig. 1.4.1 Number of dairy cows in organic farming [91]

According to the 2022 data from the Agricultural Data Centre, less than 5 % (~4.8 %) of farms have a cow count exceeding 50. Compared to 2021, the number of dairy farms decreased by ~9.4 % [84].

Previous literature shows a gap in data regarding relevant indicators for comparing organic and conventional dairy farming at the farm level [85].

1.5.   Patlands in the land use sector

Through the use of different management practices, peatlands can become valuable resources and GHG sinks [95], [96], [97], [98], [99]. Peatlands provide carbon sequestration; however, they are also among the greatest GHG emission sources. The estimated annual carbon dioxide equivalent emissions from peat worldwide are 220 million tons [86], [87].

Novel strategies, methods, and technologies must be developed to enhance the sustainable use of peatlands and achieve climate targets by 2050, as set forth by the European Commission. There is no consensus in the scientific literature on which strategies included in the policy documents are more fruitful for reducing emissions [88], [89]. There are uncertainties and knowledge gaps in the literature that summarise the cons and benefits of each strategy regarding the potential of GHG emission reduction [89], [90], [91]. Currently, peat is undervalued as a resource in the bioeconomy and innovation [92], [93]. However, increased attention is being paid to wetland ecosystems and their potential to reduce GHG emissions and opportunities to improve the conditions of endangered peatlands [94].

Annual GHG emissions from drained peatlands are ~1.2 - 1.9 Gt CO_2 eq. globally [94]. Annual GHG emissions from degraded and non-degraded European peatlands are reported to reach 582 megatons Mt of CO_2 eq. [95].

Peatland restoration aims to restore degraded peatlands to their natural status and hydrological conditions, recover their natural habitats, and, thus, increase biodiversity [96], [97], [98], [99], [100].

Peatland Management and Restoration Strategies

Various strategies and approaches are known to reduce GHG emissions, including reducing the intensity of agriculture, peatland afforestation and reforestation [101], and peatland rewetting [102], [103]. Peatland management requires striking a balance between CO_2 emissions from drained peatlands and CH_4 emissions from rewetted peatlands. Before deciding, it is important to consider longevity in the atmosphere of CO_2 and CH_4 [104].

According to Latvia's updated NECP [6], CO_2 sequestration in the land use sector currently does not cover GHG emissions. Therefore, new effective measures need to be evaluated [6]

1.6. Summary of the research topics and linkage with policies and measures of NECP

Below is table 1.6.1 summarising specific NECP policies and activities, which serves as a basis for the selection of topics and their relevance to policies or specific measures. The table shows linkages between different policy activities and their contribution to climate target achievement through GHG emission reduction, carbon sequestration, improvement in energy security, resource diversification, and an increase in RES share. Here is an explanation of how these specific climate goals can be linked to policy activities related to NECP [6].

Technology alternative:

1. **Individual heating and district heating technology sustainability;**

Increasing the production capacity of renewable energy plants and improving their energy efficiency for individual self-consumption [6].

2. **Individual and district heating technologies in the municipalities' buildings,** Increasing the production capacity of renewable energy and improving their energy efficiency in businesses and municipalities

Within the policy activity, it is expected to provide wider support for existing power plants and the installation of new plants, focusing on RES technologies.

3. **DH system resilience in municipalities**

According to NECP, one policy action is related to increasing the use of RES in DH systems and modernising their infrastructure [6].

Increasing the production capacity of renewable energy and modernising the infrastructure and networks of the DH systems.

Policies priorities

4. **Agriculture and forestry policy priorities – GHG emission reduction, carbon sequestration.**

System change

5. **Organic farming – GHG emission reduction in small and average-sized dairy farms.**
Promote the transition of small and medium-sized conventional dairy farms to an organic farming system [6].

6. **Peatland restoration, alternative use – carbon sequestration, GHG emission reduction.**
Targeted afforestation in developed peat fields, including restoring wetland forest habitats characteristic of Latvia [6].

7. **RES potential in sectors: GHG emission reduction, energy security, diversification, and share of RES** [6].

A more in-depth study on the renewable energy potential in each sector of the leading sectors of the economy (industry, agriculture, household, services, and transport) is needed to assess which RES technologies are more appropriate for each sector. It is crucial to understand in which sectors a high potential of using RES technologies is possible but in which technologies there are significant obstacles in their implementation [105], [106] (see Table 1.6.1.).

Table 1.6.1

Climate goal linkage with policy activities, measures and research topics

	Carbon sequestration	GHG emission reduction	Energy security	Diversification of energy sources	Share of RES
3.1.3.14. Increasing the production capacity of renewable energy plants and improving their energy efficiency for individual **self-consumption** [6]**.**		X	X	X	X
3.1.3.15. Increasing the production capacity of renewable energy and improving their energy efficiency in **municipalities** [6].		X	X	X	X
3.1.3.11. Increasing the production capacity of renewable energy and modernising the infrastructure and networks of the **CSA** [6].		X	X	X	X

Agriculture and forestry policy priorities [107]**.**	X	X			
3.1.2.1. Promote the transition of small and medium-sized conventional **dairy farms to an organic farming system** [6].		X			
3.1.6.5. **Afforestation in previously extracted peatlands**, including restoring wetland forest habitats characteristic of Latvia [6].	X	X			
RES potential in sectors Ensure the use of only renewable energy sources in energy production in all sectors [6].		X	X	X	X

2. METHODOLOGY

A summary of the methods used is given in Table 2.1.

Table 2.1

Summary of methods used in each case study

	Composite Index	Techno-economic evaluation	Emission calculation	Risk assessment, HHI index regression analysis	AHP
3.1.3.14. Increasing the production capacity of renewable energy plants and improving their energy efficiency for individual **self-consumption** [6].	X	X	X	X	X
3.1.3.15. Increasing the production capacity of renewable energy and improving their energy efficiency in **municipalities** [6]**.**	X	X	X		
3.1.3.11. Increasing the production capacity of renewable energy and modernising the infrastructure and networks of the **CSA** [6].	X				
Agriculture and forestry policy priorities [107].	X		X		
3.1.2.1. Promote the transition of small and medium-sized conventional **dairy farms to an organic farming system** [6].	X				
3.1.6.5. **Afforestation in previously extracted peatlands**, including restoring wetland forest habitats characteristic of Latvia [6].	X				
RES potential in sectors Ensure the use of only renewable energy sources in energy production in all sectors [6].					

2.1.　　Composite Index

The CI methodology has gained acceptance as an innovative tool that allows the inclusion of an unlimited number of indicators to measure different aspects of complex and controversial issues, such as sustainability, prosperity, innovation potential, competitiveness and many others [19], [108]. CI is commonly used by scientists when choosing the most appropriate

methodology to evaluate sustainable development. The method combines various aggregate values to determine indicators of the topic being studied. A composite index allows for comparisons to assess the sustainability performance of regions, sectors, and other factors. CI can be used to evaluate policy measures, compare them before their implementation, or assess progress in implementing defined objectives. CI methodology has gained acceptance as an innovative tool that allows the inclusion of an unlimited number of indicators to measure different aspects of complex and controversial issues, such as sustainability, prosperity, innovation potential, competitiveness and others [19], [37], [108]. Therefore, this study provides a novel decision-making tool, risk assessment, that decision-makers could use in order to identify and avoid potential blind spots and uncertainties in climate and energy policy at an early stage [37].

Main steps in creating CI

Data normalisation

When creating a Composite index, the data must first be normalised for mutual comparison of measures and indicators. Normalisation is required prior to data aggregation as the indicators often have different measurement units [109]. To standardise the indicators, the min-max method, used in sustainability studies, was used for normalisation, which is also used in environmental decision-making and policy analysis [109].

The min-max normalisation standardises the indicator values in the range [0;1], which allows a comprehensive comparison of indicators that have different units of measurement [109]. The normalisation technique for each indicator depends on its impact on the sustainability index. An indicator can either positively or negatively impact the sustainability index. Therefore, at first, each indicator was assessed with respect to its impact on the sustainability index. The indicator has a positive impact on the sustainability of its increasing value increases the sustainability [110]. For example, higher efficiency has a positive effect on the overall technological performance of the technology, and therefore, it also increases the sustainability of the technology. However, the indicator has a negative impact on the sustainability of its increasing value and decreases the sustainability of the technology. For example, higher specific emissions from the technology produce a negative effect on sustainability and, therefore, reduce the sustainability of the particular technology [37], [110].

Positive impact indicators are normalised using Equation (2.1.1), and negative impact indicators are normalised according to Equation (2.1.2).

$$I^+_{N,ji} = \frac{I^+_{act,ji} - I^+_{min,ji}}{I^+_{max,ji} - I^+_{min,ji}}$$

(2.1.1)

$$I^-_{N,ji} = 1 - \frac{I^-_{act,ji} - I^-_{min,ji}}{I^-_{max,ji} - I^-_{min,ji}}$$

(2.1.2)

where

$I^+_{N,ji}$ is ththe e normalised value of positive impact indicator,

the $I^-_{N,ji}$ is the normalised value of negative impact indicator,

$I^+_{act,ji}$ is the actual value of an indicator,

$I^-_{min,i}$ is the minimal value of an indicator among all the technologies,

$I^+_{max,i}$ is the maximum value of an indicator among all the technologies,

j denotes the specific sub-dimension,

i denotes the specific indicator in a particular sub-dimension [111], [112].

Weighting and aggregation

Indicators should be aggregated and weighted to compare the weight of each dimension. Most composite indicators rely on equal weighting, where all variables are given the same weight. Composite indicators should be transparent and fit to be decomposed into their underlying indicators or values [113], [114] (Equation 2.1.3).

$$I_{S,j} = \sum_i^n W_{ji} \times I^+_{N,ji} \, , \, W_{ji} = \frac{1}{n_{ji}}$$

(2.1.3)

Where

$I_{S,j}$ is the dimension's sub-index value,

W_{ji} is the impact weight of indicators on the dimension sub-index (application of equal weighting),

n_{ji} is the number of indicators in a particular dimension.

The final step is the aggregation in the CI results multiplied by the normalised indicator value (Equation 2.1.4).

$$I_{CI} = \sum_j^n W_j x \, I_i$$

where

I_{CI}–composite index;

W_j–equal importance indicator weight

I_i–normalised indicator value.
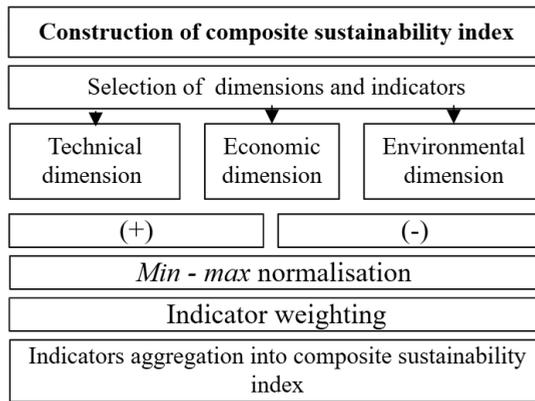
Fig. 2.1.1. Methodology for the construction of the CI [21], [115].

2.2. Comparison between individual and district heating

This study demonstrates the CI methodology's application to create a CSI for district heating and four different individual heating technologies. Sustainability is assessed in terms of the technology's compatibility with the goals of a low-carbon economy. The heat supply system is considered to be sustainable when the constructed heat production infrastructure and installed technologies are balanced with environmental, economic and social aspects of the economy [116]. It applies the sustainability framework, where general sustainability dimensions are combined with a technical dimension that represents the analysed technology's main performance parameters. As a result, the model includes four main dimensions: technical, environmental, economic, and social. Each dimension is composed of various descriptive indicators that are summarised in Table 1.2.1. As illustrated in Fig. 2.2.1., the methodology of this study is constructed based on the three main pillars: (1) the identification of internal and

external context influencing heat supply system sustainability, (2) the calculation of the CSI, and (3) the result analysis and decision-making procedure. Identifying the internal and external context includes a literature review on the common practices of sustainability assessment of energy supply technologies to identify the main sustainability aspects and design a comprehensive research methodology.

In this study, the CSI is calculated for district heating (based on natural gas) and four different technological solutions of decentralised (individual) heating such as: (1) the wood pellet boiler, (2) the natural gas boiler, (3) solar collectors, and (4) the heat pump. The choice of the heat supply technological solutions was determined by the ability of the technology to ensure the necessary heat demand of a medium-sized household. The selection of individual heat supply solutions was based (1) on a Danish study on individual heat supply solutions, (2) on the availability of the data to create a complex index, and (3) on the sustainability of the heat supply solution. Among the individual heat supply solutions using a biomass source, the study evaluated wood pellet heating as a sustainable individual heat supply solution [117].

Fig. 2.2.1. Model for the sustainability index construction and decision-making algorithm.

2.2.1. Determination of sustainability dimensions and selection of indicators

19 indicators were selected and grouped into representative dimensions. Assessment of sustainability requires an integrated approach and structure composed of several interlinked steps (Table 2.2.1).

Table 2.2.1

Selected sustainability indicators and classification into dimensions [19], [118].

Dimension	Notation	Indicator description	Source	Impact

Technical	tech1	Efficiency	Data	+
	tech2	Complexity of service and maintenance (availability of specialists on site, immediate prevention of risk situations)	Expert evaluation	-
	tech3	Stable availability of energy resources for sufficient heat production	Expert evaluation	+
	tech4	Opportunities for diversification of utilised energy resources (technology is not limited only to one type of energy resource supply)	Expert evaluation	+
	tech5	Possibility to balance the produced heat load (ability to respond to rapid seasonal and short-term changes in demand)	Expert evaluation	+
	tech6	Operational stability (stable heat supply to the grid, no or reduced heat disruptions)	Expert evaluation	+
	tech7	Opportunities for the utilisation of low-quality energy resources	Expert evaluation	+
Environ mental	env1	Specific CO_2 emissions	Data	-
	env2	Complexity of flue gas cleaning	Expert evaluation	-
Economic	econ1	Capital investments (CAPEX)	Data	-
	econ2	Service and maintenance costs (OPEX)	Data	-
	econ3	Technology lifetime	Data	+
	econ4	Specific energy costs	Data	-
	econ5	Possibility to utilise surplus heat for optimisation of heat production and maximisation of resource efficiency	Expert evaluation	+
	econ6	Opportunities for cost optimisation (choice of energy resource based on the most economically advantageous price in the market, opportunities for economies of scale)	Expert evaluation	+
Social	soc1	Consumer comfort level	Expert evaluation	+
	soc2	Consumer safety level (reduced risks of ignition, leakage, etc.)	Expert evaluation	+
	soc3	Impact on the promotion of local resources (reduction of energy imports)	Expert evaluation	+
	soc4	Consumer control level over heat consumption	Expert evaluation	+

The technical dimension representing the technology competitiveness, the technical feasibility of DH and the different individual heating technologies. The technical dimension incorporates seven different indicators, such as heat production efficiency, complexity of technology maintenance, availability of necessary energy resources, opportunities for the diversification of utilised energy resources, possibilities for heat load optimisation, operational stability, and opportunities for utilisation of low-quality energy resources.

The environmental dimension outlines emission damage that heat supply technologies produce depending on their utilised energy resources and technical capacity to minimise the environmental impacts from production processes. Two main indicators are utilised to characterise the performance of environmental dimensions of technology, such as specific CO_2 emissions and the complexity of flue gas cleaning.

The economic dimension includes all of the relevant cost positions that are associated with the specific heat production technology, such as the initial capital expenditure, service and maintenance costs, technology lifetime, energy resource costs, as well as the possibility to utilise surplus heat and opportunities for cost optimisation (e.g., the choice of the energy resource based on the most economically advantageous price in the market, opportunities for the economies of scale).

The social dimension represents both the socioeconomic impacts of technology and consumer satisfaction levels with certain technology characteristics. The socioeconomic aspects are measured by technology's ability to create a positive socioeconomic impact by promoting the utilisation of local resources. The consumer satisfaction level is measured for overall comfort, safety (reduced risks of ignition, leakage, etc.), and control over heat consumption.

2.2.2. Data collection and expert evaluation

Quantitative indicator values for each technology were determined based on two main approaches: quantitative and qualitative assessment. For the indicators where the specific values could be found from publicly available databases, scientific papers, research and reports, legislation, and technology data sheets, data were collected from relevant sources of information. These indicators were the following: technology efficiency (tech1), specific CO_2 emissions (env1), specific capital investments (econ1), specific service and maintenance costs (econ2), technology lifetime (econ3), and specific energy costs (econ4). All the utilised data inputs and data sources for quantitative indicators are listed in Table 2.2.2.

Table 2.2.2

Data and assumptions for district heating and individual heating technologies

Indicator	No.	Unit	Data source	District heating	Wood pellet boiler	Natural gas boiler	Solar collectors	Heat pump
Efficiency	tech1	%	[117], [119]	100	80	92	82 *	257
Specific CO_2 emissions	env1	g/kWh	[120], [121]	202	0	202	0 *	42 *
Capital investments	econ1	EUR		6175	10,740	6440	23,980 *	16,243
Service and maintenance costs	econ2	EUR/year	[23]	0 *	605	255	300 *	360
Technology lifetime	econ3	years	[23], [122]	25	20	19	30	20
Specific energy costs	econ4	EUR/kWh	[123]	0.036	0.038	0.04	0 *	0.058 *

* Author calculations.

Most of the data inputs for district heating, wood pellet boilers, natural gas boilers and heat pumps were taken from the Danish study [117] on the cost-effectiveness of district heating compared to individual heating technological solutions [18]. This was the most reliable data for determining specific values for district heating technologies and for achieving the current research objectives.

Economic data on initial capital investments and yearly service and maintenance costs represent the average household expenditures with an annual heat demand of 13,800 kWh. Data for the heat pump represents the average values for ground and air heat pump parameters.

Data on solar collector nominal efficiency and technology lifetime were assumed based on average values observed from technical data sheets of solar collector technology manufacturers.

The efficiency of solar collectors was calculated using the following formula (2.2.1.):

$$\eta = \eta_0 - \alpha_1 \frac{T_1 - T_2}{G} - \alpha_2 \frac{(T_1 - T_2)^2}{G},$$

(2.2.1)

Where

η - solar collector efficiency [%],

η_0 - zero heat loss efficiency of the solar collector [%],

α_1 - the heat loss coefficient [W/m^2 K],

T_1 - the average temperature of the solar collector [°C],

T_2 - the air temperature [°C],

G - the solar radiation intensity [W/m^2], and α_2 is the temperature-dependent heat loss coefficient [W/m^2 K^2].

The values for the coefficients η_0, and α2 were taken from data sheets of high-performance plate solar collectors, which correspond to the values from the study by [96].

Plate collectors are more widespread and used in the EU and Latvia. Table 2.2.3. summarises the input data used to calculate the efficiency of solar collectors. To estimate the maximum potential of the solar collectors, the values for T_2 and G were determined for May, since solar radiation is highest in this month.

Table 2.2.3

Input data for the solar collector efficiency calculation

Parameter	Value	Justification
η_0	81.7	According to technical specifications in [124]
α_1	2.741	According to technical specifications in [124]
α_2	0.0147	According to technical specifications in [124]
T_1	70	Assumed average temperature value of solar collector in a range of [60;80] °C
T_2	12.4	Average temperature in Riga, Latvia in May according to Cabinet of Ministers Construction Standard LBN 003-19 "Construction Climatology" (entered into force on 21 September 2019)

G	172,540	Average solar radiation in May in Riga, Latvia in the period from 2015 to 2017

The solar collector absorption area was calculated by deriving the following equation:

$$Q \text{ (kWh)} = S \cdot \eta \cdot R \cdot PR$$

<div align="right">(2.2.2)</div>

Where

S - the solar collector absorption area [m^2],

η - the solar collector efficiency [%],

R - the average solar radiation intensity [kWh/m^2]

PR - the solar system heat loss factor (coefficient in a range from 0.9 to 0.95) (Table 2.2.4).

<div align="right">Table 2.2.4</div>

<div align="center">Input data for the solar collector absorption area calculation</div>

Parameter	Value	Justification
Q	13,800	Assumed heat demand of an average household according to [117], [125]
η	82	According to the calculated solar collector efficiency based on the technical specification of flat plate solar collectors in [124]
R	173	Average solar radiation in May in Riga, Latvia, in the period from 2015 to 2017
PR	0.9	Assumed solar system heat loss factor (coefficient in a range from 0.9 to 0.95)

The investment costs for solar collectors were calculated for households with an average heat demand of 138,000 kWh, based on the average solar radiation in Latvia and assuming that the solar system's specific cost is 220 EUR per m^2 of the solar collector's absorption area. For a heat demand of 13,800 kWh, the solar collector's calculated absorption area is 109 m^2.

Specific CO_2 emissions for wood pellet boilers and natural gas boilers were assumed based on the Latvian Cabinet of Ministers Regulation No.42 on the methodology for Calculating GHG Emissions [121]. For the district heating unit, specific CO_2 emissions were determined, assuming that all energy is produced by natural gas. For heat pumps, specific CO_2 emissions were calculated based on the specific electricity emission factor of 109 g/kWh [120], taking into account the Coefficient of Performance (COP) of 2.57. Similarly, specific energy costs for heat pumps were calculated assuming the average electricity price is equal to 0.15 EUR/kWh [126] considering COP of 2.57. Therefore, both indicators - specific electricity emission factor and specific energy cost for heat pumps - were calculated by dividing the representative values of electricity price and emission factors with COP.

Specific energy costs for district heating and natural gas boilers were taken from the Central Statistical Bureau of Latvia and Eurostat databases, given the average values for the year 2019. Specific energy costs for wood pellets were taken from price surveys of energy producers.

The values of indicators representing particular technologies' qualitative characteristics were determined through an expert evaluation survey. Indicators were evaluated according to an 8-point impact scale, as summarised in Table 2.2.5.

Table 2.2.5

Evaluation scales for the indicator assessment

Score	Impact
1	None
2	Very low
3	Low
4	Relatively low
5	Moderate
6	Relatively high
7	High
8	Very high

In total, the assessment of qualitative indicators was carried out by a selected group of high-level industry experts who have gained extensive professional and scientific experience and knowledge in heat generation, heat supply, and the energy sector. The experts evaluated indicators based on the observations and knowledge obtained over several years of working on heat supply systems, energy-related projects and on-site objects. Each expert was asked to assign a score for each indicator based on the given impact scale. The final score for each technology was calculated as the mean of all the surveyed experts' assigned scores.

2.2.3.   Calculation of the CSI

The min-max normalisation is the most suitable for this study since the sustainability assessment includes both quantitative and qualitative indicators. As indicated in the expert evaluation, the assessment of qualitative indicators has a specifically defined scale from 1 to 8, so these values are taken as minimum and maximum values in the calculation during the normalisation procedure.

Weighting was performed in order to proceed with indicator aggregation into representative sub-indices and the final CSI. After data normalisation, weights are assessed by a two-step procedure. At first, equal weighting is applied to calculate sustainability dimension sub-index scores using equation 2.1.3. Then the analytical hierarchy process (AHP) method is utilised to account for the different impact scales of each dimension to the overall CSI.

2.2.4. Multi-criteria analysis

Multicriteria Decision-Making (MCDM) is a decision-making method used to make effective decisions by evaluating possible alternatives considering several specific criteria [127]. One of the methods used in MCDM is AHP, which is considered effective for use in research in various fields. With the help of AHP, it is possible to quantify the weight or significance of the relevant criteria. AHP consists of a formulation phase, hierarchy structure, comparison of pairs of criteria, weighting of criteria, consistency check and analysis of the obtained results. First, the criteria are defined, then the importance of the requirements is compared across pairs of criteria, and values are assigned to them on a scale of one to nine. The weighting of the criteria is vital in the further course to enable a ranking of the alternatives [127]. W_j is the impact weight of the dimension sub-index on the CSI (determined from AHP).

The application of equal weights into dimension sub-index scores represents each indicator's equal contribution and importance on the overall performance of the representative dimension [128]; however, AHP was chosen when selecting weight values for sustainability index aggregation. In the AHP method, the assessment is based on pairwise comparison, evaluating the significance of the criterion in comparison with another criterion.

Criteria were first defined, followed by a comparison of their significance across the criteria pairs, assigning them values on a scale of 1 to 9 according to the Saaty rating scale summarised in Table 2.2.6. [127]. Using the AHP method, it is possible to evaluate nine criteria at the same time [129].

Table 2.2.6

Saaty rating scale

Score	Explanation
1	Equal importance
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2, 4, 6, 8	Intermediate values

Experts were asked to compare four different dimensions according to which sustainability of technologies was compared. A calculations matrix was created based on Equation (2.2.3), where all four criteria were supplemented with the raw data obtained from the expert surveys.

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \end{bmatrix}$$

(2.2.3)

According to expert opinion and after performing the AHP calculation procedure, the following weights were obtained for each dimension: technical (0.38), environmental (0.36), economic (0.16), and social (0.10). The obtained weighting values were validated by calculating the consistency ratio where the obtained results reached the necessary threshold of 0.1.

The development process included testing various weighting methods to verify the robustness of the results obtained. When equal weights for the dimensions were given, no significant changes in the overall distribution of results were observed.

Fig. 2.2.2. outlines the overall hierarchy of the developed CSI with indicators for the district and individual heating comparison.
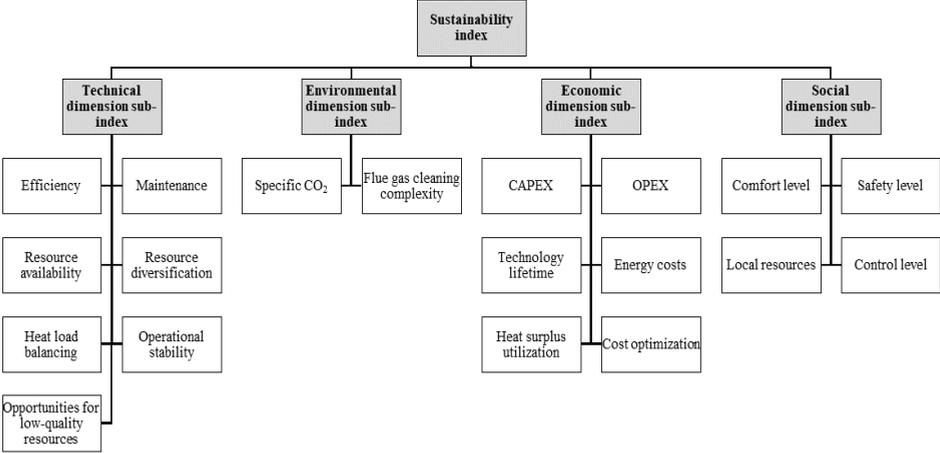
Fig. 2.2.2. The basic hierarchy of the CSI [119].

The sustainability index calculation outcomes could be further utilised to make more constructive and reasonable decisions related to achieving long-term targets for a low-carbon economy. The sustainability index results permit preliminary due diligence of technology sustainability, identify possible controversies requiring immediate governmental intervention to eliminate risks associated with sustainability, and reassess current policies that govern the heat production sector.

2.3. District heating resilience in municipalities

The main research questions of the study were the following: how do different heat production technologies and fuel mixes impact the recovery time and economic performance of DH systems, and what are the key factors that determine the resilience of DH systems in maintaining affordable heat prices. These two research questions are

answered by defining, measuring and comparing two different resilience concepts of DH systems: inherent resilience and adaptive resilience.

Ten different DH systems in Latvia with various heat production technologies and fuel mixes and their heat price changes from 2021 to 2023 were analysed. For constructing the DH resilience CI, indicators were selected and grouped into four dimensions: technical, economic, environmental, and social. The DH resilience CI merges **fourteen** different criteria and compares which DH systems are more resilient to extreme changes in external conditions.

This study's resilience assessment for DH systems measures two different resilience concepts: adaptive resilience and inherent resilience. According to Feofilovs [130]. Adaptive resilience is used to assess how quickly DH systems can adapt to extreme external changes. Inherent resilience, on the other hand, shows how ready DH systems are for various external conditions.

First, the heat tariff changes have been analysed by indicating the adaptive resilience of DH systems. Afterwards, the inherent resilience assessment of DH systems was done to fully estimate the DH system's ability to adapt and impact different external conditions.

The main research steps for the assessment of the adaptive and inherent resilience of different DH systems in Latvia are shown in Fig. 2.3.2. First, the literature analyses and data collection were done by gathering public information and necessary data from companies, identifying the impacting factors and calculating the selected indicators. Further, adaptive resilience assessment includes the analyses of heat tariff variations, determination of recovery phases, and calculation of heat tariff resilience factor. To measure inherent resilience, a criteria matrix was developed, normalised, and weighted to determine the DH resilience CI. It also includes the aggregation of indicators. Finally, the sensitivity analysis was performed by changing the weights of the dimensions.

The adaptive and inherent resilience measured was verified by comparing both values for each DH system.
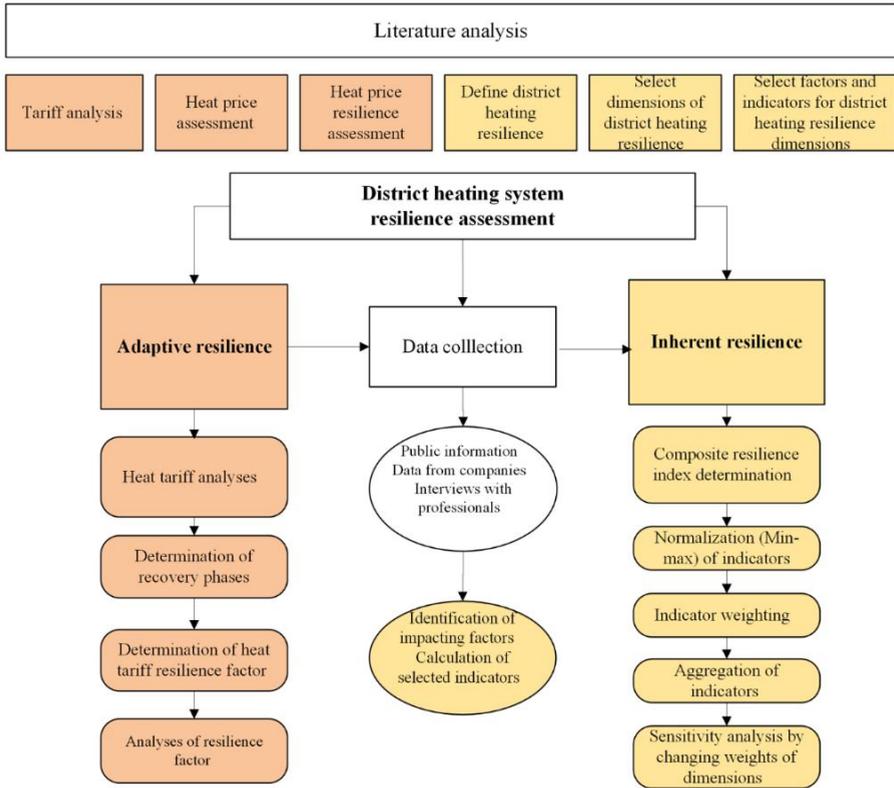
Fig.2.3.2. Main research steps for characterisation of the inherent and adaptive resilience (made by author).

2.3.1 Adaptive resilience

In this research, the stability of heat energy tariffs was examined to determine the adaptive resilience of DH systems. This allows for determining the system's capacity to adapt to changing external conditions, including economic factors [48].

The general transformation processes of the energy system during the collapse and recovery phases distinguish three states: the original state (S_0), the disruption state (SD), and the stable recovered state (SF). There are also two transitions between these states: system disturbance (from the initial state to the disruption state) and system recovery (from the disrupted state to the stable recovered state). These processes and states are linked by two key events that trigger the situations mentioned above: the moment of disruption and the resilience actions. The system operates stably until a disturbance (either internal or external) occurs at a specific point in time,

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leading to the disruption of the previously stable system. The same approach has been applied to analyse the changes in the heat price of DH systems [48].

Ten of the Latvian DH systems underwent heat tariff analyses from 2021 to 2023. The technical properties of each DH system are shown in Table 2.3.1.

Parameters of DH energy systems

No.	Fuel mix, %	Total heat produced, MWh	Heating network length, km	Municipality-owned/privately owned	Installed heat capacity, MW
DH1	RENEWABLES 90% GAS 10%	64116.7	20.6	municipality-owned	37.7
DH2	BIO 58% GAS 42%	147709	59	municipality-owned	78.6
DH3	GAS 99%, BIO 1%	28399	2.3	municipality-owned	19.3
DH4	GAS 67%, BIO 33%	145930.7	40.2	municipality-owned	111.9
DH5	BIO 93%, FOSSIL ENERGY (gas, coal) 7%	162595.7	55.1	municipality-owned	122.9
DH6	BIO 100%	30879	12.1	privately owned	17.7
DH7	BIO 82% GAS 18%	36089.7	18.8	municipality-owned	15.9
DH8	BIO 93%	29880	16	privately owned	25.3
DH9	BIO 100%	28593	9.6	municipality-owned	22.4
DH10	BIO 100%	27622	13	municipality-owned	20.2

The heat tariff analyses were done based on the following data:
- Heat energy tariff;
- Fuel costs;
- Types of fuel that affect tariffs.

To determine tariff stability and adaptive resilience factor, the proposed method of Francis and Bekera [51] was applied. The resilience of the heat supply system tariff was calculated by determining the resilience factor ρ_i. It considers the speed of DH recovery after high resource price increases, Sp, the initial heat tariff T_0 and heat tariff directly after the resource price increase, T_d, and the performance levels in the new stable state T_r (Eq.2.3.1).

$$\rho_i = S_p \frac{T_r}{T_0} \frac{T_d}{T_0}$$

(2.3.1)

Where

ρ_i - a resilience factor for DH system i;

S_P – Speed recovery coefficient;

T_0 – the initial stable performance level of the system, EUR/MWh; T_d – performance level immediately after the disturbance, EUR/MWh;

T_r – performance in the new steady state, EUR/MWh [51].

The speed recovery factor depends on the disturbance time t_δ, the time until the final system recovery t_r and the time to complete initial recovery operations $t*_r$. If, $t_r \geq t*_r$, then Sp is calculated according to Eq.2.3.2.

$$S\rho = \left(\frac{t\delta}{t*_r}\right) \exp[-a(t_r - t*_r)]$$

(2.3.2)

Otherwise, Eq. 2.3.3 is applied.

$$S\rho = \left(\frac{t\delta}{t*_r}\right) \exp\left[- a \left(\frac{t\delta}{t*_r}\right)\right]$$

(2.3.3)

Where t_r – time until the final system recovery; t_δ – disturbance time, month; $t*_r$ – time to complete initial recovery operations, month; a - a parameter that controls the decrease in elasticity (assumed to be 1) [51].

The chosen calculation method combines factors characterising the operation of the energy system: current operation, the moment of disturbance (or sudden tariff change), the return to a stable state - where the tariff stabilises after the crisis - as well as the time spent in the crisis and the period from the end of the crisis to the stabilisation of the tariff.

2.3.2. Inherent resilience

An inherent resilience assessment was made using the data for the same ten DH heat supply systems in Latvia (see Table 2.3.1) with different heat energy production technologies and fuel mix and their heat price changes from 2021 to 2023. The sustainability of each DH energy system can be assessed using combinations of indicators in different sustainability dimensions. The composite DH resilience index aggregates various indicators into one index for each of the ten DH energy systems. Studies show that the DH resilience CI method can be used in the decision-making process as a valuable instrument for choosing sustainable heating system solutions [14].

Defining criteria for the DH resilience CI

The first step in evaluating the inherent resilience of different DH energy systems is to select appropriate criteria, which include economic aspects, environmental impact, technical properties, and criteria for assessing social impact [14]. The design criteria for the

DH energy system focus on consistent performance, including the type of energy source, infrastructure, consumers, and capacity. The system's ability to withstand and recover from disruptions and adapt to changing conditions should also be considered.

To select the most appropriate criteria, a literature analysis was performed first on factors that affect DH energy resilience and sustainability [43]. The criteria were selected to consider the possibilities of transforming the existing DH system to the latest generation network system to increase DH resilience. The challenges and benefits of these transitions were mainly analysed from the perspective of current energy demand and supply scenarios, the goal of abandoning fossil fuels, and the increase in the share of RES.

According to studies [48], DH resilience should take into account various aspects of sustainability as well as technical conditions [48]. For the construction of the DH resilience CI, factors that influence DH systems sustainability were divided into dimensions that characterise and summarise different aspects of DH system conditions, including 1)technical dimension, 2)economic dimension, 3)environmental dimension and 4)social dimension. Fig. 2.3.3. shows a methodology for the establishment of the [26] Composite DH resilience index for different energy systems, taking into account four dimensions.
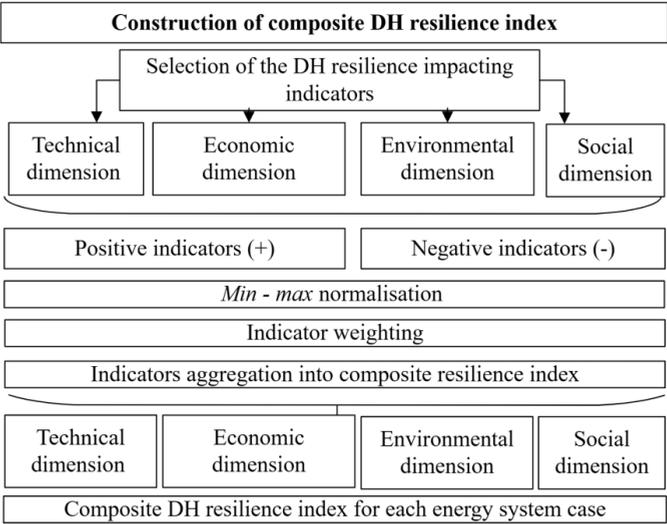
Fig. 2.3.3. The framework of the construction of the Composite DH Resilience index.

In this study, indicators in the technical dimension describe the DH energy system's technical ability to withstand unforeseen disturbances and produce heat for consumers. The technical resilience of the DH energy system describes its robustness against short-term or long-term disturbances [33].

The economic dimension of the existing DH system refers to financial and economic aspects related to improving and maintaining resilience in an existing energy system to ensure affordable heat to consumers. The environmental dimension aspects of DH resilience refer to how the system adapts to more sustainable energy production based on the climate change impact on energy production regulations. The Social dimension of DH resilience signifies the competitiveness of the system compared to other DH systems, affordability for consumers and ability to maintain the supply of heat energy [23].

Identification of impacting indicators

After defining different dimensions of DH system sustainability, appropriate indicators were selected for each dimension.

Methodology for the selection of indicators based on:

1. The aim of the study;

2. literature review - scientific publications and technical reports;

3. Factors based on previous literature on energy crisis and resilience impacting factors Scientific indicators were selected based on the following criteria: relevance, data availability and data credibility [132]. Indicators impacting DH resilience are listed in Fig. 2.3.4.
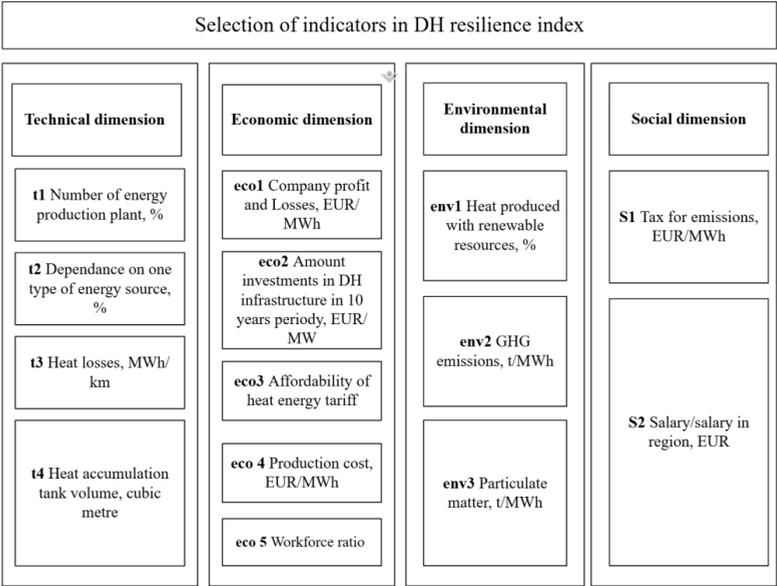
Fig. 2.3.4. Selected indicators for the construction of DH resilience CI.

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Each DH resilience dimension has a list of indicators. Indicators either positively impact the resilience of DH systems (e.g., a share of renewable energy in DH systems) or negatively impact resilience (e.g., production costs) [11]. For each of the selected indicators, a specific unit characterises them for further calculation of indicator value. A list of indicators in each of the dimensions is shown in Tables 2.3.2 – 2.3.5.

Table 2.3.2

Selected indicators of the technical dimension of DH resilience

|	Indicator	Unit	Indicator description and justification	Impact on resilience
t1	Diversification index of heat production sites [52], [133], [134]	DI_{prod}, %	Heat production depends on one or several DH production facility plants. It characterises how much heat production depends on a single production site (boiler house or cogeneration plants). The index shows the rated heat capacity of each production site according to the Herfindahl–Hirschman indicator (HHI) calculation [52]. If heat production relies on a single energy resource, it would negatively impact the resilience of the energy system. Evaluating the technical aspect of dependence on one heat production place, HHI result would be close to 10,000, which would mean complete dependence on one place of heat production [134]; a higher value indicates a negative impact on DH resilience.	–
t2	Diversification index of resources and production mix [52], [133], [134]	Resources, %	Depends on the type of energy source. The indicator describes the diversification of resources in the total heat production mix and how much is produced from each heat source [52]. Heat production in the DH company depends on one type or several types of energy sources, which is measured using the Herfindahl-Hirschman indicator. Indicator. [134]. A higher HHI result value indicates a negative impact on DH resilience.	–
t3	Heat losses [52], [133], [135]	MWh/km	Describes the heat losses per km of piping network. Heat losses through the heating network also have an impact on the heat production tariff [52], [133], [135].	–
t4	Accumulation capacity [136], [137]	m^3/MW	Accumulation volume in m^3 against the total heat produced in MW. Characterises whether a DH company can offer the possibility to continue energy production using the accumulated energy in case of system interruptions. The capacity of the heat storage site is used as an indicator. An accumulation tank is added to the DH system to cope with peak loads and store heat produced at a lower cost, like a solar collector park or waste heat in production processes [136], [137].	+

The diversification index of the heat production sites (*t1*) shows the dependence on one or several DH production facility locations, which is measured by applying the general framework of the HHI [133] by using (Eq.2.3.4).

$$DI_{prod} = s_1^2 + s_2^2 + s_3^2 + \cdots s_n^2$$

(2.3.4)

Where n – heat capacity share of the heat production site in the total installed heat capacity of the DH system, n - represents the total number of production sites [24], [26].

The diversification of heat sources is a significant factor in increasing the DH system's ability to withstand resource shortages or significant price changes. Therefore, the diversification index of heat production sites (*t2*) measures the share of particular heat sources in the total fuel mix of the DH system, similarly to t1, applying the HHI index determination methodology [134]. Lower indicator values show higher diversification rates and less risk in heat production.

Heat losses in heating networks reduce the efficiency of the entire DH system [27]. Therefore, specific heat losses (*t3*) in the piping network are expressed as total MWh related to the total piping network distance in km. Heat losses are calculated according to (Eq. 2.3.5). Higher results negatively impact DH resilience as more heat is lost per km of network.

$$Q_{los} = \frac{Q_{prod} - Q_{supl}}{L_{pipes}}$$

(2.3.5)

Where Q_{los} –heat losses in MWh/km; Q_{prod} – total heat produced, MWh per year; Q_{supl} – total heat supplied, MWh per year; L_{pipe} – total pipe length in the network in km [4].

The accumulation capacity (t4) is a key indicator in the technical dimension of DH resilience. It is calculated according to Eq. 2.3.6, where the impact of the accumulation tank is based on its volume expressed as the maximum demanded heat production capacity. The availability of storage capacity has a significant positive effect on DH resilience by enabling the system to trip down peak load demand and maintain energy-efficient heat production.

$$HS = \frac{AC}{Q_{max}}$$

(2.3.6)

Where
HS – Heat storage m^3/MW;
AC – Accumulation tank volume, m^3;

Q_{max} – Maximal demanded heat capacity, MW [140].

Five different criteria have been identified to describe DH's economic stability. These criteria indicate the financial reliability of the heat energy supply to secure a constant energy resource supply, proper business management, and reasonably priced services (see Table 2.3.3).

Table 2.3.3

List of indicators of the economic dimension of DH resilience

	Indicator	Unit	Description of the indicator	Impact on resilience
eco1	Rate of company profit and losses [11]	EUR/MWh	The ratio of the profit loss indicator is divided by the delivered heat. Describes the economic stability of DH production company [11].	+
eco2	Subsidised investments in DH	EUR/MW	10-year investment volume ratio to production capacity. The indicator describes how much has been invested in the implementation of centralised heat supply infrastructure improvement projects in the last ten years.	+
eco3	Affordability of heat energy tariff [43]	MWh/average salary	The average tariff ratio to the county's average insurance contribution salary or gross salary. Heat tariff shows how affordable it is for consumers [43].	+
eco4	Production cost [48]	EUR/MWh	The ratio of average production costs/heat produced. Describes the efficiency of heat production [48].	–
eco 5	Workforce [48]	Employees/ MWh	The ratio of the number of workers to the amount of heat produced shows how many people in the region are integrated to produce energy [33].	–

The rate of Company Profit and Losses (*Eco1*) is calculated according to Eq. 2.3.7 by the total profit or loss amount in EUR divided by the total heat supplied to consumers in MWh. It shows how financially healthy the company is. A lower score has a negative impact on resilience due to possible financial losses. If DH is municipality-owned, it may be expected to be a non-profit or low-profit business if it is part of the municipality's strategy.

$$P\&L\ rate = \frac{Profit-losses}{Q_{supl}}$$

(2.3.7)

Where *P&L* is – the company's profit and losses, EUR per year; Qsupl is the total amount of heat supplied to consumers, MWh per year [141].

Subsidised investments in DH *(Eco2)* show the amount invested in DH infrastructure and are calculated according to Eq.2.3.8, where the amount invested in DH infrastructure in the last ten years is divided by the total capacity of DH utility. Projects with EU subsidies are considered the most significant investments in energy efficiency and technology improvement, which are positively impacting DH resilience.

$$SInv_{intens} = \frac{Inv}{Q_{inst}}$$ (2.3.8)

Where Inv_{intens} – total investments in last ten years, EUR/MW.

The affordability of heat energy tariff (*Eco3*) describes the affordability of heat for consumers. The heat tariff is divided by average household income into specific regions (Eq. 2.3.9). As a result, affordability is the amount of MWh a household can afford with an average income level (2021-2023) in specific regions. Higher results positively impact resilience as it shows customers' ability to afford heat.

$$Aff = \frac{I}{T}$$

(2.3.9)

Where *Aff* – Affordability in MWh; *I* – Average income in a specific region, EUR; *T* -DH energy tariff EUR/MWh [30].

The production cost ratio (*Eco4*) is calculated according to (Eq. 2.3.10), dividing the total production cost by the total heat produced. DH supply to consumers is expected to be efficient, economically feasible, and produced with low profit. Therefore, a lower indicator result shows a company with low heat production costs, positively impacting its resilience.

$$Production\ Cost\ ratio = \frac{Production\ cost}{Q_{prod}}$$

(2.3.10)

Where production costs – total cost of production, EUR per year [48].

The workforce indicator is calculated according to (2.3.11). The formula uses data on the total workforce and specific salary in the region. Lower indicator results show a higher level of automated heat production process, network maintenance, and administration and lower production and operation costs, positively impacting its resilience.

$$Workforce\ ratio = \frac{Workforce}{Salary\ in\ region}$$

$$(2.3.11)$$

Where:

Workforce – total number of employees in the company (average value from 2021-2023).

The environmental dimension of DH resilience is included to quantify the environmental aspects (see Table 2.3.4).

Table 2.3.4

List of indicators of the environmental dimension of DH resilience

	Indicators	Unit	Description of the indicator	Impact on resilience
env1	RES share [48], [52], [135]	%	The ratio of the amount of energy produced by renewable energy to the total heat produced [52].	+
env2	CO_2 emissions [46], [135]	t/MWh	CO_2 emissions per MWh of heat produced show the amount of CO2 emissions that create specific DH systems to produce heat [50], [148], [46], [135].	–
env3	Particulate matter (PM) emissions [46], [135]	Kg/MWh	PM emissions per MWh of heat produced show the amount of PM emissions that create specific DH systems to produce heat [135].	–

The share of renewable resources (*env1*) is calculated as the total energy produced from renewables (biomass and solar collectors) divided by all energy produced according to Eq. 2.3.12. Higher results positively impact DH resilience, showing a climate-neutral way of heat production.

$$Q_{renew}\% = \frac{Q_{renew}}{Q_{prod}}$$

$$(2.3.12)$$

Where Q_{renew} % – share of energy produced with renewable resources %; Q_{renew} – energy produced with renewable resources, MWh.

Specific CO_2 emissions from fossil fuels (*Env2)* per MWh of heat produced [143] (part of the CO_2 emissions) were evaluated. Higher emission rates negatively impact the climate and DH resilience. The CO_2 emission factor of a district heating system in tCO_2/MWh heat [143] allows for evaluating how clean the energy sources are and whether renewable energy is used to decarbonise the system (Eq. 2.3.13).

$$CO_2 = \frac{\sum_{n=1} F_{CO2,n} * Q_{prod,n}}{Q_{prod}}$$

$$(2.3.13)$$

Where CO_2 -specific amount of CO_2 emitted, t/MWh; FCO_2 - emission factor for fuel n t/MWh; Q_{prod} - Amount of energy produced from fuel n, MWh per year [144].

The following CO_2 emission factors for fossil fuels were used: natural gas—0.202 t/MWh [158]; diesel fuel—0.279 t/MWh; and coal—0.264 t/MWh [135].

The dust particle pollution indicator (*env3*) quantifies the total particulate matter (PM) emissions per delivered heat. This equation has been adapted for the determination of PM10 emissions based on the CO_2 emissions methodology [143]. It is expressed as tons of PM per MWh of heat produced [143] (Eq. 2.3.14).

$$PM = \frac{\sum_{n=1} F_{PM,n} * Q_{prod,n}}{Q_{prod}}$$

(2.3.14)

Where PM– specific particulate matter emissions, kg/MWh; FPM_{10} – Particulate matter PM_{10} factor of emissions (mg/MWh); $Q_{prod,\,n}$ - Amount of energy produced from fuel n, MWh per year.

The used PM emission factor of wood chips and wood pellets is 47.15 g/kWh [83]. This is the average value of the PM_{10} emission factor for a pellet boiler (<1 MW) and a wood chip boiler (> 1 MW) [135].

Table 2.3.5. shows inficators in social dimension.

Table 2.3.5

List of indicators of the social dimension of DH resilience

	Indicator	Unit	Description of the indicator	Impact on resilience
s1	Tax of fossil fuel and emissions [48]	EUR/MWh	Tax of fossil fuel and emissions. Amount of emissions tax per MWh heat supplied [48].	–
s2	Salary competitiveness [46], [48]	EUR/EUR	Competitiveness of the workplace in the region. Salary in DH energy system/salary in the region [46], [48].	+

The total amount of tax for emissions (*s1*) (GHG, CO_2, PM) is calculated and divided by the energy sold to consumers (2.3.15). Higher results have a negative impact on DH resilience from the social dimension.

$$Tax_{em} = \frac{(Q_1 * EM_1) + \cdots + (Q_n * EM_n)}{Q_{supl}}$$

$$(2.3.15)$$

where TAX_{em} – Total emission tax amount to MWh heat produced, EUR/MWh; Q_n – Amount of energy source, MWh; Q_{supl} – total heat supplied in MWh; EM_n – Tax amount EUR/MWh

The salary competitiveness indicator (*s2*) is calculated according to (2.3.16).

$$\text{Salary competitiveness} = \frac{\text{Salary in DH company}}{\text{Salary in region}}$$

$$(2.3.16)$$

The salary in a DH company is the total salary (based on 2022 and 2023 year average values) divided by the number of employees.

Salary in the region – average salary in a specific region during the 2021-2023 time period, EUR per month.

To characterise the resilience of the DH heat supply in ten cities, data for the years 2021 to 2023 were collected from various sources: official databases, statistics regarding emissions, and annual financial reports.

2.3.3 Construction of DH resilience CI and sensitivity analysis

In normalisation, it should be taken into account that each of the indicators has a positive or negative impact on the overall DH resilience CI, as indicated in the previous section in Tables 2.3.2 – 2.3.5.

Each indicator received equal weight. In this case, the same weight (0.25) was applied to each indicator, which shows the same importance for each of the dimensions [48]. The final step is to aggregate the DH resilience CI results by multiplying them by the normalised indicator value (see chapter 2.1.).

To validate the effect of different dimension weights on the results, a sensitivity analysis was performed with different weights. In this case, the focus was on changes in the weights of the technical and economic dimensions. Table 2.3.6 shows values for sensitivity analysis, prioritising economic and technical dimensions.

Table 2.3.6

Weight of the dimension prioritising economic and technical dimensions

Dimension	Weight of dimensions, prioritising the economic dimension	Weight of dimensions, prioritising the technical dimension

Economic dimension	0.40	0.20
Technical dimension	0.20	0.40
Environmental dimension	0.20	0.20
Social dimension	0.20	0.20

2.4. Carbon-neutral municipalities

The objective of the research was to understand exactly how, in certain municipal buildings of residents (residential buildings with multiple apartments) that have a centralised heat supply using fossil fuels (natural gas) and in municipal buildings using individual natural gas boilers, a partial or complete conversion to RES heat supply solutions is possible. In the specific municipality, the issue of how to transfer the residential and municipal buildings sector from natural gas to RES is important for the municipality's progress in meeting the goals of the NECP.

The study examines two scenario complexes, including individual heating solutions in buildings or DH solutions with a centralised approach. It evaluated several alternatives to increase the share of RES (e.g., solar collectors, biomass, heat pumps, etc.) in the centralised heat supply. The study was carried out based on real data on thermal energy consumption and scientific data sources to make the assumptions.

CI was created to evaluate the most sustainable RES heat supply solutions (technology combinations) that could replace the natural gas solutions used in DH and IH in Carnikava village.

DH system

DH system consists of six interconnected boiler houses and heating networks. The total length of the heating networks is 2837 m, of which 1156 m is industrially insulated. All boiler houses have natural gas boilers with different capacities, from 520 kW to 1500 kW. The main data are shown in Table 2.4.1.

Losses in heating networks range from 15% to 17%. The loss value indicates that the heat transmission infrastructure is inferior. The main reason is the preparation of hot water outside the heating season.

Table 2.4.1

Major data on DH in the specific area

Parameter	Unit	2019	2020	2021
Natural gas consumption	1000 m^3	1076.01	1024.16	1185.29
Share of RES	%	0 %	0 %	0 %

Fuel input energy	MWh per year	10 274.8	9756.4	11 247.9
Thermal energy produced	MWh per year	9308.8	8764.0	10 085.4
Electricity produced	MWh per year	0	0	0
Production losses	MWh per year	965.9	992.4	1162.5
Efficiency of production	%	90.6 %	89.8 %	89.7 %
Thermal energy transferred to users	MWh per year	7792.0	7263.4	8617.9
Losses in heating networks	MWh per year	1516.9	1500.6	1467.6
Losses in heating networks	%	16.3 %	17.1 %	14.6 %

Municipality buildings

Municipal buildings are very diverse in terms of their functionality and building characteristics, and they are not connected to the DH system. Table 2.4.2 contains a summary of the technical parameters of municipal buildings. Each parameter was obtained using the information provided by the municipality, data on electricity and heat energy, and calculations based on real and scientific assumptions.

Table 2.4.2

Technical parameters of municipal buildings used in the case study

Parameter	Unit	Elementary school	Preschool	Cultural centre	Music & art school	Leisure centre	Office building
Technical condition	–	Renovated	–	–	–	–	Built-in 2020
Heating area	m^2	7398	2643	769	258	150	2343
Roof area	m^2	2301	2622	460	212	192	2970
Heat consumption	MWh per year	318	486	97	36	16	215
Electricity consumption	MWh per year	237	124	21	5	4	60
Max heat load	kW	110	130	35	12	10	57
Fuel type	–	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas

Analysing the specific energy consumption of municipal buildings, the buildings with the highest specific energy consumption were preschool, music and art school and culture centre

buildings (see Fig. 2.4.1). Preschool, music, and art schools had the highest specific heat energy consumption, but elementary schools had the lowest. Preschool and primary schools had the highest specific electricity consumption, while music and art schools had the lowest specific electricity consumption. On average, the specific electricity consumption was four times lower than the particular heat energy consumption. However, the most similar specific electricity and heat energy consumption was for the elementary school. Still, the biggest difference in the specific electricity and heat energy consumption was for the music and art school.
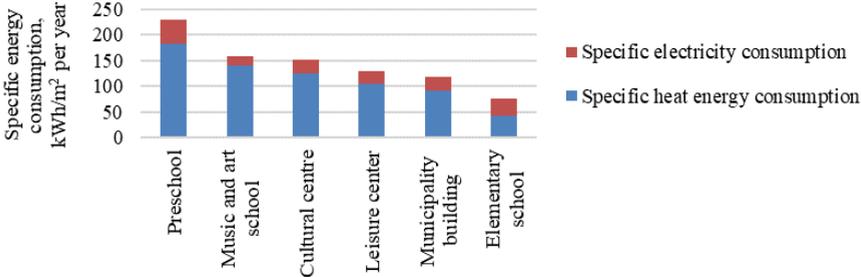
Fig. 2.4.1. Specific energy (electricity and heat) consumption in the case study.

Development scenarios

The existing DH solutions were natural gas - six local boiler houses and natural gas boiler houses in municipal buildings. To compare the sustainability of DH solutions and individual IH solutions, six DH alternatives were compared with four IH scenarios for the municipal buildings. The selection of technology combinations was carried out so that solutions with biomass - wood chips and pellets - , air heat pump solutions, which are considered economically easier to implement, as well as additional sources for covering the summer load, solar energy solutions - solar collectors for heat supply and electricity supply/ for operating the heat pump - solar panels (Table 2.4.3).

Table 2.4.3

Scenarios for district heating in municipal buildings

Scenarios	District heating	Municipal buildings
	with new consumers	
1.Wood chip boiler with flue gas condenser	1 boiler house with flue gas condenser	-
2. Wood chip boiler and PV panels + heat pump solution	+	-
3. Wood chip boiler and solar collectors with storage	+	-

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4. Natural gas boiler and solar collectors with storage		+
5. Pellet boiler	2 boilers	+
6. Pellet boiler and PV panels + heat pump solution	+	+
7. Pellet boiler and solar collectors with storage	-	+
8. Heat pump solution + PV panels		+

DH system

Six possible alternatives were defined for increasing the share of RES in DH. These alternatives can be introduced at the same time as implementing IH development scenarios. They mainly involve combining separate systems and heat networks:

      1.Wood chip boiler with flue gas condenser;

      2. Wood chip boiler and PV panels + heat pump solution;

      3. Wood chip boiler and solar collectors with storage;

      4. Pellet boiler;

      5. Pellet boiler and PV panels + heat pump solution;

      6. Pellet boiler and solar collectors with storage.

Woodchip boiler. In the scenario that envisages combining the five existing DH plants into one and connecting the municipal buildings, the construction of a woodchip boiler house was evaluated.

Pellet boiler. The construction of pellet boiler houses was evaluated in the scenario that proposes combining five existing DH systems into two separate systems and connecting municipal buildings to them. By creating two separate systems, the consumer load was slightly too low for using a wood chip boiler.

Woodchip boiler + solar collectors with storage. The scenario where solar collectors with storage are installed to cover the summer load was studied. In the case of a combined DH system, a woodchip boiler was used to cover the heating load.

Pellet boiler + solar collectors with accumulation. Considering that the consumers in the specific area are small and spread over a large area, it was planned to study the scenario where PV panels are installed in combination with an air-source heat pump to cover the summer load. They will be placed closer to the consumers. In the case of two separate DH systems, pellet boilers were used to cover the heating load.

Individual heating solutions

Four possible alternatives were defined for increasing the share of RES in the IH in municipality buildings and replacing natural gas boilers. Alternatives can be introduced at the same time as implementing DH development scenarios. There are four alternatives for IH solutions:

1. Pellet boiler.
2. Heat pump solution + PV panels.
3. Solar collectors with thermal energy storage and a natural gas boiler.
4. Solar collectors with thermal energy storage, and a pellet boiler.

Pellet boilers. One alternative was to replace natural gas boilers with pellet boilers that provide heating and hot water, solar panels, and a heat pump. The building has a summer heat load, so solar panels, which would generate electricity for the heat pump during the summer months, would be a good option.

Solar collectors. Assuming the building's roof is suitable for installing solar panels, solar collectors can be considered another heat energy alternative. Thus, solar collectors can meet the necessary summer heat load.

One of the alternatives was to replace the natural gas boilers with a pellet boiler that provides heating and hot water. The provision of thermal energy with solar panels and a heat pump was analysed as another technological solution since the heat pump does not require a large area, and the building has a large roof area that can be effectively used for solar panels. The electricity consumption of the heat pump can be covered in the summer months by using electricity from solar collectors. Therefore, this alternative evaluates the installation of both an air source heat pump and a solar power plant. In these scenarios, solar panels were considered to meet the summer load and the existing natural gas system or its replacement with a pellet boiler to meet the remaining heat load. Installation of solar collectors was not considered for buildings that have low summer hot water consumption or are heavily shaded. In addition to the solar collectors, a suitable buffer tank should be integrated to cover 2-3 days of consumption.

Decision-making analyses

Sustainability assessment requires an integrated approach and a structure of several interconnected steps. The methodology of this study is based on three main pillars:

The identification of the internal and external context that influences the sustainability of the heat supply system:

- The calculation of the CSI;
- The analysis of the results and the decision-making process.

Identifying the internal and external context includes a literature review of current practices in sustainability assessment of energy supply technologies to identify key sustainability issues and develop a research methodology.

In this study, the CSI was calculated for six district heating scenarios and four different technical solutions for decentralised (individual) heat supply. The share of solar collectors and PV panels was not considered in the efficiency calculation; however, solar collectors and PV panels were included in the investment calculations.

Identification of indicators

The second step was to identify and select appropriate criteria that are significant determinantss of the study's dependent variable. When identifying key indicators, it is crucial to consider data availability. Indicators such as fuel energy consumption (i1), specific NOx emissions (i2), specific PM emissions (i3), CO_2 reduction costs (i4), investments (i5), IRR (i6), production costs (i7), and opportunities for diversification of energy resources used (i8) were used to evaluate and compare the district heating and individual heating scenarios (Table 2.4.6).

Table 2.4.6

Indicators for the construction of CI for DH and IH technologies

No	Indicator	Units	Indicator description	(+/-)
i1	Consumption of fuel energy	MWh/MWh	The indicator considers only the consumption of used fuel energy and electricity from the grid. Fuel consumption/total energy production in MWh in each of the scenarios. The share of solar collectors and PV panels is not included in the efficiency calculation. Electricity consumption from the grid in scenarios with heat pumps is also taken into account.	–
i2	Specific NOx emissions	g/MWh	Gram per amount of energy produced in each of the scenarios	–
i3	Specific PM emissions	g/MWh	Indicates how many PM are produced from each MWh	–
i4	Costs of CO_2 reduction	EUR/t	Depending on the type of energy resource, the amount of CO_2 emissions produced varies. 0.202 (CO_2) emission factor, tCO_2/MWh. The total investment is divided per ton of CO_2. Describes how much to invest in each system.	–
i5	Investments	EUR/MWh	The investment required for the amount of energy produced	–
i6	Internal rate of return	%	Internal rate of return (IRR) or economic rate of return (ERR) characterises the interest rate at which investments in a given project are effective. If the IRR is greater than the discount rate, then the project is economically beneficial to society. The higher the value, the more efficient the project.	+
i7	Production costs	EUR MWh	Production costs include alternative fuel, electricity, service, and administrative costs.	-

I8	Opportunities for diversification of utilised energy resources (technology is not limited only to one type of energy resource supply	count	The energy resources are numerically evaluated to determine how much it is possible to use the energy resource in each of the scenarios, taking into account the production of electricity and thermal energy. Electricity and solar PV. How many energy sources are included in the solution. The number of energy resources in each of the scenarios describes the diversification of the utilised resources.	+

All scenarios were calculated based on the same input data (e.g., thermal energy consumption, thermal energy tariff, etc.) and assumptions (technology efficiency, technology investment and, operating costs, etc.). The assumptions were made based on scientific literature, technology catalogue manuals, findings of energy industry representatives and other sources. The most appropriate solution was selected based on the above indicators, including the internal rate of return (IRR), and CO_2 savings per amount of money invested. As an additional parameter, the amount of investment required was given, which describes the amount of money originally intended for implementing the project.

Calculations for each indicator

I1 Consumption of fuel energy (Eq. 2.4.1-2.4.3)

$$\text{Consumption of fuel energy} \left(\frac{\text{MWh}}{\text{MWh}}\right) = \frac{\text{fuel consumption} * \text{fuel's lowest heat of combustion}, \frac{\text{MWh}}{\text{m}^3}}{\text{total energy production}, \frac{\text{MWh}}{\text{year}}}$$

(2.4.1)

Example for calculations DH Wood chip boiler with flue gas condenser (Eq. 2.4.2; 2.4.3)

$$\text{Consumption of fuel energy} \left(\frac{\text{MWh}}{\text{MWh}}\right) = \frac{\text{wood chip consumption} * \text{wood chip lowest heat of combustionn}, \frac{\text{MWh}}{\text{m}^3}}{\text{annual amount of energy produced}, \text{MWh/year}}$$

(2.4.2)

Where,
Wood chip consumption – 10876 ber/m
Wood chip lowest heat of combustion – 0.7 MWh.ber/m^3
The annual amount of energy produced – 7689 MWh

$$\text{Consumption of DH wood chip boiler} \left(\frac{\text{MWh}}{\text{MWh}}\right) = \frac{10876 * 0.7}{7689} = 0.99$$

All GHG emissions result from the combustion and fugitive release of fuels. The emission factor is a relative measure and can be used to estimate emissions from various sources of air pollution. An emission factor is a representative value that relates the amount of a pollutant released into the atmosphere to an activity associated with the release of that pollutant. It is expressed as the mass of the pollutant divided by the unit mass, volume, distance, or duration of the activity that releases the pollutant (e.g., kilograms of particles emitted per megagram. Residential wood combustion is the primary emission source for some pollutants. PM and NO_x emissions per MWh generated vary depending on whether the boiler is small or large. PM and NO_x emission factors are once for different technologies and different resources. All NO_x and PM emission factors for each technology are based on the AARHUS UNIVERSITY Department of Environmental Science emission factors (for fuel input) database [145].

I2 Specific NO$_x$ emissions (Equation 2.4.4)

$$\text{Specific NOx emissions} = \text{Consumption of fuel energy} \left(\frac{\text{MWh}}{\text{MWh}}\right) * \text{NOx emission factor}$$

(2.4.4)

Example for calculations DH Wood chip boiler with flue gas condenser (Eq.2.7.5).

$$\text{Specific NOx emissions of DH wood chip boiler} =$$
$$\text{Consumption of DH wood chip boiler} \left(\frac{\text{MWh}}{\text{MWh}}\right) * \text{NOx emission factor for DH wood chip boiler}$$

(2.4.5)

Where,
Consumption of DH wood chip – 0.99 MWh/MWh;
NOx emission factor for DH wood chip boiler – 324 g/MWh (data based on AARHUS UNIVERSITY Department of Environmental Science emission factors [145] (group 010203 - district heating plants, wood and similar combustion plants < 50 MW (boilers)).

$$\text{Specific NOx emissions of DH wood chip boiler} \left(\frac{\text{g}}{\text{MWh}}\right) = 0.99 * 324 = 321$$

I3 Specific PM emissions (Equation 2.4.6)

$$\text{Specific PM emissions} \left(\frac{\text{g}}{\text{MWh}}\right) = \text{Consumption of fuel energy} \left(\frac{\text{MWh}}{\text{MWh}}\right) * \text{PM emission factor}$$

(2.4.6.)

Example for calculations DH Wood chip boiler with flue gas condenser (Equation 2.4.7)

Specific PM emissions of DH wood chip boiler = Consumption of wood chip (MWh/MWh)* PM emission factor for DH wood chip boiler

(2.4.7)

Specific PM emissions of DH wood chip boiler $\left(\frac{g}{MWh}\right) = 0.99 * 36 = 35.6$

Where,

Consumption of DH wood chip – 0.99 MWh/MWh

PM emission factor for DH wood chip boiler – emission factor for $PM_{2.5}$ is 36/MWh (data based on AARHUS UNIVERSITY Department of Environmental Science emission factors [145] (group 010203 - district heating plants, wood and similar combustion plants < 50 MW (boilers).

I4 Costs of CO_2 reduction

Switching from fossil fuels to RES reduces CO_2 emissions. Reducing CO_2 emissions is a priority at the national and municipal levels, as the consequences of climate change affect everyone.

The reduction of CO_2 emissions depends on the amount and type of fossil energy replaced (see Equation 2.4.8).

$$\Delta_{CO_2} = \frac{Q \text{ (annual amount of heat energy produced)}}{\text{boiler efficiency, \%}} * f_{CO2}$$

(2.4.8)

Where,

Δ_{CO_2} – reduction of CO_2 emissions, tons

Q – the annual amount of heat energy produced , MWh

f_{CO_2} – CO_2 emission factor, $kgCO_2/kWh$

Costs of CO_2 reduction (Equation 2.4.9)

$$\text{Costs of CO2 reduction} \left(\frac{EUR}{tons}\right) = \frac{\text{Total investments, EUR/year}}{CO_2 \text{ reduction, tons}}$$

(2.4.9)

Example for calculations

The reduction of CO_2 emissions for DH Wood chip boiler with flue gas condenser

Δ_{CO_2} – reduction of CO_2 emissions, tons (Eq. 2.4.10.)

Q – 7689 MWh

Boiler efficiency - 90%

f_{CO_2} – CO_2 emission factor, $kgCO_2/kWh$ – 0.202

$$\Delta_{CO_2} = \frac{7689}{90\%} * 0.202 = 1725.8$$

(2.4.10)

Cost of CO_2 reduction for DH Wood chip boiler with flue gas condenser

DH wood chip boiler Costs of Co_2 reduction (EUR/tons) $= \frac{1022215}{1726} = 592$

I5 Investments

Investments per unit of energy produced, EUR/MWh (Eq. 2.4.11)

$$\text{Investments per unit of energy produced,} \frac{\text{EUR}}{\text{MWh}} = \frac{\text{Investments per unit of energy produced, thousand. EUR/MWh}}{1000}$$

(2.4.11)

Investments per unit of energy produced, $\frac{\text{EUR}}{\text{MWh}} = \frac{132.9}{1000} = 0.13$

I6 Internal rate of return (IRR), % (Eq. 2.4.12)

$$\text{IRR, \%} = \text{IRR (net cash flow for 15 years)}$$

(2.4.12)

Internal rate of return, % for DH wood chip boiler

$$\text{IRR, \% DH wood chip boiler with condesator} = \text{IRR (project net cash flow for 15 years)} = 34.4$$

I7 Production costs

Production costs, EUR/MWh (Equation 2.4.13).

$$\text{Productions costs,} \frac{\text{EUR}}{\text{MWh}} = \frac{\text{production costs, EUR/year}}{Q \text{ (annual amount of energy produced,} \frac{\text{MWh}}{\text{year}})}$$

(2.4.13)

Where,

Production costs, EUR - 458312

Q – the annual amount of heat energy produced , MWh/year – 7689

$$\text{Productions costs}, \frac{\text{EUR}}{\text{MWh}} = \frac{458312}{7689} = 59.6$$

Calculated data for the CI construction

Table 2.4.7 shows calculated data for constructing the CI for each alternative. Values equal to 0 were denoted 0.00001 because setting the input value to 0 in the CI is not permissible.

Calculations for DH and IH comparison (based on scientific assumptions and data)

	DH wood chip boiler with flue gas condenser	DH wood chip boiler and PV panels + heat pump solution	DH wood chip boiler and solar collectors with a thermal energy storage	DH pellet boiler	DH pellet boiler and PV panels + heat pump solution	DH pellet boiler and solar collectors with an thermal energy storage	IH pellet boiler	IH heat pump solution + PV panels	IH solar collectors with thermal energy storage natural gas boiler	IH solar collectors with thermal energy storage pellet boiler
i1 MWh/MWh	0.99	0.82	0.82	1.18	0.95	0.97	1.11	0.36	0.93	1.04
i2 g/MWh	321	228	238	343	242	254	351	0.000001	41	187
i3 g/MWh	36	28	29	42	30	31	206	0.000001	0.00001	110
i4 EUR/t CO₂	592	832.8	1385.7	380.8	684.5	1145.8	587.9	19.4	5410.8	957.6
i5 EUR.thousand. /MWh	0.13	0.19	0.31	0.09	0.15	0.26	94.62	284.48	126.53	193.43
i6 %	34.45	25.74	9.40	7.75	7.29	-11.57	0.01	0.4	-0.1	0.03
i7 EUR/MWh	59.6	52.7	54.2	106.5	94.5	97.9	86.9	291.1	110.6	95.2
i8 Count of resources	2	3	3	2	3	3	2	3	3	3

In this study, the equal weighting method was chosen. Eight indicators describing the economic profitability and environmental dimension of RES technologies were chosen, and each indicator's weight was 0.13.

2.5. Construction of the CI for assessment of NECP policies

The CI [24] was used to evaluate the policy's effectiveness. The methodology includes (Fig. 2.5.1.):

The selection of specific policies and actions related to forestry and agriculture which is based on the goals and objectives:

1. Identification of indicators to evaluate specific policies.
2. Development of an expert questionnaire to assess the relevance of each indicator and rank actions according to their relevance.
3. Normalisation of indicator scores.
4. The weighting of the indicators.
5. Aggregation of indicators into CI.
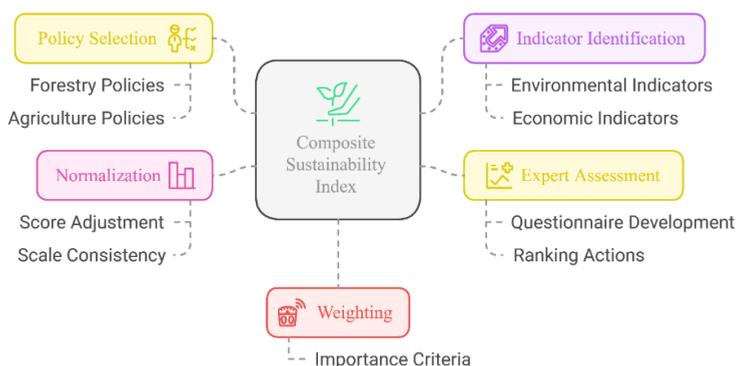
Fig. 2.5.1. Structure for the evaluation of policy actions [146].

2.5.1. Sorting policy measures

First, from Latvia's NECP (not updated 2024 version) [107] Annex 4 policy measures and actions were selected specifically for the sustainable use of resources in forestry and agriculture and for reducing GHG emissions. The study includes horizontal measures and action directions for agricultural and forestry activities. All action directions, horizontal measures related to agriculture and forestry, and the set targets to be achieved by 2030 were initially selected from Annexe 4 of the Latvian NECP (Table 2.5.1) [107]. Subsequently, from all directions of action and specific measures, it was analysed in more detail whether the identified measures can be analysed using the six identified indicators for impact analysis. For further analysis, policies were selected that provide practical measures to achieve the goals and where the descriptions of the measures contain information that can be used to conduct an indicator-based analysis using an expert survey [20].

2.5.2. Identifying indicators for performance assessment

The indicators were selected considering the indicators used in the policy evaluation and individual indicators from the Better Regulation Program. The Organisation for Economic Co-operation and Development (OECD) indicators are rated as one of the most effective indicators of policy regulation and management that can be used as tools for decision-making and policy analysis. Therefore, in addition to the indicators included in Better Regulation, the study also used some success and failure factors to characterise the success or failure of measures. The study selected one of the indicators from the success factors of the ODYSSEE-MURE project for the implementation of successful energy efficiency measures [147]. This indicator can also be used to analyse other environmental policy measures.

Based on the analysis of the scientific literature and the amount of information on policies in Annex 4 of the Latvian NECP [107] (not updated 2024 version), 6 indicators were identified that can be used to characterise the effectiveness of the policies. The indicator i1, possible adverse side effects, describes whether and which negative or positive side effects will occur during the implementation of the specific policy or bundle of policies and whether adverse effects have already been consciously identified. The side effect analysis is also a preliminary identification and assessment of risks associated with the implementation of specific policy actions [119], [158]. Indicator i2 transparency [159] is an indicator that characterises the transparency of specific measures at the definition and implementation stages. i3 Objectivity – the indicator shows whether the specific policy measure or approach will allow achieving the set climate targets following the Latvian NECP. i4 Specificity – the indicator characterises whether the specific measures and the plan for their implementation are described correctly and understandably and whether only general and unspecific tasks are set. i5 – the quality of the policy measures [114]. The indicator describes whether the policy measures and the procedure are described understandably and whether the policy measure is realistically feasible according to the given description i6 Financing – the indicator describes whether the amount of financing and the sources of funding for the specific action are clearly stated (Table 2.5.2).

Table 2.5.2

Description of the criteria

No.	Indicator	Explanation of the indicator
i1	Possible negative side effects [119], [158]	The possible adverse side effects of the specific measure are excluded (e.g., no indirect support for the use of fossil fuels in agriculture is created and, no additional energy consumption is promoted, no additional resource consumption is used), the policy measure complies with the principles of climate neutrality, efficient use of resources for policy measures or the direction of action the result does not contradict the defined environmental and climate goals.

i2	Transparency [119], [159]	Lobby influence (positive or negative side pressure) has been eliminated. The potential impact of the lobby (influencing policy—action or inaction to influence decision-making in favour of specific individuals or groups, various political interests, and private and public interests) has been identified and eliminated.
i3	Objectivity [113], [148]	Identified policies or action lines aim to achieve climate change objectives according to the documents listed in the higher-level hierarchy. A policy measure or line of action is objectively determined, and its choice is justified based on the defined objectives and the tasks to be achieved.
i4	Specificity [113], [148]	The information provided about the policy action is not generic and is described in detail. The description and mission of the action are consistent with the defined objectives. The policy action plan defines expected measurable outcomes. If necessary, the policy action or course of action is laid out for changes in a way that allows flexibility to make changes to the plan.
i5	Quality [113], [114], [148]	The policy measure or line of action and the expected results are described understandably and realistically. A policy measure or specific action line will ensure the long-term sustainability of the goals set (e.g., specific GHG emission reductions, energy savings, transition to RES), or the results will not be limited to a single measure but will contribute to a positive chain reaction and overarching goals.
i6	Funding [113], [148]	Clear sources of funding for policies or a specific course of action are identified, and funding is provided to implement appropriate actions. Funding is provided for the implementation of actions that contribute to reducing GHG emissions, following established goals to be achieved within a specified period.

2.5.3. Data normalisation and indicator weight

To create the CSI, it was necessary to determine the importance of the indicators in comparison with other indicators and evaluate each indicator's weight. Special completion forms were prepared, and the experts were asked to rate the six indicators mentioned above according to their importance, which was expressed in %. The forms were filled so that the total score of the indicators was 100 %, e.g., possible side effects – 30 %, transparency – 20 %, objectivity – 10 %, specificity – 5 %, quality – 20 %, and funding – 15 %. In the forms, scoring was done by filling in the " boxes" and indicating the corresponding percentage score for each indicator. To determine the weight of each indicator, it is possible to use expert interviews to determine the weight of the indicators or assign the same weight to each indicator so that the total weight of the indicators is one. An expert weighting technique was used in this study. Simultaneously with the assessment of the measures themselves, nine experts with extensive knowledge of bioeconomy policy and the agricultural sector were asked to assess the significance % of the indicators described above based on the indicator approach. The experts

have experience in research on bioeconomy, climate and environmental sustainability. The expert survey form was accompanied by an additional table in which each of the six indicators was given a percentage score so that the total sum of the indicators was 100 %. In this study, the weighting of the indicators was done by expert survey, and the results were also compared with the exact weighting. The overall performance index was calculated for each indicator based on the cumulative amounts with their respective weights. The CSI was calculated as the total sum of all indicators [19]. The sum of all indicators results in the final CSI, which can be used for further comparisons.

2.6. System change – comparison of organic and conventional farming

The research aims to evaluate and compare the sustainability of biological dairy farming, conventional dairy farming, and conventional and organic wheat production, using economic and environmental indicators and the CI method. Data from scientific literature sources and reports were collected and used to construct the CI. The study includes two sections: 1) To assess organic and conventional agriculture based on scientific literature and report data; 2) In the second part of the study, a CI with additional indicators was created to assess small and medium-sized organic and conventional dairy farms in Latvia. Considering that the largest sources of emissions in agriculture in Latvia in 2022 [149] were GHG emissions from agricultural soils and emissions from livestock intestinal fermentation, the study examines the comparison of organic wheat cultivation and organic dairy farming with conventional farming systems.

2.6.1. Framework of the study and criteria

1) An assessment of organic and conventional agriculture based on scientific literature and data from reports, and 2) a comparison of the economic and environmental sustainability of small and average-size organic and conventional dairy farming. To evaluate alternative solutions in decision-making, different dimensions should be assessed and their mutual interactions [150].

The study compares several systems in order to better assess the potential benefits and drawbacks of each system based on the values of different indicators. Therefore, the CI serves as a suitable method to show what performance can be expected if several dimensions, not only the economic or the environmental dimension, are taken into account. Databases such as Science Direct, Scopus and Web of Science were used to determine the indicators and their values.

After identifying the indicators and collecting the data, the data were normalised using the Min-max normalisation method. Then, the normalised economic and environmental

indicator values were collected and calculated to create a CI for conventional and organic farming strategies [151]. Inclusion criteria for the first part of the study:

- – Only Organic and conventional dairy cow farming;
- – Only Organic and conventional wheat production;
- – Only average values from scientific literature and reports.

Inclusion criteria for the second part of the study:

- – Only data based on Latvian case studies;
- – Calculations in environmental dimension based on IPCC 2006, national inventory report [149], [152];
- – Only dairy farms with cows in small and average-sized farms (1–99 cows).

2.6.2. Dimensions and indicators selection, normalisation, indicator weighting and aggregation

Scientific publications contain scattered indicators of agriculture's sustainability, and it isn't easy to group them. There is no consensus on whether the indicators should be assessed together or separately [153].

Literature-based studies regarding organic and conventional wheat production, dairy farming

In the first part of the study, based on sources found in the literature, indicators are identified whose values could be compared with each other in relation to both organic and conventional wheat production, as well as dairy farming. In the economic dimension, agricultural productivity and earned income are assigned numerical values. Profitability is determined by comparing revenues and costs or by the farm's net income from product production [154]. Sustainability in the environmental dimension can be described as a decrease in potential degradation related to pesticides, degradation of soil quality, reduction of GHG emissions, and biodiversity conservation [85], [150].

The indicators were selected based on an analysis of scientific literature and reports. The indicator values used in the study were obtained from literature, reports, and calculations based on average values. Each indicator is assigned either a negative or positive value. Indicators with a negative value (–) worsen the CI, e.g. costs, emissions, and carbon footprint. In contrast, indicators with a positive value (+) increase the CI, e.g., milk yield and income (see Table 2.6.1).

Table 2.6.1

Selected indicators for the construction of the CI

No	Indicator	Units	Negative/positive
I1	Mean total costs, EUR	EUR/ha	−
I2	Production value	EUR/ha	+
I3	Net income	EUR/ha	+
I4	Subsidies, green payments, support payments	EUR/ha	+
I5	Carbon footprint per land unit	Mg CO_2eq ha^{-1}	−
I6	Carbon footprint per product	kg CO_2eq	−

The values of the indicators are based on scientific literature and local reports. For some indicators, the average value from different studies is used, and for others, values based on scientific literature or reports are used (Table 2.6.2).

Table 2.6.2.

