Development of a District Heating Resilience Index: A Multi-criteria Assessment Approach Based on Latvian Case Studies

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Abstract. The study proposes a new approach to evaluating the resilience of district heating (DH) infrastructure by developing a District Heating Resilience multicriteria analysis (MCA). In this context, resilience is defined as the ability of a DH system to absorb, adapt to, and recover from disruptions while maintaining essential heat supply services. The methodology incorporates 24 indicators spanning technical, economic, environmental, and social dimensions. The MCA approach developed is based on many indicators related to technical, economic, social, and environmental aspects of DH. A method known as TOPSIS was used to assess and compare resilience performance across three DH networks in Latvia. To establish the framework and indicators for resilience assessment, the work draws on a wide range of literature and interviews related to DH technologies, historical development, and energy system risks. The DH networks selected for cases studies were analyzed using the defined indicators, allowing the identification of factors that most strongly influence overall resilience. Among them, energy source dependency, aging infrastructure, and exposure to weather extremes stood out. The results of this study provide a structured way to assess the resilience of heat supply systems and can help guide future development of a standardized index development for DH resilience assessment, which can improve upgrades and planning strategies in line with sustainability and energy security goals.

Keywords: District heating · Resilience · Infrastructure · Multi-criteria analysis

1 Introduction

Energy security touches on many different concerns, all pointing toward the same goal: making sure that energy remains both dependable and within reach for those who need it. In this context, energy networks stand out as especially vital officially recognized as part of what's known as Critical Infrastructure [1]. According to national law, this refers to physical or functional systems that are considered essential for the of society, concerning public safety, health, the economy, or general wellbeing. This legal framing highlights just how deeply energy networks are tied to societal resilience.

Disruptions in supply, sharp spikes in cost, and environmental impacts even more concerning with the current especially pressing issues related to geopolitical tension due

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to the war in Ukraine, which sparked by Russia's invasion in 2021 and made it impossible to ignore how energy systems are effected by such conflicts. The problem isn't only about infrastructure under attack, but also the ripple effects across supply routes, availability of resources, and economic stability that leave entire regions exposed. Dependence on a narrow resource base is another major vulnerability. If a country relies too much on one energy source, especially if that source is imported, it can quickly find itself with few options when prices shift or supply is interrupted [2].

Climate-related risks also pose a growing threat, and they cut both ways. On one hand, extreme weather like flooding, windstorms, prolonged heat or freezing events can physically damage infrastructure across the energy chain, from generation to delivery. On the other, the continued use of fossil-based systems contributes to emissions, which in turn drive further climate instability. These feedback loops make the challenge even more urgent to tackle [3].

Within this context, DH networks form a crucial part of the broader energy infrastructure. These systems include a variety of technologies designed to deliver energy services efficiently to densely populated areas. For instance, electricity grids transfer power from generation sites to end users, gas and oil pipelines serve as the backbone for fuel distribution, while DH systems are specifically designed to provide thermal energy hot or chilled water (for cooling) via insulated pipes for space conditioning in buildings. When the focus is on heating, the system is referred to as DH; when cooling dominates, it is classified as district cooling (DC). [4] Despite technological advances, recent data about 2021 indicate that more than 50% of global energy is still produced from fossil sources [5].

Thermal energy represents a significant share of total energy demand. In Europe, the DH/DC sector accounts for roughly half of all final energy consumption, outpacing both transport and electricity. The majority of this is allocated to residential applications, with around 79% of energy going toward space heating, domestic hot water, and, increasingly, space cooling [6]. A DH system requires three core components: a cost-effective heat source, a clear and stable heat demand, and a distribution network that efficiently links the two. Distance between these components is critical, as shorter pipeline distances reduce both capital investment and heat losses.

