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Developing an Algorithmic Framework for Sustainable Asset Management of District Heating Networks: A Scenario-Based Approach

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***Abstract* – The sustainable asset management of district heating networks (DHNs) presents a complex challenge, integrating ecological, economic, and social sustainability dimensions. To address this, we developed a structured methodology for an algorithmic framework that supports sustainability assessments in DHNs. The proposed framework follows nine systematic phases, including defining objectives and weights, data collection and mining, establishing a data pipeline, aligning with key performance indicators (KPIs), conducting multi-criteria decision analysis (MCDA), and performing scenario-based sensitivity analysis. These phases enable the algorithm to assess both operational and strategic aspects of asset management. By incorporating six distinct sustainability scenarios – ranging from stricter environmental regulations and economic constraints to climate resilience and circular economy transitions – the framework evaluates potential outcomes and optimal strategies. Each scenario provides insights into the trade-offs and synergies between different sustainability objectives, guiding decision-makers in balancing efficiency, cost-effectiveness, and environmental impact. The results from scenario analyses inform tailored strategies, such as infrastructure reinvestment plans, predictive maintenance schedules, or adaptive regulatory compliance measures, ensuring resilient and future-proof DHN operations. This research establishes a foundation for data-driven, scenario-based sustainability management in DHNs, offering practical guidance for decision-making based on defined criteria and KPIs. The structured approach enhances flexibility and adaptability in asset management, paving the way for empirical validation and real-world implementation.**

***Keywords* – Asset management; conceptual framework; district heating networks; KPIs; multi-criteria decision analysis; scenario analysis; sustainability.**

Nomenclature	
AHP	Analytical Hierarchy Process
DHNs	District Heating Networks
KPI	Key Performance Indicator
LCCA	Life-Cycle Cost Analysis
MCDA	Multi-Criteria Decision Analysis
MILP	Mixed-Integer Linear Programming
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations

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RES	Renewable Energy Sources
RLN	Rural Low-Temperature Network
RRN	Retrofitted Renewable Network
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
ULN	Urban Legacy Network

1. INTRODUCTION

District heating networks (DHNs) are systems that distribute heat from the centralized and decentralized heat sources to the buildings via network of pipelines [1], [2]. Over the years the efficiency of the DHNs has improved and made it a reliable infrastructure, especially on regions with harsh winters like countries around Baltic Sea. However, managing these networks sustainably presents significant challenges, as it requires balancing economic, environmental, and social factors. Some asset management approaches, such as condition-based maintenance [3], reliability-centered maintenance [4], and risk-based inspection [5], primarily focus on cost-effectiveness and operational efficiency. While these methods enhance reliability and system longevity, they often fall short in addressing broader sustainability considerations, such as long-term environmental impact, regulatory compliance, and system resilience. Recent work also highlights how operational efficiency and cost-effectiveness can be enhanced in DHNs – for example, by integrating low-temperature waste heat with economic modeling to optimize both heat recovery and pricing [6].

To bridge this gap, this research develops an algorithmic framework that facilitates systematic sustainability assessments by integrating multi-criteria decision analysis (MCDA) and scenario-based sensitivity analysis into DHN asset management which is used by multiple scholars in the topics of sustainability and environmental impact assessment [7]–[9]. The proposed methodology follows a structured, nine-phase process, including objective definition, data collection and processing, key performance indicator (KPI) alignment, and scenario evaluation. Unlike conventional methods, which mainly assess historical data for predictive maintenance and risk mitigation, our framework incorporates forward-looking sustainability scenarios. These six scenarios – ranging from stricter environmental regulations and economic constraints to climate resilience and circular economy transitions – enable a comprehensive evaluation of potential trade-offs and synergies across different sustainability objectives.

By leveraging data-driven insights and scenario-based assessments, the proposed framework provides a robust decision-support mechanism for DHN asset managers. It integrates sustainability considerations directly into engineering decision processes through a structured, nine-phase methodology (see Fig. 1). The framework begins with defining strategic targets and weighing sustainability criteria, followed by data collection, preprocessing, and workflow design to ensure analytical consistency. Key performance indicators (KPIs) are then aligned with operational, economic, and environmental objectives to guide evaluation and scoring of alternatives. Subsequent phases apply multi-criteria decision analysis (MCDA), scenario analysis, and sensitivity testing to explore trade-offs between competing sustainability goals. Finally, the outcomes inform optimization and strategy development, enabling transparent and reproducible decision-making for resilient and low-carbon DHN operation.

