VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

FACULTY OF ENVIRONMENTAL ENGINEERING

DEPARTMENT OF BUILDING ENERGETICS

Abu Muhammad Mustakim Reza

# An Investigation of Sustainable Modernization Options for the Salininkai District Heating System

*In Lithuanian:* ***Salininkų kvartalo šilumos tiekimo sistemos tvarios transformacijos tyrimas***

Master’s Degree Thesis

Building Energy Engineering Study Program (State Code 6211EX059)
Energy Engineering Specialization
Energy Engineering Study Field

Vilnius, 2025

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# AN INVESTIGATION OF SUSTAINABLE MODERNIZATION OPTIONS FOR THE SALININKAI DISTRICT HEATING SYSTEM

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Building Energy Engineering Study Program (State Code 6211EX059)

Master's Degree Thesis

Author **Abu Muhammad Mustakim Reza**, PEIfmu-23

Supervisor **Assoc. Dr. Juozas Bielskus**

Consultant **Assoc. Dr. Artur Rogoža**

Vilnius, 2025

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF BUILDING ENERGETICS

Energy Engineering study field
Building Energy Engineering study programme, state code 6211EX059
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APPROVED BY
Head of Department
Artur Rogoža
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**OBJECTIVES FOR MASTER THESIS**

No. PEIfmu-23–10889

Vilnius

For student Abu Muhammad Mustakim Reza

Master Thesis title: An Investigation of Sustainable Modernization Options for the Salininkai District Heating System

Deadline for completion of the final work according to the planned study schedule.

THE OBJECTIVES:

Description of the task: Describe the relevance of the research topic. Formulate the objectives and tasks of the thesis, and define the research object. Conduct a literature review to assess the possibilities of reducing heat losses and integrating heat pumps and solar power plants into district heating networks. Investigate the district heating network of the Salininkai district in Vilnius using monitoring data. Using the EnergyPRO software, perform an energy efficiency analysis of the existing system. Develop alternative supply scenarios with heat pumps and thermal storage, and evaluate their impact on fuel consumption, emissions, and overall system efficiency. Apply sensitivity analysis to assess the reliability of scenario results. Analyse the potential for installing a solar power plant. Evaluate the decentralisation potential by dividing the system into two zones. Present the results, conclusions, and recommendations. Prepare a scientific article covering the main findings of the research.

Academic Supervisor Associated Professor Juozas Bielskus

Vilnius, 2025

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**Thesis language:** English

**Annotation**

The aim of this Master's thesis is to evaluate the performance of the Salininkai District Heating Network (DHN) in Vilnius, Lithuania, and propose a transformation roadmap aligned with 4th Generation District Heating (4GDH) principles. The study focuses on improving system efficiency and reducing primary energy consumption in a network serving 46 buildings with two natural gas-fired boilers, facing challenges such as heat transmission losses and outdated infrastructure.

Multiple upgrade scenarios are simulated using EnergyPRO, including the integration of 1 MW air-to-water electric heat pump, large-scale thermal energy storage, and on-site solar photovoltaic generation. Additionally, structural improvements such as repositioning of heat sources and decentralization strategies are explored. The proposed alternatives are evaluated through energy demand and loss scenarios, overall system efficiency, and primary energy factor (PEF) calculations and finally vetted by technical and economic evaluation, environmental impact assessment and sensitivity analysis.

The research concludes with strategic recommendations for transforming Salininkai DHN into a modern, sustainable, and resilient heating system, potentially serving as a model for similar urban heating networks in cold-climate European cities.

The work consists of 7 parts apart from introduction: relevance and articulation of problem statement, sustainable modernization concept development, literature review, methodology, results, discussion, conclusions followed by recommendation and references.

The thesis includes 100 pages of main text, 49 figures, 7 tables, 8 equations, and 86 bibliographic entries. The supplement is included separately.

**Keywords:** District Heating Network, 4th Generation District Heating, Heat Pump integration in DHN, Thermal Energy Storage integration in DHN, Energy Transition, Sustainable Heating, Salininkai DHN, Solar Photovoltaic integration in DHN

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| Vadovas | **Juozas Bielskus** |

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| | **Kalba:** anglų |


**Anotacija**

Šio magistro darbo tikslas – įvertinti Vilniaus Salininkų centralizuoto šilumos tiekimo (CŠT) tinklo efektyvumą ir pateikti transformacijos planą, pagrįstą ketvirtos kartos centralizuoto šilumos tiekimo principais. Tyrimas orientuotas į sistemos efektyvumo didinimą ir pirminės energijos vartojimo mažinimą tinkle, kuris aptarnauja 46 pastatus, kuriems šilumą tiekia du gamtinėmis dujomis kūrenami katilai, ir susiduria su tokiomis problemomis kaip šilumos perdavimo nuostoliai bei pasenusi infrastruktūra.

Naudojant EnergyPRO programinę įrangą, modeliuojami keli atnaujinimo scenarijai, įskaitant 1 MW galios oras–vanduo tipo elektrinio šilumos siurblio, didelio tūrio šilumos talpyklos bei vietinės saulės fotovoltinės elektrinės integravimą į sistemą. Taip pat nagrinėjami struktūriniai patobulinimai, tokie kaip šilumos šaltinių išdėstymo keitimas ir decentralizacijos strategijos. Siūlomi sprendimai vertinami pagal energijos poreikio ir nuostolių scenarijus, bendrą sistemos efektyvumą bei pirminės energijos faktoriaus (PEF) skaičiavimus. Galutinis vertinimas apima techninę ir ekonominę analizę, poveikio aplinkai vertinimą bei jautrumo analizę.

