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CLIMATE AND ENERGY MEASURES EVALUATION WITH COMPOSITE SUSTAINABILITY INDEX

Summary of the Doctoral Thesis

RIGA TECHNICAL UNIVERSITY

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To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for defence at the open meeting of RTU Promotion Council on May 29, 2025, at 14:00, at the Faculty of Natural Sciences and Technology of Riga Technical University, 12/1 Āzenes Street, Room 607.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Lauma Balode ……………………………. (signature)
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The Doctoral Thesis has been written in English. It consists of an Introduction, three chapters, Conclusions, 41 figures, and 48 tables; the total number of pages is 333 with appendices. The Bibliography contains 281 titles.

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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

1. 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 dimensions;
- assign values to indicators using combinations of scientific methods;
- 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.
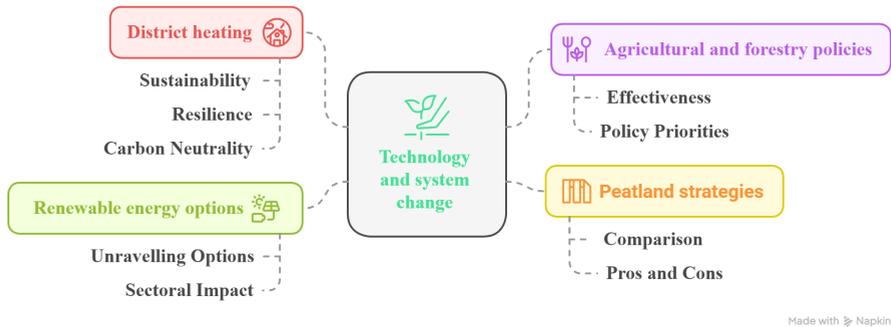

Fig. 1. Climate alternatives regarding technology and system change.

2. 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

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.

3. **Defining dimensions –** economic, environmental, social, and technical.

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

5. **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.

6. **Weighting dimensions.**

7. **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.

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

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

10. **Recommendations development.**

Methodology can be seen in Fig. 2.

1. Sector analysis	2. Climate neutrality alternative (technology and system change)			3. Defining dimensions	4. Indicator selection	5. Determining indicator values
	Replacement of heating technologies Improvement of DH system resilience	**Sustainability of climate policy measures**	**System change**	Economic		Literature analysis
Energy	1.Assessing the sustainability of individual and district heating technologies – 1 pub. 2.Assessing the sustainability of individual and district heating technologies for municipal buildings – 1 pub. 3.Comparing the resilience of municipal district heating – 1 pub.	4.Sustainability of agricultural and land use practices – 1 pub.	5.Organic farming vs conventional – 1 pub. 6. Comparison of peat strategies – 1 pub. 7. Economic and environmental sustainability of peat strategies – 1 pub. 8. Assessment of the potential of RES technologies in economic sectors – 1 pub.	Environmental Social Technical		Expert assessment Techno-economic analysis Emission calcualtion HHI index
Agriculture and land use Renewable Energy use in sectors						

6. Weighing dimensions	7. Normalizing the values of the indicators	8. Aggregation of indicators into composite index	9. Assessment of uncertainty, regression analysis	10. Development of recommendations
Expert survey AHP	Min-Max normalization method			

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.
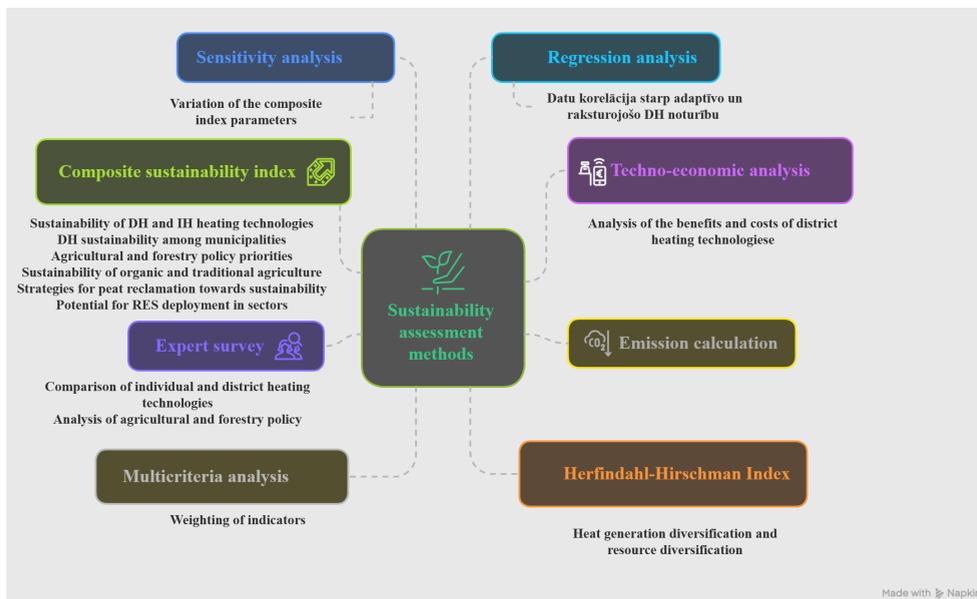
Fig. 3. Methods used in the Doctoral Thesis [16].

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.

Municipalities and companies can also use the developed methodology to analyse the drivers and weaknesses of specific measures towards sustainability. According to the new Corporate Sustainability Reporting Directive, adopted by the EU in 2024, the sustainability of

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action should also be relied on and reported on sustainability measures, taking into account environmental, economic, and social aspects.

The Doctoral Thesis offers a methodology that can help municipalities promote sustainability, focusing on the energy transition and the integration of renewable energy in heating.

Approbation of the Thesis

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

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. Pieejams: 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 Journal: Energy (under review).

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. 2021, doi: 10.2478/rtuect-2021-0030.

2.   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

3.   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

4.   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

5.   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.

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Thesis Outline

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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. METHODOLOGY

1.1. Composite Index

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 [17], [18]. 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 [17]–[19]. 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 [19].

Main steps in creating CI

When creating a CI, 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 [20]. 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 [20].

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 [20]. 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 [21], [22] (Fig. 1.1.).
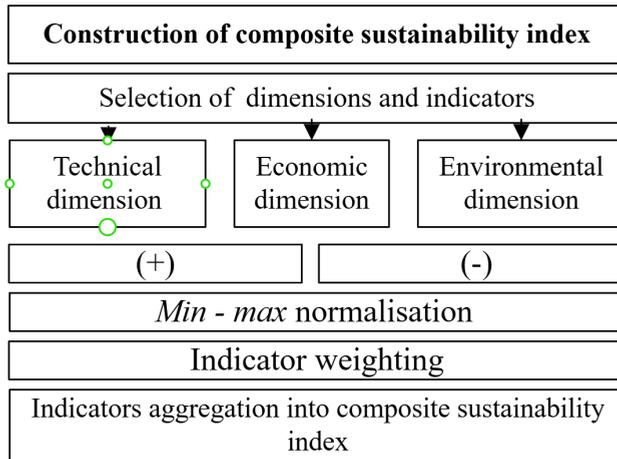
Construction of composite sustainability index
Selection of dimensions and indicators

Technical dimension	Economic dimension	Environmental dimension

(+)	(-)

Min - max normalisation
Indicator weighting
Indicators aggregation into composite sustainability index

Fig. 1.1. Methodology for the construction of the composite index [23], [24].