This paper presents the methodological foundation and computational implementation of the framework, supported by representative network case studies. The results contribute to the advancement of sustainability-oriented asset management practices and provide a basis for future empirical validation across diverse DHN configurations and climatic contexts.

2. METHODS AND TOOLS

The proposed framework follows a structured engineering-driven methodology to optimize DHN sustainability, leveraging computational modelling, multi-criteria decision support, and scenario-based analysis. Each of the methodology's nine phases (shown in Fig. 1) focuses on a different facet of sustainable asset management.

The first phase involves defining sustainability targets and assigning criteria weights based on stakeholder preferences and regulatory constraints. This step establishes key objectives, such as minimizing carbon emissions, improving energy efficiency, and optimizing operational costs. Weighting techniques, such as entropy-based analysis [10] and expert-driven decision matrices, are applied to prioritize the most critical factors in DHN management.

Following the definition of targets, data collection and determination of key variables are performed. This phase involves gathering operational, environmental, and economic data from district heating systems, including heat load profiles, fuel sources, maintenance schedules, and policy-driven constraints. Data sources include sensor networks, historical operational records, literature and governmental databases to ensure a comprehensive dataset.

Once collected, the data undergoes preprocessing and mining, where statistical methods and machine learning algorithms are applied for noise reduction, anomaly detection, and feature extraction. Techniques such as principal component analysis and clustering algorithms help identify underlying patterns and correlations among variables, enhancing the reliability of predictive modelling.

To ensure efficient analysis, a structured data pipeline and workflow are established. This phase involves automating data integration, cleaning, and real-time processing if available, facilitating dynamic decision-making and scenario assessment. The implementation of cloud-based computing and database management systems may further enhance data accessibility and computational efficiency.

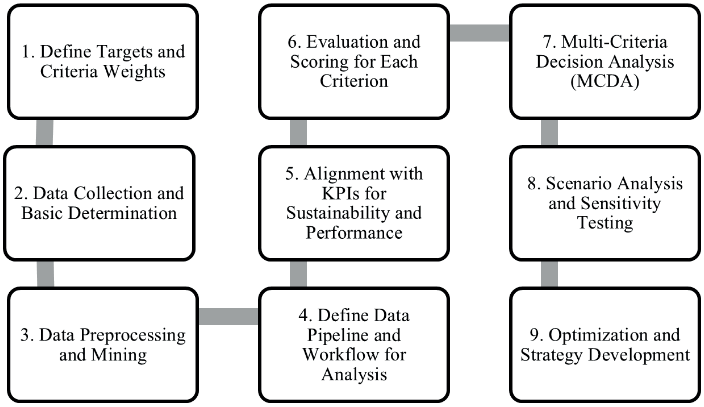

Fig. 1. Illustrated workflow for the development of a sustainability asset assessment methodology for district heating networks.

The next phase aligns the processed data with predefined key performance indicators (KPIs) for sustainability and performance assessment. These KPIs include exergy efficiency, life-cycle cost analysis (LCCA), CO_2 intensity, and resilience metrics. The KPIs are derived from three primary data categories: (i) Network metadata, encompassing information such as operator characteristics, installed capacity, primary energy source, and commissioning year; (ii) Operational data, including time series of supply and return temperatures, flow rates, heating power, and outside temperature; and (iii) Pipeline asset data, which describe the physical infrastructure through parameters such as pipe diameter, length, insulation type, construction year, and recorded damages. Depending on the assessment objective, KPIs may use these parameters directly or as derived indicators, providing a comprehensive quantitative foundation for evaluating the DHNs sustainability, efficiency, and resilience. By mapping real-time and historical data to these indicators, a robust evaluation framework is established.

The evaluation and scoring of each criterion follow, where normalization techniques, such as min-max scaling and z-score standardization, are applied to ensure comparability. This scoring system enables the ranking of DHN components and operational strategies based on sustainability metrics.

To support complex decision-making, multi-criteria decision analysis (MCDA) techniques are employed. Methods such as the Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) could be utilized to determine the most suitable asset management strategies under competing objectives.

Scenario analysis and sensitivity testing are conducted to assess the robustness of decisions under varying conditions.

The final phase focuses on optimization and strategy development. Advanced mathematical optimization techniques, including mixed-integer linear programming (MILP) and evolutionary algorithms, are applied to derive optimal asset management strategies. These strategies ensure long-term sustainability by balancing cost-efficiency, environmental impact, and system reliability.