Typical end users for DH include residential buildings, schools, hospitals, and commercial facilities. [7] Given the role of DH in ensuring reliable energy services to local communities, energy networks must remain robust in the face of external stressors. Their exposure to natural hazards such as flooding, storms, heatwaves, and sea-level rise means that even areas with temperate climates are not immune to disruption, thus long-term functionality of DH will depend not only on technical robustness but also on strategic adaptation measures that can minimize damage, service interruptions, and future repair costs [8].

This study sets out to explore the factors that influence the resilience of DH networks in Latvia. To achieve this, the research combines insights from a structured review of scientific publications with input gathered through interviews conducted with professionals working in the field. In addition, relevant technical and operational data are examined to supplement the findings. From this combined evidence base, a set of key indicators is developed—each reflecting an aspect of system resilience. These indicators are then

applied in the evaluation of selected district heating networks, providing a grounded framework for assessing their capacity to withstand and adapt to various stresses.

2 Methodology

To achieve the aim of the study, following steps are performed in this study as indicated in Fig. 1. First, based on an in-depth review of academic literature and relevant studies, this work offers a contextualized understanding of what constitutes resilience in DH systems. In this research, DH resilience is understood as: "*the system's ability to absorb shocks and recover functionality following events that threaten the continuity of heat supply. A resilient network is one that can maintain service or restore it quickly, thereby minimizing disruption for residential and commercial consumers*". This interpretation serves as the foundation for the development of a dedicated resilience indicators. The purpose of this indicators is to enable the evaluation and comparison of resilience across different DH networks by translating complex system characteristics into a structured set of measurable criteria.

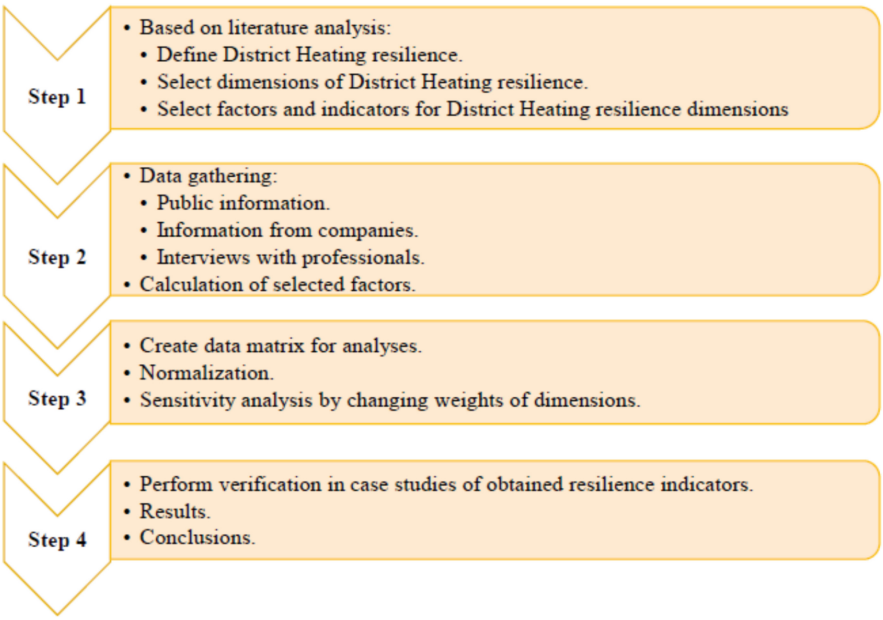

Fig. 1. Methodological steps of the study

2.1 Data Collection and Definition of DH Resilience Assessment Dimensions

In collaboration with professionals experienced in the field of district heating, this research identifies the most critical criteria influencing resilience across four main dimensions. Based on literature and expert judgment, four core dimensions were established as

central to DH resilience evaluation. Expert interviews were conducted with professionals from the DH sector, including engineers and business representatives. Participants came from private companies specializes in DH solutions. Additional insights were gathered from Latvian DH companies selected for case studies. Interviews were carried out through a mix of in-person meetings, phone calls, and email correspondence.