1.2.   Comparison between individual and district heating

This study demonstrates the composite index methodology's application to create a sustainability index for district heating and four different individual heating technologies – wood pellet boilers, natural gas boilers, solar collectors, and heat pumps. This study applies the sustainability framework, where general sustainability dimensions are combined with a technical dimension representing 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. In total, **19 indicators** were selected and grouped into representative dimensions.

Table 1.2.1

Selected sustainability indicators and classification into dimensions [17], [25]

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	+

1.2.1. 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 1.2.2.

Table 1.2.2.

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	%	[26], [27]	100	80	92	82 *	257
Specific CO_2 emissions	env1	g/kWh	[28], [29]	202	0	202	0 *	42 *
Capital investments	econ1	EUR		6175	10,740	6440	23,980 *	16,243
Service and maintenance costs	econ2	EUR/year	[30]	0 *	605	255	300 *	360
Technology lifetime	econ3	years	[30], [31]	25	20	19	30	20
Specific energy costs	econ4	EUR/kWh	[32]	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 [26] on the cost-effectiveness of district heating compared to individual heating technological solutions [33]. This was the most reliable data for determining specific values for district heating technologies and for achieving the current research objectives. Weighting of indicators 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. Then, the analytical hierarchy process (AHP) method is utilised to account for the different impact scales of each dimension on the overall CSI. Experts were asked to compare four different dimensions according to which the sustainability of technologies was compared.

1.3.   District heating resilience in municipalities

The research analyses 10 different DH systems in Latvia with various heat production technologies and fuel mixes, and their heat price changes 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 index of resilience has been developed for the DH supply systems of several municipalities in Latvia.

This study's resilience assessment for DH systems measures two different resilience concepts: adaptive resilience and inherent resilience [34]. 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 is done to fully estimate the DH system's ability to adapt and impact different external conditions.

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. The adaptive and inherent resilience measured was verified by comparing both values for each DH system.

1.3.1. 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 [35]. 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, 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 [35]. 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 1.3.1.

Table 1.3.1

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, and types of fuel that affect tariffs. To determine tariff stability and adaptive resilience factor, the proposed method of Francis and Bekera [36] 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, heat tariff directly after the resource price increase, T_d, and the performance levels in the new stable state, T_r. 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.

1.3.2. Inherent resilience

An inherent resilience assessment was made using the data for the same ten DH heat supply systems in Latvia with different heat energy production technologies and fuel mix, and their heat price changes from 2021 to 2023. To select the most appropriate criteria, a literature analysis was performed first on factors that affect DH energy resilience and sustainability [37]. 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. Figure 1.3.1 shows a methodology for the establishment of the composite DH resilience index for different energy systems, taking into account four dimensions [38].
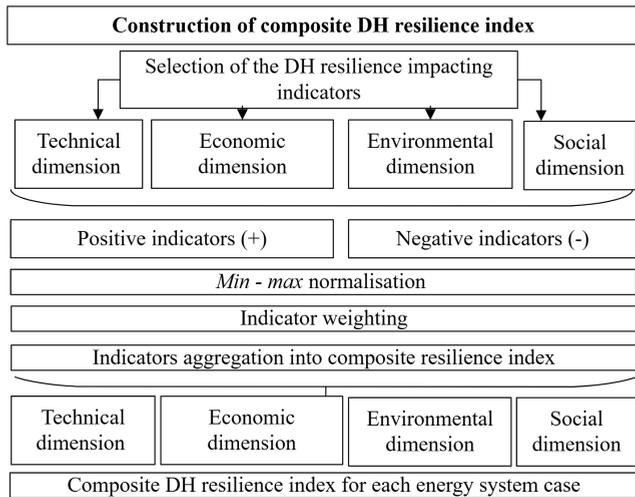
Fig. 1.3.1. The framework of the construction of the composite DH resilience index.

Identification of impacting indicators

After defining different dimensions of DH system sustainability, appropriate indicators were selected for each dimension. Scientific indicators were selected based on the following criteria: relevance, data availability and data credibility [39]. Indicators impacting DH resilience are listed in Fig. 1.3.2.

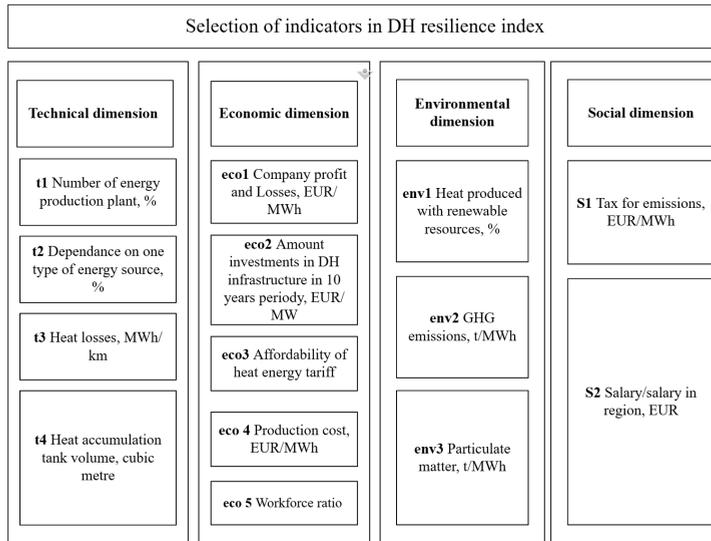| Selection of indicators in DH resilience index			
Technical dimension	**Economic dimension**	**Environmental dimension**	**Social dimension**
t1 Number of energy production plant, %	**eco1** Company profit and Losses, EUR/ MWh	**env1** Heat produced with renewable resources, %	**S1** Tax for emissions, EUR/MWh
t2 Dependance on one type of energy source, %	**eco2** Amount investments in DH infrastructure in 10 years periody, EUR/ MW	**env2** GHG emissions, t/MWh	**S2** Salary/salary in region, EUR
t3 Heat losses, MWh/ km	**eco3** Affordability of heat energy tariff	**env3** Particulate matter, t/MWh	
t4 Heat accumulation tank volume, cubic metre	**eco 4** Production cost, EUR/MWh		
	eco 5 Workforce ratio		

Fig. 1.3.2. Selected indicators for the construction of DH resilience CI.

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 1.3.2–1.3.5.