Indicator values in conventional and organic agriculture based on scientific literature and reports

		Conventional dairy farms	Source [81]	Organic dairy farms	Source [155]	Conventional wheat	Source	Organic wheat	Source [156]
i1	Total costs, EUR/ha	1410 1900		780		926.5 1023.8	[156]	762 842	
	Mean total costs, EUR/ha	1655		780		975.2	Calculated based on [156]	802	[156]
i2	Production value, EUR/ha [155]	1410 1800	2017 [155] 2021 [77]	660 810	[155] 2021 [77]	810 1200	[155] [77]	400 500	[155] [77]
	Mean production value, EUR/ha	1605		735		1005		450	
i3	Mean net income, EUR/ha	230		280		250		120	

i4	Subsidies, EUR/ha	377	[77]	372	[77]	170	[77]	190	[77]
i5	Carbon footprint per land unit, Mg CO_2eq ha^{-1} year^{-1} [157]	6.7 5.3 25.8	Denmark (2011) Denmark (2013) [157] Italy (2019)	5.36 1.6 11.5	Denmark (2011) [157] Denmark (2013) [157] Italy (2019) [157]				
	Average carbon footprint per land unit, Mg CO_2eq ha^{-1} year^{-1}	12.6		6.15		2.87	[157]	1.15	[157]
	Carbon footprint per product, kg CO_2eq kg^{-1} [157]	1.2 0.22 1.2 0.76 **0.85**	Denmark (2011) [157] Denmark (2013) [157], [158] Italy (2019) [157]Netherland (2023) [159]	1.27 0.11 1.37 0.95 **0.93**	Denmark (2011) [157] Denmark (2013) [157] Italy (2019) [157]	0.54	[160]	0.50	[160]
i6	Carbon footprint per product, kg CO_2eq kg^{-1} [157]	1.2 0.22 1.2 0.76 **0.85**	Denmark (2011) [85] Denmark (2013) [157], [158] Italy (2019) [157] Netherland (2023) [159]	1.27 0.11 1.37 0.95 **0.93**	Denmark (2011) [157] Denmark (2013) [157] Italy (2019) [157]	0.54	[160]	0.50	[160]
	Average carbon footprint per product kg CO_2eq kg^{-1}	0.85		0.93		0.54		0.50	

Normalisation, indicator weighting and aggregation on indicator values

Each selected indicator receives a weight proportional to its weight, assuming equal importance for each. Six indicators with normalised values, each with an equal weight of 0.17, were used in the construction of the CI. Assuming equal importance for each, each with an equal weight of 0.33 was used in the construction of the CI. The last step is to

calculate normalised indicator values using aggregation. Results multiply with the normalised indicator value.

2.6.3. Comparison of economic and environmental sustainability of small and average-size organic and conventional dairy farming

In the second part of the study, indicators were selected that would allow for a comparison between organic and conventional dairy farming. The indicators were divided into three dimensions: technical, characterised by the amount of milk produced; economic, characterised by the costs of each system; and environmental, characterised by GHG emissions from enteric fermentation, manure management, and emissions from grazing in the soil section.

Technical dimension

T_1 – milk, tons/day per amount of milking cows, and t_2 – average milk yield, tons of milk per number of cows, are calculated based on the average amount of milk in organic and conventional dairy farming, Eq. (2.6.1.).

$$\text{Milk, tons/day/year} = \text{Amount of milk (kg day/year) * number of cows)/1000}$$

(2.6.1)

All input data for the calculation of t_1 and t_2 are shown in Table 2.6.3.

Table 2.6.3

Input data for the calculation of t_1 and t_2

	Conventional dairy farming (1—9)	Conventional dairy farming (10—29)	Conventional dairy farming (30—49)	Conventional dairy farming 50—99	Organic dairy farming (1—9)	Organic dairy farming (10—29)	Organic dairy farming (30—49)	Organic dairy farming (50—99)
Number of dairy cows	17250	19664	10608	14720	17250	19664	10608	14720
Milk kg/day	20.5 [152]	20.5 [152]	20.5 [152]	20.5 [152]	17.5 [71]	17.5 [71]	17.5 [71]	17.5 [71]

Milk kg/year	6273 [161]	6843 [161]	6843 [161]	6843 [161]	5340 [99]	5340 [161]	5340 [161]	5340 [161]

Environmental dimension

The 2023 data of the Central Statistical Office on the number of cows in small and medium-sized dairy farms was used to calculate emissions in conventional and organic dairy farming [81].

The number of cows is divided into categories (1–9), (10–29), (30–49), and (50–99).

Emissions calculation is based on the Intergovernmental Panel on Climate Change (IPCC) 2006 methodology:

- CH_4 emissions from intestinal fermentation;
- CH_4 emissions from manure management;
- N_2O emissions from pastures [60].

Env1 CH_4 emissions from enteric fermentation kt CH_4 yr^{-1}, CO_2 eq.

Input data for calculation on enteric fermentation is summarised in Table 2.6.4.

Table 2.6.4

Input data for the calculation of enteric fermentation

Weight, kg	Weight Gain, kg/day	Feeding situation	Milk, kg/day	Protein, %	Work, hrs/day	C pregnancy coefficient, Table 10.7	Digestibility of Feed %	CH_4 Conversion %	CP, %	Day Weighted Population Mix %
570 [152]	0 [152]	0.17 [152], [149].	20.5 [152]	3.34 [162]	0 [152]	0.1 [152]	67% [152]	6.5% [152]	15% [162]	100 [152]
548 [71]	0.2 [71]	0.17 [149].	17.5 [71]	3.30 [163], [164]	0	0.1	67.0	6.5	13 based on feed content [71]	100

EF for dairy cattle has been calculated according to the 2006 IPCC Guidelines methodology represented in Equation 10.21 [149], Eq. 2.6.2.

$$EF = \left[\frac{GE * \left(\frac{Ym}{100}\right) * 365}{55.65} \right]$$

(2.6.2)

where

EF - emission factor, kg CH$_4$ head^{-1} yr^{-1};

GE - gross energy intake, MJ head^{-1} day^{-1};

Ym - methane conversion factor, % of gross energy in feed converted to methane (default values in table 10.12, from 2006 IPCC Guidelines); the factor 55.65 is the energy content of methane(MJ/kg CH$_4$) [149];

GE - MJ/day gross energy intake (GE).

The gross energy intake for dairy cattle was calculated according to the 2006 IPCC Guidelines and Equation 10.16 [149], Eq. 2.6.3.

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM}\right) + \left(\frac{NE_g}{REG}\right)}{\frac{DE\%}{100}} \right]$$

(2.6.3)

GE   - gross energy, MJ day^{-1};

Ne$_m$ - net energy required by the animal for maintenance, MJ day^{-1};

Ne$_a$ - net energy for animal activity, MJ day^{-1};

Ne$_i$ - net energy for work, MJ day^{-1};

NE$_{work}$ - net energy for work, MJ day^{-1};

Ne$_p$ - net energy required for pregnancy, MJ day^{-1};

REM - ratio of net energy available in a diet for maintenance to digestible energy consumed

Ne$_g$ - net energy needed for growth, MJ day^{-1};

REG - ratio of net energy available for growth in a diet;

DE% - digestible energy in % of gross energy [149].

NE$_m$ net energy required by the animal for maintenance, MJ day^{-1} Eq. 10.3 [149], Eq. 2.6.4.

$$Ne_m = Cf_i * (\text{Weight})^{0.75},$$

(2.6.4)

where

Ne_m - net energy required by the animal for maintenance, MJ day^{-1};

Cf_i − maintenance coefficient (default values from 2006 IPCC Guidelines, Volume 4, Chapter 10, Table 10.4 [44].

Activity (Nea) - net energy for animal activity, MJ day^{-1}
Eq. 10.4 [149], Eq. 2.6.5.

$$Ne_a = C_a * NE_m,$$

(2.6.5)

where

Ne_a - net energy for animal activity, MJ day^{-1};
C_a - coefficient corresponding to animal's feeding situation (default values from 2006 IPCC Guidelines. Volume 4, Chapter 10, Table 10.5) [44].
Ne_m - net energy required by the animal for maintenance, MJ day^{-1}.

Growth (NE$_g$) - net energy needed for growth, MJ day^{-1}
Eq 10.6 [149], Eq. 2.6.6.

$$Ne_g = 22.02 * \left(\frac{BW}{C * MW}\right)^{0.75} * WG^{1.097}$$

(2.6.6)

where

Ne_g - net energy needed for growth, MJ day^{-1};
BW - the average live body weight (BW) of the animals in the population, kg;
C - a coefficient with a value of 0.8 for female milking cows;
MW - is the mature live body weight of an adult female in moderate body condition, kg;
WG - is the average daily weight of dairy cows, kg day^{-1}.

Lactation (NE$_l$) Nel: net energy for lactation, MJ day^{-1}
Eq. 10.8 [149], Eq. 2.6.7.

$$Ne_l = Milk * (1.47 + 0.40 * Fat),$$

(2.6.7)

where

Ne_l − net energy for lactation, MJ day^{-1};
$Milk$ - amount of milk produced, kg of milk day^{-1};
Fat - content of milk, % by weight.
Pregnancy (NEp) - net energy required for pregnancy, MJ day^{-1}
(Eq. 10.13) [149], Eq. 2.6.8.

$$NE_p = C_{pregnancy} * NE_m,$$

(2.6.8)

where

Ne_p - net energy required for pregnancy, MJ day^{-1};

Cpregnancy- pregnancy coefficient (default values from 2006 IPCC Guidelines, Volume 4, Chapter 10, Table 10.7) [149].

REM - the ratio of net energy available in a diet for maintenance to digestible energy consumed [149], Eq. 2.6.9.

$$REM = \left[1.23 - (4.092 * 10^{-3} * DE\%) + [1.126 * 10^{-5} * (DE\%)^2] - \left(\frac{25.4}{DE\%}\right)\right]$$

(2.6.9)

where
REM - the ratio of net energy available in a diet for maintenance to digestible energy consumed;
DE% - digestible energy, %.

REG - the ratio of net energy available for growth in a diet to digestible energy consumed [72], Eq. 2.6.10.

$$REG = \left[1.164 - (5.160 * 10^{-3} * DE\%) + [1.308 * 10^{-5} * (DE\%)^2] - \left(\frac{37.4}{DE\%}\right)\right]$$

(2.6.10)

where
REG - ratio of net energy available for growth in a diet to digestible energy consumed;
DE% - digestible energy, 67 % or 73 % [149].

Table 2.6.5

Calculated data for emission from enteric fermentation

System	Maintenance (NEm)NEm net energy required by the animal for maintenance, MJ day-1	Activity (NEa)NEa - net energy for animal activity, MJ day-1	Growth (NEg) - net energy needed for growth, MJ day-1	Lactation (NEl) Nel: net energy for lactation, MJ day-1	Pregnancy (NEp): net energy required for pregnancy, MJ day-1	REM - ratio of net energy available in a diet for maintenance to digestible energy consumed	REG - ratio of net energy available for growth in a diet to digestible energy consumed	GE, MJ/day gross energy intake (GE)	EF, kg/head yr
	Eq 10.3 [149]	Eq 10.4 [149]	Eq.10.6 [149]	Eq 10.8 [149]	Eq 10.13 [149]	Eq 10.14 [149]		Eq10.16 [149]	Eq10.21 [149]

Conventional dairy farming	45.03	7.7	0	62.9	0	3.7	0.5	342.17	146
Organic dairy farming	43.7	7.4	0.6	60.6	0	4.4	0.5	335.93	143

In addition to 67 % feed digestibility, a situation where introducing legumes to organic farms could increase feed digestibility is considered (Table 2.6.6 and Table 2.6.7).

Table 2.6.6

Methane emissions from enteric fermentation with DE 67%

Categories	N(T)	CH_4 emissions, kt CH_4 yr^{-1}	CH_4 emissions kt CH_4 yr^{-1}, CO_2 eq.
Conventional (1−9)	17250	2.52	70.46
Organic (1−9)	17250	2.47	69.2
Conventional (10-29)	19664	2.87	80.3
Organic (10−29)	19664	2.82	78.9
Conventional (30−49)	10608	1.55	43.3
Organic (30−49)	10608	1.52	42.5
Conventional (50−99)	14720	2.15	60.1
Organic (50−99)	14720	2.11	59.0

Table 2.6.7

Methane emissions from enteric fermentation with DE 73%

Categories	N(T)	CH_4 emissions, ktCH_4 yr^{-1}	CH_4 emissions kt CH_4 yr^{-1}, CO_2 eq.
Conventional (1−9)	17250	2.52	70.46
Organic (1−9)	17250	2.20	61.6
Conventional (10−29)	19664	2.87	80.3
Organic (10−29)	19664	2.51	70.2

Conventional (30–49)	10608	1.55	43.3
Organic (30–49)	10608	1.35	37.9
Conventional (50–99)	14720	2.15	60.1
Organic (50–99)	14720	1.88	52.5

Env3 CH4 manure, kt CH4 $^{y-1}$ CO2 eq.

Manure management also generates part of the methane emissions. Therefore, methane emissions should be estimated based on specific manure management systems Eq. (2.6.11).

$$CH_{4\,manure} = \Sigma_{(T)} \; \frac{EF_{(T)} * N_{(T)}}{10^6}$$

(2.6.11)

where

CH$_{4\,Manure}$ – CH$_4$ emissions from manure management, for a defined population, kt CH$_4$ yr^{-1};

EF$_{(T)}$ – emission factor for the defined livestock population, kg CH$_4$ head^{-1} yr^{-1}

N$_{(T)}$ – the number of heads of livestock species/category T in the country;

T– category of livestock [149].

CH4 calculation of emission factor

The emission factor (EF), kt head^{-1}, year^{-1}, EF kg CH$_4$ head^{-1} year^{-1}, for estimating methane emissions from manure was determined using Eq. 10.23 in IPCC 2006 [149], Eq. (2.6.12).

$$EF_T = (VS_T * 365) * \left[B_{o(T)} * 0.67 \, \tfrac{kg}{m3} * \Sigma_{S,K} \, \tfrac{MCF_{S,K}}{100} * MS_{T,S,K} \right]$$

(2.6.12)

EF$_T$ - annual CH$_4$ emission factor for livestock category T, kg CH$_4$ animal^{-1} yr^{-1};

VS$_{(T)}$ - daily volatile solid excreted for livestock category T, kg dry matter animal^{-1} day^{-1};

Bo$_{(T)}$ - maximum methane-producing capacity for manure produced by livestock category T, m^3 (IPCC 2006 (Western/Eastern Europe) Table 10A-4).

MCF$_{(S,k)}$ - methane conversion factors for each manure management system in Table 10.17;

MS$_{(T,S,k)}$ - a fraction of livestock category manure handled using manure management system in climate region k, dimensionless [149].

Basis for calculating annual VS production, days yr^{-1} [149] Eq. (2.6.13).

$$VS = \left[GE * \left(1 - \frac{DE\%}{100}\right) + (UE * GE] * \left(\frac{1 - ASH}{18.45}\right)\right]$$

(2.6.13)

VS – volatile solid release excretion per day on a dry-organic matter basis, kg VS day[1];

GE – gross energy intake, MJ head^{-1} day^{-1};

DE – digestibility of the feed in % (67% for dairy cows);

(UE * GE) - urinary energy expressed as a fraction of GE;

ASH – the ash content of manure calculated as a fraction of the dry matter feed intake (0.08 for cattle) 18.45 conversion factor for dietary GE per kg of dry matter (MJ kg^{-1}) [149].

The number of animals and the IPCC 2006 methodology [149] were used in the calculation to convert CH_4 emissions into CO_2 equivalents. The obtained emissions were multiplied by 28 [69]. Calculated data are summarised in Table 2.6.8.

Table 2.6.8

Input data and calculations for manure management

Volatile solid excretion rates, kgVS/hd/d, eq. 20.24	kg VS(1000 kg animal mass-1) day-1	EF, kt head^{-1}, year-1, EF (kg CH_4 head-1 year-1	N(T)	CH_4 manure, kt CH4 $^{y-1}$	CH_4 manure, kt CH4 y-1 CO_2 eq.
6.31	11.08	21.16	17250	0.36	10.22
6.20	11.31	5.67	17250	0.10	2.74
6.31	11.08	20.05	19664	0.39	11.04
6.20	11.31	5.67	19664	0.11	3.12
6.31	11.08	20.05	10608	0.21	5.95
6.2	11.3	5.7	10608.0	0.06	1.69
6.31	11.08	20.05	14720	0.30	8.26
6.20	11.31	5.67	14720	0.08	2.34

Env₂ Total N₂O emissions kt CO₂ eq.

Direct N_2O emissions (kg N_2O yr^{-1}) from manure management were calculated using the IPCC 2006 Guidelines Equation (20.25). $N_{(T)}$, $Nex_{(T)}$ and $MS_{(T,S)}$ data were taken from Enteric fermentation calculations. See Eq. (2.3.14).

$$N_2O_{D\,(mm)} = \left[\Sigma_S \left[\Sigma_T \left(N_{(T)} * Nex_{(T)*MS_{(T,S)}}\right)\right] * EF_{3(S)}\right] * \frac{44}{28}$$

(2.6.14)

$N_2O_{D(mm)}$ – direct N_2O emissions from manure management, kg N_2O yr^{-1};

$N_{(T)}$ – number of head of livestock category T;

$Nex_{(T)}$ – annual N excretion rates, kg N animal^{-1} yr^{-1} (IPCC, 2006 Eq.10.31);

$MS_{(T, S)}$ – fraction of total annual nitrogen excretion for each livestock category;

$EF_{3(S)}$ – emission factor for direct N_2O emissions from manure management system S kg N_2O-N kg^{-1}N in manure management system;

S – manure management system;

T – category of livestock [149].

$N_2O_{G\,(mm)}$ – indirect N_2O emissions due to volatilisation of N from manure management, kg N_2O yr^{-1} were calculated according to IPCC 2006 Eq. 10.29. The default value for the emission factor (0.01) was used [149].

To convert total N_2O emissions (sum of direct and indirect) into CO_2 eq., the obtained emissions were multiplied by 265 [69]. Table 2.6.9 shows input data and calculated data.

Table 2.6.9

Input data and calculations for N_2O kt CO_2 eq. emission

	MCF(S,k), Table 10.17 [149]	MS(T,S,) [149]	Nex (T) Equation 10.30 [149]	N intake (T), kg N animal-1 yr-1	N retention (T) [149]	N₂OG (mm) – indirect N2O emissions due to volatilisation of N from Manure Management, kg N2O yr-1 Equation 10.27 [149]	N₂OD (mm) direct emissions (kg N2O yr-1 Equation 10.27 [149]	Total N₂O emissions kt CO₂ eq. [149]
Conventional (1−9)	Pastures 1% (0.05) Solid 2% (0.35) Liquid 10% 0.43 Digestate 2% 0.18	100%	130.0	0.45	0.2	70.46	17615.26	4.69
Organic (1−9)	Pastures 1% (0.44) Solid 2% (0.56)	100%	80.4	0.28	0.2	43.58	0	0.01
Conventional (10−29)	Pastures 1% (0.05) Solid 2% (0.35) Liquid 10% (0.43) Digestate 2% (0.18)	100%	130.0	0.45	0.2	80.32	20080.37	5.34
Organic (10−29)	Pastures 1% (0.44) Solid 2% (0.56)	100%	80.4	0.28	0.2	49.68	0	0.01

	Pastures 1% (0.05) Solid 2% (0.35) Liquid 10% (0.43) Digestate 2% (0.18)							
Conventional (30─49)	Pastures 1% (0.05) Solid 2% (0.35) Liquid 10% (0.43) Digestate 2% (0.18)	100%	130.0	0.45	0.2	43.33	10832.62	2.88
Organic (30─49)	Pastures 1% (0.44) Solid 2% (0.56)	100%	80.4	0.28	0.2	26.80	0	0.01
Conventional (50─99)	Pastures 1%(0.05) Solid 2% (0.35) Liquid 10% (0.43) Digestate 2% (0.18)	100%	130.0	0.45	0.2	60.13	15031.68	4.00
Organic (50─99)	Pastures 1% (0.44) Solid 2% (0.56)	100%	80.4	0.28	0.2	37.19	0	0.01

Env4 N2O kt CO2 eq. from soils, urine and dung deposited by dairy cows

On organic farms, dairy cows can be on pasture for up to 160 days per year in Latvian conditions. Also, on small and medium-sized conventional farms, cows can be on pasture for part of the time. FPRP is the annual amount of N deposited in the pasture, range and paddock soils by grazing animals, in this case, dairy cows. FPRP is calculated using the 2006 IPCC guidelines, Equation 11.5 [149], Eq. 2.6.15.

$$F_{PRP} = \Sigma_T \left[\left(N_{(T)} * Nex_{(T)} \right) * MS_{T,P,RP} \right]$$

(2.6.15)

Where,

$Nex_{(T)}$ – average annual amount of N excreted;

$N(T)$ – the number of heads of livestock species/category T in the country;

$MS(T,S,k)$ – a fraction of livestock category manure handled using the manure management system in climate region k.

It describes nitrogen from milking cows that is deposited on pasture. The Table 2.6.10. summarises input data and calculations.

Table 2.6.10.

Input data and N2O kt CO2 eq. from soils

Categories	N(T)	Nex(T)	Conversion of N2O-N to N2O. kg

		N$_2$O year (N$_2$O-N *molecular weight 44/28)		N$_2$O kt CO$_2$ eq.
Organic 1—9	17250	80.4	21822.5	5.78
Organic 10 —29	19664	80.4	24876.4	6.59
Organic 30—49	10608	80.4	13419.9	3.55
Organic 50—99	14720	80.4	18621.9	4.93
Conventional 1—9	17250	130	35230.51864	9.3
Conventional 10—29	19664	130	40160.7489	10.6
Conventional 30—49	10608	130	21665.2372	5.7
Conventional 50—99	14720	130	30063.37591	8.0

Economic dimension sustainability evaluation

For input data (Table 2.5.11), the number of cows was multiplied by the costs in organic and conventional dairy farming.

$$\text{EUR/number of cows in dairy farming} = \text{number of cows} * \text{EUR/number of cows}$$

$$(2.6.16)$$

Table 2.6.11

Input data for the economic dimension estimation [165]

Economic indicators	Conventional dairy farming, EUR/number of cows	Organic dairy farming, EUR/number of cows
ec$_1$ Homemade fodder EUR/number of cows	269	364
ec$_2$ Purchased fodder, EUR/number of cows	355	82
ec$_3$ Equipment depreciation, EUR/number of cows	270	232
ec$_4$ Wages and social insurance payments, EUR/number of cows	286	213
ec$_5$ Veterinary costs EUR/number of cows	112	104
ec$_6$ Administration costs, EUR/number of cows	150	173
ec$_7$ Other costs, EUR number of cows	213	139

The core element of the sustainability assessment is constructing the CI using data from scientific literature, reports, and statistics. Comparing organic dairy farming and conventional dairy farming based on sustainability indexes provides valuable insight into each system's strengths and weaknesses.

2.7.   System change – evaluation of the restoration of peatlands

In this study, the first step is to select the peatland strategies based on the economic data available in the scientific literature, reports, and local peatland projects. The next steps until the development of scenarios are related to the construction of a CI.

Based on the literature, the first step in the construction of the CI is the development of the following:

- Suitable economic indicators, divided into two groups - (1) necessary costs, (2) incomes and possible gains from grants and subsidies, etc.
- GHG emissions of each strategy.

The next step was to calculate data for each strategy based on the literature, reports, and local projects. Equal weight indicator weighting was applied to each indicator, which was determined based on the number of indicators used. The final step was indicator aggregation into the CI and sensitivity analysis.

2.7.1.   Selection of strategies

In this study, the first step is to select the peatland strategies based on the economic data available in the scientific literature, reports, and local peatland projects. Suitable economic indicators, divided into two groups – (1) necessary costs, (2) incomes and possible gains from grants and subsidies, etc. Equal weight indicator weighting was applied to each indicator, which was determined based on the number of indicators used.

Peatland strategies can be categorised into groups: (1) restoration strategies, peat biomass use in high-added-value products; (2) other land use replacing peatland, dairy farming; and (3) peat extraction. Peat biomass is used in high-added-value products based on the available scientific literature and reports. Dairy farming is based on the scientific literature and reports, and peat extraction is based on reports (Table 2.7.1).

Table 2.7.1

Selected peatland strategies

1. Restoration strategies
Peatland rewetting
Afforestation of peatlands
Perennial cultivated grasses
Paludiculture (1) cattail (typha; (2) sphagnum farming)
Water reservoir
Growing cranberries
Growing blueberries
2. Peat biomass use in high-added-value products

Production of insulation boards from cattail-based on paludiculture [1]	
3. Other land use–dairy farming on peat soils	
4. Peat extraction	

Meaningful indicators should be introduced to evaluate the strategies, evaluating both the economic and environmental dimensions.

2.7.2.   Economic and environmental data for each strategy

Table 2.7.2 shows calculated data based on the scientific literature, reports, and assumptions for each peatland strategy for the construction of the CI. It is possible to compare the economic indicators of the strategies, but due to limited information, there are no specific values for CO_2 and CH_4 emissions for each strategy. Therefore, strategies such as dairy farming, production of panels using cattail, and paludiculture using cattails and sphagnum were evaluated in CO_2 eq. ha^{-1}. For restoration strategies, CH_4 and CO_2 emissions were also compared.

Table 2.7.2

Economic and environmental indicators selected for the peatland strategy evaluation

No	Indicator	Units	Indicator Description	Impact
i1	Total investment costs to implement the strategy	EUR/ha	The indicator considers recultivation planning, recultivation, construction costs, and exploitation costs in each of the alternatives.	-
i2	Maintenance costs	EUR/ha	Maintenance costs, including depreciation costs and monitoring costs.	-
i3	Income	EUR/ha	Annual profits (including economic value from products), total revenues, EUR/tonnes, subsidies, and grants for a specific strategy.	+
i4	Potential income from ecosystem services	EUR/ha/yr	The indicator describes an alternative monetary value: potential income from ecosystem services. Calculations based on the Project Life Restore optimisation model [166] additionally take into account inflation and assumptions. Ecosystem services provide some benefit, tangible or intangible. A forest provides wood, and a peatland provides peat; therefore, both are material services.	+
i5	CO_2	ha^{-1}/yr	Carbon dioxide emissions	-
I6	CH_4	ha^{-1}/yr	Methane emissions	-
I7	Total GHG emissions on rich organic soil	CO_2-eq ha^{-1} yr^{-1}	Total GHG emissions	-

The CI cannot contain negative values or 0. If data could be used to construct the CSI, values equal to 0 are marked with 0.001 (Table 2.7.3).

Table 2.7.3

Calculated economic data for each peatland strategy

	Rewetting	Peat extraction	Production of insulation boards from cattail	Afforestation	Perennial cultivated grasses	Dairy farming	Cultivation of cattail	Cultivation of sphagnum	Growing blueberries	Water reservoir	Growing cranberries
i1 Total investments, EUR/ha	5171 [166]	11,868 [167]	3400 [168]	14,368 [166]	6087 [42]	10,570 [168]	7300 [168]	23,300 [168]	96,264 [166]	7265 [166]	29,479 [166]
i2 Potential income from ecosystem services, EUR/ha/yr	49,308 [166]	665 calculation based on [167]	43,825* [166]	45,908 [166]	899.6 [166]	0.001	43,825 Assumption based on [166]	43,825.3 Assumption based on [166]	5696 [166]	35,967 [166]	14,693 [166]
i3 Maintenance costs, EUR/ha	10,338 (including monitoring costs) [169]	425 [167]	1400 [168]	157 [166]	261.8 [166]	4035 [168]	3170 [168]	5175 [168]	4215. [166]	0.001	1597 [166]
i4 Income, EUR/ha	1442 Calculations based on average on-time payments and carbon credit [170]	3914.9 [167]	7966.7 [168]	2400 [171]	497.5 [166]		6896.7 [168]	11,891.7 [168]	7854 [166]	0.001 [166]	1570.8 [166]
i5 CO_2	2 based on [170]	7 [170]		1 [170]	12 [170]				5 [173]		4 [170]
i6 CH_4	7.2 based on [170]	1.4 [170]		0.3 [170]	1.3 [170]				0.9 [46]		0.2 [170]
i7 Total GHG emissions on rich organic soil CO_2-eq ha^{-1} yr^{-1}	9.9 [170]	11.2 [170]	3.9 [172]	3.7 [170]	19.9 [170]	20.9 [34]	2.6 [170]	2.6 [170]	11.8 [170]		9.3 [170]

CI cannot have negative values – blank space means no data available.

I1 Total investments, EUR/ha

Peat extraction

Prices defined in the 2016 methodology [167] are correct to use if the inflation rate is taken into account. Total expenses with inflation compared to 2016, 2801 EUR/ha + investments in peat extraction preparation with inflation compared to 2016, 9066.7 EUR/ha. The calculation is based on the costs from the 2016 methodology, taking into account the 2016 inflation rate for goods and services [173] (average costs EUR/ha *1.42).

Production of insulation boards

Costs for blow-in insulation.

$$\text{EUR } 1550 + \text{costs for construction EUR } 1850.$$

- Establishment of paludicultures—the cultivation of cattail: 7300/ha EUR
- Establishment of paludicultures—the cultivation of sphagnum: capital investments 23,300/ha EUR

I2 Income from ecosystem services, EUR/ha/yr.

The indicator describes the alternative monetary value (2020) for goods and services in Latvia [173] (average investments EUR/ha * 1.309).

Production of insulation boards

It is assumed that using paludiculture for product production will not reduce the value of ecosystem services.

Peat extraction

This calculation is based on income from peat extraction from the 2016 methodology [167], taking into account the 2016 inflation rate for goods and services [173] (average costs, 1.42 EUR/ha *).

Calculations of benefits from material (gross revenue from mineral extraction, income from peat extraction), 665 EUR/ha.

Production of insulation boards from cattail: assuming that these are potential income from paludiculture cultivation, EUR 43825.3.

Paludiculture for cattail and sphagnum cultivation

Assuming that the potential income from ecosystem services is equal to sphagnum farming and cattail cultivation.

Dairy farming

It is assumed that when starting dairy farming, ecosystem services are 0, and there is no ecosystem, only land use.

I3 Maintenance costs, EUR/ha

For restoration strategies, restoration strategies–average based on the existing optimisation model from local project studies, considering the inflation rate year 2018–2020 for goods and services in Latvia [173] (average investments, 1.309 EUR/ha *).

Rewetting

Maintenance costs 338 EUR + EUR 10,000 monitoring costs [169].

Peat extraction

Repair and maintenance of peatland sites 266 EUR/ha + depreciation investments 159.3 EUR/ha [174]. It is assumed that the costs of peat development and management are about 60% of the income from the sale of the peat. The average maintenance cost for peat extraction is assumed to be 3.5% of the initial capital investments [174].

Production of insulation boards from cattail

A total of 700 EUR/ha + 700 EUR/ha [168].

Dairy farming

A total of 1710 EUR + 2325 EUR/ha.

Paludiculture using cattail cultivation

A total of 2640 EUR + 530 EUR/ha.

Paludiculture using sphagnum cultivation

A total of 4000 EUR + 1175 EUR/ha.

I4 Income, EUR/ha

For restoration strategies, the average is based on the existing optimisation model from local project studies, considering the inflation rate for goods and services in Latvia from 2018 to 2020 [173] (average investments, 1.309 EUR/ha *). Subsidies, one-time payments, and carbon credits are based on the literature and added together with net income to get total income.

Rewetting

The average one-time income from case studies is 442 EUR/ha (based on + the amount of carbon credit for farmers and landowners, 1000 EUR/ha (one-time payment) [169].

Production of insulation boards

total exploitation costs EUR 7500 + annual CO_2 credit 467 EUR/ha (CO_2 credits based on 14,000 EUR/ha/30 years).

Perennial cultivated grasses

65.5 EUR + one-off payment of 432 EUR/ha.

Dairy farming

A total of 4600 EUR + 965 EUR + 400 EUR/ha.

Paludiculture using cattail cultivation

Annual potential profits 4800 EUR/ha+ annual net income 1630 EUR/ha + annual CO_2 credit 466.7 EUR/ha (CO_2 credits based on 14,000 EUR/ha/30 years)

Paludiculture using sphagnum cultivation

A total of 8800 EUR/ha + 2625 EUR/ha+ annual CO_2 credit 466.7 EUR/ha (CO_2 credits based on 14,000 EUR/ha/30 years) [168], [169], [175].

Afforestation

A minimum amount of support from funds is 2400 EUR/ha [171].

Each indicator was given equal weight, assuming that all selected economic indicators are equally important. The indicator weight is different for each scenario based on the indicator's count.

1)A total of 5 indicators were used, with a weight of 0.20 for each indicator.

2)A total of 7 indicators were used, with a weight of 0.14 for each indicator.

The final step is the aggregation of the CI results multiplied by the normalised indicator value.

2.8.   Analysis of RES potential

The study compares the sustainable development of RESs between the sectors examined – industry, services, agriculture, households, and transport. The analysis carried out aims to find out which of the RESs is the most promising and sustainable in each sector and what conditions determine this. In addition, in order to evaluate the potential of renewable energies, a mutual evaluation of the advantages, limitations, and development speed of renewable energies for the sectors mentioned above has been carried out. The analysis includes an extensive literature review in various countries around the world, including China, India, the United States, Bolivia, and European countries such as Spain, Iceland, Finland, Norway, Denmark, Sweden, Lithuania, Latvia, Greece, France, Germany, etc.

This study examines sustainable development trends of RES across different sectors such as industry, services, agriculture, transport, and households. The analysis of RESs includes solar, wind, hydro, biomass, and geothermal energy resources, which are analysed separately for each sector. The scientific novelty of the research is the development of a method that allows quantifying the qualitative assessment of the research. A large number of scientific papers were reviewed to develop the assessment. The results generate a view on a comprehensive

assessment of differences between the sectors and how identifying these differences can help to develop more tailored and sector-specific policies. Therefore, policymakers could focus on tackling the identified barriers and using the full potential of identified opportunities.

The conceptual and methodological basis of this research is shown in Fig. 2.8.1. The model combines both qualitative and quantitative research methods to provide an in-depth assessment of the key factors affecting the competitiveness and sustainable development of each RES technology in each sector
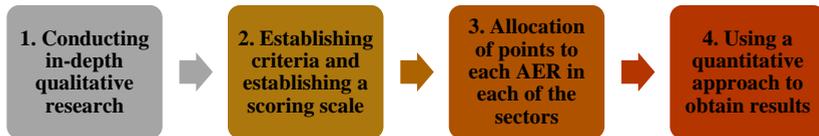
Fig.2.8.1. The steps of performing the qualitative analysis in chronological order.

2.8.1. Description of the methodology for qualitative assessment

In the beginning, a comprehensive qualitative analysis was conducted. Three essential criteria and aspects were put forward to perform the full value analysis, which was examined separately for each resource compared to the examined sectors.

First, a qualitative assessment based on a comprehensive literature review of the use of RESs in each sector was conducted. The literature review included recently published scientific publications, research papers, and assessment reports. A total of ~100 sources of information were used for the qualitative assessment. Table 2.8.1 provides an overview of the main literature used for the RES assessment of each sector.

In order to create a collection of the scientific literature on RESs (biomass, solar energy, water, wind energy, and geothermal energy), we used possibilities and answers to questions such as

- The increase in the use of technology in the future;
- Technological development and increase in utilisation rate;
- RES technology innovation opportunities and technology combinations;
- Using solar energy (for heat and electricity) technology combined with smart technology;
- The presence of any restrictions on the use of the resource;
- The availability of RESs as a limiting factor for resource use. Payback period of investments (years);
- Cost savings (EUR, %);
- Energy savings (kWh, MWh, %);
- CO_2 reduction.

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Table 2.8.1

Sources of literature for qualitative assessment

Sector	Topic	Source of Literature
Industry	• The experience of renewable energy use in the transport sector, limiting factors, and future forecasts. • Characteristics of the development of RES extraction and production technologies. • Development potential assessment for RESs, RES technology innovation opportunities, and technology combinations. • Experience with industrial companies using PV panels and collectors. • Assessment of opportunities and challenges in the industrial sector.	[176], [177], [178], [179], [180], [181], [182], [183], [184], [185], [186]
Services	• The increase in the use of technology in the future; technological development and increase in utilisation rate; and RES technology innovation opportunities and technology combinations. • Assessment of opportunities and challenges in the service sector.	[176], [187], [188], [189], [190], [191], [192], [193], [194], [195], [196], [197], [198]
Agriculture	• Experience and possibilities of using biomass technologists in agriculture. • Assessment of opportunities and challenges in the agriculture sector	[199], [200], [201], [202], [203], [204], [205], [206], [207], [208]
Households	• The increase in the use of technology in the future. • Cost savings (EUR, %). • Using solar energy technology combined with smart technology. • Energy savings (kWh, MWh, %). • Assessment of opportunities and challenges in the household sector.	[31], [56], [209], [210], [211], [212], [213], [214], [215], [216], [217]
Transport	• The presence of any restrictions on the use of the resource and RES technology innovation opportunities and technology combinations. • Assessment of opportunities and challenges in the transport sector.	[218], [219], [220], [221], [222], [223], [224], [225], [226], [227], [228], [229]

2.8.2. Description of the methodological for quantitative assessment

The methodology includes (1) conducting in-depth qualitative research; (2) setting the criteria and determining the point scale (1–5); (3) the allocation of points to each AER in each of the sectors; (4) score normalisation; (5) score weighting; (6) score aggregation; (7) a final index score; and (8) ranking technologies (Fig. 2.8.2).
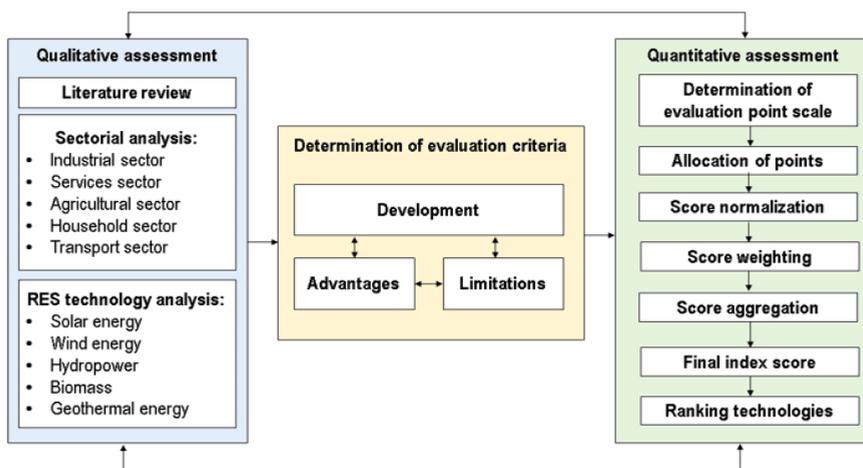
Fig. 2.8.2. The methodological framework of the study.

Determination of evaluation point scale and allocation of points

The three most important criteria and aspects were put forward, which were discussed in more detail separately for each of the resources compared to the examined sectors. The cross-sectoral comparison from the literature review is based on evaluating three main criteria-RES development tendencies, the main advantages of RESs, and the limitations of RES implementation. A five-point rating scale was developed for each criterion, with one representing the lowest score and five representing the highest score.

Points are awarded for each type of RES and sector based on the conclusions of the qualitative analysis. Table 2.8.2 provides an overview of the evaluation criteria and a description of the valuation scale. For each type of RES (solar, wind, hydro, biomass, and geothermal) in each sector (industry, services, agriculture, households, and transport), corresponding points are assigned according to Table 2.8.3. The points are summarised in tables, using MS Excel software.

Table 2.8.2

Criteria for the assessment and description of the evaluation scale

Criteria	Research question	Evaluation scale
Development	How fast is the technological development of a specific type of RES?	5–the most rapid development 4–rapid development, there are limiting factors 3–limited development 2–very slow development

		1–no development observed
Advantages	Which of the RES has the greatest advantages in use?	5–greatest advantages 4–second-greatest advantages 3–fewer advantages, there are significant constraints 2–there are many constraints 1–no significant advantages observed
Limitations	How significant are the constraints and limitations of a specific type of RES in the sector?	5–almost no limiting factors or severe limitations are observed 4–minor limitations are observed that affect the use of the specific RES 3–there are a few disadvantages that limit the use of the specific RES 2–numerous disadvantages limit the use of the source 1–many limitations hinder the utilisation of RESs

Table 2.8.3 shows the evaluation performed; each resource in each of the sectors was evaluated on a scale from 1 to 5. The evaluation was based on the scoring system developed in Table 2.8.2. These ratings are further used to perform quantitative analysis and create an index for each of the RES.

Table 2.8.3

Collected scores based on literature assessment based on defined criteria

Sector					
Industry sector	**Solar Energy**	**Wind Energy**	**Hydropower**	**Biomass**	**Geothermal Energy**
Development	5.0	3.5	3.5	4.0	3.5
Advantages	4.5	3.5	3.0	4.0	3.5
Limitations	3.0	3.0	3.5	3.5	4.0
Total	12.5	10.0	10.0	11.5	11.0
Service sector					
Development	5.0	3.0	3.0	3.5	4.0
Advantages	4.5	3.0	3.0	3.5	4.0
Limitations	4.0	3.0	3.0	3.5	4.0
Total	13.5	9.0	9.0	10.5	12.0
Agriculture sector					
Development	4.0	3.0	3.0	5.0	3.0
Advantages	5.0	3.5	3.0	5.0	3.0

Limitations	5.0	3.0	3.0	5.0	4.0
Total	14.0	9.5	9.0	15.0	10.0
Household sector					
Development	4.0	3.5	4.0	4.5	4.0
Advantages	4.5	4.0	3.5	3.5	4.0
Limitations	4.0	3.5	3.5	3.5	3.0
Total	12.5	11.0	11.0	11.5	11.0
Transport sector					
Development	4.5	4.5	3.5	5.0	3.0
Advantages	4.0	4.5	3.5	5.0	3.0
Limitations	5.0	3.5	3.0	5.0	3.0
Total	13.5	12.5	10.0	15.0	9.0

Data normalisation, weighting, and final CI

After data collection, the data were processed and normalised using the min-max normalisation technique, as shown in Eq. (2.8.1). Normalisation scales the assigned points from 0 to 1, where 0 is the lowest value, and 1 is the highest value.

$$S_{Ni} = \frac{S_i - S_{min}}{S_{max} - S_{min}}$$

(2.8.1)

where

S_{Ni} - the normalised score,

S_i - the score obtained from qualitative assessment,

S_{min} - the minimum score of the evaluation scale, which is equal to 1,

S_{max} - the maximum score of the evaluation scale, which is equal to 5.

Furthermore, weights are assigned to each normalised value. In this study, all three criteria are weighted equally because the pace of development, advantages, and limitations of specific RES technologies have an equal impact on the further progress of RES in each sector. The normalised and weighted values are aggregated into an index according to Equation (2.8.2).

$$SI = \sum w_i \times S_{Ni} , w_i = \frac{1}{n_i},$$

(2.8.2)

where

SI is the final index value for the deployment potential of the evaluation categories *i* (development, $i = 1$; advantages, $i = 2$; and limitations, $i = 3$), w_i is the determined weight of the indicator, and n_i is the number of indicators in the evaluation.

The aggregated results of each RES show the trend and potential of long-term sustainable development and competitiveness. The closer the result is to 1, the higher the long-term development and potential in a particular sector.

Based on the literature assessment, the criteria selected (development, advantages, and limitations) were evaluated on a scale of 1–5.

Table 2.8.4. shows the evaluation score in the industry sector as an example, based on the criteria presented in Table 2.8.2.

Evaluation score from qualitative assessment in the industry sector

	Solar Energy	Wind Energy	Hydropower	Biomass	Geothermal Energy
		Criteria			
Development	5	3.5	3.5	4	3.5
Advantages	4.5	3.5	3	4	3.5
Limitations	3	3	3.5	3.5	4
Total	12.5	10	10	11.5	11

All further calculations are made using the formulas given in Equations (2.8.1.) and (2.8.2.), using the industry sector as an example (Table 2.8.4).

The score for each criterion and the total index for the industry sector

	RES Technologies				
	Solar energy	Wind Energy	Hydropower	Biomass	Geothermal Energy
Criteria					
Development	1	0.7	0.7	0.8	0.7
Advantages	0.9	0.7	0.6	0.8	0.7
Limitations	0.6	0.6	0.7	0.7	0.8
	Solar energy	Wind energy	Hydropower	Biomass	Geothermal energy
Development	0.33	0.23	0.23	0.27	0.23
Advantages	0.30	0.23	0.20	0.27	0.23
Limitations	0.20	0.20	0.23	0.23	0.27
Total	**0.83**	**0.67**	**0.67**	**0.77**	**0.73**

3. RESULTS AND DISCUSSION

3.1. DH and IH tecnology comparison

Six energy sector experts participated in the survey, and the average values from the answers to the questions in the form were used in the calculations. From the expert survey, the importance of the technical, economic, environmental and social dimensions in relation to the choice of the considered heating technologies was compared (Table 3.1.1).

Table 3.1.1.

Dimension importance comparison

No	Dimension comparison	A1	A2	A3	A4	A5	A6	Average
1	Technical against environmental	1	1	3	1	2	2	1.7
2	Technical against economic	1	4	1	4	5	1	2.7
3	Technical against social	1	5	3	1	2	2	2.3
4	Environmental against economic	9	2	3	4	4	1	3.8
5	Environmental against social	9	5	5	1	2	1	3.8
6	Economic against social	1	4	6	1	3	2	2.8

The resulting matrix is shown below. The values are obtained from six expert surveys comparing dimensions. The rating is made on a 9-point scale. The calculation is performed according to the AHP method. The matrix is given in Table 3.1.2.

Table 3.1.2

Decision-making matrix

	Technical	Environmental	Economic	Social
Technical	1	1.7	2.7	2.3
Environmental	0.59	1	3.8	3.8
Economic	0.37	0.26	1	2.8
Social	0.43	0.26	0.36	1
Sum	**2.39**	**3.23**	**7.86**	**9.90**

In Table 3.1.3. shown calculations for each dimension and each dimension average weight which is the main result in AHP. Further average weight is used in CSI.

Table 3.1.3

Calculations in AHP for each dimension

Dimension	Technical	Environmental	Economic	Social	Average criteria weight	Consistency ratio
Technical	0.41	0.52	0.34	0.23	0.38	4.35
Environmental	0.24	0.30	0.48	0.38	0.35	4.44
Economic	0.15	0.08	0.12	0.28	0.16	4.22
Social	0.18	0.08	0.04	0.10	0.10	4.09

The consistency ratio shows that the CR do not exceed 0.10, so the obtained calculations have been performed correctly and it is possible to perform further actions to use the obtained weight of each indicator in the further analysis (Table 3.1.4).

Table 3.1.4

Consistency ratio

Landa (max)	4.28
n	4
RI	0.9
CI	0.09
CR	0.10

The AHP results show that the technical dimension has the highest weight (0.38), while the social dimension is the least important (0.10). The environmental dimension is assessed as almost as important as the technical dimension (0.36) (Fig. 3.1.1).
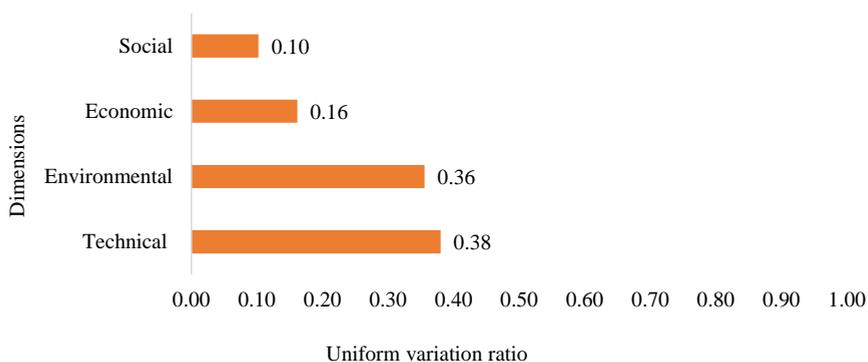
Fig. 3.1.1 Dimension weight from an expert survey

Technical dimension sub-index

The highest technical dimension sub-index was obtained for district heating (0.64), followed by heat pumps (0.51), wood pellet boilers (0.50), and solar collectors (0.26), as illustrated in Fig. 3.1.2. The absolute leader in the technical dimension was district heating, which reached the highest values in indicators, such as opportunities for diversification of utilised energy resources (tech4), operational stability (tech6), and opportunities for the utilisation of low-quality energy resources (tech6). These results are consistent with the study by [125], which argues that opportunities for excess, low quality and waste heat utilisation are essential factors and benefits of district heating systems, raising their efficiency and competitiveness above other competing individual heating solutions.

- tech1 Efficiency (%)
- tech2 Complexity of service and maintenance
- tech3 Stable availability of energy resources
- tech4 Opportunities for diversification of utilized energy resources
- tech5 Possibility to balance the produced heat load
- tech6 Operational stability
- tech7 Opportunities for the utilization of low-quality energy resources
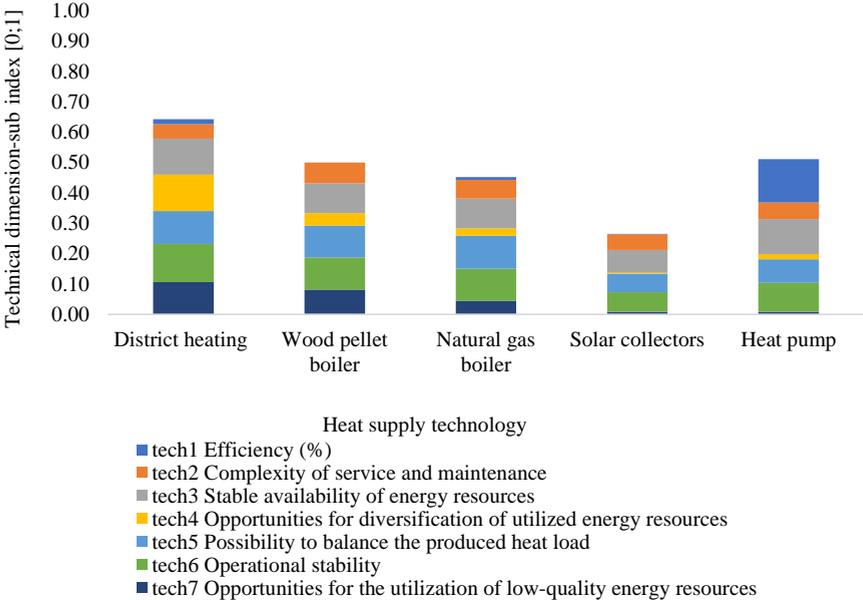
Fig. 3.1.2. Technical dimension sub-index values [119]

Heat pumps reached the second-highest score in the technical dimension due to their highest efficiency ratio and equally high score for both stable availability of energy resources (tech3) and district heating since both technologies offer unrestricted access to energy resources. Compared to district heating, wood pellet boilers and natural gas boilers, heat pumps indicated slightly lower technical performance values for operational stability (tech6). Compared to district heating and wood pellet boilers, heat pumps indicated lower opportunities for diversification of utilised energy resources (tech4) and a lower possibility of balancing the produced heat load (tech5).

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The competitive advantage of both wood pellet boilers and natural gas boilers lies in their slightly lower complexity of service and maintenance (tech2) compared to district heating, solar collectors and heat pumps. Both wood pellet and natural gas boilers showed equally high scores for the possibility of balancing the produced heat load (tech5) as the district heating unit.

Solar collectors reached the lowest scores in the technical dimension due to their inability to diversify utilised energy resources (tech4) and lower operational stability (tech6). Also, they have substantially lower constant availability of necessary energy resources (tech3) compared to other heating solutions, which is particularly relevant for Nordic region countries with a colder climate.

Environmental dimension sub-index

Renewable energy technologies reached the highest environmental dimension sub-index values: solar collectors with a score of 1.0, heat pumps with 0.70, and wood pellet boilers with 0.64. Natural gas boilers (0.23) and district heating units (0.16) reached the lowest sustainability score in the environmental dimension, determined by indicators such as the degree of complexity of flue gas cleaning and specific CO_2 emissions (see Fig. 3.1.3).

Solar collectors achieved the highest possible sustainability sub-index value in the environmental dimensions. The solar thermal system does not require flue gas cleaning in the heat supply process and does not generate CO_2 emissions during the heat production processes. Similarly, the heat produced by the heat pumps does not require flue gas cleaning. However, since the heat pumps' operations consume a considerable amount of electricity, the CO_2 emission factor is applied for electricity consumed from grids, thus making heat pumps less competitive compared to solar collectors in the environmental dimension of sustainability (see Fig. 3.1.3.).

env1 Specific CO_2 emissions (g/kWh)　env2 Complexity of flue gas cleaning
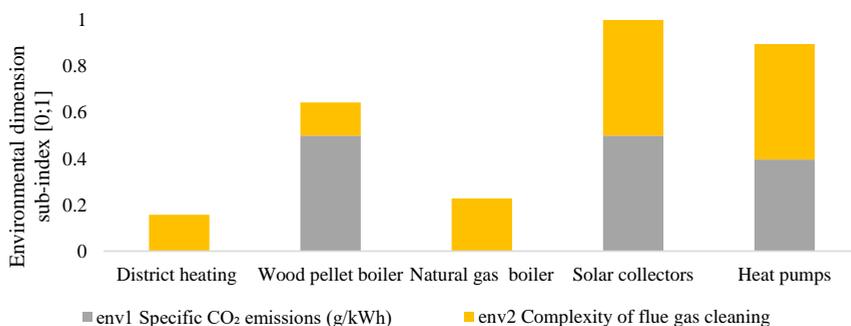
Fig. 3.1.3 Environmental dimension sub-index values [119]

Wood pellet boilers indicated lower environmental dimension sub-index values compared to other renewable technologies. Despite their CO_2 emission neutrality, wood pellet boiler operations and combustion processes produce other emissions, such as exhaust PM and specific NO_X emissions, therefore making flue gas cleaning more complex [117] (see Fig. 3.1.4.). The lowest environmental dimension sub-index values were observed for both natural gas boilers (0.23) and district heating (0.16). For both technologies, the same emission factor was used. It was assumed that natural gas is used exclusively as the main source of energy for district heating since no accurate information on the amount of renewable energy sources used in district heating in Latvia was available. The experts evaluated the complexity of flue gas cleaning as higher for district heating than natural gas boilers, resulting in a slightly decreased overall environmental dimension sub-index value for district heating. If a more precise emission factor were used for district heating, taking into account the share of renewable energy sources used in heat production, the overall heat performance in the environmental dimension would also improve.
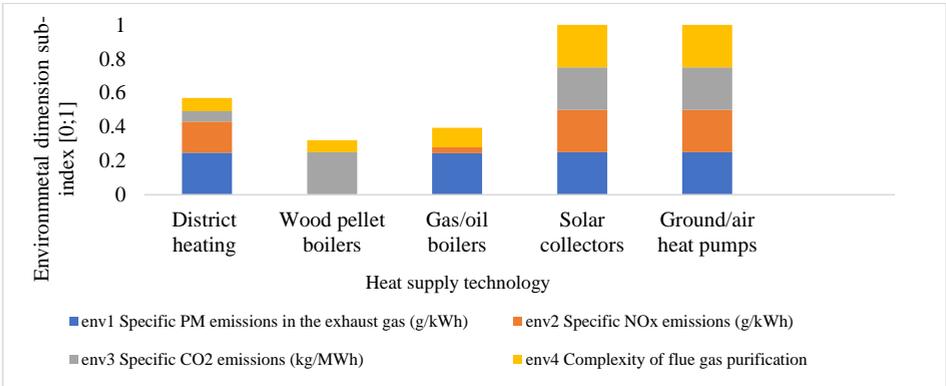
Fig. 3.1.4. Environmental dimension sub-index values [119].

Economic dimension sub-index

The highest economic dimension sub-index value was achieved by district heating units (0.77), as illustrated in Fig. 3.1.5. Solar collectors achieved the second-highest economic dimension sub-index score (0.52), followed by natural gas boilers (0.42), and wood pellet boilers (0.34). The lowest sub-index score in the economic dimension was reached by heat pumps (0.29). District heating substantially surpassed its competing technologies in indicators for capital investments (econ1), service and maintenance costs (econ2), possibility to use surplus heat (econ5), and cost optimisation options (econ6) as well as specific energy costs (econ4) that ranked district heating in the leading position of the economic dimension sub-

index. Overall, district heating shows the highest economic and cost efficiency compared with individual heating technologies.

Initial capital investments for natural gas boilers are significantly lower than for solar collectors to match the average household's heat demands, therefore improving the overall sub-index score for natural gas boilers. By comparison, solar collectors reached the lowest specific energy costs since it is the only technology that does not require the purchase of external energy sources to produce heat. Heat pumps indicated the lowest score in the economic dimension sub-index mainly due to considerably higher specific energy costs (econ4), capital investments (econ1), and a lower technology lifetime (econ3).

Compared with other technologies, wood pellet boilers indicated the highest service and maintenance costs (econ2) and specific energy costs (econ4) that negatively impacted the overall economic dimension sub-index score. A lower technology lifetime (econ3) and fewer possibilities to utilise surplus heat (econ5) also hindered the overall economic dimension score for the wood pellet boilers, ranking it in the lowest position of the economic dimension sub-index overall.

Fig. 3.1.5. Economic dimension sub-index values

Social dimension sub-index

Overall, social dimension sub-index scores are less distributed compared with the other sustainability dimensions (see Fig. 3.1.6). Solar collectors reached the highest sustainability sub-index (0.8). Three technologies, district heating, wood pellet boilers, and heat pumps, achieved equally high results (0.77). Natural gas boilers obtained the lowest social dimension sub-index score (0.58).

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District heating reached the highest indicator values for consumer comfort level (soc1) and consumer safety level (soc2), which can be explained by the fact that in district heating, an operator is providing consumers with a certain level of comfort and safety but for technologies with individual heating solutions, all responsibility lies with the consumer. By contrast, the indicator value for consumer control level over heat consumption (soc4) was assessed to be the lowest for district heating. Unlike the individual heating solutions, in district heating, supplied heat amounts are controlled by the grid operators, not the end-users. In total, the social dimension sub-index scores for district heating indicated that it can offer high user convenience as an individual heating solution. These results are also supported by findings from the study by [20] that show that consumers are willing to pay more to utilise district heating instead of switching to individual heating solutions due to higher convenience and loyalty to the district heating supply system. The total score of the social dimension sub-index for solar collectors surpassed district heating and other technologies due to their ability to combine two essential aspects: consumer satisfaction levels with safety, control over heat consumption, and promotion of local resources. Consumer comfort level (soc1) was indicated as the lowest for solar collectors compared with other technologies. That could be partly attributed to solar energy's periodicity and the necessity to compensate for the lack of solar energy with other heat supply technologies.

Both heat pump and wood pellet boiler technologies obtained the highest scores for consumer control level over heat consumption (soc4). Wood pellet boilers indicated a substantially higher score for impact on the promotion of local resources (soc3), which was the lowest for natural gas boilers. However, unlike the other technologies, the wood pellet and natural gas boiler technologies indicated the lowest scores for the consumer safety level (soc2), possibly associated with risks such as leakage or other types of accidents that could, in turn, affect the consumers' choice of these technologies.
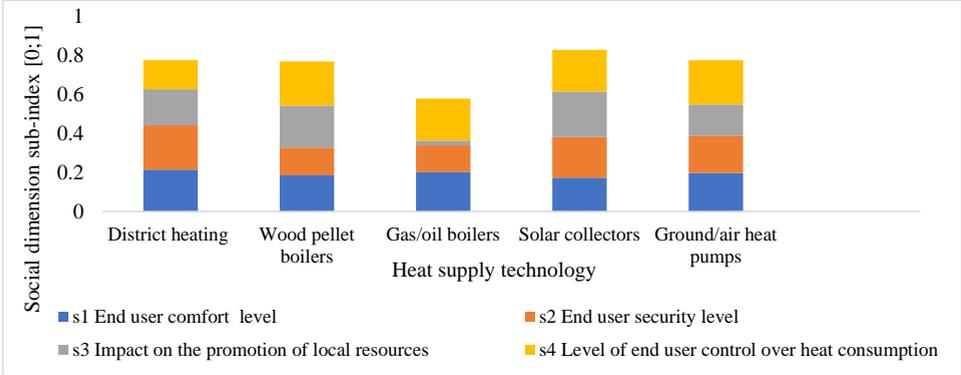
Fig. 3.1.6 Social dimension sub-index values [119]

CSI

The highest CSI was rated for individual heat supply technologies which utilise renewable energy, use local resources and can be used in order to achieve the climate neutrality goals: heat pumps (0.64), solar collectors (0.63), and wood pellet boilers (0.55). A slightly lower sustainability index was estimated for district heating (0.50). Still, the lowest sustainability index was obtained by natural gas boilers (0.38) that utilise fossil fuels as the main energy source as opposed to a low-carbon transition strategy [37].

Fig. 3.1.7 shows the result distribution by the dimension sub-index categories for each technology. The composite sustainability index results identify each technology's competitive advantages and critical positions that currently hinder the achievement of higher sustainability. Due to remarkably higher technical efficiencies and environmental benefits, the heat pumps represent the highest sustainability despite having the lowest score in the economic dimension compared to district heating and other individual heating technologies. However, the heat pump installation choice, as the higher initial investment and specific energy costs, influences the main heat supply technology. Likewise, the wood pellet boiler's score is affected by specific energy costs and service and maintenance costs, which pose a negative impact on higher technology market diffusion.

District heating is the absolute leader in technical and economic dimensions, indicating higher technology efficiency and economic viability compared to individual heating solutions. District heating indicated equally competitive social dimension sub-index values by showing high indicator values for consumer safety and comfort levels.

Although the solar collector indicated the second-highest sustainability score due to its high performance in the environmental dimension, the inconsistent solar energy supply technology requires additional heating solutions to get sufficient heat coverage, which is also represented in lower values of the technical dimension sub-index. Despite the widespread public perception that solar collector installation can only be afforded by high-income households, the results show that, in terms of economic dimension, solar collectors are the second most sustainable technology after district heating.

Due to the considerably low impact of the economic dimension sub-index on the overall CSI, the lowest economic sub-index scores for the heat pump did not significantly affect its overall sustainability scores. Therefore, in further studies, it is suggested to perform a more detailed investigation and scenario analysis in applying different weights for the representative dimensions.
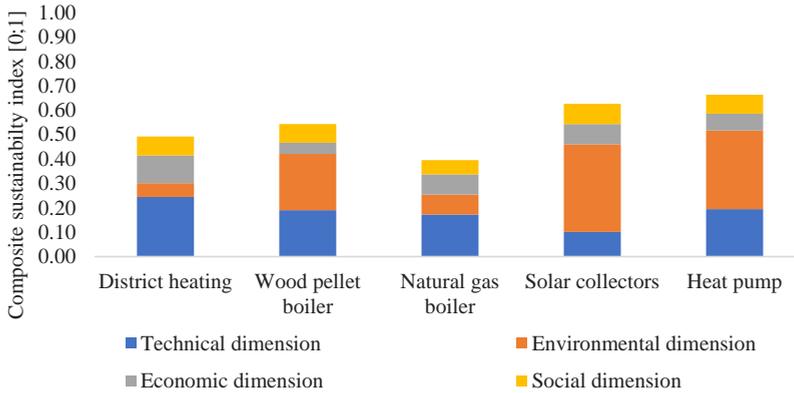
Fig. 3.1.7 CSI for heating technologies

Identification of controversies in heat technologies

In the calculations of the environmental dimension sub-index for district heating, a natural gas emission factor was used without considering the RES share in district heating. As a result, district heating achieved the lowest environmental dimension sub-index value. Moreover, due to higher flue gas cleaning complexity, the environmental dimension results ranked district heating lower than the individual natural gas boilers. It is essential to take into account that the actual emission factor of district heating could be achieved at a significantly lower level than it is generally portrayed in the studies or legislation if the share of RES would be increased. The results showed that district heating obtained the highest sustainability scores for all dimensions except for the environmental dimension, indicating that higher sustainability could be achieved by cutting the utilisation of fossil energy resources, such as natural gas, for combustion processes and replacing them with renewable energy sources [37].

District heating has proven to serve as one of the most effective solutions in energy system decarbonisation since it provides unlimited opportunities for more efficient and sustainable utilisation of energy resources. With new-generation technological solutions, it is possible to diversify the district heating supply system by using cleaner technologies, such as renewable geothermal energy technologies, solar collectors, and large-scale heat pumps, and by increasing energy efficiency by utilising the surplus heat from different industrial processes [230]. Moreover, biomass such as wood and agricultural residues could be used as primary energy resources to decarbonise district heating. Decarbonisation of district heating has helped to significantly reduce CO_2 emissions in Sweden, which have diminished from 90 g/MJ in the 1970s to 9 g/MJ in 2014 [231].

Although high biomass consumption is considered a sustainable solution since it is a renewable energy resource, its combustion inefficiency and significantly higher PM emissions production negatively influence air quality, especially in urban areas. Therefore, district heating could serve as the most efficient solution to coordinate collective decontamination and decarbonisation of the heat supply system. Findings from the paper by [230], therefore, challenge the obtained results of this study, indicating that even though district heating performed poorly in the environmental dimension of the composite sustainability index, by looking at the perspective of created air pollution, the DH sustainability is higher compared to wood pellet boilers. Although wood pellet boilers are promoted as one of the most sustainable individual heating technologies due to their carbon neutrality, their generated PM emissions are substantially higher than those of other technologies, which is reflected in the higher complexity of flue gas cleaning. According to experts, the pellet boiler has the highest flue gas cleaning complexity among the technologies. Considering that PM particles are a significant factor influencing the environment, but are formed in small amounts or not at all (solar collectors) in other considered technological solutions of heat supply, it was not considered separately in the environmental dimension. The model includes the complexity of flue gas cleaning as an indicator, which includes the PM particles' influence. Flue gas cleaning was included as an indicator as it applies to both individual gas boilers, district heating boilers and wood pellet boilers, with PM being most relevant for pellet boilers. Another reason for not including PM particles as an indicator in the environmental dimension was that it is possible to technologically reduce PM particles from flue gases, e.g., through filters, which is considered difficult but can reduce pollution and improve the environmental dimension through treatment plants. Therefore, in the case of the pellet boiler, it would be essential to consider the various treatment methods used if the PM particles produced were used as a separate indicator in the environmental dimension [232].

Although the use of wood pellet boilers is considered to be environmentally friendly, the combustion of wood biomass generates a significant amount of particulate matter (PM) and the flue gases must be cleaned of PM emissions before being released into the atmosphere. The composite sustainability sub-index in the environmental dimension for the wood pellet boiler could be higher if the complexity of flue gas cleaning were reduced. Therefore, in order to increase environmental sustainability, it would be necessary for consumers of pellet boilers to identify technologies that would be able to clean flue gases from PM as efficiently as possible [232]. Nevertheless, efficient flue gas cleaning for pellet boilers is influenced by the fact that flue gas cleaning and equipment maintenance are completely dependent on the consumer; therefore, it would be necessary to develop certain standards to ensure higher cleaning efficiency of wood boiler equipment. For example, studies have estimated that ceramic filters can remove up to 96% of $PM_{2.5}$ and PM_{10} particulate matter from flue gases and, therefore, can be used effectively to clean wood boiler flue gases; moreover, the ceramic filters are assessed

as effective in achieving climate goals [232]. In addition, to ensure higher efficiency of wood pellet boilers, it is necessary to regularly clean the boilers to reduce the ash content and operate the boiler at a higher load [233]. A study by [231] outlines additional contradictions regarding the choice of the most sustainable energy policy. Current policies supporting the decarbonisation of heat supply systems significantly push district heating towards higher biomass utilisation, thus increasing the share of renewable energy sources in heat production. However, high biomass utilisation in heat-only boilers contradicts the energy efficiency opportunities offered by district heating units that allow the use of recovered heat from primary processes. Policies that favour the use of renewable energy sources force district heating to switch to biomass instead of heat recovery, which is especially true if heat is produced from fossil energy resources. Substituting secondary heat with primary energy reduces the share of fossil energy resources by a minimal amount and, therefore, has a lower impact on reaching climate neutrality targets [230], [231].

There is conflicting information in the literature as to whether district heating systems are more expensive. From the perspective of policy-makers, district heating is often criticised for the system's high cost compared to individual heating solutions [20]. According to the results district heating has the lowest costs among the heat supply technologies, which is reflected in the highest sustainability indicators in the economic dimension [37].

3.2. Adaptive and inherent resilience assessment

The adaptive resilience of DH systems under high energy price shocks has been assessed through heat tariff changes. Fig. 3.2.1. shows the relative changes of heat tariffs for ten analysed DH systems by considering 2020 as the base year. DH systems, which are fully natural gas-based, have faced even more than a 300% heat price increase during 2022. On the other hand, the heat tariff increases less significantly in biomass-based DH systems, which use mainly solid biomass

However, it can also be seen that the stabilisation period of heat tariff differs a lot among the analysed DH systems, which requires additional analyses. The ratio of the amount of energy produced by renewable energy to the total heat produced for each of the municipalities is shown in Table 3.2.1. The information in the table allows us to judge how much renewable energy and fossil energy are used in each of the 10 systems considered. DH 3 and DH 4 are systems that are predominantly based on the use of fossil energy in district heating.

Table 3.2.1

The ratio of the amount of energy produced by renewable energy to the total heat produced

Energy system	DH1	DH 2	DH 3	DH 4	DH 5	DH 6	DH 7	DH 8	DH 9	DH 10
The ratio of the amount of energy produced by renewable energy to the total heat produced, %	90	58	1	33	93	100	81.7	93	99.8	100

Calculated data for the further determination of the heat tariff resilience index for each of the DH systems is shown in Table 3.2.2. Results of the heat price analyses for various DH energy systems show that gas-dependent systems have higher heat prices after recovery (T_r) and significantly higher after an initial post-disruption (T_d) in comparison to energy systems based on biomass or other renewables. Energy systems based on gas can be more vulnerable to energy price fluctuations in comparison to biomass-based.

Table 3.2.2

Data for the construction of the Heat tariff resilience index

	DH 1	DH 2	DH 3	DH 4	DH 5	DH 6	DH 7	DH 8	DH 9	DH 10
T_0	55.24	92.76	39.64	42.8	54.9	55.71	56.86	71.66	46.06	55.05
T_d	89.59	225.62	279.51	216.69	89	109.39	143.39	135.55	85.73	105.45
T_r	65.39	92.36	94.06	73.69	78.6	76	87.05	88.06	69.45	71.5
t_r	14	7	9	14	8	9	15	16	10	11
t_d	5	4	2	11	3	5	11	5	1	1
t^*_r	3	5	4	12	4	4	14	15	3	4

Results show that DH energy systems based on renewable energy have lower original system heat prices (T_o) in comparison to gas-based DH systems. Heat price after disruption (steep price increase in 2022/2023) shows that gas-based systems are more vulnerable to heat price fluctuations. According to the results heat price after recovery gets higher in comparison to the original heat price before disruption. In comparison, heat prices for biomass and solar collector-based DH energy systems did not experience such a big heat price rise as that for gas-based systems. Renewable energy (biomass and solar collectors) has a lower original system heat price than gas-based (e.g. DH3 and DH4) systems. Also, biobased DH energy systems are more price-resilient during disruption. After heat price recovery, the price is close to the original price before the disruption. Results of the heat price analyses for various systems are shown in Table 3.2.2, with colour transitions, where green indicates more resilient systems regarding heat tariff and red means less price-

resilient systems. Fig. 3.2.1. shows the calculated speed recovery factor and heat tariff resilience factor in ten different DH energy systems. The highest speed recovery factor is for DH 7 due to the long recovery period for heat tariff stabilisation. Still, the lowest speed recovery factor is for DH systems, which have lower total disruption time from heat tariff increase to returning to a new stable state. The highest calculated resilience factor, which in this study indicated lower resilience to external price changes, is for DH 3, which faced a higher heat tariff increase. Also, the biomass-based DH 7 has a relatively high resilience index due to the high heat tariff after the recovery phase.
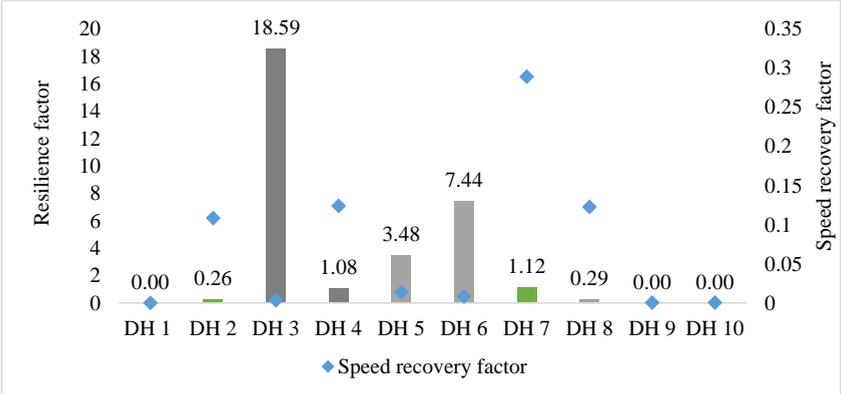
Fig 3.2.1. Heat price resilience factor

Inherent resilience assessment

To evaluate the inherent resilience of DH systems, various indicators were calculated according to the methodology previously presented. Table 3.2.2 shows a summary of the matrix used to construct the DH resilience CI. The matrix is coloured from green to red, where red represents the most negative result between technologies, and green is the result with the most positive meaning in the composite resilience index.

Table 3.2.2

Calculated data for the construction of the DH resilience CI

Type	DH 1	DH 2	DH 3	DH 4	DH 5	DH 6	DH 7	DH 8	DH 9	DH 10
t1	0.91	0.23	0.11	0.47	0.51	0.52	0.27	0.86	0.90	0.51
t2	0.59	0.50	0.97	0.58	0.87	1.00	0.47	0.87	0.84	0.85
t3	322.77	340.40	964.14	554.04	411.81	570.55	447.98	324.63	353.80	365.44
t4	283.19	0.00	28.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
env1	90%	58%	1%	33%	93%	100%	82%	93%	100%	100%
env2	0.034	0.071	0.142	0.157	0.016	0.000	0.037	0.010	0.000	0.000
env3	0.000028	0.000023	0.00001	0.000011	0.00405	0.000054	0.000038	0.000031	0.000044	0.000037
eco1	0.00	13.72	0.00	1.90	1.96	6.40	0.00	0.00	0.00	1.68
eco2	24258	7253	143	8094	646	3897	2213	21689	5685	0
eco3	0.05	0.08	0.11	0.10	0.05	0.08	0.09	0.07	0.06	0.07
eco4	59.80	72.44	180.58	82.72	56.53	39.33	57.18	47.53	59.54	55.58
eco5	0.0003	0.0004	0.0037	0.0004	0.0005	0.0006	0.0006	0.0004	0.0060	0.0006
s1	0.47	0.74	2.52	11.49	0.11	0.02	0.95	0.12	0.02	0.12
s2	1.22	1.28	0.82	1.34	1.16	2.13	1.35	1.01	0.87	1.00

In the technical dimension, the highest score in the DH resilience composite index was for DH 1 and DH 2, which are large-sized DH energy systems in Latvia. DH 1 (renewables – biomass and solar collectors) have the highest result (90 %) for having a heat accumulation tank and excess heat production capacity among systems considered. Heat storage provides more predictable system reactions in case of unforeseen disruptions and a more successful ability to return to the system's initial state. Also, the DH 1 system has a lower value for heat losses. In the technical dimension, the lowest score in the DH resilience composite index was for DH 6, which is dependent on a single energy source. Heat loss in the piping had a negative impact on resilience; the largest heat loss was for DH 3 (gas 99 %) (see Fig. 3.2.2.).
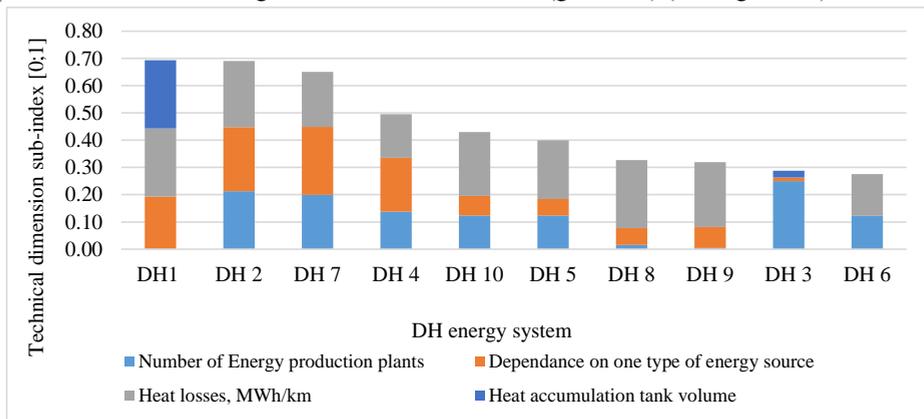
Fig. 3.2.2. Technical dimension sub-index

In the economic dimension, the highest score in the resilience index was for DH 1 and DH 2, which are large-scale DH energy systems in Latvia. The rate of company profit and loss has a great impact on the resilience index in the economic dimension. DH 2 has the largest profits

from all the analysed DH systems. The lowest score in the resilience index was for DH 9, which is a biomass-based system with a lack of historical large-scale subsidised investment projects for the improvement of DH infrastructure (see Fig. 3.2.3).
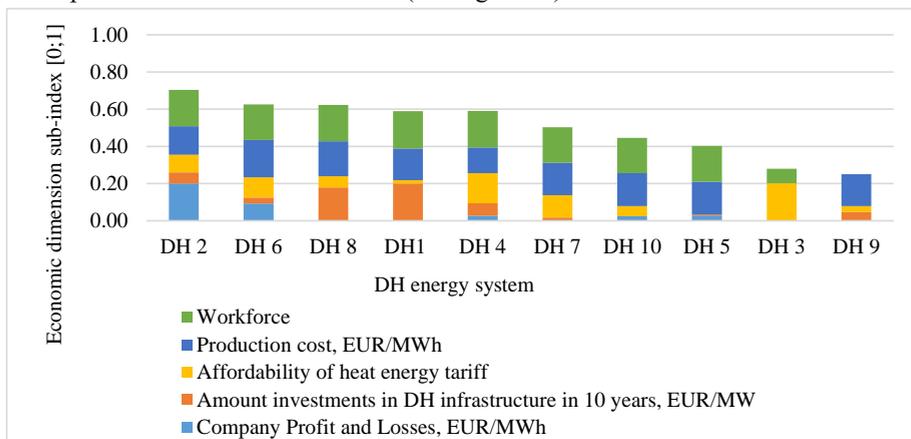
Fig. 3.2.3. Economic dimension sub-index values

Results show that the overall DH resilience composite index for different DH energy systems varies from 0.72 for DH 6, which is a fully biomass-based DH system, to DH 3: GAS 99 %, biomass 1 %, with an overall score of 0.33 in the DH resilience composite index.

Results show that the highest DH resilience composite index was for energy systems that are based on biomass and a mix of biomass and gas. The highest score in the DH resilience composite index was for full biomass-based DH system DH 6, with the highest score in the environmental dimension among the systems considered, and the highest score in the social dimension based on criteria s1 and s2.

The second highest score is for the system that is based on fuel mix, solar collectors, biomass, and 10% gas in total share. The lowest result was for DH 3, which has the greatest negative impact on CO_2 emissions and a low proportion of renewable resources used for heat production. It also has the lowest economic dimension among systems. These results disprove the idea that a system based on renewable resources is more expensive and less economically viable compared to systems using fossil fuels (see Fig. 3.2.4).
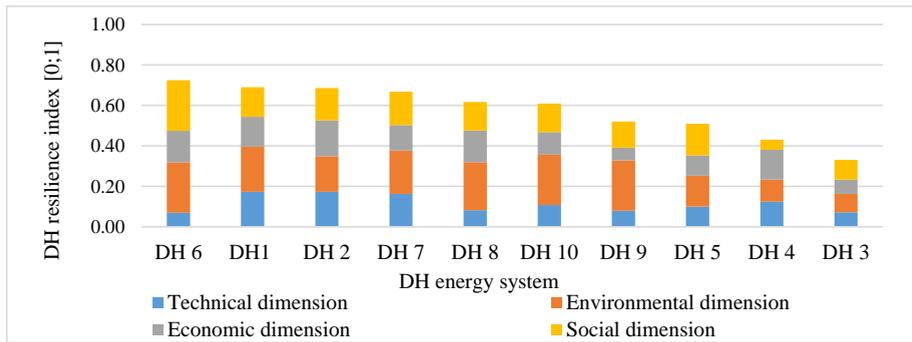
Fig. 3.2.4. Comparison of DH resilience index among different DH energy systems

Sensitivity analysis with different weights for dimensions

A sensitivity analysis was performed to assess how changing the weights for economic and technical dimensions would affect the results. In the sensitivity analysis, the weights for these dimensions were adjusted to 0.40, while a weight of 0.20 was assigned to the other dimensions. The first sensitivity analysis focuses on the impact of changing the weight of the economic dimension, while the second sensitivity analysis investigates the changes in the technical dimension.

When weights were raised for the economic dimension, the highest score was given to DH 6, a fully biomass-based DH energy system. This system features an effective workforce ratio, affordable production costs, and a reasonable heat tariff. In contrast, the lowest scores were given to gas-based systems DH3 and DH4 (see Fig. 3.2.5).
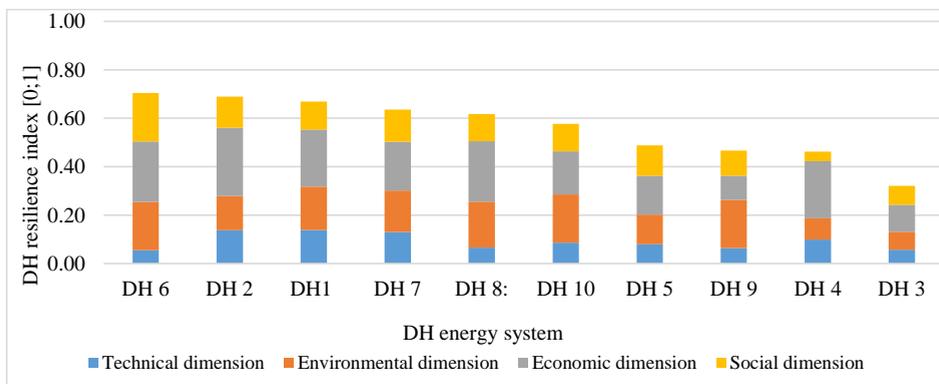
Fig. 3.2.5. Sensitivity analysis with higher weights for Economic dimension

By prioritising the technical dimension, the result remains similar to the initial DH resilience CI, with the greatest score for the largest DH systems, DH1 and DH2, and the lowest score for

mostly gas-based DH systems. This coincides with the original DH resilience CI, which has equal weights for each dimension (see Fig. 3.2.6.).
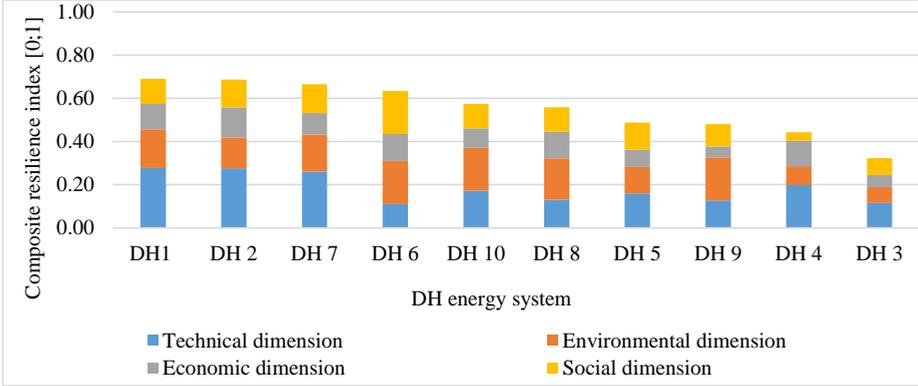
Fig. 3.5.6. Sensitivity analysis with higher weights for the Technical dimension

To investigate the relation between calculated adaptive and inherent resilience metrics, a linear regression analysis was performed using a constructed DH resilience CI (on the x-axis) and heat tariff resilience factor (on the y-axis) (see Fig. 3.2.7.).