As a result of this information gathering, the following dimensions are defined for DH resilience assessment:

- Technical Dimension: Captures the system's capacity to resist and adapt to mechanical faults, supply interruptions, or aging infrastructure while continuing to deliver heat to users.
- Economic Dimension: Addresses financial viability, investment capacity, and the affordability of heat supply; factors that determine whether the system can sustain resilience improvements over time.
- Climate and Environmental Dimension: Relates to how the system integrates renewable or low-emission sources and adapts to regulatory frameworks shaped by climate policy and environmental considerations.
- Social Dimension: Reflects the societal impact of resilience, including equitable access, public perception, and the ability to shield vulnerable groups from energy insecurity during disruptions.

Assessing resilience across multiple dimensions is essential because district heating systems are complex socio-technical infrastructures influenced by more than just technical reliability. A system may be technically sound yet economically unsustainable, environmentally incompatible, or socially inequitable. By evaluating resilience through technical, economic, environmental, and social lenses, it becomes possible to capture interdependencies and trade-offs that would be missed in a single-domain assessment. This comprehensive perspective allows for better-informed decisions that address not only system performance but also affordability, regulatory alignment, and societal acceptance. These dimensions, along with their respective indicators defined next step of methodology, form the analytical core of the DH Resilience Index.

2.2 Definition of DH Resilience Indicators

The process of indicator selection for defined DH resilience dimensions begins with a critical analysis of existing academic literature, where common themes and recurring elements in the definition of infrastructure resilience, particularly within energy systems, are identified. These findings are then tailored to a case of Latvia's energy landscape. The definition of indicators is based on the factors attributed to be important for describing DH resilience characteristics.

The selection of factors is guided by their relevance to reflect meaningful, system-level responses to various types of disturbance (e.g. technical failures, climate-related stresses, economic shocks, or social vulnerabilities). These factors are selected by summarizing the findings from academic studies, policy documents, and expert interviews conducted with engineers, utility operators, and specialists in DH system planning.

Once the key factors are defined, indicators are selected as measurable proxies that represent each factor in a quantifiable way. The selection process for indicators focuses on three main criteria:

- Relevance – The indicator must meaningfully represent a specific aspect of resilience within one of the four dimensions (economic, technical, environmental, or social).
- Data availability – Indicators are chosen based on the accessibility and reliability of underlying data, either from public sources or through direct cooperation with DH companies.
- Comparability – The selected indicators should be applicable across multiple case study locations to allow for comparative analysis.

Table 1. Presents a structured overview of the technical dimension of DH resilience, highlighting key factors, indicators, measurement units, and their impact on resilience. The technical resilience of a DH system is essential for ensuring stable and uninterrupted heat supply, especially in the face of infrastructure failures, supply disruptions, and external hazards. The table provides a structured overview of the technical indicators affecting DH resilience. Positive indicators (+) contribute to resilience, while negative indicators (−) indicate vulnerability within the system.

Table 1. Indicators of the Technical Dimension of DH Resilience

Factors of Technical Dimension	Indicator	Measure	Impact on Resilience
Heat production capacity	Excess production capacity	%	+
Diversification of production	Dependence on number of heat production plants	HHI	−
Diversification of resources	Dependence on one type of energy source	HHI	−
Heat losses	Heat losses in the DH network	MWh/km	−
Aging infrastructure	Industrially insulated pipes	%	+
Digitalization	Level of automation	Scale	+
Heat storage	Heat accumulation tank volume	L/MW	+
Low-temperature DH	DH technical parameters of supply and return temperature	Scale	+
Investments in infrastructure	Amount of investments in DH infrastructure over a 10-year period	EUR/MW	+

(*continued*)

Table 1. (*continued*)

Factors of Technical Dimension	Indicator	Measure	Impact on Resilience
Consumer energy efficiency	Average heat consumption per unit area	kWh/m^2	–
Natural hazards – Cold waves	Resilience to extreme cold conditions	Scale	–
Natural hazards – Floods	Resilience to flood risk	Scale	–

Table 2 presents economic indicators aligned with the key economic factors that influence the resilience of DH systems. Economic resilience ensures that DH operators can sustain operations, manage financial risks, and maintain affordable heating services despite fluctuations in energy markets and policy changes. A financially stable and cost-efficient DH system is better positioned to adapt to disruptions, invest in modernization, and maintain long-term service reliability.