Table 1.3.2

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 [40]–[42]	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 [40].	–
t2	Diversification index of resources and production mix [40]–[42]	Resources, %	Depends on one 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 [40]. Heat production in the DH company depends on one type or several types of energy sources, which is measured using the Herfindahl-Hirschman index [42]. A higher HHI result value indicates a negative impact on DH resilience.	–
t3	Heat losses [40], [41], [43]	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 [40], [41], [43].	–
t4	Accumulation capacity [44], [45]	m^3/MW	Accumulation volume in m^3 against the total heat produced in MW. Characterises whether the DH company can offer the possibility to continue energy production using the accumulated energy in case of system interruptions. An accumulation tank is added to the DH system to cope with peak loads [44], [45].	+

Table 1.3.3

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/M-Wh	The ratio of the profit loss indicator is divided by the delivered heat. Describes the economic stability of the 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 [37]	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 [37].	+
eco4	Production cost [35]	EUR/MWh	The ratio of average production costs/heat produced. Describes the efficiency of heat production [35].	
eco5	Workforce [35]	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 environmental dimension of DH resilience is included to quantify the environmental aspects (see Table 1.3.4).

Table 1.3.4

List of indicators of the environmental dimension of DH resilience

	Indicators	Unit	Description of the indicator	Impact on resilience
env1	RES share [35], [40], [43]	%	The ratio of the amount of energy produced by renewable energy to the total heat produced [40].	+
env2	CO_2 emissions [43], [46]	t/MWh	CO_2 emissions per MWh of heat produced show the amount of CO_2 emissions that are created by specific DH systems to produce heat [45], [48], [43], [46].	−
env3	Particulate matter (PM) emissions [43], [46]	Kg/MWh	PM emissions per MWh of heat produced show the amount of PM emissions that are created by specific DH systems to produce heat [43].	−

Table 1.3.5

List of indicators of the social dimension of DH resilience

	Indicator	Unit	Description of the indicator	Impact on resilience
s1	Tax on fossil fuel and emissions [35]	EUR/MWh	Tax on fossil fuels and emissions. Amount of emissions tax per MWh of heat supplied [35].	–
s2	Salary competitiveness [35], [46]	EUR/EUR	Competitiveness of the workplace in the region. Salary in DH energy system/salary in the region [35], [46].	+

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 [35].

1.4. Carbon-neutral municipalities

The study examines two scenario complexes, including 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 municipality buildings and scientific data sources to evaluate the most sustainable RES heat supply solutions (technology combinations) that could replace the natural gas solutions used in DH and IH. Six municipal buildings were analysed. Municipal buildings were very diverse in terms of their functionality and building characteristics, and they were not connected to the DH system. Table 1.4.1 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, as well as calculations based on real and scientific assumptions.

Table 1.4.1

Technical parameters of municipal buildings

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

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.

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.

Selection of indicators

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 1.4.2).

<div align="right">Table 1.4.2</div>

Indicators for the construction of CI 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 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	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, 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.

Calculated data for the CSI construction

Table 1.4.3 shows calculated data for constructing the CSI for each alternative. Values equal to 0 are denoted 0.00001 because setting the input value to 0 in the CI is not permissible.

Table 1.4.3

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 a 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 number of resources	2	3	3	2	3	3	2	3	3	3

The min-max method was used to normalise the indicators. 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 is 0.13. The CSI is calculated as the total sum of all indicators. The sum of all indicators results in the final CSI, which can be used for further comparisons.

1.5. Construction of the CSI for assessment of NECP policies

The CSI [24] was used to evaluate the policy's effectiveness. The methodology includes 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 CSI.

Sorting policy measures

From Latvia's NECP (previous version of NECP) [47], Annex 4, policy measures and actions were selected for the GHG emissions reduction in agriculture and forestry. Subsequently, from all directions of action and already concrete measures, it is 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].

Identifying indicators for performance assessment

Indicators were selected considering the indicators used in the policy evaluation and individual indicators from the Better Regulation Program. The OECD indicators are rated as among the most effective indicators of policy regulation and management that can be used as tools for decision-making and policy analysis (Table 1.5.1).

Table 1.5.1

Description of the indicators

No.	Indicator	Explanation of the indicator
i1	Possible negative side effects [119], [158]	The measure excludes possible adverse side effects (e.g., indirect support for the use of fossil fuels in agriculture is not created, additional energy consumption is not promoted, and no additional resource consumption is used). The policy measure complies with the principles of climate neutrality and efficient resource use and does not contradict the defined environmental and climate goals.
i2	Transparency [119], [159]	Lobby influence (positive or negative side pressure) has been eliminated.
i3	Objectivity [21], [49]	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 [21], [49]	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.
i5	Quality [21], [22], [49]	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. Still, it will contribute to a positive chain reaction and overarching goals.
i6	Funding [21], [49]	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.

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 %.

The CSI was calculated as the total sum of all indicators [17]. The sum of all indicators results in the final CSI, which can be used for further comparisons.

1.6. System change – comparison of organic and conventional dairy farming

The study aims to evaluate and compare the sustainability of biological dairy farming, conventional dairy and conventional dairy farming, 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. A composite index with additional indicators was created to assess small and medium-sized organic and conventional dairy farms in Latvia. 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 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.

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 [50]. 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;**

Methane emissions should be estimated based on specific manure management systems, the number of animals, and the IPCC 2006 methodology [51]. Used in the calculation to convert CH_4 emissions into CO_2 equivalents, the obtained emissions were multiplied by 28 [52].

- **N_2O emissions from manure management [53].**

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.

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) [51].

Evaluation of economic dimension sustainability

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

1.7.   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. Suitable economic indicators, divided into two groups – (1) necessary costs, (2) incomes and possible gains from grants and subsidies, etc. To normalise data, 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.

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. (Table 1.7.1.).

Table 1.7.1

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.

1.7.1. Economic and environmental data for each strategy

Table 1.7.2 shows calculated data based on the scientific literature, reports, and assumptions for each peatland strategy for the construction of the composite index.

Economic indicators selected for peatland strategy evaluation

No	Indicator	Units	Indicator Description	+/–
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	Potential income from ecosystem services. Calculations based on the Project Life Restore optimisation model [54] additionally take into account inflation and assumptions.	+
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 1.7.3).