The coefficient of determination suggests that the DH resilience index can explain 40.74% of the heat price resilience factor. Although the linear relationship is moderate, the trend suggests that DH systems with higher scores in DH resilience tend to have lower heat price resilience factors, which indicates higher adaptive resilience of the system. These systems demonstrate greater price stability in the event of system disruption and a downward trend in the price resilience factor as the DH resilience index increases.

$$y = -15.1\ln(x) - 5.4199$$
$$R^2 = 0.4074$$
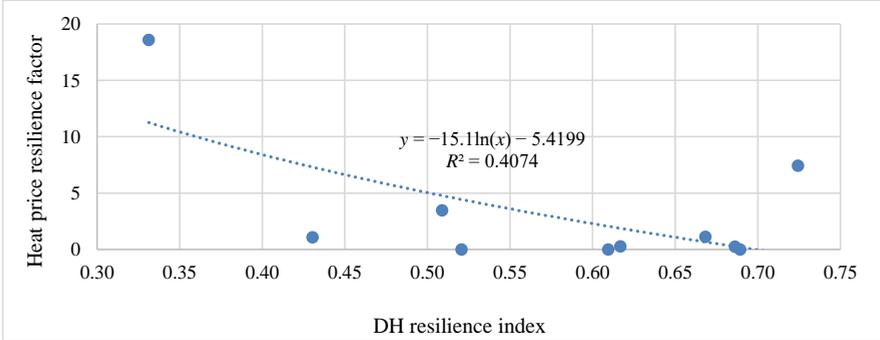
Fig. 3.5.7. Relation between DH resilience index and heat price resilience factor.

This means that systems with higher DH indexes are more price resilient in case of system disruption than systems with lower resilience index scores.

Indicators like fuel consumption and cost, GHG emissions, particulate matter emissions, heat load, price, heat losses, etc., are included when performing an analysis of the DH systems [234]. Results show that the affordability of heat energy tariff is highest for systems based on fossil energy use, such as DH3 and DH4, which can be a significant factor, especially for small municipalities [235]. Although variable heat tariffs promote energy savings, simultaneously, heat tariffs should be affordable in a specific region or municipality [236]. A carbon tax increase that could force DH companies to choose biomass or other renewable sources-based solutions, also in low fossil fuel price periods, might be of great importance to DH system sustainability [236].

Some of the technical barriers to a wider share of RES in DH are related to the lack of suitable infrastructure and skills for implementing these technologies [237]. Previous research shows that one of the challenges in increasing the resilience of the DH system is related to ageing infrastructure and a lack of investment in improving its performance. The results of the study show that some municipalities are not investing enough in DH infrastructure, and that negatively impacts the DH resilience index [31], [238]. The resilience index's lowest score was for DH 9, a biomass-based system with no historical large-scale subsidised investment. According to [63], investments in DH infrastructure projects can improve the resilience of the DH networks [239].

The highest DH resilience CI was for energy systems that are based on biomass and a mix of biomass and gas. One of the most important solutions for the improvement of energy security is increasing the share of RES in DH systems [41]. Using a mix of energy sources can have a positive impact on system resilience, including the use of solar collectors or heat pumps as a heating source [42], [240]. The use of multiple energy sources can improve the diversity of heat supply, improving the overall resilience and flexibility of the system, which is also shown by the results of the study. In case of disturbances, these systems will be more resilient and the return to the initial state will be faster in comparison to those that are dependent on one source of energy. Previous studies show that dependence on fossil energy sources increases the insecurity of overall energy supply disruptions [41]. A study [241] shows that resilient DH systems can be characterised as systems that use multiple heat sources, including renewable heat sources, to improve heat supply security and several fuel heat plants [242]. Using multiple fuel sources with RES integration can decrease dependence on fossil energy sources and improve the overall resilience of the DH system [243]. Spare boilers can serve as a vital addition to improve the security of the heat supply network[20], [25], [27].

The results of this study confirm that systems using renewable energy resources are more resilient to extreme events and energy crises, as also confirmed by previous literature, compared to fossil energy resources. Such systems are also more resistant to price shocks, proving was

also one of the goals of the study [244]. DH systems use a share of RES as a metric for the overall sustainability assessment of the DH network, and such systems are seen as energy efficient with the potential to save energy and reduce GHG emissions [241]. Such heat supply companies are expected to make a positive contribution, both by reducing emissions and by improving social aspects, such as creating new workplaces, which is also confirmed by the results of the study because such systems require a larger number of employees [245].

Results of the study show that thermal storage of heat is not provided in a large part of the municipalities considered. Still, in those who have, the DH resilience index is higher in comparison to other municipalities. One of the solutions for improving the resilience of the heat supply is the installation of thermal storage, which increases the reliability of the DH system overall and in case of unforeseen disturbances, natural or human-caused. Heat storage provides more predictable system reactions in case of unforeseen disruptions and a more successful ability to return to the system's initial state. Previous studies show that heat storage of renewable energy is mostly integrated with smart grid control and serves as an effective solution for the improvement of environmental and economic sustainability [41], [240]. Seasonal storage in the network could help to increase the total savings for large-size DH systems, storing surplus heat as a backup solution [14].

Previous studies confirm that DH systems can be mutually evaluated using the CI method, but this concept has not been previously used to measure resilience. Evaluation based on quantitative indicators can be a tool for successful decision-making when choosing the most sustainable and resilient solution for future development [48].

Limitations of the study

The varying resilience index among DH systems with similar energy mixes suggests that additional factors significantly influence their resilience, including additional indicators in the social dimension. Also, there are still no DH systems that use novel heat production solutions in Latvia, e.g., heat pumps, or electric boilers. Therefore, additional criteria could be added to the technical dimension for electrified DH system resilience assessment.

For the best outcome of Composite resilience DH index analysis, it is advisable to test the proposed methodology on more DH systems with various heat production technologies. However, data is not always possible to obtain from companies as they may not be counted and reported financially in the same way in each company.

The study does not include in-depth analyses of the ownership structure of DH systems and their impact on stable heat costs. Municipality-owned DH utilities should not be highly profitable as their main purpose is to supply affordable heat to their consumers. A high heat tariff and high company profit do not make DH companies an attractive heat supplier to new consumers.

3.3. Heat technologies in municipality buildings

The selected indicators allow for assessing the economic potential of the selected DH and IH alternatives, characterised by the costs of implementing the relevant technologies instead of the existing natural gas boilers, the technical possibilities for diversifying resources, and the impact of technological solutions on the environment. Economic dimension indicators. The calculations show that out of the six alternatives offered in the centralised heat supply and four alternative solutions in the individual heat supply, the highest fuel energy consumption is for the alternatives DH pellet boiler and IH pellet boiler. The highest investment in the energy produced is calculated for the alternative IH Heat pump solution + PV panels. Among the technological solutions, the lowest IRR, replacing the existing natural gas boiler by introducing one of the RES technologies, was evaluated for DH alternatives, Pellet boiler and solar collectors with storage, but the highest for DH alternative wood chip boiler with flue gas condenser. The highest costs of CO_2 production are calculated for IH Solar collectors with storage and natural gas boilers. IH Heat pump solution + PV panels are rated as the highest production cost alternatives. Based on environmental dimension indicators, the IH wood pellet boiler was assessed as having the highest NOx and PM emissions among the alternatives.

From the calculated indicators, it is not unequivocally determined which of the proposed alternatives will be the most sustainable solutions, which should be introduced in the municipality as the first and whether they will be DH or IH technological heat supply solutions, which will allow to partially or wholly abandon the existing heat supply solution - natural gas boilers. In order to determine the sustainability of these solutions based on the calculated indicators for each of the alternatives, CSI was created.

Assessment of alternatives in DH and IH

The CI results show the highest score for three DH alternatives – DH wood chip boiler and PV panels + heat pump solution (0.79); DH wood chip boiler and solar collectors with storage (0.73); DH pellet boiler and PV panels + heat pump solution (0.69). All three solutions rated above combine either wood chip boilers or wood pellet boilers in combination with heat pumps and/or solar panels or solar collectors. Two higher-rated DH alternative solutions include air-type heat pumps, and two include PV panels. All three alternatives have lower production costs and investments needed compared to the other alternatives, and it is also possible to diversify energy sources. The fourth highest-rated alternative was the IH heat pump solution + PV panel (0.66). This technological solution does not require fuel energy consumption; emissions are formed only from the electricity required to operate the pump. It also has the lowest CO_2 reduction costs of the alternatives. Four lower-rated alternatives were three solutions for individual heat supply for municipal buildings and one DH alternative solution: IH Solar

collectors with storage and natural gas boiler (0.59), IH Solar collectors with storage and pellet boiler (0.54), DH Pellet boiler (0.49), and IH Pellet boiler (0.34).

IH alternatives with solar collectors with storage and a natural gas boiler are undervalued due to economic indicators such as IRR and investments/produced energy. Therefore, the lowest indicator for the alternative of solar collectors with a natural gas boiler is the IRR, which determines that installing such a combination of technologies for a specific municipal building is not profitable. Similarly, it is with *IH solar collectors with storage and a pellet boiler* in case of an alternative. The low score for individual heat supply with solar collectors can be explained by the fact that a specific urban building was evaluated and not a set of several buildings in this case. Therefore, in the case of solar collectors, a larger investment is required for one building, and the maximum roof area of the urban building for installing solar collectors must also be considered. The *DH Pellet boiler* alternative is rated with the second-lowest rating in CI. Such indicators as fuel energy consumption and NOx emissions influence the low rating of the alternative. The lowest alternative in the sustainability index is the installation of an *IH pellet boiler* instead of existing natural gas boilers, which is determined by such indicators as fuel energy consumption, emissions, and IRR, which characterises the fact that such a project will not be economically feasible to implement (see Fig. 3.3.1.) [54].
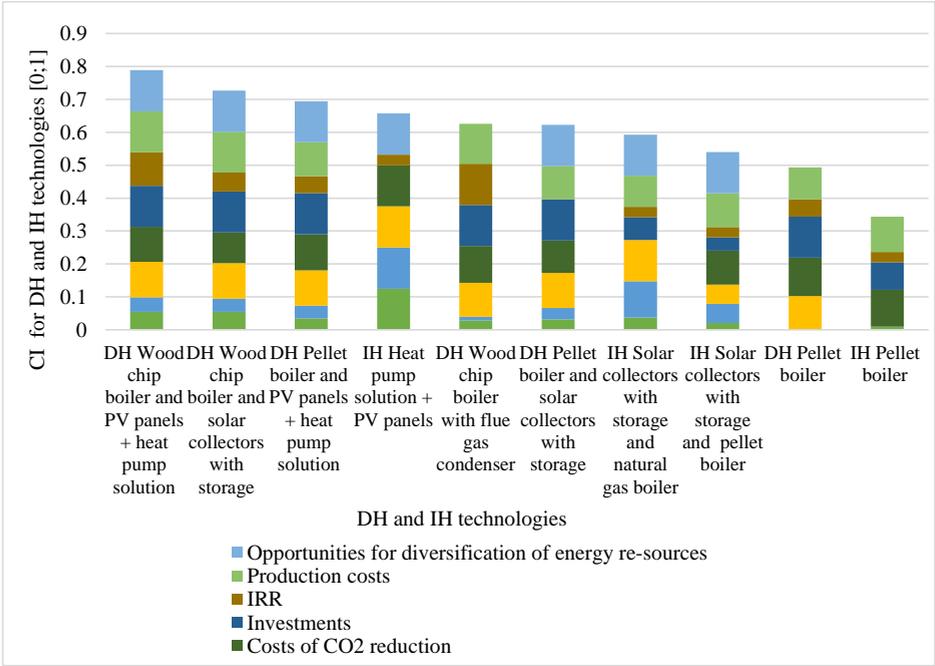
Fig. 3.3.1. CI for DH and IH technologies

Limitations to the study

The low score is influenced by the fact that a solution with solar collectors was only considered for a single municipal building, but solutions for other technologies are considered for multiple buildings, adding up the volume produced and the total investment by types of alternatives. Solar collectors are one of the highest investments in terms of technology, and the maximum roof area of each building influences the possible number of collectors. In addition, this scenario includes the installation of a pellet boiler. Therefore, compared to the other alternatives, it is not economical for the specific urban building to implement this solution, which is also reinforced by the low IRR indicator. In future studies, it would be necessary to use expert surveys to add indicators characterising the social dimension to the economic and environmental indicators for the complete analysis.

3.4. Evaluation of agriculture and land use policy impact

The highest score in the CI was for the policy direction of action *12.1. Improving public knowledge, awareness, and understanding of climate change mitigation, RES use, and resource efficiency* (score 0.77). On the other hand, the lowest score in the CSI was *8.11. Supporting and promoting the installation of green fallow before winter crops* (0.58), *8.10. Supporting and promoting wider use of passer in cereal crops* (0.57), and *9.9. Promoting wood use in construction* (0.55).

The direction of action *12.1 Improving public knowledge, awareness, and understanding of climate change mitigation, RES use, and resource efficiency* (0.77) – at the national level, there are no long-term measures to educate the public about solutions for efficient resource use [18]. A sub-priority of the European Green Deal is to promote even broader knowledge transfer, education and involvement of even broader social groups in environmental decision-making [66].

Based on the data in the assessment of experts, the direction of action: *9.10. Promote the cascade principle in the use of wood and biomaterials also received a high index* [107] (0.71). Detailed information on related activities under the NECP was not provided. It is expected that the sources of funding will come from both the state budget and the European Structural Funds. It is not specified how much funding will be needed to implement the planned activities. One of the environmental policy documents related to the priority directions of the European Green Deal is the New Forest Strategy, carbon sequestration and the cascade principle for wood is one of the main priorities. The European New Forest Strategy for 2030 states that the amount of wood used should be used as much as possible to obtain higher value-added products or raw materials by expanding its use following the basic principles of the circular economy and the cascade principle [246].

8.5. Facilitate ration planning (planning feed rations) (0.71) – From the given description, it is necessary to clarify what part of the funding amount is required for the development of regulations and what part is required for the achievement of the established indicators. However, the evaluation of the measures proposed for this activity is quantitatively measurable and, in the medium term, could measure progress towards the goals set for 2030.

H.14 Develop research programmes to stimulate research needs to achieve energy and climate goals [107] (0.71) – one of the highly rated environmental measures refers to the promotion of environmental research programs to achieve the set climate goals and to promote the development and use of new innovative technologies and products. In the description, there is a lack of concreteness regarding the tasks to be fulfilled to promote research programs, as well as achievable, measurable indicators. NECP indicates in the section on research that both practical research programs with commercialisation, technology transfer centres, and centres of excellence on decarbonisation issues should be created [107]. In line with the European Green Deal [66], closer collaboration between universities, research institutions and companies in the field of climate change, future nutrition and sustainable energy use will be further promoted [247].

8.2. Promote Fertilisation Planning (0.70) – one of the agricultural policies that scored highly in the CI was the promotion of fertiliser planning to reduce emissions generated in agriculture. Although clearly stated achievable indicators, the measure lacks a specific implementation plan for how the indicator will be achieved – implementation of fertiliser planning in 27 % of affected farms [107]. The level of funding is not broken down by activities or periods, only the funding for the entire package of measures is indicated. The package of measures to promote fertiliser planning in Latvia was rightly proposed because one of the most important problems of Latvian agriculture is the excessive use of mineral fertilisers.

The promotion of fertiliser planning is in line with the agricultural goals set out in both the Green Deal and the Common Agricultural Policy, which calls for a reduction in the use of fertilisers [61], [66]. Fertiliser planning and more prudent use of fertilisers are the measures that make it possible to improve the balance between emissions generated by agriculture and overall emissions [248]

8.4. Organic dairy farming – to reduce emissions caused by dairy farming (0.70) [107]. Compared to the other measures described, this set provides specific, achievable indicators to be achieved in each period. This offers the opportunity to measure progress against the plan or revise the measures and targets for 2030. The package of measures is reasonably chosen and solves a current problem in Latvia while showing a potential solution that can help reduce and regulate emissions caused by livestock farming while developing the direction of organic dairy farming. The European Green Deal requires that precision agriculture and organic farming be included and developed in national energy and climate plans and other national environmental documents for agriculture and forestry. The European Green Deal and CAP require all European

member states to increase the area used for organic farming [65], [70]. Therefore, the measure proposed in the Latvian NECP will promote progress and fulfilment of this goal.

9.12. Promote support for innovative technologies, development of technologies and innovative solutions to promote GHG reduction/carbon sequestration in forestry, and resource efficiency [107] (0.68) – although the measures include several activities that could be stated as achievable and measurable indicators, the stated performance indicator is the funding program. Both the European Structural Fund, private funds and the state budget are indicated for the implementation of these actions by 2030, but the total funding of the actions is unknown. It is not clear from the given description whether the implementation of the listed tasks will be done through the creation of funding programs. The objectives of the New Forest Strategy developed by the European Commission have been incorporated into the European Green Deal, and measures to promote carbon sequestration in forests have been identified as one of the priority directions for achieving climate neutrality goals [66], [246]. However, no quantitatively measurable, achievable indicators have been established to monitor and measure the progress of the proposed actions, the additional actions and the measures needed to achieve the targets. Based on the results, the following action directions received the lowest score in the CI: *8.11. Supporting and promoting the installation of green fallow before winter crops* [107] (0.58). This course of action of the agricultural sector was given one of the lowest scores on the CI. No funding was indicated for the implementation of the course of action and the achievement of the defined indicator, indicating that the sources of funding will be the European Union Structural Funds, the state budget and private financing. The measures are rather general, and the NECP 2030 also needs to explain why this direction of the measures is essential and how important they are compared to the other measures, nor does it clearly state the planned funding and funding sources. *8.10 Supporting and promoting wider use of passer in cereal crops* (0.57). The second lowest score in the sustainability index was given to the Agriculture sector action line: Support and promote wider Use of passers in cereal crops [107]. Similar to the previous action line, this action line does not even give an approximate amount of funding required. The funding sources are European Union structural funds, private funds, and funds from the state budget. Neither the description of the action plan nor the Latvian NECP [107] itself describes or otherwise explains why the specific action is essential and what conditions should be developed. It is not explained how monitoring should be carried out to ensure that the established indicator is achieved.

9.9. Promoting wood use in construction (0.55): The action direction to promote wood in construction received the lowest score on the sustainability index. Under the action direction, it is planned to establish at least one incentive program to promote the use of wood in construction by 2030. The total amount needed or the approximate amount of funding is not specified in this case. The national budget, European structural funds, and private funds are mentioned as sources of funding [107]. The new EU Forestry Strategy described above

identifies promoting the use of wood in construction as one of the most crucial carbon sequestration solutions. The forestry strategy emphasises that it is possible to reduce climate change both by sequestering CO_2 and accumulating carbon in wood and replacing fossil-origin materials with wood, including wood construction, furniture, and household items as higher value-added and CO_2-neutral products [246], [249].

Therefore, in the case of Latvia, more attention should be paid to promoting carbon sequestration through the use of wood in higher value-added wood products to reduce the amount of wood used for energy production and achieve the set climate neutrality targets in 2050. Also, from the New Forestry Strategy of the Union of European Member States, European priorities should currently refer to the more sustainable use of wood materials, including wood used in construction and demolition – reuse and recycling [250] (see Fig. 3.4.1.) [251].
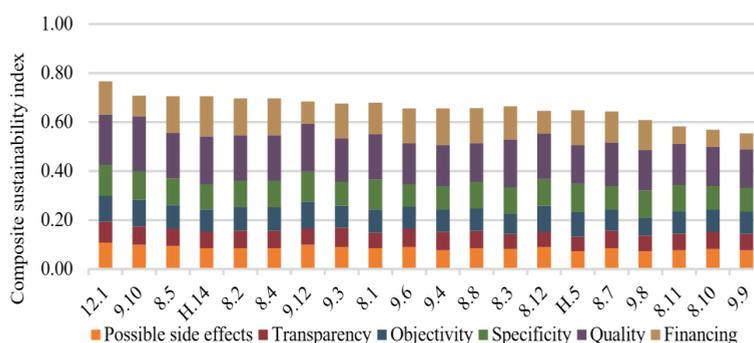
Fig. 3.4.1 CI of agriculture and forestry policy.

Table 3.4.1

Agriculture and forestry measures from NECP [107]

12.1	Improve public knowledge, understanding of climate change mitigation, use of RES, and resource efficiency
9.10	Promote the use of the cascade principle in the use of wood and biomaterials
8.5	Facilitate feed ration planning
H.14	Develop research programmes to promote and stimulate research for achieving energy and climate goals.
8.2	Promote fertilisation planning
8.4	Organic dairy farming (emission-reducing dairy farming)
9.12	Promote support for innovative technologies and solutions to promote GHG reduction/carbon sequestration in forestry, resource efficiency
9.3	Promote forest development and crop quality in naturally overgrown areas
8.1	Encourage and support the accurate use of mineral fertilisers
9.6	Encourage young-adult tree felling
9.4	Promote the replacement of unproductive, low-carbon forest stands

8.8	Improve the inclusion of the taw winter in crop rotation to promote nitrogen removal
8.3	Directly promote and support the incorporation of organic fertiliser into the soil (transporting liquid vehicles using hose systems or casks and using injectors in the soil)
8.12	Promote support for the development of innovative technologies and solutions to promote resource efficiency and reduce GHG/carbon emissions from agriculture
H.5	Promote the production of biogas and biomethane and the use of biomethane
8.7	Improve the maintenance of amelioration systems in agricultural lands, thereby reducing indirect FROM runoff
9.8	Encourage recultivation of historically used peat harvesting sites by selecting the most appropriate type of recultivation
8.11	Support and promote the installation of green fallow before winter crops
8.10	Support and promote wider use of passer in cereal crops
9.9	Promote wood use in construction

Importance of the indicators

Regarding the importance of each indicator, indicators such as funding and quality were the most important. The weights determined by the expert evaluation were also compared for the weights where each indicator was equally important. The results showed no significant differences in the distribution – it is equally possible to use the same weighting method and the weights from an expert survey. Each measure in the NECP should include a detailed description of the specific measure and achievable targets. In addition, a measurable target achievement indicator should be provided for each defined action, not just the target achievement indicator for the entire course of action. For each of the action areas included in the NECP, objective and verifiable indicators should be defined that can be monitored to verify at an earlier stage whether progress is being made towards the goals set or whether the action in question needs to be revised to avoid partial or total non-compliance with the plan at the end of its implementation. The indicators to be achieved must be expressed in numbers (quantitative and qualitative indicators to be achieved by 2030), all necessary funding (including monitoring activities), and additional funding sources.

Limitations of using the CSI

One of the study's identified limitations is that more objective results could be expected if more indicators were used. The indicators were selected based on the scientific literature and the minimum amount of information available for each horizontal measure and action line in the NECP [107]. In such a case, if the policy planning documents contain more detailed information on policy objectives, achievable indicators, monitoring, and required funding, other indicators not included could be proposed for evaluation. Expert ratings were compared with

the same weighting for each indicator. With a larger group of experts, the weighting of the indicators would be more different, and the result would be more objective. To create an evidence-based and reliable sustainability index that shows the sustainability of each measure, the raw data and the availability of the data are most important. In this case, the data were more descriptive. Therefore, indicators such as quality were chosen to indicate how detailed and precise the course of action was described.

3.5. System change – comparison of conventional and organic farming

The overall score in CI for organic wheat production is 0.51, which is smaller than for conventional wheat production (Fig. 3.5.1). Organic wheat production has the highest score in CI for carbon footprint per land unit. Previous literature studies confirm that the transition to organic farming increases both the carbon sequestration capacity and also reduces the carbon footprint per land unit [158]. Conventional wheat production gets the greatest score among strategies for carbon footprint per product EUR/ha (wheat) The lowest overall score among strategies is based on possible low income during seasons. Organic wheat farming has the second-highest mean total costs score. It is less expensive, considering operations like fertilisation and weeding are restricted [69]. Regarding total costs EUR/ha, conventional wheat production got a lower score than organic wheat production but got a considerably higher score in CI for net income EUR/ha. Previous studies show that during 2019-2020 average price for wheat was 420 EUR/tons [156].
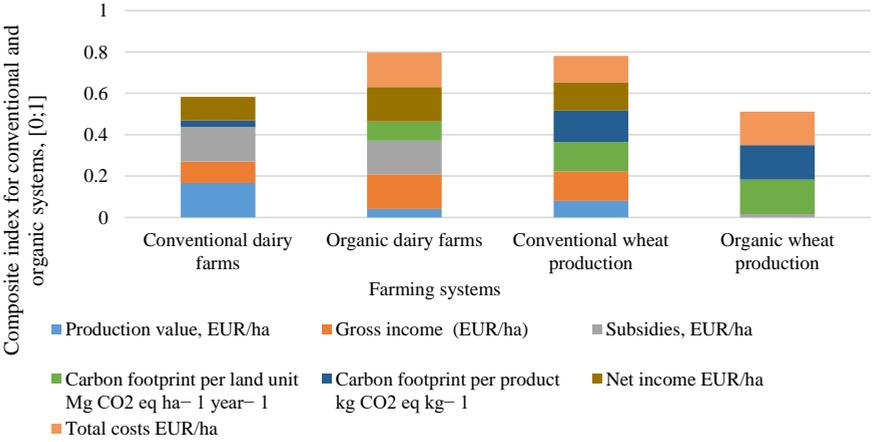
Fig. 3.5.1. CI for conventional and organic farming strategies.

Conventional dairy farming has the lowest score in CI regarding total costs, which means the highest total costs EUR/ha for traditional farming of dairy among strategies.

Organic dairy farms got the highest overall score in CI, but conventional dairy farming had the lowest score among farming strategies based on total costs EUR/ha. The highest score for organic dairy farming is mainly partly based on total costs (EUR/ha) and net income (EUR/ha). Organic dairy farming has the highest score in CI among strategies for net income EUR/ha. Organic farming has lower operating costs and higher product costs, which can increase overall incomes. The highest support payments in net added value are for organic dairy farms. In organic farms, support payments play a significant role in generating revenue that can compensate for costs and lower yield in organic dairy farming [158].

EU member states can receive compensation and support payments to ensure the transition from conventional to organic agriculture, compensate for financial losses, and cover expenses that arise in organic farming [252]. Organic dairy farming has a lower production value in CI than conventional dairy farming. Conventional dairy farms have the highest score in CI regarding production value EUR/ha, with a score of 0.17 [58].

Based on 2021 data, conventional dairy farming is the leader in creating production value [77]. Organic dairy farming has a lower carbon footprint per land unit than conventional dairy farming, which got the lowest score in CI for carbon footprint per land unit. As the number of dairy cows on farms increases, GHG emissions per land unit also rise By improving the quality of cow feed, CH_4 emissions from cow manure can be reduced [149]. The literature shows that organic dairy farming can have a higher carbon footprint per product than conventional dairy farming [83].

The economic viability of small dairy farms depends on the existing EU support for agriculture [158], [253]. The results suggest that farms with 30-49 cows are more economically efficient in terms of profitability than larger or smaller farms (see Fig. 3.8.2.). Results show that farms with 30-49 or 50-99 cows indicate that larger operations benefit from economies of scale—where the cost per cow decreases as the farm grows in size. Farms with fewer than thirty cows might struggle to cover fixed costs and achieve profitability, potentially due to higher per-cow costs and lower overall efficiency. In Fig.3.8.2, it is also shown that organic dairy farms are more profitable than traditional ones when they operate with the same number of cows. Organic farms may have cost advantages in terms of lower feed and chemical inputs, although they might also have higher labour costs or certification costs [165]. The costs EUR/number of cows tend to be lower than those in conventional farms of the same size, especially in terms of purchased fodder [165]. This could be because organic dairy farms often grow their own feed, there is no need for chemical inputs, which can reduce the overall cost of production and lower veterinary costs [165].

Organic dairy farms tend to have higher-quality feed, and organic standards encourage the use of natural remedies and holistic approaches to animal care; the animals usually have better health, lowering veterinary costs [165]. Organic dairy farming is better aligned with

sustainability goals, while conventional dairy farming provides more efficient production through technological advancements.
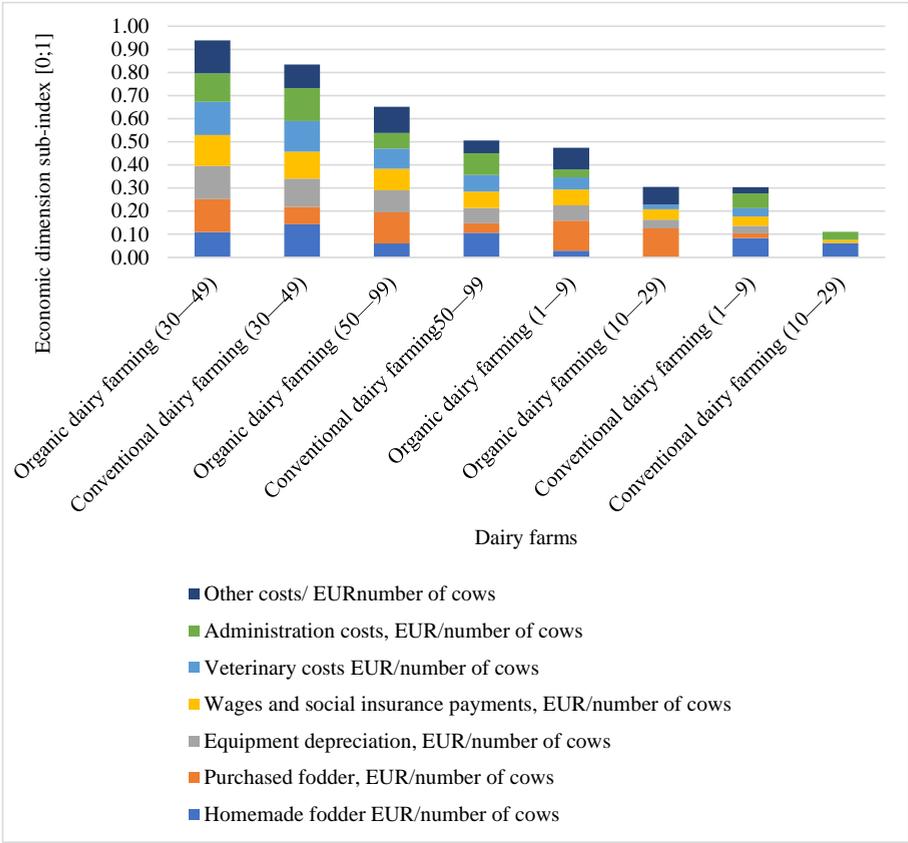

Fig. 3.5.2. Local-based economic dimension sub-index for conventional and organic dairy farming strategies.

From an environmental perspective, organic dairy farming outperforms conventional farming, regardless of herd size. This could suggest that practices in organic farming, such as the use of organic feed and reduced chemicals, contribute positively to the cow's digestive system and produce lesser amounts of N_2O and CH_4 [61]. The results of the CSI suggest that organic dairy farming has advantages in comparison to conventional dairy farming in terms of overall sustainability. Results show that increasing feed digestibility has a positive

effect on emissions resulting from intestinal fermentation processes. On a per-cow basis, results show that organic dairy farms produce lower GHG emissions. On the other hand, conventional dairy farming seems to have an advantage in the technical dimension.

Organic dairy farming demonstrates better environmental performance and competitive scores in the economic dimension. In terms of milk production, conventional dairy farming has higher scores in the technical dimension (see Fig. 3.5.3.).
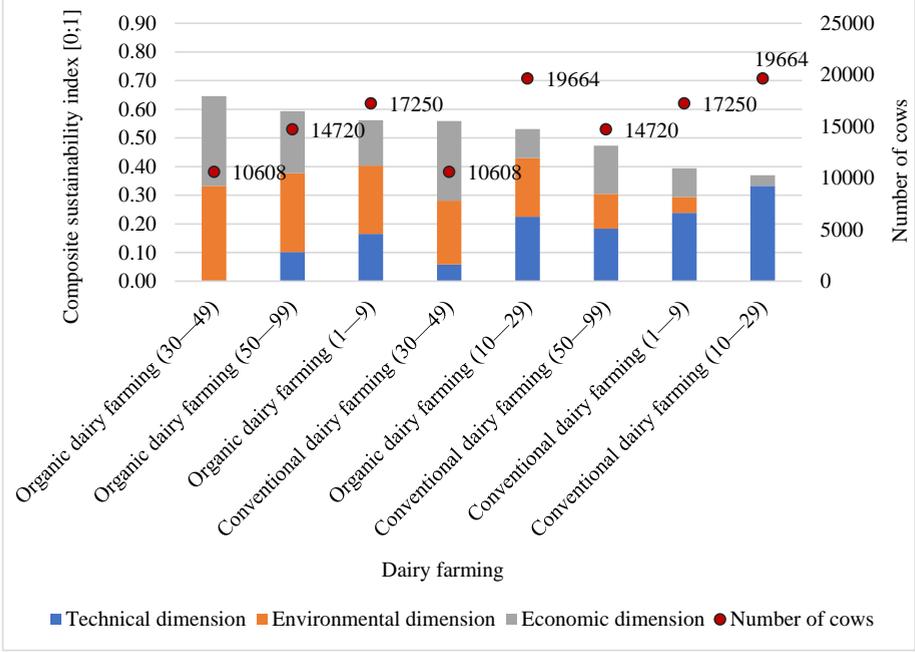
Fig. 3.5.3. Composite index for conventional and organic dairy farming strategies with DE 67 %.

Limitations of the study

The CI created in the first part of the study was based on data available in the literature on wheat cultivation and dairy farming in organic and conventional systems. The authors included only those indicators that can be compared with each other. Future research envisages additional indicators. Including the inclusion of a biodiversity indicator if reliable data is found. Some data are averaged based on calculations, and some are from scientific articles or local reports. Additional environmental indicators, like the biodiversity index or parameters describing soil quality, should be included. Carbon footprint should be compared in different studies, geographic-based on locations, which can greatly impact carbon footprint [68].

Research indicated that organic dairy farming aligns more closely with sustainability goals, while conventional dairy farming achieves greater efficiency in technical dimension, through technological advancements. However, it is crucial to also consider the broader implications, such as social indicators like employment level and farmers' opinions.

Overall, the findings highlight the necessity and advantages of transitioning to organic dairy farming. This evaluation approach may enhance the adoption of more sustainable practices in the dairy sector and contribute to achieving the EU sustainability goals.

3.6. System change – restoration of peatlands

By comparing the costs, benefits, and GHG emissions of peatland restoration strategies, it is possible to assess which strategies are considered important in Latvian conditions. Among the restoration strategies, afforestation on drained organic soils (0.87) received the highest rating in CI. The lowest rating was for perennial cultivated grasslands, which have higher emissions compared to other strategies (0.40) (see Fig. 3.6.1.).

Restoration strategies
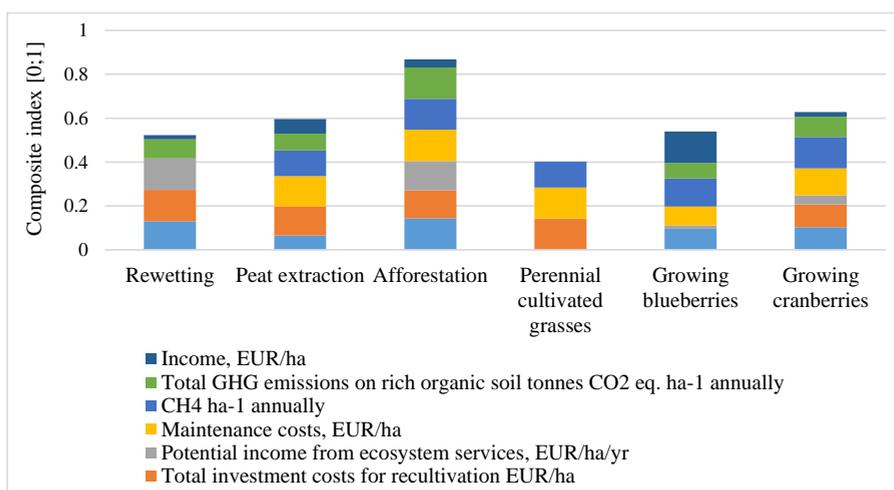
Fig. 3.6.1. Peatland restoration strategies

Restoration strategies + alternative strategies

The highest score on the composite index, taking into account alternatives, was for the production of insulation panels using cattail (*Typha*) (0.87) (see Fig. 3.6.2). The indicators that

most determine the advantages of thermal insulation panels are the required amount of investment and the relatively low emissions of CO_2 eq. Also, paludicultures using sphagnum farming (0.84) and cattail (0.82) received the second and third highest results in the CI, respectively. Peat rewetting received (0.53) due to the higher maintenance costs, including monitoring costs. However, from the alternatives mentioned before, the rewetting of peatland has the highest potential income from potential ecosystem services.
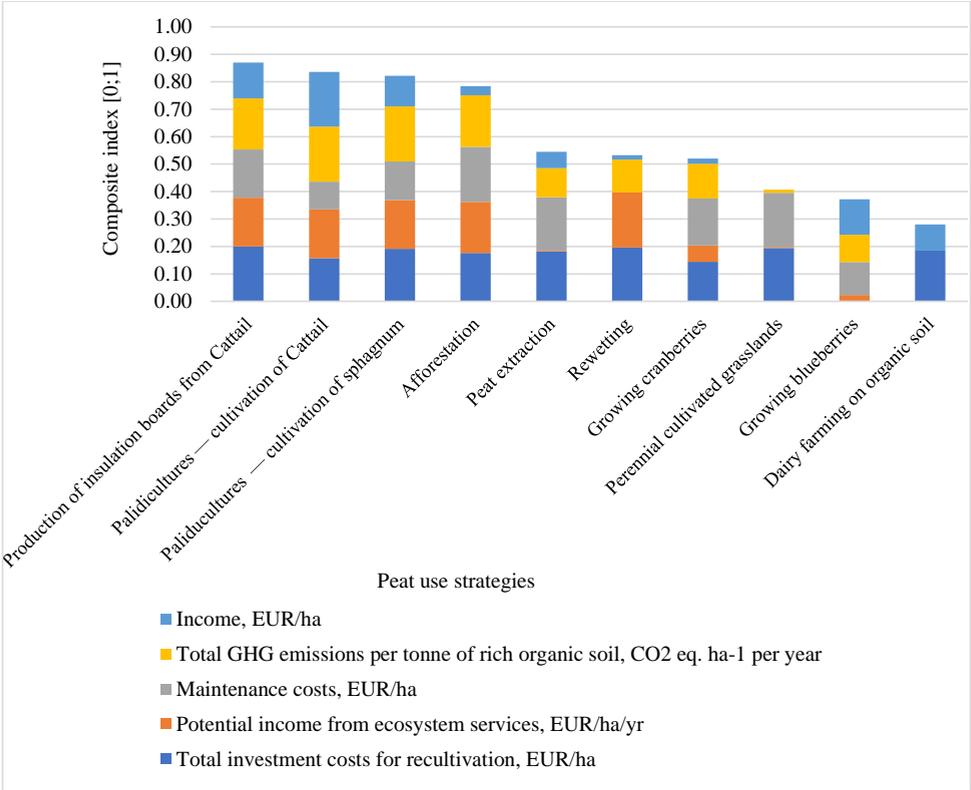
Fig. 3.6.2. Restoration strategies and alternative use of peat.

Rewetting of peatlands can be evaluated as an attractive solution regarding financial compensation (EUR/ha) after rewetting [169], [254]. However, in the case of land rewetting, landowners can experience serious negative effects on their future agricultural activities. The negative effects of rewetting are related to the loss of income due to land use change. Land area after rewetting is not economically viable for landowners and nearby farmers for agricultural activities.

After rewetting, the soil is not suitable for further cultivation of crops or dairy farming, including rewetted soil limited by the capacity to carry agricultural equipment [172], [255]. A

previous study from the Netherlands shows that increasing the water level due to rewetting from 80 cm under the surface to 10 cm above the surface can cause a market income loss of up to 1358 EUR/ha [256]. Pressure drainage can be implemented after rewetting farmlands to stabilise the water level [254].

Paludiculture is considered a viable strategy for reducing GHGs while providing opportunities for landowners and the development of new services and products. Although paludiculture has several benefits, only a small area of peatlands is used in paludiculture [172]. Switching to paludiculture can reduce GHG emissions and land subsidence while providing productive use of land [257], [258].

Cultivation of cattail can promote suitable conditions for the development of ecosystem services. Previous studies show that after processing peat by separating fibres, incomes can reach 300 EUR/ton to 500 EUR/ton [259]. Cattail, as a raw material, can generate an average turnover of ~2000 EUR/year and ~ 4800 EUR/year in processed material [198]. Net incomes from paludiculture can also generate carbon credits for landowners [169], [172]. Harvested cattails have the potential to be used in different kinds of goods, including mats, baskets, and toys, and valuable products such as building materials and insulation boards, where peat can be used as a raw material or additive [260]. Cattail characteristics make it appropriate and competitive as an insulation material. In cattail-based insulation material, it is feasible to store biogenic carbon for a long period [172].

In the case of afforestation of peatlands, the necessary total capital investments highly depend on the tree species to be planted in previously drained peatlands. One of the highest investments is necessary for the plantation of willow (~1549 EU/ha^{-1}). The high costs of seed materials could explain that. It has been estimated that lower initial costs are for the planting of pine (1042 EUR/ha^{-1}) and spruce - 1090 EUR/ha^{-1} [261], [262]. It is calculated that high market revenues in drained peatlands are from plantations of poplar (7557 EUR/ha), in 20 years and 40 years, hybrid aspen. One of the lower incomes is from grey alder - in 20 years (3306 EUR/ha), and from pine - in 40 years [261], [262].

Previous studies show that the average costs are 382.8 EUR/ha for preparing a site, 633.2 EUR/ha for labour and seedling costs, 374.8 EUR/ha for maintaining stands, 429.6 ha for thinning before commercialisation, and 391.9 EUR/ha for fertilisation [168], [171].

Although dairy farming makes income from the production of products, the negative aspect is related to the degradation of ecosystem services, transforming peatlands into grasslands for dairy farming [258]. Restoration by introducing perennial cultivated grasses can have various establishment costs that depend on the methods used, ecology, and the specific restoration site [263], [264].

More attention should be focused on the techniques and necessary investment reduction for the cultivation of paludicultures as an alternative for the rewetting of peatlands. The connection between global indicators and national or local policy and reporting needs strengthening [265]. Indicators should be scalable where there are local or national data - which are typically more relevant to local policy and more accurate through the inclusion of local knowledge and data [62].

Limitations of the study

There is a lack of a specific cost-effectiveness assessment of the impact of peatland restoration strategies [266], [267]. According to the literature, global funding for peatland restoration is assessed as insufficient [268]. It is estimated that both public and private financing is less than required for peatland restoration [259], [267].

 One limitation of the study is the scarcity of specific data regarding costs and gains on thermal insulation panels. Revenues and incomes from sphagnum farming can greatly vary, but incomes can be expected after several years [175], [269]. Other environmental factors that could be included in future studies are the Ecosystem Health Index and indicators that rely on land-use change and biodiversity, such as the Species Habitat Index and Biodiversity Intactness Index [265].

3.7. Renewable energy potential in sectors

Industrial Sector

The results show that solar energy and biomass are the key dominators for the industry compared with other types of RESs, as shown in Fig. 3.7.1. Solar energy has the highest value compared to other resources, with a value of 0.83 on the value index. This is mainly because the resources have developed the fastest and have greater technological advantages. The technological development of solar energy systems has significantly maximised the solar energy utilisation potential in the industry over the past decade. The use of solar energy has become more attractive thanks to a number of technological advances in solar energy systems. These include integrated systems that make it possible to control the temperature required for industrial production processes and ensure that solar energy is used for crucial production processes such as water heating, steam generation, drying, and other processes. The possibility of energy supply shortages is considered the most important obstacle limiting production plants in the implementation of solar energy systems. This explains why the overall index score for solar energy was below the maximum score of 1, which is the highest possible score. However, due to the rapid technological development of solar energy and the advantages of its use, as

well as the shorter payback period of the investment, these limitations are not a major obstacle to the potential use of this energy source. Moreover, solutions already exist to compensate for the limiting factors of solar energy and to achieve greater use of solar energy in industrial enterprises
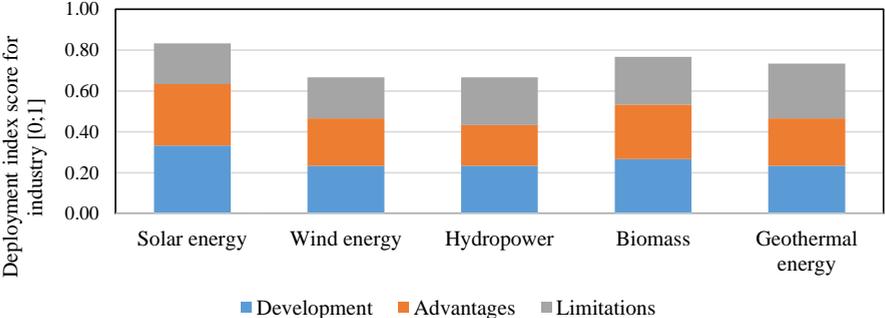

Fig. 3.7.1. Industrial RES development potential index results

Biomass was determined to have a potential use of 0.77, placing it second among all sectors in terms of potential use. The rapid development of the potential of biomass utilisation can already be observed and predicted for the future. Higher biomass consumption is observed in pulp, paper, and wood production industries, all of which generate waste in the form of biomass as a byproduct of their production processes. Technological solutions are mentioned as the main advantages of biomass, such as reaching the temperature range required for efficient industrial processes. Constant energy supply throughout the year without energy shortages is highlighted as the main advantage of biomass use in industry, which has been identified as the main limitation of solar energy use. The main disadvantage of using biomass in industry is that there is not enough biomass available to meet the energy needs of the sector unless agricultural residues are used for energy production.

Geothermal energy has not yet achieved an assessment score (0.73) for deployment potential in an industry that could compete with solar (0.83) or biomass (0.77). Geothermal energy allows the storage and reuse of heat, which greatly improves the efficiency of production processes, even at high loads. Geothermal energy can be combined with other technologies to provide uninterrupted power to facilities when solar energy is limited. The main limitation associated with using geothermal energy in industry is the availability of the resource.

Deployment potential index scores in the industry for *wind energy and hydropower* each reached a value of 0.67, which is the lowest value compared to other RES energy resources. Both resources are developing at a limited pace compared to other RES. Wind energy, like solar energy, is limited due to energy generation dependency on seasons. However, wind energy can be used in combined systems where another RES can make up for a shortage of wind energy.

One significant advantage of wind energy application in the industrial sector is that wind turbines possess the capability to generate a greater amount of energy per unit area and time compared to solar photovoltaic systems, assuming equal potentials for both in the given region.

In terms of limitations, both technologies are constrained by their intermittent production nature and geographical needs, requiring substantial spatial demands. Hydropower also has limited advantages because it requires a high capital and technical capacity to produce energy. However, hydropower is able to adapt and compensate for bottlenecks and interruptions in wind energy. Despite the industry's slower development pace of wind and hydropower technologies, both RES are expected to develop more rapidly.

Service Sector

The Fig. 3.7.2. shows the potential of RES in the service sector. According to the results, the use of solar energy has the highest value of 0.90. The pace of development of technological solutions for solar energy has accelerated in recent years, so the demand for solar technologies in the service sector continues to grow. The growth rate in the development of solar technology solutions is favoured by combining these technologies with smart solutions or integrating smart technological solutions with solar technologies. In recent years, more solar technologies have been used together with integrated smart meters. Such technological solutions are also used in educational institutions and other public buildings to control better the energy consumed and the load. One of the subsectors of the service sector, tourism, is increasingly using solar solutions that can cover a large part of the required energy.
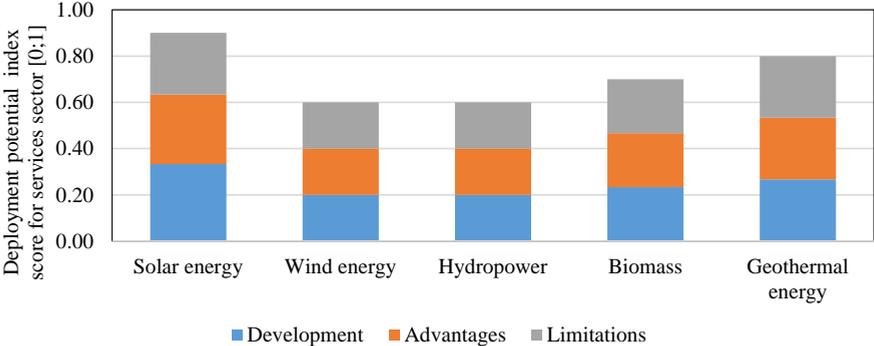
Fig. 3.7.2. Development potential in the service sector by RES types.

Solar solutions have a growing trend, such as heat recovery from wastewater, using heat pumps in addition to PV solar solutions. Integrating solar solutions with smart technologies can directly reduce the consumption of thermal energy, electricity, and hot water in the service

sector. A disadvantage of using solar technology in the service sector is the insufficient amount produced during the relevant months of the year. This disadvantage could be eliminated by using an additional source that provides the necessary energy throughout the year. Heat pumps, which are also increasingly common in the household and service sectors, can compensate for energy shortages at a lower cost compared to the industrial sector.

According to the results, the use of *geothermal energy* in the service sector achieves a high score of 0.80. Geothermal energy is mainly used in the tourism sector, especially in the recreation sector. Geographical and regional differences affecting the availability of resources can be mentioned among the disadvantages of exploitation.

Compared to the other RES sources discussed above, the use of biomass (0.70) in the service sector is considered slower in terms of development speed. On the other hand, especially in the hospitality sector, the development speed of biomass utilisation has been increasing, and it is expected that the development speed of utilisation will continue to increase in the future. The hospitality industry collects biological waste and non-recyclable residues from various hospitality facilities. The application of biogas in the service sector is limited by the fact that while the hospitality industry generates a sufficient amount of organic residues and waste, other areas of the service sector must generate a sufficient amount of organic waste for further use in biogas. This prevents the service sector as a whole from fully realising the potential benefits of biogas.

Similar to the industrial sector already reviewed, hydropower and wind energy use in the service sector was rated as having the lowest development potential, with each resource RES receiving a rating of 0.60. The use of both resources and the rate of development in the service sector are influenced by social factors such as the public's opinion of using these resources, the impact on the landscape, and the quality of the environment. Wind energy parks are associated with a negative impact on tourism development. In recent years, regarding the use of wind energy in socially responsible hotels and guesthouses, the rate of use of both wind and hydroelectric power is significantly influenced by social factors, so the use of these resources is characterised by slower rates of development compared to other RES resources.

Agriculture sector

Fig. 3.7.3. shows the assessment of RES potential for the agriculture sector. The use of biomass for energy production was rated with the highest development potential among the analysed RES. One of the most demanded biomass feedstocks in biogas plants is manure enriched with agricultural residues and residues from cereals and sugarcane. The demand for biomass fuels for biogas production is expected to continue to increase. Its advantages have been evaluated for use in combined systems, for example, to meet necessary energy needs during solar power outages.
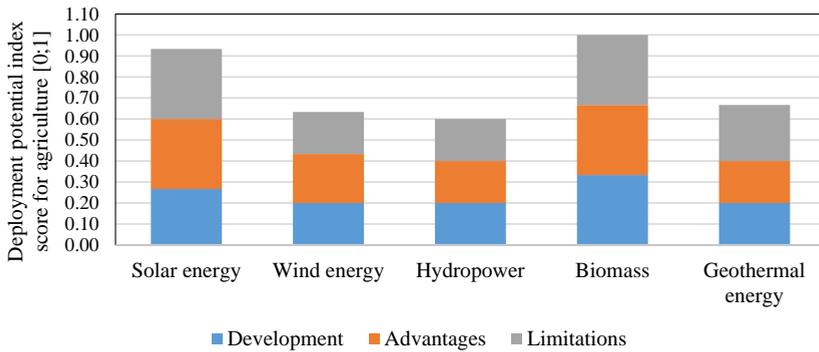
Fig. 3.7.3. Comparison of the potential of the agriculture sector for the development of RES.

In the agricultural sector, the second-greatest development potential for using solar energy was identified after using biomass. The use of solar energy technologies in agriculture is characterised by a rapid rate of development in recent years and is expected to continue growing. Smart technologies combined with solar panels and collectors ensure agricultural processes, for example, to monitor soil moisture. The increase in solar energy use in agriculture is also favoured by economic sustainability; the payback period of investments is less than ten years, and there are more and more RES support programs that can reduce the necessary investment in installing solar technologies. The least constraints were identified for using solar energy in the agricultural sector. To avoid solar energy interruptions, smart systems that control the energy needed can be used.

Geothermal energy (0.67) received the third highest score in the sustainability development potential assessment. The potential for geothermal energy development is limited by resource availability, influenced by geographic conditions. Examples show that geothermal energy has been used as a resource in aquaculture farms to provide the specific temperature required for trout farming.

Similar to the service and industrial sectors discussed above, *wind energy* and *hydropower* use in agriculture have lower sustainability potential scores compared to other RES - wind energy and hydropower use with (0.63). The use of wind energy is also affected by geographic conditions. Combining wind energy with cogeneration can eliminate the limitations of wind energy use. It can also power a variety of agricultural activities, including water pumping and electrochemical soil cultivation.

Similar to using wind energy, opportunities to use hydropower are limited by geographic conditions and resource availability. The use of hydropower is influenced by social factors such as the population's attitude and environmental factors, including the impact on fauna and

landscape. The correctness of the obtained results is influenced by the number of literature sources and case studies studied, which was lower compared to other technologies.

Household sector

Fig. 3.7.4. shows the sustainability potential rating of the previously discussed RES types. Solar energy received the highest score of 0.83 among the RES types. This is explained by the fact that in recent years, there has been an increase in the use of micro-energy production and the installation of solar panels at the household level. The use of solar solutions is promoted by subsidy programs that cover part of the necessary investments for the installation of technologies, and the payback period of the invested funds becomes shorter, which is favoured by the annual decrease in the cost of solar energy technologies. Applying solar energy in a household is associated with the fewest potential disadvantages. A limitation is related to insufficient solar intensity. Still, in case of interruptions in solar radiation, the needed energy can be obtained with the help of hybrid systems, which provide additional sources to cover the shortage and accumulation systems.
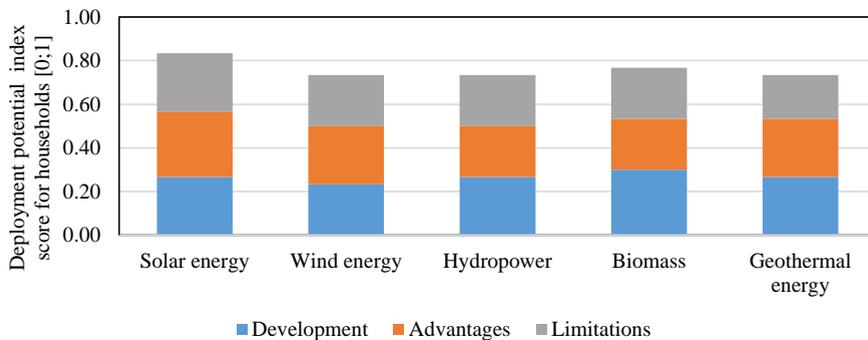
Fig. 3.10.4. Household RES development potential comparison.

Biomass use had the second-greatest sustainable development potential (0.77). One benefit of using biomass is the possibility of generating heat and electricity from biomass residues before they undergo thermal treatment. This is made possible by the fact that biomass residues can be used. The development rate of biomass residue utilisation may also increase in the future, as biomass residues are increasingly used for energy production.

For wind, geothermal, and hydro energy, the development potential in the household is estimated to be the same (0.73). Regarding wind energy, it is anticipated that the installation of small wind turbines on residential rooftops will increase in the future, and it is expected that the installation of these turbines will become less expensive. It is expected that wind energy will

be increasingly used in combination with solar panels at the household level, thus avoiding energy interruptions and increasing efficiency.

Wind, hydro, and geothermal energy technologies demonstrate moderate progress in the residential sector, with notable advancements seen in small-scale solutions. However, their sustainability and viability are limited at the household level.

Transport sector

The Fig. 3.7.5. compares the RES potential of various resources for use in the transport sector. The highest potential score was for using biomass, which received the highest possible score in the transport sector (1). This is because improving biomass quality and obtaining biomethane that can be used as fuel for vehicles should have a high potential for current and future use in the transport sector. Biomass-derived biofuel is one of the most effective ways to replace fossil fuels in transportation and meet climate goals. Compared to other RES types, biomass use in transportation was rated with the lowest use constraints. However, one drawback that significantly determines whether biomass can be used to power vehicles is the quality of the biomass and which biomass feedstocks are used and in what proportions. Not all biomass raw materials can achieve the concentration required to produce biomethane.
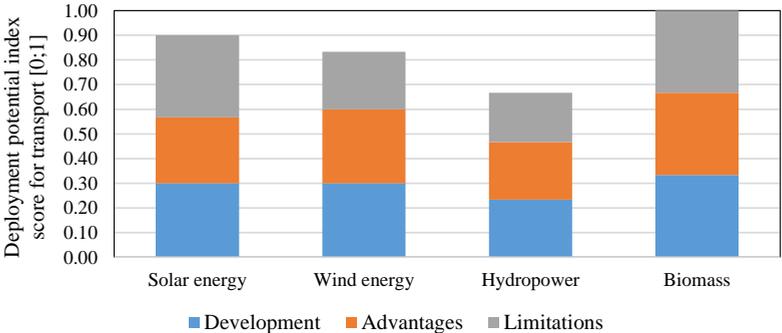
Fig. 3.7.5. Comparison of RES development potential in the transport sector.

The use of solar energy received the second-highest potential score for use in transportation (0.90) among RES. The proportion of electric car use has increased in recent years, and it is expected that to achieve the set climate targets for transport, the use of electric cars will also increase. The demand for environmentally friendly car charging will also increase. Solar modules can be used in homes and businesses as well as in public charging stations that are in public charging stations integrated into road infrastructure. Similar to other sectors, solar energy constraints are associated with intermittency. When it is necessary to use an additional source to meet demand, one of the solutions is to use solar energy accumulation.

The potential of using wind energy in the transportation sector was given the third-highest score (0.83). As the number of hydrogen-powered cars increases, the share of wind energy in transportation will also increase. It is predicted that with the increase in hydrogen-powered cars, the number of cars powered by wind energy will also increase. There are constraints on the use of wind energy in the transportation sector, such as geographic limitations.

Among the types of RES studied, hydropower in the transport sector was given the lowest rating. To avoid a false comparison with other RESs, the potential of using geothermal energy in transportation was not analysed because there were not enough studies to compare it with other types of RES. Table 3.7.1 shows the final index scores for each RES in each sector.

Table 3.7.1

The final index score for RES

Sector	Solar Energy	Wind Energy	Hydropower	Biomass	Geothermal energy
Industry sector					
Development	0.33	0.23	0.23	0.27	0.23
Advantages	0.30	0.23	0.20	0.27	0.23
Limitations	0.20	0.20	0.23	0.23	0.27
Total	0.83	0.67	0.67	0.77	0.73
Service sector					
Development	0.33	0.20	0.20	0.23	0.27
Advantages	0.30	0.20	0.20	0.23	0.27
Limitations	0.27	0.20	0.20	0.23	0.27
Total	0.90	0.60	0.60	0.70	0.80
Agriculture sector					
Development	0.27	0.20	0.20	0.33	0.20
Advantages	0.33	0.23	0.20	0.33	0.20
Limitations	0.33	0.20	0.20	0.33	0.27
Total	0.93	0.63	0.60	1.00	0.67
Household sector					
Development	0.27	0.23	0.27	0.30	0.27
Advantages	0.30	0.27	0.23	0.23	0.27
Limitations	0.27	0.23	0.23	0.23	0.20
Total	0.83	0.73	0.73	0.77	0.73
Transport sector					
Development	0.30	0.30	0.23	0.33	0.00
Advantages	0.27	0.30	0.23	0.33	0.00
Limitations	0.33	0.23	0.20	0.33	0.00
Total	0.90	0.83	0.67	1.00	0.00

A cross-sector comparison to assess the sustainability potential of the use of RES

The second part of the study produced a score reflecting an assessment of each resource's sustainable development potential and a comparison of sectors by RES type (Fig. 3.7.6). Table 3.7.2 summarises the points obtained, clearly showing the normalised result for each RES type, with which it is possible to characterise the RES utilisation potential.
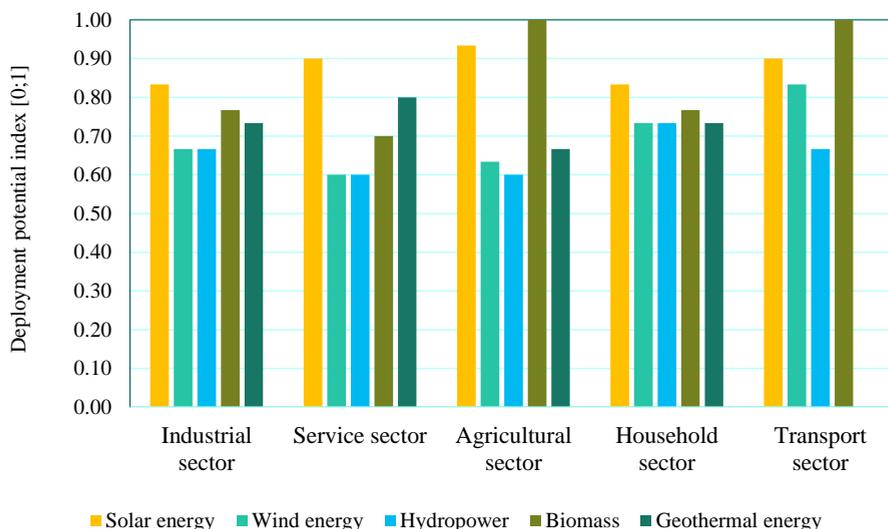

Fig. 3.7.6. Comparison of the development trends of RES between the sectors

The potential of biomass use in the agriculture and transport sectors achieved the highest assessment level for sustainable development. In these two sectors, biomass received the highest possible score, 1. Thus, in both the agriculture and transport sectors, the rapid development of biomass energy production has already been observed and predicted for the future. The second-highest potential rating was given to the potential of biomass use in industry and households.

Table 3.7.2

Summary of RES normalised points by sector

	Solar energy	Wind energy	Hydropower	Biomass	Geothermal energy
Industrial sector	0.83	0.67	0.67	0.77	0.73
Service sector	0.90	0.60	0.60	0.70	0.80
Agricultural sector	0.93	0.63	0.60	1.00	0.67
Household sector	0.83	0.73	0.73	0.77	0.73
Transport sector	0.90	0.83	0.67	1.00	0.00
Average values	0.88	0.69	0.65	0.85	0.59 (0.73 *)

* The average value of four sectors, excluding the transport sector [105].

The potential of solar energy use is currently and in the future estimated to be highest in sectors such as services, households, and industry. Solar energy received the second-highest potential rating in agriculture and transport, right after biomass use after biomass use. According to the average score, the use of solar energy ranks first with a score of 0.88, while in second place according to the score is biomass (0.85), which has the fewest constraints for use in transport and agriculture among RESs. Compared to the potential use of solar energy and biomass, the other three RES types, whose development can be described as slower, scored lower in the evaluation. Wind energy is still in the development phase of its potential [270], [271], [272], which is limited by geographical conditions as well as by social factors and the population's aversion to wind turbines near their homes. Despite the limitations mentioned above, the potential for using wind energy in the transport sector and residential sector received the third-highest rating in these sectors. The potential of wind energy is to replace fossil energy resources for hydrogen production and to meet the electricity demand required for installing micropower plants in households [272]. The combined results of the study reveal that equal values were obtained for wind energy and hydropower in the industrial and service sectors and for wind energy, hydropower, and geothermal energy in the household sector. This can be explained by the fact that similar constraints limit their use and affect the overall results of the deployment index for the technologies.

As indicated, the utilisation of a five-point scale indicates that there were no significant variations in the outcomes across different technology sectors. This can be attributed to the implementation of a limited range of evaluation scale dispersion [105].

Solutions for the development of solar energy

Combined systems that compensate for solar deficits or accumulation improve market competitiveness, reduce energy consumption, and lower the price of the required energy [190]. Solar energy technologies have increasingly lower prices and shorter payback periods [194], which increases their acceptance [105].

Solar and wind energy shortages can be offset with biomass, including agricultural residues, smart technologies that compensate for solar energy shortages by using energy exactly when it is generated, and smart agricultural monitoring. The Internet of Things (IoT) is becoming increasingly prevalent in the agricultural sector. The solar energy obtained has a wide range of applications. It can be used, for example, in irrigation systems, in drying processes, for higher efficiency through hybrid drying systems combining several RES, for wastewater treatment [274], and for cleaning the soil from heavy metals and herbicides. Hybrid drying systems can compensate for solar energy deficits and improve drying efficiency and product quality [204],

[275], [276]. Similarly, the use of thermal energy storage systems can compensate for lack of solar energy during spring and winter [200].

In households, there is the possibility of using smart grids, smart meters, and other smart technologies that can use solar energy more efficiently as a source of energy [214]. Solar collectors can be incorporated into a wide range of building components. Since collectors and PV panels are often used in passive houses, it is expected that these technologies will increase in the future [277].

Solar road technologies are becoming more common and are also essential for increasing the share of electric cars, as they provide a solution to the problem of charging station availability. Solar road technologies can be an indispensable component of a decentralised energy supply. Wind-generated compressed and stored hydrogen can be used as a fuel in the transportation sector, reducing imports of fossil fuels and GHG emissions [278].

Solutions for the development of biomass use

In the industrial sector of biomass use, there is considerable potential for use in the food and beverage industry, where residues and wastes from the same processes can be used to generate energy for other operations. Actual and potential uses are estimated to be lower in different subsectors of the industry. Agricultural residues, in combination with manure, offer broad opportunities for biomethane production [279]. The agricultural sector assesses biomass and its residues as one of the most important sources of renewable energy, with even greater prospects for the future. By using biomass residues or wastes, it is possible to compensate for the lack of other energy sources, such as solar or wind. Agricultural residues [280], [281] are increasingly being used as feedstock for biomethane with high methane content. Biomethane can also be used in commercial vehicles, buses, and certain heavy-duty trucks [105], [280], [281].

Limitations of the study

When collating the data, it was found that in places, the points awarded in the qualitative analysis ranged, for example, between 4 and 5, based on 4 reflecting the current situation and five being expected in the near future. As mentioned in this example, the average value was taken, i.e., 4.5 (in this example). In addition, it was observed that three objects were not given a specific mark in the qualitative analysis because there was insufficient information about any of the RESs in the particular sector. For example, in the agricultural sector analysis, very limited information was available on hydropower development trends and limitations in using the specific sector. In that case, the model assigned a score of 3, the most neutral value on the scale. In addition, the lack of information on any use of RES in the industry suggests that the lack of

information to provide a degree of development or other considerations in the qualitative analysis means that the development of a particular RES is limited. This explains the rating score of 3 reflects certain limitations in developing a particular RES.

Data processing and normalisation were performed after data collection and replacement of missing values. The obtained points for each criterion and each RES in the corresponding sectors were normalised so that the obtained values range from 0 to 1, where 0 is the lowest value, and 1 is the highest value. Assuming that each criterion has the same impact on sustainable RES development, they were assigned the same impact weight categories on the overall RES sustainable development result. Such a data normalisation technique is often used in sustainable development analysis and research to produce transparent and verifiable results. The range of scores from 0 to 1 makes it possible to interpret the results and draw valuable conclusions about the current performance of each RES and the sector's sustainable development level.

The overall score obtained for each RES reflects its sustainable development performance and overall long-term potential. The closer the score is to 1, the higher the respective industry's long-term development and assessed potential. Literature-related specific criteria and sectors are a limiting factor impacting the index results.

CONCLUSIONS

A methodology with the composite sustainability index has been developed to analyse the environmental policy measure driving forces and weaknesses based on the indicator approach (covering environmental, social, economic, and technical factors).

The hypothesis was confirmed by conducting a comprehensive assessment using a combination of different methods, which allowed for assessing the drivers and weaknesses of climate and energy measures.

The sustainability index results permit preliminary due diligence of technology sustainability, identify possible controversies requiring immediate governmental intervention to eliminate risks associated with sustainability, and reassess current policies that govern the heat production sector.

In total, **19 indicators** were selected and grouped into representative dimensions.

Heat pumps obtained the highest score in the CSI regarding heat technologies in households (0.64), followed by solar collectors (0.63), wood pellet boilers (0.55), and district heating (0.50). Natural gas boilers obtained the lowest index value (0.38). The results indicate that district heating is highly competitive and cost-efficient compared to individual heating solutions since it obtained the highest sustainability scores for the technical and economic dimension sub-indices.

The DH resilience CI merges **fourteen indicators.** DH resilience assessment results show that gas-dependent systems have higher heat prices after recovery (Tr) and significantly higher after an initial post-disruption (Td) than energy systems based on biomass or other renewables. Biomass-based DH energy systems are more price-resilient during disruption. Fossil fuel-based systems are more vulnerable to heat price fluctuations in case of unforeseen events.

The highest DH resilience CI was for energy systems based on biomass or a mix of biomass and gas.

The lowest result was attributed to DH 3, which has the most significant negative impact on CO_2 emissions, a low proportion of renewable resources used for heat production, and ranks the lowest in the economic dimension among systems evaluated. These findings disprove the idea that a system based on renewables is more expensive and less economically viable than those relying on fossil energy.

This research uncovers the key factors that should be considered when designing and constructing resilient DH systems, highlighting the need for further investigation. Assessment of adaptive and inherent resilience could serve as a metric to evaluate the DH system's resilience to external changes. Evaluation of DH system vulnerability can identify blind spots and weaknesses in the system promptly before unforeseen disruptions occur.

CI of heat technologies merges **eight** indicators. The results of CI for heat technologies for municipality buildings show the highest score for three DH alternatives: DH woodchip boiler and PV panels + heat pump solution (0.79), DH woodchip boiler and solar panels with storage (0.73), and DH pellet boiler and PV panels + heat pump solution (0.69). Only the fourth highest-rated alternative was the IH alternative - heat pump solution + PV panel (0.66).

One of the lowest-rated alternatives was IH solar collectors with storage and natural gas boiler (0.59) and IH solar collectors with storage and pellet boiler (0.54). Alternatives that include wood pellet boiler solutions are most affected by indicators such as fuel energy consumption and NOx emissions. IRR and investments per unit of energy produced significantly impact the sustainability rating in CSI.

DH solutions in the case of Carnikava are more sustainable, which is determined by economic indicators such as IRR and investments, economic and technical indicators such as fuel energy consumption, and environmental indicators such as NOx emissions.

The results suggest that the description of the policy measures should be more detailed, with specific activities, indicators to be achieved, and amounts and funding sources planned for each activity. According to the experts, indicators such as funding and quality were the most important when evaluating these policies.

Organic dairy farms received the highest overall score in CI, while conventional dairy farming had the lowest score among farming strategies. Organic dairy farming can be superior to conventional dairy farming regardless of herd size by producing smaller amounts of GHG and contributing to their reduction if the cow's feed digestibility values are higher than the used feed values in conventional dairy farms.

Regarding alternative uses of peatland, the highest score was for the production of insulation boards by cultivating cattail (0.87). The second highest score in the CI was for the cultivation of paludicultures – cattail and sphagnum. Indicators such as net income, income from ecosystem services, and market revenue influence the low rating of these alternatives.

Solar energy and biomass derived from agricultural residues are subject to the fewest restrictions on their use. In the overall assessment across all sectors, solar energy is rated the highest regarding the potential use of RES at 0.88, and biomass use potential is rated second at 0.85. This study assessed the overall potential and limitations of renewable energy deployment in various sectors without conducting a detailed analysis of techno-economic parameters and indicators.

RECOMMENDATIONS

- A sustainability index could improve policymakers' decision-making process when implementing energy policies. The composite sustainability index method can serve as a useful tool to determine which technologies need or should be promoted. Most importantly, it can help identify the critical aspects of each technology that need to be addressed to avoid potential blind spots in energy policies.

- The study can serve as a potentially viable method to assess the specific problem, taking into account all relevant dimensions, each of which is assessed using indicators that quantify each dimension and the overall sustainability index. The study serves as a test case to analyse other identified contradictions in energy policy in this way. The method can serve as an initial risk analysis to evaluate the effectiveness of the measures and the risks, drawbacks, and benefits of their implementation using indicators, first descriptively and then numerically.

- The analysis and creation of CI based on real data and assumptions based on scientific literature serves as an effective method that can be used in the decision-making process to simultaneously evaluate the economic and environmental dimensions and decide on the most sustainable solutions so that municipalities can decide to increase RES in centralised and individual heat supply. The use of a sustainability index could improve the decision-making process for policymakers when implementing energy policies. The composite sustainability index method can serve as a useful tool for determining which technologies should be promoted. Most importantly, it can help identify the critical aspects of each technology that need to be addressed to avoid potential blind spots in climate and energy policies.

- DH companies should look for solutions to increase the profitability and efficiency of heat supply through cost reduction and flexible heat production solutions. DH companies with economic losses should improve profitability and maintain financial stability in the economic dimension of DH resilience.

- The future outlook for DH networks is lower supply temperatures and more renewable resources. In Latvia, DH companies still use a high proportion of fossil fuels, and governmental support is available for investments in changing energy source technology.

- Another solution to improve the resilience of the heat supply is the installation of thermal storage, which increases the reliability of the DH system overall and in case of unforeseen disturbances, natural or human-caused. Previous studies show that renewable energy heat storage is mostly integrated with smart grid control and serves as an effective solution to improve environmental and economic sustainability. Seasonal storage on the network, storing surplus heat as a backup solution, could help increase total savings for large DH systems.

- The description of the policy measures should be more detailed, with specific activities, indicators to be achieved, and amounts and funding sources planned for each activity. The plan should introduce indicators to be achieved in the middle phase and at the end of the planning period, from the beginning to evaluate the progress in achieving the objectives or to re-evaluate the established achievable indicators in the middle phase, and determine whether the established actions have not lost their relevance. Action lines and specific measures are fragmented in agriculture and forestry and lack a common framework. Several actions can be combined and complemented.

- Peat products and materials can compete with similar products on the market due to their unique properties. Peat products can replace some products where fossil materials are used. Peat, as a resource, has a wide range of applications in industry, from agriculture and construction to pharmaceuticals and medicine.

- Future peatland management strategies should consider alternatives to peat treatment, storage, and technological solutions to produce high-value-added peat products and materials that sequester carbon in the environment in production processes. Peat-derived materials can also be used as components in biodegradable packages, biosorbents, and filtering materials for the purification of water and bioremediation for the purification of contaminated soils.

- The success of rewetting should be evaluated over a longer period; some studies even argue that there is no decrease in CH_4 emissions after 30 years of rewetting. To achieve successful results and mitigate emissions, both methods - rewetting and revegetation - should be combined, especially for peat extraction sites, to be defined as restoration. According to studies, rewetting is an increase in the water table and cannot be defined as restoration.

- After rewetting, revegetation should be performed by introducing sphagnum species that can pump out methane, which increases after rewetting and causes faster peat accumulation. Paludiculture can also be the solution to further income for landowners and the development of new innovative products using the biomass of harvested paludiculture plants.

- The biomass grown in paludicultures can be harvested and used for the production of products. Peatland biomass is based on the cultivation of cattail or sphagnum instead of the extraction of peat. Attention should be focused on techniques and investment reductions for cultivating paludicultures as an alternative to rewetting

- Combined systems that compensate for solar deficits or accumulation improve market competitiveness, reduce energy consumption, and lower prices.

- Solar energy's periodicity is considered one of the limiting factors for its use. Energy storage systems can solve this, and an additional source of heating, such as a heat pump or biomass, can also be used. Technologies powered by solar energy are increasingly being combined with smart technologies that allow energy to be used wisely and processes to be controlled remotely, reducing overall energy consumption.

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Article

The Contradictions between District and Individual Heating towards Green Deal Targets

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Abstract: The blind spot can be defined as the area around the vehicle where the driver cannot see through the mirrors without turning their head or taking their eyes off the road. Similar blind spots occur in energy policy. Blind spots can occur in forecasting economic development and creating policy documents. This study uncovers potential blind spots and controversies in the sustainability assessment of energy supply technologies. A composite sustainability index was constructed to compare district heating with four individual heating technologies—wood pellet boilers, natural gas boilers, solar collectors, and heat pumps. A total of 19 indicators were selected and grouped into four dimensions of sustainability—technical, environmental, economic, and social. The results reveal that district heating can compete with individual heating technologies in all dimensions of sustainability; however, a possible blind spot lies in evaluating environmental performance indicators of the different heating technologies. This study provides a novel decision-making tool that policy-makers could use to identify and avoid potential blind spots and uncertainties in energy policy at an early stage.

Keywords: energy policy; contradictions; composite sustainability index; sustainability dimensions; heating technologies

1. Introduction

The transition to a low-carbon economy is one of the most pressing challenges on the global policy agenda. Five years after the Paris agreement came into force, the European Union has committed itself to taking on a leading role in the global fight against climate change [1]. Only a year after launching the European Green Deal, in December 2020, EU leaders have agreed on a common target to decrease greenhouse gas emissions by at least 55% by the year 2030, compared to levels in 1990, thereby significantly surpassing its initial goal of 40% [1]. This political commitment forces the EU and its Member States to reassess current energy policies and legislation to reach the ambitiously raised climate change mitigation goals [2].

Over the last decade, numerous strategies, regulations, and policies have been enforced to drive decarbonization, increase energy efficiency, and accelerate and advance the adaptation of green energy solutions [3]. National regulatory authorities have their own responsibility to launch policy instruments that meet the transition objectives for a low carbon economy. However, the policies pursued and the enforcement mechanisms used are not always highly effective and often fall short of the necessary climate targets set by policy-makers [4]. Therefore, one of the most essential cornerstones of energy policy is to understand the main drivers of the policy ambiguities and controversies that hinder the achievement of the climate goals. There are situations when the government can not overlook existing blind spots in policy-making. They tend to treat climate change issues solely as technical matters while most of the challenges are highly reliant on social and political aspects [5]. Lack of understanding and ignorance of all the underlying forces of

sustainability create systematic risks and contradictions of the intended goals [6], which can lead to costly consequences that affect the entire economy.

The ongoing debates among policymakers over the most optimal, cost-efficient and sustainable energy infrastructure outlines a number of controversial issues, such as: choice of distributed electricity generation versus centralized electricity generation, renewable energy as opposed to fossil fuels, centralized compared to decentralized production of electricity and heat supply, and many others. These are just a few examples of the issues that require careful investigation to preliminarily identify possible blind spots in energy policy and avoid decision-making biases.

It is estimated that heat supply is the most carbon and energy-intensive sector in the European Union, accounting for about 50% of the total demand of the European Union [7]. Sustainable heating systems focus on mitigating climate change by replacing fossil fuels with renewable energy solutions and residual heat, and reducing fuel intensity and improving energy efficiency while reducing energy consumption. Sustainable heating systems are categorized by the temperature at which heat is supplied, the heat source, and whether it is a central or individual heating system. Sustainable heating systems are categorized according to the temperature at which the heat is delivered, the heat source and whether it is a collective system that includes district heating or individual heating solutions [8].

Most studies comparing district heating and individual heating focus primarily on one perspective: analysing either the cost-effectiveness, technical performance, or environmental impact of the different heating technologies. Looking at only one dimension and neglecting other sustainability dimensions can create unexpected blind spots in energy policy. Since each of these sustainability indicators is composed of different measures, it is necessary to develop a comprehensive methodology that allows for a full-fledged sustainability assessment that includes a unified consideration of all aspects together. This study demonstrates the composite index methodology's application to create a sustainability index for district heating and four different individual heating technologies. The composite index methodology has gained acceptance as an innovative tool that allows the inclusion of an unlimited number of indicators to measure different aspects of complex and controversial issues, such as sustainability, prosperity, innovation potential, competitiveness and many others [9,10]. Therefore, this study provides a novel decision-making tool that policy designers could use in order to identify and avoid potential blind spots and uncertainties in energy policy at an early stage.

The aim of this study is to design a methodology to analyze contradictions and validate the methodology by revealing some of the controversies of the energy sector. This study's main objective is to compare the sustainability of district heating with different individual heating solutions. The subject of the study is not individual heating and district heating solutions in a particular country, but the study aims to highlight the existing trends in the sustainability of heating solutions. Sustainability is assessed in terms of the compatibility of the technology with the goals of a low-carbon economy.

1.1. Literature Review

A number of factors influence household energy consumption behaviour and it is estimated that changing household behaviour patterns and learning to use energy more efficiently can reduce existing energy consumption by up to 10–30%. Evidence shows that the greatest energy savings can be achieved by combining sustainable technological solutions with consumer behaviour change. Therefore, it is essential also to consider the dimension of social sustainability when pursuing more efficient energy use [11]. Objective and subjective factors influence energy consumer behaviour. Objective factors are characterized, for example, by energy prices, income levels, housing characteristics, energy policies, or climatic conditions. Subjective factors, in turn, are related to consumers' own choices and understanding of energy use [11].

Similarly, it is estimated that certain consumer behaviours could reduce carbon dioxide emissions by 25% in the case of the European Union [12]. It is recognized that one of the biggest obstacles to changing the behaviour of electricity and heat consumers is consumer habits, which are difficult to change. In households, economic incentives to save heating or electricity are one of the reasons for changing consumer behaviour [12].

It is estimated that domestic heating generates significant energy demand [13,14]. Although significant amounts of fossil fuels are still used for heat supply, in recent years, biomass and heat pumps have been increasingly used alongside fossil resources [14]. The energy consumption is determined by a number of factors, such as the energy required for heating, which is determined by the house's construction and location. The consumption required for heating depends on average winter temperatures. It is estimated that in climates with lower temperatures, the energy consumption is two thirds [14].

In order to meet the decarbonisation goals set in Europe, heating and cooling have been identified as priorities in the energy sector, accounting for almost half of total energy consumption. The largest heating consumption takes place mainly in the household sector and in the industrial and tertiary sectors [15]. Several factors need to be considered in the transition to a sustainable heat supply, including social and consumer behavioural barriers. A sustainable heat supply is characterised by the efficient use of renewable energy sources for heat supply, both through the use of renewable energy sources in individual heat supply and through their integration into district heating systems [16]. Although global heat supply accounts for one third of total carbon emissions, energy policy is more concerned with electricity generation, which could be explained by the fact that both district heating systems and technological plants of different sizes, temperatures and types are used for heat supply, which complicates decision-making processes [17,18]. It is estimated that 53% of total household energy consumption is used for heating and 16% for hot water [18]. For private households, there are a number of factors that can influence the type of heat supply. Important factors that determine the type of heat supply include safety, cost and comfort. District heating, which uses renewable energy sources as fuel, has been assessed as the most suitable heating solution for households. Other common solutions include district heating that uses fossil fuels and heating with gas boilers or heat pump technologies [19].

The availability of fuel also influences the choice of fuel for heat supply. Countries that did not have access to natural gas for space heating in the recent past, e.g., Germany, Austria, switched from fossil energy to renewable energy relatively early. Due to the taxation of fossil fuels, for example in countries like Denmark, Sweden and Finland, automated wood pellet boilers are increasingly used for heating [14]. Since space heating is one of the main consumers of energy, renewable energy sources are increasingly being used for district heating in Sweden, for example [14]. It is estimated that the transition to net zero CO_2 will only be possible if the transition to a more sustainable heat supply is secured [16].

1.2. Impact on Energy Consumption Change Due to COVID-19 Crisis

As a result of the COVID-19 pandemic, energy demand has changed significantly, and the changes in energy consumption and demand in 2020 are expected to be the largest in the last 70 years. Compared to 2019, total energy consumption has decreased by 6%. [20]. It is estimated that total energy consumption in some parts of Europe decreased during the pandemic COVID-19, but the household sector shows different trends. It is acknowledged that more renewable energy than fossil energy was used for heating during the constraints, which is partly explained by the limited availability of fossil fuels. The pandemic's timing constraints also had a significant impact on changes in energy users' consumption patterns and the household sector saw a significant increase in energy consumption in contrast to other sectors [21].

In the first half of 2020, the global coal market is estimated to have declined by 8% compared to the first months of 2019, which is partly explained by the decline in economic activity. The coal market is not expected to recover from the pandemic fully and

will not return to pre-pandemic levels. As a result, other, more environmentally friendly solutions will be more widely used in the future energy sector. It is estimated that the world experienced a significant drop in natural gas demand in the first months of 2020—natural gas demand dropped by 2%. It is estimated that most demands for natural gas fell in the United States, China, as well as Europe. In contrast, the opposite trend was observed in renewable energy demand. It is estimated that in the first months of 2020, demand for the use of renewable energy for electricity and heat increased by 1.5%. This was partly due to the increasing capacity of solar and wind power plants. However, the demand for renewables varied significantly from country to country over the period of COVID-19 and depended on national policies [22]. The COVID-19 pandemic is expected to increase uncertainty about global energy demand and user consumption. However, it is recognized that the impact of pandemic restrictions on energy consumption and user behaviour will vary from country to country, and will be highly dependent on country-specific COVID-19 restrictions and measures taken [23].