Table 2. List of Indicators of the Economic Dimension of DH Resilience

Factors of Economic Dimension	Indicator	Measure	Impact on Resilience
Economic Stability of DH Production Company	Company profit	EUR/MWh	+
Prices of Energy Sources	Energy source price fluctuation	%	–
Heat Consumers	Average heat consumption by customers with individual substations	EUR/MWh	–
Efficiency of Heat Production	Cost of energy source	EUR/MWh	–
	Production cost	EUR/MWh	–
Workforce Productivity	Employees per unit of heat produced	Employees/MWh	–
Affordability of Heat Energy	Affordability of heat energy tariff	MWh	+
Subsidized Investments in Infrastructure	Subsidized investments in DH	%	+

Within this study, the climate and environmental aspects of DH resilience are captured through a set of specific factors and corresponding indicators, as outlined in Table 3.

In this context, the technologies and fuel sources used for heat generation are particularly influencing emissions, regulatory exposure, and adaptability to long-term climate goals.

Table 3. List of Indicators of the Climate and Environment Dimension of DH Resilience

Factors of Climate and Environment Dimension	Indicator	Measure	Impact on Resilience
Technologies and Innovation	Heat produced with renewable resources	%	+
GHG Emissions	Total greenhouse gas emissions	t/MWh	–
CO_2 Emissions	Carbon dioxide emissions	t/MWh	–
Air Quality	Particulate matter emissions	t/MWh	–

The social dimension of DH resilience focuses on how reliably and affordably heat is delivered to people, and how well systems are managed to prevent or respond to disruptions. Key factors include:

- Whether energy management and risk planning are in place at the municipal and company levels.
- The energy efficiency of buildings, which lowers demand and increases system stability.
- The impact of taxes on affordability, with higher taxes making heat less accessible.
- Consumer preference and trust, reflected in how many users stay connected to DH services.

Together, these factors determine how well DH systems support public well-being, especially during periods of stress or change (Table 4).

2.3 Creation of Model for Resilience Assessment

The defined indicators are integrated into multi-criteria decision analysis (MCDA) using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [9–11] for ranking of different district heating networks based on resilience performance. The TOPSIS allows to find best solution by defining closeness to the ideal solution (best-case scenario) and as far as possible from the worst-case scenario. This method helps understand which systems are most resilient and where improvements are needed. Steps in the TOPSIS Process:

1) Definition of indicators
   Each DH system is evaluated based on a set of resilience indicators, such as heat production capacity, energy source diversification, financial stability, emissions levels, and consumer affordability. These indicators represent both positive and negative factors affecting system resilience.

Table 4. List of Indicators of the Social Dimension of DH Resilience

Factors of Social Dimension	Indicator	Measure	Impact on Resilience
Municipal Energy Management System	DH as a separate focus in the municipality energy management system	Scale	+
DH Company Risk Management Plan	Existence and implementation of a risk management plan	Scale	+
Energy Efficiency Improvement of Consumers	Potential of heat consumption reduction at consumers	%	+
Tax on Fossil Fuels and Emissions	Excise tax on fossil fuel	EUR/MWh	−
	Tax on emissions	EUR/MWh	−
Customer Preference for DH	Proportion of DH consumers in the area	%	+