Table 1.7.3

Calculated economic data for each peatland strategy

	Rewetting	Peat extraction	Production of insulation boards from cattail	Affores-tation	Perennial cultivated grasses	Dairy farming	Cultivation of cattail	Cultivation of sphagnum	Growing blueberries	Water reservoir	Growing cranberries
i1 Total investments, EUR/ha	5171 [54]	11 868 [55]	3400 [56]	14 368 [54]	6087 [42]	10 570 [56]	7300 [56]	23 300 [56]	96 264 [54]	7265 [54]	29 479 [54]
i2 Potential income from ecosystem services, EUR/ha/yr	49 308 [54]	665 calculation based on [55]	43 825 [54]	45 908 [54]	899.6 [54]	0.001	43 825 Assumption based on [54]	43 825.3 Assumption based on [54]	5696 [54]	35 967 [54]	14 693 [54]
i3 Maintenance costs, EUR/ha	10,338 (including monitoring costs) [57]	425 [55], [58]	1400 [56]	157 [54]	261.8 [54]	4035 [56]	3170 [56]	5175 [56]	4215. [54]	0.001	1597 [54]
i4 Income, EUR/ha	1442 Calculations based on average on-time payments and carbon credit [59]	3914.9 [55]	7966.7 [56]	2400 [60]	497.5 [54]		6896.7 [56]	11,891.7 [56]	7854 [54]	0.001 [54]	1570.8 [54]
i5 CO_2	2 based on [59]	7 [59]		1 [59]	12 [59]				5 [173]		4 [59]
i6 CH_4	7.2 based on [59]	1.4 [59]		0.3 [59]	1.3 [59]				0.9 [46]		0.2 [59]
i7 Total GHG emissions on rich organic soil CO_2-eq ha^{-1} yr^{-1}	9.9 [59]	11.2 [59]	3.9 [61]	3.7 [59]	19.9 [59]	20.9 [34]	2.6 [59]	2.6 [59]	11.8 [59]		9.3 [59]

Note:

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

To use the calculated data or data found in the literature, the data must first be normalised. 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. The final step is the aggregation in the CI results multiplied by the normalised indicator value.

1.8. Analysis of RES potential

The study compares the sustainable development of RES between the sectors examined – industry, services, agriculture, households, and transport. The analysis aims to find out which RESs are the most promising and sustainable in each sector and what conditions determine this. The analysis of RESs includes solar, wind, hydro, biomass, and geothermal energy resources, which are analysed separately for each sector. The conceptual and methodological basis of this research is shown in Fig. 1.8.1. 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. 1.8.1. The steps of performing the qualitative analysis in chronological order.

Description of the qualitative methodology

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. A total of ~ 100 sources of information were used for the qualitative assessment.

Description of the methodological approach 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. 1.8.1).

Determination of evaluation point scale and allocation of points

Points are awarded for each type of RES and sector based on the conclusions of the qualitative analysis. Table 1.8.2 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 1.8.2.

Table 1.8.2

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 1.8.3 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 1.8.2. These ratings are further used to perform quantitative analysis and create an index for each of the RES.

Table 1.8.3

Collected scores based on literature assessment based on defined criteria.

Sector					
Industry sector	**Solar energy**	**Wind energy**	**Hydro power**	**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. RESULTS AND DISCUSSION

2.1. 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 (Fig. 2.1.1).
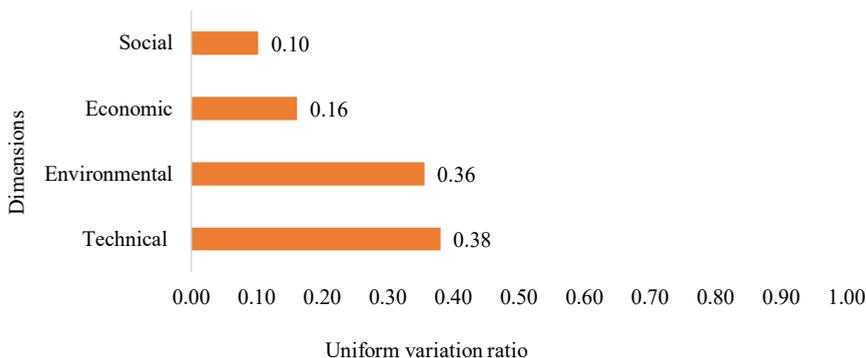

Fig. 2.1.1. Dimension weight from an expert survey.

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. 2.1.2. 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).
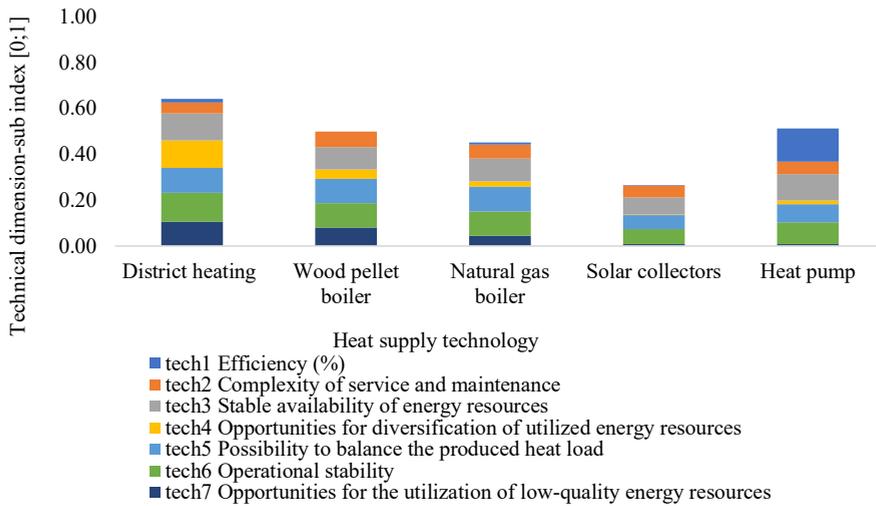
Fig. 2.1.2. Technical dimension sub-index values [27].

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).

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. 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. 2.1.3).
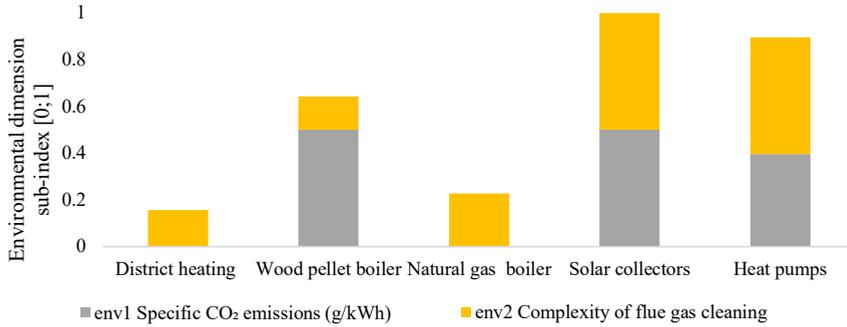
Fig. 2.1.3. Environmental dimension sub-index values [27].