2.1. Computational Tools

The proposed framework is implemented through a suite of computational tools and numerical methods designed to support rigorous engineering analysis and data-driven decision-making. Its structure provides a systematic approach for integrating sustainability considerations into DHN asset management. By coupling advanced computational techniques with scenario-based evaluations, the framework facilitates comprehensive assessment of alternative strategies, promoting resilient and efficient network development. The complete framework will be made available as open-source software upon project completion to ensure transparency, reproducibility, and wider applicability within both research and professional communities.

2.2. Input Data

Three hypothetical DHNs were selected to reflect current real-world practices. These include:

1. Urban Legacy Network (ULN) – A large-scale, high-temperature third-generation DHN, typical of those found in major urban areas;
2. Rural Low-Temperature Network (RLN) – A small-scale, low-temperature fourth-generation DHN, characteristic of rural or low-density regions;
3. Retrofitted Renewable Network (RRN) – A medium-sized DHN upgraded to incorporate a higher share of renewable energy sources (RES).

Table 1, which illustrates the three DHNs and shows different scales, technologies, and degrees of renewable integration, provides more information about these networks and reflects a variety of contemporary activities in both urban and rural areas.

TABLE 1. KEY CHARACTERISTICS OF THREE REPRESENTATIVE DHNS

Characteristic	**ULN**	**RLN**	**RRN**
Renewable Share	15 %	85 %	45 %
Smart Controls	Moderate (50 %)	Basic (30 %)	Advanced (85 %)
CO_2 Emissions	High (80 000 tons/yr)	Low (2000 tons/yr)	Medium (30 000 tons/yr)
Expansion Potential	High (80 %)	Low (40 %)	Medium (60 %)
Network Length	500 km	150 km	250 km
Operating Temperature	90–110 °C	55–60 °C	70–75 °C

The assumed values in this Table were gathered and derived from multiple literature sources to ensure the analysis closely reflects real-world conditions [11]–[20]. This approach enables a better understanding of how network characteristics influence outcomes when evaluated using a multi-criteria smart analysis.

3. RESULTS

The analysis of DHNs in this study is based on eight carefully defined criteria, which encompass a wide range of sustainability dimensions, including social, economic, and environmental aspects as seen in Table 2.

TABLE 2. THE EIGHT DEFINED CRITERIA USED TO ANALYZE DHNS, FOCUSING ON MULTIPLE SUSTAINABILITY FACETS

Criterion	**Description**
Adaptability to Future Needs	Assesses how easily the system can be modified or expanded to accommodate future changes, such as demand growth or integration of renewable sources.
Ecological Quality	Measures the environmental impact of the system, focusing on emissions, energy consumption, and the overall ecological footprint.
Economic Efficiency	Evaluates the financial performance over the system's life, including initial costs, maintenance, and long-term cost-effectiveness.
Heat Distribution Efficiency	Reflects how efficiently heat is delivered from source to end-users, minimizing losses and maximizing system performance.
Reliability & Material Durability	Assesses the robustness and longevity of materials and system components, including how often failures occur and how quickly repairs are made.
Social Impact	Considers the effect on end-users and communities, including satisfaction, service reliability, and potential health impacts.
Use of Resources	Evaluates the sustainability of materials used, including efficiency and the extent to which recycled or low-impact materials are incorporated.
Waste Management	Focuses on how waste is handled at the end of the asset life, including recyclability and the cost or impact of disposal.

These criteria were selected to ensure a comprehensive assessment of the DHNs' performance, resilience, and long-term sustainability in the face of evolving challenges. Each criterion is further delineated by multiple KPIs that provide quantifiable measures to justify the scoring process. These KPIs serve as benchmarks for evaluating the system's performance and are instrumental in understanding the trade-offs between different sustainability goals [21].

The scoring methodology is underpinned by input data, which is iteratively processed across various scenarios (see Table 3). The iterative approach allows for a dynamic analysis, capturing the impact of different variables and potential future developments. By simulating a range of scenarios, such as changes in environmental regulations, technological advancements, economic constraints, and climate resilience, the model produces a robust set of scores that reflect the DHNs' adaptability and performance under diverse conditions. This iterative process ensures that the evaluation considers both present and future uncertainties, facilitating a more comprehensive and forward-looking sustainability assessment.