2) Standardization and Weighting of Indicators
   Since indicators have different units and scales, they are standardized to ensure comparability across all DH systems. Each indicator is then assigned a weight, which reflects its importance in the overall resilience assessment. To ensure transparency and reduce the influence of subjective assumptions, the assignment of indicator weights was carried out using structured expert consultations. Specialists with experience in district heating operations, energy planning, and infrastructure risk analysis were invited to evaluate the relative importance of each resilience dimension and associated indicators.
3) Determining Ideal and Worst-Case Scenarios
   The ideal solution represents the best possible performance across all indicators, such as high renewable energy integration, low emissions, and strong financial stability. The worst-case scenario represents poor performance, such as high reliance on fossil fuels, high emissions, and financial instability.
4) Comparison of DH Systems Against Ideal and Worst-Case Scenarios
   Each DH system is then compared to both the ideal and worst-case scenarios. Systems that perform well across multiple indicators will be closer to the ideal solution, while less resilient systems will be closer to the worst-case scenario.
5) Final Ranking of District Heating Systems
   A resilience score is calculated for each DH system based on its proximity to the ideal and worst-case scenarios. The systems are then ranked from most resilient to least resilient, providing a clear basis for decision-making and prioritizing improvements.

The TOPSIS method offers a comprehensive evaluation of DH resilience by considering multiple performance indicators simultaneously. Unlike single-metric assessments, which may overlook key resilience factors, TOPSIS ensures a holistic analysis that can incorporate technical, economic, environmental, and social dimension indicators. This

approach allows for a fair comparison between different DH systems, even when they vary in size, technology, and energy sources, making it a valuable comparative tool.

Additionally, TOPSIS serves as a decision-support tool by providing a quantitative basis for policy and investment decisions. It enables energy planners to identify vulnerabilities, prioritize improvements, and allocate resources effectively, ensuring that resilience-enhancing measures are both strategic and impactful. Its flexibility and adaptability further strengthen its applicability, as the methodology can be extended beyond district heating to assess the resilience of other critical energy infrastructures.

2.4 Definition of Case Study

The methodology has been tested using three district heating case studies from Latvia. These three DH systems in Latvia were selected for the case study analysis, representing a range of infrastructure sizes, energy sources, and technological modernization levels as given Table 5.

Table 5. List of companies selected for research and description

Activities	Total Heat Capacity (MW)	Annual Heat Production (MWh)	Fuel Used	Heat Tariff (EUR, 2023)	Consumers	Ownership
Salaspils Siltums Ltd	37.71	65187	Woodchips, natural gas, solar	73.05	201	Municipality
Jūrmalas Siltums Ltd	78.57	137610	Woodchips, natural gas	120.77	324	Municipality
Ķekavas Nami Ltd	19.33	28083	Wood pellets, natural gas	141.78	135	Municipality

The selection of the case study systems is guided by the intention to capture a representative spectrum of district heating conditions in Latvia. These systems vary in terms of installed capacity, energy source diversity, infrastructure modernization level, and consumer base size. Together, they reflect common typologies found across Latvia's DH sector, ranging from small municipal operators to larger, more diversified systems.

3 Results

The results of the resilience evaluation using the TOPSIS method offer insight into how each DH company performs when assessed against ideal and non-ideal benchmarks (see Table 5). "Salaspils Siltums" Ltd came out on top, followed closely by "Jūrmalas Siltums" Ltd, while "Ķekavas Nami" Ltd ranked third (Table 6).

Table 6. Results of TOPSIS analysis for defined case study

DH Company	Ideal	Anti-Ideal	Pi Value	Final Valuation
"Salaspils Siltums" Ltd	0.0056	0.0163	0.7449	1
"Jūrmalas Siltums" Ltd	0.005	0.0133	0.7262	2
"Ķekavas Nami" Ltd	0.0233	0.004	0.1465	3

The Fig. 2. Shows normalized dimension scores with ranked weights, starting form Technical dimension with highest weight, followed by Economical dimensions, then Environmental, and Social with lowest weight. According to the results with ranked weights, Technical resilience plays the most decisive role in shaping final outcomes, but it also highlights the risks posed by weak economic performance, which can offset strengths in other areas. The relatively uniform distribution of values in the environmental and social dimensions across all three companies also suggests these may carry less discriminatory power in the current index weighting.