Economic dimension sub-index

District heating units achieved the highest economic dimension sub-index value (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). Heat pumps achieved the lowest sub-index score (0.29). 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 (see Fig. 2.1.4).
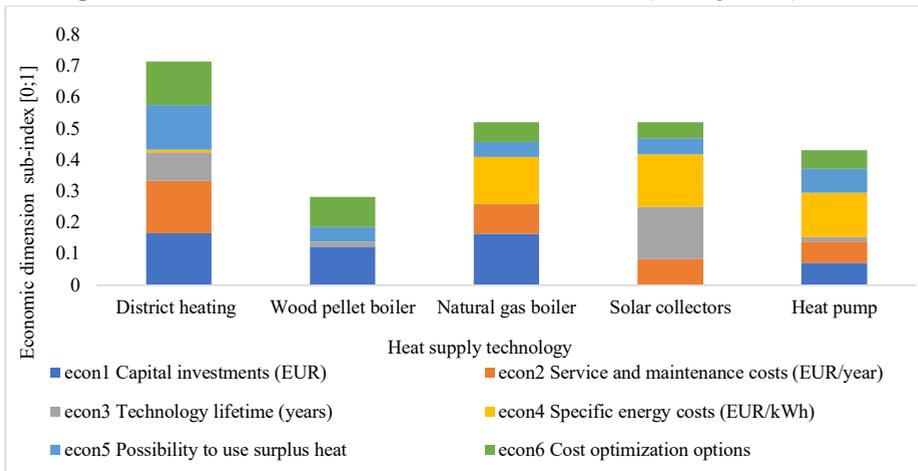

Fig. 2.1.4. Economic dimension sub-index values.

Social dimension sub-index

Overall, social dimension sub-index scores are less distributed compared with the other sustainability dimensions (see Fig. 2.1.5). Solar collectors reached the highest sustainability sub-index (0.8). Three technologies, DH, 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). DH 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.
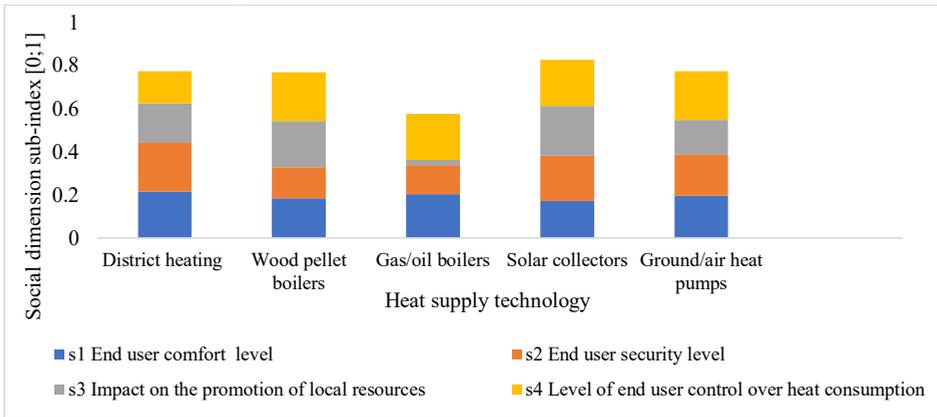

Fig. 2.1.5. Social dimension sub-index values [27].

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 value in the sustainability index was estimated for district heating (0.50). Still, the lowest score in the 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 [19] (see Fig. 2.1.6).
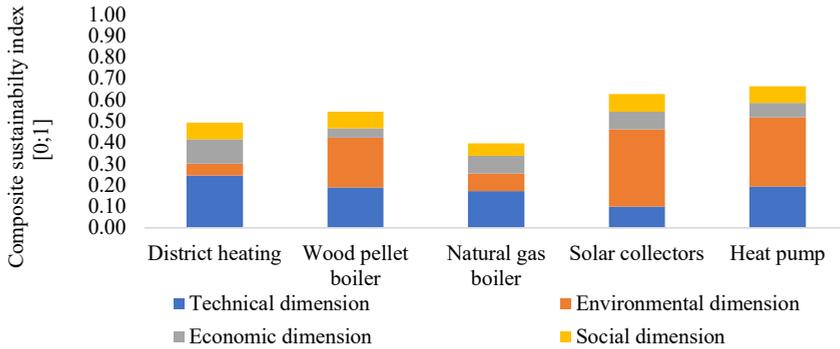
Fig. 2.1.6. CSI for heating technologies.

2.2. Adaptive and inherent resilience assessment

Figure 2.2.1 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. 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 systems. 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 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.
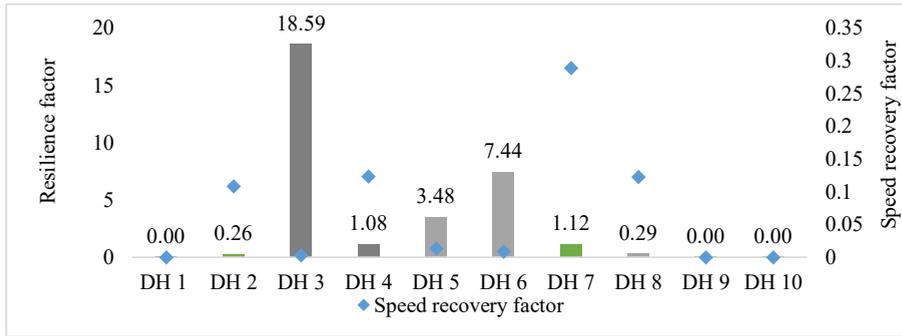
Fig. 2.2.1. Heat price resilience factor.

Inherent resilience assessment

To evaluate the inherent resilience of DH systems, various indicators were calculated according to the methodology previously presented. Table 2.2.1 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.

Table 2.2.1

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

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. 2.2.2).
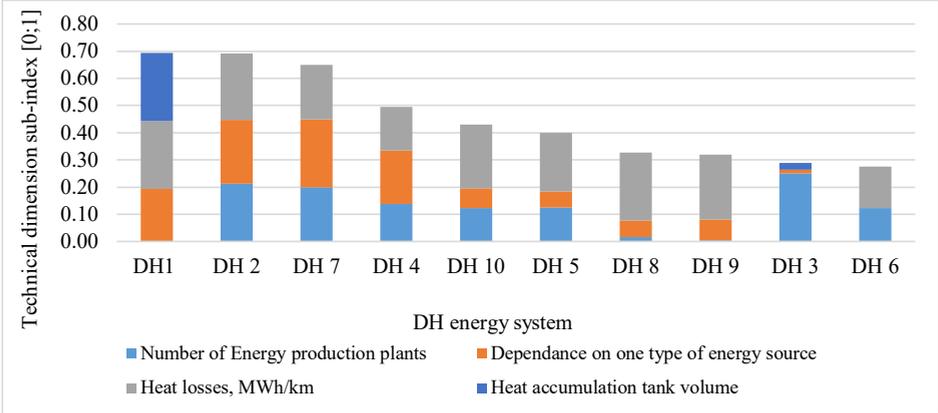

Fig. 2.2.2. Technical dimension sub-index.