The study predicted that compared to energy consumption in February 2019, heating and cooling consumption will increase by 60% between January and February 2020 due to COVID-19 restrictions. With a longer stay in households during a pandemic, electricity and heating are expected to increase significantly. In the case of electricity, it is estimated that at the beginning of the restrictions, in March 2020, electricity costs are projected to increase by 95%, in April by 35% and in May by 22%. During pandemic restrictions, household consumers are more active in the use of household electrical appliances and there is more need for heat supply for heating or hot water. It can be concluded that household energy consumption and energy costs are significantly affected by the various national pandemic restrictions and implemented national mitigation measures [24].

The main changes during a pandemic are related to the need to stabilize and restore energy demand, as it is variable during the pandemic and depends on the implemented and different national policies to reduce the pandemic. Only by stabilizing energy consumption will it be possible to achieve economic sustainability. Economic sustainability is characterised by ensuring economic growth without compromising social, environmental or cultural aspects [17]. Consequently, trends in changes in energy demand need to be monitored at the national level. Rationalisation of energy needs and regular energy consumption are among the main tasks to stabilise energy consumption Local and national incentives are needed to stabilise energy demand. It is projected that after the end of the pandemic, if economies and energy consumption return to previous levels, by using environmentally friendly energy solutions, it may be possible to reduce global warming by 0.3 °C by 2050. Thus, renewable energy is becoming an increasingly important solution for economic recovery and sustainable energy [20].

The literature review shows that there have been several attempts to compare centralised and decentralised energy supply solutions outlining the advantages and disadvantages of both options. A decentralised energy system's benefits relate to the autonomy of the end-user and sustainability [25].

1.3. Individual Heating

Decentralised energy systems often use renewable energy sources, promoting the development of decentralised energy systems and carbon-neutral energy production. Decentralised energy can be more expensive than centralised energy in some cases, so it is not available to everyone for financial reasons; statistically, decentralised energy supply to residential buildings is chosen by more financially stable residents [25]. Decentralised heating solutions include a variety of different technologies such as gas/oil boilers, air/ground source heat pumps, solar thermal, wood pellet boilers, and electrical panel/radiators [26,27].

Individual natural gas boilers, which use natural gas as fuel which is a type of fossil fuel [28], are common in the industrial sector as well as in households. Despite its widespread use, the use of natural gas is influenced by environmental aspects, such as the

proportion of carbon and hydrogen in natural gas [16]. Another major disadvantage of individual gas boilers is the increased risk of fire [26].

Heat pumps are electrically powered thermal technologies that use solar energy stored in natural heat sources such as air, water or soil to generate heat. They are increasingly used in residential heating and cooling, influenced by heat pumps' high energy efficiency [29,30]. Heat pumps can be described as technological devices where, using mechanical or electrical energy, heat is transferred using refrigerant circulation. The thermal energy produced can be used to provide space heating or hot water. Heat pump technologies can be used in commercial buildings and factories, as well as in households. Heat pumps are considered environmentally friendly and highly energy efficient, and can be integrated into existing systems [7].

Heat pump systems can use a variety of heat sources, such as surface water, ground heat or air, which are the most commonly used heat sources. Depending on the heat source used, heat pumps are classified as ground source heat pumps, hydrothermal heat pumps, or aerothermal heat pumps [7]. Depending on the type of heat pump, the efficiency and operating parameters of the heat pump also change [31].

One type of heat pump is the air-source heat pump, the basic principle of which is based on the use of air as a heat source. Low-grade heat is extracted from the air, which is raised to such a level that the extracted heat can be used, for example, to supply heat to households. It is estimated that the amount of electricity consumed by this type of heat pump to operate the system is less than the amount of heat produced [7]. Air-source heat pumps are divided into two types, depending on the source used—they can be either air-to-air or air-to-water [7].

Air-to-air heat pump systems generate hot air that is circulated by fans; in contrast, air-to-water heat pumps produce heat through wet central heating systems. In combination with underfloor heating, air source heat pumps are considered an efficient solution for hot water supply and space heating [7].

Another type of heat pump is water source heat pump technology that uses water, such as water bodies or groundwater, as a heat source. The operation of these heat pumps is based on the conversion of low-value heat from water into usable heat. One of the advantages of water source heat pumps over air source heat pumps is lower carbon emissions during operation and greater cost savings. Although water source heat pumps have been evaluated as effective technological solutions, their disadvantages are related to the applicability of limiters because, in addition to heat pumps, there must be a heat source—water bodies or the possibility of installing water storage tanks. Consequently, the wider application of this type of heat pump may be affected by climatic and geographical conditions [7].

Ground source heat pumps use the heat stored in the ground as a heat source, which is converted into usable heat energy for further use. Ground source heat pumps have been evaluated as the most environmentally friendly technological solutions with the highest efficiency due to the relatively stable underground temperature. This type of heat pump can be used regardless of climatic conditions. [7,31].

Heat pumps have been evaluated as one of the heat supply technologies on the way to sustainable heat supply, both for use in individual heat supply solutions and in district heating systems [31]. Regardless of whether heat pumps are used as individual heat supply solutions or integrated into district heating networks, they play an important role in decarbonisation [7]. Evidence shows that the use of heat pump systems reduces energy consumption and increases efficiency. One of the advantages of heat pump technology is that heat pumps can be used to convert the excess energy into heat. Another advantage of using heat pump technologies in buildings is that it is possible to ensure the required temperature conditions throughout the year, providing heat in winter but cooling in warm weather conditions. [7].

The Danish energy system analysis estimated that by 2035 the integration of heat pumps into the heat supply system could reduce system costs by 16% and reduce biomass consumption by up to 70% [7].

Despite the high efficiency and sustainability of these technologies, it is estimated that only 3% use heat pumps as a heating solution for heating buildings; however, there are recent increasing trends in the use of heat pumps. In recent years, policy-makers have identified heat pump technologies as one of the most important possible solutions for a more sustainable energy supply, which is reflected in various measures for the installation and diffusion of heat pumps [7].

With the exception of Switzerland and Sweden, the use of geothermal energy sources to reduce greenhouse gas emissions is still low, mainly because heat pumps have higher installation costs compared to other technological solutions [31]. It is estimated that smaller heat pump technologies may incur higher operating costs, but the introduction of large heat pumps may require additional capital investment, such as building modernisation or boiler replacement [7].

Solar collectors are individual heat supply technologies that use solar energy as a heat source which converts solar irradiation into solar thermal energy [28]. During the solar collector operation, solar irradiation is absorbed, then the absorbed heat is transferred to a working fluid, which may be, for example, oil, air or water. The heat generated can be used for heating water, as well as solar energy storage [32].

There are several possible types of solar collectors; the most commonly used solar collectors include both evacuated tube collectors and flat plate collectors. Out of the mentioned solar collector types, flat plate collectors are chosen as the most preferred heating solution. It is influenced by the lower prices of these solar collectors, the simple design and the desired achievable heating temperatures [33].

With the increasing use of solar collectors, it is possible to significantly reduce the demand for fossil energy resources and use solar energy instead. In recent years, solar collectors have been increasingly used in the construction of buildings to reduce carbon emissions. By using solar collectors, it is possible not only to provide space heating, but also to meet the demand for hot water [20] efficiently. The disadvantages of solar collectors are related to the periodicity of solar energy and the need to combine solar collectors with other heat supply solutions in case of insufficient heat energy [26].

Wood pellet boilers are individual technological devices for the production of thermal energy, in which wood pellets, obtained by granulating wood fibres, are used as fuel. Wood pellets are one of the forms of renewable energy that can be used to achieve climate goals. The heating system of pellet boilers consists of such elements as a heat accumulator, boiler and building, which is a unit of energy consumption [28].

Electrical panels/radiators such as an office or household electrical appliances for space heating, are widely used and are capable of converting electrical energy into heat using heating elements [34].

1.4. District Heating

In district heating, heat is delivered centrally to the end user by transporting hot water or steam through a network of pipes. Centralised heating systems use high-capacity combustion plants with higher energy efficiency and improved air pollution control. District heating is considered to be environmentally friendly for heating buildings and is recognized as one of the solutions to mitigate climate change [22].

One of the advantages of district heating is that the heat source can be any process that generates heat. The heat source can be a geothermal process, solar collectors, biomass boilers or heat generated in industrial production. The possibility of using different energy sources also offers financial advantages, as the possibility of optimising costs also depends on the price of the energy source used. This also contributes to the stability of the supply system [26].

Another advantage in favour of district heating is the possibility of using low-grade energy. Thus, district heating offers the possibility of using energy sources that are difficult or impossible to use in individual heating solutions. If district heating is to use renewable energy, such as solar thermal, then seasonal storage of the generated energy is possible through storage systems [12]. District heating technologies can be used to prevent the inefficient use of individual heat supply solutions for heating or hot water supply [35].

District heating is easily accessible, specific sources do not limit its use, and district heating is assessed as an essential element for achieving the European Union's climate goals in the future [26]. It is estimated that in Europe, district heating systems can reduce emissions by 113 million tonnes of CO_2 per year, which is 2.6% of total CO_2 emissions [36]. Several countries have implemented various policies to promote the district heating infrastructure since it is an essential element of a low carbon energy system. It is particularly true for colder climate countries that have higher average space heating and hot water consumption [37]. Cold climatic conditions strongly influence the share of district heating use; in the Baltic States, Nordic countries, as well as in the countries of Eastern Europe, district heating systems have a share of 36–92% of the total heat supply [38]. The competitiveness of district heating systems in residential buildings depends on factors such as the heating system's price, the price of fuel or electricity, the efficiency used, and the expected price increase [36,39]. District heating is positively recognised for its ability to effectively use waste, excess heat and low-grade heat sources to produce heat for household demand [27]. In several countries, district heating systems are positioned as one of the key elements in national strategic plans [26]. It has been assessed that district heating will become more profitable and cost-effective in the future, and district heating using renewable energy sources is estimated as one of the most important solutions on the way to the decarbonisation of the energy sector [19]. However, district heating is often criticised by policy-makers for its high capital intensity, arguing about its lower cost efficiency against decentralized heating solutions [13].

Although district heating systems have several advantages, there may be some obstacles. One of the disadvantages is, for example, the possible heat loss along the pipe-lines in cases of inadequate design of distribution networks [26,35]. Heat losses in district heating systems are affected by linear heat density. High heat losses up to 25% occur at low linear heat densities, while at high linear heat densities, heat losses can be below 5%. In the case of new and upgraded district heating networks, heat losses are up to 10% [40]. One of the major uncertainties in district heating is related to the initial investment in district heating. The distribution network cost depends on several factors, including the heat demand, such as the ratio of building to the area. [12].

1.5. District Heating versus Individual Heating

District heating systems and individual heating solutions, which differ in the way they generate heat, meet hot water needs, and the particular type of heat supply, have different management. Individual and district heating differ in the degree of comfort they provide to the consumer. Compared to district heating systems, where the hot water can be used immediately with individual heating technologies, it takes time for the water to heat up to the appropriate temperatures [41].

It is estimated that heat consumers with a higher level of education as well as a higher income choose the district heating system, while other consumers prefer individual heat supply solutions [29]. Studies show that, due to the ability of heat source diversification, cheaper fuels, and high technology efficiency, the new district heating system is the most cost-efficient and competitive solution compared to different individual heating technologies [8,9].

It is believed that district heating costs are more expensive than individual heating costs, with the necessity of generating extra investments related to pipeline damage or steam leakage as one of the reasons [41]. In fact, district heating systems are cost-effective and competitive systems that can be used in both cities and outside urban areas [26].

The United Kingdom, in a study, estimated that heat pumps could reduce costs and emissions even by 37%. Another study estimates that the use of heat pumps can reduce the consumption required for heating by 72% compared to individual natural gas boilers [42].

Although different information on district heating costs can be found in the literature, individual solutions for the initial supply of heat generally require higher initial investments compared to district heating [7]. It is estimated that, for example, installing district heating networks in a household has a lower cost than investing in a household by installing a single boiler. It is estimated that district heating's annual cost is 19% lower than individual natural gas boilers and 30–31% lower than individual water source heat pumps and individual biomass boilers. For district heating, efficiency is strongly influenced by a new or existing district heating system. It is estimated that new district heating systems have a more competitive heating price than individual heating solutions [43].

It is proven that by integrating individual renewable energy technologies into the district heating supply, higher efficiency, lower energy consumption and a more environmentally friendly heat supply can be achieved. Therefore, in order to achieve the set climate goals, district heating and individual heating solutions must be considered in their interaction and not separately. In Northern California, a study was conducted to analyse the benefits of district heating in low-energy buildings. It found that the highest efficiency was achieved by integrating geothermal heat pumps into a district heating system [28]. District heating's high efficiency was evaluated in the new district heating system with an electric compression heat pump or a wood chip boiler [43].

2. Data and Methodology

Assessment of sustainability requires an integrated approach and structure that is composed of several interlinked steps. As illustrated in Figure 1, the methodology of this study is constructed based on the three main pillars: (1) the identification of internal and external context influencing heat supply system sustainability, (2) the calculation of the composite sustainability index, and (3) the result analysis and decision-making procedure.
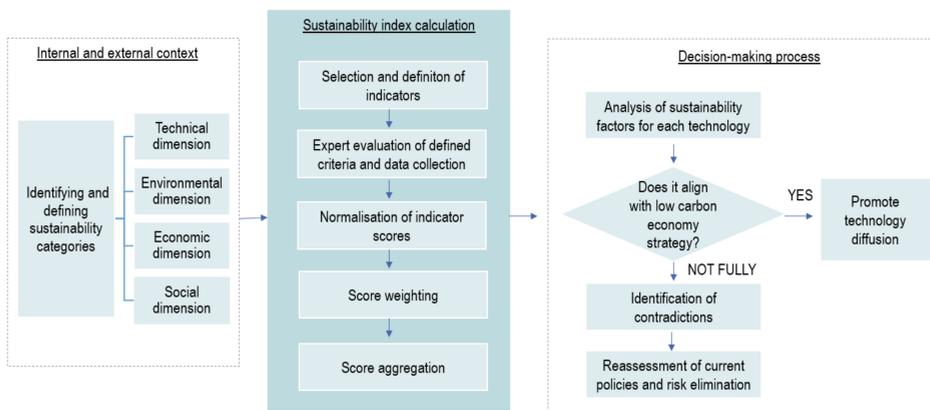

Figure 1. Model for the sustainability index construction and decision-making algorithm.

Identifying the internal and external context includes a literature review on the common practices of sustainability assessment of energy supply technologies to identify the main sustainability aspects and design a comprehensive research methodology.

The core element for the sustainability assessment is the construction of the composite sustainability index. In this study, the composite sustainability index is calculated for district heating (based on the natural gas) and four different technological solutions of decentralised (individual) heating such as: (1) the wood pellet boiler, (2) the natural gas boiler, (3) solar collectors, and (4) the heat pump. The choice of the heat supply

technological solutions was determined by the ability of the technology to ensure the necessary heat demand of a medium-sized household. The selection of individual heat supply solutions was based (1) on a Danish study on individual heat supply solutions, (2) on the availability of the data to create a complex index, and (3) on the sustainability of the heat supply solution. Among the individual heat supply solutions using a biomass source, the study evaluated wood pellet heating as a sustainable individual heat supply solution [43]. It was necessary to select individual heat supply solutions that are used at the household level and for which relevant and reliable data can be obtained. The study excluded consideration of the electrical heater since this application is usually used as an additional heating element and not as a primary heating supply source.

The sustainability index in the context of this study is defined as a tool that is composed of different indicators that measure the long-term sustainability of a heat supply system. The heat supply system is considered to be sustainable when the constructed heat production infrastructure and installed technologies are balanced with environmental, economic and social aspects of the economy [44].

The sustainability index calculation outcomes could be further utilised to make more constructive and reasonable decisions related to the achievement of long-term targets for a low carbon economy. The sustainability index results permit preliminary due-diligence of technology sustainability and identify possible controversies requiring immediate governmental intervention to eliminate risks associated with sustainability, and reassess current policies that govern the heat production sector.

2.1. Determination of Sustainability Dimensions and Selection of Indicators

Although there is no consensus amongst scientists and policy-makers on the main aspects that should be included in the sustainability assessment of energy supply technologies, the general sustainability framework suggests that different technological solutions should be evaluated with regard to their effects on three main dimensions of sustainability: environmental, economic, and social [45]. The sustainability framework is applied in this study, where general sustainability dimensions are combined with a technical dimension that represents the analysed technology's main performance parameters. As a result, the model includes four main dimensions: technical, environmental, economic, and social. Each dimension is composed of various descriptive indicators that are summarised in Table 1.

In total, 19 indicators were selected and grouped into representative dimensions. The indicators were selected and reassessed carefully to avoid the unnecessary bias of correlations among indicators.

The technical dimension represents the technology competitiveness, technical feasibility of district heating and different individual heating technologies. The technical dimension incorporates seven different indicators, such as heat production efficiency, complexity of technology maintenance, availability of necessary energy resources, opportunities for the diversification of utilised energy resources, possibilities for heat load optimisation, operational stability, and opportunities for utilisation of low-quality energy resources.

The environmental dimension outlines emission damage that heat supply technologies produce depending on their utilised energy resources and technical capacity to minimize the environmental impacts from production processes. Two main indicators are utilised to characterise the performance of environmental dimensions of technology such as specific CO_2 emissions and the complexity of flue gas cleaning.

The economic dimension includes all of the relevant cost positions that are associated with the specific heat production technology, such as the initial capital expenditure, service and maintenance costs, technology lifetime, energy resource costs, as well as the possibility to utilise surplus heat and opportunities for cost optimisation (e.g., the choice of the energy resource based on the most economically advantageous price in the market, opportunities for the economies of scale).

The social dimension represents both socioeconomic impacts of technology and consumer satisfaction levels with certain technology characteristics. The socioeconomic aspects are measured by technology's ability to create positive socioeconomic impact by promoting utilisation of local resources. The consumer satisfaction level is measured for overall comfort level, safety level (reduced risks of ignition, leakage, etc.) and to control over heat consumption.

Table 1. Selected sustainability indicators and classification into dimensions [9,23].

Dimension	Notation	Indicator Description	Source	Impact
Technical	tech1	Efficiency	Data	+
	tech2	Complexity of service and maintenance (availability of specialists on site, immediate prevention of risk situations)	Expert evaluation	-
	tech3	Stable availability of energy resources for sufficient heat production	Expert evaluation	+
	tech4	Opportunities for diversification of utilised energy resources (technology is not limited only to one type of energy resource supply)	Expert evaluation	+
	tech5	Possibility to balance the produced heat load (ability to respond to rapid seasonal and short-term changes in demand)	Expert evaluation	+
	tech6	Operational stability (stable heat supply to the grid, no or reduced heat disruptions)	Expert evaluation	+
	tech7	Opportunities for the utilisation of low-quality energy resources	Expert evaluation	+
Environmental	env1	Specific CO_2 emissions	Data	-
	env2	Complexity of flue gas cleaning	Expert evaluation	-
Economic	econ1	Capital investments (CAPEX)	Data	-
	econ2	Service and maintenance costs (OPEX)	Data	-
	econ3	Technology lifetime	Data	+
	econ4	Specific energy costs	Data	-
	econ5	Possibility to utilise surplus heat for optimisation of heat production and maximisation of resource efficiency	Expert evaluation	+
	econ6	Opportunities for cost optimisation (choice of energy resource based on most economically advantageous price in the market, opportunities for the economies of scale)	Expert evaluation	+
Social	soc1	Consumer comfort level	Expert evaluation	+
	soc2	Consumer safety level (reduced risks of ignition, leakage, etc.)	Expert evaluation	+
	soc3	Impact on the promotion of local resources (reduction of energy imports)	Expert evaluation	+
	soc4	Consumer control level over heat consumption	Expert evaluation	+

2.2. Data Collection and Expert Evaluation

Quantitative indicator values for each technology were determined based on two main approaches: quantitative and qualitative assessment. For the indicators where the specific values could be found from publicly available databases, scientific papers, research and reports, legislation, and technology data sheets, data were collected from relevant sources of information. These indicators were the following: technology efficiency (tech1), specific CO_2 emissions (env1), specific capital investments (econ1), specific service and maintenance costs (econ2), technology lifetime (econ3), and specific energy costs (econ4). All the utilised data inputs and data sources for quantitative indicators are listed in Table 2.

Table 2. Data and assumptions for district heating and individual heating technologies.

Indicator	Notation	Unit	Data Source	District Heating	Wood Pellet Boiler	Natural Gas Boiler	Solar Collectors	Heat Pump
Efficiency	tech1	%	[26,43]	100	80	92	82 *	257
Specific CO$_2$ emissions	env1	g/kWh	[46,47]	202	0	202	0 *	42 *
Capital investments	econ1	EUR		6175	10,740	6440	23,980 *	16,243
Service and maintenance costs	econ2	EUR/year	[27]	0 *	605	255	300 *	360
Technology lifetime	econ3	years	[27,48]	25	20	19	30	20
Specific energy costs	econ4	EUR/kWh	[27,48–51]	0.036	0.038	0.04	0 *	0.058 *

* authors' calculations.

Most of the data inputs for district heating, wood pellet boilers, natural gas boilers and heat pumps were taken from the Danish study [27,43] on the cost effectiveness of district heating compared to individual heating technological solutions. Due to limited data, the performance data in Table 2 were taken from the Danish Technology Catalogue and various sources in research [23]. This was the most reliable data for determining specific values for district heating technologies and for achieving the current research objectives.

Economic data on initial capital investments and yearly service and maintenance costs represent the average household expenditures with an annual heat demand of 13,800 kWh. Data for the heat pump represent the average values for ground and air heat pump parameters.

Data on solar collector nominal efficiency and technology lifetime were assumed based on average values observed from solar collector technology manufacturers' technical data sheets.

The efficiency of solar collectors was calculated using the following formula:

$$\eta = \eta_0 - \alpha_1 \frac{T_1 - T_2}{G} - \alpha_2 \frac{(T_1 - T_2)^2}{G}, \tag{1}$$

where η is solar collector efficiency [%], η_0 is zero heat loss efficiency of the solar collector [%], α_1 is the heat loss coefficient [W/m^2 K], T_1 is the average temperature of the solar collector [°C], T_2 is the air temperature [°C], G is the solar radiation intensity [W/m^2], and α_2 is the temperature-dependent heat loss coefficient [W/m^2 K^2]. The values for the coefficients η_0, α_1, α_2 were taken from data sheets of high performance plate solar collectors which correspond to the values from the study by [33]. Plate collectors are more widespread and used in the EU and Latvia. Table 3 summarizes the input data used to calculate the efficiency of solar collectors. To estimate the maximum potential of the solar collectors, the values for T_2 and G were determined for May, since solar radiation is highest in this month.

The solar collector absorption area was calculated by deriving the following equation:

$$Q \text{ (kWh)} = S \cdot \eta \cdot R \cdot PR \tag{2}$$

where S is the solar collector absorption area [m^2], η is the solar collector efficiency [%], R is the average solar radiation intensity [kWh/m^2], and PR is the solar system heat loss factor (coefficient in a range from 0.9 to 0.95) (Table 4).

Table 3. Input data for the solar collector efficiency calculation.

Parameter	Value	Justification
η_0	81.7	According to technical specification in [33]
α_1	2.741	According to technical specification in [33]
α_2	0.0147	According to technical specification in [33]
T_1	70	Assumed average temperature value of solar collector in a range of (60–80) °C
T_2	12.4	Average temperature in Riga, Latvia in May according to Cabinet of Ministers Construction Standard LBN 003-19 "Construction Climatology" (entered into force on 21 September 2019)
G	172,540	Average solar radiation in May in Riga Latvia in the time period from 2015 to 2017

Table 4. Input data for the solar collector absorption area calculation.

Parameter	Value	Justification
Q	13,800	Assumed heat demand of an average household according to [27,43]
η	82	According to calculated solar collector efficiency based on technical specification of flat plate solar collectors in [33]
R	173	Average solar radiation in May in Riga Latvia in the time period from 2015 to 2017
PR	0.9	Assumed solar system heat loss factor (coefficient in a range from 0.9 to 0.95)

The investment costs for solar collectors were calculated for households with an average heat demand of 138,000 kWh, based on the average solar radiation in Latvia and assuming that the solar system's specific cost is 220 EUR per m^2 of the absorption area of the solar collector. For a heat demand of 13,800 kWh, the solar collector's calculated absorption area is 109 m^2.

Specific CO_2 emissions for wood pellet boilers and natural gas boilers were assumed based on the Latvian Cabinet of Ministers Regulation No. 42 on the methodology for Calculating Greenhouse Gas Emissions [47]. For the district heating unit, specific CO_2 emissions were determined assuming that all energy is produced by natural gas. For heat pumps, specific CO_2 emissions were calculated based on the specific electricity emission factor of 109 g/kWh [46], taking into account Coefficient of Performance (COP) of 2.57. Similarly, specific energy costs for heat pumps were calculated assuming the average electricity price is equal to 0.15 EUR/kWh [51] considering COP of 2.57. Therefore, both indicators—specific electricity emission factor and specific energy cost for heat pumps—were calculated by dividing the representative values of electricity price and emission factors with COP.

Specific energy costs for district heating and natural gas boilers were taken from the Central Statistical Bureau of Latvia and Eurostat databases given the average values for the year 2019. Specific energy costs for wood pellets were taken from price surveys of energy producers.

For the part of indicators that represented particular technologies' qualitative characteristics, the values were determined through an expert evaluation survey. Indicators were evaluated according to an 8-point impact scale as summarized in Table 5.

Table 5. Evaluation scales for the indicator assessment.

Score	Impact
1	None
2	Very low
3	Low
4	Relatively low
5	Moderate
6	Relatively high
7	High
8	Very high

In total, the assessment of qualitative indicators was carried out by a selected group of high-level industry experts who have gained extensive professional and scientific experience and knowledge in heat generation, heat supply, and the energy sector. The experts evaluated indicators based on the observations and knowledge obtained over several years of working on heat supply systems, energy-related projects and on-site objects. Each expert was asked to assign a score for each indicator based on the given impact scale. The final score for each technology was calculated as the mean of all the surveyed experts' assigned scores.

2.3. Data Normalisation

Results were normalised using a min–max normalisation technique. The min–max normalisation standardises the indicator values in the range (0–1) which allows comprehensive comparison of indicators that have different units of measurement [52]. The min–max normalisation is the most suitable for this study since the sustainability assessment in this study includes both quantitative and qualitative indicators.

The normalisation technique for each indicator depends on its impact on the sustainability index. An indicator can either positively or negatively impact the sustainability index. Therefore, at first, each indicator was assessed with respect to its impact on the sustainability index. The indicator has a positive impact on the sustainability if its increasing value increases the sustainability [53]. For example, higher efficiency has a positive effect on the overall technological performance of the technology and therefore it also increases the sustainability of the technology. However, the indicator has a negative impact on the sustainability if its increasing value decreases the sustainability of the technology. For example, higher specific emissions from the technology produces a negative impact on the sustainability and therefore decreases the sustainability of the particular technology. Figure 1 summarises the impact assessment for each indicator. Positive impact indicators are normalised using Equation (3), and negative impact indicators are normalised according to Equation (4).

$$I_{N,ji}^{+} = \frac{I_{act,ji}^{+} - I_{min,ji}^{+}}{I_{max,ji}^{+} - I_{min,ji}^{+}} \tag{3}$$

$$I_{N,ji}^{-} = 1 - \frac{I_{act,ji}^{-} - I_{min,ji}^{-}}{I_{max,ji}^{-} - I_{min,ji}^{-}} \tag{4}$$

where

$I_{N,ji}^{+}$ is the normalised value of positive impact indicator,

$I_{N,ji}^{-}$ is the normalised value of negative impact indicator,

$I_{act,ji}^{+}$ is the actual value of an indicator,

$I_{min,i}^{-}$ is the minimal value of an indicator among all the technologies,

$I_{max,i}^{+}$ is the maximum value of an indicator among all the technologies,

j denotes the specific sub-dimension,

i denotes the specific indicator in a particular sub-dimension.

Since the assessment of qualitative indicators has the specifically defined scale from 1 to 8 as indicated in the expert evaluation Table 1, then these values are taken as minimum and maximum values in the calculation during the normalisation procedure.

2.4. Weighting and Indicator Aggregation into Sustainability Index

Weighting is performed in order to proceed with indicator aggregation into representative sub-indices and the final composite sustainability index. After data normalisation, weights are assessed by a two-step procedure. At first, equal weighting is applied to calculate sustainability dimension sub-index scores using Equation (5). Then the analytical hierarchy process (AHP) method is utilised to account for the different impact scales of each dimension to the overall sustainability index using Equation (6).

$$I_{S,j} = \sum_{i}^{n} W_{ji} \times I_{N,ji}^{+}, \ W_{ji} = \frac{1}{n_{ji}} \qquad (1) \quad (5)$$

where

$I_{S,j}$ is the dimension's sub-index value,
W_{ji} is the impact weight of indicators on the dimension sub-index (application of equal weighting),
n_{ji} is the number of indicators in a particular dimension.

$$I_{CSI} = \sum_{j}^{n} W_j \times I_{S,j} \qquad (6)$$

where

I_{CSI} is the composite sustainability index,
W_j is the impact weight of the dimension sub-index on the composite sustainability index (determined from AHP).

The application of equal weights into dimension sub-index scores represents each indicator's equal contribution and importance on the overall performance of the representative dimension [54]; however, the method of analytical hierarchy process (AHP) was chosen when selecting weight values for sustainability index aggregation. Using the AHP method, it is possible to quantify the weight or significance of the relevant criteria. In the AHP method, the assessment is based on the pairwise comparison, evaluating the significance of the criterion in comparison with another criterion. The AHP consists of a formulation phase, a hierarchy structure, comparison of criteria pairs, weighting criteria, consistency checks and an analysis of the results obtained. Criteria are first defined, followed by a comparison of the significance of the criteria across the criteria pairs, assigning them values on a scale of 1 to 9 according to the Saaty rating scale that is summarized in Table 6. The weighting of the criteria is essential in further process to allow ranking alternatives [55]. Using the AHP method, it is possible to evaluate nine criteria at the same time [56].

Table 6. Saaty rating scale.

Score	Explanation
1	Equal importance
3	Somewhat more important
5	Much more important
7	Very much more important
9	Absolutely more important
2, 4, 6, 8	Intermediate values

The AHP method was used to collect expert opinion on each dimension's impact on the overall sustainability. Experts were asked to compare four different dimensions according to which sustainability of technologies was compared. A calculations matrix

was created based on Equation (7) where all four criteria were supplemented with the raw data obtained from the expert surveys.

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \end{bmatrix} \tag{7}$$

According to expert opinion and after performing the AHP calculation procedure, the following weights were obtained for each dimension: technical is 0.38, environmental is 0.36, economic is 0.16, and social is 0.10. The obtained weighting values were validated by calculating the consistency ratio where the obtained results reached the necessary threshold of 0.1.

The application of different weighting methods was experimented with during the model development process and calculation procedures to check for the robustness of the obtained results. No significant changes in the overall distribution of results were observed when equal weights for the dimensions were given.

Figure 2 outlines the overall hierarchy of the developed composite sustainability index for the district and individual heating comparison.
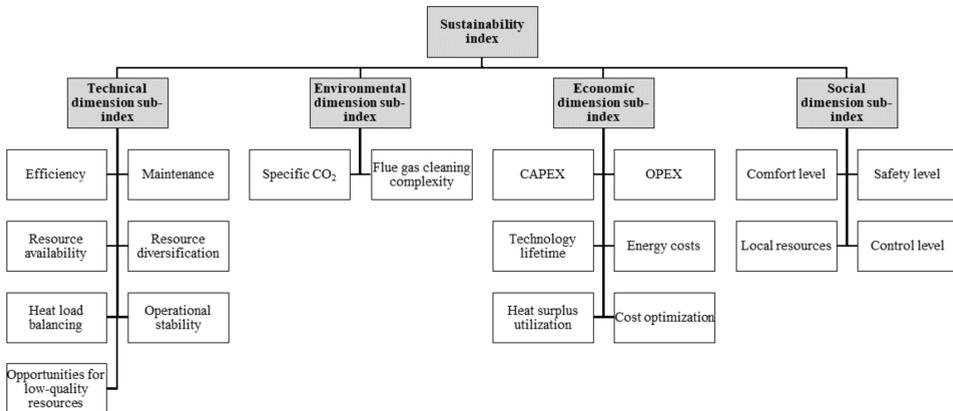
Figure 2. Basic hierarchy of the composite sustainability index [26,43].

3. Results

3.1. Technical Dimension Sub-Index

The highest technical dimension sub-index was obtained for district heating (0.64), followed by heat pumps (0.51), wood pellet boilers (0.50), and solar collectors (0.26), as illustrated in Figure 3. The absolute leader in the technical dimension was district heating which reached the highest values in indicators, such as opportunities for diversification of utilised energy resources (tech4), operational stability (tech6), and opportunities for the utilisation of low-quality energy resources (tech6). These results are consistent with the study by [27] and argues that opportunities for excess, low quality and waste heat utilisation are essential factors and benefits of district heating systems, raising their efficiency and competitiveness above other competing individual heating solutions.
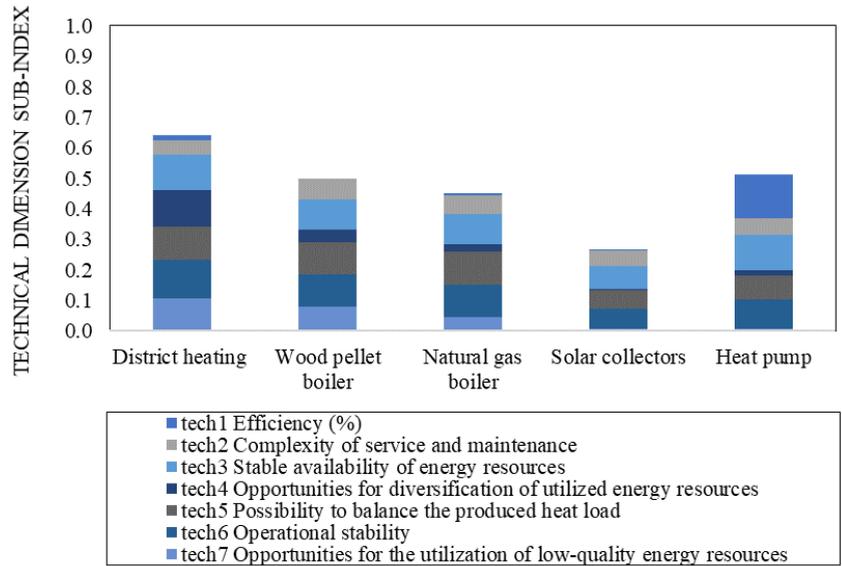
Figure 3. Technical dimension sub-index values [26,43].

Heat pumps reached the second-highest score in the technical dimension due to their highest efficiency ratio and equally high score for both stable availability of energy resources (tech3) and district heating since both technologies offer unrestricted access to energy resources. Compared to district heating, wood pellet boilers and natural gas boilers, heat pumps indicated slightly lower technical performance values for operational stability (tech6). Compared to district heating and wood pellet boilers, heat pumps indicated lower opportunities for diversification of utilised energy resources (tech4) and a lower possibility to balance the produced heat load (tech5).

The competitive advantage of both wood pellet boilers and natural gas boilers lies in their slightly lower complexity of service and maintenance (tech2) compared to district heating, solar collectors and heat pumps. Both wood pellet and natural gas boilers showed equally high scores for the possibility to balance the produced heat load (tech5) as the district heating unit.

Solar collectors reached the lowest scores in technical dimension due to their inability to diversify utilised energy resources (tech4), and lower operational stability (tech6): also, they have substantially lower constant availability of necessary energy resources (tech3) compared to other heating solutions that are particularly relevant for Nordic region countries with a colder climate.

3.2. Environmental Dimension Sub-Index

Renewable energy technologies reached the highest environmental dimension sub-index values: solar collectors with a score of 1.0, heat pumps with 0.70, and wood pellet boilers with 0.64. The lowest sustainability score in the environmental dimension was reached by natural gas boilers (0.23) and district heating units (0.16), determined by indicators such as the degree of complexity of flue gas cleaning and specific CO_2 emissions (see Figure 4).
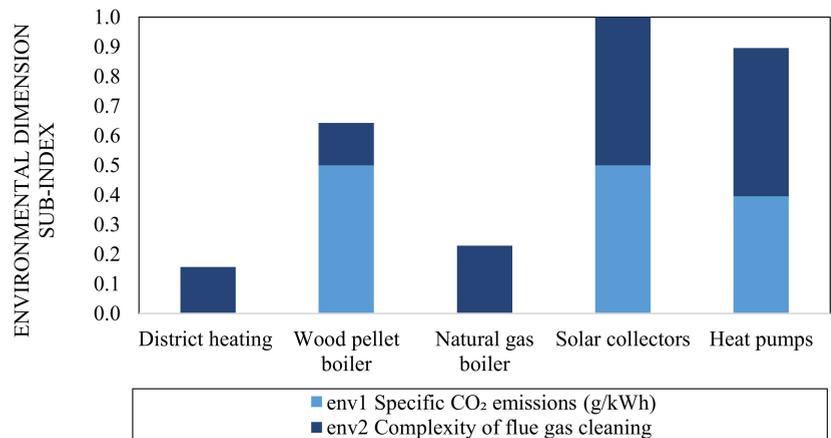
Figure 4. Environmental dimension sub-index values [26,43].

Solar collectors achieved the highest possible sustainability sub-index value in the environmental dimensions as the solar thermal system does not require flue gas cleaning in the heat supply process and does not generate CO_2 emission during the heat production processes. Similarly, the heat produced by the heat pumps does not require flue gas cleaning. However, since the heat pumps' operations consume a considerable amount of electricity, the CO_2 emission factor is applied for electricity consumed from grids, thus making heat pumps less competitive compared to solar collectors in the environmental dimension of sustainability.

Wood pellet boilers indicated lower environmental dimension sub-index values compared to other renewable technologies. Despite the CO_2 emission neutrality, wood pellet boiler operations and combustion processes produce other emissions such as exhaust particulate matter (PM) and specific NO_X emissions, therefore making higher complexity of flue gas cleaning [43]. The lowest environmental dimension sub-index values were observed for both natural gas boilers (0.23) and district heating (0.16). For both technologies, the same emission factor was used. It was assumed that natural gas is used exclusively as the main source of energy for district heating since no accurate information on the amount of renewable energy sources used in the district heating in Latvia was available. The experts evaluated the complexity of flue gas cleaning as higher for district heating than natural gas boilers, resulting in a slightly decreased overall environmental dimension sub-index value for district heating. If a more precise emission factor were used for district heating, taking into account the share of renewable energy sources used in heat production, the overall heat performance in the environmental dimension would also improve.

3.3. Economic Dimension Sub-Index

The highest economic dimension sub-index value was achieved by district heating units (0.77), as illustrated in Figure 5. Solar collectors achieved the second-highest economic dimension sub-index score (0.52), followed by natural gas boilers (0.42), and wood pellet boilers (0.34). The lowest sub-index score in economic dimension was reached by heat pumps (0.29). District heating substantially surpassed its competing technologies in indicators for capital investments (econ1), service and maintenance costs (econ2), possibility to use surplus heat (econ5), and cost optimisation options (econ6) as well as specific energy costs (econ4) that ranked district heating in the leading position of the economic dimension sub-index. Overall, district heating shows the highest economic and cost efficiency compared with individual heating technologies.
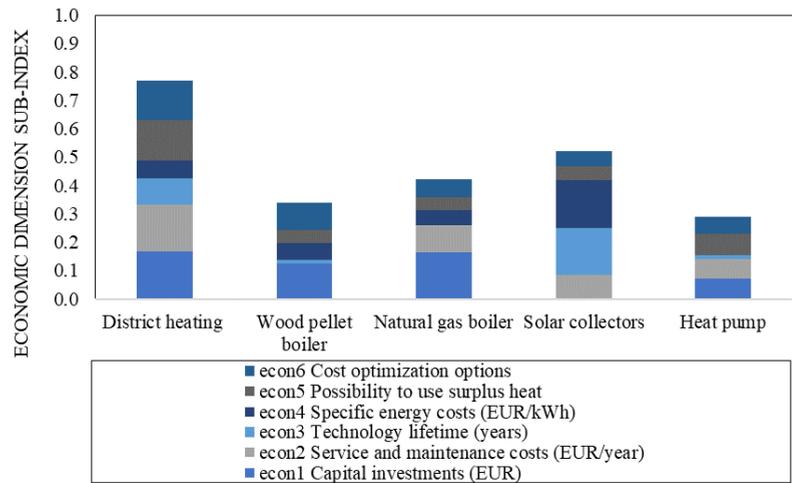
Figure 5. Economic dimension sub-index values [26,43].

Initial capital investments for natural gas boilers are significantly lower than for solar collectors to match the average household's heat demands, therefore improving the overall sub-index score for natural gas boilers. By comparison, the solar collectors reached the lowest specific energy costs since it is the only technology that does not require the purchase of external energy sources to produce heat. Heat pumps indicated the lowest score in the economic dimension sub-index mainly due to considerably higher specific energy costs (econ4), capital investments (econ1), and a lower technology lifetime (econ3).

Compared with other technologies, wood pellet boilers indicated the highest service and maintenance costs (econ2) and specific energy costs (econ4) that negatively impacted the overall economic dimension sub-index score. A lower technology lifetime (econ3) and fewer possibilities to utilise surplus heat (econ5) also hindered the overall economic dimension score for the wood pellet boilers, ranking it in the lowest position of the economic dimension sub-index overall.

3.4. Social Dimension Sub-Index

Overall social dimension sub-index scores are less distributed compared with the other sustainability dimensions (see Figure 6). The highest sustainability sub-index was reached by the solar collectors (0.8). Equally high results (0.77) were achieved by three technologies: district heating, wood pellet boilers, and heat pumps. The lowest social dimension sub-index score was obtained by the natural gas boilers (0.58).

District heating reached the highest indicator values for consumer comfort level (soc1) and consumer safety level (soc2), which can be explained by the fact that in district heating, an operator is providing consumers with a certain level of comfort and safety but for technologies with individual heating solutions, all responsibility lies with the consumer. By contrast, the indicator value for consumer control level over heat consumption (soc4) was assessed to be the lowest for the district heating. Unlike the individual heating solutions, in district heating, supplied heat amounts are controlled by the grid operators, not the end-users. In total, the social dimension sub-index scores for district heating indicated that it can offer high user convenience as an individual heating solution. These results are also supported by findings from the study by [41] that show that consumers are willing to pay more to utilise district heating instead of switching to individual heating solutions due to higher convenience and loyalty to the district heating supply system.
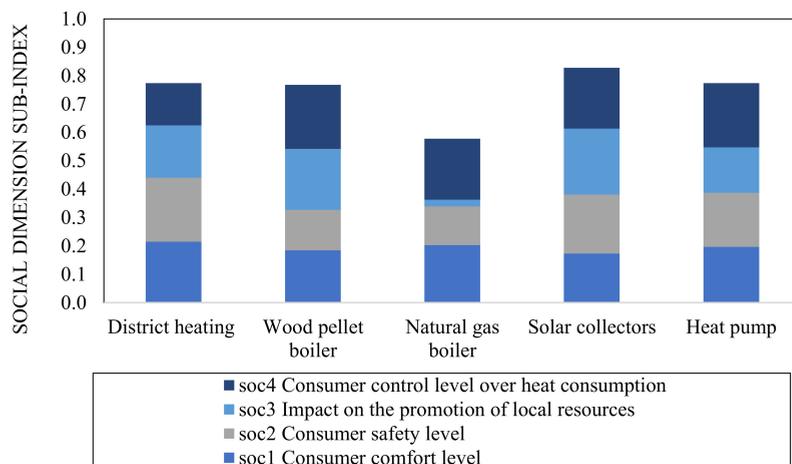
Figure 6. Social dimension sub-index values [26,43].

The total score of the social dimension sub-index for solar collectors surpassed district heating and other technologies due to their ability to combine two essential aspects: consumer satisfaction levels with safety and control over heat consumption, and promotion of local resources. Consumer comfort level (soc1) was indicated the lowest for the solar collectors compared with other technologies. That could be partly attributed to solar energy's periodicity and the necessity to compensate for the lack of solar energy with other heat supply technologies.

Both heat pump and wood pellet boiler technologies obtained the highest scores for consumer control level over heat consumption (soc4). Wood pellet boilers indicated a substantially higher score for impact on the promotion of local resources (soc3), which was the lowest for natural gas boilers. However, unlike the other technologies, the wood pellet and natural gas boiler technologies indicated the lowest scores for the consumer safety level (soc2), possibly associated with risks such as leakage or other type of accidents that could, in turn, affect the consumers' choice of these technologies.

3.5. Composite Sustainability Index

The highest composite sustainability index was rated for individual heat supply technologies which utilise renewable energy, use local resources and can be used in order to achieve the climate neutrality goals: heat pumps (0.64), solar collectors (0.63), and wood pellet boilers (0.55). A slightly lower sustainability index was estimated for district heating (0.50), but the lowest sustainability index was obtained by natural gas boilers (0.38) that utilise fossil fuels as the main energy source as opposed to a low carbon transition strategy.

Figure 7 shows the result distribution by the dimension sub-index categories for each technology. The composite sustainability index results identify the competitive advantages for each technology, as well as critical positions that currently hinder the achievement of higher sustainability.

Due to remarkably higher technical efficiencies and environmental benefits, the heat pumps represent the highest sustainability, despite having the lowest score in the economic dimension compared to district heating and the other individual heating technologies. However, the heat pump installation choice as the main heat supply technology is influenced by the higher initial investment and specific energy costs. Likewise, the wood pellet boiler's score is affected by specific energy costs and service and maintenance costs, which pose a negative impact on higher technology market diffusion.

District heating is the absolute leader in technical and economic dimensions, indicating higher technology efficiency and economic viability compared to the individual heating

solutions. District heating indicated equally competitive social dimension sub-index values by showing high indicator values for consumer safety and comfort levels.

Although the solar collector indicated the second-highest sustainability score due to its high performance in the environmental dimension, the inconsistent solar energy supply technology requires additional heating solutions to get sufficient heat coverage which is also represented in lower values of the technical dimension sub-index. Despite the widespread public perception that solar collector installation can only be afforded by high-income households, the results show that, in terms of economic dimension, solar collectors are the second most sustainable technology after district heating.

The authors argue that due to the considerably low impact of the economic dimension sub-index on the overall composite sustainability index, the lowest economic sub-index scores for the heat pump did not significantly affect its overall sustainability scores. Therefore, in further studies, it is suggested to perform a more detailed investigation and scenario analysis in applying different weights for the representative dimensions.
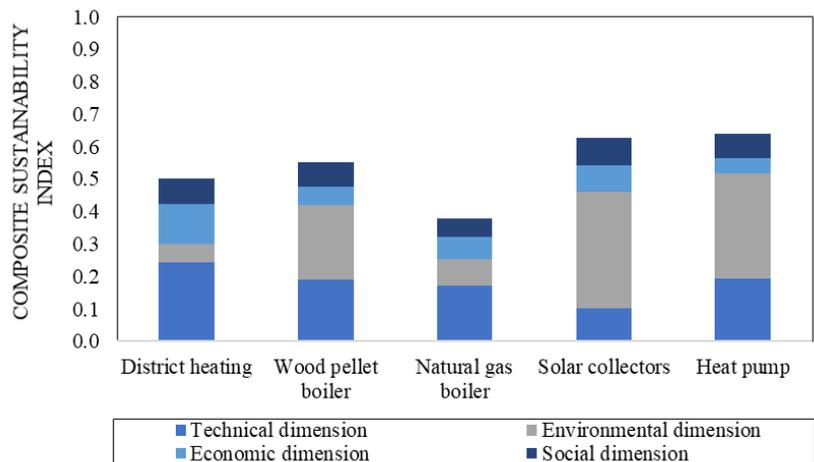
Figure 7. Composite sustainability index values [26,43].

3.6. Identification of Controversies and Blind Spots in Energy Policies

The study highlighted several potential blind spots of a sustainable energy supply system. One of the blind spots is represented in the environmental dimension of the composite sustainability index. In the calculations of the environmental dimension sub-index for district heating, a natural gas emission factor was used without considering the RES share in district heating. As a result, district heating achieved the lowest environmental dimension sub-index value. Moreover, due to higher flue gas cleaning complexity, the environmental dimension results ranked district heating lower than the individual natural gas boilers. It is essential to take into account that the actual emission factor of district heating could be achieved at a significantly lower level than it is generally portrayed in the studies or legislation if the share of RES would be increased. The results showed that district heating obtained the highest sustainability scores for all dimensions except for the environmental dimension, indicating that higher sustainability could be achieved by cutting the utilisation of fossil energy resources, such as natural gas, for combustion processes and replacing them with renewable energy sources.

District heating is proved to serve as one of the most effective solutions in energy system decarbonisation since it provides unlimited opportunities for more efficient and sustainable utilisation of energy resources. With new generation technological solutions, it is possible to diversify the district heating supply system by using cleaner technologies, such as renewable geothermal energy technologies, solar collectors, large-scale heat pumps,

and by increasing energy efficiency by utilising the surplus heat from different industrial processes [57]. Moreover, biomass such as wood and agricultural residues could be used as primary energy resources to decarbonise district heating. For example, in Sweden, the district heating mostly utilises wood, sawdust and wood chips, followed by wood pellets and briquettes. In addition, bio-oil, wood residues, and by-products from pulp production, such as tall oil, are also used as fuels. Decarbonisation of district heating has helped to significantly reduce CO_2 emissions in Sweden, which have diminished from 90 g/MJ in the 1970s to 9 g/MJ in 2014 [58].

Another controversy over the district heating environmental impact compared to individual heating solutions is outlined in a study by [37] which concludes that in countries where a large proportion of heating consists of burning local biomass resources in individual stoves, the issue of air quality and decontamination is more crucial than the decarbonisation of the heat supply system. Although high biomass consumption is considered a sustainable solution since it is a renewable energy resource, its combustion inefficiency and significantly higher PM emissions production negatively influence air quality, especially in urban areas. Therefore, district heating could serve as the most efficient solution to coordinate collective decontamination and decarbonisation of the heat supply system.

Findings from the paper by [57] therefore challenge the obtained results of this study, indicating that even though district heating performed poorly in the environmental dimension of the composite sustainability index, by looking at the perspective of created air pollution, the DH sustainability is higher compared to wood pellet boilers. Although wood pellet boilers are promoted as one of the most sustainable individual heating technologies due to its carbon neutrality, its generated PM emissions are substantially higher than those of other technologies, which is reflected in the higher complexity of flue gas cleaning. According to experts, the pellet boiler has the highest flue gas cleaning complexity among the technologies. Considering that PM particles are a significant factor influencing the environment, but are formed in small amounts or not at all (solar collectors) in other considered technological solutions of heat supply, it was not considered separately in the environmental dimension. The model includes the complexity of flue gas cleaning as an indicator, which includes the PM particles' influence. Flue gas cleaning was included as an indicator as it applies to both individual gas boilers, district heating boilers and wood pellet boilers, with PM being most relevant for pellet boilers. Another reason for not including PM particles as an indicator in the environmental dimension was that it is possible to technologically reduce PM particles from flue gases, e.g., through filters, which is considered difficult but can reduce pollution and improve the environmental dimension through treatment plants. Therefore, in the case of the pellet boiler, it would be essential to consider the various treatment methods used if the PM particles produced were used as a separate indicator in the environmental dimension.

Although the use of wood pellet boilers is considered to be environmentally friendly, the combustion of wood biomass generates a significant amount of particulate matter (PM) and the flue gases must be cleaned of PM emissions before being released into the atmosphere. The composite sustainability sub-index in the environmental dimension for the wood pellet boiler could be higher if the complexity of flue gas cleaning would be reduced. Therefore, in order to increase environmental sustainability, it would be necessary for consumers of pellet boilers to identify technologies that would be able to clean flue gases from PM as efficiently as possible. Nevertheless, efficient flue gas cleaning for the pellet boilers is influenced by the fact that flue gas cleaning and equipment maintenance is completely dependent on the consumer; therefore it would be necessary to develop certain standards to ensure higher cleaning efficiency of wood boiler equipment. For example, studies have estimated that ceramic filters can remove up to 96% of $PM_{2.5}$ and PM_{10} particulate matter from flue gases and therefore can be used effectively to clean wood boiler flue gases; moreover, the ceramic filters are assessed as effective in achieving climate goals [59]. In addition, to ensure higher efficiency of wood pellet boilers, it is

necessary to regularly clean the boilers to reduce the ash content and operate the boiler at a higher load [60].

A study by [58] outlines additional contradictions regarding the choice of the most sustainable energy policy. Current policies supporting decarbonisation of heat supply systems significantly push district heating towards a higher utilisation of biomass, thus increasing the share of renewable energy sources in heat production. However, high biomass utilisation in heat-only boilers contradicts the energy efficiency opportunities offered by district heating units that allow utilising recovered heat from primary processes. Policies that favour the use of renewable energy sources force district heating to switch to biomass instead of heat recovery, which is especially true if heat is produced from fossil energy resources. Substituting secondary heat with primary energy reduces the share of fossil energy resources by a minimal amount and therefore has a lower impact on reaching climate neutrality targets [57,58]. These findings are supported by the sustainability index results that showed the highest sustainability level for heat pumps.

There is conflicting information in the literature as to whether district heating systems are more expensive. From the perspective of policy-makers, district heating is often criticized for the system's high cost compared to individual heating solutions [41]. Using the results obtained in the study, it was found that district heating has the lowest costs among the heat supply technologies, which is reflected in the highest sustainability indicators in the economic dimension.

3.7. The Value of Research for Further Practice

The use of a sustainability index could improve the decision-making process for policy-makers when implementing energy policies. The composite sustainability index method can serve as a useful tool to determine which technologies need or should be promoted. Most importantly, it can help identify the critical aspects of each technology that need to be addressed in order to avoid potential blind spots in energy policies.

During research, a methodology was developed for evaluating a complex sustainability index using reliable data sources and weighting the dimensions using the expert survey method. The developed methodology can be adapted by assigning equal weights rather than using expert interviews, but this did not significantly change this study's result. The sustainability of the most popular heating solutions was quantified by considering four dimensions: technical, environmental, economic and social. Information on the advantages and disadvantages of each heating solution can be found in the literature, but in this study, the specific heating solutions are evaluated in four dimensions by creating several indicators that make it possible to evaluate each dimension and the overall sustainability of the heating systems and to determine whether these heating solutions will achieve the emission reduction targets set by policy-makers.

The study can serve as a potentially viable method for evaluating the specific problem, taking into account all relevant dimensions, each of which is assessed using indicators that quantify each dimension and the overall sustainability index. The study serves as a test case to analyse other identified contradictions in energy policy in this way. This method can be used to assess controversial issues and uncertainties in energy and other sectors such as bioeconomy. In this way, policy-makers can think in several dimensions and avoid the risks of unforeseen blind spots without underestimating any of the dimensions.

4. Conclusions

The composite sustainability index was constructed to compare sustainability levels of district heating with four different individual heating solutions: wood pellet boilers, natural gas boilers, solar collectors, and heat pumps. A wide range of indicators were selected, including both quantitative and qualitative assessment methods. The sustainability index was composed of 19 different indicators that were grouped in four sustainability dimensions: technical, environmental, economic, and social. Indicators were normalised using a min–max normalisation technique that scaled sub-indices and index values in a

range of [0;1], allowing comprehensive interpretation of the obtained results. The criteria were weighted using an AHP weighting technique. According to the industry experts' assessment, technical and environmental dimensions were evaluated as the most essential determinants of a heat supply system's sustainability. After the model approbation process, it was concluded that it is important to carefully select indicators to obtain an objective assessment of technological solutions and consistent calculations.

The study presented the importance of including several aspects in the analysis since the distribution of results for each dimension showed significant differences among technologies. Blind spots often arise due to solely looking at one-dimension factors; however, in the sustainability assessment, technical performance indicators must be analysed in the context of economic, environmental and social aspects, combined.

The highest sustainability index was obtained by heat pumps (0.64), followed by solar collectors (0.63), wood pellet boilers (0.55), and district heating (0.50). The lowest index value was obtained by natural gas boilers (0.38).

The results indicated that district heating is highly competitive and cost-efficient compared to individual heating solutions since it obtained the highest sustainability scores for the technical and economic dimension sub-indices. However, a potential blind spot was identified in environmental dimension sub-index values where district heating reported poor values due to higher flue gas complexity and emission factor assumptions made during the calculation procedure. The results showed that higher sustainability for the district heating could be achieved by cutting the utilisation of fossil energy resources, such as natural gas, for combustion processes and replacing them with biomass.

The discussion of the results concluded that, although there is an increase in biomass utilisation in district heating as well as the installation of wood pellet boilers, they seem to be a sustainable and environmentally friendly alternative due to their positive impact on carbon neutrality targets, and policy-makers should put more emphasis on finding sustainable ways to promote flue gas cleaning and air decontamination from biomass combustion processes.

The utilisation of a sustainability index could improve policy-makers' decision-making processes during the implementation of energy policies. The composite sustainability index method can serve as a useful tool for determining which technologies should be promoted. Above all, it can help identify the critical aspects of each technology that need to be addressed to avoid possible blind spots in energy policy.

The state of knowledge significantly influences the objectivity of the research results based on the literature about which advantages district heating systems and individual heating solutions have, which disadvantages, which current trends there are, and which blind spots in the political decision-making process can result from underestimation or evaluation based on only one aspect without joint consideration of all dimensions.

The success of the study depends mainly on which indicators are selected and which data sources are used: whether they are representative and whether they are based on the literature; whether it is possible to use them to make an objective assessment of all dimensions; whether the indicators chosen characterise the sustainability of the systems or, on the contrary, show their inefficiency; and whether it is possible to create a complex environmental sustainability index based on the selected indicators, which can be compared with each other.

The results could be influenced by the participation of industry experts who are able to objectively evaluate and compare heating solutions. In this study, only experts from the energy sector with the relevant knowledge and experience in heating supply issues participated in the expert interviews. In this study, less importance should be given to the experts' weighting, as the results obtained by additional analysis and by assigning the same weight to all dimensions did not change significantly.

Data availability was one of the major limitations of this study. The collection of reliable and relevant data in this study was limited in terms of sources. If it had been possible, the authors would have certainly selected multiple sources and then combined

them to obtain the final data. Since it was not possible to find other data sources as reliable as those used in the study, based on specific values for home heating solutions in the Danish Technology Catalog and the calculations and assumptions clearly presented in the study, the authors decided to use data from the Danish research.

The study does not consider whether it is an existing or new district heating system. According to literature, new district heating systems are evaluated as very efficient systems, so this could be one of the factors that should be considered when evaluating the sustainability of district heating systems.

The study does not take into account whether the technologies considered are used in urban areas or outside cities, as no specific cases are considered, but the sustainability of the technologies is evaluated. Nevertheless, based on the literature, technological solution choice is also significantly influenced by the geographical location and the distance to the connection possibility to district heating networks.

The results of the study are influenced by the assumption that only natural gas is used in district heating, regardless of the fact that renewable energy sources are also used in district heating. However, the results obtained show the trends and according to which indicators district heating is more sustainable compared to other heating solutions.

The drawback of the study is that no data are available to determine the sustainability of heating heat pumps, solar panels or wood pellets in district heating. National policies and incentives for district heating or individual heating solutions were not considered as this was not the aim of the study, but these factors should be considered in further studies.

This is one of several studies planned to analyse contradictions in energy policy. Further research is linked to the analysis of other contradictions in energy policies, assessing sustainability and the factors that contribute to or hinder the achievement of climate goals. Further research would be needed at the national or regional level, taking into account the share of renewable energy sources in district heating, the policies implemented in the field of renewable energy and district heating, and whether the dimensions of sustainability are taken into account in the decision-making. The role and use of renewable energy sources in district heating vary from country to country and this is a factor that has a significant impact on the sustainability of district heating.

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District heating resilience under high energy price shocks

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ABSTRACT

Maintaining sustainable heating price levels is a crucial aspect of the future development of district heating (DH) systems to provide a low-carbon and affordable heat supply. The recent extreme increase in resource prices during the energy crisis in 2022/2023 has raised an important question of how to increase the overall resilience of energy systems. This research focuses particularly on the ability of DH systems to maintain affordable heat price levels under significantly increased resource prices. The simple definition of resilience has been attributed to the ability of a system to recover from adversity. A novel resilience capacity quantification methodology has been applied. The research analyses 10 different DH systems in Latvia with various heat production technologies and fuel mixes and their changes in heat prices from 2021 to 2023. The study identifies the resilience curves of each DH system and compares their ability to recover after the disruption. A composite resilience index has been developed for the DH supply systems of several municipalities in Latvia. To construct the DH resilience composite index, indicators were selected and grouped into four dimensions: technical, economic, environmental, and social. The DH resilience composite index merges fourteen criteria and compares which DH systems are more resilient to extreme changes in external conditions.

1. Introduction

In Baltic countries, DH systems are crucial to the energy infrastructure and are the main heating source in residential buildings. Improving DH systems is crucial to achieving city climate neutrality targets [1,2]. DH energy systems can integrate renewable energy sources (RES) into the energy supply to reduce the impact of fossil fuel use and move toward decarbonisation goals in the energy sector [3]. The DH and cooling energy sector currently account for 50 % of final energy consumption and is the largest energy consumer in Europe, ahead of transport and electricity. A large part is used for residential heating, where 79 % of the energy is used for space heating, water heating, and space cooling [4,5]. According to 2021 statistics, more than half of the required energy globally is still produced with fossil fuels, such as natural gas and coal, and one of the reasons is a stable energy supply [5,6]. Energy systems are subject to major disruptions when affected by hazards that can be natural or human-caused. If an energy system, including the DH system, is disturbed, its failure to operate impacts the infrastructure, economic activities, and society. Energy systems, including DH systems, are critical infrastructure. All energy services depend on the efficient functionality of the respective energy networks, so their protection against external factors is essential for consumer safety and usability [6].

Energy security means providing a stable and uninterrupted energy supply to all energy consumers at a reasonable price [7]. The main current concerns when thinking about energy security are following: Geopolitical instability. Although geopolitical conflicts on a smaller or larger scale have always been on the daily ongoing war in Ukraine, triggered by Russia's invasion in 2021, it is a stark reminder of the potential threats to global energy security [8].

- Energy resource dependence. If a country's energy system is dependent on one type of resource, such as imported resources, it can become out of control [8].

The heat supply service must be available, economically beneficial, high-quality, environmentally friendly, and energy efficient. Possible disruptions due to energy source price or availability limitations and extreme weather events can leave residents vulnerable [9]. The timely assessment of the vulnerability of DH energy systems is a crucial part of well-thought-out decision-making. Therefore, improving the resilience of the DH system becomes a more important issue for a stable and sustainable energy system [9,10]. Energy system resilience could be

defined as the capacity of an engineered system to resist, absorb, buffer and recover from stressors [11,12]. and the effects of various hazards [2, 13]. The DH system must be reliable to known and predictable threats and resilient to high-low probability (HILP) events [14]. The increasing frequency and severity of these events require the development of more resilient systems [4,14]. Quantitative and timely measurements of the resilience of the DH system against threats and their overall sustainability are critical to eliminating threats to energy security [2,10].

The study examines changes in the price of heat during extreme fluctuations in the price of resources. It aims to assess the economic, technical, environmental, and social resilience of DH systems and propose improvements for their transformation. The main research questions of the study are the following: how do different heat production technologies and fuel mixes impact the recovery time and economic performance of DH systems, and what are the key factors that determine the resilience of DH systems to maintain affordable heat prices. These two research questions are answered by defining, measuring and comparing two different resilience concepts of DH systems: inherent resilience and adaptive resilience.

2. Literature analysis

2.1. Definition of energy security and resilience impacting factors

Energy security can be defined and measured based on elements that characterise system conditions, such as stability, resilience, flexibility, and robustness [5]. Resilience characterises the system's ability and reaction to natural or human-caused stressors and disturbances. Systems with low resilience to threats and disturbances cannot be sustainable [12]. According to Web of Science data, scientific articles have put "resilience" as a keyword in more than 50,000 publications. The term "energy system resilience" has been marked as a keyword in about 503 publications over the years. Most publications are done in China, Italy and the United States of America; at least four studies have already been published in Latvia [15].

According to Web of Science, there are 793 total research papers from Denmark related to "district heating" and at least six research papers that include the combination of keywords "district heating" and "resilience" [16]. HILP events, like natural hazards or cyber-attacks, impact system resilience [13]. Resilient energy systems can recover more easily to their initial state after disturbances and interruptions. On the contrary, systems with low resilience will be more vulnerable to unexpected threats, and recovery to a normal state might take longer [5].

Resilience is defined by factors such as robustness, redundancy, rapidness, and resourcefulness [13]. Energy systems' robustness refers to their ability to withstand disturbances and maintain their functionality. Systems' robustness can have a positive impact on recovery after disturbances. The main factor for energy systems' robustness is the diversity of energy sources used to produce energy [5,17].

The robustness of an energy system refers to its ability to withstand disturbances and maintain its functionality. This can have a positive impact on recovery after disturbances. The main factor in the robustness of energy systems is the diversity of energy sources used to produce energy [5,17]. Resilient systems are better able to manage HILP events, which allows them to maintain functionality and continue their purpose while contributing to sustainability [10] (see Fig. 1).

After a HILP or sudden extreme event that causes a system breakdown, redundancy characterises how fast system recovery will be. If backups are in place, redundancy helps decrease downtime after failure. If a system is designed with backup options, it will allow it to operate at least in limited capacity. On-ground electrical networks are vulnerable to damage; some critical transmission lines should have backup plans such as parallel connections [17]. Rapidness is a time measure that characterises a systems ability to recover fully or partially from a HILP. Resourcefulness refers to the availability of alternative resources to
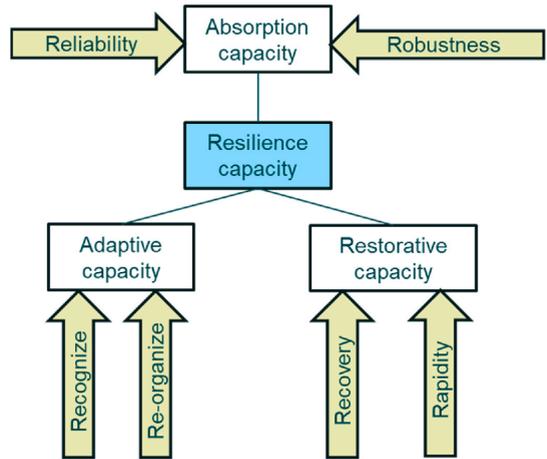

Fig. 1. Resilience capacity [10].

continue energy production and recover in the initial state faster after extreme events and disturbances [10].

Resilience can be visualised in the following way. It starts with HILP or an extreme event that affects the system. There are expected four behaviours after the event: "Collapsing" behaviour indicates the system's inability to recover; it stays out of operation; The "Ductile" behaviour of the system characterises the system's partial recovery after collapsing; "Robust" behaviour indicates the ability to return to initial conditions; "Adaptive" behaviour returns into systems operation on an even higher level [17].

Currently, most studies [18] are dedicated to assessing the overall resilience of the energy system or the resilience of the power system. For example, in the resilience analyses, the optimisation method was demonstrated in two cities, and their energy systems were compared based on costs and emissions [9,16].

Less focus has been paid to analysing the overall resilience of the heat supply in various extreme conditions [18].

2.2. Threats to DH system energy security

Energy security threats can include natural hazards, cyber-attacks and physical attacks that cause disturbances and disruptions in energy systems. Recently, energy systems have become more vulnerable [7,8, 19] which is partly explained by the increased frequency of cyber-attacks and natural hazards [5,20].

Natural hazards, including severe weather conditions, can affect the operational resilience of an energy system. Natural disasters, such as earthquakes, floods, and extreme winter temperatures, may impact the resilience of the DH system [12]. Geographically, in Northern Europe, including Latvia, there is a probability of extreme storms, floods, and extreme cold weather [21]. Some of the human-caused HILP events that impact DH systems are energy source disruptions, cyber-attacks, energy consumption peaks and infrastructure damage [13,19]. Energy source disruptions [13], such as physical availability of heating capacity or price fluctuations that impact heat costs, are a great vulnerability to the DH system [8,13]. Cyber-attacks can cause issues in large-scale DH networks. In DH systems, digitalisation is used for heat production optimisation, automatisation, monitoring, and replacement of manpower. This is convenient for energy production, distribution, and billing services in case a cyber-attack system malfunctions by stopping heat production, uncontrolled supply temperature, pipe damage exceeding supply temperature, or freezing pipes [13].

Extreme weather events, like extreme cold, usually cause a peak heat consumption for several days [5]. If various climate conditions are not included in the design criteria, the system may not be resilient to an extreme cold period [13]. However, installing additional heating capacities requires additional investments, may reduce efficiency, and, therefore, can increase the overall cost of heating. Another aspect is that DH is vulnerable to failures in the operation of the equipment. To avoid production disturbances, pipes are usually buried in the ground and have less risk of external damage. DH production process involves specific parameter equipment usage due to wearing out or simply breaking down the boiler, heat exchanger or other critical components that can pause or stop heat production [13].

2.3. DH in Latvia and price fluctuations

The study examines the resilience of several DH systems in Latvia as a case study. DH plays a significant role in Latvia's energy supply and is the primary type of heat supply in cities. Due to DH's importance for Latvian citizens, these heat prices are regulated by the state, but municipalities organise the availability of DH energy on their territory. Latvia's consumer price of heat or final heat tariff consists of three components: production, distribution, and realisation rate. The highest role of these components is for the production component, but the realisation costs are the lowest [22]. DH heating tariffs vary based on several factors, such as taxes, fuel prices, investments, and operational parameters [22].

The heat supply in Latvia has recently faced a switch to solid biomass. However, some DH systems still use natural gas as the main heat source. In 2018, 61.2 % of the heat was produced in boiler houses using biomass and 37.6 % using natural gas [23]. Therefore, the increase in gas prices after Russia invaded Ukraine significantly affected the price of the final energy product [8]. In addition, the cost of wood chips and pellets increased due to the ban on wood imports from Russia and Belarus and the increased demand for solid biomass. Fig. 2 indicates the changes in fuel prices from January 2020 to March 2024 in Latvia, which is further assessed in this study.

The impact of price changes on the economic resilience of DH systems can vary depending on the energy sources purchased in high-price peak or low-price situations. Therefore, the study analyses how the final heat tariff has changed for DH systems with different fuel mixes, indicating their resilience to extreme price increases. Additionally, other factors that affect DH resilience have been identified through the assessment of the DH resilience composite index.

3. Methodology

This study's resilience assessment for DH systems measures two different resilience concepts: adaptive resilience and inherent resilience. According to Feofilovs [1,23,24,24,25]. Adaptive resilience is used to assess how quickly DH systems can adapt to extreme external changes.
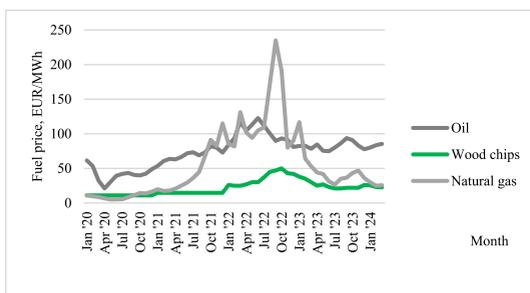
Inherent resilience, on the other hand, shows how ready DH systems are for various external conditions (see Fig. 3).

First, the heat tariff changes have been analysed by indicating the adaptive resilience of DH systems. Afterwards, the inherent resilience assessment of DH systems is done to fully estimate the DH system's ability to adapt and impact different external conditions.

The main research steps for the assessment of the adaptive and inherent resilience of different DH systems in Latvia are shown in Fig. 4. First, the literature analyses and data collection was done by gathering public information and necessary data from companies, identifying impacting factors and calculating selected indicators. Further, adaptive resilience assessment includes the analyses of heat tariff variations, determination of recovery phases, and calculation of heat tariff resilience factor.

To measure inherent resilience, a criteria matrix was developed, normalised, and weighted to determine the DH resilience composite index. It also includes the aggregation of indicators. Finally, the sensitivity analysis was performed by changing the weights of the dimensions.

The adaptive and inherent resilience measured was verified by comparing both values for each DH system.

3.1. Adaptive resilience

In this research, the stability of heat energy tariffs was examined to determine the adaptive resilience of DH systems. This allows for determining the system's capacity to adapt to changing external conditions, including economic factors [12].

In Fig. 5., the general transformation processes of the energy system during the collapse and recovery phases are illustrated, distinguishing three states: the original state (S_0), the disruption state (SD), and the stable recovered state (SF). There are also two transitions between these states: system disturbance (from the initial state to the disruption state) and system recovery (from the disrupted state to the stable recovered state). These processes and states are linked by two key events that trigger the situations above: the moment of disruption and the resilience actions. The system operates stably until a disturbance (either internal or external) occurs at a specific point in time, leading to the disruption of the previously original stable system. The same approach has been applied to analyse the changes in the heat price of DH systems [12].

Heat tariff analyses were performed for the period from 2021 to 2023 in ten of the Latvian DH systems. The technical properties of each DH system are shown in Table 1.

The heat tariff analyses were done based on the following data.

- Heat energy tariff;
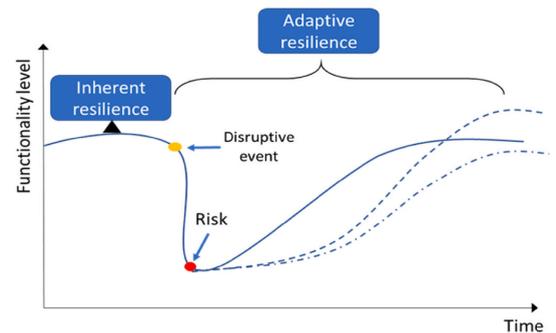- Fuel costs;
- Types of fuel that affect tariffs.

Fig. 2. Changes in fuel prices [23].

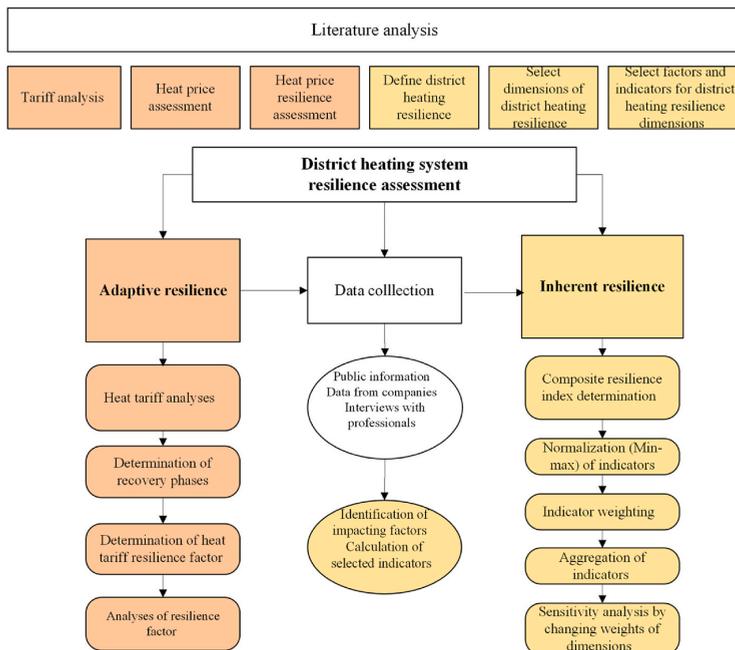**Fig. 3.** Characterization of the inherent and adaptive resilience [24].

Fig. 4. Main research steps for characterisation of the inherent and adaptive resilience (made by author).
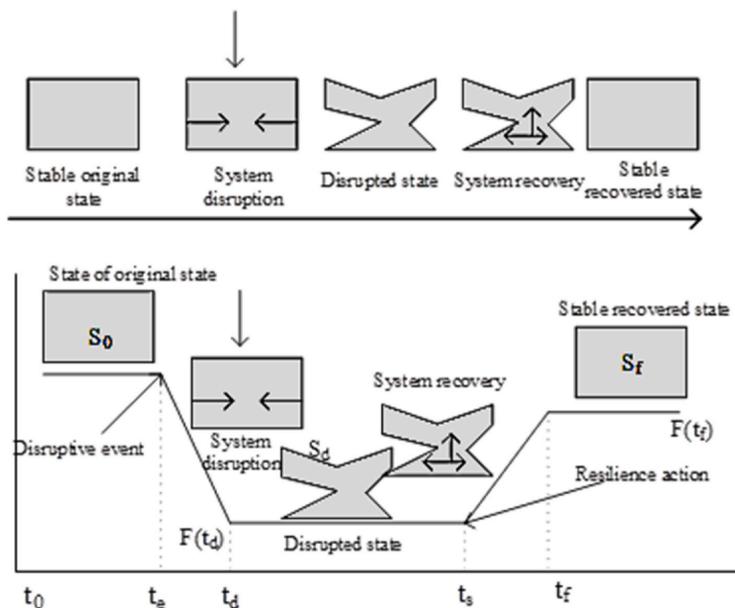

Fig. 5. System recovery phases (made by the author) [12].

To determine tariff stability and adaptive resilience factor, the proposed method by Francis&Bekera [10] was applied (1). The resilience of the heat supply system tariff was calculated by determining the resilience factor ρ_i. It considers the speed of DH recovery after high resource price increases Sp, the initial heat tariff T_0 and heat tariff directly after the resource price increase T_d and the performance levels in the new stable state T_r (1).

Table 1
Parameters of DH energy systems.

No.	Fuel mix, %	Total heat produced, MWh	Heating network length, km	Municipality-owned/ privately owned	Installed heat capacity, MW
DH1	Renewables 90 % GAS 10 %	64116.7	20.6	municipality-owned	37.7
DH2	BIO 58 % GAS 42 %	147709	59	municipality-owned	78.6
DH3	GAS 99 %, BIO 1 %	28399	2.3	municipality-owned	19.3
DH4	GAS 67 %, BIO 33 %	145930.7	40.2	municipality-owned	111.9
DH5	BIO 93 %, FOSSIL ENERGY (gas, coal) 7 %	162595.7	55.1	municipality-owned	122.9
DH6	BIO 100 %	30879	12.1	privately owned	17.7
DH7	BIO 82 % GAS 18 %	36089.7	18.8	municipality-owned	15.9
DH8	BIO 93 %	29880	16	privately owned	25.3
DH9	BIO 100 %	28593	9.6	municipality-owned	22.4
DH10	BIO 100 %	27622	13	municipality-owned	20.2

$$\rho_i = S_p \frac{T_r}{T_0} \frac{T_d}{T_0} \qquad (1)$$

Where ρ_i - a resilience factor for DH system i; S_P – Speed Recovery Coefficient; T_0 – the initial stable performance level of the system, EUR/MWh; T_d – performance level immediately after the disturbance, EUR/MWh; T_r – performance in the new steady state, EUR/MWh [10].

The speed recovery factor depends on the disturbance time t_δ, the time until the final system recovery t_r, and the time to complete initial recovery operations $t*_r$. If, $t_r \geq t*_r$, then Sp is calculated according to (2).

$$S\rho = \left(\frac{t\delta}{t*_r}\right) \exp\left[-a(t_{-}(r) - t*_r)\right] \qquad (2)$$

Otherwise, (3) is applied.

$$S\rho = \left(\frac{t\delta}{t*_r}\right) \exp\left[-a\left(\frac{t\delta}{t*_r}\right)\right] \qquad (3)$$

where t_r – time until the final system recovery; t_δ – disturbance time, month; $t*_r$ – time to complete initial recovery operations, month; a - a parameter that controls the decrease in elasticity (assumed to be 1) [10]. The chosen calculation method combines factors characterising the operation of the energy system: current operation, the moment of disturbance (or sudden tariff change), the return to a stable state, where the tariff stabilises after the crisis—as well as the time spent in the crisis and the period from the end of the crisis to the stabilisation of the tariff.

3.2. Inherent resilience

An inherent resilience assessment was made using the data for the same ten DH heat supply systems in Latvia (see Table 1.) with different heat energy production technologies and fuel mix and their heat price changes from 2021 to 2023. The sustainability of each DH energy system can be assessed using combinations of indicators in different sustainability dimensions. The composite DH resilience composite index aggregates various indicators into one index for each of the ten DH energy systems. Studies show that the DH resilience composite index method can be used in the decision-making process as a valuable instrument for choosing sustainable heating system solutions [14].

3.2.1. Defining criteria for the DH resilience composite index

The first step in evaluating the inherent resilience of different DH energy systems is to select appropriate criteria, which include economic aspects, environmental impact, technical properties, and criteria to evaluate social impact [14]. The design criteria of the DH energy system relate to regular system performance, including type of energy source, infrastructure, consumers, and capacity. The system's ability to withstand and recover from disruptions and adapt to changing conditions should also be considered.

To select the most appropriate criteria, a literature analysis was performed first on factors that affect DH energy resilience and sustainability [2].

The criteria were selected to consider the possibilities of transforming the existing DH system to the latest generation network system to increase DH resilience [26]. The challenges and benefits of these transitions were mainly analysed from the perspective of current energy demand and supply scenarios, the goal of abandoning fossil fuels, and the increase in the share of renewable energy source (RES) resources.

According to studies, DH resilience should take into account various aspects of sustainability as well as technical conditions [12]. For the construction of the DH resilience composite index, factors that influence DH systems sustainability were divided into dimensions that characterise and summarise different aspects of DH system conditions, including 1)technical dimension, 2)economic dimension, 3)environmental dimension and 4)social dimension. Fig. 6 shows a methodology for the establishment of the DH resilience composite index for different energy systems, taking into account four dimensions.

In this study, indicators in the technical dimension describe the technical ability to withstand unforeseen disturbances and produce heat for consumers. The technical resilience of the DH energy system describes its robustness against short-term or long-term disturbances [12].

The economic dimension of the existing DH system refers to financial and economic aspects related to improving and maintaining resilience in an existing energy system to ensure affordable heat to consumers. The environmental dimension aspects of DH resilience refer to how the system adapts to more sustainable energy production based on climate change impact on energy production regulations. The Social dimension of DH resilience signifies the systems competitiveness compared to other DH systems, affordability for consumers and ability to maintain the supply of heat energy [25].

3.2.2. Identification of impacting indicators

After defining different dimensions of DH system sustainability, appropriate indicators were selected for each dimension.

Methodology for the selection of indicators based on.

1. The aim of the manuscript
2. literature review - scientific publications and technical reports
3. Factors based on previous literature on energy crisis and resilience impacting factors

Scientific indicators were selected based on the following criteria: relevance, data availability and data credibility[27].

Indicators impacting DH resilience are listed in Fig. 7.

Each DH resilience dimension has a list of indicators Indicators either positively impact the resilience of DH systems (e.g., a share of renewable energy in DH systems) or have a negative impact on resilience (e.g., production costs) [11]. For each of the selected indicators, a specific unit was applied that characterises these indicators for further calculation of indicator value.

A list of indicators in each of the dimensions is shown in Tables 25.