TABLE 3. VARIOUS SCENARIOS CONSIDERED TO EVALUATE THE DHNS

Scenario	**Description**
Enhanced Environmental Regulations	Tighter environmental laws push DHNs to adopt cleaner technologies, reduce emissions, and align with decarbonization goals, requiring strategic upgrades and sustainable investments.
Technological Advancements in Heat Distribution	New technologies (e.g., smart meters, AI, low-temperature networks) enhance efficiency and monitoring, demanding agile asset management to integrate innovation and boost system performance.
Economic Downturn with Budget Constraints	Financial limitations require prioritization of essential upgrades and cost-effective solutions. Emphasis is placed on lifecycle cost reduction and maintaining performance within limited budgets.
Increased Demand and Urban Expansion	Growing urban areas increase heat demand and network complexity, requiring scalable, future-proof infrastructure planning and strategic asset expansion to maintain service quality and sustainability.
Climate Change and Extreme Weather Resilience	More frequent climate-related events call for robust, adaptive infrastructure. Asset management must focus on resilience, risk reduction, and maintaining service under extreme conditions.
Shift Towards Circular Economy	A focus on resource efficiency and reuse drives DHNs to integrate recycled materials, waste heat recovery, and sustainable construction practices, aligning asset strategies with circular economy principles.

The analysis reveals distinct performance patterns across the three DHNs under varying scenarios as shown in Fig. 2. The ULN demonstrates high reliability (peaking at 9.89 under Urban Expansion) but suffers from critical economic inefficiencies, scoring zero in Economic Efficiency across all scenarios possibly due to high capital costs and short infrastructure lifespans. In contrast, the RLN excels in ecological performance (Ecological Quality: 21.67) and social impact, benefiting from renewable integration (85 % RES) and lower operational temperatures (55–60 °C), though its adaptability remains limited (max 17.7). The RRN strikes a balance, achieving superior heat distribution efficiency (13.8) and adaptability (18.15) through advanced controls, though reliability varies significantly (3.17–17.02) due to legacy infrastructure constraints. Notably, the Circular Economy scenario yields the highest Waste Management scores (22.0) across all networks, while Climate Resilience proves most effective for rural reliability (16.84). These results underscore inherent trade-offs: urban systems require economic policy support, rural networks need smart technology integration, and retrofits must address reliability risks to optimize performance.

Fig. 2. The results of the sustainability asset assessment of the three hypothetical district heating networks.

4. DISCUSSION

The comparative analysis of urban, rural, and retrofitted DHNs reveals critical insights into the trade-offs between sustainability, economic viability, and technological adaptability in future energy systems. Our results demonstrate that no single network archetype performs optimally across all scenarios, highlighting the need for context-specific solutions tailored to regional infrastructure, resource availability, and policy priorities.

In Urban DH systems, it exhibits strong reliability (peaking at 9.89 under Urban Expansion) due to centralized infrastructure and high-temperature (90–110 °C) operation, which ensures stable heat delivery in dense environments. However, their consistently zero Economic Efficiency scores – driven by high capital costs (€ 800 k/km) and short lifespans (25 years) – reflect a systemic vulnerability. This aligns with [22], who identified urban DH systems as capital-intensive. These networks could be economically fragile without subsidies or carbon pricing based on the defined properties. The Technological Advancements scenario mitigates some inefficiencies (e.g., improving Heat Distribution Efficiency to 13.35), but smart controls alone cannot overcome the fundamental cost barriers of urban infrastructure. These findings underscore the need for hybrid financial models, such as public-private partnerships or green bonds, to support urban DH decarbonization.

In the second hypothetical case study, the RLN outperforms in ecological and social metrics, achieving the highest Ecological Quality (21.67) and Social Impact (14.7) scores. Their low-temperature operation (55–60 °C) and renewable reliance (85 % RES) minimize emissions (2k tons CO_2/yr), corroborating 's findings on geothermal-biomass synergies. However, their lower smart control adoption (30 %) limits adaptability (max 17.7), suggesting that rural systems could benefit from targeted digitalization without compromising their low-complexity advantage. The Economic Downturn scenario's surprising viability (Economic Efficiency: 18.34) further indicates that rural DH systems may be more resilient to macroeconomic shocks than urban ones, provided local biomass supply chains remain stable.

The final case study, the RRN demonstrates the potential of digitalization, with the Technological Advancements scenario achieving unmatched adaptability (18.15) and heat efficiency (13.8). Their reliability scores, however, range greatly (3.17–17.02), highlighting the dangers of repurposing aging infrastructure and reflecting a study by [12] that found the majority of the retrofitting needed to be on the distribution lines. This could be interpreted that retrofication faces a "reliability penalty" unless paired with pipe upgrades. The Circular Economy scenario's universal success in Waste Management (22.0 across all networks) suggests that material recycling is a no-regret strategy, though its economic returns depend on scale.