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. 2.2.3).
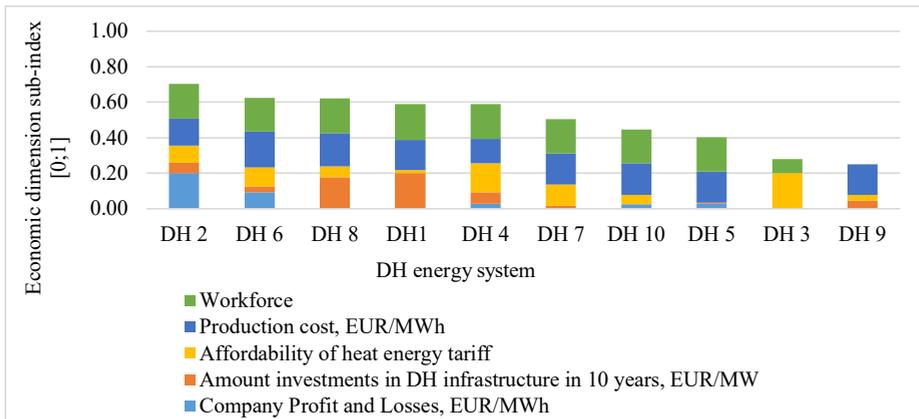
Fig. 2.2.4. Economic dimension sub-index values.

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, and also the lowest among systems in the 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. 2.2.5).
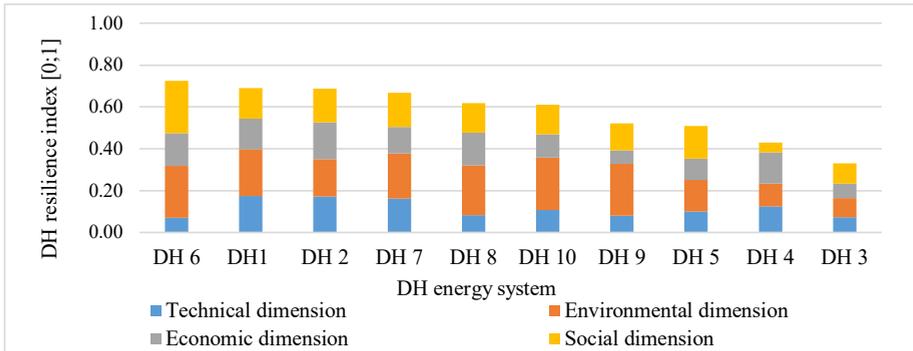
Fig. 2.2.5. Comparison of DH resilience index among different DH energy systems.

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. 2.2.6). 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.
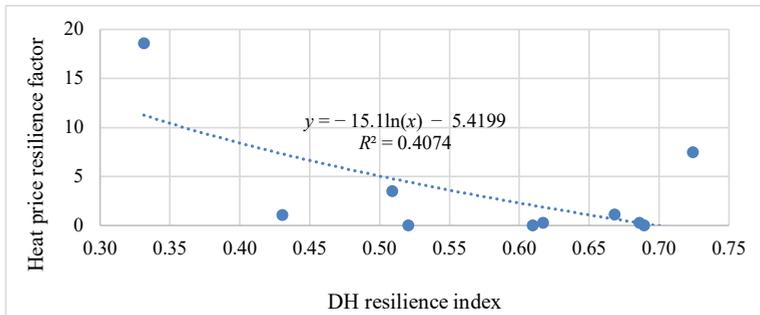

Fig. 2.2.6. Relation between DH resilience index and heat price resilience factor.

This means that systems with higher DH indexes are more price resilient to system disruption than systems with lower resilience index scores. Results show that the affordability of heat energy tariffs is highest for systems based on fossil energy use, such as

DH 3 and DH 4, which can be a significant factor, especially for small municipalities [62]. 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 [63].

The highest DH resilience composite index was for energy systems that are based on biomass and a mix of biomass and gas. 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, which was also one of the goals of the study [64]. Results of the study show that thermal storage of heat is not provided in a large part of the municipalities considered.

Evaluation based on quantitative indicators can be a tool for successful decision-making when choosing the most sustainable and resilient solution for future development [35].

2.3. Heat technologies in municipal buildings

The composite index 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.

Individual heating (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 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 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 characterises the fact that such a project will not be economically feasible to implement (see Fig. 2.3.1) [65].

Indicators such as fuel energy consumption and NO_x emissions influence the alternative's low rating. 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 characterise the fact that such a project is not economically feasible.
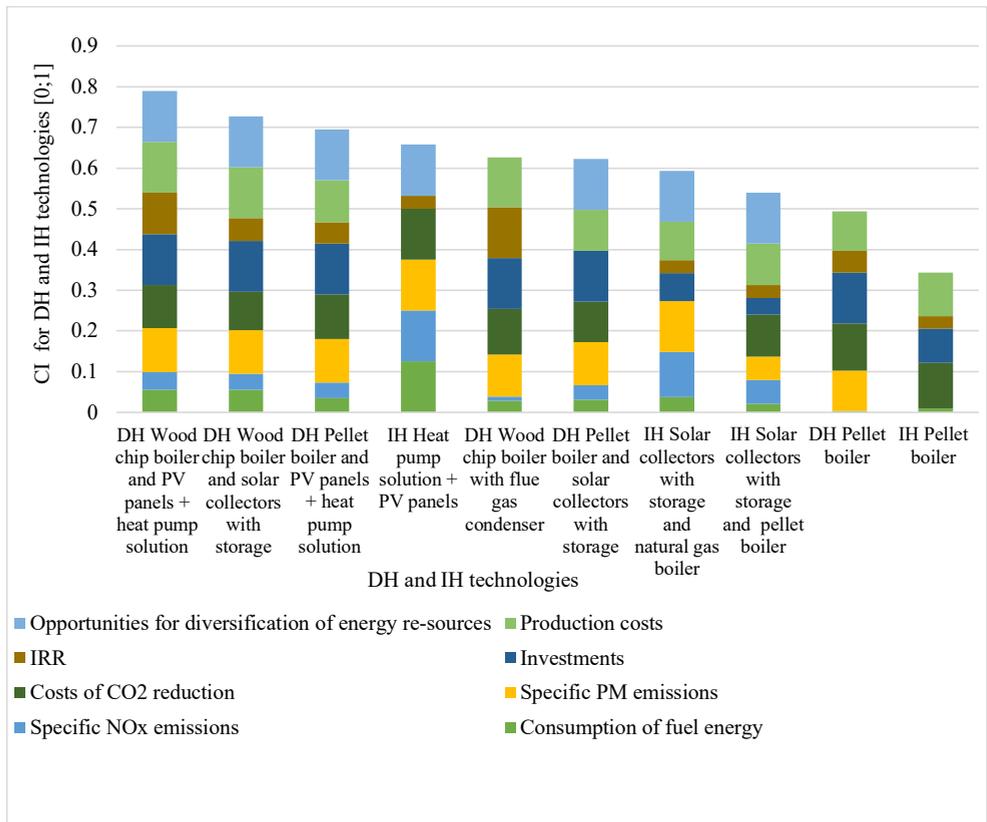

Fig. 2.3.1. CI for DH and IH technologies.

2.4. Evaluation of agriculture and forestry policies

The highest score in the CSI 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).

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 [66], [67] (see Fig. 2.4.1).