The diversification index of the heat production sites (t1) shows the dependence on one or several DH production facility locations, which is measured by applying the general framework of the HHI [28] by using (4).
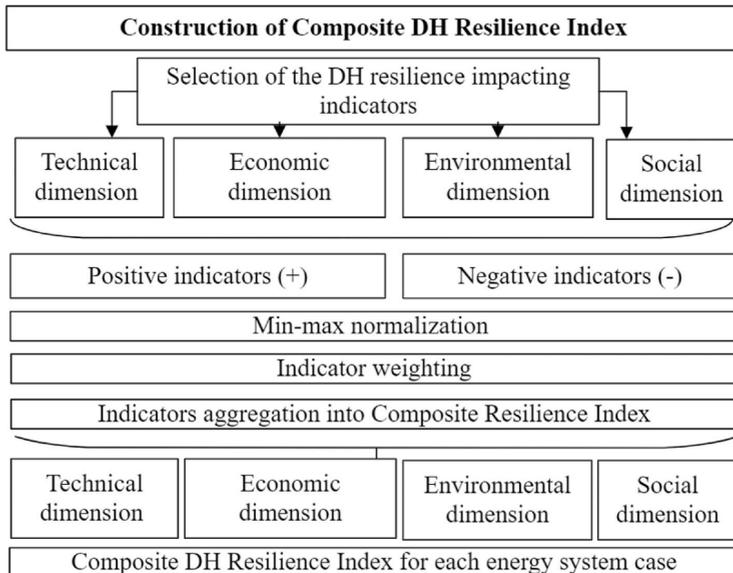
Fig. 6. The framework of the construction of the DH resilience composite index.
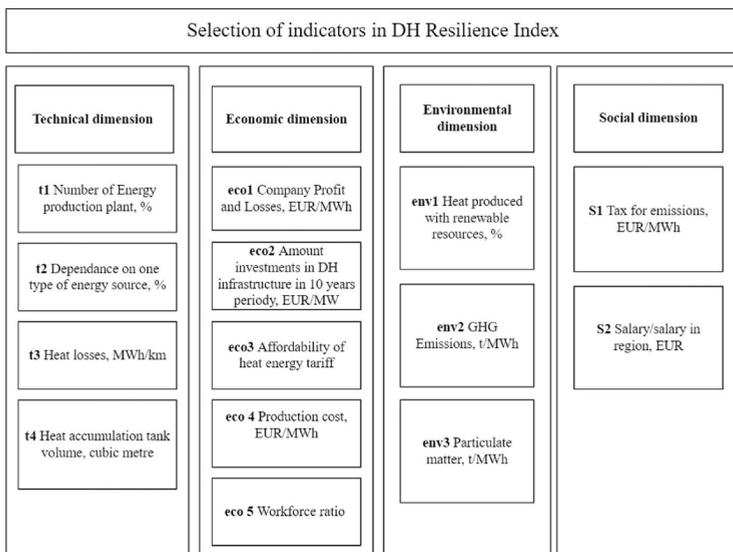

Fig. 7. Selected indicators for the construction of DH resilience composite index.

$$DI_{prod} = s_1^2 + s_2^2 + s_3^2 + \dots s_n^2 \qquad (4)$$

where n – heat capacity share of the heat production site in total installed heat capacity of DH system, n - represents the total number of production sites[27], [29].

Diversification of heat sources can significantly increase the DH system's ability to withstand a shortage of resources or significant price changes. Therefore, the diversification index of heat production sites (t2) measures the share of particular heat sources in the total fuel mix of

the DH system, similarly to t1, applying the HHI index determination methodology [29]. Lower indicator values show higher diversification rates and less risk in heat production.

Heat losses in heating networks reduce the efficiency of the entire DH system [30]. Therefore, specific heat losses (*t3*) in the piping network are expressed as total MWh related to the total piping network distance in km. Heat losses are calculated according to (5). Higher results negatively impact DH resilience as more heat is lost per km of network.

Table 2

Selected indicators of the technical dimension of DH resilience.

	Indicator	Unit	Indicator description and justification	Impact on resilience
t1	Diversification index of heat production sites [22], [28], [29]	DIprod, %	Heat production depends on one or several DH production facility plants. Describes how much heat production depends on a single production site (boiler house or cogeneration plants). The index shows the rated heat capacity of each production site according to the Herfindahl-Hirschman indicator (HHI)calculation [22]. If heat production relies on a single energy resource, it would negatively impact the resilience of the energy system. Evaluating the technical aspect of dependence of one heat production place HHI result would be close to 10,000 would mean complete dependence on one place of heat production [29], higher value indicates a negative impact on DH resilience.	–
t2	Diversification index of resources and production mix [22], [28], [29]	DIresources, %	Depending on one type of energy source Indicator describes the diversification of resources in the total heat production mix and how much is produced from each heat source [22]. Heat production in DH company depends on one type or several types of energy source, which is measured using the Herfindahl-Hirschman indicator. Indicator. If company is producing heat only from one type of energy source HHI result close to 10,000 and would mean complete dependence on a kind of energy resource, lower value show impact on resource diversification and less risk in heat production [29] Higher HHI result value indicates a negative impact on DH resilience	–
t3	Heat losses [22], [28], [30]	MWh/km	Describes the heat losses per km of piping network. Heat losses through the heating network also have an impact on the heat production tariff [22], [28], [30].	–
t4	Accumulation capacity [31], [32]	m3/MW	Accumulation volume in m3 against the total heat produced in MW. Characterises if DH company can offer the possibility to continue energy production using	+

Table 2 (*continued*)

Indicator	Unit	Indicator description and justification	Impact on resilience
		the accumulated energy in case of system interruptions. The capacity of the heat storage site is used as an indicator. An accumulation tank is added to the DH system to cope with peak loads and store heat produced at a lower cost, like a solar collector park or waste heat in production processes [31], [32]	

Table 3

List of indicators of the economic dimension of DH resilience.

	Indicator	Unit	Description of the indicator	Impact on resilience
Eco1	Rate of Company Profit and Losses [11]	EUR/MWh	The ratio of the profit loss indicator is divided by the delivered heat. Describes the economic stability of DH production company [11].	+
Eco2	Subsidised investments in DH	EUR/MW	10-year investment volume ratio to production capacity. The indicator describes how much has been invested in the implementation of centralised heat supply infrastructure improvement projects in the last ten years.	+
Eco3	Affordability of heat energy tariff [2]	MWh	The average tariff ratio to the county's average insurance contribution salary or gross salary. Heat tariff shows how affordable it is for consumers [2].	+
Eco4	Production cost [12]	EUR/MWh	The ratio of average production costs/heat produced. Describes the efficiency of heat production [12].	-
Eco 5	Workforce [12]	Employees/ MWh	The ratio of the number of workers to the amount of heat produced shows how many people in the region are integrated to produce energy [12].	-

$$Q_{los} = \frac{Q_{prod} - Q_{supl}}{L_{pipes}} \tag{5}$$

where Q_{los} –heat losses in MWh/km; Q_{prod} – total heat produced, MWh per year; Q_{supl} – total heat supplied, MWh per year; L_{pipe} – total pipe length in the network in km [4].

Accumulation capacity (*t4*) is calculated according to (6), where the impact of the accumulation tank is based on its volume expressed as the maximum demanded heat production capacity. The availability of storage capacity has a positive effect on DH resilience by the ability to trip down peak load demand and maintain energy-efficient heat production.

Table 4
List of indicators of the environmental dimension of DH resilience.

	Indicators	Unit	Description of the indicator	Impact on resilience
env1	RES share [12,22, 30]	%	The ratio of the amount of energy produced by renewable energy to the total heat produced [22].	+
env2	CO_2 emissions [7, 30]	t/MWh	CO_2 emissions per MWh heat produced show the amount of CO_2 emissions that create specific DH systems to produce heat [7, 30].	-
env3	Particulate matter (PM) emissions [7,30]	Kg/MWh	Particulate matter (PM) emissions per MWh of heat produced show the amount of PM emissions that create specific DH systems to produce heat [30].	-

Table 5
List of indicators of the social dimension of DH resilience.

	Indicator	Unit	Description of the indicator	Impact on resilience
s1	Tax of fossil fuel and emissions [12]	EUR/MWh	Tax of fossil fuel and emissions. Amount of emissions tax per MWh heat supplied [12].	-
s2	Salary competitiveness [7, 12]	EUR/EUR	Competitiveness of the workplace in the region. Salary in DH energy system/salary in the region [7,12].	+

$$HS = \frac{AC}{Q_{max}} \qquad (6)$$

where HS – Heat storage m³/MW; AC – Accumulation tank volume, m³; Q_{max} – Maximal demanded heat capacity, MW [33].

Five different criteria have been identified to describe DH's economic stability, which indicates the financial reliability of the heat energy supply to secure a constant energy resource supply, proper business management, and reasonably priced services (see Table 2).

The rate of Company Profit and Losses (*Eco1*) is calculated according to (7) by the total profit or loss amount in EUR divided by the total heat supplied to consumers in MWh. It shows how financially healthy the company is. A lower score has a negative impact on resilience due to possible financial losses. If DH is municipality-owned, it may be expected to be a non-profit or low-profit business if it is part of the municipality's strategy.

$$P\&L \, rate = \frac{Profit - \text{Losses}}{Q_{supl}} \qquad (7)$$

where $P\&L$ – company's profit and losses, EUR per year; Q_{supl} – Total amount of heat supplied to consumers, MWh per year [34].

Subsidised investments in DH (*Eco2*) show the amount invested in DH infrastructure and are calculated according to (8), where the amount invested in DH infrastructure in the last ten years is divided by the total capacity of DH utility. Projects with EU subsidies are considered the most significant investments in energy efficiency and technology improvement, which are positively impacting DH resilience.

$$SInv_{intens} = \frac{Inv}{Q_{inst}} \qquad (8)$$

where Inv_{intens} – total investments in last ten years, EUR/MW.

The affordability of heat energy tariff (*Eco3*) describes the affordability of heat for consumers. The heat tariff is divided by average

household income into specific regions (9). Asa result, affordability is the amount of MWh a household can afford with an average income level (2021–2023) in specific regions. Higher results positively impact resilience as it shows customers' ability to afford heat.

$$Aff = \frac{I}{T} \qquad (9)$$

where *Aff* – Affordability in MWh; *I* – Average income in a specific region, EUR; *T* -DH energy tariff EUR/MWh [35].

The production cost ratio (*Eco4*) is calculated according to (10), dividing the total production cost by the total heat produced. DH supply to consumers is expected to be efficient, economically feasible, and produced with low profit. Therefore, a lower indicator result shows a company with low heat production costs, positively impacting its resilience.

$$Production \, Cost \, ratio = \frac{Production \, cost}{Q_{prod}} \qquad (10)$$

where *Production costs* – total cost of production, EUR per year [12].

The workforce indicator is calculated according to (11). The formula uses data on the total workforce and specific salary in the region. Lower indicator results show a higher level of automated heat production process, network maintenance, and administration and lower production and operation costs, positively impacting its resilience.

$$Workforce \, ratio = \frac{Workforce}{Salary \, in \, region} \qquad (11)$$

where:

Workforce – total number of employees in the company (average value from 2021 to 2023).

The environmental dimension of DH resilience is included to quantify the environmental aspects (see Table 4).

The share of renewable resources (*env1*) is calculated as the total energy produced from renewables (biomass and solar collectors) divided by all energy produced according to (12). Higher results positively impact DH resilience, showing a climate-neutral way of heat production.

$$Q_{renew}\% = \frac{Q_{renew}}{Q_{prod}} \qquad (12)$$

where Q_{renew} % – share of energy produced with renewable resources %; Q_{renew} – energy produced with renewable resources, MWh.

Specific CO_2 emissions from fossil fuels (*Env2*) per MWh of heat produced [36] (part of the CO_2 emissions) were evaluated. Higher emission rates negatively impact the climate and DH resilience.

The CO_2 emission factor of a district heating system in tCO₂/MWh heat [36] allows for evaluating how clean the energy sources are and whether renewable energy is used to decarbonise system (13).

$$CO_2 = \frac{\sum_{n=1} F_{CO2,n} * Q_{prod,n}}{Q_{prod}} \qquad (13)$$

where CO_2 -specific amount of CO_2 emitted, t/MWh; FCO_2 - emission factor for fuel *n* t/MWh; Q_{prod} - Amount of energy produced from fuel *n*, MWh per year [37].

The following CO_2 emission factors for fossil fuels were used: natural gas - 0.202 t/MWh [38]; diesel fuel - 0.279 t/MWh; coal - 0.264 t/MWh [30].

The dust particle pollution indicator (*env3*) quantifies the total particulate matter (PM) emissions per delivered heat. This equation has been adapted for the determination of PM10 emissions based on the CO_2 emissions methodology [36]. It is expressed as tons of PM per MWh of heat produced [36] (14).

$$PM = \frac{\sum_{n=1} F_{PM,n} * Q_{prod,n}}{Q_{prod}} \qquad (14)$$

where PM – specific particulate matter emissions, kg/MWh; FPM$_{10}$ – Particulate matter PM$_{10}$ factor of emissions (mg/MWh); Q$_{prod,\,n}$ - Amount of energy produced from fuel n, MWh per year.

The used PM emission factor of wood chips and wood pellets is 47.15 g/kWh. Šī ir vidējā PM10 emisijas koeficienta vērtība granulu katlā ($<$1 MW) un šķeldas katlā ($>$1 MW).

[30]. Table 5 shows indicators for the social dimension.

The total amount of tax for emissions (*s1*) (GHG, CO$_2$, particulate matter) is calculated and divided by energy sold to consumers (15). Higher results have a negative impact on DH resilience from the social dimension.

$$Tax_{em} = \frac{(Q_1 * EM_1) + \ldots + (Q_n * EM_n)}{Q_{supl}} \qquad (15)$$

where *TAX*$_{em}$ – Total emission tax amount to MWh heat produced, EUR/MWh; *Q*$_n$ – Amount of energy source, MWh; *Q*$_{supl}$ – total heat supplied in MWh; EM$_n$ – Tax amount EUR/MWh.

The salary competitiveness indicator (*s2*) is calculated according to (16). The formula use

$$Salary\ competitiveness = \frac{Salary\ in\ DH\ company}{Salary\ in\ region} \qquad (16)$$

The salary in a DH company is the total salary (based on 2022 and 2023 year average values) divided by the number of employees.

Salary in the region – average salary in a specific region during the 2021–2023 time period, EUR per month.

To characterise the resilience of the DH heat supply in 10 cities, data for the years 2021–2023 were collected from various sources: official databases, statistics regarding emissions, and annual financial reports.

3.2.3. Construction of DH resilience composite index and sensitivity analyses

To be able to integrate various indicators into one DH resilience composite index, normalisation of the collected data should first be done. The DH resilience composite index min-max method is used as a normalisation method. This method is widely used in decision-making analysis and scientific research; results are made unified on a scale of 0–1 [12]. In normalisation, it should be taken into account that each of the indicators has a positive or negative impact on the overall DH resilience composite index, as indicated in the previous section in Tables 1–4 Therefore, normalisation differs based on the impact on the indicator (positive or negative). Positive indicators are normalised using (17), but indicators with negative impact are calculated based on (18).

$$I^+_{N,ji} = \frac{I^+_{act,ji} - I^+_{min,ji}}{I^+_{max,ji} - I^+_{min,ji}} \qquad (17)$$

$$I^-_{N,ji} = 1 - \frac{I_{act,ji} - I^-_{min,i}}{I^-_{max,i} - I^-_{min,i}} \qquad (18)$$

Where $I^+_{N,ji}$ normalised value of positive impact indicator; $I^-_{N,ji}$ normalised value of negative impact indicator; $I^+_{act,ji}$ actual value of an indicator; $I^-_{min,i}$ minimal value of an indicator among DH energy systems; $I^+_{max,i}$ maximum value of an indicator among DH energy systems; *j* denotes the specific sub-dimension; *i* denotes the specific indicator in a particular sub-dimension [39,40].

Each indicator received equal weight. In this case, the same weight (0.25) was applied to each indicator, which shows the same importance for each of the dimensions [12]. The final step is to aggregate the DH resilience composite index results by multiplying them by the normalised indicator value (19).

$$I_{CI} = \sum_{j}^{n} W_j x\ I_i \qquad (19)$$

Where I_{CI} is the DH resilience composite index, W_j is the impact weight of the dimension sub-index on the DH resilience composite index, I_i Normalised indicator value

[40,41].new.

To validate the effect of different dimension weights on the results, a sensitivity analysis was performed with different weights. In this case, the focus was on changes in the weights of the technical and economic dimensions. Table 6 shows values for sensitivity analysis, prioritising economic and technical dimensions.

4. Results and discussion

4.1. Adaptive resilience assessment through heat price changes

The adaptive resilience of DH systems under high energy price shocks has been assessed through heat tariff changes. Fig. 8. shows the relative changes of heat tariffs for ten analysed DH systems by considering 2020 as the base year. Fig. 8 shows that the DH systems, which are fully natural gas-based (marked with grey colour), have faced even more than a 300 % heat price increase during 2022. On the opposite, the heat tariff increases less significantly in biomass-based DH systems, which use mainly solid biomass (marked in green in Fig. 8). However, it can also be seen that the stabilisation period of heat tariff differs a lot among the analysed DH systems, which requires additional analyses. The ratio of the amount of energy produced by renewable energy to the total heat produced for each of the municipalities is shown in Table 7. The information in the table allows us to judge how much renewable energy and fossil energy are used in each of the 10 systems considered. DH 3 and DH 4 are systems that are predominantly based on the use of fossil energy in district heating.

Calculated data for the further determination of the heat tariff resilience index for each of the DH systems is shown in Table 8. Results of the heat price analyses for various DH energy systems show that gas-dependent systems have higher heat prices after recovery (T$_r$) and significantly higher after an initial post-disruption (T$_d$) in comparison to energy systems based on biomass or other renewables. Energy systems based on gas can be more vulnerable to energy price fluctuations in comparison to biomass-based.

Results show that DH energy systems based on renewable energy have lower original system heat prices (T$_o$) in comparison to gas-based DH systems. Heat price after disruption (steep price increase in 2022/2023) shows that gas-based systems are more vulnerable to heat price fluctuations. According to the results heat price after recovery gets higher in comparison to the original heat price before disruption. In comparison, heat prices for biomass and solar collector-based DH energy systems did not experience such a big heat price rise as that for gas-based systems.

Renewable energy (biomass and solar collectors) has a lower original system heat price than gas-based (e.g. DH3 and DH4) systems. Also, biobased DH energy systems are more price-resilient during disruption.

Table 6
Weight of dimension prioritising economic and technical dimensions.

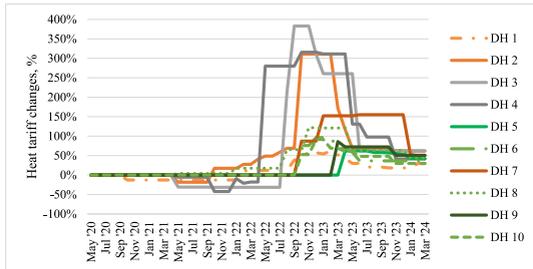| Dimension	Weight of dimensions, prioritising Economic dimension	Weight of dimensions, prioritising Technical dimension
Economic dimension	0.40	0.20
Technical dimension	0.20	0.40
Environmental dimension	0.20	0.20
Social dimension	0.20	0.20

Fig. 8. Heat tariff changes of analysed DH systems from May 2020 to March 2024.

After heat price recovery, the price is close to the original price before the disruption. Results of the heat price analyses for various systems are shown in Table 8 with colour transitions, where green indicates more resilient systems regarding heat tariff and red means less price-resilient systems.

Fig. 9 shows the calculated speed recovery factor and heat tariff resilience factor in ten different DH energy systems. The highest speed recovery factor is for DH 7 due to the long recovery period for heat tariff stabilisation. Still, the lowest speed recovery factor is for DH systems, which have lower total disruption time from heat tariff increase to returning to a new stable state. The highest calculated resilience factor, which in this study indicated lower resilience to external price changes, is for DH 3, which faced a higher heat tariff increase. Also, the biomass-based DH 7 has a relatively high resilience index due to the high heat tariff after the recovery phase.

The results show that the chosen method can measure the adaptive resilience of DH systems by including the assessment of functionality changes and recovery speed. However, it does not indicate which factors could increase the overall resilience. Therefore, it could be merged with the inherent resilience assessment presented in Section 3.2.

4.2. Inherent resilience assessment

To evaluate the inherent resilience of DH systems, various indicators were calculated according to the Methodology presented in Section 2.3. Table 9 shows a summary of the matrix used to construct the DH resilience composite index. The matrix is coloured from green to red, where red represents the most negative result between technologies, and green is the result with the most positive meaning in the composite resilience index.

In the technical dimension, the highest score in the DH resilience composite index was for DH1 and DH2, which are large-size DH energy

systems in Latvia. DH1 (Renewables - biomass and solar collectors) 90 % have the highest result for having a heat accumulation tank and excess heat production capacity among systems considered. Heat storage provides more predictable system reactions in case of unforeseen disruptions and a more successful ability to return to the system's initial state. Also, the DH1 system has a lower value for heat losses.

In the technical dimension, the lowest score in the DH resilience composite index was for DH6, which is dependent on a single energy source. Heat loss in the piping had a negative impact on resilience; the largest heat loss was for DH 3 (gas 99 %) (see Fig. 10).

In the economic dimension, the highest score in the resilience index was for DH 1 and DH 2, which are large-size DH energy systems in Latvia. The rate of company profit and loss has a great impact on the resilience index in the economic dimension. DH 2 has the largest profits from all analysed DH systems. The lowest score in the resilience index was for DH 9, which is a biomass-based system with a lack of historical large-size subsidised investment projects for the improvement of DH infrastructure (see Fig. 11.).

Results show that the overall DH resilience composite index for different DH energy systems varies from 0.72 for DH6, which is a fully biomass-based DH system, to DH 3: GAS 99 %, biomass 1 % with an overall score of 0.33 in the DH resilience composite index.

Results show that the highest DH resilience composite index was for energy systems that are based on biomass and a mix of biomass and gas. The highest score in the DH resilience composite index was for full biomass-based DH system DH6, with the highest score in the environmental dimension among the systems considered with also the highest score in the social dimension based on criteria *s1* and *s2*. The second highest score is for the system that is based on fuel mix, solar collectors, biomass and 10 % gas in total share.

The lowest result was for DH 3, which has the greatest negative impact on CO_2 emissions and a low proportion of renewable resources used for heat production and also the lowest among systems in the
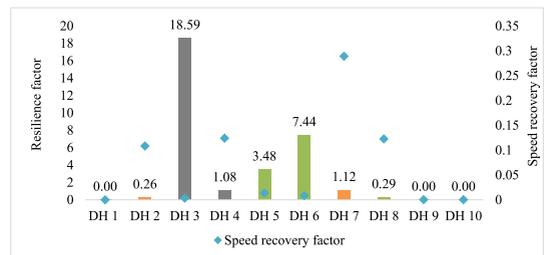

Fig. 9. Heat price resilience factor.

Table 7
The ratio of the amount of energy produced by renewable energy to the total heat produced.

Energy system	DH1	DH 2	DH 3	DH 4	DH 5	DH 6	DH 7	DH 8	DH 9	DH 10
The ratio of the amount of energy produced by renewable energy to the total heat produced, %	90	58	1	33	93	100	81.7	93	99.8	100 %

Table 8
Calculated data for the Heat tariff Resilience Index.

	DH 1	DH 2	DH 3	DH 4	DH 5	DH 6	DH 7	DH 8	DH 9	DH 10
T_0	55.24	92.76	39.64	42.8	54.9	55.71	56.86	71.66	46.06	55.05
T_d	89.59	225.62	279.51	216.69	89	109.39	143.39	135.55	85.73	105.45
T_r	65.39	92.36	94.06	73.69	78.6	76	87.05	88.06	69.45	71.5
t_r	14	7	9	14	8	9	15	16	10	11
t_δ	5	4	2	11	3	5	11	5	1	1
t^*_r	3	5	4	12	4	4	14	15	3	4

Table 9
Calculated data for the construction of the DH resilience composite index.

Type	DH 1	DH 2	DH 3	DH 4	DH 5	DH 6	DH 7	DH 8	DH 9	DH 10
t1	0.91	0.23	0.11	0.47	0.51	0.52	0.27	0.86	0.90	0.51
t2	0.59	0.50	0.97	0.58	0.87	1.00	0.47	0.87	0.84	0.85
t3	322.77	340.40	964.14	554.04	411.81	570.55	447.98	324.63	353.80	365.44
t4	283.19	0.00	28.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
env1	90%	58%	1%	33%	93%	100%	82%	93%	100%	100%
env2	0.034	0.071	0.142	0.157	0.016	0.000	0.037	0.010	0.000	0.000
env3	0.000028	0.000023	0.00001	0.000011	0.00405	0.000054	0.000038	0.000031	0.000044	0.000037
eco1	0.00	13.72	0.00	1.90	1.96	6.40	0.00	0.00	0.00	1.68
eco2	24258	7253	143	8094	646	3897	2213	21689	5685	0
eco3	0.05	0.08	0.11	0.10	0.05	0.08	0.09	0.07	0.06	0.07
eco4	59.80	72.44	180.58	82.72	56.53	39.33	57.18	47.53	59.54	55.58
eco5	0.0003	0.0004	0.0037	0.0004	0.0005	0.0006	0.0006	0.0004	0.0060	0.0006
s1	0.47	0.74	2.52	11.49	0.11	0.02	0.95	0.12	0.02	0.12
s2	1.22	1.28	0.82	1.34	1.16	2.13	1.35	1.01	0.87	1.00

Fig. 10. Technical dimension sub-index.

Fig. 11. Economic dimension sub-index values.

Fig. 12. Comparison of DH resilience index among different DH energy systems.

Fig. 13. Sensitivity analysis with higher weights for Economic dimension.
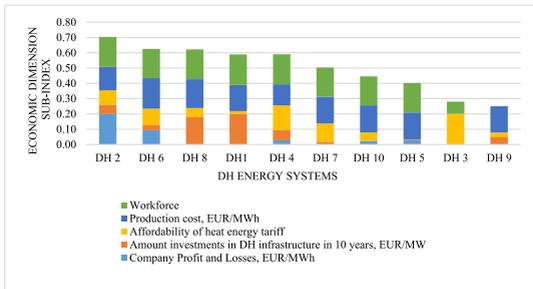
economic dimension. These results disprove the idea that a system based on renewable resources is more expensive and less economically viable compared to systems using fossil fuels (see Fig. 12).

4.3. Sensitivity analysis with different weights for dimensions

To assess how the results would be affected by changing weights for economic and technical dimensions, a sensitivity analysis was performed. In sensitivity analysis, the weights for these dimensions were adjusted to 0.40, while a weight of 0.20 was assigned to the other dimensions. The first sensitivity analysis focuses on the impact of changing the weight of the economic dimension, while the second sensitivity analysis investigates the changes in the technical dimension.
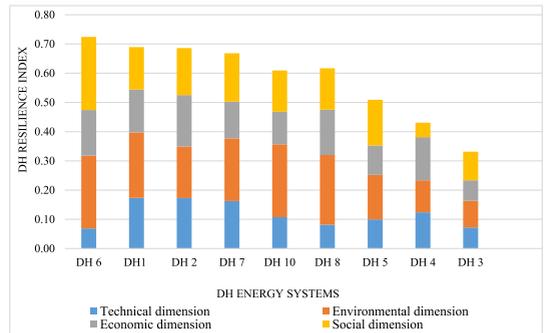
In the case of raising weights for the economic dimension, the highest score was given for DH 6, a fully biomass-based DH energy system. This system features an effective workforce ratio, affordable production costs, and a reasonable heat tariff. In contrast, the lowest scores were given to gas-based systems DH3 and DH4 (see Fig. 13).

By prioritising the technical dimension, the result remains similar to the initial DH resilience composite index, with the greatest score for the largest DH systems, DH1 and DH2, and the lowest score for mostly gas-based DH systems. This coincides with the original DH resilience composite index, which has equal weights for each dimension (see Fig. 14).
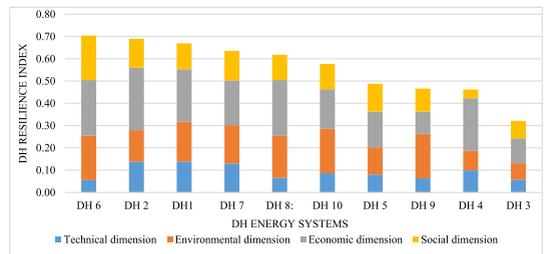
4.4. Relation between DH resilience index and heat price resilience factor

To investigate the relation between calculated adaptive and inherent resilience metrics, a linear regression analysis was performed using a constructed DH resilience composite index (on the x-axis) and heat tariff resilience factor (on the y-axis) (see Fig. 15).

The coefficient of determination suggests that the DH resilience index can explain 40.74 % of the heat price resilience factor. Although the linear relationship is moderate, the trend suggests that DH systems with higher scores in DH resilience tend to have lower heat price resilience factors, which indicates higher adaptive resilience of the system. These systems demonstrate greater price stability in the event of system disruption and a downward trend in the price resilience factor as the DH resilience index increases.

5. Discussion

When developing DH systems, it is necessary to take into account both economic, environmental, energy-efficient and social aspects [42]. Indicators like fuel consumption and cost, GHG emissions, particulate matter emissions, heat load, price, heat losses, etc., are included when performing an analysis of the DH systems [43].

Results show that the affordability of heat energy tariff is highest for systems based on fossil energy use, such as DH3 and DH4, which can be a significant factor, especially for small municipalities [44]. Although variable heat tariffs promote energy savings, simultaneously, heat tariffs should be affordable in a specific region or municipality [45]. A carbon tax increase that could force DH companies to choose biomass or other renewable sources-based solutions also in low fossil fuel price periods might be of great importance to DH system sustainability [45].

Some of the technical barriers to a wider share of RES in DH are related to the lack of suitable infrastructure and skills for implementing these technologies [46]. Previous research shows that one of the challenges in increasing the resilience of the DH system is related to ageing infrastructure and a lack of investment in improving its performance. The results of the study show that some municipalities are not investing enough in DH infrastructure, and that negatively impacts the DH resilience index [47,48]. The resilience index's lowest score was for DH 9, a biomass-based system with no historical large-scale subsidised investment. According to [63], investments in DH infrastructure projects can improve the resilience of the DH networks [49].

The highest DH resilience composite index was for energy systems that are based on biomass and a mix of biomass and gas. One of the most important solutions for the improvement of energy security is increasing the share of RES in DH systems [5]. Using a mix of energy sources can have a positive impact on system resilience, including the use of solar collectors or heat pumps as a heating source [1,50]. The use of multiple energy sources can improve the diversity of heat supply, improving the overall resilience and flexibility of the system, which is also shown by the results of the study. In case of disturbances, these systems will be more resilient and the return to the initial state will be faster in comparison to those that are dependent on one source of energy. Previous
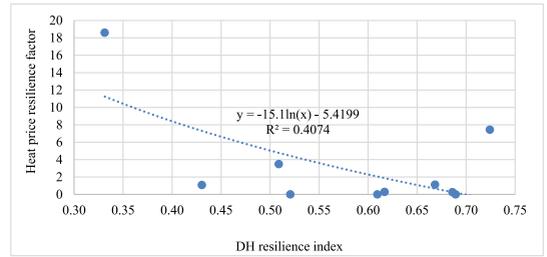

Fig. 15. Relation between DH resilience index and heat price resilience factor.

studies show that dependence on fossil energy sources increases the insecurity of overall energy supply disruptions [5]. A study [19] shows that resilient DH systems can be characterised as systems that use multiple heat sources, including renewable heat sources, to improve heat supply security and several fuel heat plants [51]. Using multiple fuel sources with RES integration can decrease dependence on fossil energy sources and improve the overall resilience of the DH system [52]. Spare boilers can serve as a vital addition to improve the security of the heat supply network [22,28,30].

The results of this study confirm that systems using renewable energy resources are more resilient to extreme events and energy crises, as also confirmed by previous literature, compared to fossil energy resources. Such systems are also more resistant to price shocks proving was also one of the goals of the study [20]. DH systems use a share of RES as a metric for the overall sustainability assessment of the DH network, and such systems are seen as energy efficient with the potential to save energy and reduce GHG emissions [48,19]. Such heat supply companies are expected to make a positive contribution, both by reducing emissions and by improving social aspects, such as creating new workplaces, which is also confirmed by the results of the study because such systems require a larger number of employees [53].

Results of the study show that thermal storage of heat is not provided in a large part of the municipalities considered. Still, those who have the DH resilience index is higher in comparison to other municipalities. One of the solutions for improving the resilience of the heat supply is the installation of thermal storage, which increases the reliability of the DH system overall and in case of unforeseen disturbances, natural or human-caused. Heat storage provides more predictable system reactions in case of unforeseen disruptions and a more successful ability to return to the system's initial state. Previous studies show that heat storage of renewable energy is mostly integrated with smart grid control and serves as an effective solution for the improvement of environmental and economic sustainability [5,50]. Seasonal storage in the network could help to increase the total savings for large-size DH systems, storing surplus heat as a backup solution [14].

Various aspects and solutions should be considered to ensure an affordable and uninterrupted heat supply. Previous studies confirm that DH systems can be mutually evaluated using the composite index method, but this concept has not been previously used to measure resilience. Evaluation based on quantitative indicators can be a tool for successful decision-making when choosing the most sustainable and resilient solution for future development [12].

5.1. Limitations of the study

The varying resilience index among DH systems with similar energy mixes suggests that additional factors significantly influence their resilience, including additional indicators in the social dimension. Also, there are still no DH systems that use novel heat production solutions in Latvia, e.g., heat pumps, or electric boilers. Therefore, additional criteria could be added to the technical dimension for electrified DH system
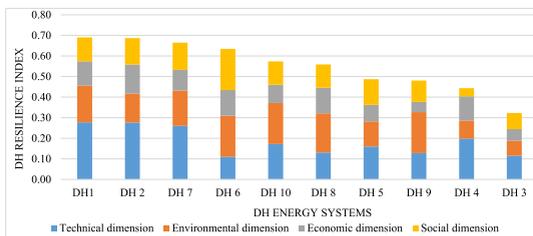

Fig. 14. Sensitivity analysis with higher weights for the Technical dimension.

resilience assessment.

For the best outcome of DH resilience composite index analysis, it is advisable to test the proposed methodology on more DH systems with various heat production technologies. However, data is not always possible to obtain from companies as they may not be counted and reported financially in the same way in each company.

The study does not include in-depth analyses of the ownership structure of DH systems and their impact on stable heat costs. Municipality-owned DH utilities should not be highly profitable, as their main purpose is to supply affordable heat to their consumers. A high heat tariff do not make DH companies attractive to heat suppliers and new consumers.

6. Conclusions

Research conducted an adaptive DH resilience assessment through tariff analysis and evaluation of inherent resilience using a composite index for ten different municipalities in Latvia. This study analyses inherent resilience from four dimensions: economic, technical, environmental, and social. In total, fourteen indicators were quantified for analysis. The economic and technical dimensions have the most indicators included. The significance of sub-dimensions in the DH resilience index was evaluated using both equal and different weights.

Results show that gas-dependent systems have higher heat prices after recovery (Tr) and significantly higher after an initial post-disruption (Td) in comparison to energy systems based on biomass or other renewables. Analysis reveals that renewables-based DH systems effectively mitigated extreme heat price increases. Heat prices for biomass energy systems did not experience such a large increase as those for gas-based systems. Biomass-based DH energy systems are more price-resilient during disruption. Fossil fuel-based systems are more vulnerable to heat price fluctuations in case of unforeseen events.

The highest DH resilience composite index was for energy systems based on biomass or a mix of biomass and gas. The lowest result was attributed to DH 3, which has the most significant negative impact on CO_2 emissions and a low proportion of renewable resources used for heat production and ranks the lowest in the economic dimension among systems evaluated. These findings disprove the idea that a system based on renewables is more expensive and less economically viable than those relying on fossil energy.

The trend suggests that DH systems with higher scores in DH resilience tend to have lower heat price resilience factors, which indicates higher adaptive resilience of the system. These systems demonstrate greater price stability in the event of system disruption and a downward trend in the price resilience factor as the DH resilience index increases.

The proposed methodology for adaptive resilience quantification allows us to compare which DH systems can adapt to external changes faster and more efficiently.This research uncovers the key factors that should be considered when designing and constructing resilient DH systems, highlighting the need for further investigation. Assessment of adaptive and inherent resilience could serve as a metric to evaluate the DH system's resilience to external changes. Evaluation of DH system vulnerability can identify blind spots and weaknesses in the system promptly before unforeseen disruptions occur.

DH companies should look for solutions to increase the profitability and efficiency of heat supply through cost reduction and flexible heat production solutions. DH companies with economic losses should improve profitability and maintain financial stability in the economic dimension of DH resilience.

The future outlook for DH networks is lower supply temperatures and more renewable resources. In Latvia, DH companies still use a high proportion of fossil fuels, and governmental support is available for investments in changing energy source technology.

CRediT authorship contribution statement

Ieva Pakere: Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Lauma Balode:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Guntars Krīgers:** Visualization, Data curation. **Dagnija Blumberga:** Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ieva Pakere reports financial support was provided by Latvian Council of Science. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Article

Carbon Neutrality in Municipalities: Balancing Individual and District Heating Renewable Energy Solutions

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Abstract: Carbon neutrality in municipalities can be achieved by combining individual heating and district heating solutions involving the use of renewable energy sources. Each approach has advantages and disadvantages, but the best solution depends on the specific circumstances of each municipality. As an environmentally friendly and efficient energy use, a decentralised heat supply contributes to achieving energy conservation and emissions reduction goals. Decentralised energy use, such as solar collectors with thermal energy storage or biomass as a resource, reduces dependence on centralised heat generation and transmission. The appropriate infrastructure for connection to district heating networks has not yet been built. On the other hand, it is easier to make investments to construct proper infrastructure in the case of large-scale centralised heat supplies. Moreover, a centralised heat supply with renewable energy sources can provide more inhabitants with renewable heat energy. Within the framework of the study, the possibilities of using renewable energy sources in one of the municipalities of Latvia—the Carnikava parish of Ādaži Municipality—are analysed. The study examines two scenario complexes including individual heating solutions in buildings or district heating solutions with a centralised approach. The study evaluates several alternatives to increase the share of RES (solar collectors, biomass, heat pumps, etc.) in the centralised heat supply. To evaluate individual RES solutions in various municipal buildings, this study evaluates alternatives with different technical solutions that increase the use of RES in heat supply.

Keywords: carbon neutrality; municipalities; individual heating; district heating; renewable energy

1. Introduction

1.1. Nature of the Study

The progress of the European Union (EU) towards increasing the share of renewable energy sources (RES) in the energy sector is dynamic. From 2014 until May 2022, four regulatory legislative measures were announced, setting out the target for the share of RES in the energy sector to be achieved by 2030. Initially, the target was only 27%, but given the recent developments in the world and the Russian Federation's aggression against Ukraine, it soared to 45% [1]. Given that the Republic of Latvia (RoL) is an EU Member State, participation in the achievement of this target is its responsibility. According to Latvia's National Energy and Climate Plan 2021–2030 [2,3], it plans to increase the share of RES to be used in energy production by 2030 from 40% to 50%. One way of achieving this objective is to modernise different municipalities' district heating (DH) systems.

Before modernisation, an in-depth study is carried out with a structured analysis of each case and a description of the existing situation. It is standard practice worldwide to develop a Sustainable Energy Action and Climate Plan (SECAP) in a city/municipality context [4]. Municipalities have competence in achieving the energy transition objectives locally, including

increasing the RES share in the energy mix [5,6]. Various aspects must be considered, which can accelerate and ease the energy transition process or make it more difficult.

The main strength of the local government in such matters is its influence [7]. Influence can be seen through local regulatory legislative measures, investments, taxes, and fees [8]. The main area for improvement is related to the search for attracting, splitting, and relating the bureaucracy of funding sources. There are examples where the rational use of local government influence resulted in high-value results for achieving the energy transition objectives. Municipal green energy initiatives have contributed significantly to energy diversification and have influenced energy policy in countries such as Denmark (Denmark has consistently reduced both primary and final energy consumption since 2010, and Denmark [9] installed significant amount of large-scale solar heating plants [10] and set the national target for a building sector solely supplied by RES in 2035 [11]), Germany (Germany has a long history of seasonal thermal energy storage development [10] and a number of policies to reduce greenhouse gas (GHG) emissions [12]), and Britain, United Kingdom (UK) (the UK has set itself on a transition to carbon neutrality in both its economy and society, through the imposition of a goal, under the 2008 Climate Change Act, of reducing GHG emissions by 80% by 2050 [9]). In the meantime, such examples apply to DH and do not relate to initiatives and actions in local or individual heating (IH) [10]. In some municipalities, the share of IH may be higher than DH, which means that the influence should be directed to supporting IH in the transition to RES. It is necessary to balance DH and IH support to move optimally towards carbon neutrality [11–13]; however, most studies are based on a theoretical approach while manuscripts with case studies rarely occur.

Despite a narrow range of similar analyses, the study described in this article brings new scientific contributions. First, a developed methodology offers access to the analysis of the various DH and IH alternatives using three different parameter categories: technical, economic, and environmental. This approach makes it possible to identify an economically viable alternative and a more sustainable and environmentally friendly one. The methodology's structure can be reproduced in other similar studies and adapted for specific purposes. Secondly, the methodology developed was examined in a case study (see Section 2.1). The study's calculations are based on the real system, not on the model. Thirdly, alternative variations consist of a variety of RES technology combinations. Each alternative is scientifically justified.

1.2. Comparison of DH and IH

Various factors determine the difference between DH and IH [12–14]. By nature, DH and the IH differ in the level of centralisation. For example, local boilers may be installed in each private property or apartment, which in some ways ensures tariff independence and allows for a more intensive change in their consumption [15–18]. DH provides continuous heating through heating networks from heat generators (e.g., boilers, cogeneration plants, etc.) which are located away from the consumer [19–21]. Two further factors are related to infrastructure nuances—distribution costs (including building/renewal and periodical management of the heating networks) and heat losses in heating networks [11,16]. The distribution costs are closely linked to the shares of DH and IH in each municipality. This share can be characterised by linear heat density [16]. A higher share of DH means a higher linear heat density value. Accordingly, the higher linear heat density value means heating distribution costs for consumers [11]. Heat losses in heating networks only exist in the case of DH and affect the need for a higher-power boiler. This is certainly reflected in costs [17]. The reduction in heat loss in networks can be achieved by transitioning to a fourth-generation DH [18,19]. In this respect, the fourth generation means reducing the temperature regime in the heating networks (low-temperature network) by considering the specific thermal energy consumption of each connected building, which impacts the heat loss and fuel consumption reduction [6,18]. There are examples of good practices where the transition to the fourth-generation DH positively impacted the development of municipal infrastructure [6]. Since 2013, the German company BTB GmbH Berlin has

implemented a project aimed at a low-temperature network with two-way connections and network substations. A new residential area called "Life in Camp" was created, including 1200 apartments in single-family homes, row houses, and multi-apartment houses—sixty-two buildings with low heat demand, five buildings with low energy consumption, and three buildings with additional energy. The main characteristic is developing a low-temperature district heating network (60/40 °C) using a return stream from a conventional heat grid (110/55 °C). This is probably due to a low thermal energy consumption of less than 15 W/m² [20].

Under Project LowTEMP: Low-Temperature District Heating for the Baltic Sea Region, fourth-generation DH was tested and implemented from 2017 to 2020 in the village of Gulbene municipality, Latvia. The project renovated a boiler house (replacing a 1 MW wood boiler with a modern high-efficiency container-type 200 kW pellet boiler) and heating networks. The heating system was rescheduled to minimise the length of the heating networks and thus reduce heat losses. The renovated buildings were switched to low-temperature DH, reducing heat supply temperature and reducing total heat losses. Heat transmission losses decreased from 40% to 5% due to heat reconstruction and reduced heat carrier temperature [21].

Within the framework of the study, the possibilities of using renewable energy sources in one of the municipalities of Latvia—the Carnikava parish of Ādaži Municipality—are analysed.

The objective of the research is to understand exactly how, in certain municipal buildings of residents (residential buildings with multiple apartments) that have a centralized heat supply using fossil fuels (natural gas) and in municipal buildings using individual natural gas boilers, a partial or complete conversion to RES heat supply solutions is possible. In the concrete municipality, the issue of how to transfer the residential and municipal buildings sector from natural gas to RES is important for the municipality's progress in meeting the goals of the Latvian National Energy and Climate Plan and the European Green Deal in the buildings sector.

This study examines two scenario complexes including IH individual heating solutions in buildings or DH solutions with a centralised approach. The study evaluates several alternatives to increase the share of RES (e.g., solar collectors, biomass, heat pumps, etc.) in the centralised heat supply. The study was carried out based on real data on the thermal energy consumption of Carnikava's buildings and scientific data sources in order to make assumptions.

In order to evaluate the most sustainable RES heat supply solutions (technology combinations) that could replace the natural gas solutions used in DH and IH in Carnikava village, the CSI was created.

2. Methodology

2.1. Case Study

Carnikava is a village and the centre of the Carnikava parish of Ādaži Municipality in Latvia. The geographical limits of the study were defined (see Appendix B). The area includes twenty-eight residential buildings, six municipal buildings, and five commercial buildings.

2.1.1. DH System

The Carnikava DH system consists of six interconnected boiler houses and heating networks. The total length of the heating networks is 2837 m, of which 1156 m is industrially insulated. All boiler houses have Viessmann natural gas boilers with different capacities, from 520 kW to 1500 kW (as shown in Appendix B). The main data on DH in Carnikava are shown in Table 1. Losses in heating networks range from 15% to 17%. The loss value indicates that the heat transmission infrastructure is inferior. The main reason is the preparation of hot water outside the heating season. As summer consumption is meagre, the percentage of heat losses is very high in the summer months.

Table 1. Major Data on DH in Carnikava Village.

Parameter	Unit	2019	2020	2021
Natural gas consumption	1000 m^3	1076.01	1024.16	1185.29
Share of RES	%	0%	0%	0%
Fuel input energy	MWh per year	10,274.8	9756.4	11,247.9
Thermal energy produced	MWh per year	9308.8	8764.0	10,085.4
Electricity produced	MWh per year	0	0	0
Production losses	MWh per year	965.9	992.4	1162.5
Efficiency of production	%	90.6%	89.8%	89.7%
Thermal energy transferred to users	MWh per year	7792.0	7263.4	8617.9
Losses in heating networks	MWh per year	1516.9	1500.6	1467.6
Losses in heating networks	%	16.3%	17.1%	14.6%

2.1.2. Municipality Buildings

According to 2019 data, the municipality has more than 9500 inhabitants and in the case of this study 6 municipal buildings were analysed. Therefore, municipal buildings are very diverse in terms of their functionality and building characteristics, and they are not connected to the DH system. Table 2 contains a summary of the technical parameters of municipal buildings. Each parameter is obtained using the information provided by the municipality, data on electricity, heat energy, as well as calculations based on real and scientific assumptions. Scientific assumptions for making calculations are summarized in Appendix A.

Table 2. Technical Parameters of Municipal Buildings in Carnikava Village.

Parameter	Unit	Elementary School	Preschool	Cultural Centre	Music and Art School	Leisure Centre	Office Building
Technical condition	-	Renovated	-	-	-	-	Built-in 2020
Heating area	m^2	7398	2643	769	258	150	2343
Roof area	m^2	2301	2622	460	212	192	2970
Heat consumption	MWh per year	318	486	97	36	16	215
Electricity consumption	MWh per year	237	124	21	5	4	60
Max heat load	kW	110	130	35	12	10	57
Fuel type	-	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas

Figure 1 shows the average monthly heat and electricity consumption from 2019 to 2021. The largest energy consumers are the elementary school, preschool, and office building. The largest heat energy consumption is in the heating season, especially in winter. During the summer, the heat energy consumption is for preparing hot water. From September to April, electricity consumption is higher in the preschool and elementary school, but in other buildings the difference in electricity consumption between winter and summer is up to 1 MWh per month.

Analysing the specific energy consumption of municipal buildings, the buildings with the highest specific energy consumption are preschool, music and art school, and culture centre buildings (see Figure 2). The preschool and music and art school have the highest specific heat energy consumption, but the elementary school has the lowest. The preschool and primary school have the highest specific electricity consumption, while the music and art school has the lowest specific electricity consumption. On average, the specific electricity consumption is four times lower than the specific heat energy consumption. However, the most similar specific electricity and heat energy consumption is for the elementary school, but the biggest difference in the specific electricity and heat energy consumption is for the music and art school.
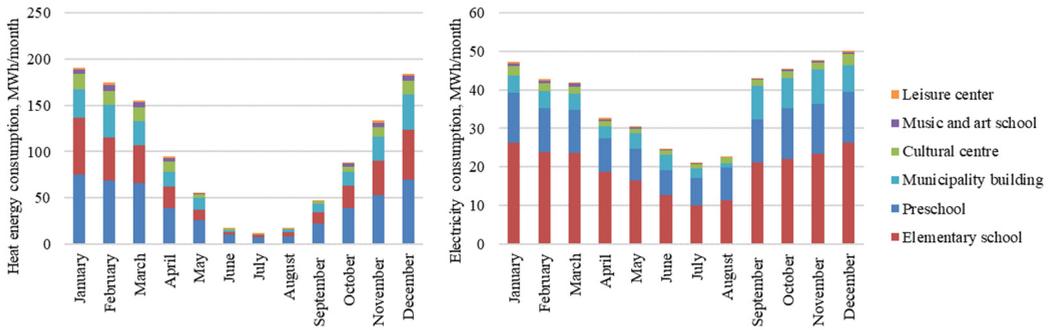
Figure 1. Average heat and electricity consumption (2019–2021), MWh/month (2019–2021) in Carnikava Village.
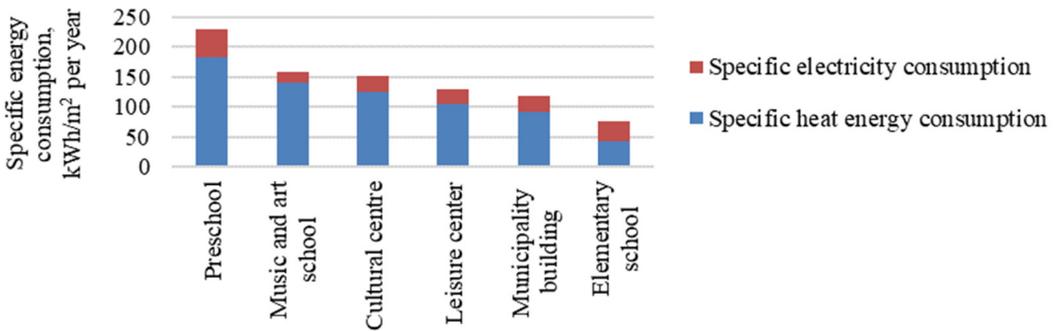

Figure 2. Specific energy (electricity and heat) consumption in municipal buildings in Carnikava village.

2.2. Development Scenarios

The existing solutions in Carnikava's district heating are natural gas—six local boiler houses and natural gas boiler houses in municipal buildings. To compare the sustainability of DH solutions and individual IH solutions, by comparing the values of different factors, the case of Carnikava is used and six DH alternatives are compared with -four IH scenarios for municipality buildings. In the case of district heating, different scenarios are evaluated by combining existing and connecting new consumers. Based on research in the scientific literature, alternative RES solutions have been selected and identified, which can be used in DH residential buildings and IH municipal buildings. The selection of technology combinations was carried out in such a way that solutions with biomass, e.g., wood chips and pellets; air heat pump solutions, which are considered economically easier to implement; as well as additional sources for covering the summer load, including solar energy solutions, i.e., solar collectors for heat supply and electricity supply/for operating the heat pump and solar panels, were included (Table 3).

Scenarios		District Heating	Municipal Buildings
		With New Consumers	
1.	Wood chip boiler with flue gas condenser	1 boiler house with flue gas condenser	-
2.	Wood chip boiler and PV panels + heat pump solution	+	-
3.	Wood chip boiler and solar collectors with storage	+	-
4.	Natural gas boiler and solar collectors with storage		+
5.	Pellet boiler	2 boilers	+
6.	Pellet boiler and PV panels + heat pump solution	+	-
7.	Pellet boiler and solar collectors with storage	-	+
8.	Heat pump solution + PV panels		+

2.2.1. District Heating System

Six possible alternatives were defined for increasing the share of RES in DH. Alternatives can be introduced at the same time as the implementation of IH development scenarios. They mainly involve the combination of separate systems and heat networks.

Different RES alternatives for consumer scenarios were evaluated for the scenario of existing consumers and the scenario of connecting new consumers. Two cases of DH development were evaluated—the five boiler houses on the left side of the railroad and the DH system contained in them were combined into a whole, and two DH were combined according to their distance from each other. Since the DH in Carnikava is also used for hot water production, which means that there is also a summer load, the scenarios of installing heat pumps and solar collectors were also evaluated when comparing the alternatives. For the created large gas boiler plant, the scenario of installing a wood chip boiler was evaluated, while in the case of the two smaller created plants, the installation of pellet boilers was evaluated as a basic alternative. The heat pump and solar collector scenarios are each supplemented by the fuel boiler used for each system—wood chips for the large system and pellets for the two smaller systems. The six alternatives for DH are listed in Table 4.

Woodchip boiler. In the scenario that envisages combining the five existing DH plants of Carnikava into one and connecting the municipal buildings, the construction of a woodchip boiler house was evaluated.

Pellet boiler. The construction of pellet boiler houses was evaluated in the scenario that proposes to combine Carnikava's five existing DH systems into two separate systems and connect municipal buildings to them. By creating two separate systems, the consumer load is slightly too low for using a wood chip boiler.

Woodchip boiler + solar collectors with storage. Considering that the number of consumers in Carnikava is small and distributed over a large area, the scenario where solar collectors with storage are installed to cover the summer load will be studied. They should be placed closer to the consumers. A woodchip boiler will be used to cover the heating load in the case of a combined CSA system.

Pellet boiler + solar collectors with storage. Considering that the number of consumers in Carnikava is small and spread over a large area, it is planned to study the scenario where PV panels are installed in combination with an air source heat pump to cover the summer load. They will be placed closer to the consumers. In the case of two separate CSA systems, pellet boilers will be used to cover the heating load.

Table 4. Alternative DH in multi-apartment buildings—the current situation with new consumers.

1.	Wood chip boiler with flue gas condenser
2.	Wood chip boiler and PV panels + heat pump solution
3.	Wood chip boiler and solar collectors with storage
4.	Pellet boiler
5.	Pellet boiler and PV panels + heat pump solution
6.	Pellet boiler and solar collectors with storage

2.2.2. Individual Heating Solutions

Four possible alternatives were defined for increasing the share of RES in IH in municipality buildings, replacing natural gas boilers Alternatives can be introduced at the same time as the implementation of DH development scenarios. The alternatives for IH solutions are as follows in Table 5.

Table 5. Alternatives for individual heating solutions in municipality buildings.

1.	Pellet boiler
2.	Heat pump solution + PV panels
3.	Solar collectors with thermal energy storage and natural gas boiler
4.	Solar collectors with thermal energy storage and pellet boiler

Pellet boilers. One of the alternatives is to replace natural gas boilers with a pellet boiler that provides heating and hot water: solar panels and a heat pump. The building has a summer heat load, so one alternative is *solar panels*, which would generate electricity for the *heat pump* during the summer months. *Solar collectors*. Assuming the roof of the building is suitable for installing solar panels, solar panels can be considered another heat energy alternative. Thus, the necessary summer heat load can be met with solar collectors.

One of the alternatives is to replace the natural gas boilers with a pellet boiler that provides heating and hot water. The provision of thermal energy with solar panels and a heat pump was analyzed as another technological solution since the heat pump does not require a large area, and the building has a large roof area that can be effectively used for solar panels. The electricity consumption of the heat pump can be covered in the summer months by using electricity from solar collectors. Therefore, this alternative evaluates the installation of both an air source heat pump and a solar power plant. In these scenarios, solar panels are considered to meet the summer load and the existing natural gas system or its replacement with a pellet boiler to meet the remaining heat load. Solar collectors could meet the summer load of the building's hot water consumption, provided the building's roof is suitable for solar collector installation. The installation of solar collectors is not considered for buildings that have low summer hot water consumption or are heavily shaded. In addition to the solar collectors, a suitable buffer tank should be integrated to cover 2–3 days of consumption.

2.3. Decision-Making Analyses

Sustainability assessment requires an integrated approach and a structure with several interconnected steps. The methodology of this study is based on three main pillars:

- The identification of the internal and external context that influences the sustainability of the heat supply system

- The calculation of the composite sustainability index
- The analysis of the results and the decision-making process.

Identifying the internal and external context includes a literature review of current practises in the sustainability assessment of energy supply technologies to identify key sustainability issues and develop a research methodology. The core element of the sustainability assessment is the construction of the composite sustainability index.

Composite indices are commonly used amongst scientists when choosing the most appropriate methodology to evaluate sustainable development. The method combines various aggregate values that are used to determine indicators of the topic being studied. Composite index is commonly used in research projects for policymakers to simplify the problem and highlight significant findings. A composite index allows for easy comparisons to assess the sustainability performance of regions, sectors, and other factors.

The main chronological steps that are applied when developing a composite sustainability index are illustrated in Figure 3 below.
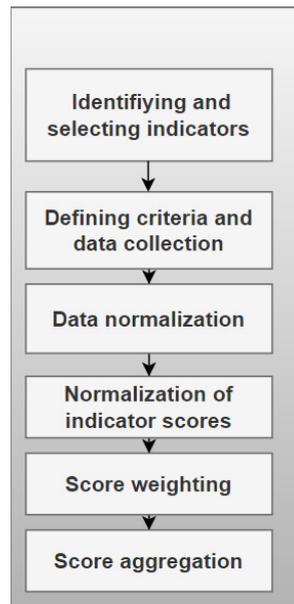
Figure 3. Construction of CSI [16,22].

In this study, the composite sustainability index is calculated for six district heating scenarios and four different technical solutions for decentralised (individual) heat supply. The indicator considers only the consumption of primary resources, shown as fuel consumption/total energy production in MWh in each of the scenarios. The share of solar collectors and PV panels are not considered in the calculation of efficiency; however, solar collectors and PV panels are included in the investment calculations.

The methodology of composite sustainability and the selected indicators were chosen following the study in [15].

2.3.1. Identification of Criteria

The second step is to identify and select appropriate criteria that are significant determiners of the study's dependent variable. When identifying key indicators, it is crucial to consider data availability for the indicators (see Table 6).

Table 6. Indicators for the construction of CSI for DH and IH technologies.

No	Indicator	Units	Indicator Description	Impact
I1	Consumption of fuel energy	MWh/MWh	The indicator considers only the consumption of used fuel energy and electricity from grid. Fuel consumption/total energy production in MWh in each of the scenarios. The share of solar collectors and PV panels are not included in the efficiency calculation. Electricity consumption from grid at scenarios with heat pumps also taken into account.	-
I2	Specific NOx emissions	g/MWh	Gram per amount of energy produced in each of the scenarios.	-
I3	Specific PM emissions	g/MWh	Indicates how much PM is produced from each MWh.	-
I4	Costs of CO_2 reduction	EUR/t	Depending on the type of energy resource, the amount of CO_2 emissions produced varies. Emission factor of 0.202 (CO_2), tCO_2/MWh. The total investment is divided per ton of CO_2. Describes how much to invest in each system.	-
I5	Investments	EUR/MWh	The investment required for the amount of energy produced	-
I6	Internal rate of return	%	Internal rate of return (IRR) or economic rate of return (ERR) characterizes the interest rate at which investments in a given project are effective. If the IRR is greater than the discount rate, then the project is economically beneficial to society. The higher the value, the more efficient the project.	+
I7	Production costs	EUR MWh	Production costs include alternative fuel, electricity, service, and administrative costs.	-
I8	Opportunities for diversification of utilised energy resources (technology is not limited only to one type of energy resource supply	count	The energy resources are numerically evaluated as to how much it is possible to use the energy resource in each of the scenarios, taking into account the production of electricity and thermal energy. Electricity and solar PV. How many energy sources are included in the solution. The number of energy resources in each of the scenarios describes the diversification of utilised resources.	+

Indicators such as fuel enerrgy consumption (i1), specific NOx emissions (i2), specific PM emissions (i3), CO_2 reduction costs (i4), investments (i5), IRR (i6) (example of net cash flow for technologies in Table 7), production costs (i7), and opportunities for diversification of energy resources used (i8) were used to evaluate and compare the district heating and individual heating scenarios.

Table 7. Net cash flow EUR/year (for 15 years) for DH wood chip boiler with flue gas condenser technologies.

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.
EUR/year	−1,022,215	318,937	331,662	344,770	358,270	372,176	386,499	401,251	416,446	432,097	44,828	464,822	48,194	499,539	517,683

All scenarios are calculated based on the same input data (e.g., thermal energy consumption, thermal energy tariff, etc.) and assumptions (technology efficiency, technology investment and operating costs, etc.). The assumptions were made based on the scientific literature, technology catalogue manuals, findings of energy industry representatives, and other sources. At the same time, the selected parameter values reflect the current situation and are partially subject to uncertainties related to the authors' vision and the energy sector's rapidly changing situation (see parameters in Appendix A). The most appropriate solution was selected based on the above indicators, including the internal rate of return (IRR) and CO_2 savings per amount of money invested. As an additional parameter, the amount of investment required is given, which describes the amount of money originally intended for implementing the project.

Calculations for each indicator.

I1 Consumption of fuel energy (Equation (1)):

$$\text{Consumption of fuel energy}\left(\frac{\text{MWh}}{\text{MWh}}\right) =$$
$$\frac{\text{fuel consumption} \times \text{fuel's lowest heat of combustion}, \frac{\text{MWh}}{\text{m}^3}}{\text{total energy production, MWh/year}} \tag{1}$$

Example calculations for DH wood chip boiler with flue gas condenser:

$$\text{Consumption of fuel energy}\left(\frac{\text{MWh}}{\text{MWh}}\right) =$$
$$\frac{\text{wood chip consumption} \times \text{wood chip lowest heat of combustion}, \frac{\text{MWh}}{\text{m}^3}}{\text{annual amount of energy produced, MWh/year}}$$

where
Wood chip consumption—10,876 ber/m.
Wood chip lowest heat of combustion—0.7 MWh.ber/m^3.
Annual amount of energy produced—7689 MWh.

$$\text{Cosumption of DH wood chip boiler}\left(\frac{\text{MWh}}{\text{MWh}}\right) = \frac{10,876 \times 0.7}{7689} = 0.99$$

All greenhouse gas emissions result from the combustion and fugitive release of fuels. The emission factor is a relative measure and can be used to estimate emissions from various sources of air pollution. An emission factor is a representative value that relates the amount of a pollutant released into the atmosphere to an activity associated with the release of that pollutant. It is expressed as the mass of the pollutant divided by the unit mass, volume, distance, or duration of the activity that releases the pollutant (e.g., kilograms of particles emitted per megagram). Residential wood combustion is the primary emission source for some pollutants. PM and NO_x emissions per MWh generated vary depending on whether the boiler is small or large. PM and NO_x emission factors once for different technologies and different resources. All NO_x and PM emission factors for each technology are based on the AARHUS UNIVERSITY department of Environmental Science emission factors (for fuel input) database [23].

I2 Specific NO_x emissions (Equation (2)):

$$\text{Specific NOx emissions} = \text{Consumption of fuel energy}\left(\frac{\text{MWh}}{\text{MWh}}\right) \times \text{NOx emission factor} \tag{2}$$

Example calculations for DH wood chip boiler with flue gas condenser:

$$\text{Specific NOx emissions of DH wood chip boiler} =$$
$$\text{Consumption of DH wood chip boiler}\left(\frac{\text{MWh}}{\text{MWh}}\right) \times \text{NOx emission factor for DH wood chip boiler}$$

where
Consumption of DH wood chip—0.99 MWh/MWh.
NOx emission factor for DH wood chip boiler—324 g/MWh (data based on AARHUS University Department of Environmental Science emission factors [24] (group 010203—district heating plants, wood and similar combustion plants <50 MW (boilers)).

$$\text{Specific NOx emissions of DH wood chip boiler} =$$
$$\text{Consumption of DH wood chip boiler}\left(\frac{\text{MWh}}{\text{MWh}}\right) \times \text{NOx emission factor for DH wood chip boiler}$$
$$\text{Specific NOx emissions of DH wood chip boiler}\left(\frac{\text{g}}{\text{MWh}}\right) = 0.99 \times 324 = 321$$

I3 Specific PM emissions (Equation (3)):

$$\text{Specific PM emissions} \left(\frac{g}{MWh}\right) = \text{Consumption of fuel energy} \left(\frac{MWh}{MWh}\right) \times \text{PM emission factor} \tag{3}$$

Example calculations for DH wood chip boiler with flue gas condenser:

Specific PM emissions of DH wood chip boiler = Consumption of wood chip (MWh/MWh) × PM emission factor for DH wood chip boiler.

$$\text{Specific PM emissions of DH wood chip boiler} \left(\frac{g}{MWh}\right) = 0.99 \times = 35.6$$

where

Consumption of DH wood chip—0.99 MWh/MWh.

PM emission factor for DH wood chip boiler—emission factor for $PM_{2.5}$ is 36/MWh. (Data based on AARHUS UNIVERSITY Department of Environmental Science emission factors [24]. Group 010203—district heating plants, wood, and similar combustion plants <50 MW (boilers)).

I4 Costs of CO_2 reduction

By switching from fossil fuels to RES, a reduction in CO_2 emissions is achieved. Reducing CO_2 emissions is one of the priorities at the national and municipal levels, as the consequences of climate change affect everyone.

(1)　The reduction in CO_2 emissions depends on the amount of fossil energy replaced and the type of fossil energy (see Equation (4)).

$$\Delta_{CO_2} = \frac{Q(\text{annual amount of heat energy produced})}{\text{boiler efficiency}, \%} \times f_{CO_2} \tag{4}$$

where

Δ_{CO_2}—reduction in CO_2 emissions, tons.

Q—the annual amount of heat energy produced, MWh.

f_{CO_2}—CO_2 emission factor, $kgCO_2/kWh$.

(2)　Costs of CO_2 reduction (Equation (5)):

$$\text{Costs of } CO_2 \text{reduction (EUR/tons)} = \frac{\text{Total investments}, \text{EUR/year}}{CO_2 \text{ reduction, tons}} \tag{5}$$

Example calculations:

1.　The reduction in CO_2 emissions for DH wood chip boiler with flue gas condenser:

Δ_{CO_2}—reduction in CO_2 emissions, tons;

Q—7689 MWh;

Boiler efficiency—90%;

f_{CO_2}—CO_2 emission factor, $kgCO_2/kWh$—0.202.

$$\Delta_{CO_2} = \frac{7689}{90\%} \times 0.202 = 1725.8$$

2.　Cost of CO_2 reduction for DH wood chip boiler with flue gas condenser:

$$\text{DH wood chip boiler } Costs \ of \ CO_2 \text{ reduction (EUR/tons)} = \frac{1,022,215}{1726} = 592$$

I5 Investments—investments per unit of energy produced, EUR/MWh (see Equation (6)):

$$\text{Investments per unit of energy produced}, \tfrac{EUR}{MWh} = \frac{\text{Investments per unit of energy produced}, \text{thousand.EUR/MWh}}{1000} \tag{6}$$

$$\text{Investments per unit of energy produced,} \frac{\text{EUR}}{\text{MWh}} = \frac{132.9}{1000} = 0.13$$

I6 Internal rate of return (IRR), % (Equation (7))

$$\text{IRR, \%} = \text{IRR (net cash flow for 15 years)} \tag{7}$$

Internal rate of return, % for DH wood chip boiler:

$$\text{IRR, \% DH wood chip boiler with condesator} = \text{IRR(project net cash flow for 15 years)} = 34.4$$

I7 Production costs

Production costs, EUR/MWh (Equation (8)).

$$\text{Productions costs,} \frac{\text{EUR}}{\text{MWh}} = \frac{\text{production costs, EUR/year}}{Q(\text{annual amount of energy produced,} \frac{\text{MWh}}{\text{year}})} \tag{8}$$

where production costs, EUR—458,312. Q—the annual amount of heat energy produced, MWh/year—7689.

$$\text{Productions costs,} \frac{\text{EUR}}{\text{MWh}} = \frac{458,312}{7689} = 59.6$$

Calculated data for CSI construction

Table 8 shows the calculated data for constructing the composite sustainability index for each alternative. Values equal to 0 are denoted as 0.00001 because setting the input value to 0 in the complex index is not permissible.

Table 8. Calculations for district heating and individual heating comparison (based on scientific assumptions and Appendix A).

	DH Wood Chip Boiler with Flue Gas Condenser	DH Wood Chip Boiler and PV Panels + Heat Pump Solution	DH Wood Chip Boiler Additionally, Solar Collectors with Thermal Energy Storage	DH Pellet Boiler	DH Pellet Boiler and PV Panels + Heat Pump Solution	DH Pellet Boiler and Solar Collectors with Thermal Energy Storage	IH Pellet Boiler	IH Heat Pump Solution + PV Panels	IH Solar Collectors with Thermal Energy Storage Natural Gas Boiler	IH Solar Collectors with Thermal Energy Storage Pellet Boiler
I1 MWh/MWh	0.99	0.82	0.82	1.18	0.95	0.97	1.11	0.36	0.93	1.04
I2 g/MWh	321	228	238	343	242	254	351	0.000001	41	187
I3 g/MWh	36	28	29	42	30	31	206	0.000001	0.00001	110
I4 EUR/t CO$_2$	592	832.8	1385.7	380.8	684.5	1145.8	587.9	19.4	5410.8	957.6
I5 EUR.thousand./MWh	0.13	0.19	0.31	0.09	0.15	0.26	94.62	284.48	126.53	193.43
I6 %	34.45	25.74	9.40	7.75	7.29	−11.57	0.01	0.4	−0.1	0.03
I7 EUR/MWh	59.6	52.7	54.2	106.5	94.5	97.9	86.9	291.1	110.6	95.2
I8 Count of resources	2	3	3	2	3	3	2	3	3	3

2.3.2. Data Normalization

When creating a complex composite sustainability index, the data must first be normalized for mutual comparison of measures and indicators. To compare and compile indicators, the data must first be normalized. To standardise the indicators, the min–max method was used in sustainability studies for normalization. The min–max normalization method was used for normalisation, which is also used in environmental decision making and policy analysis. This method presents the results on a scale of [0;1]. The indicators selected for the study were normalized using Equation (9).

$$I_{N,ij}^{+} = \frac{I_{act,ji}^{+} - I_{min,ji}^{+}}{I_{max,ji}^{+} - I_{min,ji}^{+}} \tag{9}$$

where

$I^+_{N,ij}$ Normalized indicator;
$I^+_{act,i}$ The actual value of indicator;
$I^-_{min,i}$ Minimum value of an indicator;
$I^+_{max,i}$ Maximum value of an indicator;
i Specific indicator [16,24,25].

2.3.3. Weighting of Indicators

To determine the weight of each indicator, it is possible to use expert interviews to determine the importance of the indicators or assign the same weight to each indicator so that the total weight of the indicators is one. An equal weighting technique was used in this study. Since eight indicators have been chosen, which describe the economic profitability and environmental dimension of RES technologies, the weight of each indicator is 0.13.

The composite sustainability index is calculated as the total sum of all indicators, according to Equation (10).

2.3.4. Aggregation of Indicators into CSI

The sum of all indicators results in the final CSI, which can be used for further comparisons.

$$I_{CSI} = \Sigma_j^n W_j \times I_i \tag{10}$$

where

I_{CSI} is a composite sustainability index;
W_j the impact weight of indicators of equal importance (calculated in %) [23,25]
I_i the normalized value of an indicator.

3. Results and Discussion

The selected indicators make it possible to assess the economic potential of the selected DH and IH alternatives, characterized by the costs of implementing the relevant technologies instead of the existing natural gas boilers, the technical possibilities for diversifying resources, as well as the impact of technological solutions on the environment.

Economic dimension indicators. The calculations show that out of the six alternatives offered in the centralized heat supply and four alternative solutions in the individual heat supply, the highest fuel energy consumption is for the alternatives DH pellet boiler and IH pellet boiler. The highest investment in the energy produced is calculated for the alternative IH heat pump solution + PV panels. Among the technological solutions, the lowest IRR, replacing the existing natural gas boiler by introducing one of the RES technologies, was evaluated for the DH alternatives pellet boiler and solar collectors with storage, but the highest for the DH alternative wood chip boiler with flue gas condenser. The highest costs of CO_2 production are calculated for IH solar collectors with storage and natural gas boiler. The IH heat pump solution + PV panels are rated as the highest-production-cost alternatives.

For the **environmental dimension indicators,** among the alternatives, the highest NOx and PM emissions were assessed for the IH wood pellet boiler.

From the calculated indicators, it was not unequivocally determined which of the proposed alternatives will be the most sustainable solution, which should be introduced in the municipality as the first, and whether they will be DH or IH technological heat supply solutions, which would allow the existing heat supply solution—natural gas boilers—to be partially or wholly abandoned. In order to determine the sustainability of these solutions based on the calculated indicators for each of the alternatives, the CSI was created.

Assessment of Alternatives in DH and IH

The composite index results (see Figure 4) show the highest score for three DH alternatives—DH wood chip boiler and PV panels + heat pump solution (0.79); DH wood chip boiler and solar collectors with storage (0.73); and DH pellet boiler and PV panels

+ heat pump solution (0.69). All three solutions rated above combine either wood chip boilers or wood pellet boilers in combination with heat pumps and/or solar panels or solar collectors. Two higher rated DH alternative solutions include air-type heat pumps, and two include PV panels. All three alternatives have lower production costs and investments needed compared to the other alternatives, and it is also possible to diversify energy sources.

The fourth highest rated alternative was the IH heat pump solution + PV panel (0.66). This technological solution does not require fuel energy consumption, emissions are formed only from the electricity required to operate the pump, and it also has the lowest CO_2 reduction costs of the alternatives.

Four lower rated alternatives were three alternative solutions for individual heat supply for municipal buildings and one DH alternative solution—IH solar collectors with storage and natural gas boiler (0.59); IH solar collectors with storage and pellet boiler (0.54); DH pellet boiler (0.49); and IH pellet boiler (0.34).

IH alternatives with solar collectors with storage and natural gas boilers are undervalued due to economic indicators such as IRR and investments/produced energy. Therefore, the lowest indicator for the alternative of solar collectors with a natural gas boiler is the IRR, which determines that installing such a combination of technologies for a specific municipal building is not profitable. Similarly, IH solar collectors with storage and pellet boilers in the case of an alternative. The low score for individual heat supply with solar collectors can be explained by the fact that a specific urban building was evaluated and not a set of several buildings in this case. Therefore, in the case of solar collectors, a larger investment is required for one building, and the maximum roof area of the urban building for installing solar collectors must also be considered.
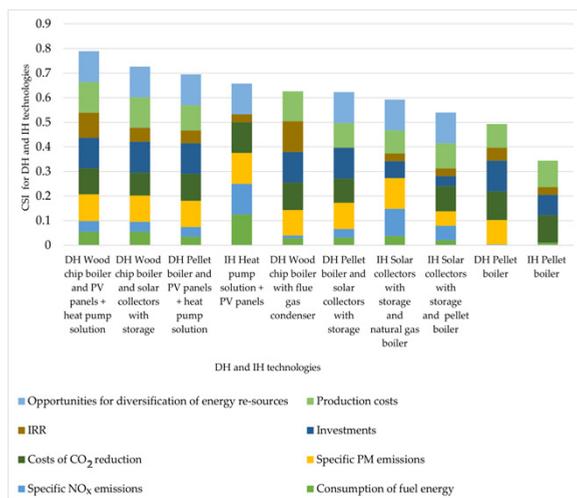
Figure 4. CSI for IH and DH technologies.

The DH pellet boiler alternative is rated with the second lowest rating in CSI. Such indicators as fuel energy consumption and NO_x emissions influence the low rating of the alternative. The lowest alternative in the sustainability index is the installation of an IH pellet boiler instead of existing natural gas boilers, which is determined by such indicators as fuel energy consumption, emissions, and IRR, which characterize the fact that such a project will not be economically feasible to implement.

The following are the limitations of the study: The low score is influenced by the fact that a solution with solar collectors was only considered for a single municipal building, but solutions for other technologies were considered for multiple buildings, adding up

the volume produced and the total investment by types of alternatives. Solar collectors are one of the highest investments in terms of technology, and the maximum roof area of each building influences the possible number of collectors. In addition, this scenario includes the installation of a pellet boiler. Therefore, compared to the other alternatives, it is not economical for the specific urban building to implement this solution, which is also reinforced by the low IRR indicator.

In future studies, it would be necessary to use expert surveys to add indicators characterizing the social dimension to the economic environmental indicators for the most complete analysis.

4. Conclusions

This research aims to understand how it is possible to switch to renewable energy technologies in multi-apartment buildings and municipal buildings in Carnikava, where natural gas is used as fuel. Furthermore, it asks which economic or environmental indicators affect the potential and sustainability of RES technologies. This study was conducted based on real data on the thermal energy consumption of Carnikava's buildings and scientific data sources to make assumptions.

The two main technological solutions compared to existing natural gas combustion systems were wood chip and pellet boilers. Solar collectors and heat pumps were evaluated as additional alternative scenarios to complement the wood chip and pellet boilers. The scenario with solar collectors included the installation of a wood chip or pellet boiler to meet the heating load, supplemented by solar collectors with storage to meet the summer hot water load. The scenario with heat pumps also provided for installing a wood chip or pellet boiler to cover the heating load, supplemented by installing heat pumps to cover the summer hot water load. Since electricity is needed to operate the heat pump, installing heat pumps and solar panels to generate electricity was considered. Air-to-water-type heat pumps were chosen for the analysis of alternatives.

The composite index results show the highest score for three DH alternatives—DH woodchip boiler and PV panels + heat pump solution (0.79); DH woodchip boiler and solar panels with storage (0.73); and DH pellet boiler and PV panels + heat pump solution (0.69). Only the fourth highest rated alternative was for the IH alternative heat pump solution + PV panel (0.66).

The lowest rated alternatives were IH solar collectors with storage and natural gas boiler (0.59) and IH solar collectors with storage and pellet boiler (0.54). The low ratings of the solar collector solutions can be explained by the fact that the possibilities of installing solar collectors were analyzed for a municipal building, where the implementation of such a project is too expensive, and that the low rating is mainly influenced by factors such as the IRR and the total investment concerning the total amount of energy generated.

The DH pellet boiler (0.49) and IH pellet boiler (0.34) boiler alternatives are rated the second lowest and lowest in CSI. Indicators such as fuel energy consumption and NOx emissions influence the low rating of the alternatives. The lowest alternative in the sustainability index is the installation of an IH pellet boiler instead of the existing natural gas boilers. This is determined by indicators such as fuel energy consumption, emissions, and IRR, which characterize the fact that such a project is not economically feasible. It can be concluded that the significant impact on the sustainability rating in CSI comes from IRR and investments per unit of energy produced. If the alternative is not economically feasible to implement and the invested investments do not pay off, this determines that the alternative will have a lower rating in the long-term evaluation. Alternatives that include wood pellet boiler solutions are most affected by indicators such as fuel energy consumption and NOx emissions.

It can be concluded that DH solutions in the case of Carnikava are more sustainable, which is determined by economic indicators such as IRR and investments, economic and technical indicators such as fuel energy consumption, and environmental indicators such as NOx emissions. The analysis and creation of a CSI based on real data and assumptions based on the scientific literature serves as an effective method that can be used in the decision-

making process to simultaneously evaluate the economic and environmental dimensions and decide on the most sustainable solutions, so that municipalities can decide to increase RES in centralized and individual heat supply.

Nomenclature

Individual heating	IH
District heating	DH
Composite sustainability index	CSI
Renewable energy sources	RES
Particulate matter emissions	PM emissions

Appendix A

Table A1. Parameters and values used in the study.

Parameter	Value	Unit
Technology creators		
Natural gas boiler efficiency	90	%
Chip boiler efficiency	87	%
Pellet boiler efficiency	85	%
Diesel boiler efficiency	90	%
Solar panel area	1.92	m^2
Power of one solar panel	405	W
Nominal efficiency of solar panels	0.211	
Loss factor of solar panels	0.95	
Nominal efficiency of the solar collector	78.8	%
Maximum efficiency of the solar collector	0.89	%
The average temperature of the solution circulating in the solar collector at the given hour	70	°C
Absorption area of the solar collector	1.78	m^2
Solar panel area	2.05	m^2
Technology costs		
Pellet boiler	$526.803.94 \times x^{(-0.299)}$	EUR/kW
Pellet boiler with hydraulic system	$104.0117.4 \times x^{(-0.349)}$	EUR/kW
- Part of the boiler and equipment costs	40	%
- Part of construction and design costs	45	%
- Part of the cost of the heating unit and thermal insulation	6	%
- Part of other costs	9	%
Chipped boiler house	$-4081.6 \times x^3 + 74{,}447.43 \times x^2 - 452{,}854.13 \times x + 1{,}151{,}845.31$	EUR/kW

Table A1. *Cont.*

Parameter		Value	Unit
-	Part of the boiler and equipment costs	33	%
-	Part of construction and design costs	45	%
-	Part of the cost of the heating unit and thermal insulation	6	%
-	Part of other costs	16	%
	Flue gas condenser	100	EUR/kW
	Heat pump (technology + installation)	266.36	EUR/kW
	Solar panels (technology + installation)	$y = 5883.3086467157x - 0.3743667246$ [1]	EUR/kW
	Solar collectors (high-power projects)	155.4	EUR/m^2
	Solar collectors (low-power projects)	275.3	EUR/m^2
	Thermal energy storage (large-capacity projects)	113.8	EUR/m^3
	Thermal energy storage (low-capacity projects)	735	EUR/m^3
	The heating unit of the building	50	EUR/kW
	CSS pipeline (metal pipe)	$=1.3756 \times x + 150.89$ [2]	EUR/m
	Fuel indicators		
	The lowest heat of combustion of natural gas	9.5	MWh/1000 m^3
	The lowest heat of combustion of wood chips	0.7	MWh/t
	The lowest heat of combustion of pellets	5	MWh/t
	The lowest heat of combustion of diesel fuel	9.91	Mwh/m^3
	Cost of energy resources		
	The price of natural gas	90.00	EUR/MWh
	Chip price	32.00	EUR/MWh
	The price of pellets	64.00	EUR/MWh
	Electricity tariff	300.00	EUR/MWh
	Electricity price for electricity transferred to the network (within the Net settlement system)	250.00	EUR/MWh
	Electricity received from the network (within the Net settlement system)	50.00	EUR/MWh
	The price of diesel fuel	93.24	EUR/MWh
	Heat energy production indicators		
	Service costs		
	Natural gas	12.500	EUR/MW gadā [3]
	A splinter	20.000	EUR/MW gadā
	Granules	17.500	EUR/MW gadā
	Diesel fuel	12.500	EUR/MW gadā
	Administrative costs and salaries		
	Natural gas	15.000	EUR/MW gadā
	A splinter	25.000	EUR/MW gadā
	Granules	20.000	EUR/MW gadā
	CO_2 taxes		
	Natural gas	15	EUR/tCO_2
	A splinter	0	EUR/MWh (saražoto)
	Granules	0	EUR/MWh (saražoto)
	Additional costs (not fuel)		
	Natural gas	20.0	%
	A splinter	50.0	%
	Granules	30.0	%

[1] x—technology capacity, kw. [2] x—pipeline diameter, mm. [3] The installed capacity of the technology.
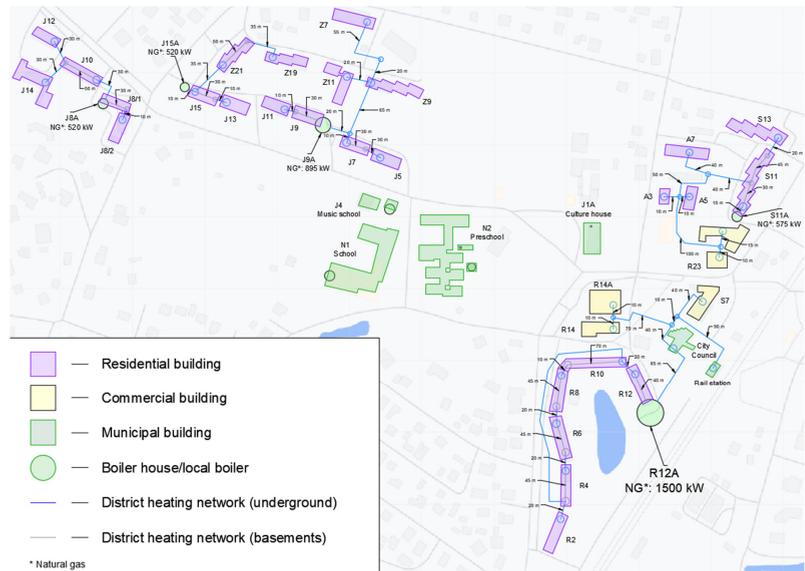
Appendix B

Figure A1. The area of Carnikava village, that falls within the scope of the study (created by authors).

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Evaluating the Effectiveness of Agricultural and Forestry Policies in Achieving Environmental Goals Through Policy Documents

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Abstract* – To achieve the climate targets set by 2030 and become climate neutral by 2050, each Member State must develop a National Energy and Climate Plan (hereinafter NECP) containing practical and effective measures to achieve the targets. The research sought a connection between the measures or action lines in the Latvian NECP related to agriculture and forestry, the European Green Deal goals and related strategies. The effectiveness of the agricultural and forestry measures defined in the Latvian NECP was evaluated by defining appropriate indicators, an expert survey and a composite sustainability index. The results show that the effectiveness of agricultural and forestry measures is most influenced by quality, financing, and specificity factors. The lowest-scoring measures were specific measures whose impacts cannot be measured and are not explicitly mentioned in the European Green Deal. Therefore, the description of the measures should be more detailed, with specific activities, indicators to be achieved, and amounts and funding sources planned for each activity.