The discussed results are illustrated on a radar chart for better understanding in Fig. 3.

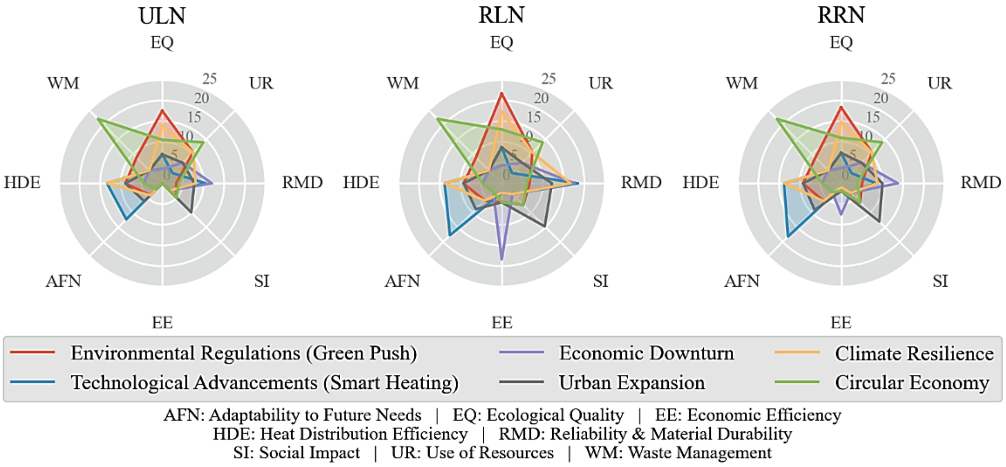

Fig. 3. Scenario visualization of three hypothetical district heating networks.

5. CONCLUSION

This study introduces a conceptual framework for sustainable asset management of DHNs, integrating MCDA and scenario-based evaluation to assess sustainability performance across economic, environmental, and social dimensions. The framework was applied to three representative DHN archetypes evaluated against eight criteria under six distinct scenarios. The results demonstrate that no single archetype consistently outperforms the others, underscoring the context-dependent nature of sustainability optimization and the need for tailored asset management strategies.

Key insights include:

- **ULNs** require economic and policy reforms, such as revised subsidy mechanisms or carbon pricing adjustments, to offset high investment costs and long asset lifecycles;
- **RLNs** benefit most from digitalization and smart control technologies to improve operational flexibility while preserving environmental advantages;
- **RRNs** demand enhanced reliability and risk mitigation measures to manage uncertainties associated with legacy infrastructure retrofits.

The observed variability in the Economic Efficiency criterion suggests that weighting factors may need iterative calibration as more granular and longitudinal data become available. Overall, the proposed framework offers a transparent and adaptable decision-support tool for guiding the sustainable development of DHNs. It provides a methodological foundation for policymakers and practitioners to balance competing objectives and design context-specific strategies that advance decarbonization, resilience, and long-term system efficiency.

6. FUTURE WORKS

Building on the presented framework, three primary research directions are planned to enhance its applicability, robustness, and empirical grounding:

1. Hybrid scenario analysis: future studies will extend the current scenario framework to interconnected urban – rural DHNs, enabling the quantification of lifecycle emissions, costs, and resource flows across integrated regional systems. This approach will provide deeper insights into the cross-scale dynamics of sustainability and efficiency transitions;
2. Uncertainty modelling: advanced stochastic techniques – such as Monte Carlo simulations and probabilistic sensitivity analyses – will be applied to evaluate the influence of external uncertainties, including fluctuating energy prices, evolving regulatory conditions (e.g., carbon pricing and emission standards), and climate-induced variability in thermal demand. These methods will improve the framework's capacity to handle real-world volatility and decision uncertainty;
3. Empirical validation: ongoing collaboration with several DHN operators aims to assess data availability and establish procedures for converting operational and asset data into measurable Key Performance Indicators (KPIs). This step is essential for verifying the framework's practicality and ensuring its seamless integration into real-world asset management systems. The resulting datasets will also support the iterative refinement of criteria weighting and model calibration.

Collectively, these research directions will strengthen the framework's predictive rigor, enhance its scalability across different network typologies, and ensure its relevance for guiding sustainable transitions throughout the lifetime of the project and beyond.

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