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 to the weights where each indicator was equally important.
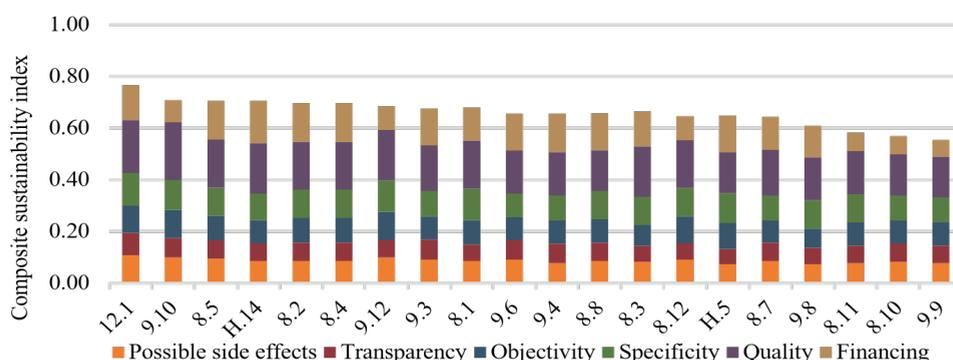

Fig. 2.4.1. CSI of agriculture and forestry policies ranking.

Table 2.4.1

Agriculture and forestry measures from NECP [47]

12.1	Improve public knowledge, awareness, and 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 stock 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

49

Table 2.4.1 (continued)

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

2.5. **System change – comparison of conventional and organic farming**

Results show that farms with 30–49 cows 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 [68]. 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 [68]. 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 [68] (see Fig. 2.5.1).
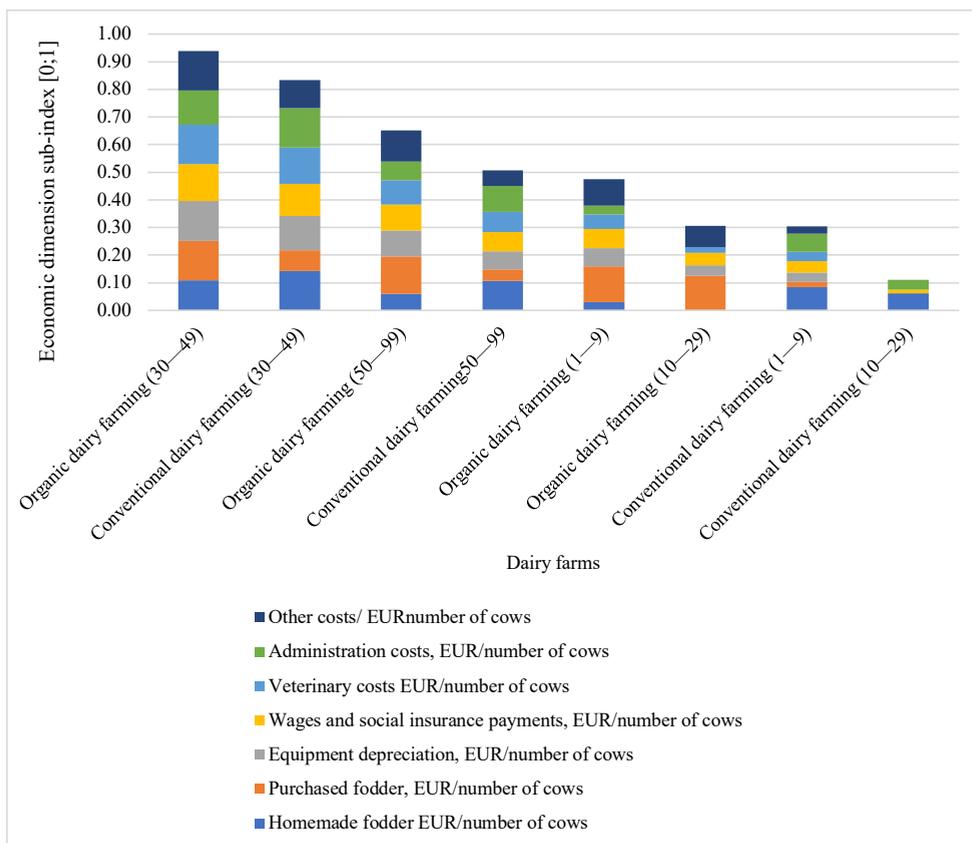
Fig. 2.5.1. Economic dimension sub-index for conventional and organic dairy farming strategies.

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. 2.5.2).
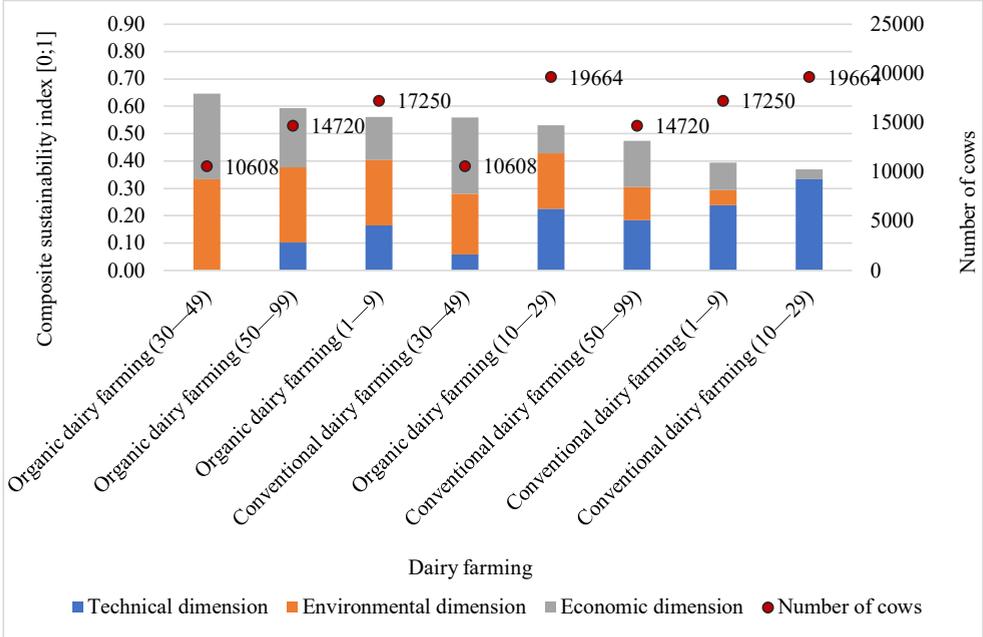

Fig. 2.5.2. Composite index for conventional and organic dairy farming strategies with digestible energy(DE) 67 %.