***Keywords* – Agricultural policies; composite sustainability index; forestry policies; National Energy and Climate plan.**

1. INTRODUCTION

Many European Union environmental policies have been developed and integrated simultaneously to strengthen the European Green Deal and achieve its goals. To achieve European Green Deal goals [1], [2] new policies and strategies are being developed [3] that identify directions and actions to preserve biodiversity, reduce greenhouse gas emissions, or improve resource efficiency [2]–[5]. The role of the bioeconomy in the Green Deal is covered in several ways, including biodiversity conservation and carbon reduction measures in the Biodiversity Strategy for the European Union [6], the Farm to Fork Strategy [7]. the European Union Forestry Strategy, and the Circular Economy [8], [9]. At the same time, solutions are sought for the efficient consumption and production of resources and the preservation of biodiversity without exceeding the capacity to use resources [1], [2], [10]. Coinciding with the publication of the European Green Deal, the European Commission published the Biodiversity Strategy 2030, which is one of the policy documents associated with the European Green Deal [10]. One of the main goals and objectives of the strategy is to protect ecosystems and restore natural values by 2030 and 2050. Concerning agriculture, the Biodiversity Strategy defines the restoration of arable land ecosystems in agriculture and the

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restoration of biodiversity as one of the priority areas. The objectives of the strategy are consistent with and complementary to the priorities of the Farm to Fork Strategy, as they have a more direct link to food security and sustainable production [9]–[11]. Food production is the sector that causes various types of environmental pollution, including soil degradation, water, air, biodiversity degradation, and climate change, which need to be addressed to reduce the overall environmental impact of agriculture [12] in the processes of food cultivation, producing, and usage [6]. To improve the sustainability of food production and the food system as a whole, the European Commission has developed the Farm to Fork strategy, which is also part of the European Green Deal [1], [2], [10], [13]. The strategy emphasizes not only the importance of food security and safe food, but also the importance of sustainable food production in building the economy [3]. The Farm to fork strategy for the countries of the European Union sets out the recommendations that should be taken into account when developing and implementing measures at the national level to increase sustainability in the food industry [3], [8]. The Farm to Fork strategy's main objectives are to reduce the entire food chain's environmental impact at the European Union level, promote sustainable resource use, and provide safe, affordable food [8], [13]. The strategy sets targets for 2030 that determine the reduction of the use of pesticides in food production in the European Union by introducing a series of specific additional measures and revising regulations so that the use of chemical pesticides can be reduced by 50 % within the specified period [14]. In addition to reducing the use of pesticides, the strategy also aims to reduce the use of fertilizers in agriculture by 20 % by 2030. Considering the objectives set out in the Fertilizer Use Reduction Strategy, the European Commission has highlighted the role of precision fertilization in ensuring sustainable agriculture and reducing fertilizer use [8], [15]–[17].

In addition to ensuring sustainable agriculture, it is also necessary to promote sustainable forest management and mitigate climate change by sequestering CO_2, by defining appropriate measures and actions. One of the planned solutions to improve forestry policy is the New European Forest Strategy [13] and its integration into the national plans of the Member States of the European Union [10]. The main goals of the new Forest Strategy concern measures and actions to conserve and restore European forests while maintaining biodiversity and increasing CO_2 absorption, reducing the frequency of forest fires and efficient forest management [5], [13], [16]. Promoting the development of a sustainable bioeconomy can help to achieve the goals defined in the European Green Deal in the following key areas: 1) it would help improve the environment and ecosystems and preserve biodiversity; 2) promote the transition from fossil energy to bioresources, including the creation of value-added products from bioresources; 3) thereby increase economic prosperity and create new jobs [10], [13]. In Latvia, agriculture and forestry are on the list of activities that, together with households, account for a significant share of greenhouse gas emissions [18], [19]. Agriculture is the second largest sector in terms of emissions [15]. According to 2017 data, agricultural soils accounted for 60.8 % of greenhouse gas emissions, and 31.2 % were from fermentation processes in animal intestines across the agricultural sector. Projections show that the volume of agricultural emissions could increase by 30.1 %. The largest increase in emissions is predicted for emissions from agricultural soils and from animal fermentation processes. The projections show that emissions from agricultural soils will account for about 58.9 %, while emissions from the fermentation of cattle intestines will account for 32.5 %. In addition, methane emissions from agricultural manure could increase by 36.9 % by 2030 compared to 2017 data [20]. In Latvia, one of the specific problems in agriculture is that the number of poultry and livestock kept has increased in recent years, and with it the activity of the digestive processes of farm animals and the amount of greenhouse gas emissions they produce. Each Member State of the European Union is required to prepare a National Energy

and Climate Plan and set achievable measures and policies to achieve the European Green Deal targets. According to the NECP, to achieve the plan goal, it is necessary to reduce unsustainable resource consumption (fossil fuels) by facilitating the transition to using renewable energy resources. Several action directions and sub-measures have been identified for developing agriculture and forestry in the Latvian NECP until 2030. Promoting sustainable forest management and integrating climate change mitigation measures is necessary to ensure sustainable agriculture. Therefore, it is necessary to simultaneously assess the directions of action and specific measures related to agriculture and forestry. Also, in the NECP, the directions related to agriculture and forestry are combined, and it would be correct to evaluate these directions together. Action line eight includes measures to reduce greenhouse gas emissions and promote resource efficiency in the agricultural sector, in contrast action line nine focuses on measures to reduce greenhouse gas emissions and promote carbon sequestration [21]. while promoting sustainable resource use. These action lines and the measures under them were used in the study, and some horizontal measures related to agriculture or forestry were included [20].

Although the Latvian NECP identifies several directions and sub-measures to achieve the set 2030 targets, including developing the agricultural and forestry sectors, some of these measures cannot quantify the impact, according to the European Commission's assessment [22]. It is unclear which measures would be the most important and how the measures were measured or achieved. This study aims to analyse and evaluate the effectiveness of agricultural and forestry measures in the NECP of Latvia. The evaluation of individual measures is based on the indicator approach. This study applies the policy effectiveness evaluation methodology to determine which are the most important measures that should be implemented in forestry and agriculture and whether the priority measures are also consistent with the priorities of the European Green Deal [3], [20], [23].

2. METHODOLOGY

2.1. Approach to the Study

Two methods have been chosen to identify and literature review the Composite sustainability index. The Composite sustainability index [24] was used to evaluate the policy's effectiveness. The methodology includes (Fig. 1):

1. The selection of specific policies and actions related to forestry and agriculture is based on the goals and objectives;
2. Identification of indicators to evaluate specific policies;
3. Development of an expert questionnaire to assess the relevance of each indicator and rank actions according to their relevance.
4. Normalization of indicator scores;
5. The weighting of the indicators;
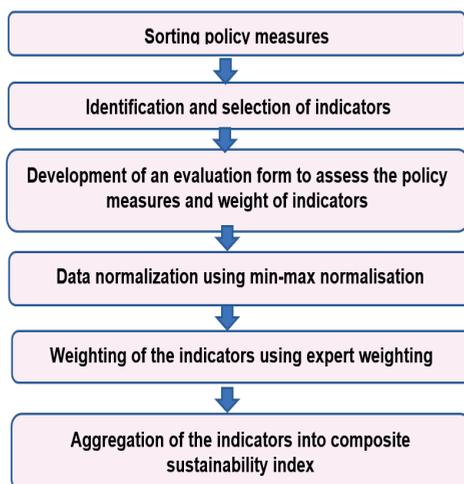6. Aggregation of indicators into Composite sustainability index [25]–[27].

Fig. 1. Model for the evaluation of policies and measures [28].

2.2. Construction of the Composite sustainability index

The Composite sustainability index can be used instead of the method 'The Technique for Order of Preference by Similarity to Ideal Solution' of multicriteria analysis [26]. The composite sustainability index is used in various studies, including the analysis of multiple environmental policies and aspects of long-term assessment. With the help of the sustainability index, the results clearly show the ranking and the most important aspects and factors influencing the result, thus already offering the possibility to analyse the causes further. Collecting and categorising indicators according to the selected indicators makes it possible to obtain a sustainability index that identifies which indicators affect the system the most and which affect it the least. The Composite sustainability index can be used in decision-making processes to determine which solutions have the highest value in a given case [17], [18], [28]. The compilation of indicators in the sustainability index is reliable and meaningful if clear assumptions are made [29].

2.3. Sorting policy measures

First, from Latvia's NECP Annex Four, policy measures and actions were selected specifically for the sustainable use of resources in forestry and agriculture and for reducing GHG emissions Annex 4 of the Latvian NECP [20] defines packages of measures covering several directions of action in the relevant sectors – horizontal measures and specific directions related only to certain actions. The study includes horizontal measures and action directions for agricultural and forestry activities [20]. All action directions, horizontal measures related to agriculture and forestry, and the set targets to be achieved by 2030 were initially selected from Annex 4 of the Latvian NECP (Table 1) [2]. Subsequently, from all directions of action and already concrete measures, it is already analysed in more detail whether the identified measures can be analysed using the six identified indicators for impact analysis. For further analysis, policies are selected that provide practical measures to achieve the goals and where the descriptions of the measures contain information that can be used to conduct an indicator-based analysis using an expert survey [20].

The NECP includes a common section on agriculture, land use, and forestry (4.12. Agriculture, Land Use, and Forestry). Although agriculture and forestry account for a large share of emissions, the amount of information in the plan is smaller than in other sectors such as household, transport

and industry. In the European Green Deal and the Biodiversity Strategy, forests and sustainable forestry are essential for climate regulation and achieving climate neutrality by 2050 [20].

2.3.1. Description of the specific agriculture and forestry actions

H.14 develop research programmes to stimulate research needs to achieve energy and climate goals. One of the highly rated environmental measures relates to support for environmental research programs to meet established climate goals and to encourage the development and use of new innovative technologies and products. Horizontal measure H.14 provides for the continuation, expansion, and promotion of the activities of national research programs, the promotion of market-oriented research, and the promotion of national research projects with a practical orientation.

- *8.1. Promote and support the exact use of mineral manure.* It is expected that conditions will be developed to apply the measure to target farms (achievable indicators - the measure has been implemented in 37.5 % of wheat and rapeseed areas managed by cluster 2 farms (intensive grain farming farms).
- *8.2. Promote Fertilisation Planning.* One of the agricultural policies that scored high in the long-term index assessment was the promotion of fertilizer planning to reduce emissions generated in agriculture. In Annex 4 of the Latvian NECP, the list of measures and achievable indicators stipulates that regulations will be developed for mixed, medium-sized farms with grazing, which account for 25.4 % of the total number of farms in the country, and the list of measures also stipulates that the promotion of manure planning in 2030. As a result, 27 % of agricultural land in these farms will be implemented.
- *8.4. Organic dairy stock farming* – to reduce emissions caused by dairy farming. The event's activities envisage that the regulations will be developed so that in 2020 they account for 17 % of the total number of dairy cows, in 2025, 21 % of the number of cows in organic dairy farming and in 2030 already, 22 %. Similarly, the overall achievable indicators of the measures specify that ammonia emissions from dairy farming will be reduced by 4 %.
- *8.5. Facilitate ration planning (planning feed rations).* The action plan provides for the development of conditions for applying the measure in the target farms, including 31 408 dairy cows.
- *8.7. Improving the maintenance of amelioration systems in agricultural lands, thereby reducing indirect runoff.* The course of action envisages that conditions will be developed to apply the set of measures to all farm groups, covering 100 thousand ha.
- *8.8. Improve the inclusion of taw winter in the crop rotation to promote nitrogen removal.* The course of action foresees that the conditions will be developed in order to apply the measure to target farms, covering a total of 172.331 thousand ha (clusters 1, 2 and 3, which together make up about 26 % of all farms in Latvia and occupy about 70 % of the total agricultural land).
- *8.10. Supporting and promoting wider use of passer in cereal crops* – The action plan provides that using a passer increases carbon sequestration (application of the measure on 17.5 thousand ha of agricultural land) (achievable indicators - the increase in carbon yield increases carbon accumulation in the soil by 7 tons ha^{-1}).
- *8.11.* The course of action envisages that conditions will be developed to ensure that green fallow is established before winter sowing, which increases carbon sequestration (100,858 ha of agricultural land). Achievable indicators - the increase in carbon yield contributes to soil carbon accumulation by 7 tons ha^{-1}.

- *8.12. Support the development of innovative technologies to promote resource efficiency, reduce greenhouse gas emissions, and increase CO_2 emissions in agriculture.* The action envisages that support is provided for the implementation of research, technology development, and demonstration projects to improve resource efficiency, reduce greenhouse gas emissions/increase carbon sequestration in agriculture, and support the development of new technologies and innovative solutions (legislation and support programs have been developed).
- *9.3. Promoting the development of forests and the quality of the crop in naturally overgrown areas.* Implementation is planned for 10 thousand ha during the year. Implementation is planned for 10 thousand ha during the year.
- *9.4. Encourage the replacement of unproductive low-carbon forest stands.* The operation is planned to be carried out in 10 thousand ha during the year.
- *9.6. Encourage young-adult felling.* The action plan envisages 120 thousand young adults being felled by 2030.
- 9.8. *Encourage recultivation of historically used peat harvesting sites by selecting the most appropriate type of recultivation.* The direction of action requires that guidelines have been developed to ensure a comprehensive assessment of areas for decision-making and development of action plans for the recultivation of areas. Within the framework of the Common Agricultural Policy, the establishment of perennial plantations (a total of 18 thousand ha) was supported.
- *9.9. Promoting wood use in construction.* According to the framework of the action direction, it is planned to launch at least one promotion program to stimulate the use of wood in construction by 2030.
- *9.10. Promote the cascade principle in the use of wood and biomaterials.* According to the Latvian NECP in Annex 4, preparing legal acts and developing at least one support program for applying the cascade principle of measures on wood-related products are foreseen. However, detailed information on related activities under the action plan was not provided.
- 9.12. *Promote support for innovative technologies, development of technologies and innovative solutions to promote greenhouse gas reduction/carbon sequestration in forestry and resource efficiency.* The package of measures envisions promoting cooperation between state and local government institutions, educational institutions, and enterprises to develop new innovative technological solutions for sequestering CO_2 from forestry and improving resource use efficiency. The stated performance indicator is the funding program.
- *12.1. Improve public knowledge, awareness, and awareness of climate change mitigation, use of RES, and resource efficiency.* At least once a year, information campaigns are conducted on: ways to reduce daily resource consumption, the importance and necessity of RES and its contribution and benefits to the economy, society, nature and the climate, the principles of socially responsible use of RES [20].

TABLE 1. DESCRIPTION OF THE ACTIONS IN NECP [20]

Action lines related to agriculture and forestry measures	Measures or action lines related to agriculture and forestry
Horizontal measures	8.10 Supporting and promoting wider use of passer in cereal crops
H.5 Promoting the production of biogas and the use of biomethane biomethane	8.11 Support and promote the establishment of green fallow before winter crops
H.14 Develop research programmes to promote and stimulate research for achieving energy and climate goals.	8.12 Support the development of innovative technologies to promote resource efficiency, reduce greenhouse gas emissions, and increase CO_2 emissions in agriculture. Support the development of innovative technologies and solutions to promote resource efficiency, reduce greenhouse gas emissions, and increase carbon sequestration in agricultural activities.
8. Direction of action. Efficient use of resources and reduction of GHG emissions in agriculture	9. Direction of action. Sustainable use of resources and reduction of greenhouse gas emissions and increase of CO_2 reduction in land use, land use change and forestry.
8.1 Promote and support the exact use of mineral manure	9.3 Promoting the development of forests and the quality of the crop in naturally overgrown areas
8.2 Promote Fertilisation Planning	9.4 Encourage the replacement of unproductive low-carbon forest stands
8.3 Directly promoting and supporting the incorporation of organic fertiliser into the soil	9.6 Encourage young-adult felling
8.4 Organic dairy stock farming (emission-reducing dairy farming)	9.8 Encourage recultivation of historically used peat harvesting sites by selecting the most appropriate type of recultivation
8.5 Facilitate ration planning	9.9 Promote the use of wood in construction
8.7 Improving the maintenance of amelioration systems in agricultural lands, thereby reducing indirect runoff	9.10 Promote the use of the cascade principle in the use of wood and biomaterials
8.8 Improve the inclusion of tawwinter in the crop rotation to promote nitrogen removal	9.12 Promote and support innovative technologies and solutions to promote greenhouse gas reduction/carbon sequestration in forestry, resource efficiency
12.1. Improve public knowledge, awareness, and awareness of climate change mitigation, use of RES, and resource efficiency	

2.4. *Identifying Indicators for Performance Assessment*

To create a representative composite sustainability index, it is essential that the selected indicators characterize the problems of the respective system and that the selected indicators allow for mutual comparison of the effectiveness of different policy measures, which is the aim of this study. Therefore, the indicators were selected considering the indicators used in the policy evaluation and individual indicators from the Better Regulation Program. Better Regulation Regulatory Policy The OECD indicators are rated as one of the most effective indicators of policy regulation and management that can be used as tools for decision-making and policy analysis [30]. Therefore, in addition to the indicators included in Better Regulation, the study also used some success and failure factors to characterize the success or failure of measures. The study selected one of the indicators from the success factors of the ODYSSEE-MURE project for the implementation of successful energy efficiency measures. However, this indicator can also be used to analyse other environmental policy measures. Based on the analysis of the scientific literature and the amount of information on

policies in Annex 4 of the Latvian NECP, six indicators were identified that can be used to characterize the effectiveness of the policies. The indicator i1, possible adverse side effects, describe whether and which negative or positive side effects will occur during the implementation of the specific policy or bundle of policies and whether adverse effects have already been consciously identified. The side effect analysis is also a preliminary identification and assessment of risks associated with the implementation of specific policy actions [31] indicator i2 transparency [32] – Transparency is an indicator that characterizes the transparency of specific measures at the definition and implementation stages. i3 Objectivity – the indicator shows whether the specific policy measure or approach will allow achieving the set climate targets following the Latvian NECP. i4 Specificity – the indicator characterizes whether the specific measures and the plan for their implementation are described correctly and understandably and whether only general and unspecific tasks are set. i5 – the quality of the policy measures [30]. The indicator describes whether the policy measures, the procedure is described understandably and whether the policy measure is realistically feasible according to the given description i6 Financing – the indicator describes whether the amount of financing and the sources of financing for the specific action are clearly stated (Table 2).

TABLE 2. DESCRIPTION OF THE INDICATORS

No.	Indicator	Explanation of the indicator
i1	Possible negative side effects [28], [33], [34]	The possible adverse side effects of the specific measure are excluded (e.g., no indirect support for the use of fossil fuels in agriculture is created and no additional energy consumption is promoted, no additional resource consumption is used), the policy measure complies with the principles of climate neutrality, efficient use of resources for policy measures or the direction of action the result does not contradict the defined environmental and climate goals.
i2	Transparency [28], [32]	Lobby influence has been eliminated (positive or negative side pressure). The potential influence of the lobby (influencing policy - action or inaction to influence decision-making in favour of specific individuals or groups, various political interests, and private and public interests) has been identified and eliminated.
i3	Objectivity [28], [32]	Identified policies or action lines are based on achieving climate change objectives according to the documents listed in the higher-level hierarchy. A policy measure or line of action is objectively determined and its choice is justified following the defined objectives and the tasks to be achieved.
i4	Specificity [28], [32]	The information provided about the policy action is not generic and is described in detail, the description and mission of the action or course of action are consistent with the defined objectives. The policy action plan defines expected measurable outcomes. If necessary, the policy action or course of action is laid out for changes in a way that allows flexibility to make changes to the plan.
i5	Quality [28], [32]	The policy measure or line of action and the expected results are described understandably and realistically. A policy measure or specific action line will ensure the long-term sustainability of the goals set (e.g., specific greenhouse gas emission reductions, energy savings, transition to RES), or the results will not be limited to a single measure, but will contribute to a positive chain reaction and overarching goals.
i6	Funding [28], [32]	Clear sources of funding for policies or a specific course of action are identified and funding is provided to implement appropriate actions. Funding is provided for the implementation of actions that contribute to the reduction of greenhouse gas emissions following established goals to be achieved within a specified period.

Each indicator is evaluated according to a severity scale. The indicators were scored on a scale of one to five, with a score of one representing very poor performance and a score of five representing very good performance that impacts the success of the policy. The assessment was conducted by nine experts in environment and agriculture.

2.5. Data Normalization

When creating a complex composite sustainability index, the data must first be normalized for mutual comparison of measures and indicators. To compare and compile indicators, the data must first be normalized. To standardise the indicators, the min-max method, used in sustainability studies, was used for normalization. The Min-max normalization method was used for normalisation, which is also used in environmental decision-making and policy analysis. This method presents the results on a scale of [0;1]. The indicators selected for the study were normalized using Eq. (1).

$$I_{N,ij}^{+} = \frac{I_{act,ji}^{+} - I_{min,ji}^{+}}{I_{max,ji}^{+} - I_{min,ji}^{+}}, \qquad (1)$$

where

$I_{N,i}^{+}$ Normalized indicator;
$I_{act,i}^{+}$ The actual value of indicator;
$I_{min,i}^{-}$ Minimum value of an indicator;
$I_{max,i}^{+}$ Maximum value of an indicator;
i Specific indicator [27].

2.6. The weighting of the indicators

To create the composite sustainability index, it is necessary to determine the importance of the indicators in comparison with other indicators and evaluate each indicator's weight. Special completion forms were prepared and the experts were asked to rate the six indicators mentioned above according to their importance, which was expressed in %. The forms were filled so that the total score of the indicators was 100 %, e.g., Possible side effects 30 %, Transparency, 20 %, Objectivity 10 %, Specificity, 5 %, Quality, 20 %, Funding 15 %. In the forms, scoring is done by filling in the " boxes" and indicating the corresponding percentage score for each indicator. To determine the weight of each indicator, it is possible to use expert interviews to determine the weight of the indicators or assign the same weight to each indicator so that the total weight of the indicators is one. An expert weighting technique was used in this study. Simultaneously with the assessment of the measures themselves, nine experts with extensive knowledge of bioeconomy policy and the agricultural sector were asked to assess the significance % of the indicators described above, based on the indicator approach. The experts have experience in research on bioeconomy, climate and environmental sustainability. The expert survey form was accompanied by an additional table in which each of the six indicators was given a percentage score, so that the total sum of the indicators was 100 %. In this study, the weighting of the indicators was done by expert survey, and the results were also compared with the exact weighting. The overall performance index is calculated for each indicator based on the cumulative amounts with their respective weights. The composite sustainability index is calculated as the total sum of all indicators, according to Eq. (2) [27].

2.7. Aggregation of indicators in to Composite sustainability index

The sum of all indicators results in the final Composite Sustainability Index, which can be used for further comparisons.

$$I_{CSI} = \sum_{j}^{n} W_j \cdot I_i, \qquad (2)$$

where
I_{CSI} is a composite sustainability index;
W_j the impact weight of indicators determined from the expert surveys (calculated in %) [27], [35];
I_i the normalized value of an indicator.

3. RESULTS AND DISCUSSION

3.1 Evaluation of policy impact

The highest score in the composite sustainability index got policy action direction *12.1. Improving public knowledge, awareness, and understanding of climate change mitigation, RES use, and resource efficiency* (score 0.77). On the other hand, the lowest scores in the Composite sustainability index got actions *8.11. Supporting and promoting the installation of green fallow before winter crops* (0.58), *8.10. Supporting and promoting wider use of passer in cereal crops* (0.57), *9.9. Promoting wood use in construction* (0.55).

The direction of action *12.1 Improving public knowledge, awareness, and understanding of climate change mitigation, RES use, and resource efficiency* (0.77) – at the national level, there are no long-term measures to educate the public about solutions for efficient resource use [18]. A sub-priority of the European Green Deal is to promote even broader knowledge transfer, education and involvement of even broader social groups in environmental decision-making. To achieve the set goals in environmental education, the European Commission has developed a set of competencies that include recommendations and best practices and examples that promote an understanding of how to integrate environmental education and climate issues into educational programs [36]. To implement the goals defined in the Farm to Fork Strategy, the involvement of all food system stakeholders, including society, is essential. The implementation of the adopted measures should consider the needs of the people and the regional characteristics, while also considering the interests of producers [14]. Based on the data in the assessment of experts, the direction of action: *9.10. Promote the cascade principle in the use of wood and biomaterials also received a high index* (0.71). Detailed information on related activities under the Action Plan was not provided. It is expected that the sources of funding will come from both the state budget and the European Structural Funds, and it is not specified how much funding will be needed to implement the planned activities [18]. One of the environmental policy documents related to the priority directions of the European Green Deal and their implementation in the field of forestry and carbon sequestration is the European Union New Forest Strategy and the cascade principle for wood is one of the main priorities. The European New Forest Strategy for 2030 states that the amount of wood used should be used as much as possible to obtain higher value-added products or raw materials by expanding its use following the basic principles of the circular economy and the cascade principle [17]. *8.5. Facilitate ration planning (planning feed rations)* (0.71) – specific financial requirements for individual activities are not specified. However, the financial needs for the development of conditions and their implementation (the achievable indicator is 10 % in the first group and 50 % in the third and fourth groups) amount to 4.7 million EUR, with both private and European Union structural funds indicated as sources of funding. From the given description, it is necessary to clarify what part of the funding amount is required for the development of regulations and what part is required for

the achievement of the established indicators. However, the evaluation of the measures proposed for this action is quantitatively measurable, and in the medium term could measure progress towards the goals set for 2030. *H.14 Develop research programmes to stimulate research needs to achieve energy and climate goals* (0.71) – one of the highly rated environmental measures refers to the promotion of environmental research programs to achieve the set climate goals and to promote the development and use of new innovative technologies and products. Similar to the other measures and action directions, the funding required for each activity or direction is not allocated here, but the total funding for the implementation of the package of measures is reported to be around 280 million euros. Several sources are indicated for financing the package of measures, including private funds and the state budget. In the description, there is a lack of concreteness regarding the tasks to be fulfilled to promote research programs, as well as achievable, measurable indicators that would make it possible to evaluate progress and determine whether and for how long the set goals are being achieved and whether they need to be revised [18]. In line with the NECP itself, the vision defined in the plan includes measures to promote support programs and increase export capacity through support to distributors and to develop new innovative technologies and innovations that promote the commercialization of research results. NECP indicates in the section on research that both practical research programs with commercialization, technology transfer centres, and centres of excellence on decarbonization issues should be created. In line with the European Green Deal, closer collaboration between universities, research institutions and companies in the field of climate change, future nutrition and sustainable energy use will be further promoted [35]. *8.2. Promote Fertilisation Planning* (0.70) – one of the agricultural policies that scored highly in the long-term index assessment was the promotion of fertilizer planning to reduce emissions generated in agriculture. Although clearly stated achievable indicators, the measure lacks a specific implementation plan for how the indicator will be achieved – implementation of fertilizer planning in 27 % of affected farms. The level of funding is not broken down by activities or periods only the funding for the entire package of measures is indicated. The package of measures to promote fertilizer planning in Latvia was rightly proposed because one of the most important problems of Latvian agriculture is the excessive use of mineral fertilizers. The promotion of fertilizer planning is in line with the agricultural goals set out in both the Green Deal and the Common Agricultural Policy, which calls for a reduction in the use of fertilizers. Fertilizer planning and more prudent use of fertilizers are the measures that make it possible to improve the balance between emissions generated by agriculture and overall emissions [9]. *8.4. Organic dairy stock farming – to reduce emissions caused by dairy farming* (0.70). Compared to the other measures described, this set provides specific, achievable indicators to be achieved in each period. This provides an opportunity to measure progress against the plan or revise the measures and targets for 2030 [10]. In Latvia, organic dairy farming is an open niche and regionally suitable, as there are many dairy farms in Latvia. However, the livestock of the farms is small, so organic livestock production is possible. The package of measures is reasonably chosen and solves a current problem in Latvia while showing a potential solution that can help reduce and regulate emissions caused by livestock farming while developing the direction of organic dairy farming. The European Green Deal requires that precision agriculture and organic farming be included and developed in national energy and climate plans and other national environmental documents for agriculture and forestry. The European Green Deal requires all European member states to increase the area used for organic farming. Therefore, the measure proposed in the Latvian NECP will promote progress and fulfilment of this goal [6]. *9.12. Promote support for innovative technologies, development of technologies and innovative solutions to promote greenhouse gas*

reduction/carbon sequestration in forestry, and resource efficiency (0.68) – although the measures include several actions and activities that could be stated as achievable and measurable indicators, the stated performance indicator is the funding program. Both the European Structural Fund, private funds and the state budget are indicated for the implementation of these actions by 2030, but the total funding of the actions is unknown. It is not clear from the given description whether the implementation of the listed tasks will be done through the creation of funding programs. The objectives of the New Forest Strategy developed by the European Commission have been incorporated into the European Green Deal, and measures to promote carbon sequestration in forests have been identified as one of the priority directions for achieving climate neutrality goals. However, no quantitatively measurable, achievable indicators have been established to monitor and measure the progress of the proposed actions, the additional actions and the measures needed to achieve the targets. Based on the results, the following action directions received the lowest score in the composite sustainability index: *8.11. Supporting and promoting the installation of green fallow before winter crops* (0.58). This course of action of the agricultural sector was given one of the lowest scores in the sustainability Index. No funding was indicated for the implementation of the course of action and the achievement of the defined indicator, not even close to the required amount, indicating that the sources of funding will be the European Union Structural Funds, the state budget and private financing. The measures are rather general, and the NECP 2030 also needs to explain why this direction of the measures is essential and how important they are compared to the other measures, nor does it clearly state the planned funding and funding sources. *8.10 Supporting and promoting wider use of passer in cereal crops* (0.57). The second lowest score in the sustainability index was given to the Agriculture sector action line: Support and promote wider Use of passers in cereal crops. Similar to the previous action line, this action line does not even give an approximate amount of funding required. The funding sources are European Union structural funds, private funds, and funds from the state budget. Neither the description of the action plan nor the Latvian NECP itself describes or otherwise explains why the specific action is essential and what conditions should be developed. Moreover, it is not explained how monitoring should be carried out to ensure that the established indicator is achieved. *9.9. Promoting wood use in construction* (0.55): The action direction to promote wood in construction received the lowest score on the sustainability index. Under the action direction, it is planned to establish at least one incentive program to promote the use of wood in construction by 2030. The total amount needed or the approximate amount of funding is not specified in this case, and the national budget, European structural funds, and private funds are also mentioned as sources of funding. The new European Union Forestry Strategy described above identifies promoting the use of wood in construction as one of the most crucial carbon sequestration solutions. The forestry strategy emphasizes that it is possible to reduce climate change both by sequestering CO_2 and accumulating carbon in wood and replacing fossil-origin materials with wood, including wood construction, furniture, and household items as higher value-added and CO_2-neutral products [17]. Therefore, in the case of Latvia, more attention should be paid to promoting carbon sequestration through the use of wood in higher value-added wood products to reduce the amount of wood used for energy production and achieve the set climate neutrality targets in 2050. Also, from the New Forestry Strategy of the Union of European Member States, European priorities should currently refer to the more sustainable use of wood materials, including wood used in construction and demolition – reuse and recycling [15]; see Fig. 2 and Table 3.
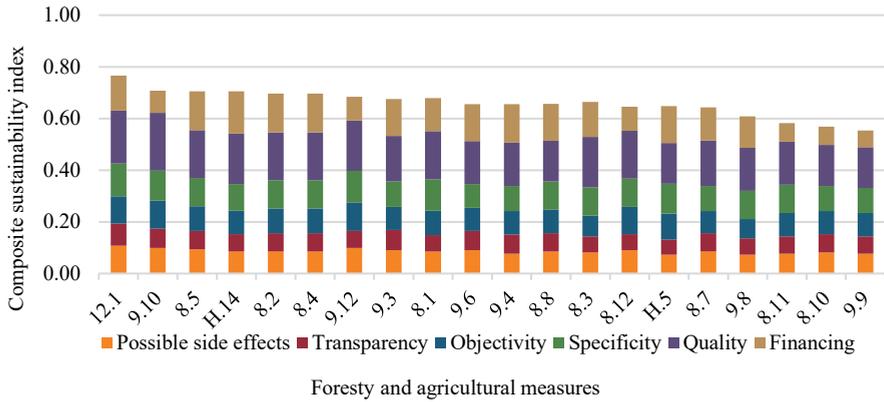
Fig. 2. Composite sustainability index of agriculture and forestry policy.

TABLE 3. AGRICULTURAL AND FORESTRY MEASURES FROM NECP [20]

12.1	Improve public knowledge, awareness, and awareness of climate change mitigation, use of RES, and resource efficiency
9.10	Promote the use of the cascade principle in the use of wood and biomaterials
8.5	Facilitate feed ration planning
H.14	Develop research programmes to promote and stimulate research for achieving energy and climate goals.
8.2	Promote Fertilisation Planning
8.4	Organic dairy stock farming (emission-reducing dairy farming)
9.12	Promote support for innovative technologies and solutions to promote greenhouse gas reduction/carbon sequestration in forestry, resource efficiency
9.3	Promote forest development and crop quality in naturally overgrown areas
8.1	Encourage and support the accurate use of mineral fertilisers
9.6	Encourage young-adult felling
9.4	Promote the replacement of unproductive, low-carbon forest stands
8.8	Improve the inclusion of taw winter in crop rotation to promote nitrogen removal
8.3	Directly promoting and supporting the incorporation of organic fertiliser into the soil (transporting liquid vehicles using hose systems or casks and using injectors in the soil)
8.12	Promote support for the development of innovative technologies and solutions to promote resource efficiency and reduce greenhouse gas/carbon emissions from agriculture
H.5	Promoting the production of biogas and biomethane and the use of biomethane
8.7	Improving the maintenance of amelioration systems in agricultural lands, thereby reducing indirect FROM runoff
9.8	Encourage recultivation of historically used peat harvesting sites by selecting the most appropriate type of recultivation
8.11	Supporting and promoting the installation of green fallow before winter crops
8.10	Supporting and promoting wider use of passer in cereal crops
9.9	Promoting wood use in construction

3.2. Importance of the indicators

Regarding the importance of each indicator, indicators such as funding and quality were the most important. The weights determined by the expert evaluation were also compared for the weights where each indicator was equally important (Fig. 3). The results showed no significant differences in the distribution – it is equally possible to use the same weighting method and the weights from an expert survey.
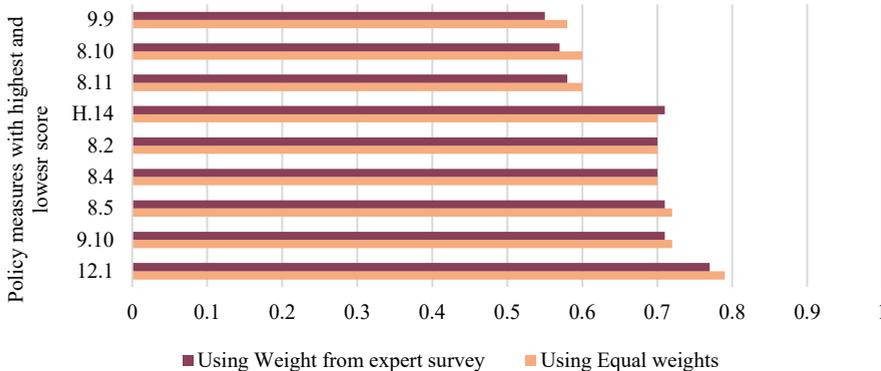
Fig. 3. Comparison of weight from the expert survey and equal weight.

3.3. Revision of the established agricultural and forestry measures

According to Chapter 8 of the Latvian NECP, the first progress report on the impact of the measures defined in the NECP must be submitted to the European Commission by March 2023, including a more detailed assessment of the impact of the measures on the reduction of greenhouse gas emissions and energy consumption, and the definition of specific achievable indicators [18]. Each horizontal measure and course of action in the NECP Annex should include a detailed description of the specific measure and achievable targets. In addition, a measurable target achievement indicator should be provided for each defined action, not just the target achievement indicator for the entire course of action. For each of the action areas included in the NECP, objective and verifiable indicators should be defined that can be monitored to verify at an earlier stage whether progress is being made towards the goals set or whether the action in question needs to be revised to avoid partial or total non-compliance with the plan at the end of its implementation. The indicators to be achieved must be expressed in numbers (quantitative and qualitative indicators to be achieved by 2030), all responsible institutions and co-responsible institutions must be indicated, all necessary funding (including monitoring activities); additional funding sources.

3.4. Limitations of using the composite sustainability index method

One of the study's identified limitations is that more objective results could be expected if more indicators were used. The indicators were selected based on the scientific literature and the minimum amount of information available for each horizontal measure and action line in the NECP. In such a case, if the policy planning documents contain more detailed information on policy objectives, achievable indicators, monitoring, and required funding, other indicators not included could be proposed for evaluation. Expert ratings were compared with the same weighting for each indicator. With a larger group of experts, the weighting of the indicators would be more different, and the result would be more objective. To create an evidence-based

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and reliable sustainability index that shows the sustainability of each measure, the raw data and the availability of the data are most important. In this case, the data were more descriptive. Therefore, indicators such as quality were chosen to indicate how detailed and precise the course of action was described.

4. CONCLUSIONS

The study shows what actions are essential to achieve the goals of the NECP. The actions with the greatest impact were *12.1. Improving public knowledge, awareness, and understanding of climate change mitigation, use of RES and resource efficiency*, and *9.10. Promoting the cascade principle in using wood and biomaterials, facilitating feed ration planning, developing research programs, and promoting fertilizer planning.* These measures coincide with the goals of the Green Deal. European Forestry Strategy, as one of the binding documents of the European Green Deal, identifies the promotion of the cascade principle in using wood as one of the priorities. Measures 8.10 and 8.11 with the lowest score are specific and need to explain why these measures are essential and clearly state the proposed funding and funding sources. The lowest-scoring actions are specific actions whose impacts cannot be measured and are not explicitly mentioned as relevant in the European Green Deal. The description of the policy measures should be more detailed, with specific activities, indicators to be achieved, and amounts and funding sources planned for each activity. According to the experts, indicators such as funding and quality were the most important. The deadline for the implementation of most measures extends to the end of 2030, which does not allow for an objective assessment of the implementation of the measures based on achievable indicators. The plan should introduce indicators to be achieved in the middle phase and at the end of the planning period from the beginning, to be able to evaluate the progress in achieving the objectives or to re-evaluate the established achievable indicators in the middle phase and determine whether the established actions have not lost their relevance. Several of the action lines are similar, and it would be possible to combine them into one action line, e.g., reforestation. The action lines and specific measures are fragmented in agriculture and forestry and lack a common framework. Several actions can be combined and complemented. The sustainability index method can be used to analyse local, regional, national, and international policy planning plans and strategies. Using the composite sustainability index, it is possible to determine how to avoid failing to meet established goals by identifying impeding factors as early as possible in the planning process. It is also possible to assess whether the defined actions will achieve the defined indicators and whether reviewing and detailing the defined action directions is necessary.

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Organic versus Conventional Agriculture: Comparison of Economic and Environmental Sustainability

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Abstract – **Reduction of the level of greenhouse gas emissions from agriculture is one of the most serious issues across the European Union. The dairy industry generates significant emissions from enteric fermentation, manure and long-term storage. The emissions produced depend greatly on factors such as livestock feeding, manure management systems, feed content, and quality. The research aims to evaluate the environmental and economic dimensions of conventional wheat production and dairy farming and compare them in terms of their environmental and economic sustainability. The core element of the sustainability assessment is the construction of the composite sustainability index using data from scientific literature, reports, and statistics. The comparison between organic dairy farming and conventional dairy farming based on sustainability indexes provides valuable insight into the strengths and weaknesses of each system. Organic farming systems present stronger environmental sustainability but require substantial financial support. Organic and traditional farming have their advantages and disadvantages. Policymakers, farmers, and consumers play crucial roles in shaping a future where farming systems can be both productive and sustainable.**

Keywords – **Composite sustainability index; dairy farming economic dimension; environmental dimension; greenhouse gas emissions; organic agriculture.**

Nomenclature	
GHG	Greenhouse gas emissions
EU	European Union
CO_2	Carbon dioxide
CH_4	Methane emissions
N_2O	Nitrous oxide

1. INTRODUCTION

The agricultural sector is one of the sectors that create challenges for the European Union (EU) member states in achieving the set goals of climate neutrality by 2030 and 2050. Depending on how it is managed, the agricultural sector can be both a source of greenhouse gas (GHG) emissions and an attractor of GHG emissions [1]. The agricultural sector plays an

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essential role in promoting safe food, economic competitiveness, and sustainable development [1]. European Green Deal states that by 2030, emissions must be reduced by at least 55 % compared to the level of GHG emissions in 1990 [1], [2]. The European Green Deal incorporates the achievable goals in the agricultural sector set in the European Common Agricultural Policy Plan (CAP) [3]. CAP is one of the key policies designed to promote sustainable agriculture and reduce GHG emissions in the agricultural sector [4]–[6].

The European Green Deal and the Farm to Fork strategy established by the CAP promote organic farming [3], [4]. Similar to the national energy and climate plans, each EU member state must develop national CAPs [3] to set priorities and achievable goals in the agricultural sector [3], [5]. The Farm to Fork strategy aims to reduce pesticide use in the EU by 50 % by 2030 and fertiliser use by 20 % [7]. The Farm to Fork strategy and action plan encourage an increase in organic farming, intending to convert 25 % of agricultural land to organic farming by 2030 [4], [7]. According to 2023 data, about 13.2 % of total GHG emissions in the EU in 2021 were directly related to agriculture [7], [8]. Agricultural emissions come primarily from manure management and livestock intestinal fermentation, croplands, and nitrous oxide (N_2O) emissions from soil management [8]. In the EU, more than ~54 % of GHG emissions from agriculture are methane (CH_4) emissions from agricultural processes [1], [9]. According to 2022 data, the agricultural sector accounted for 2253.8 kt CO_2 eq. [10], or more than 22 % of the total national emissions that year, ranking just behind the energy sector [10]. Emissions from agricultural soils were the largest contributor to agricultural emissions in this period, creating about 46.5 % of the sector's greenhouse gas emissions. This period's second largest emission source was GHG emissions from enteric fermentation processes, contributing approximately 42 % of the total agricultural emissions [10]. According to the data from 2022, the largest volume of the harvested crop was winter wheat, accounting for more than 69 % of the harvested grains. The area for wheat was 539 thousand hectares in 2022 [10]. The importance of organic farming is emphasised in the EU agro-environmental policy and strategies, which stipulate that by 2030, at least 25 % of agricultural land should be farmed with organic farming methods [11], [12]. Sustainable agriculture is characterised by the interaction of environmental, economic and social dimensions, taking into account the impacts of these dimensions [13], [14]. Several factors influence agriculture, including subsidies, technological capabilities, and knowledge of sustainable agricultural development [14]. Clear indicators characterising farming systems are needed to evaluate organic farming [14]. There are literature sources in which organic farming, with an emphasis on organic dairy farming and organic cereals, is considered economically or ecologically more disadvantageous than conventional farming [14]. Previous literature shows a gap in data regarding relevant indicators for comparing organic and conventional dairy farming at the farm level [15]. From the above-mentioned data, it follows that dairy farming and emissions from agricultural soils, including wheat production, which make up a large part of the amount of harvested grain, are important sources of emissions, and it is necessary to evaluate alternative solutions for increasing sustainability in these sectors. The National Energy and Climate Plan of Latvia (NECP) states to promote organic dairy farming (low-emission dairy farming) [16]. The main goal of the policy measure is to promote the transition of small and medium-sized conventional dairy farms to the organic farming system, promoting low-emission dairy farming. The article aims to evaluate and compare the sustainability of biological dairy farming, conventional dairy farming, and conventional and organic wheat production, using economic and environmental indicators and the composite index method. Data from scientific literature sources and reports are collected and used to construct the composite index. The study includes two sections: 1) To assess organic and conventional agriculture based on scientific literature and report data; 2) In the second part of the study, a

composite index with additional indicators was created to assess small and medium-sized organic and conventional dairy farms in Latvia. Considering that the largest sources of emissions in agriculture in Latvia in 2022 were GHG emissions from agricultural soils and emissions from livestock intestinal fermentation, the study examines the comparison of organic wheat cultivation and organic dairy farming with conventional farming systems.

2. ORGANIC VERSUS CONVENTIONAL FARMING

Organic agriculture is a production system that relies on prevention to control pests and maintain productivity. The area of organic farming in the EU is estimated to be more than 14.7 million hectares (ha) [17]. Regarding organic agriculture in the EU, France makes up more than 2.5 million hectares, Spain more than 2.4 million hectares, Italy more than 2 million hectares, and Germany 1.6 million ha [18] Organic farms make up a total of more than 9.1 % of agricultural land in the EU [18] Sustainable agricultural activity is characterised as the management of agriculture and the use of resources in a way that preserves biological diversity promotes regeneration and productivity in the future, and combines social, economic, and environmental functions [19]. Organic farming has been assessed for its potential for carbon sequestration, increasing the organic matter content in the soil, and reducing GHG emissions [20].

2.1. Crop Farming and Organic Crop Farming

Cereals include wheat, barley, oats, rye, buckwheat, and corn [21]. In the EU, the yield (kilogram/hectare of harvested land) from cereals is estimated to reach 5260 kg in 2022 [21]. The areas of arable land managed in biological agriculture can be evaluated as an important indicator of reducing GHG emissions because mineral fertilisers are not used in these areas [22]. Grain cultivation in Latvia is estimated to account for ~ 60 % of the production of agricultural products [23]. Organic farming areas have grown since 2015. Cereals occupy more than three-quarters of the organic crop cultivation area, and organic cereals have increased more than twice compared to 2015. However, yield rates are lower than in organic farming areas [24]. In 2021, 4121 farms switched to organic farming, 63 more than in 2020. The number of organic farming operators also increased, reaching 4439 in 2021 (in comparison to 3587 operators in 2012) [24], [25]. In Latvia, it is estimated that more than 304 000 ha, of the land used for agriculture is certified organic farming areas [24]. Based on the 2021 data, the share of cereals by crop type in organic agriculture was 62863 ha. Of these, 1 270 367 ha were wheat [25]. Grain areas are increasing, and the amount of organic grain produced in the total organic farming system has also increased from 70 000 tons in 2018 to 111 000 tons in 2022 [26].

2.2. Dairy Farming and Organic Dairy Farming

It is estimated that in the EU, around 77 % [27] of methane emissions are generated in agriculture from the intestinal fermentation of dairy cattle [19], [28]. In Latvia, intestinal fermentation is one of the biggest sources of methane emissions in agriculture. In 2022, CH_4 emissions from cattle intestinal fermentation accounted for about 42 % of the total emissions in the agriculture sector or ~946 kt CO_2 equivalent [10]. Emissions depend on the feeding tactics and feed content quality [9]. The increased GHG emissions in intensive agriculture are partially explained by the fact that as the production yield increases, the milking of cows also increases, and the amount of manure produced causes higher CH_4 emissions [9]. Both conventional and organic dairy farming produce CH_4 emissions from manure and enteric

processes, CO_2 emissions from feed production, and N_2O emissions from feed production. The amount of methane emissions generated from manure is largely influenced by the composition of the cow's diet and the digestibility of the feed, manure management method [10]. Farms with herd sizes between ten and fifty cows were estimated to have the highest environmental impact, which decreased with increasing herd size. GHG emissions in dairy farming are affected by both the number of animals and their variability, as well as the amount of nitrogen fertilisers [9].

Forage quality has a significant impact on methane production; if forage is low digestible, the amount of methane gas emissions increases [10], [29]. The optimal digestibility index is 67 %; if it is 50 % and below, there is an increased risk of methane emissions and a decrease in productivity [10], [30]. Factors such as the species composition of dairy cow forage influence the quality of forage; the inclusion of legumes can improve the quality of feed. The inclusion of legumes in the composition of pasture is an essential element for obtaining higher-value forage, increasing the protein content in the feed [31]. One of the requirements set for organic farms is the presence of legumes in grasslands and balanced feed rations. There must be a balance between protein in the feed and energy in the feed, if there is no balance in the feed distribution, then a larger amount of nitrogen is excreted into the environment [32]. Dairy cows feed on pastures; in organic dairy farming, most of the feed must be home-grown. Forage available on pasture contains more fibre, which can reduce methane emissions. Methane emissions can be reduced if high-quality grass fodder and concentrated feed with high-fat content are used [1], [33].

TABLE 1. DIFFERENCES IN ORGANIC DAIRY FARMING

Factors	Organic dairy farming	Source
Fertiliser	Synthetic fertilisers and pesticides are not used in organic dairy farming; biopesticides are subject to separate regulation regulations.	[35]
Differences in feed	– There should be a large proportion of roughage in the feed of cows. – in biological dairy farming, there is a condition that the feed ration must consist of at least 60 % coarse dried or fresh fodder or silage. – At least 60 % of the feed must be self-grown on a biological farm. – The minimum amount of fodder should be pasture grass that is used as feed.	[1]–[3]
Health and antibiotics	*One of the main conditions of organic farming is the maximum restriction of antibiotics and regular veterinary care and welfare maintenance of dairy cows.	[35]
Welfare	Compared to conventional dairy farming, biological dairy farming has stricter conditions regarding the improvement of animal welfare in animal housing as one of the main conditions. However, such a requirement is not stipulated in the law.	[36]
Holding conditions	– Dairy cows must be outdoors for longer periods in addition to the grazing period. During the grazing period, they must be outdoors for at least twelve hours a day. – Free pasture – During the summer season, Animals must have freedom of movement and be led to pasture. – The need for a high level of welfare and free access to pasture. Livestock tethering is allowed only on a case-by-case basis after obtaining a special permit.	[35]
Requirements for Dairy Cow Shelters	In organic dairy farming, animal housing without litter is prohibited for the welfare of dairy cows.	[35]
Milk production	Lower milk yield compared to conventional farms due to the consumption of less feed concentrate.	[36]

In organic farming, chemical fertilisers and pesticides are prohibited, reducing nitrogen oxide emissions formed from chemical fertilisers in conventional agriculture [3], [5]. Using organic fertilisers and including buttercups can reduce carbon dioxide emissions and increase carbon accumulation in the soil. Switching to organic farming from conventional farming is considered a promising alternative for reducing GHG emissions by reducing the use of synthetic fertilisers [34]. Table 1 lists and briefly describes the requirements for organic dairy farming, which differ from those for conventional dairy cow farming.

In 2022, the number of cows in dairy farming was 127 759, but in 2023, 119042 cows [37]. In 2022, 15 800 were cows in organic dairy farming (Fig. 1). In 2020–2021, the produced cow's milk was 988 000, of which 87 000 was organic milk [38]. Although the number of dairy cows continued to decrease, the average milk yield per dairy cow increased by 1.8 %, reaching 7492 kg per year [39]. Less than half of the organic milk produced is processed as organic milk products due to logistical problems in collecting organic milk, high retail prices and low consumer demand [37], [39].
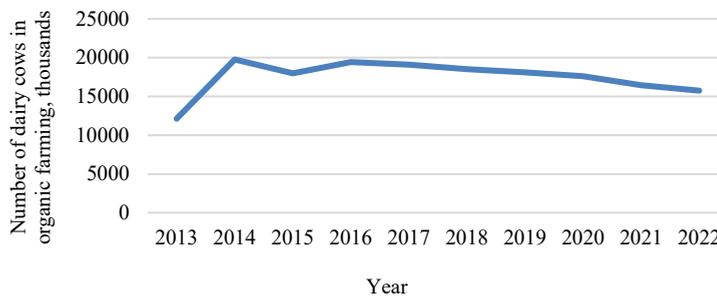
Fig. 1. Number of dairy cows in organic farming [41].

According to the 2022 data from the Agricultural Data Center, less than 5 % (~4.8 %) of farms have a cow count exceeding 50. Compared to 2021, the number of dairy farms decreased by ~9.4 % [39].

3. METHODOLOGY

3.1. Framework of the Study and Criteria

The study includes two sections: 1) An assessment of organic and conventional agriculture based on scientific literature and data from reports, and 2) a comparison of economic and environmental sustainability of small and average-size organic and conventional dairy farming. To evaluate alternative solutions in decision-making, different dimensions should be evaluated and their interrelationships [42]. Sustainability index are widely used in policy development and evaluation. For policymakers, such indicators would make it possible to evaluate ex-ante policies, develop or improve policy instruments, and evaluate climate policy measures [15]. The study compares several systems to better assess the potential benefits and drawbacks of each system based on the values of different indicators. Therefore, the composite index serves as a suitable method to show what performance can be expected if several dimensions, not only the economic or the environmental dimension, are taken into account. Databases such as Science Direct, Scopus and Web of Science were used to determine the indicators and their values. After identifying the indicators and collecting the

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data, the data were normalised using the Min-max normalisation method. Then, the normalised economic and environmental indicator values were collected and calculated to create a composite index for conventional and organic farming strategies (Fig. 2) [34].
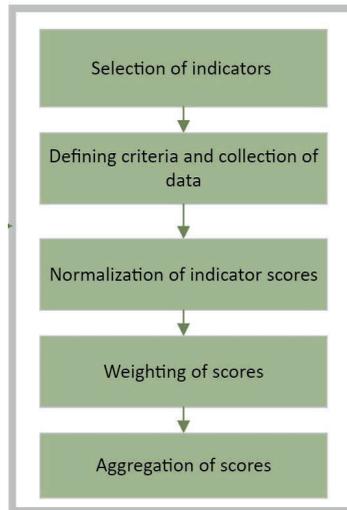

Fig. 2. Methodology of the study.

Inclusion criteria for the first part of the study:
 – Only Organic and conventional dairy cow farming;
 – Only Organic and conventional wheat production;
 – Only average values from scientific literature and reports.
Inclusion criteria for the second part of the study:
 – Only data based on Latvian case studies;
 – Calculations in environmental dimension based on IPCC 2006, national inventory report [10], [44];
 – Only dairy farms with cows in small and average size farms (1–99 cows).

3.2. Dimensions and Indicators Selection

Indicators to assess the sustainability of agriculture in scientific publications are scattered, and it is difficult to group them. There is no consensus on whether the sustainability indicators of agriculture should be assessed together or separately by indicator [45].

Literature-based studies regarding organic and conventional wheat production, dairy farming

In the first part of the study, based on sources found in the literature, indicators are identified whose values could be compared with each other in relation to both organic and conventional wheat production, as well as dairy farming. In the economic dimension, agricultural productivity and earned income are assigned numerical values. Profitability is determined by comparing revenues and costs or by farm net income product production [13]. Sustainability in the environmental dimension can be described as a decrease in potential degradation related to pesticides, degradation of soil quality, reduction of GHG emissions,

and biodiversity conservation [42], [43]. The indicators were selected based on an analysis of scientific literature and reports. The indicator values used in the study were obtained from literature, reports, and calculations based on average values. Each indicator is assigned either a negative or positive value. Indicators with a negative value (−) worsen the composite index, e.g., costs, emissions, carbon footprint, while indicators with a positive value (+) increase the composite index, e.g., milk yield, income (see Table 2).

TABLE 2. SELECTED INDICATORS FOR THE CONSTRUCTION OF THE COMPOSITE INDEX

No	Indicator	Units	Negative/positive
I1	Mean total costs, EUR	EUR/ha	−
I2	Production value	EUR/ha	+
I3	Net income	EUR/ha	+
I4	Subsidies, green payments, support payments	EUR/ha	+
I5	Carbon footprint per land unit	Mg CO_2eq ha^{-1}	−
I6	Carbon footprint per product	kg CO_2eq	−

The values of the indicators are based on scientific literature and local reports. For some indicators, the average value from different studies is used, and for others, values based on scientific literature or reports are used (Table 1 in the Annex).

3.3. Normalisation

Data calculated or obtained from literature must first be normalised. Min-max method is a common normalisation approach used in decision-making analysis, where the results are scaled from 0 to 1 [46]–[48].

$$I_{N,ij}^+ = \frac{I_{\text{act},ji}^+ - I_{\text{min},ji}^+}{I_{\text{max},ji}^+ - I_{\text{min},ji}^+} \ , \tag{1}$$

where

$I_{N,ij}^+$ normalised indicator;

$I_{\text{act},i}^+$ indicator actual values;

$I_{\text{min},i}^-$ indicator minimum value;

$I_{\text{max},i}^+$ indicator maximum value;

i indicator.

3.4. Indicator Weighting

Each selected indicator receives a weight proportional to its weight, assuming equal importance for each. Six indicators with normalised values, each with an equal weight of 0.17, were used in the construction of the CI.

Assuming equal importance for each, each with an equal weight of 0.33 was used in the construction of the CI.

3.5. Aggregation of Normalised Indicator Values into CI

The last step is to calculate normalised indicator values using Aggregation. Results multiply with the normalised indicator value.

$$I_{CI} = \sum_j^n W_j \times I_i, \tag{2}$$

where
I_{CI} composite index;
W_j indicator weight (equal for each indicator) [46], [49], [50];
I_i indicator value (normalised).

3.6. Comparison of Economic and Environmental Sustainability of Small and Average-size Organic and Conventional Dairy Farming

In the second part of the study, indicators were selected that would allow for a comparison between organic and conventional dairy farming. The indicators were divided into three dimensions – technical, which is characterised by the amount of milk produced; economic – which is characterised by the costs of each system; and environmental – which is characterised by GHG emissions from enteric fermentation, manure management, and emissions from grazing in the soil section. As before, to perform normalisation, the indicators were divided into + or − impact indicators, and then the Min-max normalisation method was used. Then, the normalised data was aggregated into a composite index (Fig. 3).
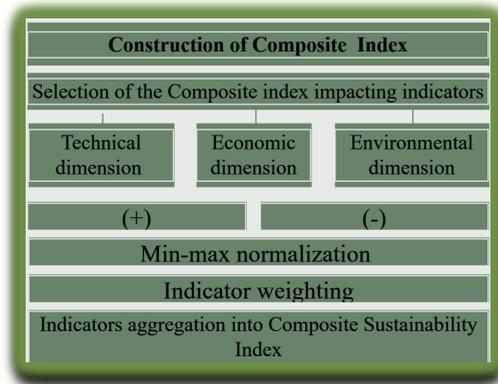
Fig. 3. Structure of the construction of the composite index.

3.6.1. Technical dimension

t_1 milk, tons/day per amount of milking cows and t_2 average milk yield, tons of milk per number of cows, are calculated based on the average amount of milk in organic and conventional dairy farming Eq. (3).

$$\text{Milk, tons/day/year} = \text{Amount of milk (kg day/year)} \times \text{number of cows)/1000} \tag{3}$$

All input data for the calculation of t_1 and t_2 are shown in Table 2 in the Annex.

3.6.2. Environmental dimension

Calculation of emissions in conventional and organic dairy farming was conducted using the 2023 data of the Central Statistical Office on the number of cows in small and medium-sized dairy farms [37]. The number of cows is divided into categories (1–9), (10–29), (30–49), and (50–99).

Emissions calculation is based on the Intergovernmental Panel on Climate Change (IPCC) 2006 methodology

- CH_4 emissions from intestinal fermentation are performed;
- CH_4 emissions from manure management are being performed;
- N_2O emissions from pastures [10].

Calculations of indicator values in the Environmental dimension are summarised in the Annex Tables 3–9.

3.6.3. env_1 CH_4 emissions from enteric fermentation kt $CH_4 yr^{-1}$, CO_2 eq

All input data for calculation on enteric fermentation is summarised in Tables 3–6 in Annex. EF for dairy cattle has been calculated according to the 2006 IPCC Guidelines methodology represented in Equation 10.21 [44], see Eq. (4).

$$EF = \left| \frac{GE \times \left(\dfrac{Ym}{100} \right) \times 365}{55.65} \right|, \tag{4}$$

where
EF emission factor, kg CH_4 head^{-1} yr^{-1};
GE gross energy intake, MJ head^{-1} day^{-1};
Ym methane conversion factor, % of gross energy in feed converted to methane (default values in table 10.12, from 2006 IPCC Guidelines); the factor 55.65 is the energy content of methane (MJ/kg CH_4) [44];
GE gross energy intake, MJ day^{-1}.

The gross energy intake for dairy cattle was calculated according to the 2006 IPCC Guidelines and Equation 10.16 [44], Eq. (5).

$$GE = \left| \frac{\left(\dfrac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} \right) + \left(\dfrac{NE_g}{REG} \right)}{\dfrac{DE\%}{100}} \right|, \tag{5}$$

where
GE gross energy, MJ day^{-1};
NE_a net energy for animal activity, MJ day$^{-1;}$
NE_i net energy for work, MJ day^{-1};
NE_{work} net energy for work, MJ day^{-1};
NE_p net energy required for pregnancy, MJ day^{-1};
REM ratio of net energy available in a diet for maintenance to digestible energy consumed;

NE_g net energy needed for growth, MJ day^{-1};
REG   ratio of net energy available for growth in a diet;
DE%   digestible energy in % of gross energy [44].

NE_m – net energy required by the animal for maintenance, MJ day^{-1}, see Eq. 10.3 [44], Eq. (6).

$$NE_m = Cf_i \times (\text{Weight})^{0.75},\tag{6}$$

where
NE_m net energy required by the animal for maintenance, MJ day^{-1};
Cf_i maintenance coefficient (default values from 2006 IPCC Guidelines, Volume 4, Chapter 10, Table 10.4 [44].

Activity (NE_a): net energy for animal activity, MJ day^{-1}, see Eq. (10.4) [44], Eq. (6).

$$NE_a = C_a \times NE_m,\tag{7}$$

where
NE_a net energy for animal activity, MJ day^{-1};
C_a coefficient corresponding to animal's feeding situation (default values from 2006 IPCC Guidelines. Volume 4, Chapter 10, Table 10.5) [44];
NE_m net energy required by the animal for maintenance, MJ day^{-1}.

Growth (NE_g): net energy needed for growth, MJ day^{-1}, see Eq. (10.6) [44], Eq. (8).

$$NE_g = 22.02 \left(\frac{BW}{C \times MW} \right)^{0.75} \times WG^{1.097}\tag{8}$$

where
NE_g net energy needed for growth, MJ day^{-1};
BW   the average live body weight of the animals in the population, kg;
C   a coefficient with a value of 0.8 for female milking cows;
MW   the mature live body weight of an adult female in moderate body condition, kg;
WG   the average daily weight of dairy cows, kg day^{-1}.

Lactation (NE_l): net energy for lactation, MJ day^{-1}, see Eq. (10.8) [44], Eq. (9).

$$NE_l = Milk \times \left(1.47 + 0.40 \times Fat \right),\tag{9}$$

where
NE_l net energy for lactation, MJ day^{-1};
Milk   amount of milk produced, kg of milk day^{-1};
Fat   fat content of milk, % by weight.

Pregnancy (NE_p): net energy required for pregnancy, MJ day^{-1}, see Eq. (10.13) [44], Eq. (10).

$$NE_p = C_{pregnancy} \times NE_m,\tag{10}$$

where
NE_p net energy required for pregnancy, MJ day^{-1};
$C_{pregnancy}$ pregnancy coefficient (default values from 2006 IPCC Guidelines, Volume 4, Chapter 10, Table 10.7 [44].

REM – the ratio of net energy available in a diet for maintenance to digestible energy consumed [44], Eq. (11).

$$REM = \left| 1.23 - \left(4.092 \times 10^{-3} \times DE\%\right) + \left[1.126 \times 10^{-5} \times (DE\%)^2 \right] - \left(\frac{25.4}{DE\%} \right) \right|, \quad (11)$$

where
REM   the ratio of net energy available in a diet for maintenance to digestible energy consumed;
DE%   digestible energy, %.

$$REG = \left| 1.164 - \left(5.160 \times 10^{-3} \times DE\%\right) + \left[1.308 \times 10^{-5} \times (DE\%)^2 \right] - \left(\frac{37.4}{DE\%} \right) \right|, \quad (12)$$

where
REG   ratio of net energy available for growth in a diet to digestible energy consumed;
DE%   digestible energy, 67 % or 73 %.

In addition to feed digestibility, 67 % consider introducing legumes to organic farms could increase feed digestibility.

3.6.4. *env₃ CH₄ manure, kt CH₄ $^{y-1}$ CO₂ eq*

Part of methane emissions is also generated in manure management. Therefore, methane emissions should be estimated based on specific manure management systems Eq. (13).

$$CH_{4\,manure} = \Sigma_{(T)} \frac{EF_{(T)} \times N_{(T)}}{10^6}, \quad (13)$$

where
$CH_{4manure}$ CH₄ emissions from manure management, for a defined population, kt CH₄ yr^{-1};
$EF_{(T)}$ emission factor for the defined livestock population, kg CH₄ head^{-1} yr^{-1}
$N_{(T)}$ the number of heads of livestock species/category *T* in the country;
T   category of livestock.

3.6.5. *CH₄ calculation of emission factor*

The emission factor (EF), kt head^{-1}, year^{-1}, EF kg CH₄ head^{-1} year^{-1}, for estimating methane emissions from manure was determined using Equation 10.23 in IPCC 2006 [44], Eq. (14).

$$EF_T = \left(VS_T \times 365\right) \times \left| B_{o(T)} \times 0.67 \frac{\text{kg}}{\text{m}^3} \times \Sigma_{S,K} \frac{MCF_{S,K}}{100} \times MS_{T,S,K} \right|, \quad (14)$$

where
EF_T annual CH₄ emission factor for livestock category *T*, kg CH₄ animal^{-1} yr^{-1};
VS_T daily volatile solid excreted for livestock category *T*, kg dry matter animal^{-1} day^{-1};
$B_{o(T)}$ maximum methane-producing capacity for manure produced by livestock category *T*, m³ (IPCC 2006 (Western/Eastern Europe) Table 10A-4);
$MCF_{(S,k)}$ methane conversion factors for each manure management system in Table 10.17 [44];
$MS_{(T,S,K)}$ a fraction of livestock category manure handled using manure management system in climate region *k*, dimensionless.

Basis for calculating annual *VS* production, days yr⁻¹ [44] Eq. (15).

$$VS = \left\lfloor GE \times \left(1 - \frac{DE\%}{100}\right) + (UE \times GE) \times \left(\frac{1 - ASH}{18.45}\right)\right\rfloor, \tag{15}$$

where

VS	volatile solid release excretion per day on a dry-organic matter basis, kg day⁻¹;
GE	gross energy intake, MJ head⁻¹ day⁻¹;
DE%	digestibility of the feed in % (67 % for dairy cows);
UE×GE	urinary energy expressed as a fraction of *GE*;
ASH	the ash content of manure calculated as a fraction of the dry matter feed intake (0.08 for cattle);
18.45	conversion factor for dietary *GE* per kg of dry matter (MJ kg⁻¹).

The number of animals and IPCC 2006 methodology used in the calculation to convert CH_4 emissions into CO_2 equivalents, the obtained emissions were multiplied by 28 [1]. Calculated data are summarised in Table 7 in the Annex.

3.6.6. env₂ Total N₂O emissions kt CO₂ eq.

Direct N_2O emissions (kg N_2O yr⁻¹) from manure management were calculated using the IPCC 2006 Guidelines Equation 20.25. $N_{(T)}$, $Nex_{(T)}$ and $MS_{(T,S)}$ data were taken from Enteric fermentation calculations, see Eq. (16).

$$N_2O_{D(mm)} = \left[\Sigma_s\left[\Sigma_T\left(N_{(T)} \times Nex_{(T)} \times MS_{(T,S)}\right)\right] \times EF_{3(S)}\right] \times \frac{44}{28}, \tag{16}$$

$N_2O_{D(mm)}$	direct N_2O emissions from Manure Management, kg N_2O yr⁻¹;
$N_{(T)}$	number of head of livestock category *T*;
$Nex_{(T)}$	annual N excretion rates, kg N animal⁻¹ yr⁻¹ (IPCC, 2006 Eq.10.31);
$MS_{(T,S)}$	fraction of total annual nitrogen excretion for each livestock category;
$EF_{3(S)}$	emission factor for direct N_2O emissions from manure management system S kg N_2O-N kg⁻¹ N in manure management system;
S	manure management system;
T	category of livestock [44];
$N_2O_{G(mm)}$	indirect N_2O emissions due to volatilisation of *N* from Manure Management, kg N_2O yr⁻¹ were calculated according to IPCC 2006 Equation 10.29. The default value for the emission factor (0.01) was used [44].

To convert total N_2O emissions (sum of direct and indirect) emissions into CO_2 equivalents, the obtained emissions were multiplied by 265 [1]. Input data and calculated data are shown in Table 8 in the Annex.

3.6.7. env₄ N₂O kt CO₂ eq. from soils urine and dung deposited by dairy cows

On organic farms, dairy cows can be on pasture for up to 160 days per year in Latvian conditions. Also, on small and medium-sized conventional farms, cows can be on pasture for part of the time. FPRP is the annual amount of N deposited in the pasture, range and paddock soils by grazing animals, in this case, dairy cows. FPRP is calculated using the 2006 IPCC guidelines, Equation 11.5 [44], Eq. (17).

$$F_{PRP} = \Sigma_T \left[\left(N_{(T)} \times Nex_{(T)} \right) \times MS_{T,P,RP} \right], \tag{17}$$

where

$Nex_{(T)}$ average annual amount of N excreted;

$N_{(T)}$ the number of heads of livestock species/category T in the country;

$MS_{T,P,RP}$ a fraction of livestock category manure handled using manure management system in climate region k.

It describes nitrogen from milking cows that is deposited on pasture. Table 9 in Annex summarises input data and calculations.

3.7. Economic Dimension Sustainability Evaluation

For input data (Table 4), the number of cows was multiplied by costs in organic and conventional dairy farming, see Eq. 18.

EUR/number of cows in dairy farming = number of cows × EUR/number of cows.   (18)

TABLE 4. INPUT DATA FOR THE ECONOMIC DIMENSION ESTIMATION [55]

Economic indicators	Conventional dairy farming, EUR/number of cows	Organic dairy farming, EUR/number of cows
Ec$_1$ Homemade fodder EUR/number of cows	269	364
Ec$_2$ Purchased fodder, EUR/number of cows	355	82
Ec$_3$ Equipment depreciation, EUR/number of cows	270	232
Ec$_4$ Wages and social insurance payments, EUR/number of cows	286	213
Ec$_5$ Veterinary costs EUR/number of cows	112	104
Ec$_6$ Administration costs, EUR/number of cows	150	173
Ec$_7$ Other costs, EUR number of cows	213	139

A summary of the obtained indicator values, which were further used to create the composite index, is available in Table 10 in the Annex.

4. RESULTS AND DISCUSSION

The overall score in CI for organic wheat production is 0.51, which is smaller than for conventional wheat production (Fig. 4). Organic wheat production has the highest score in CI for carbon footprint per land unit. Previous literature studies confirm that the transition to organic farming increases both the carbon sequestration capacity and also reduces the carbon footprint per land unit [56]. Conventional wheat production gets the greatest score among strategies for carbon footprint per product EUR/ha (wheat) The lowest overall score among strategies is based on possible low income during seasons. Organic wheat farming has the second-highest mean total costs score. It is less expensive, considering operations like fertilisation and weeding are restricted [1]. Regarding total costs EUR/ha, conventional wheat production got a lower score than organic wheat production but got a considerably higher score in CI for net income EUR/ha. Previous studies show that during 2019–2020 average price for wheat was 420 EUR/tons [57]. The lowest overall score among strategies is based on possible low income during seasons.

Fig. 4. Composite index for conventional and organic farming strategies.

Conventional dairy farming has the lowest score in CI regarding total costs, which means the highest total costs EUR/ha for traditional farming of dairy among strategies. Organic dairy farms got the highest overall score in CI, but conventional dairy farming had the lowest score among farming strategies based on total costs EUR/ha. The highest score for organic dairy farming is mainly partly based on total costs (EUR/ha) and net income (EUR/ha). Organic dairy farming has the highest score in CI among strategies for net income EUR/ha. Organic farming has lower operating costs and higher product costs, which can increase overall incomes. The highest support payments in net added value are for organic dairy farms. In organic farms, support payments play a significant role in generating revenue that can compensate for costs and lower yield in organic dairy farming [56]. EU member states can receive compensation and support payments to ensure the transition from conventional to organic agriculture, compensate for financial losses, and cover expenses that arise in organic farming [12]. Organic dairy farming has a lower production value in CI than conventional dairy farming. Conventional dairy farms have the highest score in CI regarding production value EUR/ha, with a score of 0.17. Based on 2021 data, conventional dairy farming is the leader in creating production value [24]. Organic dairy farming has a lower carbon footprint per land unit than conventional dairy farming, which got the lowest score in CI for carbon footprint per land unit. The more dairy cows in a group of farms, the higher the GHG emissions per land unit. The carbon footprint per land unit is thought to be lowest in organic farms [38]. By improving the quality of cow feed, CH_4 emissions from cow manure can be reduced [44]. Literature shows that the carbon footprint per product can be higher for organic farming than for conventional dairy farming [39].

The economic viability of small dairy farms depends on the existing European Union support for agriculture [58]. The results suggest that farms with 30–49 cows are more economically efficient in terms of profitability than larger or smaller farms. Because results indicate that having 30–49 or 50–99 cows indicates that larger operations benefit from economies of scale – where the cost per cow decreases as the farm grows in size. On the other hand, farms with fewer than 30 cows might struggle to cover fixed costs and achieve profitability, potentially due to higher per-cow costs and lower overall efficiency. In the figure, it is also shown that organic dairy farms are more profitable than traditional ones when

they operate with the same number of cows. Organic farms may have cost advantages in terms of lower feed and chemical inputs, although they might also have higher labour costs or certification costs [38]. The costs EUR/number of cows tend to be lower than those in conventional farms of the same size, especially in terms of purchased fodder [55]. This could be because organic dairy farms often grow their own feed, there is the absence of chemical inputs, and they rely on natural methods, for example, in fertility management (e.g., composting, manure), which can reduce the overall cost of production and lower veterinary costs [38]. Organic dairy farms tend to have higher quality feed, and organic standards encourage the use of natural remedies and holistic approaches to animal care; the animals usually have better health, lowering the veterinary costs [55]. These findings suggest that there are notable trade-offs between the two farming systems, with each excelling in different areas. Organic dairy farming is better aligned with sustainability goals, while conventional dairy farming provides more efficient production through technological advancements.
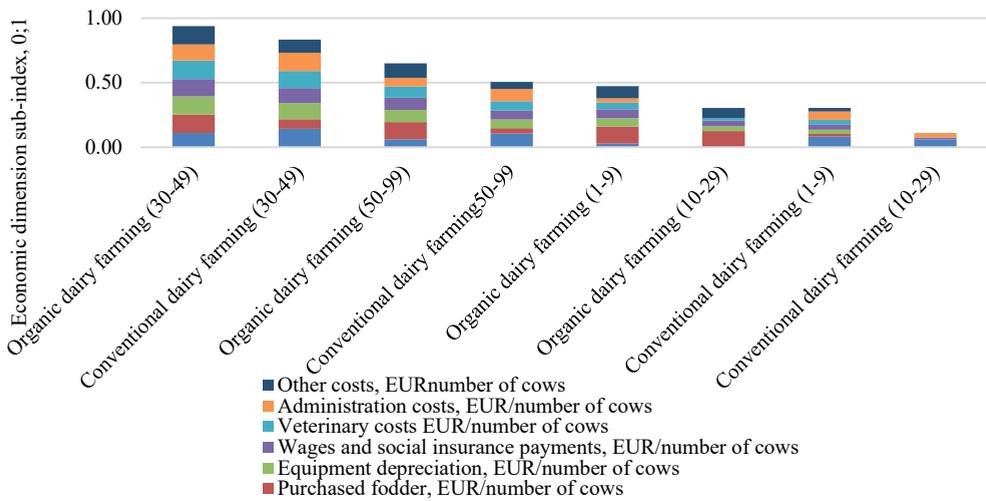
Fig. 5. Local-based economic dimension sub-index for conventional and organic dairy farming strategies.

The results of the sustainability index (Fig. 5) suggest that organic dairy farming has advantages in comparison to conventional dairy farming in terms of overall sustainability. From an environmental perspective, organic dairy farming outperforms conventional farming, regardless of herd size. This could suggest that practices in organic farming – such as the use of organic feed and reduced chemicals contributed positively to the cow's digestive system and produced lesser amounts of N_2O and CH_4 [61]. Results show that Increasing feed digestibility positively affects emissions resulting from intestinal fermentation processes (Fig. 6 and Fig. 7). On a per-cow basis, results show that organic dairy farms produce lower GHG emissions. On the other hand, conventional dairy farming seems to have an advantage in the technical dimension. From an economic point of view, based on results organic dairy farms are profitable compared to conventional ones of the same size. This could be because organic products often fetch higher market prices, and there may be lower input costs for chemicals and fertilisers despite potentially higher labour and certification costs [55]. In summary, organic dairy farming shows stronger environmental performance and better economic outcomes, while conventional dairy farming is more technically efficient in terms of production metrics. These findings highlight the trade-offs involved in dairy farming

systems and the need to balance environmental, technical, and economic factors when evaluating sustainability (Fig. 6).
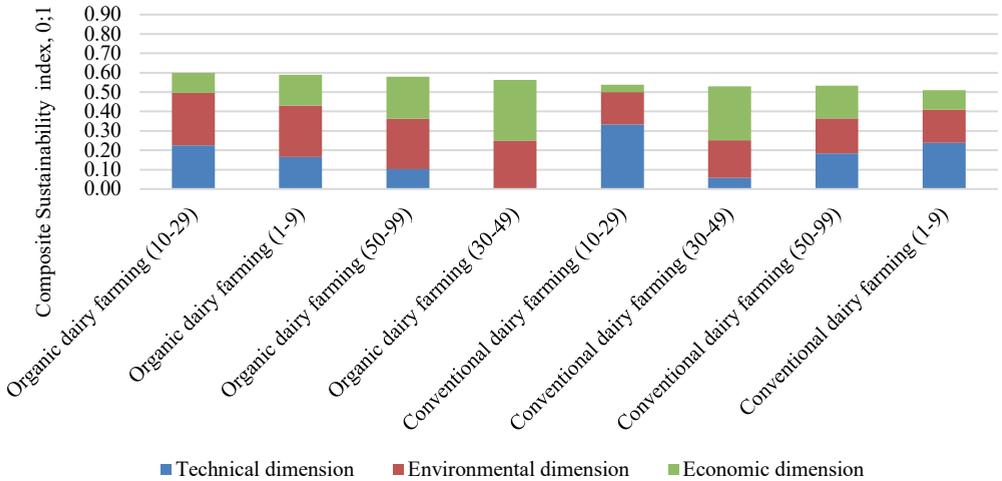
Fig. 6. Local-based Composite index for conventional and organic dairy farming strategies with DE 67 %.
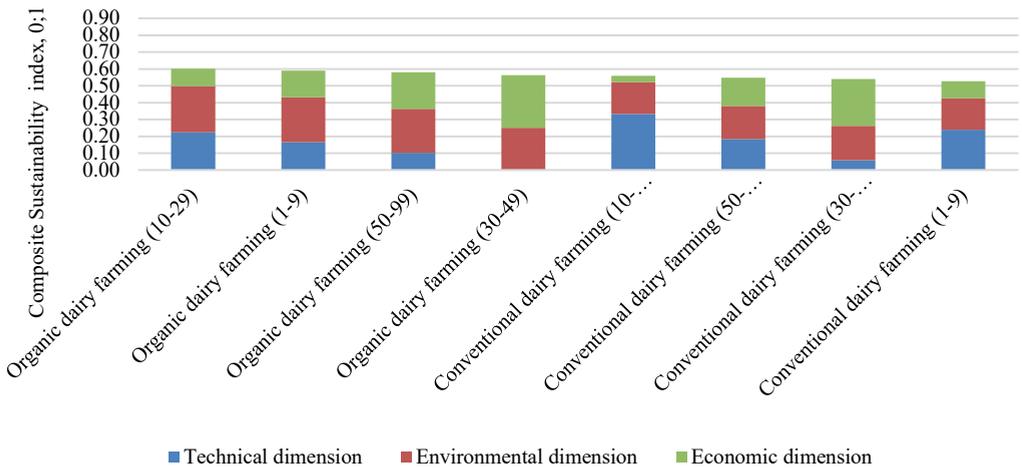

Fig. 7. Local-based Composite index for conventional and organic dairy farming strategies with DE 73 %.

4.1. Limitations of the Study

The composite index created in the first part of the study was based on data available in the literature on wheat cultivation and dairy farming in organic and conventional systems. The authors included only those indicators that can be compared with each other. Future research envisages additional indicators. including the inclusion of a biodiversity indicator if reliable data is found. Some data are averaged based on calculations, and some are from scientific articles or local reports. Additional environmental indicators, like the biodiversity index or parameters describing soil quality, should be included. Carbon footprint should be compared in different studies, geographic-based on locations, which can greatly impact carbon

footprint [14]. Findings suggest that there are notable trade-offs between the two farming systems, with each excelling in different areas. Organic dairy farming is better aligned with sustainability goals, while conventional dairy farming provides more efficient production through technological advancements. However, the broader implications of strengths and weaknesses could be considered. For example, while conventional farming may be more technically efficient, it could promote ecological (social indicators like employment and the opinion of the farmers). The overall picture that emerges from these sustainability indexes emphasises the necessity and benefits of the transition to organic dairy farming. Future agricultural systems may benefit from integrating the method used in this study for evaluating other industry areas from a sustainability perspective. This could improve the adoption of sustainable practices in this sector and help achieve the European Union's goals.

5. CONCLUSION

Organic dairy farms received the highest overall score in CI, while conventional dairy farming had the lowest score among farming strategies. Organic farming has a smaller footprint per land unit than conventional dairy farming, which got the lowest score in CI for carbon footprint per land unit. However, the carbon footprint per product unit in CI was higher for organic dairy farming than for conventional dairy farming. Organic wheat systems have a lower carbon footprint per unit of land compared to conventional systems. However, organic farming and its economic viability are greatly influenced by the availability of financing and support programs. Results suggest that organic farming systems, particularly in wheat production, present stronger environmental sustainability due to lower carbon footprints but require substantial financial support to remain economically viable. The comparison between organic dairy farming and conventional dairy farming based on sustainability indexes provides valuable insight into each system's strengths and weaknesses. In general, organic dairy farming shows an advantage in terms of environmental sustainability and economic performance, while traditional farming excels in technical efficiency. In terms of environmental indicators, case studies show that organic dairy farming can be superior to conventional dairy farming regardless of herd size by producing smaller amounts of greenhouse gases and contributing to their reduction if the cow's feed digestibility values are higher than the used feed values in conventional dairy farms. Conventional dairy farming outperforms organic systems in terms of technical indicators. both organic and traditional dairy farming have their advantages and disadvantages, and specific goals and long-term sustainability objectives should guide the choice between them. Policymakers, farmers, and consumers play crucial roles in shaping a future where farming systems can be both productive and sustainable. The method can be used for an initial analysis in decision-making, evaluating which farming strategies are more economically viable, which has the lowest carbon footprint, and how to choose from different alternatives.

ANNEX

Available at: https://zenodo.org/records/14636964

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Pros and Cons of Strategies to Reduce Greenhouse Gas Emissions from Peatlands: Review of Possibilities

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Abstract: Peatlands can become valuable resources and greenhouse gas sinks through the use of different management practices. Peatlands provide carbon sequestration; however, they are also among the greatest greenhouse gas emissions sources. The estimated annual carbon dioxide equivalent emissions from peat worldwide are 220 million tons. Novel strategies, methods, and technologies must be developed to enhance the sustainable use of peatlands and achieve climate targets by 2050, as set forth by the European Commission. There is no consensus in the scientific literature on which strategies included in the policy documents are more fruitful for reducing emissions. There are uncertainties and knowledge gaps in the literature that summarise the cons and benefits of each strategy regarding the potential of GHG emission reduction. Currently, peat is undervalued as a resource in the bioeconomy and innovation—a way that could save costs in peatland management. This review paper aims to analyse existing and potential strategies to minimise greenhouse gas emissions from peatlands. Studies show significant debates in the literature on whether the rewetting of peatlands and afforestation of previously drained peatlands can be defined as restoration. A more effective management of peatland restoration should involve combining restoration methods. The rewetting of peatlands should be realised in combination with top-soil removal to minimise methane emissions. The rewetting of peatlands should be used only in combination with revegetation after rewetting. One of the promising solutions for methane emission reduction could be paludiculture using sphagnum species. Products from paludiculture biomass can reduce GHG emissions and store long-term emissions in products. Paludiculture can also be the solution for further income for landowners and innovative products using the biomass of harvested paludiculture plants.