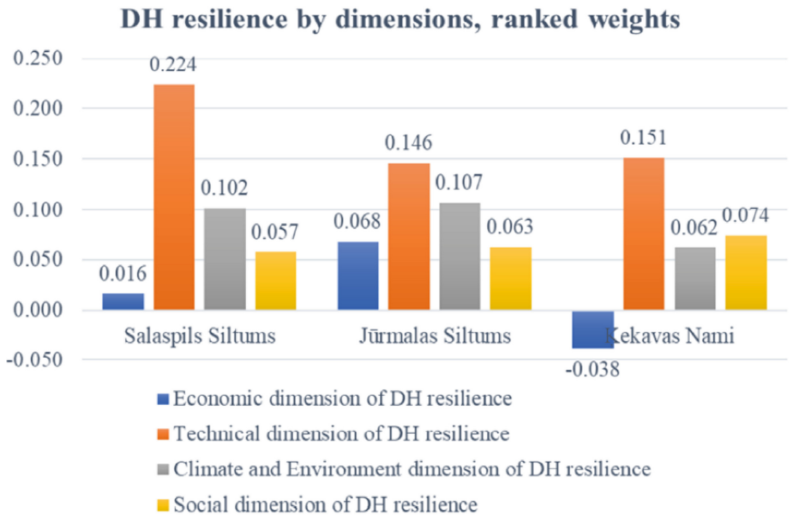

Fig. 2. DH resilience assessment: dimensions normalized and ranked weight values.

Certain indicators have a more significant impact on the final result simply because there is more variation in their values across the cases. Where companies differ greatly, for example, in emissions per MWh or network heat loss, those indicators tend to influence the distance to ideal more noticeably. Other indicators might show similar values across all companies, reducing their influence in the model regardless of their conceptual importance.

4 Conclusions

The results of the TOPSIS analysis for DH resilience assessment reflect a complex interplay of indicator values, dimension weights, and distances to benchmark performance levels. The high ranking of "Salaspils Siltums" suggests relatively strong performance across core dimensions, particularly technical and environmental. Conversely, "Ķekavas Nami" shows lower resilience due to weaker scores likely in technical and climate-related metrics. Improving the balance and transparency in weighting and indicator distribution would enhance the index's reliability, fairness, and applicability in future assessments.

Moreover, sensitivity testing can help clarify how much results change if weights are adjusted. This is especially useful for uncovering whether the model is overly dependent on one or two variables. Since real data can be hard to obtain and varies between companies, transparency in data availability and how it's treated is also key.

To improve the methodology and enhance fairness in future assessments of DH resilience with unitary index, a few considerations are worth noting. First, weights should be reviewed critically, not just assumed or assigned arbitrarily. Ideally, they should reflect expert input, stakeholder priorities, or observed impact, rather than being set equal by default. Second, the number of indicators in each dimension should either be balanced or the weighting structure should be correct for any imbalance. If one area dominates the data structure, it may overshadow other relevant aspects of resilience.

While the current version of the model provides a structured basis for comparing system resilience, further steps are planned to increase its practical value. This includes tailoring the framework to specific local conditions by introducing context-sensitive scoring criteria and exploring real-time data integration for adaptive updates. In the long term, the development of unitary DH resilience index could be strengthened by introducing more context-aware scoring. Not all DH systems operate under the same conditions—what's achievable in a large urban network may not be realistic in a smaller or more isolated system. Adapting benchmarks to reflect local conditions would make the tool more practical. Finally, as energy systems evolve, so should the indicators. The index should remain flexible to accommodate new risks, technologies, and policy developments over time. By integrating feedback from system operators and decision-makers, the approach can be further refined as a decision-support tool, guiding infrastructure investments and resilience planning in diverse settings.

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