2.6. System change – testoration 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 received the highest rating (0.87) in CI. The lowest rating was for perennial cultivated grasslands, which have higher emissions compared to other strategies (0.40) (see Fig. 2.6.1).
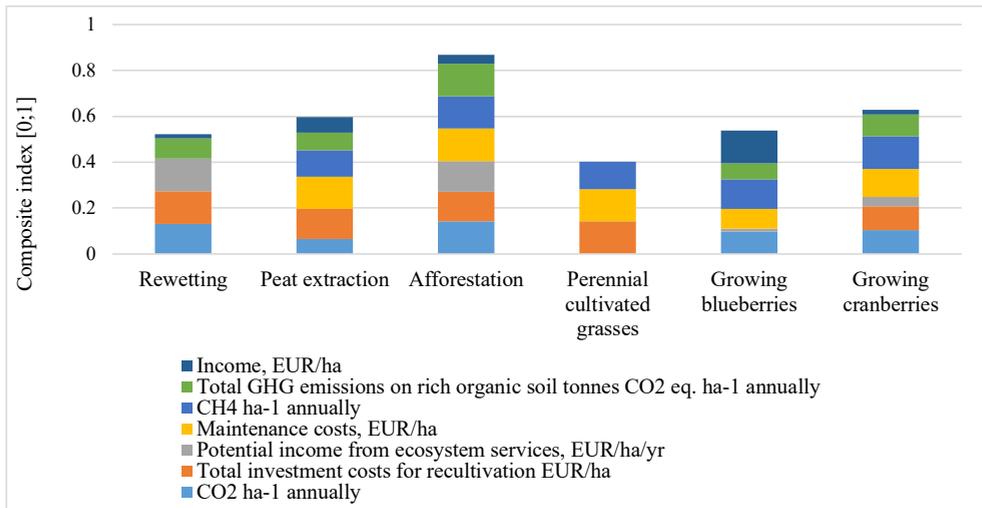
Fig. 2.6.1. Peatland restoration strategies.

The highest score on the composite index, taking into account alternatives, was forthe production of insulation panels using cattail (*Typha*) (0.87) (see Fig. 2.6.2). 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.
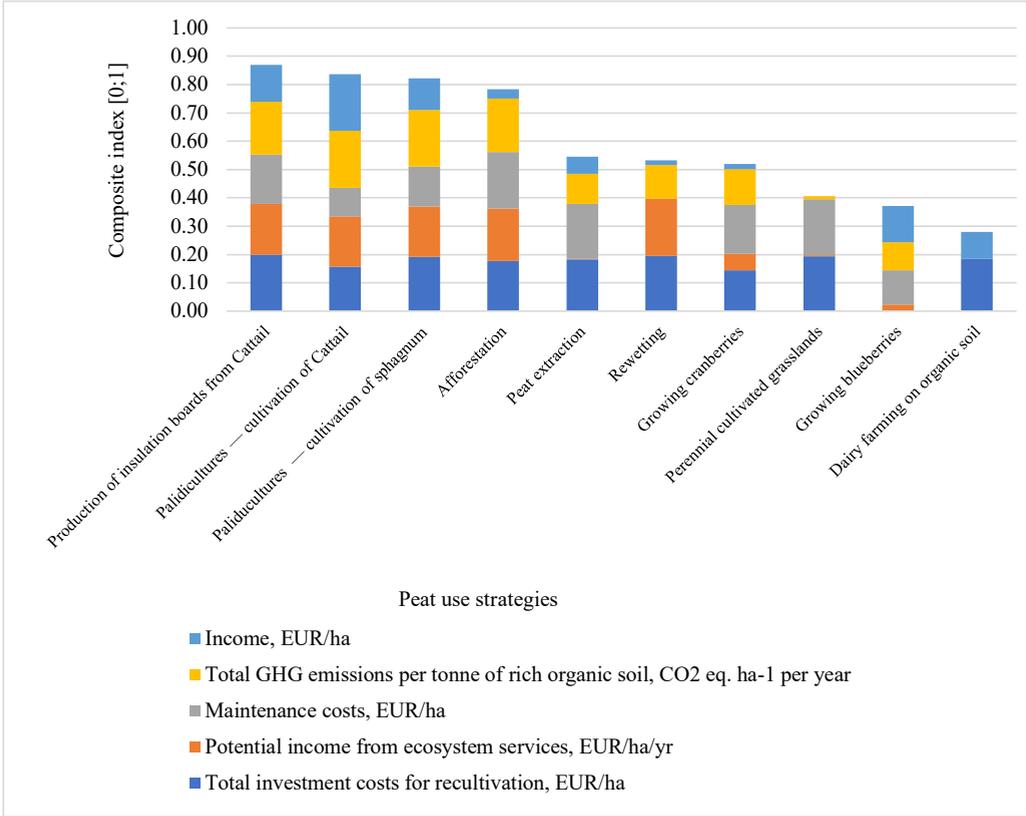
Fig. 2.6.2. Restoration strategies and alternative use of peat.

Rewetting of peatlands can be evaluated as an attractive solution regarding financial compensation (EUR/ha) after rewetting [57], [69]. 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. 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 [61]. Switching to paludiculture can reduce GHG emissions and land subsidence while providing productive use of land [70], [71].

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 [72]. 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 [57], [61]. 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 [73]. 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 [61].

2.7. Renewable energy potential in sectors

The use of solar energy received the second-highest potential score for use in transportation (0.90) among RES. The potential of using wind energy in the transportation sector was given the third-highest score (0.83). Table 2.7.1 shows the final index scores for each RES in each sector.

Table 2.7.1

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					

Table 2.7.1 (continued)

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. 2.7.2). Table 2.7.1 summarises the points obtained, clearly showing the normalised result for each RES type, with which it is possible to characterise the RES utilisation potential.
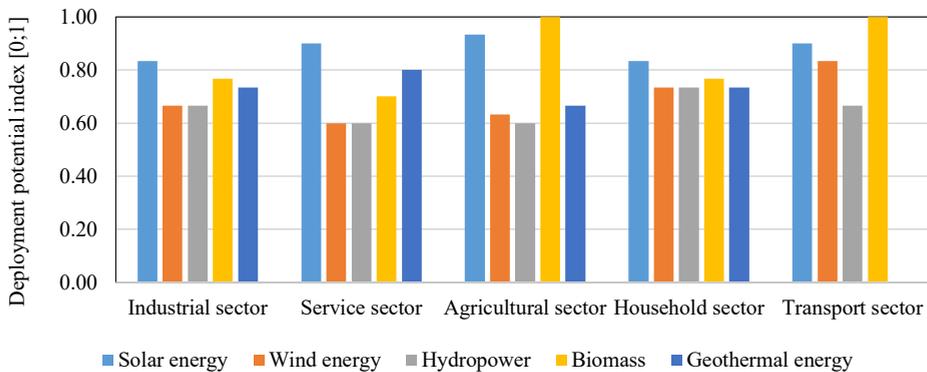
Fig. 2.7.2. Comparison of the development trends of RES between the sectors.

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 2.7.2

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 [74].

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. 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 RES.

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.

Heat pumps obtained the highest score in the sustainability index 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.

DH resilience assessment results 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. 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 CO2 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.

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 composite index 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.

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