Keywords: climate change; emissions; peatland management; restoration; value-added products

1. Introduction

Peat plays a vital role in peatland ecosystems for vegetation growth and habitats, ensuring biological diversity [1–3]. Peatlands are critical in climate regulation as carbon sinks [1,4–9]. Peatlands are the most significant natural terrestrial carbon sink, which can continuously attract carbon from the atmosphere over long periods [8,10,11]. While peatlands cover only 3% [12–14] of the area, they store 30% of the world's carbon [8,9]. The resource's quality has decreased [15–18], and peat is currently viewed more as an emission source [5,15,19,20]. Peatlands have to be managed sustainably, interrupting extensive peatland drainage and extraction [21]. It is estimated that more than half of the peatlands in Europe are lost [22]. The increase in population density and intensity of agricultural practices has driven the increased drainage of large European peatlands [23]. In Europe, 25% of peatlands are estimated to be degraded [23].

In Europe, peatlands can be found in wide areas in Eastern Europe, Central Europe, and Northern Europe. These regions include Ireland, the United Kingdom, Germany,

Austria, The Netherlands, Poland, the Nordic countries, and all the Baltic states [24–26]. In Finland, more than 30% of the territory is covered with peatlands [12,17], but in Sweden, it is approximately 15% of the territory's land surface [4]. In Iceland, peatlands cover ~9% of the total area [27], while in Norway, peatlands cover ~6% of the land territory [12].

About 12% of the peatland area has been drained and used for forestry and agriculture [28]. The water table is low at the drained peatland level; therefore, carbon dioxide (CO_2) emissions increase. In peatlands where drainage has been carried out, CO_2 is the main GHG emission [29]. It has been determined that drained peatland causes ~2% to 5% of the emissions of greenhouse gas (GHG) emissions and ~10% of CO_2 emissions in total [30]. Degraded peatlands produce large GHG emissions and greatly affect peatlands' water-holding resistance [31].

Peat continues to be one of the main energy sources in Europe, for example, in Sweden and Finland [32]. The extensive drainage of peatlands for agricultural use, extraction as an energy source, and removal of all but a thin peat layer explain the decrease in peat quality [20,33]. It is predicted that in northern peatlands, GHG emissions from peatlands might increase in the following years because of global warming [34]. The European Union (EU) is rated as the third greatest carbon dioxide (CO_2) emitter of degraded peatlands after Russia and Indonesia [31], with annual GHG emissions of roughly 220 million megatons of CO_2 equivalents/year [35,36]. Some of the greatest CO_2 emissions in the EU from degraded peatlands are in Poland, Germany, and Finland [31].

The degraded peatlands used for agriculture are significant emission sources, emitting CO_2 and CH_4 into the atmosphere [37–39]. In their natural conditions, peatlands are also CH_4 emitters [40]. At the same time, natural peat bogs sequester CO_2 from the atmosphere and, thus, compensate for the emission of CH_4. The effect of N_2O on global warming is higher than that of CO_2 by an approximate factor of 265 [41–43]. Nitrous oxide (N_2O-N) emissions increase along with the increase in peat soil degradation. In the form of N_2O-N, EU peatlands release around 145 gigagrams of nitrogen per year [44,45]. The amounts of GHG emissions from peat are affected by the type of peat, the carbon-to-nitrogen ratio in the soil, hydrology, temperature, land use, and biodiversity [1,2,7,46].

In 2015, climate targets were set at the Paris Climate Conference (COP 21)—to reduce the GHG emissions in the EU by 40% by 2030 compared to 1990. The EU signed a binding agreement with states to act towards achieving these targets. To achieve these targets, the GHG emissions from peatlands must also be minimised [47]. Peat production in Europe is estimated to be twenty million tons annually [47]. If degraded peatlands are not restored in time, peatland ecosystems will be more fragile to carbon loss and could transform into dry forests, for example [48]. Peatlands' restoration aims to restore their natural functions [49]. After the drainage, the peatland decomposes and releases carbon [50]. Peatland restoration promotes carbon sequestration and emissions of N_2O reduction [34].

Returning hydrologic changes similar to previous conditions before drainage is one of the goals of peatland restoration [50]. Peatland restoration can increase ecosystem resilience against extreme weather conditions, biodiversity, soil health improvement, and climate change mitigation [22]. It is estimated that a thoughtful extraction site restoration might transform peatlands into carbon sinks in approximately twenty years. Peatland rewetting and revegetation are currently some of the most widespread approaches [49]. However, these strategies have disadvantages [51–53]. Thus, other solutions must also be explored to minimise peatland GHG emissions. Some studies in the literature show that severe uncertainties and underwater rocks exist in connection with restoration using inundation, resulting in nutrient leakage and increased methane emission concentrations [51]. Previous studies show that, when comparing nearly pristine peatlands and peatlands after rewetting, there are some uncertainties regarding the impact of the rewetting and its efficiency over a long period [50].

According to previous studies, the part of climate scientists and decision-makers do not assign a sufficiently influential role to peatland management as an instrument for climate change mitigation in the future. Also, there is a lack of requirements for reporting the removal of GHG emissions from wetlands [51,53]. Although there are several peatland

conservation policies for implementation in EU member states, there is a lack of mandatory requirements for governments [49]. Both policy documents and the scientific literature outline several strategies and methods to restore peatlands and reduce GHG emissions. However, there are some knowledge gaps and contradictive views on which strategies may be the most effective and appropriate [54,55]. Particularly, it is true for EU countries where peat is used for energy production [29,47,55–57]. Existing peatland strategies do not always solve issues regarding the restoration and management of peatland in sufficient detail [49].

Choosing proper peatland strategies and their effective realisation is crucial for reducing GHG emissions [54] and restoring peatland functions [48]. The selection of inappropriate peatland policies can have further adverse effects on peatlands, making them more vulnerable [49]. Among alternative approaches is the production of innovative peat-based products and materials if it is economically justified [57–59]. The potential of peat as a high-value natural resource has so far been undervalued [32,33].

Unlike other reviews, this review focuses on both the pros and cons of each peatland strategy and the alternative use of peat as a valuable resource for high-added products to reduce GHG emissions from peatlands, focusing on European peatlands.

This review paper is structured as follows: first, it is crucial to understand existing restoration strategies and their pros and cons to find innovative solutions. It analyses whether and how peatland emissions change after implementing each strategy. Data on strategies and techniques from the literature are analysed to identify the most effective ones in GHG emission reduction from peatlands.

Peat processing methods to obtain high-added-value peat products and materials to sequester emissions in these products are reviewed in the closing section.

2. Materials and Methods

This review emphasises the significance of peatlands' restoration in climate change mitigation, ecosystem services provision, and biodiversity conservation. The need for the sustainable management, restoration, and conservation of peatlands to preserve these valuable ecosystems and reduce GHG emissions is highlighted. Future research and integrated approaches are crucial to addressing peatland conservation and management challenges affecting climate change.

2.1. Framework for the Study

To identify and evaluate the potential approaches that could help reduce emissions when the source of the emissions is peat, the literature review consists of the following steps. The review first examines peatland restoration strategies and some risks associated with implementing these strategies. The review also examines peatland restoration alternatives and their advantages and disadvantages.

The final part of the review is focused on peat processing methods and potential solutions for peat as a valuable resource in various products and materials.
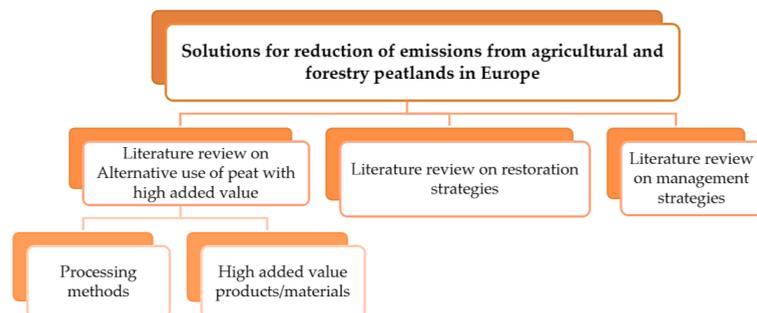
The framework of the study is shown in Figure 1.

Figure 1. The framework of the study.

First, the research field was identified, along with the knowledge gap and research question in the scientific literature, aimed at addressing the critical challenge in Europe—the reduction of GHG emissions from peat.

Within the framework of the defined research question, the possibilities of reducing GHG emissions of existing and potential peatland strategies and their obstacles were investigated. There are deep-seated knowledge gaps and uncertainties regarding which restoration strategies are more effective and what kind of blind spots and risks may occur after implementing these strategies. Similarly, there is also a question of the kind of benefits that can be expected after introducing strategies. This includes research into existing and potential strategies and innovative solutions for storing emissions using peat. The selected well-known bibliographic databases for a comprehensive investigation of peat and peatland literature analysis (More than 160 literature sources in total) were Web of Science, SCOPUS, Science Direct, and *Google Scholar.*

Inclusions criteria for qualitative analysis:

A collection of the scientific literature and reports was reviewed, addressing the following questions:

- Methane, carbon dioxide, and nitrous emissions from peatlands;
- Strategies to reduce emissions from peatlands;
- Mitigation measures and degraded peatlands;
- Negative side effects of strategies related to emissions, biodiversity, and hydrology functions;
- Potential of peat use in high-added-value products.

After defining the main questions, appropriate keywords and their combinations to answer these questions were selected. Keywords of four distinct categories were chosen—(1) overview of the state-of-the-art peatlands, (2) emissions, (3) restoration and management strategies, (4) and peat use for materials and products—for a qualitative analysis of the scientific literature combined with the study of reports.

For the qualitative analysis, as many literature sources as possible were used, focusing on those published in the last five years and related to European peatlands.

Sources regarding tropical peatlands were not included in the analysis due to their specifics.

The main keywords used to answer the research question are listed in Table 1.

Table 1. Summary of keywords used in the review paper.

Overview of State-of-the-Art	Emissions	Restoration and Management Strategies	Production of Materials and Products from Peat
Drained peatlands Drained peatlands in Europe Peatland protection Peatland management Sustainable management of peatlands Mitigation measures in degraded peatlands Peatland management scenarios Peat extraction in Europe Peat trade in Europe Energy and non-energy peat in Europe	Emissions from peatlands Methane, carbon dioxide, and nitrous emissions from peatlands Reduction of emissions from peatlands Potential emission savings from peatlands Greenhouse gas fluxes from peatlands Carbon emission reduction Carbon storage C sequestration	Strategies to reduce emissions from peatlands GHG emission effects of rewetting drained peatlands Rewetting strategies, water table peatlands Methane emissions from rewetting Peatland conservation strategies Paludiculture Fire management in peatlands Afforestation strategies in peatlands Topsoil removal Slow rewetting	Energy peat, peat as fuel, non-energy peat Peat processing techniques, peat production Peat in biotechnology The potential of peat use High-added-value products Peat is a valued resource for products with added value After the use of peat Possibilities of peat use Peat utilisation options Biochar from peat Horticulture Peat as insulation material, insulation panels, building materials Biofuel from peat as raw material Composite materials from peat
Main literature sources: [60–70]	[45,63,71–76]	[5,29,45,56,66,72–91]	[6,92–112]

3. Literature Review

3.1. Conservation and Restoration Policies and Strategies to Reduce Emissions from Peatlands and Their Side Effects

Increased attention is being paid to wetland ecosystems and their possibility of reducing GHG emissions and opportunities to improve the conditions of endangered peatlands [50]. Annual GHG emissions from drained peatlands are ~1.2–1.9 gigatons (Gt) CO_2 equivalent globally [105]. Annual GHG emissions from degraded and non-degraded European peatlands are reported to reach 582 megatons (Mt) of CO_2 equivalent [25].

For effective peatland restoration, it is necessary to consider both the hydrology of peatlands and species diversity and conservation. Peatland restoration is aimed at restoring degraded peatlands to their natural status and hydrological conditions, recovering their natural habitats, and, thus, increasing biodiversity [1,106–109].

3.1.1. Policies Related to Peatland Restoration

The Convention of Ramsar regulates wetland management policies internationally (since 1975) [53]. The Ramsar Convention is based on three principles: wetland smart usage, notification of the profound negative changes in wetlands, and provision of international cooperation regarding wetlands [54]. Despite the establishment of the Ramsar Convention, wetlands have been lost through drainage and degradation until today [54]. In the case of climate change mitigation policies, there are gaps in specific directions and rules in the Convention [54]. Some gaps arise concerning the defined wetland restoration aims and their generality regarding climate change mitigation [53]. There are some uncertainties in monitoring and evaluating the achievements of the farmer and landowner sides [54].

Within the scope of the Directive of Water Framework, the EU has considered the ecological conditions of wetlands. Still, the Water Framework Directive directly emphasises water quality conservation as a crucial element of sustainability [53]. In 2019, the Directive of Water Framework was revised, establishing that climate change mitigation solutions will be sought through developing guidelines and adaptation practices [53]. In 2019, the United Nations Environment Assembly, in cooperation with the Convention of Ramsar, promoted the establishment of a worldwide peatland inventory [50].

In the EU Biodiversity Strategy of the European Commission (revision 2020) [110], a vision for restoring nature in Europe, aimed at benefiting the environment, nature, and citizens, was set. Policies included in the strategy are aimed at preserving and restoring peatlands with an emphasis on the role of peat in carbon sequestration, as well as preserving valuable habitats for various species [21,110].

The United Nations' Sustainable Development Program has been established to promote peatland management in Europe for 2030 [49]. In its framework, specifically the Peatland Restoration program for sustainable water resources, it aims to increase knowledge for more sustainable decision-making. Support for peatland restoration as a priority in peatland conservation is the main aim of the program. Realising strategies and management activities for peatlands, the program will encourage the biological diversity of the peatland ecosystem and maintain previous conditions before drainage. The benefits of this program are also related to the increased well-being of the peatland ecosystem, including peatland fauna and flora [110].

Globally predicted investments diverted to peatland restoration are approximately USD 19 billion yearly [64,112]. In the year 2020, the Government of Scotland committed to investing more than EUR 250 million in the next ten years for peatland restoration [113–116]. Costs for peatland restoration can be long-term and short-term. Costs can be divided into capital costs for restoration and staff costs, including workers and costs regarding peatland restoration experts [117].

In order to achieve the aims of national peatland strategies, there is a crucial role for private finance. One of the most significant financial sources for peatland restoration and the realisation of strategies is the European Agricultural Fund for Rural Development and the EU Common Agricultural Policy and EU Life Program. One of the options for

revenue from private investors is carbon finance. For the reduction of GHG emissions from peatlands, it is possible to obtain carbon certificates [31].

3.1.2. Peatland Management and Restoration Strategies

Peatland management can be realised in different ways, including reducing GHG emissions by maintaining wet conditions in peatlands, including paludiculture [36] and restoring degraded peatlands [36]. Several policy instruments can be applied to regulate European peatland management. For example, the Peatland Code [31,115] includes standards to evaluate GHG emissions from peatlands. Carbon labelling and certification, used successfully in France, can be mentioned among other policy instruments in peatland management. Regulations of peatlands [3,8] provide binding provisions and initiatives to engage landowners in peatland restoration and management. Restoration programmes for deteriorated peatlands include rewetting and revegetation in large areas [117].

Among several member states in the European Union, national strategies were developed for more effective peatland management in sectors [53]. Even though the specific aims defined in the national peatland strategies differ for each country, the main strategies are related to protection through sustainable management and the use of peatlands [31]. Peatland national strategies can significantly affect the increase in the sustainable use of peatland [31]. On the other hand, a shortage of peatland policies at the national level can hinder local climate change mitigation solutions [53]. Although the structure of national peatland strategy depends on country specifics, strategies should include insight into issues regarding peatland conservation and restoration, also including specific measures for sustainable peatland use [31].

National peatland strategies have already been developed and adapted, for example, in England, Finland, Irelan Austria, Germany, and Scotland [31]. In the context of drained peatlands, European countries like Finland, Germany, and Poland are the most significant CO_2 emitters. In the time period of 2011–2015, Ireland, Scotland, and Finland developed their national strategies, but strategies regarding peatland were implemented only in the years 2020 and 2021 [31]. In these places in Europe, the role of sustainable peatland management has increased in recent years [31].

England's action plan regarding peatland conservation and restoration was issued in 2021 and aimed to move towards zero-emissions targets related to peatland restoration. According to the plan, the aim is to achieve appropriate peatland conditions for peatlands in the territory and move towards more sustainable peatland management by 2040 [31].

In 2021, Northern Ireland issued its national peatland strategy defining targets for 2040. The strategy focuses more on semi-natural peatland conservation measures, aiming to reach good conditions in 2040 for all semi-natural peatlands in Northern Ireland [31]. Austria and Germany developed their national peatland strategies in 2022. Austria's strategy focuses on the conservation of peatlands, the achievement of a more sustainable use of peat, and less use of peat in horticulture. According to the strategy, support for carbon emission reduction development programmes is included in the national peatland strategy of Austria [31].

Germany's national peatland strategy focuses on returning and conserving natural conditions in peatlands using a rewetting approach. Also, the strategy focuses on peatland use in paludiculture and the more sustainable further use of peat. The strategy aims to reduce 5 million tons of CO_2 from peatlands in Germany by 2030. One of the greatest steps defined for CO_2 emission reduction from peatland is to terminate the extraction of peat in Germany by 2040. Regarding strategy in the time period of 2027–2031, peat use in horticulture will also be gradually discontinued [31].

Various strategies and approaches are known to reduce GHG emissions, including the reduction of the intensity of agriculture, peatland afforestation and reforestation [73], and peatland rewetting [117,118]. Also, paludiculture methods have become more widely used in recent years [119]. Other restoration methods include, for example, restoring natural marsh vegetation or planting vegetation [40]. The existing emission mitigation strategies are shown in Figure 2.
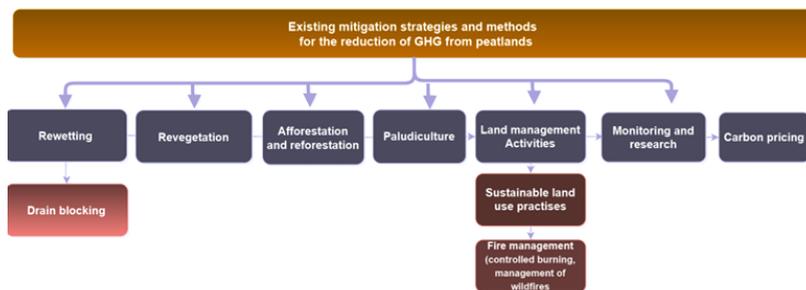
Figure 2. The existing mitigation strategies for the reduction of emissions from peatlands.

(1)   Rewetting may cause nutrient leakage in peatlands

One of the most often used methods to raise groundwater levels is peatland rewetting. Peatland rewetting is performed in degraded and drained peatlands to restore hydrological conditions [29]. According to estimations, peatland rewetting is effective if the water table is 20–30 cm [29] below the peat surface throughout the year [29].

Technological solutions such as drainage blocking allow for water retention in previously drained peatlands. It gradually raises the groundwater level, hence restoring a hydrological regime similar to that before the artificial drainage of the peatlands [120].

Methods of peatland rewetting

The rewetting of peatlands using drainage blocking, small dam construction, and other methods is further described. Drain-blocking is a method used in rewetting peatlands, where the drainage areas of drained peatlands are blocked using technological structures, thus raising the water level. Ultimately, the drainage paths are blocked to prevent debris and trees from entering. Peat may settle within the dams and cause leakage. Therefore, the dams are recommended to be higher than the surrounding bog surface [12,121]. Another rewetting method to prevent CO_2 emissions from degraded peatlands is drainage blocking with small dam constructions. It is estimated that an annual CO_2 emission reduction of 1.4–1.6 million tonnes yearly can be achieved by rewetting a peatland forest area of 590 km^2 using small dams [122].

Pros and cons of peatland rewetting

Studies predict that by delaying or refusing to rewet, GHG emissions from degraded peatlands could reach 12 to 41% by the year 2100 [32,42,117]. Previous studies show that CO_2 emissions decrease after the rewetting of peatlands [123]. Peatland rewetting reduces emissions from peat mineralisation processes and reduces land subsidence [78,124,125]. The benefits of peat rewetting are not only related to the reduction of GHG emissions, but studies indicate that rewetting can also preserve and even increase biodiversity and restore ecosystem services because after rewetting, peatlands can be returned close to the state they were in before the drainage was performed and restore species' habitats. Also, studies show that peat rewetting can improve the nutrient balance regulation in peat [124]. Peat rewetting can gradually reduce the overall global warming potential, reducing the emissions of GHG from the soil in the long term (100 years) [124].

Groundwater level

Although rewetting methods have several benefits, rewetting as a strategy for peatland restoration also has drawbacks [52]. During and after peat rewetting by drain-blocking or small dams, CO_2 emissions decrease, but the groundwater level rises, which can also change surface water levels, resulting in increased CH_4 emissions. Variability in the groundwater level and incomplete flooding may also affect the anticipated reduction of CO_2 emissions. For peatland rewetting to be successfully implemented and effective, the hydrological regime must be controlled, and no water level fluctuations are permitted; the water level must be sufficiently high and stable. Blocking runoff is considered the most economically

feasible solution for small areas of agricultural land. However, in this case, it is more difficult to control the groundwater level [14,117].

Due to peat rewetting, the groundwater level must not be too low or too high. A low groundwater level will affect vegetation in the peatland, causing carbon emissions. A groundwater level that is too high will cause surface water to accumulate and form lakes. A groundwater level that is too high will cause surface water to accumulate, forming lakes that, in turn, also hinder vegetation growth and negatively affect biodiversity [52] in peat bogs [65]. Therefore, the groundwater level must be continuously monitored. One can also use peat or wood for drain-blocking or dam construction. However, there is less information about the efficiency of using such raw materials in peatland rewetting [81]. The amount of GHG emissions reduction after rewetting can differ regarding peatlands' biological processes [5]. Also, emissions vary due to factors like vegetation, level and water table fluctuation, and land use history [5].

Carbon dioxide (CO$_2$)

Based on the literature, it is estimated that CO$_2$ emissions will reduce after the water table level increases [29]. It is estimated that increasing the water table level by about 10 cm can reduce emissions of three tons of CO$_2$ equivalent ha^{-1} yearly [30]. Some studies suggest that rewetting peatlands and restoring the hydrological conditions using dams or drainage blocking can reduce CO$_2$ emissions by 70%, and rewetting peatlands can reduce or even stop carbon loss [45]. As previously mentioned, GHG emissions after rewetting can vary, from strong sinks of ~8 tons of CO$_2$ equivalent ha annually to 0.71 tons of CO$_2$ equivalent ha annually [5]. For large emissions sources, it could be even 25 to 53 tons of CO$_2$ equivalent ha annually [5]. Studies in 2023 [29] showed that rewetting drained peatlands can reduce CO$_2$ emissions by 1.343 ± 0.36 Mg CO$_2$ -C ha^{-1} year $^{-1}$ [29]. For the EU, peatland mitigation potential through rewetting is estimated to be ~51–54 megatons of CO$_2$ equivalents annually [36]. The European Commission estimated that interrupting peat extraction would be possible to achieve an emission reduction of ~9 megatons CO$_2$ equivalent annually [5]. According to studies, rewetting can reduce annual CO$_2$ emissions in forested peatlands by as much as 15.4 tons of CO$_2$ equivalent per hectare, 25% lower than emissions before forested peatland rewetting [29]. If the rewetting of degraded grasses is carried out on peat soils, it is estimated that it is possible to reduce emissions by 20 tons of CO$_2$ equivalent per hectare annually. The rewetting of cultivated crops can reduce CO$_2$ emissions by even 30 tons of CO$_2$ equivalent ha^{-1} annually. There is a reported annual reduction in GHG 773 tons CO$_2$ equivalent for a rewetted peatland in northeastern Germany [126]. From 1990 to 2019, roughly 150 hectares of drained organic soils were rewetted on forest land in Sweden. The cumulative decrease in emissions was 9.5 kilotons over two decades, but the factual numbers could be higher [127]. It is estimated that rewetting all organic soils in Denmark will result in a reduction of CO$_2$ emissions of about 4.1 million tons [127].

Methane (CH$_4$) emissions

Determinants of CH$_4$ emissions in naturally formed peatlands include the pH level of vegetation and soil, hydrological regime, and groundwater depth [40,125]. As a result of the increase in water table level due to rewetting, methane forms a more potent greenhouse gas than CO$_2$ [49]. The radiation efficiency of CH$_4$ is substantially larger than that of CO$_2$ [125]. In drained peatlands, CH$_4$ emissions are low if the water level is less than 20 cm below the surface [39]. Rewetting may increase the CH$_4$ emissions and cause the input of nutrients in the short term [39]. Peatlands, after rewetting and sequestering CO$_2$, may emit up to 46% more CH$_4$ [25,40].

The uncertainty in the scientific literature regarding emissions from rewetted peatlands is significant [29,45,83]. The 2014 Intergovernmental Panel on Climate Change (IPCC) Wetlands Supplement excluded emissions from rewetted drainage ditches. After rewetting, ditch systems or networks of plugged or backfilled canals are left open, and the rise in the water table results in CH$_4$ emissions [128]. Few studies have shown that CH$_4$ emissions from peatlands in northern regions have been rewetted for more than ten years [106]. For

this reason, changes in GHG emissions from these peatlands remain to be discovered. After peatland rewetting, litter decomposes faster, which may raise CH_4 emissions for up to 30 years [37,112]. One of the latest studies has shown that drained peatland rewetting can cause an increase in CH_4 emissions of 0.033 ± 0.003 Mg CH_4-C ha^{-1} on average after rewetting yearly [29]. CH_4 emissions could be reduced through diverse vegetation growth [37,40,112].

Nitrous oxide (N_2O)

Where drainage has been previously performed, peatlands can act as a potent or insignificant N_2O emission source. This depends on land use and geographical location [39]. Natural peatlands usually emit low amounts of N_2O. Rewetting has often been proposed to reduce GHG emissions from drained peatlands. An assumption made by the IPCC is that undrained and rewetted peatlands do not emit N_2O. It is based on research results that saturated and undrained peatlands emit nitrous oxide in minimal amounts [129].

During the rewetting of drained peatlands, the production of N_2O and, thus, its emissions may increase in the short term [39]. Vastly degraded peat with a high nutrient availability contributes to increased nitrification and denitrification [39]. Studies on changes in nitrous oxide emissions after rewetting are fewer for degraded peatlands. Comparative studies have been conducted on the N_2O emissions of rewetted and naturally formed peatlands. According to the estimations, emissions from nutrient-poor peatlands are 0.08 m^{-2} a^{-1}, and from nutrient-rich peatlands, they are 0.05 m^{-2} a^{-1}. Peat rewetting effectively reduces N_2O emissions in drained peatlands, and it has been believed that by rewetting, it is possible to achieve emissions close to the state of natural peatlands, producing from 0.022 to 0.191 m^{-2} a^{-1} annually [129]. If the water level throughout the year approaches the surface, the emissions are minimal or even non-existent. If the water level annually is 10 to 30 cm below the soil surface [29], both aerobic and anaerobic conditions are maintained on top of the soil, and nitrification and denitrification produce N_2O. Thus, with this water level, peatland rewetting can create N_2O-N emissions [29,45,72,125]. In the literature, rewetting is considered the most effective approach to decreasing N_2O emissions from degraded peatlands. An estimated reduction in N_2O emissions by ~70% in the next 30 years has been reported [45], and all degraded peatlands in Europe are rewetted—an essential step towards climate goals [11,129].

Rewetting less degraded peatlands first would give an estimated 30% reduction in emissions. It is important to understand the processes generating each GHG separately. However, there is also a need to assess the total emissions of multiple GHGs objectively. The cumulative N_2O, CO_2, and CH_4 emissions after peat rewetting should be evaluated because these gases accumulate in the atmosphere, but the duration of their residence there is different [11].

Nutrients and dissolved organic carbon (DOC).

The drainage of peatlands results in nutrient accumulation in the upper layer of the peat. Therefore, rewetted peatlands can be phosphate and ammonium nutrient sources. Regarding nitrate, rewetted peatlands can be a sink of nutrients [39]. It has been confirmed that the drainage of peatlands causes increased concentrations and fluxes of dissolved organic carbon (DOC) in streams and rivers [130]. Rewetting of peatlands in temperate and boreal regions can positively affect the DOC concentrations in freshwater [130]. Despite this positive effect, peat rewetting may cause nutrient leakage in the short term [39] and phosphate ion (PO_4^{3-}) mobilisation, which may lead to further eutrophication due to the input of nutrients. There are a few contradicting studies that claim that peat rewetting increases DOC concentrations in waterbodies and promotes an increase in CH_4 emissions [39].

Rewetting is not suitable for all cases of peatlands. The prospects of peat rewetting are influenced by the location of the peat and the need to maintain a regularly high level of water. Rewetting after peat cutting could be a sustainable strategy, as rewetting is often more straightforward when the peat is removed [117,121].

In the short term, rewetting may have negative consequences, such as degraded water quality in downstream areas or aggravating GHG emissions [106,117,131]. Rewetting is also

reported to cause slight changes in the chemical composition of the peat. The quality and chemical composition of the water used for rewetting affects the efficiency of the rewetting of peatlands [55,71]. When water with high phosphorus concentrations is used for peat rewetting, nutrient leakage and eutrophication risks will increase [70,71]. It is possible to use salt water, brackish water, or freshwater from rivers or groundwater [39].

Peatland management requires striking a balance between CO_2 emissions from drained peatlands and CH_4 emissions from rewetted peatlands. Before deciding, it is important to consider both the radiative properties and longevity in the atmosphere of CO_2 and CH_4. CO_2 is a weaker GHG with a longer lifetime, while CH_4 is a potent GHG with a short residence time in the atmosphere [62]. Despite the environmental gains from peat rewetting, the cultivation of crops (not wet-adapted) and conventional agriculture, in general [20], is hardly possible due to the high water level. The lands nearby are also not functional for agricultural practice [20,117,127].

The restoration of rewetted peatlands to their original conditions may not happen instantly; it may take decades. This is especially true for peatlands in temperate climate areas due to substantial disturbance and prolonged drainage. These peatlands are predominantly fed by groundwater, and oxidation occurs during drainage, altering the peat's physical properties. The changes include increased bulk density, decreased porosity, hydraulic conductivity, and storage capacity. These changes, in turn, lead to more substantial fluctuations in groundwater levels. The effects of peatland rewetting have been studied in the field. Among the main gains from rewetting is a substantial decrease in soil subsidence [125], which prevents carbon mineralisation in deep soil [78].

Farmers and landowners receive carbon certificates as financial compensation mechanisms for peat rewetting on their lands, for reducing CO_2 emissions per hectare per year after rewetting. Monitoring and reliable measurements are needed to establish emission reductions accurately so that landowners can be compensated [116,132,133].

(2) Revegetation of peatlands

In addition to peatland rewetting, revegetation can be an appropriate measure in peatland restoration [50]. After peat rewetting, revegetation is the next stage to restore the peatland to its initial condition regarding species diversity. Restoring vegetation is also essential to reducing GHG emissions [1,134]. Planting vascular plants after rewetting can have a positive effect on the reduction of increased CH_4 emissions, promoting pumping out CH_4 [50]. Scientists have estimated that active revegetation can be a promising solution for introducing sphagnums and lowering CH_4 emissions after rewetting [50]. In some studies, it is estimated that rewetting should be combined with revegetation methods after rewetting to reduce CH_4 emissions, and without appropriate revegetation, it is complicated to gain emission reduction [50].

Revegetation can improve carbon sequestration, while in peatlands without a sufficient vegetation layer, soil carbon is reduced; there are also soil erosion risks. Revegetation directly impacts whether peatland rewetting will be considered sufficiently effective in the long term [1,134]. Restoring vegetation is critical for peat formation processes, and it is possible to restore degraded peatlands [7,134]. Peatland-typical plants are used in revegetation [3,134]. In peatlands, where the hydrological regime and vascular plants have been restored, the soil accumulates higher amounts of carbon and organic matter, characteristic of peat soils [7].

Other hydrological regime restoration methods are described in the scientific literature, which are discussed less than peat rewetting with drain-blocking or dam constructions. These methods rely on the slow rewetting [51] or top-soil removal of peatlands before rewetting [70,87,88]. When the water table in a peatland is raised over a more extended period, the risk of rising phosphorus concentrations, nutrient leakage, and CH_4 emissions is reduced. In the slow rewetting process, the water table is gradually raised, leading to a partial saturation of the degraded soil layer, which reduces phosphorus mobilisation [51].

(3) Topsoil removal of peatlands.

To reduce the risks of nutrient leakage and restore nutrient-poor conditions, it is possible to remove the top layer of soil before peat rewetting [39]. This practice is called top-soil removal. After peat extraction, nutrients are most released in pre-drained peatlands and bogs [117,135]. Top-soil removal methods increase the effectiveness of peat rewetting and reduce GHG emissions. In peatland regeneration and GHG emission reduction plans, top-soil removal is recommended to reduce nutrient release, mobilisation, and CH_4 emissions that form after rewetting by first removing the eutrophic topsoil and promoting peat regeneration [70,89].

The wider use of the method is restricted by high investments and a lack of knowledge. Removing the topsoil before peat rewetting decreases nitrogen and phosphorus levels, reduces the risk of eutrophication and algal blooms, and diminishes DOC, CH_4, and CO_2 emissions. Studies have estimated that by removing the nutrient-rich topsoil in agricultural lands before rewetting, the risk of eutrophication decreases by 80 to 90%, DOC losses by 60%, and CH_4 emissions by 99% [70]. The estimated global warming potential is reduced by 50–70% by first performing top-soil removal [70]. The removed topsoil can be used in agriculture against land subsidence. In general, top-soil removal can contribute to the soil's carbon balance and enhance peatlands' rewetting efficiency [70,89].

(4) Afforestation of peatlands

In the literature, another method of peat restoration is the afforestation of peatlands. It is an efficient way to store atmospheric CO_2. Studies have shown that afforestation can reduce emissions, reduce net sinks, and increase tree biomass. CO_2 is absorbed and sequestered through afforestation in wood biomass grown in degraded peatlands. The afforestation of degraded peatlands can also improve ecosystem resilience [136,137]. It is estimated that if the afforestation of previously drained agricultural lands is completed, it is possible to reduce the annual CO_2 emissions by 7.8–9.8 tons of CO_2 equivalent/hectare [127].

EU member states prefer a vast peatland afforestation of drained and degraded peatlands, insisting that afforestation without rewetting can be considered restoration based on the Nature Restoration Law [. However, some studies indicate that only the afforestation of degraded peatlands is insufficient to restore the peatland ecosystem, return the wetland species, restore habitats, and return biodiversity to the original state [37,86]. To restore deteriorated peatlands, the hydrological regime must first be recovered [86]. The drained and degraded peatlands emit CO_2, and CO_2 storage in trees after afforestation does not entirely compensate for these emissions [46,138].

Growing trees in degraded peatlands causes tree transpiration and lowers the water table [106]. Fire is a risk in peatlands after afforestation. Forest fires have increased in boreal regions due to climate change. Fires in reforested peatlands cause carbon loss. Reforestation also impacts nutrient release and water storage capacity [46]. CO_2 uptake exceeds CH_4 losses, resulting in a net CO_2 equivalent reduction in the longer period [139]. Studies have demonstrated that net carbon emissions from peatland reforestation exceed the emissions the planted trees absorb. In Scotland, afforestation on shallow peat and mineral soils with minimal disruption has increased carbon storage. Afforestation is not a common method in Scotland to restore peatlands due to scientifically indicated risks and alternative methods being investigated [12,139].

(5) Paludiculture

The paludiculture method implies land-use change, from degraded pre-drained peatlands to cultivating plants typical in peatlands in wet conditions. In recent years, paludiculture has become an increasingly used method to reduce GHG emissions from peatlands [119,140]. In paludiculture, plants that tolerate wet conditions are grown. The constant hydrological conditions and cultivated wetland plants reduce peat oxidation and CO_2 emissions [141]. Paludiculture strategies are classified into two categories—deliberately cultivated plants such as Cattail (Typha) or sphagnum moss, which are planted and harvested. The second category is moisture-resistant plants that seed naturally, for example, reeds,

which are harvested after a certain period [25]. The cultivated plant biomass is a suitable bioresource for sustainable energy production. The paludiculture approach can reduce N_2O and CO_2 emissions [119,142–144]. Besides reducing emissions, the peatland quality is improved as peatland-native plant species are planted and cultivated, and farmers and landowners gain financially from cultivating and harvesting the plants [143].

In paludiculture, farmers and landowners use the land, but after rewetting, the land is not suitable for growing crops. Paludiculture allows for growing and harvesting moisture-resistant plants and using the harvest to produce energy or innovative products and materials [45,119]. Similarly to peat rewetting, the plants used in paludiculture need a high water table that does not change throughout the year, contributing to CO_2 emission reduction [25]. Areas proper for paludiculture, mire, shallow lakes, or wet forests can be formed after the rewetting of peatlands [34].

Cultivating paludiculture crops in peatlands can be considered carbon farming on organic soils. Carbon farming implies agricultural practices that increase the rate at which CO_2 is captured from the atmosphere and converted to soil organic matter. Carbon farming in paludiculture can reduce peatland GHG emissions [84,144]. Emission and emission reduction from paludiculture can be hard to evaluate because of the diversity of the wetlands plants that can be used in paludiculture practices. In shallow lakes, CO_2 emissions might be low to moderate [11].

Paludiculture practices and paludiculture-based products can positively affect emissions reduction from traditionally used energy-intensive products and the storage of carbon in these products [5]. The harvested biomass may serve as a resource to produce high-added-value products [25].

Paludiculture lowers CO_2 emissions compared to agriculture, and emissions can also be reduced through carbon storage in products [5,84]. Paludiculture products can replace products that create high carbon emissions [5]. Reed substrate application in agricultural lands can reduce the emissions and store GHG. Greenhouse gases are stored in various products obtained from paludiculture biomass [83]. It is estimated that reed substrate and insulation boards from cattail positively impact GHG emission reduction, compared to land use for agriculture. Reed substrate is ~3 tons of CO_2 equivalent ha^{-1}, and for cattail (Typha) insulation boards, they are ~6 tons of CO_2 equivalent ha^{-1} average [5]. For Reed, the CH_4 emission reduction potential is influenced by the level or water table. According to studies, for the achievement of a larger potential for emissions reduction, greater control of emissions in paludiculture should be carried out [5].

Cattail (*Typha latifola* or *Typha angustifola*), canary grasses, or sweet grasses are examples of plants [82] that are deliberately grown in paludiculture. The applications of harvested paludiculture biomass include insulation and sound insulation panels as building materials and other materials for the construction industry and the energy sector [57]. It is estimated that berries, especially cranberries, are also proper for restoring and capturing carbon using paludiculture practices [34]. Further research is needed to investigate paludiculture and its potential to reduce CO_2 and other GHG emissions in peatlands, as there are knowledge gaps and uncertainties in the scientific literature [5].

(6) Peatland management to prevent fire

Forest and peatland fires create large carbon emissions, and degraded peatlands are particularly at risk [85,145,146]. Peatlands where the drainage has been performed before are more vulnerable to wildfire risks [34]. Afforested peatlands, where drainage had previously been performed, are especially seriously exposed to wildfire risks because of their more frequent periods of drought [34].

It is estimated that vast boreal peatlands are exposed to wildfire risk. During boreal peatland wildfires in the combustion process, carbon fluxes are released in the amount of ~85 kg m^{-2} [30]. Boreal peatland's intensive use as a gas or an oil may increase drainage speed and wildfire risks in peatlands [30]. Boreal peatland wildfires can result in a 10% increase in carbon emissions in previously drained peatlands [30].

Early warning systems, controlled burning, and the construction of firebreaks are among the fire prevention measures in peatlands [85,145,146]. Controlled burning is an efficient measure, but knowing how to contain fire is critical. After controlled burning, vegetation in peatlands grows and develops, increasing the carbon sequestration ability [76,141,145].

Reducing emissions from peatlands requires new management methods, innovative technological solutions, and instructions to farmers and landowners [141]. To monitor and prevent peatland fires, firefighting stations may be located near degraded peatlands to allow for acting in the case of fire in the shortest possible time. The firefighting department's role is not only to prevent and extinguish fires but also to cooperate with the local authorities and advise landowners on the best peatland management practices [1,74,118,147,148].

3.2. Peat Processing Technologies and Peat Applications

To reduce peat emissions in Europe, effective restoration measures and, together with scientists and industry representatives, investigating how peat is a valuable resource for producing higher-added-value materials and products are needed. Storing carbon in products reduces emissions from peatlands [12,67,95,125].

3.2.1. Technologies and Technological Processes in Peat Processing

Peat can serve as a replacement for fossil-based resources. The potential applications of peat biomass include using it as a raw material for building materials, in the food industry, and even as pharmaceutical products. Only a limited perspective can be found in the scientific literature on how peat can be processed for use in innovative products and materials as the key component or additive [57,117,149]. Peat can be used for energy production through gasification, direct combustion to produce electricity, or methane production [150]. Direct combustion for power production is a simple method for converting biomass energy into electrical energy. The process involves converting chemical energy into steam and then using this steam to rotate the turbine and generate power [150].

Gaseous and liquid substances are transformed at high and elevated temperatures in the gasification process. The thermochemical processes include drying, pyrolysis, combustion, cracking, and reduction. Biomass is converted into gaseous biofuels. It is a more complicated method than direct combustion [150].

Peat methane utilisation is a processing method for use with methane fuels, converting biogenic gas into electricity. The actual collection of CH_4 from peatlands is meant here [150].

Processing techniques for energy peat are summarised in Figure 3.

In Finland, 3–5% is used as a fuel resource [150]. However, peat is also used as a raw material in agriculture and livestock farming [150]. In northern Europe, peatlands are often transformed into grasslands, which can be used for dairy and livestock farming. In recent years, the bioeconomy has become a possible solution for the more sustainable use of peatlands [36,46,126]. The use of peat for energy purposes is evaluated with the lowest added value [33]. Developing technologies that can convert biomass into liquid biofuels, such as hydrothermal liquefaction, pyrolysis, and gasification, is an active area of research. Volatile organic compounds and carbon found in peat biomass can be converted into liquid biofuel [102,151].

Using different methods, peat can produce thermal insulation and raw materials in various construction materials substrates, and pharmaceutical products [152–156]. Also, an agro-industrial resource, peat, has a high but not fully used potential [57,58]. The following section discusses technologies and processing processes for producing non-energy peat materials and products. Before peat can be used as a raw material in products or materials, peat must undergo chemical and thermal treatment processes [55,98,102]. Various methods can be applied to process non-energy peat, such as extraction, pyrolysis, hydrolysis, thermal dissolution, and chemical modification [95,150]. Peat hydrolysis allows for the extraction of biologically active compounds from organic matter. Peat wax with valuable properties can be obtained for industry and medicinal applications. Pyrolysis produces liquid fuel, coke, and fuel gas [95,150]. The processing methods of non-energy peat are shown in Figure 4.
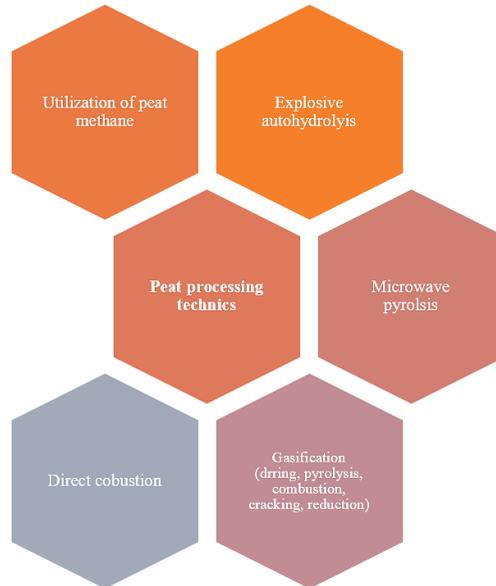
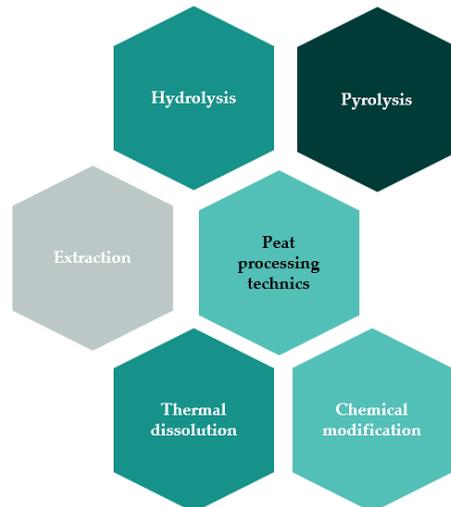**Figure 3.** Peat processing techniques for energy [150].

Figure 4. Peat processing technologies for peat product manufacturing [95,150].

3.2.2. The Potential of High Added Value of Peat Products and Materials

After the literature review regarding peat processing methods, a further investigation of opportunities for peat's industrial use in high-added-value products is required. Biomass from paludiculture can be used for innovative product production that might positively affect GHG emission reduction, partly replacing existing products that generate higher emissions [5].

- **Building materials**

Peat's possibilities have been proven in the building sector, where peat soil composite materials can be used as raw materials or additives. Peat soil can be a promising addi-

tive in construction materials, strengthening the durability of masonry blocks to meet necessary building standards. It is possible to improve building materials' characteristics, including insulation properties, using peat as an additive or producing the products themselves [99,152–156]. In building materials, cement has often been used with high-lying peat, moistening peat with water first. Then, after the peat is wholly saturated with water, calcium oxide, which can be obtained by calcining limestone, is added to the peat [154]. The search for alternative and innovative thermal insulation solutions in renovation has been more common recently, including using peat as a raw material or additive in thermal insulation panels [57,93,155,156].

In Finland, research has been conducted on peat moss use as an effective insulation solution in buildings. It is also possible to use lowland peat as a raw material to produce thermal insulation materials. Thermal insulation materials using peat consist of peat binders, additives, and components for creating a framework [94,156]. It has been found that thermally treated fen peat, also known as black peat, can be mixed with gypsum and tar, which can then be used to produce thermal insulation materials [33,157].

There are examples of successful models in which the raw materials for creating heat insulation panels are wood in combination with peat, and the peat serves as a binder. Using peat as a binder makes it possible to produce sound-absorbing panels, whereas several models use natural fibres. These panels, made from natural resources, compete with synthetic materials [99,152].

If the thermal conductivity of a thermal insulation material is to be assessed, thermal insulation materials where peat is used can be compared to mineral wool on the market. It is estimated that the coefficient of thermal conductivity of peat moss material is 0.35 mW/mK [100], which is significantly lower than other insulation materials. In the panel production process, resin strengthens the thermal insulation panels [99,100].

Peat moss has potential use in the thermal insulation boards used in construction, with lower thermal conductivity in comparison to other materials [100]. Mats and moss slabs with a 100 kg/m^3 density are estimated to have a thermal conductivity of 0.04 W/mK [100]. Peat moss is estimated to absorb ~30 times its weight in water before it becomes saturated [100]. Insulation panels made from peat moss possess better mechanical properties than wood panels. Peat moss panels are denser in comparison to other materials. Peat moss boards that contain tannin are comparable to cotton, and wet-processed peat moss boards have a higher water absorption than dry-processed [100].

3D-printed houses.

Peat mixture as an innovative solution in the building sector has emerged in recent years in Europe. Peat use in construction materials is more common in Norway, where peat is used in building new houses or renovating. Peat's use in producing 3D-printing technologies as a construction material has been investigated in Estonia [156–158]. Geokar peat blocks are made using peat processed into a paste combined with straw or sawdust, which can be used to construct thermal insulation panels. Peat blocks can even be used for up to 75 years. It is estimated that using peat blocks in the building sector can reduce energy consumption. Architects have increasingly used biopositive materials in renovation and eco-building. Another possibility for peat use in construction is fibreboard made from agricultural residues and peat moss. Fibreboard using peat moss was evaluated as an effective and practical solution among the other insulation materials [156,158].

Peat has been successfully used as an effective thermal insulation material with high thermal properties. Peat's thermal conductivity as an insulation material is from 0.037 to 0.08 W/m/K [158]. Peat also has attractive antibacterial properties for use in construction materials [158].

A new type of peat composite building material was developed, allowing for the three-dimensional printing of entire house structures (walls, floors, ceilings, etc.). Peat can be used as a filler to improve materials' thermal properties. The test samples were 3D-printed using a novel printing apparatus. The print head was a nozzle that conveyed a moist peat–ash mixture with compressed air [158]. In existing 3D printing technologies,

concrete fibre clay has been used, but in test samples, a mixture of peat, silica, ash, and water was used for printing. The samples were kept at room temperature and 100% relative humidity [158]. Currently, the vast majority of production is focused on either planting substrates or using the product as fuel for heating purposes. It is possible to utilise peat as a building material, including for the 3D printing of whole buildings and for creating panels that provide thermal and acoustic insulation. Peat composite materials and their use as construction materials have been evaluated for their potential to reduce CO_2 emissions from peat [158].

- **Biocomposites from peat**

Peat composite materials in blocks or pellets are estimated to have potential in design and construction. The possibility of using peat is presented in the production of biological adhesives, where peat is a binder. For peat to be used as a biological binder, it must first be treated using hydro cavitation [159]. Biodegradable polymers should also be added to composite materials. Composite materials can be used both in construction and as a material for furniture production [160].

- **Packaging**

Research shows that it is possible to use peat as an ingredient in biodegradable packaging, also promoting carbon sequestration. These packaging materials are an alternative solution to traditional plastics from fossil materials, reducing GHG emissions. Studies have shown a promising efficiency for peat as a raw material in packaging production. It has been investigated that it is possible to use peat as a raw material in producing biodegradable containers and films, thus offering the opportunity to use biological materials instead of traditional fossil materials. Such materials are rated as highly resistant to moisture and rotting risks [30,94,95].

- **Sorbents**

It is possible to produce biosorbents from peat. Sorbents can be made from unprocessed peat. Biochar, where peat is used as a raw material, can serve as an alternative solution to chemical sorbents. Using biochar produced from peat positively affects carbon sequestration and water retention and improves soil fertility. Peat has been assessed as having a high potential for environmental remediation [161]. Using peat and producing activated carbon to purify liquid or gaseous media from pollution is also possible. The processing methods used are heat treatment and chemical modification. During the pyrolysis of peat, volatile organic compounds and moisture are separated, forming a denser carbon content. After removing organic compounds, the structure is porous, and biochar can provide better sorption. Decomposed peat can produce solid sorbents used to purify water from heavy metals, wastewater, and radioactive compounds [146,147,162]. The use of peat moss in biochar production has proven the possibility of removing higher concentrations of heavy metals from polluted water—with peat biochar, it was possible to remove more than 80% of lead and almost 40% of cadmium compounds from polluted water. Due to its porous structure and hydrophobicity, peat can be used as a sorbent to separate crude oil from water. Peat biosorbents are both a cost-effective solution, and biologically produced sorbents have been used more in recent years to remove crude oil in marine compared to chemical sorbents [146,147,162].

Activated carbon can also be used in the food industry, as well as in the pharmaceutical field. The possibilities of using activated carbon are also highly appreciated in the chemical industry, as it can be used to produce synthetic fibres. Compared to synthetic fibres, peat fibres are rated at lower costs. A low ash content characterises peat, and it is, therefore, evaluated as promising to produce activated carbon as a sorbent [162].

- **Filtration systems**

The possibility of peat has been assessed for use in water filtration systems and municipal wastewater treatment. Peat is suitable for water treatment because of its porosity

and filtering properties, essential for removing pollution from water. Peat is used as activated carbon or as a peat filter. With a peat filter or activated carbon, it is possible to purify water from heavy metals and organic compounds [163]. Peat moss can be used as a raw material to produce activated carbon. Activated carbon can be widely used in soil and water purification from organic and inorganic pollution sources [6].

- **Medicine and cosmetics**

The possibilities of using peat are still being studied in pharmaceuticals and medicine. The use of peat in physiotherapy has been estimated as a potential application due to its heat capacity because of its decomposition state. Other uses include natural steroid formulations that use peat or anti-wrinkle products with peat ingredients. The selection of proper preparations requires research and the selection of raw materials, as the preparations must have a certain chemical composition and organic and mineral compounds [6,162].

- **Use of Humic acids**

It is possible to dye paper with peat humic acids, reducing the release of hazardous compounds into wastewater that the dyed paper would otherwise cause. Studies have indicated that peat humic acids can be used as additives to influence the structure and properties of lubricants. Peat can be converted into humic acids and used to mix and process rubber. Humic acids have a wide range of uses: possible additives, antioxidants, pigment dispersants, and colourants [33].

- **Remediation of degraded soils**

The potential for using peat has been assessed directly for the economically beneficial restoration of degraded soils. Peat material is used as a solution in rehabilitation processes. The use of peat to restore degraded soils is also called bioremediation. During this, peat separates oil and other polluting substances from soils, for example. In bioremediation, the absorbed oils are transformed into water and CO_2 using peat [14,33].

The applications of peat based on the literature mentioned above are shown in Figure 5.
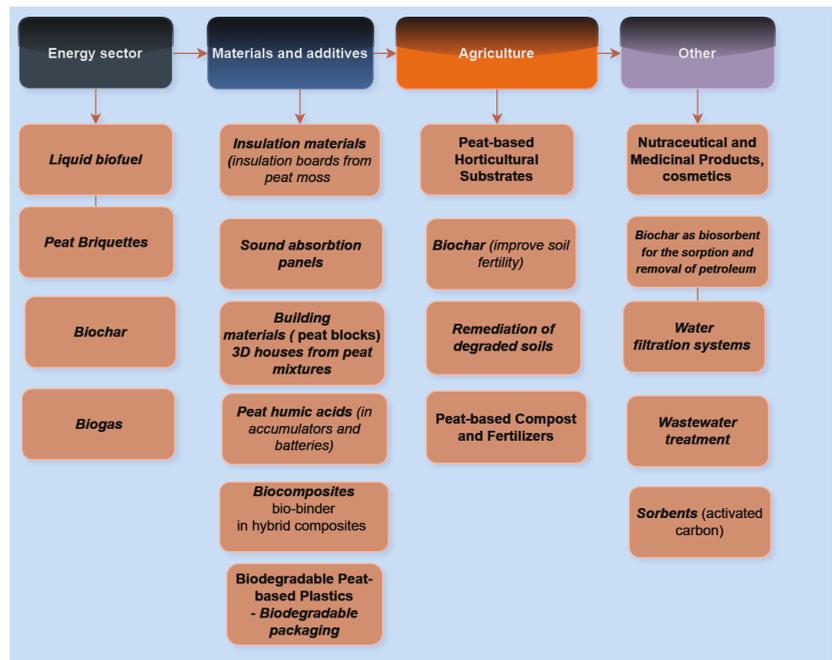
Figure 5. Applications of peat [3,33,57,93–100,146,152–162].

4. Discussion

An analysis of the methods of peatland restoration shows that biochemical trade-offs do not often need to be sufficiently considered. This is mainly due to the lack of long-term ecosystem-level monitoring of CH_4 in northern peatlands. Plant species composition, depth of water table, or soil pH are not sufficiently taken into account [40,125]. To reduce GHG emissions from peatlands, attention must be paid to agricultural lands where drainage has occurred. These degraded peatland restoration strategies are related to the improvement of landowner and farmer knowledge about the effects of drainage, peatland rewetting afforestation of peatlands, and the impacts on peatland hydrology and climate change [63,71,117]. Increased concentrations of DOC in water bodies are often associated with peatland drainage and degraded peatlands. Naturally formed northern peatlands are estimated to be a significant source of GHG emissions due to their constant wet conditions [40,164].

In a study [29], it was estimated that in the first four years after rewetting, CH_4 emissions increased by ~0.033 ± 0.003 Mg CH_4/ha^{-1} yearly [29]. To evaluate the effect of rewetting, a prolonged period should be considered. Often, there are arguments that increased CH_4 emissions after rewetting will decrease after a brief period. In the case of a lack of water table control after rewetting, GHG emissions could remain high for a long period [5]. Some studies [11] even estimated that more than 30 years after rewetting, the average yearly emissions of CH_4 are approximately twice as high as before the extraction of peatland [11].

The effect on nutrient flow and GHG emissions using brackish water for rewetting is still uncertain compared to freshwater [39]. Regarding coastal peatlands, a study [39] estimated that using brackish water for rewetting can have smaller CH_4 emissions compared to rewetting where freshwater is used [39]. Peatland rewetting impacts nutrient mobilisation and eutrophication in nearby water bodies and releases an essential amount of CH_4. Similarly, peat saturated with water promotes nitrate attraction [39]. Studies [39] have shown that rewetting previously drained coastal peatlands can be a GHG emission source in the first year. Regarding coastal peatlands, it is estimated that rewetting can result in unmonitored inputs of nutrients in nearby water in the short term [39]. After the peatlands' rewetting, the peat bulk's density could remain high. Therefore, because of rewetting, new biotopes like eutrophicated lakes can form on the degraded soil [12,52].

According to the literature sources, there is still some uncertainty regarding the DOC concentration level after peatland rewetting [29]. Some studies have shown no effects on DOC concentrations after peatland rewetting, or the effect is vague [29]. For a successful restoration strategy and mobilisation, it is vital to assess CH_4 fluxes. It is estimated that rewetting might reduce net CO_2 emissions in reforested sites by ~15.4 Mg CO_2 equivalent ha^{-1} annually, a 25% reduction in the total [29]. Monitoring should be improved to ensure control over the nutrient release in nearby water bodies near peatlands. The monitoring of vegetation and hydrology should be simultaneously evaluated [51]. Monitoring should be conducted before and after peatland restoration [51]. Several methods can be used in peatland monitoring, including spatial analysis, aerial and drone photos, and a combination of vegetation, hydrology, and GHG emission measurements [50].

Brackish water use for peatland rewetting can reduce GHG emissions. It is also estimated that the reduction of CH_4 emissions after rewetting can be achieved by using fresh water for rewetting [29]. Reducing CH_4 emissions from rewetting and restoring the balance of the carbon topsoil removal can be used to avoid additional nutrient release. Removing the topsoil before rewetting can reduce eutrophication by 80–95% and DOC mobilisation by 60% [70]. Using topsoil removal, it is possible to reduce CH_4 emissions by 99% in comparison to emissions without topsoil removal [40,70].

It is estimated that the rewetting of peatland in combination with paludiculture using sphagnum farming [34] can have a positive impact on climate change mitigation [125]. Recent studies have shown that among restoration methods, the highest rate of sequestration of $CO_2 > 1000$ kg carbon ha^{-1} y^{-1} is from paludiculture practices [34]. According to

recent studies, peatland restoration should include a hydrology restoration regime. On the other hand, afforestation should not be defined as restoration [34,86]. According to the literature, some sustainable land practices might reduce peat loss, including zero tillage in agriculture and cover cropping on fields [30]. Cover cropping combined with a higher water table may result in the reduction of GHG emissions and reduce nutrient inputs. However, there is essential indeterminacy regarding the long-term effect of cover cropping on peatlands [30]. In Finland, several solutions are used, including increasing vegetation, reducing soil tillage, avoiding peatland cutting, and converting land into paludiculture or peat forests [127]. Zero tillage combined with increasing water table seasonally could reduce GHG emissions [30]. This contradicts studies that determined that these practices might have the minimum effect on reducing GHG emissions [30].

To promote sustainable peatland management, peatland national strategies based on peatland conservation and promotion of the achievement towards sustainable development goals are crucial, which is not only in countries with great peatland areas [31]. In recent years, several European countries have developed their national peatland strategies, and other countries that still need to develop their strategies can gain common knowledge from other strategies [31]. For the establishment of national strategies, the absence of proper data can be an issue for correct evaluations [31].

According to earlier scientific studies, there is potential and necessity for improvements regarding peatland restoration strategies and methods [50]. Some of the recommendations are related to the opportunity to combine ecological and hydrological methods in peatland restoration [18,50].

National peatland policy aims should be more precise and specific, linking requirements with international principles in peatland restoration [50]. Peatland restoration success is affected by the gaps in restoration targets, a lack of detail, and the inability to determine the measurability of the results of the defined goals [50]. Peatland restoration can be negatively affected by policies that are too generic without specific, measurable outcomes regarding the quality of water [49]. Recommendations based on previous studies implementing more precise protocols for measuring data [49].

To select the right instrument among the substantial number of policies, one must consider environmental and socioeconomic factors, as well as landowner rights [112,116,127] Landowners and farmers can implement publicly available best practices in peatland management even if specific government regulations are not established [53]. Previous studies show that there is still a gap in knowledge regarding the estimation of carbon sequestration and storage possibilities among policymakers and ecosystem managers [50,53].

According to previous studies, on the path to sustainability, it is crucial to investigate innovative practices in peatland management [53].

5. Conclusions

There are a lot of uncertainties regarding GHG emission reduction in the long term. The success of rewetting should be evaluated over a longer period; some studies even argue that there is no decrease in CH_4 emissions after 30 years of rewetting. To gain successful results of rewetting and achieve emission mitigation, both methods—rewetting and revegetation—should be combined, especially for peat extraction sites, to be defined as restoration. According to studies, rewetting is a water table rise and cannot be defined as restoration. After rewetting, revegetation should be performed by introducing sphagnum species that can pump out methane that increases after rewetting and causes faster peat accumulation.

Recent studies argue that the afforestation of peatlands should not be considered as restoration. Also, drained and afforested peatlands, especially in boreal zones, are more vulnerable to wildfire risks, generating a great amount of GHG emissions from wildfires.

For sustainable peatland management, proper strategies and methods are required to reduce the degradation of peatlands. To advance peatland management, more involvement of landowners and local communities in the decision-making process is required, enhancing knowledge of peatland's role in reducing GHG emissions. Industries and scientists should be allowed to promote more innovations and alternative solutions in peatland management. Strategies should also include more active interactions between organisations, industry, scientists, government, and landowners for sustainable peatland restoration and the creation of innovative solutions. Part of peatland management is continuous research promotion to encourage the production of new technologies and products where peat is used as a valuable raw material.

Coherent policy and peat use as an energy resource, not as a commercially usable resource, are some of the drawbacks in peatland management. One of the solutions for better and more effective management of peatland restoration should be to use a greater combination of restoration methods. For example, the rewetting of peatlands should be realised in combination with topsoil removal before rewetting and revegetation after rewetting. After rewetting, one of the promising solutions for methane emission reduction could be paludiculture using sphagnum species. Paludiculture can also be the solution for further income for landowners and new innovative product development using biomass of harvested paludiculture plants.

This review confirms that peat products and materials can compete with similar products in the market because of their unique properties. Peat products can replace some products where fossil materials are used. Peat, as a resource, has a wide range of applications in industry, from agriculture and construction to pharmaceuticals and medicine. Future peatland management strategies should consider alternatives to peat treatment, storage, and technological solutions to produce high-value-added peat products and materials that sequester carbon in the environment in production processes. The materials obtained from peat can also be used as a component in biodegradable packages, biosorbents, and filtering materials for water purification, and in bioremediation for the purification of contaminated soils. It is possible to obtain humic acids from peat, widely used in industry as dyes, air filtration systems, and batteries. Using peat in the bioeconomy can reduce the losses caused by peatland management and emission and also provide new innovative options for mitigating and managing the effects of climate change and achieving climate goals. Therefore, exploring alternative and novel strategies to reduce CO_2 emissions from peatlands, improve peat processing, and develop new, commercially viable peat-based products is critical.

Nomenclature

GHG	Greenhouse gas
EU	European Union
UK	United Kingdom
CO_2	Carbon dioxide
N_2O-N	Nitrous oxide
CH_4	Methane
Mt	Megatons
DOC	Dissolved organic carbon
Eq.	Equivalents

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Comparison of the Economic and Environmental Sustainability for Different Peatland Strategies

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Abstract: Previous studies of the literature show that there are great uncertainties regarding costs and gains for peatland restoration strategies and that the monetary estimation of peatland restoration and possible alternatives can be complicated. The research aims to compare the economic costs and benefits of existing peatland restoration strategies and alternative use of peat and peatlands. A core method for the evaluation of the economic aspects of each strategy used is the composite index method. Information for constructing the composite index is based on data from the scientific literature, reports, and local project studies. In the study, peatland strategies, peat extraction, and alternative use in products were mutually compared with existing strategies. The highest composite index among strategies was for the production of insulation boards and cultivation of paludicultures using cattail or sphagnum farming. Cultivation of paludicultures can be an economically viable strategy if costs and gains are evaluated. Cultivation of cattail or sphagnum can make economic gains for landowners and farmers, and solutions for the reduction in necessary initial investments should be sought. Harvested biomass can be used for high-added-value products, in this case, insulation boards from cattail (Typha). Therefore, peat biomass can be used as an economically valuable resource, and raw material for insulation board production is obtained without the extraction of peat. Also, ecosystem services and potential income are not reduced.

Keywords: investments; emissions; value-added products; composite; composite index

1. Introduction

Organic soils include land with a peat layer at the surface [1]. Peatlands are crucial for carbon storage and the conservation of endangered species [2]. Peatlands are crucial carbon sources, accounting for 21% of global carbon stocks due to their high carbon density [3]. As a result of drainage, oxygen enters the soil, promoting peat microbial decomposition and leading to greenhouse gas emissions (GHG). Drained peatlands are sources of GHG emissions such as methane (CH_4), nitrous oxide (N_2O), as well as carbon dioxide (CO_2) [3]. As the depth of peatland drainage increases, the amount of GHG emissions also increases. It is estimated that 1 hectare (ha) of drained soil emits approximately 30–40 tons of GHG emissions [1]. Degraded peatlands are known to account for ~5% of human-caused GHG emissions, releasing ~2 gigatonnes (Gt) of CO_2 annually. Globally, agriculture, including the production of agricultural products and the extraction of peat for horticulture, is one of the largest anthropogenic producers of peat emissions [1].

It is estimated that approximately 50% of the area of peatlands in Eastern Europe and the Nordic countries (~350,000 km²) has been assessed as degraded, mentioning peat extraction, forestry, and the use of peat in agriculture and horticulture as the main causes of degradation [4]. In the context of GHG emissions from peatlands, the second highest emission rate is indicated in the European Union (EU) member states, accounting for around

15% of the total emissions emitted by peatlands. It is estimated that the volume of emissions in the EU is approximately 230 megatons (Mt) of CO_2 equivalent (eq) [5,6]. In the EU, Germany, Finland, Poland, Ireland, Sweden, Romania, Latvia, Lithuania, and the Netherlands are the countries where the largest amount of GHG emissions from peatlands is estimated. In the Baltic States, it is estimated that the amount of annual emissions from peatlands is greater than 50 Mt CO_2, ranking them as one of the largest emitters of GHG emissions from peatlands within the EU [7].

A total of 12% of Latvia's territory consists of peatlands, of which approximately 39,500 ha have been identified as degraded peatlands [7]. In Latvia, from a total land area, there are ~40% wetlands, 5% grassland, more than 3% peat extraction sites, and below 1% rewetted peatlands [8]. In deteriorated peatlands in Latvia, one of the most used peatland strategies is afforestation, which can be realised in ~50% of drained peatlands [8].

To achieve the climate neutrality set by the Paris Agreement by 2050, it is necessary to stop the drainage of peatlands altogether, supporting environmental and climate policy measures that promote the reduction in emissions from degraded peatlands [9]. In order to move towards this goal, the developed Common Agricultural Policy Plan (CAP) is of great importance in relation to the further use and restoration of peatlands [10]. Within the framework of the CAP, policy strategies and measures aimed at reducing emissions from degraded peatlands are developed [9]. The common agricultural policy plan determines that large rewetting of organic soils needs to be carried out in order to achieve the reduction in GHG emissions in forestry and agriculture. Also, a reduction in peat extraction for agriculture or forestry is required [11,12]. From strategies for peatland restoration, one of the most used is peatland rewetting in peatland policy. Peatland rewetting's aim is a deliberate rise of water level using filling ditches, dam constructions, drain blocking, or other rewetting methods [6,13]. Following Latvian guidelines for the sustainable use of peat for 2030 [7], Latvia's Strategy of Drained and Degraded Peatland Restoration has a high potential for GHG emission reduction [4]. The Sustainable Use of Peat (2020–2030) sets out peat restoration strategies and aspects of peat extraction [14].

Some countries use peatlands as a source of income for national economies or local communities. Before restoring peatlands, a reliable analysis of costs and benefits should be carried out [1,2]. In peatland restoration, cost-effectiveness is crucial for decision-makers in implementing strategies [15]. Emissions from peatlands cause not only environmental and climate damage but also economic losses to the national economy. Germany, as one of the biggest emitters from degraded peatlands in the EU, suffers from losses estimated at 7.4 billion every year. In order to promote the reduction in emissions from peatlands, approximately EUR 410 million is allocated to it in the form of subsidies within the framework of the CAP. It is known that further use of degraded peatlands in agriculture is often low productivity, and agricultural production is only possible due to the financial support granted by the state [9].

The scientific literature and statistics are uncertain regarding precise peatland restoration costs [13]. Based on the literature, it can be complicated to estimate the monetary value of the results of peatland restoration projects [16]. Non-market evaluation methods should be used to evaluate the monetary value of ecosystem services [1,2]. To evaluate the results of restoration projects, ecosystem conditions before and after restoration are compared [2,10,16]. In the scientific literature and reports, there is a scarcity of information related to precise peatland restoration investments. The cost interval mentioned in the literature [17] is between 200 and 10,000 EUR/ha [17–19]. For peatland restoration strategies, initial implementation costs are in the range of 300 EUR/ha for heathland peats and 500 EUR/ha for previously drained peatlands [19].

In the recent literature, paludiculture and water management are considered effective strategies for GHG emission reduction while having a high initial cost [20]. Additional opportunity costs might be expected regarding the loss of production volumes. Some costs can arise related to the gaps in knowledge in the transition phase from agriculture to paludiculture practice [20]. According to the literature, financing mechanisms can be

one of the solutions for farmers [21]. The research aims to evaluate peatland restoration strategies and alternative use economic aspects, defining costs, gains, and emissions from each of the strategies using the composite index (CI). Studies are based on the scientific literature and reports combined with average values from local existing project optimisation models and assumptions. Information for constructing the composite index is based on data from the scientific literature, reports, and local project studies. In the study, peatland strategies and alternative use in products were mutually compared with existing strategies, which are determined in the Guidelines for the Sustainable Use of Peat 2020–2030 of Latvia [14].

2. Greenhouse Gas Emissions from Peatlands and Economic Aspects of Peat

2.1. Main Greenhouse Gas Emission and Economic Aspects of Peatland Strategies

GHG emissions from organic soils are classified as emissions from agricultural activities, as well as land use, and forestry activities [22]. In order to estimate the total contribution of GHG emissions, CO_2, CH_4, and N_2O emissions must be transformed into the CO2 eq. [22]. The amount of released GHG emissions is affected by whether the bog is considered nutrient-poor or nutrient-rich, so it must first be defined [22–24].

Costs for restoring peatlands include initial investments, annual maintenance costs, monitoring costs, and costs for loss of production volumes and previous incomes [9]. Peatland restoration costs may also include establishment costs, which contain expenditure work costs, costs regarding land acquisition, and further permanent costs of maintenance and monitoring if necessary [15]. Cost and gain analysis should include potential gains from ecosystem services from restored peatlands [2].

Average peatland restoration costs in Scotland by the year 2020 were about 1227 EUR/ha, but in 2021 they were ~1878 EUR/ha. It is assumed that the average cost per ha for peatland restoration in 2022 is about EUR 1026 [25]. In other sources, costs for peatland restoration vary from 5000 EUR/ha to 150,000 EUR/ha [21]. In the Netherlands and Germany [14], the average restoration costs of peatland vary from~1500 EUR/h to ~3500 EUR/ha. For France, it is calculated that, on average, peatland restoration costs are in the range of 10,000 EUR/ha—40,000 EUR/ha [21]. On the other hand, from Peatland Code restoration projects, it is known that the cost necessary for restoration can be between 5000 EUR/ha and 15,000 EUR/ha on average [21].

It is estimated that the drainage of peatland forests aims to increase the production of wood and generate losses that can be evaluated in the amount of EUR 309 million a year [26]. Regarding peatland rewetting, there are studies that have evaluated economic gains that yearly reach approximately EUR 170 million [26]. It is calculated that drainage has significantly lower maintenance costs than rewetting peatland forests using dams. Estimations have shown that maintenance costs for drainage annually reach EUR 1.7 million, but for rewetting, are approximately EUR 17 million a year [26].

One-off payment

Although peatland restoration strategies and methods remain more common and their importance in climate policy and society increases, agricultural drainage continues to be subsidised, hindering landowners' desire to carry out peatland restoration measures [24]. As one of the encouraging instruments for the restoration of degraded peatlands, there are one-off payments for the performed restoration measures. One of the examples where one of the payments is implemented in peatland management is Scotland, where a one-time payment is received for restoring the hydrological regime of peatlands. A one-time payment is granted for peat rewetting, including using methods such as drain breaking or ditch blocking. Denmark can receive one-off payments for the feasibility study of peatlands and to reduce the costs of peatland project construction. Since peatland restoration is a long-term activity, it is recognised that support funding for the implementation of peatland restoration projects is possible for a period of approximately five years. In England, receiving support payments can take up to ten years in some cases [10].

One-time payments for peatland restoration projects can even be covered by 100% of the initial costs, including construction costs [10]. When rewetting degraded peatlands, farmers often suffer economic losses because, after the hydrological level has increased, rewetting makes it no longer possible to carry out the previous agricultural activity. To compensate for economic losses, landowners can receive one-time support payments. The amount of support varies considerably in the literature and can be, on average, from 40 EUR/ha to more than 467 EUR/ha over a 20-year period [10].

2.1.1. Peatland Rewetting

Previous studies of the literature show that in order to stop the release of GHG emissions from degraded peatlands, a partial increase in the water level is not enough, but extensive rewetting measures must be taken to maintain a high hydrological regime in peatlands [4]. As a result of rewetting, by taking measures to raise the water level, for example, by using drain blocking or ditching blocks, similar conditions and hydrological regimes are restored in the peatlands as before the peatlands were drained. Rewetting has been evaluated as one of the most promising methods for reducing CO_2 emissions from degraded peatlands. However, increasing the hydrological regime increases the amount of CH_4 emissions, which is one of the GHGs [27]. Despite the increase in CH_4 emissions after rewetting, this GHG remains in the atmosphere for a shorter time (~12 years) before being converted to CO_2 compared to CO_2. After peat rewetting, under the influence of anaerobic conditions, a rapid increase in CH_4 emissions is observed, which decreases over the years to the level found in wetlands. The type of bogs influences the amount of emitted emissions; it is estimated that in transition bogs, the amount of CH_4 emissions is around 274 kg CH4-C ha^{-1} per year, while in high years, the amount of CH_4 reaches ~133 kg CH4-C ha^{-1} [28].

At the EU level, it is calculated that rewetting 35% of degraded peatlands used in agriculture, including grasslands and croplands, could reduce GHG emissions by 45 Mt CO_2 eq. [4]. The possible emission reduction after the type of land use influences the result of rewetting. It has been numerically proven that rewetting of former peat drainage sites can reduce GHG emissions, which can be measured by 6 Mt CO_2 per ha, reaching 39 Mt CO_2 eq annually. On the other hand, by rewetting former peatlands that are used for croplands, it is possible to achieve a reduction in emissions that is ten tons CO2 eq. greater than the reduction in GHG emissions from rewetting grasslands [4].

It is estimated that by primarily performing cropland rewetting, it would be possible to annually achieve ~57 Mt CO_2 eq. higher GHG emission reduction compared to grassland [4].

Hydrological-level restoration measures can be classified as one-off measures, such as filling ditches or dams, or a set of measures that aim to ensure active regulation of the groundwater level. It is calculated that restoring the hydrological regime and vegetation in previously drained and degraded peatlands can be expensive [21].

In previous studies, it was calculated that rewetting degraded peatland forests yearly could save EUR 170 million [26]. Gains from rewetting peatlands exceed conditions where the drained peatland forests are left without restoration [26]. The cost of 1 dam is in the range of EUR 196 to EUR 3153 [26]. Thereby, on average, the cost per dam reaches EUR 1487 [26]. For Lithuania, previous studies estimated, based on a 40-year period, that the lowest costs for rewetting previously drained forests of peatlands using wood constructions of dams are ~8 EUR/ha yearly; on the other hand, costlier rewetting methods—ditch dams of rock and wood—are 120.4 EUR/ha annually [26].

Restoration costs for rewetting peatlands are highly variable. As a result of peatland rewetting, new short-term and long-term costs arise for farmers and landowners related to the cessation or reduction in production volumes in the long term [21]. One mechanism for economically viable rewetting could be to implement long-term measures regarding carbon credits and ecosystem service payments [29,30]. It is possible to use carbon credits

from rewetting to partly reduce rewetting costs. The carbon credit described avoided CO_2 emissions from the atmosphere [29].

Carbon credits serve as a compensation mechanism for farmers and landowners after rewetting. Germany's established MoorFutures provided the first carbon credits for the implementation of peatland rewetting [10] The price of carbon credits depends on the amount of reduction in CO_2 emissions after rewetting [30]. The amount of carbon credits per ton of CO_2 eq. for rewetting depends on the total costs of projects. Depending on the size of the projects, carbon credits vary from EUR 35 to more than EUR 670 per ton of mitigated CO_2 eq. [10] Based on studies from the Netherlands, raising the water level from 60 cm to 40 below the level can have a minimum compensation of ~ 26 EUR/ ton CO_2 for carbon emissions, but raising the level by 40 cm increases the compensation to 57 EUR/ton CO_2 [31]. In the Netherlands, carbon credit sales reached 70 EUR/ha in 2020 [29].

2.1.2. Paludiculture

The concept of paludiculture has been known for many years, but it has become more common in recent years. It can be described as a world-recognized milkfish management practice, especially in areas where rewetting has already been carried out. Paludiculture gives landowners the opportunity to use the land specifically for the cultivation of plants and their further use [24]. Paludiculture as a peatland management strategy is included in the Ramsar Convention on Wetlands, as well as the Intergovernmental Panel on Climate Change (IPCC) GHG emission guidelines [24]. In order to restore peatlands using the practice of paludiculture, it is first necessary to perform rewetting. With paludiculture, it is possible to reduce GHG emissions from already rewetted peatlands. Paludiculture provides not only environmental benefits but also socio-economic ones. Financial benefits can be obtained both from the harvested biomass and also from using the harvested biomass for the production of high-added-value products [24,32]. Sometimes, there is a misconception that paludiculture is the same restoration strategy as rewetting peatlands. Paludiculture can be defined as agriculture or forestry on rewetted peatlands [12]. Opposite to conditions in rewetted peatlands, paludiculture uses water close to the groundwater level [12].

In sites where paludiculture practices are used, carbon sequestration and storage are promoted. Biotopes in which wetland plants are cultivated using the paludiculture approach contribute to the preservation of biological diversity [24].

As a prerequisite for the implementation of paludiculture practice and avoiding carbon losses, there is regulation of the water level that should be close to the surface throughout the seasons [24]. The essence of paludiculture includes cultivating wetland plants in sites where the water level is close to the surface. Cultivated wetland plants can capture CO_2 emissions released from peatlands, reducing the total emissions from peatlands. Another solution for reducing GHG emissions is the use of harvested wetland plant biomass in high-value products, where the storage of CO_2 emissions can be an option [24,33,34].

Depending on the species of cultivated wetland plants, the amount of possible biomass that can be harvested after growth also differs. Reed canary grass is one of the wetland plants suitable for paludiculture practice on drained former peatland soils. Compared to other wetland plants, it is rated with a high potential yield [23]. One factor hindering the wider development of paludiculture is the lack of appropriate policies and support mechanisms. It is estimated that the EU policy hinders the cultivation of wetland plants with high yields from harvested biomass, such as peat mosses, reeds, and cattails [10].

Regarding paludiculture practices, there are uncertainties and variabilities in the necessary initial costs for implementation and expected gains [35]. Based on studies of the literature [35], paludiculture practices can be evaluated as effective, economically justified solutions [35]. In Latvia, one of the sites where sphagnum farming in ~1 ha areal is Rāķa

bog [12]. Previous studies calculated that capital costs for the implementation of sphagnum farming in Rāķa bog reach ~38,540 EUR/ha [12]. Another peatland where previous studies have been carried out is Ķemeru bog, where initial costs for sphagnum farming introduction reach 32,300 EUR/ha [12]. Previous studies show that for Rāķa bog, total water management costs were EUR 12701, but in Ķemeru bog, they were EUR 1530 for overflow construction. Sphagnum farming provides economically viable land use and opportunity for long-term carbon storage [12]

The Paludiculture approach provides ecosystem services, including emissions reduction and biodiversity promotion; these services can be monetarily valued, but it is often not included in the financial benefits [1].

Peat Biomass Options for High-Added-Value Products

Wetland plant species for commercial use in raw materials and products in paludiculture exceed even 200 species. Wetland biomass products occupy an increasingly high place in the market and, in the construction sector, create competition for existing construction materials. According to their thermal conductivity, thermal insulation panels have been evaluated as a promising alternative. Wetland plant biomass can also be used as a growth substrate or in raw material packaging [9].

Previous studies evaluated the possibilities of using individual wetland plants as raw materials or for the production of value-added products. Reed, canary grass, or common reed can be used for biogas production, and the potential for use has also been evaluated in cattails. Cattails can also be used as raw materials in construction and as alternative solutions for wastewater treatment [1].

The possibilities of using peat-based thermal insulation boards grown from cattails are still being researched. However, it is estimated that cattail-based insulation panels can compete with similar insulation materials [34]. Peat-based panels are mould-resistant and provide suitable humidity and air quality conditions. These products can store biogenic carbon [34].

Previous studies using the life cycle approach show that cultivation of cattail produces ~2.6 CO_2 eq. ha^{-1}. To use the harvested cattail biomass to produce thermal insulation panels, it is first necessary to dry it so that the moisture content does not exceed 6%. It is estimated that the impact caused by drying cattail biomass is approximately ~2.6 tons of CO_2 eq. [34]. The panel production process itself includes fibre shredding (0.6 tons CO_2 eq. ha^{-1}). Development of a single panel, including manufacturing, fibre processing, and packaging cutting, has a combined impact of ~4 tons of CO_2 eq. ha^{-1} [34]. Total life cycle emissions in cattail cultivation and panel production are ~9.7 tons of CO_2 eq. [34].

2.1.3. Afforestation of Peatlands

A study was conducted in Latvia, where afforestation with coniferous trees was carried out in a former peat extraction site. Emissions that would be formed if peat extraction continued at this site (~1.09 tons of CO_2 eq. ha^{-1} per year) and the emissions after afforestation with coniferous trees (~0.96 tons of CO_2-C ha^{-1} per year) were calculated. Emissions from afforestation are affected by previous land use. In the context of CH_4 emissions, it is estimated that afforestation can achieve low emissions in afforested croplands (producing ~1 kg CH_4 ha^{-1} per year) [28].

Initial investments are necessary for seedlings or seeds, shading trees, thinning, and maintenance of new tree growth for peatland afforestation. Previously drained peatland afforestation can reduce GHG emissions and, after the afforestation, mineralisation [33]. In peatland afforestation, the main costs are regarding plantation—preparation of soil and planting site and investments for planting [36]. Implementing restoration in a large area is necessary to carry out the afforestation of peatlands so that it is economically beneficial [25].

Restoration of peatlands where drainage has previously occurred using the afforestation strategy includes land opportunity costs, planting costs, and the costs of restoration [37].

The costs required for afforestation include the initial costs of tree planting, labour, and fertilizer, as well as logistics. The average total cost is estimated to be about 1100 EUR/ha-^{1}yr-^{1} [34].

2.1.4. Perennial Cultivated Grasslands

One of the tasks defined within the CAP is to promote the preservation of perennial grasslands [1]. The study calculated that the transformation of former peat fields into grassland can have a negative impact on CO_2 emissions, resulting in 3.2 tons CO_2-C ha^{-1}. [28].

Compared to other restoration methods, a smaller amount of funding is necessary for the introduction of grasslands. For the establishment of perennial grasslands, traditional agriculture techniques can be used [33]. The establishment of perennial cultivated grasses includes peat extraction site transformation into agricultural lands that are regularly mowed and grazed afterwards [33]. Fertilisation controls environmental conditions in cultivated grasslands. Perennial cultivated grass is used for energy production from biomass and fodder [33]. The most crucial aspect of successful recultivation using perennial cultivated grasses is evaluating the correct hydrology conditions [33].

In Estonia, one of the determined soil protection measures includes support for the cultivation of perennial grasses under the condition that 90% of the soil composition consists of peat [10].

2.1.5. Water Reservoir

Restoration foresees the establishment of artificial water reservoirs in former peat extraction sites. The peat extraction site is being flooded, and the water reservoir is used as a habitat for flora and fauna or for recreation. Artificial reservoirs have the potential to use the land for recreation or fisheries [33]. According to the guidelines for the sustainable use of peat in Latvia, as mentioned before, the establishment of water reservoirs is one of the methods of restoring peatlands suitable for Latvian conditions. It is estimated that the establishment of an artificial water reservoir is suitable for former peat extraction sites where a swamp has formed due to overgrowth of the water body [33].

2.1.6. Growing Cranberries and Blueberries

Previous studies have calculated that the average amount of CO_2 emissions from cranberry fields per year is approximately ~2.6 tons of CO_2—C ha^{-1} [28]. Therefore, it is assumed that the conversion of former peat fields into cranberry plantations can lead to a reduction in GHG emissions [28]. The milling peat extraction method can be used to get a level field. If no field alignment is required, then it is possible to reduce cranberry field establishment costs. Successful restoration using cranberry cultivation can have gains regarding the reduction in GHG emissions [33].

2.1.7. Peat Extraction

One of the sources of GHG emissions in the energy sector is peat extraction [33]. In the peat extraction process, peat is taken off together with carbon [33,38].

Peat extraction has socio-economic value; it promotes rural employment and develops the local economy [33]. After 2003, peat extraction used for energy has significantly decreased [33]. In Latvia, peat deposits form 1.5 billion tons of peat, which compose 0.4% of peat resources globally [33].

In Latvia, companies that can extract peat and that have received a license for peat extraction are also obliged to perform restoration after peat extraction [7]. According to

the Latvia guidelines for the sustainable use of peat for 2030, it is significant to avoid further peat extraction in new peat deposits [33]. Also, it is important for the economy to restore former peat extraction sites using restoration strategies to renew degraded areas into economic activity [33]. Previous guidelines determined that more modernisation in technologies and processes should be carried out in the near future to reduce GHG emissions from peat extraction [33].

Tax revenues from peat extraction are estimated to be EUR 18.5 million annually [33,39]. There are no tax incentives in Latvia for peat extraction, and market principles are used [33].

2.1.8. Dairy Farming on Peat Soils

Previously conducted research is related to dairy farming on peat soils with grassland for grazing. The dairy farm of the study had 69 cows, and 35 ha were used as perennial grassland [34]. The average warming potential (GWP) of dairy production was 19.4 tons CO_2-eq ha^{-1} year $^{-1}$, with an average GWP of milk produced in the Netherlands (1.19 kg $CO_2 \cdot$eq kg^{-1}) [34,40,41]. The aforementioned research determined that the impact of dairy production was 20.9 tons CO_2-eq ha^{-1} [34]. The research calculates that the net revenue is approximately 1350 EUr/ha^{-1} for 16,218 kg milk ha^{-1} on peatlands [34].

3. Materials and Methods

3.1. Framework of the Study

In this study, the first step is to select the peatland strategies based on the economic data available in the scientific literature, reports, and local peatland projects. The next steps until the development of scenarios are related to the construction of a composite index (CI). The CI is one of the methods, together with multicriteria decision analysis, that can be used in decision-making processes in cases where the best alternative needs to be sought.

The composite index is used to evaluate policy measures, to compare them before their implementation, or to assess progress in the implementation of defined objectives. Policymakers use the composite index in the decision-making process to make choices about the most effective solutions. The advantage of the composite index in this study is the ability to simultaneously assess several factors and their overall contribution. It is possible to include social indicators, but in this study, due to data availability, it was decided to use economic indicators and environmental indicators affecting GHG emissions.

Based on the literature, the first step in the construction of the CI is the development of the following:

1. Suitable economic indicators, divided into two groups—(1) necessary costs, (2) incomes and possible gains from grants and subsidies, etc.
2. GHG emissions of each strategy.

The next step is to calculate data for each strategy based on the literature, reports, and local projects. Where the literature does not provide precise or specific information, assumptions related to calculated data must also be developed.

To construct data normalisation for CI development, the Min–Max method was used. Equal weight indicator weighting was applied to each indicator, which was determined based on the number of indicators used. The final step is indicator aggregation into the CI Development of Scenarios (Figure 1).
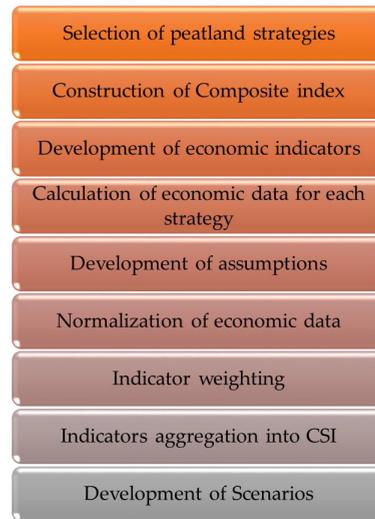
Figure 1. The framework of the study.

3.2. Selection of Strategies

Peatland strategies can be categorised into groups—(1) restoration strategies; peat biomass use in high-added-value products; (2) other land use replacing peatland—dairy farming; and (3) peat extraction. Restoration strategies—peatland rewetting; peatland rewetting; establishment of perennial cultivated grasses, paludiculture; establishment of water reservoir; cultivation of cranberries; and cultivation of blueberries, based on the *Guidelines for the Sustainable Use of Peat 2020–2030* of Latvia [33].

Peat biomass is used in high-added-value products based on the available scientific literature and reports. Dairy farming is based on the scientific literature and reports, and peat extraction is based on reports (Table 1).

Table 1. Selected peatland strategies.

1. Restoration strategies
Peatland rewetting
Afforestation of peatlands
Perennial cultivated grasses
Paludiculture (1) cattail (typha; (2) sphagnum farming)
Water reservoir
Growing cranberries
Growing blueberries
2. Peat biomass use in high added value product
Production of insulation boards from cattail-based on paludicultures [1]
3. Other land use—dairy farming on peat soils
4. Peat extraction

3.3. Development of Indicators

Meaningful indicators should be introduced to evaluate the strategies, evaluating both the economic and environmental dimensions.

3.4. Economic and Environmental Data for Each Strategy

Table 2 shows calculated data based on the scientific literature, reports, and assumptions for each peatland strategy for the construction of the composite index. It is possible to compare the economic indicators of the strategies, but due to limited information, there are no specific values for CO_2 and CH_4 emissions for each of the strategies. Therefore, strategies such as dairy farming, production of panels using cattail, and paludiculture using cattails and sphagnum are evaluated in CO_2 eq. ha^{-1}. For restoration strategies, CH_4 and CO_2 emissions are also compared.

Table 2. Economic indicators selected for peatland strategy evaluation.

No	Indicator	Units	Indicator Description	Impact
i1	Total investment costs to implement strategy	EUR/ha	The indicator considers recultivation planning, recultivation, construction costs, and exploitation costs in each of the alternatives.	-
i2	Maintenance costs	EUR/ha	Maintenance costs, including deprecation costs and monitoring costs.	-
i3	Income	EUR/ha	Annual profits (including economic value from products), total revenues, EUR/tonnes, subsidies, and grants for a specific strategy.	+
i4	Potential income from ecosystem services	EUR/ha/yr	The indicator describes alternative monetary value: potential income from ecosystem services. Calculations based on The Project Life Restore optimisation model additionally take into account inflation and assumptions. Ecosystem services provide some benefit—tangible or intangible. A forest provides wood, and a peatland provides peat; therefore, both are material services.	+
i5	CO_2	ha^{-1}/yr	Carbon dioxide emissions	-
I6	CH_4	ha^{-1}/yr	Methane emissions	-
I7	Total GHG emissions on rich organic soil	CO_2-eq ha^{-1} yr^{-1}	Total GHG emissions	-

The composite index cannot contain negative values or 0. If data could be used to construct the CSI, values equal to 0 are marked with 0.001 (Table 3).

Table 3. Calculated economic data for each peatland strategy.

	Rewetting	Peat Extraction	Production of Insulation Boards from Cattail Based on Paludicultures	Afforestation	Perennial Cultivated Grasses	Dairy Farming	Establishment of Palidicultures—The Cultivation of Cattail	Establishment of Paludicultures—The Cultivation of Sphagnum	Growing Blueberries	Water Reservoir	Growing Cranberries
I1 Total investments, EUR/ha	5171 Calculation based on [42]	11,868 Calculation based on [43]	3400 Calculation based on [44]	14,368 Calculation based on [42]	6087 Calculation based on [42]	10,570 Calculation based on [44]	7300 Calculation based on [44]	23,300 Calculation based on [44]	96,264 Calculation based on [42]	7265 Calculation based on [42]	29,479 Calculation based on [42]
I2 Potential income from ecosystem services, EUR/ha/yr	49,308 Calculation based on [42]	665 *Calculation based on [43]	43,825 * Calculation based on [42]	45,908 Calculation based on [42]	899.6 Calculation based on [42]	0.001	43,825 [42]	43,825.3 Calculation based on [42]	5696 Calculation based on [42]	35,967 Calculation based on [42]	14,693 Calculation based on [42]
I3 Maintenance costs, EUR/ha	10,338 (including monitoring costs) [30]	425. Calculation based on [43]	1400. Calculation based on [44]	157 Calculation based on [42]	261.8 Calculation based on [42]	4035. Calculation based on [44]	3170 Calculation based on [44]	5175 Calculation based on [44]	4215. Calculation based on [42]	0.001	1597 Calculation based on [42]
I4 Income, EUR/ha	1442	3914.9 Calculation based on	7966.7 Calculation based on	2400 [45]	497.5	5965 Calculation based on	6896.7 Calculation based on	11,891.7 Calculation based on	7854 Calculation based on [42]	0.001	1570.8 Calculation based on [42]

	Calculations based on average on-time payments and carbon credit	[43]	[44]		Calculation based on [42]	[44]	[44]	[44]	Calculation based on [42]	
CO_2	2 based on [46]	7 based on [46]		1 based on [46]	12 based on [46]				5 based on [46]	4 based on [46]
CH_4	7.2 based on [46]	1.4 based on [46]		0.3 based on [46]	1.3 based on [46]				0.9 based on [46]	0.2 based on [46]
Total GHG emissions on rich organic soil CO_2-eq ha^{-1} yr^{-1}	9.9 [46]	11.2 [46]	3.9 [34]	3.7 [46]	19.9 [46]	20.9 [34]	2.6 [46]	2.6 [46]	11.8 based on [46]	9.3 based on [46]

CI cannot have negative values. – blank space means no data available. .

Calculations and assumptions of strategies

I1 Total investments, EUR/ha

Peat extraction:

It is estimated in [31] that prices defined in the 2016 methodology [21] are correct to use if the inflation rate is taken into account. In [31], it is defined that until objective information is available and a new methodology is developed regarding initial costs for peat extraction, it is correct to use costs from the 2016 methodology considering the inflation rate [31].

Total expenses with inflation compared to 2016 2801 EUR/ha + investments in peat extraction preparation with inflation compared to 2016 (9066.7 EUR/ha). The calculation is made based on the calculation of costs from the 2016 methodology, taking into account the 2016 inflation rate for goods and services (average costs EUR/ha *1.42) [43].

Production on insulation boards:

Costs for blow-in insulation.

EUR 1550 + costs for construction EUR 1850.

- Establishment of paludicultures—the cultivation of cattail: 7300/ha EUR [44].
- Establishment of paludicultures—the cultivation of sphagnum: capital investments 23,300/ha EUR [44]

I2 Income from ecosystem services, EUR/ha/yr.

The indicator describes the alternative monetary value (2020) for goods and services in Latvia (average investments EUR/ha * 1.309).

Production on insulation boards: it is assumed that using paludiculture for product production will not reduce the value of ecosystem services.

Peat extraction.

This calculation is based on income from peat extraction from the 2016 methodology, taking into account the 2016 inflation rate for goods and services (average costs, 1.42 EUR/ha *) [7]. Calculations of benefits from material (gross revenue from mineral extraction income from peat extraction), 665 EUR/ha.

Production of insulation boards from cattail: assuming that these are potential income from paludiculture cultivation, EUR 43825.3.

Paludiculture for cattail and sphagnum cultivation:

Assuming that potential income from ecosystem services is equal to sphagnum farming and cattail cultivation.

Dairy farming:

It is assumed that when starting dairy farming, ecosystem services are 0, and there is no ecosystem, only land use.

I3 Maintenance costs, EUR/ha

For restoration strategies, restoration strategies–average based on the existing optimisation model from local project studies considering the inflation rate year 2018–2020 for goods and services in Latvia (average investments, 1.309 EUR/ha *).

Rewetting:

Maintenance costs 338 EUR + EUR 10,000 monitoring costs.

Peat extraction:

Repair and maintenance of peatland sites 266 EUR/ha + depreciation investments159.3 EUR/ha.

It is assumed that the costs of peat development and management are about 60% of the income from the sale of the peat. The average maintenance cost for peat extraction is assumed to be 3.5% of the initial capital investments [47].

Production of insulation boards from cattail [44]:

A total of 700 EUR/ha + 700 EUR/ha.

Dairy farming:

A total of 1710 EUR + 2325 EUR/ha.

Paludiculture using cattail cultivation:

A total of 2640 EUR + 530 EUR/ha.

Paludiculture using sphagnum cultivation:

A total of 4000 EUR + 1175 EUR/ha.

I4 Income, EUR/ha

For restoration strategies, restoration strategies–average based on the existing optimisation model from local project studies considering the inflation rate from 2018 to 2020 for goods and services in Latvia (average investments, 1.309 EUR/ha *). Subsidies, one-time payments, and carbon credit are based on the literature and added together with net income to get total income.

Rewetting:

The average one-time income from case studies is 442 EUR/ha (based on + the amount of carbon credit for farmers and landowners, 1000 EUR/ha (one-time payment) [44].

Production of insulation boards: total exploitation costs EUR 7500 + annual CO_2 credit 467 EUR/ha (CO2 credits based on 14,000 EUR/ha/30 years)

Perennial cultivated grasses 65.5 EUR + one-off payment 432 EUR/ha

Dairy farming:A total of 4600 EUR + 965 EUR + 400 EUR/ha

Paludiculture using cattail cultivation:

Annual potential profits 4800 EUR/ha+ annual net income 1630 EUR/ha + annual CO_2 credit 466.7 EUR/ha (CO2 credits based on 14,000 EUR/ha/30 years)

Paludiculture using sphagnum cultivation [44]:

A total of 8800 EUR/ha + 2625 EUR/ha+ annual CO_2 credit 466.7 EUR/ha (CO2 credits based on 14,000 EUR/ha/30 years)

Afforestation: minimum amount of support from funds 2400 EUR/ha [45]

3.5. Normalization of Data

To use the calculated data or data found in the literature, the data must first be normalised. The CI Min–Max method is used as a normalization method for data construction. This method is widely used in decision-making analysis; results are made on a scale of 0–1.

$$I^+_{N,ij} = \frac{I^+_{act,ji} - I^+_{min,ji}}{I^+_{max,ji} - I^+_{min,ji}} \tag{1}$$

where

$I^+_{N,ij}$—normalised indicator;
$I^+_{act,i}$—actual value of the indicator;
$I^-_{min,i}$—indicator minimum value;
$I^+_{max,i}$—indicator maximum value;
i—specific indicator.
[48–50]

3.6. Indicator Weighting

Each of the indicators got equal weight assuming that all selected economic indicators are equally important. For each scenario, the indicator weight is different based on the count of the indicator in each scenario.

1. A total of 5 indicators were used with a weight 0.20 for each indicator.
2. A total of 7 indicators were used with a weight 0.14 for each indicator.

3.7. Indicators Aggregation into CI

The final step is the aggregation in the CI results multiplied with the normalized indicator value.

$$I_{CI} = \sum_j^n W_j x \, I_i \tag{2}$$

where

I_{CI}—composite index;
W_j—equal importance indicator weight [50,51];
I_i—normalized indicator value.
[50,51]

4. Results

The highest score on the composite index for the production of insulation panels using cattail (*typha*) is (0.87). The indicators that most determine the advantages of thermal insulation panels are the required amount of investment and the relatively low emissions of CO_2 eq. Also, paludicultures using sphagnum farming (0.84) and cattail (0.82) received the second and third highest results in the CI, respectively.

Peat rewetting received (0.53) due to the higher maintenance costs, including monitoring costs. Among the alternatives mentioned before, peatland rewetting has the highest potential income from potential ecosystem services (see Figure 2).
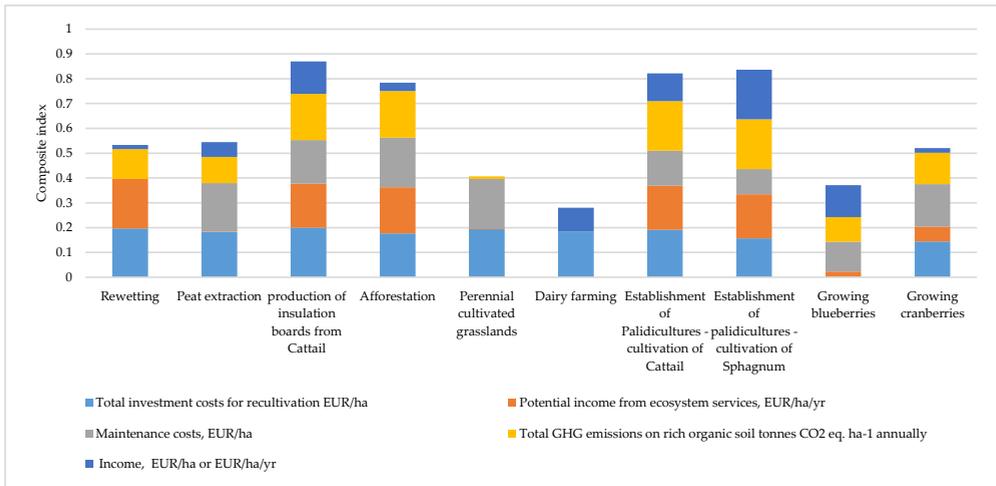
Figure 2. Restoration strategies and alternative use of peat.

By directly comparing the costs, benefits, and GHG emissions of peatland restoration strategies, it is possible to assess which strategies are considered important in Latvian conditions. Among the restoration strategies, afforestation on drained organic soils (0.87) received the highest rating. The lowest rating was perennial cultivated grasslands, which have higher emissions compared to other strategies (0.40) (see Figure 3).
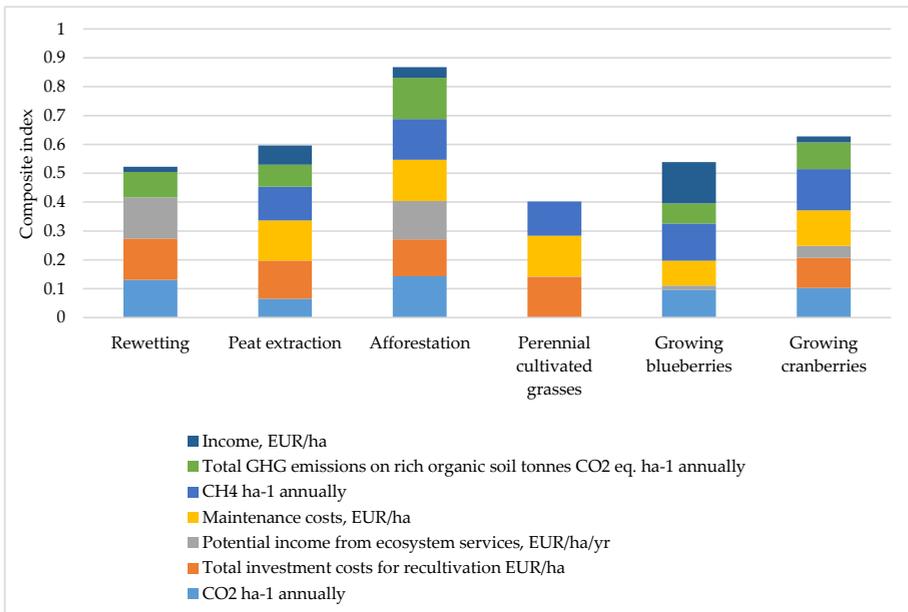

Figure 3. Peatland restoration strategies.

5. Discussion

The distance impacts restoration costs; scale of restoration and terrain can play a role [52]. Whether restoration will be profitable depends on the areas of restored peatlands [15].

Regarding economic viability, some of the latest studies confirm that net present worth after peatland restoration is higher than restoration costs [15]. It should be taken into account that, besides capital costs for restoration, annual maintenance costs for restoration sites make up one part of the costs [29]. It is predicted that the monetary value of ecosystem services for non-timber products will rise in the coming years [26]. Paludiculture is considered a viable strategy for reducing GHGs while providing opportunities for landowners and the development of new services and products. Although paludiculture has several benefits, only a small area of peatlands is used in paludiculture [34]. Bog cultivation is not widely implemented due to socio-economic challenges and historical support for peatland drainage. Implementing paludiculture requires a joint decision of the landowners, which makes it difficult to expand the practice [1].

Transforming drained and pristine peatlands in paludiculture can promote several ecosystem services and, therefore, incomes from ecosystem services [35]. By switching to paludiculture, it is possible to reduce GHG emissions and land subsidence while providing productive use of land [40,41,45,47]. In paludiculture cultures, great results have been shown with cattail (Typha), peat moss, and black alder [53,54].

Cultivation of cattail (Typha) can promote suitable conditions for the development of ecosystem services. Cattail growth conditions are better in nutrient-rich biotopes, including freshwater wetlands and brackish bogs [53]. It is calculated that one ton of harvested dry cattail can make a return of about EUR 100–200 [44].

Previous studies show that after processing peat by separating fibres, incomes can reach 300 EUR/ton to 500 EUR/ton [44]. Cattail as a raw material can make a turnover of ~2000 EUR/year on average and ~4800 EUR/year in processed material [44]. Net incomes from paludiculture can also make carbon credits for landowners [44]. The literature confirms that better initiatives and monetary motivation for farmers should be introduced in order to facilitate more extensive paludiculture implementation [35]. It is crucial to promote innovative peat product export and production with high added value in the building sector, including peat-based thermal insulation panels and materials [33]. Harvested cattails have the potential to be used in different kinds of goods, including mats, baskets, and toys, and valuable products such as building materials and insulation boards where peat can be used as a raw material or additive [53]. Cattail characteristics make it appropriate and competitive as a use of insulation material. In cattail-based insulation material, it is feasible to store biogenic carbon for a long period of time [34].

In paludiculture using sphagnum farming, it should be taken into account that part of the white peat layer cannot be used to make a profit, and it should be conserved [12,55]. Regarding the implementation of sphagnum farming, several barriers can delay the broader use of paludicultures using sphagnum. One of the drawbacks is related to the high initial costs for land transformation into paludiculture. Also, revenues and incomes from sphagnum farming can greatly vary, and incomes can be expected after several years [55,56].

In the case of afforestation of peatlands, the necessary total capital investments highly depend on the tree species to be planted in previously drained peatlands. From the trees to be planted, one of the highest investments is necessary for the plantation of willow (~1549 EU/ha^{-1}). The high costs of seed materials could explain that. It has been estimated that lower initial costs are for the planting of pine (1042 EUR/ha^{-1}) and spruce—1090 EUR/ha^{-1} [36,57]. It is calculated that high market revenues in drained peatlands are from plantations of poplar (7557 EUR/ha)—in 20 years, and in 40 years—hybrid aspen. One of the lower incomes is from grey alder—in 20 years (3306 EUR/ha), and from pine—in 40 years [36,57].

Previous studies show that the average costs are 382.8 EUR/ha for preparing a site, 633.2 EUR/ha for labour and seedling costs, 374.8 EUR/ha for maintaining stands, 429.6 ha for thinning before commercialization, and 391.9 EUR/ha for fertilization [44,45]. Afforested peatlands might negatively impact the competition for land and result in increased food prices [37].

Previous studies in the literature confirm that capital costs for the implementation of rewetting as a restoration strategy are lower than for other GHG emission mitigation strategies [31]. In accordance with the previous literature, gains from rewetting raise the water table level and are mostly greater than the initial costs necessary for rewetting [58]. Peatland rewetting can be evaluated as an attractive solution regarding financial compensation (EUR/ha) after rewetting, although in the case of land rewetting, landowners can have serious negative effects on their further agricultural activities [31]. The negative effects of rewetting are related to the loss of income due to land use change [31]. Landowners, after rewetting, can experience a loss of income regarding farming, including limited availability of land and changes in pastures linked to unsuitable conditions for cows in wet periods [31]. One of the changes in income is related to the fact that cows should be brought in earlier in the spring or during the wet periods, as the grass reaches the ground later [31]. Land area after rewetting is not economically viable for landowners and nearby farmers for agricultural activities [34]. After rewetting, the soil is not suitable for further cultivation of crops or dairy farming, including rewetted soil limited by the capacity to carry agricultural equipment [8,34]. A previous study from the Netherlands shows that increasing the water level due to rewetting from 80 centimetres under the surface to 10 centimetres above the surface can cause a market income loss of up to 1358 EUR/ha [29]. Studies in the Netherlands estimated that by raising the water level by 20 cm in peat-based soil farmlands, economic income loss reached 846 EUR/ha [31].

According to the literature, one solution to reduce the loss of income after rewetting if it is planned to continue farming could be to reduce milk production and the number of cows [46]. Pressure drainage can be implemented after rewetting farmlands to stabilize the water level and reduce costs for fodder and manure [31].

The previous literature shows that compared to dairy farming on sandy soil, dairy farming on peat soils results in lower income and also higher global warming potential [59]. Incomes from dairy farming come from the production of milk and subsidies for dairy farming [29]. Conversion from peatland to dairy farming will make net income dairy production [34] and, at the same, reduce potential income from ecosystem services [34]. Although dairy farming makes income from the production of products, the negative aspect is related to the degradation of ecosystem services, transforming peatlands into grasslands for dairy farming [40]. Subsidies for dairy farming can be larger than incomes from milk production itself. In Germany, it was calculated that EUR ~35,000 can be made from subsidies but only EUR 10,000 from milk production [29]. In contrast, the average income in the Netherlands is from milk production, at EUR 90,000, and only EUR 20,000 is from subsidies for dairy farming [29].

It is possible to transform land use from dairy production into paludiculture. It is calculated that the capital costs for land transformation are approximately 7300 EUR/ha on average based on the North Netherlands study [44]. Previous studies confirm that the implementation of paludiculture cultivating cattail and sphagnum and harvesting might compete economically with dairy farming and income from milk production [44].

Restoration by introducing perennial cultivated grasses can have various establishment costs that depend on the methods used, ecology, and the specific restoration site [60]. Previous studies show (2019) that total incomes per ha can reach EUR 769, including direct incomes and incomes from subsidies (~356 EUR/ha) [29]. Cultivation of cranberries and blueberries ranks lower based on low income and high capital costs for blueberry cultivation. Latvia's climate is appropriate for the cultivation of cranberries in previously drained peatlands. Income is not instant for cranberry cultivation; three years after planting cranberries, the first harvest might be expected [33]. For effective peatland management, cooperation between landowners, farmers, government, companies, scientists, and other related stakeholders should be promoted [19,61].

A united approach should be implemented for the better evaluation of the changes in ecosystem services and more precise cost-effectiveness of restoration by implementing

unified protocols [16]. The experience of restoration workers and the availability of equipment might have a beneficial effect on the reduction in capital costs for restoration [16]. More attention should be focused on the techniques and necessary investment reduction for the cultivation of paludicultures as an alternative for the rewetting of peatlands. The connection between global indicators and national or local policy and reporting needs strengthening [62]. Indicators should be scalable where there are local or national data—which are typically more relevant to local policy and more accurate through the inclusion of local knowledge and data [62].

Limitations of the Study

There is a lack of a specific cost-effectiveness assessment of the impact of peatland restoration strategies [6]. According to the literature, global funding for peatland restoration is assessed as insufficient [1]. It is estimated that both public and private financing is less than required for peatland restoration [2].

Defining peatland strategies and specific measures in peatland restoration requires initially providing and foreseeing adequate financing for their implementation [51].

One limitation of the study is the scarcity of specific data regarding costs and gains on thermal insulation panels. Revenues and incomes from sphagnum farming can greatly vary, but incomes can be expected after several years. Other environmental factors that could be included in future studies are the Ecosystem Health Index [62] and indicators that rely on land-use change and biodiversity such as the Species Habitat Index and Biodiversity Intactness Index [62].

6. Conclusions

In this study, peatland strategies and alternative uses in products were mutually compared with existing strategies, which are determined in Latvia's *Guidelines for the Sustainable Use of Peat 2020–2030*.

The highest score in both scenarios is for the production of insulation boards by cultivating cattail. The second highest score in the composite index is for the cultivation of paludicultures—cattail and sphagnum—in the first scenario. The lowest score is for the cultivation of cranberries and blueberries based on lower incomes and high initial costs for blueberry cultivation.

Indicators such as net income, income from ecosystem services, and market revenue influence the low rating of these alternatives. It can be concluded that the significant impact on the sustainability rating in the CI comes from total investments EUR/ha and the net income realising strategy. If the strategy is not economically feasible to implement and the invested investments do not pay off, this determines that the peatland strategy will have a lower rating in the long-term evaluation. The analysis and creation of a CI based on real data and assumptions based on the scientific literature serve as an effective method that can be used in the decision-making process to simultaneously evaluate different factors related to economic feasibility.

After rewetting, the soil is not suitable for further cultivation of crops. It should be taken into account that incomes from rewetting like carbon credits or other subsidies of EUR/ha are one-time payments, in comparison to other strategies [31]. The practice of paludiculture can make gains for net income for landowners and farmers and make high income for potential ecosystem services. Production of thermal insulation boards based on paludicultures is a possible alternative, as it is possible to use peat in an economically justified way. In this case, peat is not used as an energy resource: biomass grown by paludiculture as a raw material for added value product production is possible without peat extraction. The cultivation of paludicultures and the production of high-added-value goods are closely linked. The biomass grown in paludicultures can be harvested and used for the production of products. One of the recommendations is to use peatland biomass based on cultivated cattail or sphagnum farming instead of the extraction of peat.

Nomenclature

GHG	Greenhouse gas
CO_2	Carbon dioxide
EU	European Union
Ha	Hectare
EUR/ha	EUR per hectare

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Article

Sector-Specific Pathways to Sustainability: Unravelling the Most Promising Renewable Energy Options

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Abstract: Energy consumption across industries accounts for more than seventy-five per cent of total greenhouse gas emissions in the European Union. Energy is a top priority for achieving climate goals and low greenhouse gas emission levels. The comparison of sustainable development patterns in renewable energy sources is carried out for all the different sectors analysed for the study, such as industry, services, agriculture, transport, and households. Specifically, researchers examined trends in each of these sectors. This study aims to create a model that combines qualitative and quantitative research approaches to obtain the most objective and descriptive data on RES technologies used in different sectors of the economy. According to the results, both solar energy and biomass have strong development potential overall, which is reflected in the higher average values of the overall results. This is also the case when looking at the impacts individually.

Keywords: renewable energy; sustainability; development potential; sectors of economy

1. Introduction

The European Green Deal adopts essential measures to support progress towards the 2030 climate targets set and to achieve climate neutrality in European Union member states as early as 2050 [1]. The European Green Deal states that increased use of renewable energy sources (RESs) to replace fossil fuels should be a priority [2,3]. Fossil fuel use is one of the significant contributors to greenhouse gas emissions from residential heating and cooling systems, commercial and institutional buildings, transportation systems, agricultural machinery, and industrial activities [4]. The residential sector of the energy industry accounts for more than 39% of total energy consumption in Sweden, which is more than fifty per cent of the whole consumption in Saudi Arabia, more than 26% of the energy sector in Japan, and more than 25% of total consumption in the United States [1]. As the wealth of part of the population and the population as a whole increases, the service sector has also experienced rapid development and, at the same time, an increase in energy consumption among the population [2].

The service sector can be understood as a set of different services that need to be provided on a daily basis, such as various hospitality services, tourism services, hotels and guesthouses, retail and wholesale trade, various technology and research services, sports and cultural services, and educational services [3]. In terms of employment, the service sector has experienced one of the largest increases among the sectors [4,5].

It is estimated that, on average, the service sector [6] accounts for a quarter or a third of total energy demand. It is projected that energy demand in residential and service sectors could average about 40% of total energy demand by 2050 [7–9]. According to current research findings, the usage rate of RESs in the commercial sector has increased in recent years [9]. However, the possible potential of renewable energy resources is not utilised; for example, the potential energy source from heat residues is not fully used [10–12]. Looking at specific countries and their progress in the use of RESs as a substitute for fossil energy resources,

we can mention China, which, in recent years, has made progress in the development of solar and wind energy technologies and an increase in the share of production, and these technologies are used worldwide, as well as renewable technologies, whose production has reduced the cost and investment required to install the equipment. In recent years, large-scale production companies such as British Petroleum and Shell have invested in electric cars, charging them with RESs. Countries such as Pakistan, Srilanka, Nepal, and India are also investing more and more in expanding the use of solar, biomass, wind, and hydropower instead of fossil fuels [12]. In the industrial sector, various processes need to be supplied with thermal energy [13,14]. Based on the indicators of the member states of the European Union, it is calculated that, on average, more than 28% of the required thermal energy is generated in industrial sectors such as pulp and paper, tobacco, food and beverage, steel and iron production, and oil and chemical industries [14]. Another sector that produces a significant amount of greenhouse gas emissions is agriculture, which is responsible for more than 21% of total greenhouse gas emissions due to processes such as mechanical intensive tillage and intensive fertilisation [15,16]. In agricultural production plants, one of the most energy-intensive processes is drying. Here, new solutions are being sought to ensure the necessary energy, for example, through the use of solar panels to ensure the temperatures required for drying [17]. In the transport sector, there are several ways to reduce emissions to zero by 2050. One of the solutions to reduce emissions is electric cars, the use of which is increasing but depends on the existence of a suitable infrastructure [18]. The use of electric cars, which is increasing, is one of the possible answers to the problem of replacing fossil fuels and reducing emissions to reach zero emissions by 2050. However, the use of electric cars is limited by several issues, including the need to develop appropriate infrastructure and the accessibility of charging stations [18]. It is predicted that electrification of the transport sector can achieve a CO_2 reduction of 25–30%. For a more sustainable energy system development, electrification and increasing the share of renewable energies in combination with smart technologies and combined systems are important elements [19].

Therefore, a more in-depth study on the renewable energy potential in each sector of the leading sectors of the economy (industry, agriculture, household, services, and transport) is needed to assess which RES technologies are more appropriate for each sector. It is crucial to understand in which sectors a high potential of using RES technologies is possible but in which technologies there are significant obstacles in their implementation. Using this method, it is possible to assess which policies would be useful to implement now and which RES solutions should be given a lower priority.

The study compares the sustainable development of RESs between the sectors examined in the study—industry, services, agriculture, households, and transport. The analysis carried out aims to find out which of the RESs is the most promising and sustainable in each sector and what conditions determine this. In addition, in order to evaluate the potential of renewable energies, a mutual evaluation of the advantages, limitations, and development speed of renewable energies for the above-mentioned sectors has been carried out. This study does not refer to the economy of any particular country. The objective of this study was to gain a comprehensive understanding of the key benefits and limitations associated with the development and implementation of RESs in various industries using a novel approach. The analysis includes an extensive literature review in various countries around the world, including China, India, the United States, Bolivia, and European countries such as Spain, Iceland, Finland, Norway, Denmark, Sweden, Lithuania, Latvia, Greece, France, Germany, etc. It is essential to realise that the applications of RESs in different industries depend on various factors that may vary from country to country. Several critical considerations need to be taken into account, including resource availability (such as wind or sunlight availability and proximity to water sources), spatial and geographical constraints, cost considerations, specific energy demand profiles, and other relevant factors. These factors collectively contribute to determining the feasibility and suitability of RES deployment in specific industries and countries.

The initial framework applied to the research is found in section one, section three highlights the primary insights gained through the composite sustainability index, and the final section provides a comprehensive overview.

2. Methodology

This study examines sustainable development trends of renewable energy resources (RESs) across different sectors such as industry, services, agriculture, transport, and households. The analysis of RESs includes solar, wind, hydro, biomass, and geothermal energy resources, which are analysed separately for each sector. The study's main objective is to determine which RESs are the most competitive and sustainable across all sectors and which factors contribute to these results. First, the methodological approach is presented to conduct the analysis and obtain research results. Then, the obtained results are demonstrated in each sector, describing the most important factors influencing the results.

The scientific novelty of the research is the development of a method that allowed quantifying the qualitative assessment of the research. A large number of scientific papers were reviewed to develop the assessment.

The results generate a view on a comprehensive assessment of differences between the sectors and how identifying these differences can help to develop more tailored and sector-specific policies. The results allow us to spot and highlight the untapped potential of specific renewable energy resources in each sector. Therefore, policymakers could focus on tackling the identified barriers and using the full potential of identified opportunities.

The conceptual and methodological basis of this research is shown in Figure 1. The model combines both qualitative and quantitative research methods to provide an in-depth assessment of the key factors affecting the competitiveness and sustainable development of each RES technology in each sector.
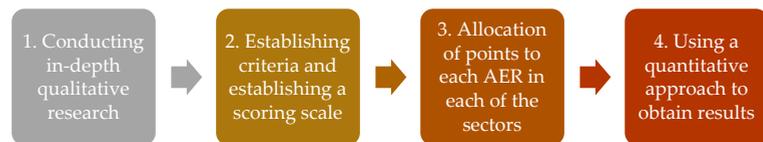

Figure 1. The steps of performing the qualitative analysis in chronological order.

2.1. Description of the Methodology for Qualitative Assessment

In the beginning, a comprehensive qualitative analysis was conducted. This analysis is based on the literature, in-depth studies, reports, and other accessible sources of information on the use of RESs, development trends, and characteristics in each of the sectors studied. Three essential criteria and aspects were put forward to perform the full value analysis, which was examined separately for each resource compared to the examined sectors.

First, a qualitative assessment based on a comprehensive literature review of the use of RESs in each sector was conducted. The literature review includes a review of recently published scientific publications, research papers, and assessment reports. A total of 100 sources of information were used for the qualitative assessment. Table 1 provides an overview of the main literature used for the RES assessment of each sector.

In order to create a collection of the scientific literature on RESs (biomass, solar energy, water, wind energy, and geothermal energy), we used possibilities and answers to questions such as

- The increase in the use of technology in the future;
- Technological development and increase in utilisation rate;
- RES technology innovation opportunities and technology combinations;
- Using solar energy (for heat and electricity) technology combined with smart technology;
- The presence of any restrictions on the use of the resource;
- The availability of RESs as a limiting factor for resource use. Payback period of investments (years);

- Cost savings (EUR, %);
- Energy savings (kWh, MWh, %);
- CO_2 reduction.

Table 1. Sources of literature for qualitative assessment.

Sector	Topic	Source of Literature
Industry	- The experience of renewable energy use in the transport sector, limiting factors, and future forecasts. - Characteristics of the development of RES extraction and production technologies. - Development potential assessment for RESs, RES technology innovation opportunities, and technology combinations. - Experience of industrial companies using PV panels and collectors. - Assessment of opportunities and challenges in the industrial sector.	[11,14,19–55]
Services	- The increase in the use of technology in the future; technological development and increase in utilisation rate; and RES technology innovation opportunities and technology combinations. - Assessment of opportunities and challenges in the service sector.	[38,51,56–69]
Agriculture	- Experience and possibilities of using biomass technologists in agriculture. - Assessment of opportunities and challenges in the agriculture sector	[17,20,55,70–95]
Households	- The increase in the use of technology in the future. - Cost savings (EUR, %). - Using solar energy technology combined with smart technology. - Energy savings (kWh, MWh, %). - Assessment of opportunities and challenges in the household sector.	[17,20,24,55,70–72,74–81,84,86–88,96–117]
Transport	- The presence of any restrictions on the use of the resource and RES technology innovation opportunities and technology combinations. - Assessment of opportunities and challenges in the transport sector.	[38,51,56,118–127]

System boundaries of this research:

The research evaluated the development potential of RESs across various sectors, considering on-site renewable energy generation and the potential for self-consumption within each sector.

CO_2 emissions are not directly included in the assessment but are based on scientific publications—reviews and articles describing case studies where the use of RES technologies reduced CO_2 emissions compared to the situation before the equipment was installed. In cases where the scientific literature does not indicate specific numbers that confirm the reduction in emissions using specific RESs, when analysing the AER potential for each source, it is taken into account that the studies show a reduction in emissions. A more qualitative assessment can be prepared for those sectors and RES sources where case studies confirm specific emission reductions. It is taken into account that one of the factors that affected the reliability of the results obtained in the study is the limited numerical information in the scientific literature about specific industries.

Figure 1 illustrates the main steps of the methodological framework in a simple way.

2.2. Description of the Methodological for Quantitative Assessment

The methodology includes (1) conducting in-depth qualitative research; (2) setting the criteria and determining the point scale (1–5); (3) the allocation of points to each AER in each of the sectors; (4) score normalisation; (5) score weighting; (6) score aggregation; (7) a final index score; and (8) ranking technologies (Figure 2).
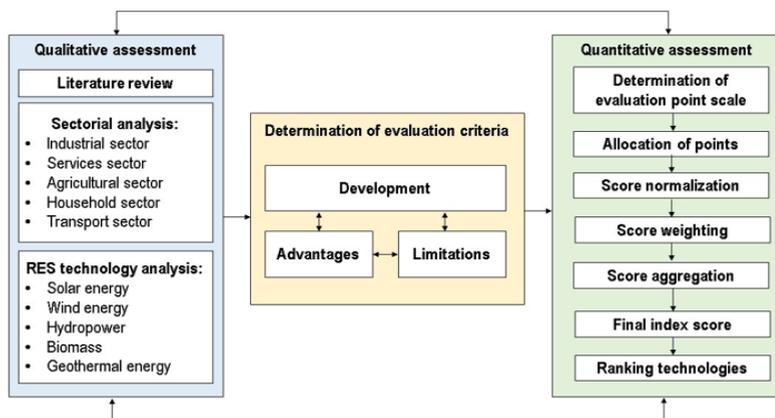
Figure 2. The methodological framework of the study.

2.2.1. Determination of Evaluation Point Scale and Allocation of Points

The three most important criteria and aspects were put forward, which were discussed in more detail separately for each of the resources compared to the examined sectors.

The cross-sectoral comparison from the literature review is based on evaluating three main criteria—RES development tendencies, the main advantages of RESs, and the limitations of RES implementation. A five-point rating scale was developed for each criterion, with one representing the lowest score and five representing the highest score. Points are awarded for each type of RES and sector based on the conclusions of the qualitative analysis. Table 2 provides an overview of the evaluation criteria and a description of the valuation scale. For each type of RES (solar, wind, hydro, biomass, and geothermal) in each sector (industry, services, agriculture, households, and transport), corresponding points are assigned according to Table 2. The points are summarised in tables, using MS Excel software.

Table 2. Criteria for the assessment and description of the evaluation scale.

Criteria	Research Question	Evaluation Scale
Development	How fast is the technological development of a specific type of RES?	5—the most rapid development 4—fast development, there are limiting factors 3—limited development 2—very slow development 1—no development observed
Advantages	Which of the RES has the greatest advantages in use?	5—greatest advantages 4—second-greatest advantages 3—fewer advantages, there are significant constraints 2—there are many constraints 1—no significant advantages observed
Limitations	How significant are the constraints and limitations of a specific type of RES in the sector?	5—almost no limiting factors or severe limitations are observed 4—minor limitations are observed that affect the use of the specific RES 3—there are few disadvantages that limit the use of the specific RES 2—numerous disadvantages limit the use of the source 1—Many limitations hinder the utilisation of RESs

Table 3 shows the evaluation performed; each resource in each of the sectors is evaluated on a scale from 1 to 5. The evaluation was based on the scoring system developed in Table 2. These ratings are further used to perform quantitative analysis and create an index for each of the RES.

Table 3. Collected scores based on literature assessment based on defined criteria.

Sector					
Industry Sector	**Solar Energy**	**Wind Energy**	**Hydropower**	**Biomass**	**Geothermal Energy**
Development	5.0	3.5	3.5	4.0	3.5
Advantages	4.5	3.5	3.0	4.0	3.5
Limitations	3.0	3.0	3.5	3.5	4.0
Total	12.5	10.0	10.0	11.5	11.0
Service sector					
Development	5.0	3.0	3.0	3.5	4.0
Advantages	4.5	3.0	3.0	3.5	4.0
Limitations	4.0	3.0	3.0	3.5	4.0
Total	13.5	9.0	9.0	10.5	12.0
Agriculture sector					
Development	4.0	3.0	3.0	5.0	3.0
Advantages	5.0	3.5	3.0	5.0	3.0
Limitations	5.0	3.0	3.0	5.0	4.0
Total	14.0	9.5	9.0	15.0	10.0
Household sector					
Development	4.0	3.5	4.0	4.5	4.0
Advantages	4.5	4.0	3.5	3.5	4.0
Limitations	4.0	3.5	3.5	3.5	3.0
Total	12.5	11.0	11.0	11.5	11.0
Transport sector					
Development	4.5	4.5	3.5	5.0	3.0
Advantages	4.0	4.5	3.5	5.0	3.0
Limitations	5.0	3.5	3.0	5.0	3.0
Total	13.5	12.5	10.0	15.0	9.0

2.2.2. Data Normalisation, Score Weighting, and Final Index Score

After data collection, the data were processed and normalised using the min–max normalisation technique, as shown in Equation (1). Normalisation scales the assigned points in a range from 0 to 1, where 0 is the lowest value and 1 is the highest value.

$$S_{Ni} = \frac{S_i - S_{min}}{S_{max} - S_{min}} \tag{1}$$

where S_{Ni} is the normalised score, S_i is the score obtained from qualitative assessment, S_{min} is the minimum score of the evaluation scale, which is equal to 1, and S_{max} is the maximum score of the evaluation scale, which is equal to 5.

Furthermore, weights are assigned to each normalised value. In this study, all three criteria are weighted equally because the pace of development, advantages, and limitations of specific RES technologies have an equal impact on the further progress of RESs in each sector. The normalised and weighted values are aggregated into an index according to Equation (2).

$$SI = \sum w_i \times S_{Ni} \, , \, w_i = \frac{1}{n_i} \tag{2}$$

where SI is the final index value for the deployment potential of the evaluation categories i (development, $i = 1$; advantages, $i = 2$; and limitations, $i = 3$), w_i is the determined weight of the indicator, and n_i is the number of indicators in the evaluation, which is equal to 2 [100,128–130].

The aggregated results of each RES show the trend and potential of long-term sustainable development and competitiveness. The closer the result is to 1, the higher the long-term development and potential in a particular sector [131,132].

Based on the literature assessment, the criteria selected (development, advantages, and limitations) were evaluated on a scale of 1–5 (see Table 2).

Table 4 shows the evaluation score in the industry sector based on the criteria presented in Table 2.

Table 4. Evaluation score from qualitative assessment in the industry sector.

	Solar Energy	Wind Energy	Hydropower	Biomass	Geothermal Energy
			Criteria		
Development	5	3.5	3.5	4	3.5
Advantages	4.5	3.5	3	4	3.5
Limitations	3	3	3.5	3.5	4
Total	12.5	10	10	11.5	11

All further calculations are made using the formulas given in Equations (1) and (2), using the industry sector as an example (Table 5).

Table 5. The score for each criterion and total index for the industry sector.

	RES Technologies				
	Solar energy	Wind Energy	Hydropower	Biomass	Geothermal Energy
Criteria					
Development	1	0.7	0.7	0.8	0.7
Advantages	0.9	0.7	0.6	0.8	0.7
Limitations	0.6	0.6	0.7	0.7	0.8
Development	0.33	0.23	0.23	0.27	0.23
Advantages	0.30	0.23	0.20	0.27	0.23
Limitations	0.20	0.20	0.23	0.23	0.27
Total	**0.83**	**0.67**	**0.67**	**0.77**	**0.73**

3. Results and Discussion

The following is a comparison of the sustainable development of RESs in the most important sectors of the economy.

3.1. Industrial Sector

The results show that solar energy and biomass are the key dominators for the industry compared with other types of RESs, as shown in Figure 3. Solar energy has the highest value compared to other resources, with a value of 0.83 on the value index. This is mainly because the resources have developed the fastest and have greater technological advantages. Solar energy drives many company processes. Industrial companies install solar energy systems to save 50–70% of energy consumption. The technological development of solar energy systems has significantly maximised the solar energy utilisation potential in the industry over the past decade. The use of solar energy has become more attractive thanks to a number of technological advances in solar energy systems. These include integrated systems that make it possible to control the temperature required for industrial production processes and ensure that solar energy is used for crucial production processes such as water heating, steam generation, drying, and other processes. However, the amount of solar energy generated depends highly on the weather, so significant energy supply shortages might appear in seasons with low solar radiation. For industrial companies, uninterrupted energy suppliers are critical to ensure a flawless production process. Therefore, the possibility of energy supply shortages is considered the most important obstacle limiting production plants in the implementation of solar energy systems. This explains why the overall index score for solar energy was below the maximum score of 1, which is the highest

possible score. However, due to the rapid technological development of solar energy and the advantages of its use, as well as the shorter payback period of the investment, these limitations are not a major obstacle to the potential use of this energy source. Moreover, solutions already exist to compensate for the limiting factors of solar energy and to achieve greater use of solar energy in industrial enterprises.
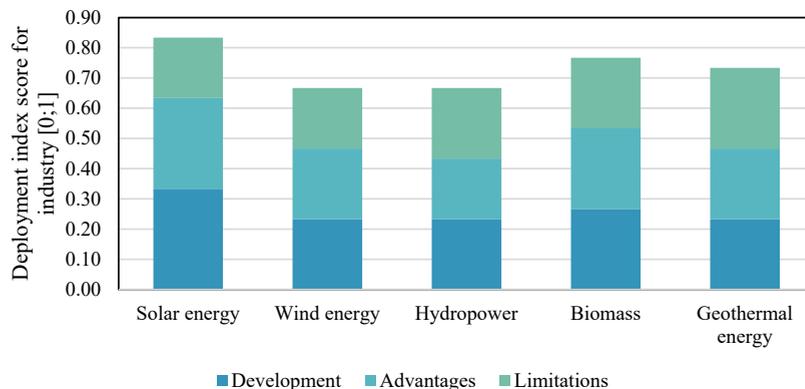

Figure 3. Industrial RES development potential index results.

Biomass was determined to have a potential use of 0.77, placing it second among all sectors in terms of potential use. The rapid development of the potential of biomass utilisation can already be observed and predicted for the future. Higher biomass consumption is observed in pulp, paper, and wood production industries, all of which generate waste in the form of biomass as a byproduct of their production processes. Technological solutions are mentioned as the main advantages of biomass, such as reaching the temperature range required for efficient industrial processes. Constant energy supply throughout the year without energy shortages is highlighted as the main advantage of biomass use in industry, which has been identified as the main limitation of solar energy use. Most biomass comes from the many types of organic waste produced in forests, on uncultivated land, and by agricultural and forestry operations. However, the main disadvantage of using biomass in industry is that there is not enough biomass available to meet the energy needs of the sector, unless agricultural residues are used for energy production.

Geothermal has not yet achieved an assessment score (0.73) for deployment potential in an industry that could compete with solar (0.83) or biomass (0.77). On the other hand, geothermal energy has many advantages that could help it become more essential and accelerate its widespread use in the commercial sector. Geothermal energy allows the storage and reuse of heat, which greatly improves the efficiency of production processes, even at high loads. In addition, geothermal energy can be combined with other technologies to provide uninterrupted power to facilities when solar energy is limited. The technological advantages of geothermal energy can significantly reduce production costs, especially for high-capacity manufacturing plants. The main limitation associated with using geothermal energy in industry is the availability of the resource.

Deployment potential index scores in the industry for wind energy and hydropower each reached a value of 0.67, which is the lowest value compared to other RES energy resources. Both resources are developing at a limited pace compared to other RESs. The deployment potential of hydropower depends on the availability of hydropower resources in the region where the manufacturing company operates. Wind energy, like solar energy, is limited due to energy generation dependency on seasons. However, wind energy can be used in combined systems where another RES can make up for a shortage of wind energy. One significant advantage of wind energy application in the industrial sector is that wind turbines possess the capability to generate a greater amount of energy per unit

area and time compared to solar photovoltaic systems, assuming equal potentials for both in the given region. However, solar energy offers several key advantages over wind energy in the industrial sector, primarily resulting from its lower capital expenditure, reduced maintenance requirements, and simplified integration into the grid and existing energy supply model. In terms of limitations, both technologies are constrained by their intermittent production nature and geographical needs, requiring substantial spatial demands. Hydropower also has limited advantages because it requires a high capital and technical capacity to produce energy. However, hydropower is able to adapt and compensate for bottlenecks and interruptions in wind energy. Despite the industry's slower development pace of wind and hydropower technologies, both RESs are expected to develop more rapidly.

3.2. Service Sector

Figure 4 shows the potential of RESs in the service sector—according to the results, the use of solar energy has the highest value of 0.90. The pace of development of technological solutions for solar energy has accelerated in recent years, so the demand for solar technologies in the service sector continues to grow. The growth rate in the development of solar technology solutions is favoured by combining these technologies with smart solutions or integrating smart technological solutions with solar technologies. In recent years, more solar technologies are used together with integrated smart meters. Such technological solutions are also used in educational institutions and other public buildings to better control the energy consumed and the load. One of the subsectors of the service sector, tourism, is increasingly using solar solutions that can cover a large part of the required energy.
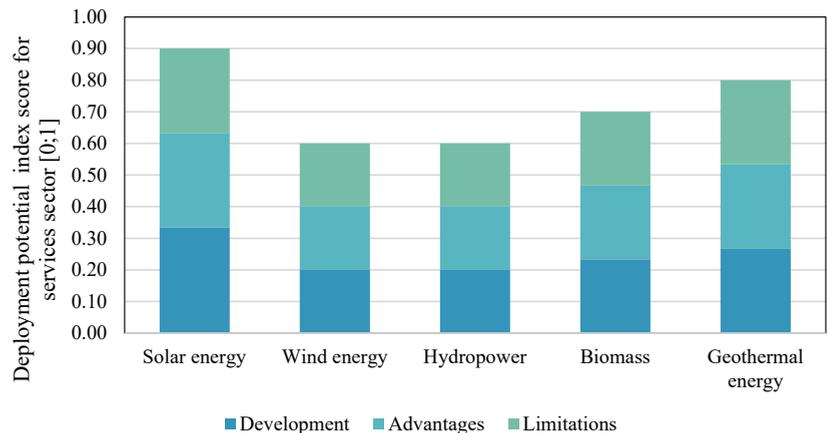

Figure 4. Development potential in the service sector by RES types.

Solar solutions have a growing trend, such as heat recovery from wastewater, using heat pumps in addition to PV solar solutions. Solar solutions are suitable because they are suitable for both low and medium temperatures required for operation in the service sector.

It has been studied that integrating solar solutions with smart technologies can directly reduce the consumption of thermal energy, electricity, and hot water in the service sector. In recent years, there is a trend that solar solutions have a shorter and shorter payback period, so these technologies are becoming more and more financially favourable, and the payback period of these technologies is less than 10 years. Therefore, solar solutions have become more accessible and interesting for the service sector. A disadvantage of using solar technology in the service sector is the insufficient amount produced during the relevant months of the year. This disadvantage could be eliminated by using an additional source that provides the necessary energy throughout the year. The solution lies in the use of combined systems. For example, heat pumps, which are also increasingly common in

the household and service sectors, can compensate for energy shortages at a lower cost compared to the industrial sector.

According to the results, the use of geothermal energy in the service sector achieves a high score of 0.80. Geothermal energy as an energy resource is mainly used in the tourism sector, especially in the recreation sector. Geothermal energy is relatively underutilised in other service subsectors. However, it is expected that the use of geothermal energy in other service sector subsectors will also increase.

In the qualitative analysis, the second-greatest advantage is attributed to geothermal energy, since using this energy source does not require large investments. Regarding the use of geothermal energy, the absence of such use is the least valued. Geographical and regional differences affecting the availability of resources can be mentioned among the disadvantages of exploitation. On the other hand, the third place (0.70) in evaluating sustainable development is occupied by the possibility of using biomass. Compared to the other RES sources discussed above, the use of biomass in the service sector is considered slower in terms of development speed. On the other hand, especially in the hospitality sector, the development speed of biomass utilisation has been increasing, and it is expected that the development speed of utilisation will continue to increase in the future. The hospitality industry collects biological waste and non-recyclable residues from various hospitality facilities. It then transports them to the appropriate biogas plants, which are processed into biogas.

This considerably lowers the amount of discarded and unprocessed waste. Utilising surplus from the hospitality industry can reduce the total amount of waste that is not properly used because the hospitality industry generates a large amount of organic waste that is not recycled. Unlike solar or wind energy, biogas can be used year-round regardless of weather conditions, and it is also possible to use a range of organic wastes as feedstocks for biogas. The application of biogas in the service sector is limited by the fact that while the hospitality industry generates a sufficient amount of organic residues and waste, other areas of the service sector must generate a sufficient amount of organic waste for further use in biogas. This prevents the service sector as a whole from fully realizing the potential benefits of biogas.

Similar to the industrial sector already reviewed, hydropower and wind energy use in the service sector was rated as having the lowest development potential, with each resource RES receiving a rating of 0.60. The use of both resources and the rate of development in the service sector are influenced by social factors such as the public's opinion of using these resources, the impact on the landscape, and the quality of the environment. The prevailing opinion in society is that the construction of hydroelectric power plants will negatively impact fauna and will change water quality and the landscape. Wind energy parks, in turn, are associated with a negative impact on tourism development. At the same time, the number of hotels in the tourism industry thinking about sustainable tourism and energy use is increasing, and so is the tendency to use small wind turbines in this type of hotel or guesthouse to generate the electricity they need. Despite the above-mentioned trends in recent years regarding the use of wind energy in socially responsible hotels and guesthouses, the rate of use of both wind and hydroelectric power is significantly influenced by social factors, so the use of these resources is characterised by slower rates of development compared to other RES resources.

3.3. Agricultural Sector

Figure 5 shows the assessment of RES potential for the agricultural sector. The use of biomass for energy production was rated with the highest development potential among the analysed RES. In evaluating biomass development potential, it received the highest possible rating. Biomass in the agricultural sector is evaluated as the most competitive among RESs. The high rating is justified because agricultural processes generate a significant amount of agricultural leftovers and biological waste that can be converted into energy. Biomass use in agriculture is rapidly increasing, and fossil fuels are expected to be replaced in

the near future by RESs. One of the most demanded biomass feedstocks in biogas plants is manure enriched with agricultural residues and residues from cereals and sugarcane. The demand for biomass fuels for biogas production is expected to continue to increase. Biomass can be used year-round, unlike other RESs. Its advantages have been evaluated for use in combined systems, for example, to meet necessary energy needs during solar power outages.
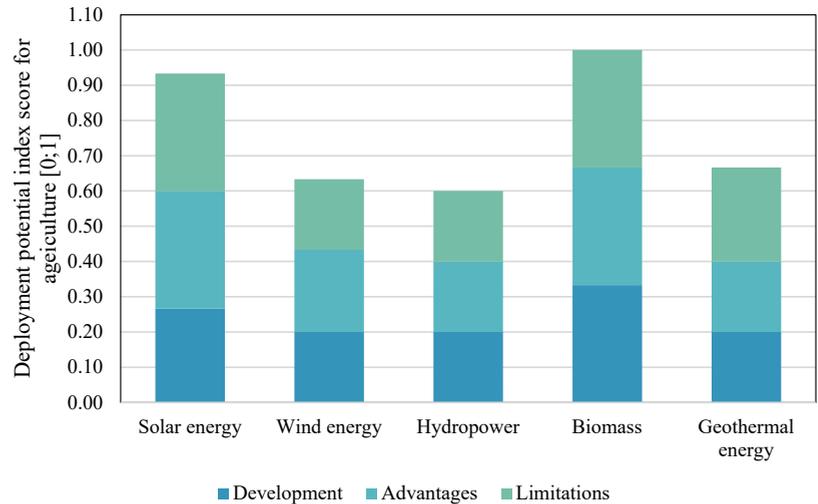

Figure 5. Comparison of the potential of the agricultural sector for the development of RESs.

In the agricultural sector, the second-greatest development potential for using solar energy was identified after using biomass. The use of solar energy technologies in agriculture is characterised by a rapid rate of development in recent years and is expected to continue growing. Smart technologies combined with solar panels and collectors ensure agricultural processes. Such integrated, combined technologies are used, for example, to monitor various parameters such as soil moisture. The increase in solar energy use in agriculture is also favoured by economic sustainability, the payback period of investments is less than ten years, and there are more and more RES support programs that can reduce the necessary investment in installing solar technologies. It is estimated that solar energy in combination with the Internet of Things has the potential for use on farms. This combination of technologies can be used, for example, to more accurately determine the amount of nutrients needed for crops. Using solar energy makes it possible to ensure a number of agricultural processes, for example, by operating equipment necessary for production, such as for the operation of grain threshing machines or ensuring a certain temperature in greenhouses. The least constraints were identified for using solar energy in the agricultural sector, since agricultural processes are usually carried out in the season when it is possible to generate solar energy in sufficient quantities, possibly in combination with an additional source. To avoid solar energy interruptions, you can choose smart systems that control the energy needed.

Geothermal energy (0.67) received the third highest score in the sustainability development potential assessment. The potential for geothermal energy development is limited by resource availability, influenced by geographic conditions. Examples show that geothermal energy has been used as a resource in aquaculture farms to provide the specific temperature required for trout farming.

Similar to the service and industrial sectors discussed above, wind energy use and hydropower use in agriculture have a lower sustainability potential score compared to other RESs—wind energy with 0.63 and hydropower use with 0.63. Similar to the sectors

mentioned above, social factors affect the development potential of hydropower and wind energy in agriculture. Local cooperatives and energy communities can promote the use of wind energy. The use of wind energy is also affected by geographic conditions—places with insufficient wind speed to meet necessary demand and windless conditions that cause wind energy interruptions.

The limitations of wind energy use can be eliminated by combining wind energy with cogeneration. Wind energy can be used for numerous agricultural processes where it is necessary to meet the required electricity demand. Wind energy can be used to power a variety of agricultural activities, including water pumping and electrochemical soil cultivation.

Similar to using wind energy, opportunities to use hydropower are limited by geographic conditions and resource availability. Thus, similar to the use of wind energy, the use of hydropower is influenced by social factors such as the population's attitude and environmental factors including the impact on fauna and landscape. The evaluation of the potential of hydropower utilisation is based on scientific research, case studies, and review articles on the possibilities and advantages of hydropower utilisation in agriculture. The correctness of the obtained results is influenced by the number of literature sources and case studies studied, which was lower compared to other technologies. The more scientific literature there is that evaluated the possibilities of using hydropower in agriculture, the higher the assessment of sustainability potential is likely to be.

3.4. Household Sector

Figure 6 shows the sustainability potential rating of the previously discussed RES types. When comparing the sustainability potential of the RES types, solar energy received the highest score of 0.83 among the RES types. This is explained by the fact that in recent years, there has been an increase in the use of microenergy production and the installation of solar panels on the roofs of houses. The use of solar solutions at the household level is promoted by subsidy programs that cover part of the necessary investments for the installation of technologies, and the payback period of the invested funds becomes shorter, which is favoured by the annual decrease in the cost of solar energy technologies. It is possible to produce solar energy electricity with solar cells installed on building roofs or facades, as well as to produce the necessary thermal energy with the help of solar collectors, which promotes energy independence. The use of solar energy makes it possible to reduce the cost of energy consumed and improve the energy efficiency of buildings.
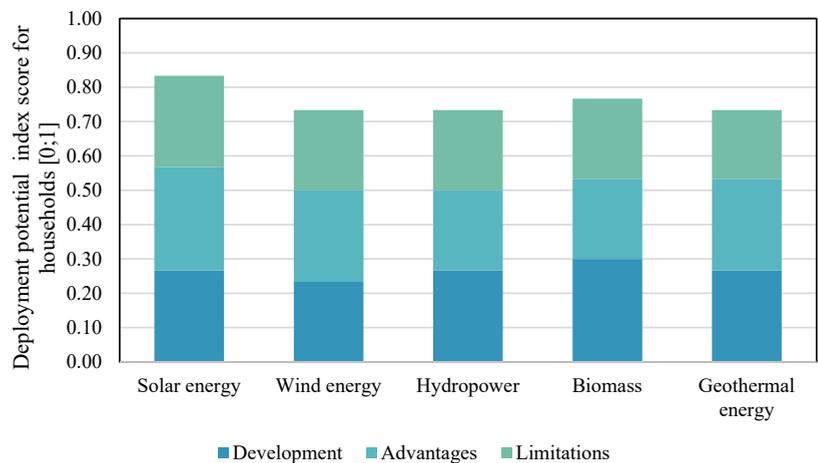

Figure 6. Household RES development potential comparison.

Applying solar energy in a household is associated with the fewest potential disadvantages. A limitation is related to insufficient solar intensity, but in case of interruptions in

solar radiation, the needed energy can be obtained with the help of hybrid systems, which provide additional sources to cover the shortage and storage systems.

Biomass use had the second-greatest sustainable development potential (0.77). Biomass fuel is used both in centralised heat supply and for heating and hot water in individual households. One of the benefits of using biomass is the possibility of generating heat and electricity from biomass residues before they undergo thermal treatment. This is made possible by the fact that biomass residues can be used. It is estimated that the development rate of biomass residue utilisation may also increase in the future and that biomass residues are increasingly used for energy production.

For wind, geothermal, and hydro energy, the development potential in the household is estimated to be the same (0.73). Regarding wind energy, it is anticipated that the installation of small wind turbines on residential rooftops will increase in the future, and it is expected that the installation of these turbines will become less expensive. The energy generated in the household can be used to cover the household's own consumption or to form energy communities. The advantages of wind energy utilisation are related to the fact that it is possible to integrate wind energy into hybrid systems. For example, it is expected that wind energy will be increasingly used in combination with solar panels at the household level, thus avoiding energy interruptions and increasing efficiency. In places where resource availability is assured, the development potential of using hydropower to meet electricity demand will increase. As for hydroelectric power, the use of hydraulic systems (PHP systems) that do not first require the construction of a dam system is increasing. Such systems can meet the necessary electricity needs for villages and communities of up to 30 households. Even though hydropower has several advantages, the use of this resource is at the same time affected by the accessibility of the resource and the impact of hydropower plants on the surrounding environment and landscape. The aforementioned PHP systems are better suited for use in mountainous regions. In countries with colder climates, it is expected that the installation of heat pumps powered by geothermal energy will continue to increase. Although installing heat pumps requires a particular investment and is more complicated than other RES technologies, it has been shown that heat pumps have the second-highest savings potential for households.

Wind, hydro, and geothermal energy technologies demonstrate moderate progress in the residential sector, with notable advancements seen in small-scale solutions. However, at the individual household level, their sustainability and viability are limited. Therefore, the formation of energy communities, which unite multiple households, presents a more sustainable option for the future. This approach enables the integration of larger-scale wind, hydro, and geothermal technologies that are further developed and offer enhanced efficiency compared to small-scale solutions.

3.5. Transport Sector

Figure 7 compares the RES potential of various resources for use in the transport sector. From the results, it can be concluded that the highest potential score was for using biomass, which received the highest possible score in the transport sector (1). This is because improving biomass quality and obtaining biomethane that can be used as fuel for vehicles should have a high potential for current and future use in the transport sector. It has been determined that biomass-derived biofuel is one of the most effective ways to replace fossil fuels in transportation and meet climate goals. Compared to other RES types, biomass use in transportation was rated with the lowest use constraints. However, one drawback that significantly determines whether biomass can be used to power vehicles is the quality of the biomass and which biomass feedstocks are used and in what proportions. A high methane concentration is required to produce biomethane that can be used in vehicles, and not all biomass raw materials can achieve the concentration required to produce biomethane.
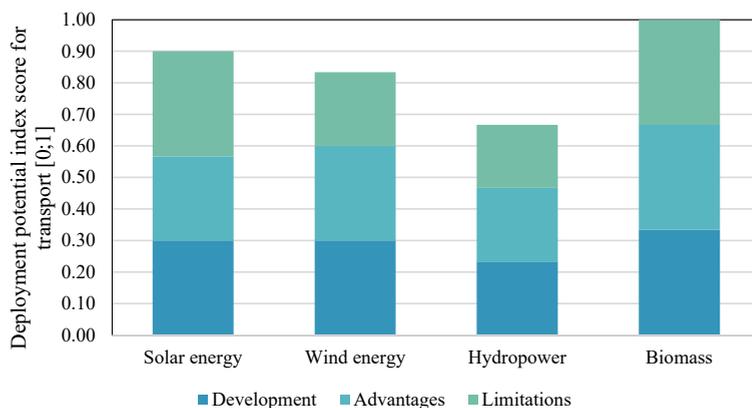
Figure 7. Comparison of RES development potential in the transport sector.

The use of solar energy received the second-highest potential score for use in transportation (0.90) among RESs. Based on the analysis, the use of solar technology in vehicle charging will also likely increase in the future. The proportion of electric car use has increased in recent years, and it is expected that to achieve the set climate targets for transport, the use of electric cars will also increase. With the growth of electric cars, the demand for environmentally friendly car charging will also increase. One such solution is offered by solar energy technologies, which make it possible to charge cars in a decentralised manner, for example, by using energy generated in households with solar panels to charge electric cars. The advantages of using solar panels include the fact that solar panels can be adapted for use in different infrastructures and that with solar panels, it is possible to generate the necessary amount of electricity to ensure the charging of cars. Solar modules can be used in homes and businesses as well as in public charging stations that are in public charging stations integrated into road infrastructure. Similar to other sectors, solar energy constraints are associated with intermittency. When it is necessary to use an additional source to meet demand, one of the solutions is to use solar energy accumulation.

The potential of using wind energy in the transportation sector was given the third-highest score (0.83). As the number of hydrogen-powered cars increases, the share of wind energy in transportation will also increase. It is predicted that with the increase in hydrogen-powered cars, the number of cars powered by wind energy will also increase. To achieve the climate targets set, it is expected that compressed hydrogen will be used as an energy source to power cars, using wind energy rather than fossil energy to produce it. Similar to the sectors described above, there are constraints on the use of wind energy in the transportation sector, such as geographic limitations. A certain speed of wind energy is mandated when it is not possible to meet the necessary demand.

Among the types of RESs studied, hydropower in the transport sector was given the lowest rating. The study concludes that, similar to wind energy, hydropower can be used as an energy source for the production of hydrogen, which is used to power cars. Although the use of hydropower for hydrogen production is recognised as an environmentally friendly and feasible alternative, the potential for using hydropower is geographically limited. To avoid a false comparison with other RESs, the potential of using geothermal energy in transportation was not analysed because there were not enough studies to compare it with other types of RESs.

Table 6 shows the final index scores for each RES in each sector (Table 6).

Table 6. The final index score for RES.

Sector	Solar Energy	Wind Energy	Hydropower	Biomass	Geothermal Energy
Industry Sector					
Development	0.33	0.23	0.23	0.27	0.23
Advantages	0.30	0.23	0.20	0.27	0.23
Limitations	0.20	0.20	0.23	0.23	0.27
Total	0.83	0.67	0.67	0.77	0.73
Service sector					
Development	0.33	0.20	0.20	0.23	0.27
Advantages	0.30	0.20	0.20	0.23	0.27
Limitations	0.27	0.20	0.20	0.23	0.27
Total	0.90	0.60	0.60	0.70	0.80
Agriculture sector					
Development	0.27	0.20	0.20	0.33	0.20
Advantages	0.33	0.23	0.20	0.33	0.20
Limitations	0.33	0.20	0.20	0.33	0.27
Total	0.93	0.63	0.60	1.00	0.67
Household sector					
Development	0.27	0.23	0.27	0.30	0.27
Advantages	0.30	0.27	0.23	0.23	0.27
Limitations	0.27	0.23	0.23	0.23	0.20
Total	0.83	0.73	0.73	0.77	0.73
Transport sector					
Development	0.30	0.30	0.23	0.33	0.00
Advantages	0.27	0.30	0.23	0.33	0.00
Limitations	0.33	0.23	0.20	0.33	0.00
Total	0.90	0.83	0.67	1.00	0.00

3.6. A Cross-Sector Comparison to Assess the Sustainability Potential of the Use of RES

The second part of the study produced a score reflecting an assessment of the sustainable development potential of each resource and a comparison of sectors by RES type (Figure 8). Table 7 summarises the points obtained, clearly showing the normalised result for each RES type, with which it is possible to characterise the RES utilisation potential.

The potential of biomass use in the agriculture and transport sectors achieved the highest assessment level for sustainable development. In these two sectors, biomass received the highest possible score, 1. Thus, in both the agriculture and transport sectors, the rapid development of biomass energy production has already been observed and predicted for the future. The second-highest potential rating was given to the potential of biomass use in industry and households.

The potential of solar energy use is currently and in the future estimated to be highest in sectors such as services, households, and industry. Solar energy received the second-highest potential rating in agriculture and transport, right after biomass use after biomass use. According to the average score, the use of solar energy ranks first with a score of 0.88, while in second place according to the score is biomass (0.85), which has the fewest

constraints for use in transport and agriculture among RESs. Compared to the potential use of solar energy and biomass, the other three RES types, whose development can be described as slower, scored lower in the evaluation. Wind energy is still in the development phase of its potential, which is limited by geographical conditions as well as by social factors and the population's aversion to wind turbines near their homes. Despite the limitations mentioned above, the potential for using wind energy in the transport sector and residential sector received the third-highest rating in these sectors.
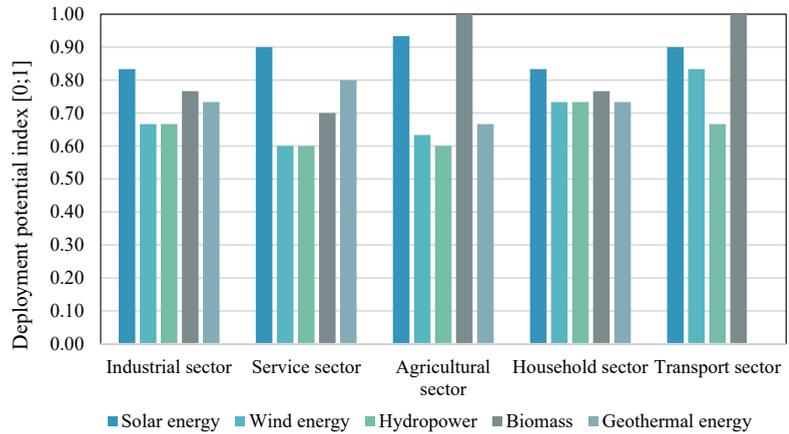
Figure 8. Comparison of the development trends of RESs between the sectors.

Table 7. Summary of RES normalised points by sector.

	Solar Energy	Wind Energy	Hydropower	Biomass	Geothermal Energy
Industrial sector	0.83	0.67	0.67	0.77	0.73
Service sector	0.90	0.60	0.60	0.70	0.80
Agricultural sector	0.93	0.63	0.60	1.00	0.67
Household sector	0.83	0.73	0.73	0.77	0.73
Transport sector	0.90	0.83	0.67	1.00	0.00
Average values	0.88	0.69	0.65	0.85	0.59 (0.73 *)

* The average value of four sectors, excluding the transport sector.

The potential of wind energy is to replace fossil energy resources for hydrogen production and to meet the electricity demand required for installing micro power plants in households. The combined results of the study reveal that equal values were obtained for wind energy and hydropower in the industrial and service sectors and for wind energy, hydropower, and geothermal energy in the household sector. This can be explained by the fact that there are similar constraints for these technologies that limit their use and affect the overall results of the index for the technologies. Based on the utilisation of a five-point scale, as indicated in Table 2, it can be inferred that there were no significant variations in the outcomes across different sectors of technology. This can be attributed to the implementation of a limited range of evaluation scale dispersion.

3.6.1. Solutions for the Development of Solar Energy and Biomass Use
Solar Energy

Industry. Combined systems that compensate for solar deficits or accumulation are used to improve market competitiveness, reduce energy consumption, and lower the price of the required energy. Solar energy technologies have increasingly lower prices and shorter payback periods, which increase their acceptance.

Services. There are numerous applications in the public sector, including the tourism industry, office buildings, and data on solar energy systems in public facilities, including providing thermal energy and electricity for schools. It is evaluated as an effective solution when combined systems are used to cover peak loads during the cold season. This already provides the actual and potential ways of using this energy.

Agriculture. Solar and wind energy shortages can be offset with biomass, including agricultural residues, smart technologies that compensate for solar energy shortages by using energy exactly when it is generated, and smart agricultural monitoring. Solar panels collect and store the energy needed to power an Internet of Things sensor node, which is then used to charge the sensor node. The Internet of Things (IoT) is becoming increasingly prevalent in the agricultural sector. The solar energy obtained has a wide range of applications—it can be used, for example, in irrigation systems, in drying processes, for higher efficiency through hybrid drying systems combining several RESs, for wastewater treatment, and for cleaning the soil from heavy metals and herbicides. As technology advances, it is expected that a greater portion of energy needs will be met by solar sources. Hybrid drying systems can compensate for solar energy deficits and improve drying efficiency and product quality. Similarly, the use of thermal energy storage systems can compensate for the lack of solar energy during bad weather.

In households, there is the possibility of using smart grids, smart meters, and other smart technologies that can use solar energy more efficiently as a source of energy. The use of solar energy contributes to regional and national energy independence. Solar panels and collectors can be incorporated into a wide range of building components. Since collectors and PV panels are often used in passive houses, it is expected that these technologies will increase in the future.

Solar street technologies are becoming more common and are also essential for increasing the share of electric cars, as they provide a solution to the problem of charging station availability. Solar road technologies can be an indispensable component of a decentralised energy supply. Wind-generated compressed and stored hydrogen can be used as a fuel in the transportation sector, reducing imports of fossil fuels and greenhouse gas emissions.

Biomass

In the industrial sector of biomass use, there is considerable potential for use in the food and beverage industry, where residues and wastes from the same processes can be used to generate energy for other operations. In different subsectors of the industry, actual and potential uses are estimated to be lower.

In the catering industry, processing biodegradable waste from kitchens in biogas plants offers further potential applications. Biogas is enriched with organic kitchen waste to produce biomethane that can be used in vehicles. The processing of waste generated in the catering industry has a high potential for energy production. However, there is not enough information on the other service sectors to make an assessment.

Agricultural residues in combination with manure offer broad opportunities for biomethane production. The agricultural sector assesses biomass and its residues as one of the most important sources of renewable energy with even greater prospects for the future. By using biomass residues or wastes, it is possible to compensate for the lack of other energy sources such as solar or wind.

Agricultural residues, which can be used in various ways in all five resource categories, are increasingly being used as feedstock for biomethane with high methane content. Biomethane can also be used in commercial vehicles, buses, and certain heavy-duty trucks.

3.6.2. Previous Research

Previous studies regarding the determination of RES potential show that there are several studies to assess the potential of renewable energy. However, the studies provide conflicting results and depend on the technologies used. The potential of the RESs and their

combinations is evaluated based on payback durations, energy generation, and reduction in CO_2 emissions [27,133–135].

According to previous research, for 100% self-sufficiency in energy production, the Latvian energy system can rely not only on renewable energy systems that are economically viable in the short term (such as biomass) but also on systems that are less economically attractive in the short term (such as wind power and solar PV) [136,137].

Previous studies have shown that solar panels have payback times of less than 7 years, and solar hybrid systems have an average payback period of 5.5 to 6.5 years.

Previous studies have also assessed that geothermal energy has the potential to replace traditional fossil resources. However, one of the main factors limiting the use of the resource is the geographical location and, therefore, the availability of the resource [138].

3.6.3. Limitations of the Study

When collating the data, it was found that in places, the points awarded in the qualitative analysis ranged, for example, between 4 and 5, based on 4 reflecting the current situation and 5 being expected in the near future. As mentioned in this example, the average value was taken, i.e., 4.5 (in this example).

In addition, it was observed that three objects were not given a specific mark in the qualitative analysis because there was insufficient information about any of the RESs in the particular sector. The result was a data gap. For example, in the agricultural sector analysis, very limited information was available on hydropower development trends and limitations in using the specific sector. In that case, the model assigned a score of 3, the most neutral value on the scale. In addition, the lack of information on any use of RESs in the industry suggests that the lack of information to provide a degree of development or other considerations in the qualitative analysis means that the development of a particular RES is limited. This explains the rating—a score of 3 reflects certain limitations in developing a particular AER.

Data processing and normalisation were performed after data collection and replacement of missing values. The obtained points for each criterion and each AER in the corresponding sectors were normalised so that the obtained values range from 0 to 1, where 0 is the lowest value and 1 is the highest value. Assuming that each criterion has the same impact on sustainable RES development, they were assigned the same impact weight categories on the overall RES sustainable development result. Such a data normalisation technique is often used in sustainable development analysis and research to produce transparent and verifiable results. The range of scores from 0 to 1 makes it possible to interpret the results and draw valuable conclusions about the current performance of each RES and the sector's sustainable development level.

The overall score obtained for each RES reflects its sustainable development performance and overall long-term potential. The closer the score is to 1, the higher the long-term development and assessed potential of the respective industry. Literature-related specific criteria and sectors are a limiting factor impacting the index results.

4. Conclusions

This study examines the potential of RESs in various sectors, focusing on agriculture, transportation, industry, and households. By assessing the sustainable development of biomass, solar, wind, hydro, and geothermal energy, we aim to identify untapped opportunities and remove barriers to their full integration. The results will enable policymakers to prioritise strategies to overcome barriers and harness the enormous potential of RESs to promote a sustainable and green future.

The potential for biomass use in agriculture and transport received the highest rating for sustainable development. In these two sectors, biomass received the highest possible score, 1. Rapid growth in biomass energy production has been observed in both agriculture and transportation and is expected in the future. The second-highest score for heat potential was given to the potential for biomass use in industry and households. Solar energy and

biomass derived from agricultural residues are subject to the fewest restrictions on their use. It is predicted that the potential for solar energy use will increase and that solar cells will be increasingly used to charge electric cars. In the overall assessment across all sectors, solar energy is rated the highest regarding the potential use of RESs at 0.88, and biomass use potential is rated second at 0.85.

For solar energy, the investment required to install solar technology has decreased in recent years. The payback period for the investment is less than ten years and continues to decrease as solar technology becomes cheaper and cheaper. The periodicity of solar energy is considered one of the limiting factors for the use of the resource. It can be solved by using energy storage systems, and it is also possible to use an additional source for heating, such as a heat pump or biomass. Technologies powered by solar energy are increasingly being combined with smart technologies that allow energy to be used wisely and processes to be controlled remotely, reducing overall energy consumption.

To deal with the periodicity of wind energy, it is necessary to provide an additional source through combined systems. With the help of smart technological solutions, it is also possible to determine when wind strength is sufficient and when it is necessary to compensate for the lack of wind energy. Geothermal energy can be combined with heat pumps to generate the necessary thermal energy in the environment. The potential of using geothermal energy depends mainly on the availability of resources, which is determined by the geographical location. The use of geothermal energy is limited to the service sector, industry, and agriculture. However, there is a small number of studies on the potential of using geothermal energy in the transport sector.

The results allow us to spot and highlight the untapped potential of specific renewable energy resources in each sector; therefore, policymakers could focus on tackling the identified barriers and using the full potential of identified opportunities. This study assessed the overall potential and limitations of renewable energy deployment across various sectors without conducting a detailed analysis of technoeconomic parameters and indicators. Additional investigations should prioritise the careful analysis of the economic viability of renewable energy across diverse industries, in order to acquire a comprehensive comparison of the economic viability considering sector-specific variables.

The method can serve as an initial risk analysis to evaluate the effectiveness of measures and the risks, drawbacks, and benefits of their implementation using indicators, first descriptively and then numerically. To obtain accurate results, it is crucial to define relevant indicators and select enough relevant information. The developed method is a practical solution necessary to evaluate the implementation of planning documents and specific actions, performing an analysis based on indicators and assigning them a score.

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