Tyrimas baigiamas strateginėmis rekomendacijomis, kaip Salininkų CŠT tinklą transformuoti į modernią, tvarią ir atsparią šildymo sistemą, galinčią tapti pavyzdžiu panašiems centralizuoto šilumos tiekimo tinklams šalto klimato Europos miestuose.

Darbas, be įvado, susideda iš septynių dalių: problemos ir aktualumo pristatymo bei suformulavimo, tvarios modernizacijos koncepcijos kūrimo, literatūros apžvalgos, metodologijos, rezultatų, diskusijos, išvadų bei rekomendacijų, ir bibliografinių šaltinių.

Darbą sudaro 100 puslapių pagrindinio teksto, 49 paveikslai, 7 lentelės, 8 lygtys ir 86 bibliografiniai šaltiniai. Priedas pateikiamas atskirai



**Prasminiai žodžiai:** Centralizuoto šilumos tiekimo tinklas, ketvirtosios kartos centralizuotas šildymas, šilumos siurblio integracija į CŠT, šiluminės energijos kaupimo integracija į CŠT, energetinis perėjimas, tvarus šildymas, Salininkų CŠT, saulės fotovoltinės energijos integracija į CŠT

**CONSENT TO THE USE OF PERSONAL DATA**

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(Date)

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# VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Abu Muhammad Mustakim Reza, 20234214

Faculty of Environmental Engineering

Building Energy Engineering Study Program (State Code 6211EX059)

## DECLARATION OF AUTHORSHIP IN FINAL DEGREE PROJECT

2025 May 20

I confirm that my final degree project, which topic is "**An Investigation of Sustainable Modernization Options for the Salininkai District Heating System**" is written independently. The material presented in this final degree project is not plagiarized. Quotations from other sources used directly or indirectly are indicated in the literature references.

The final degree project is inspected by **Assoc. Dr. Juozas Bielskus**.

| | |
|---|---|
| | Abu Muhammad Mustakim Reza |
| Signature | Name & Surname |

Vilnius, 2025

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## List of Abbreviation and Symbol (English)

*4GDH – $4^{th}$ Generation District Heating*
*4G-LTDHN – $4^{th}$ Generation Low Temperature District Heating Network*
*ABS – Acrylonitrile Butadiene Styrene*
*ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers*
*COP – Coefficient of Performance*
*DHW – Domestic Hot Water*
*EIA – Environmental Impact Assessment*
*EU – European Union*
*GHG – Greenhouse Gas*
*GWP – Global Warming Potential*
*HP – Heat Pump*
*IEA – International Energy Agency*
*ISO – International Organization for Standardization*
*kWh – Kilowatt Hour*
*LCA – Life Cycle Assessment*
*LT – Low Temperature*
*MJ – Megajoule*
*NG – Natural Gas*
*PEF – Primary Energy Factor*
*PV – Photovoltaic*
*R-134a – Tetrafluoroethane Refrigerant*
*TES – Thermal Energy Storage*

## List of Abbreviation and Symbol (Lithuanian)

*4GDH – Ketvirtosios kartos centralizuoto šilumos tiekimo sistema*
*4G-LTDHN – Ketvirtosios kartos žemos temperatūros centralizuoto šilumos tiekimo tinklas*
*ABS – Akrilonitrilo butadieno stirenas*
*ASHRAE – Amerikos šildymo, vėdinimo, oro kondicionavimo ir šaldymo inžinierių draugija (American Society of Heating, Refrigerating and Air-Conditioning Engineers)*
*COP – Naudingumo koeficientas (Coefficient of Performance)*
*DHW – Karštas buitinis vanduo (Domestic Hot Water)*
*EIA – Poveikio aplinkai vertinimas (Environmental Impact Assessment)*
*ES – Europos Sąjunga (European Union)*
*ŠESD – Šiltnamio efektą sukeliančios dujos (Greenhouse Gas – GHG)*
*GWP – Pasaulinis atšilimo potencialas (Global Warming Potential)*
*ŠP – Šilumos siurblys (Heat Pump)*
*TNA – Tarptautinė energetikos agentūra (International Energy Agency – IEA)*
*ISO – Tarptautinė standartizacijos organizacija*
*kWh – Kilovatvalandė*
*GVĮ – Gyvavimo ciklo vertinimas (Life Cycle Assessment – LCA)*
*ŽT – Žema temperatūra (Low Temperature)*
*MJ – Megadžaulis*
*GD – Gamtinės dujos (Natural Gas – NG)*
*PEF – Pirminės energijos faktorius (Primary Energy Factor)*
*SP – Saulės fotovoltinė sistema (Photovoltaic – PV)*
*R-134a – Tetrafliuoretanas (šaldymo agentas)*
*ŠES – Šiluminės energijos kaupimas (Thermal Energy Storage – TES)*

# Introduction

District heating (DH) systems have long been integral to Lithuania's energy infrastructure, providing centralized thermal energy to urban populations in a climate where heating is a vital necessity. The country's first DH installation was established in June 1939 at the Vytautas Magnus University Medical Campus in Kaunas, marking Lithuania's initial step toward centralized heating (Lukoševičius, 2019). Since then, DH systems have evolved significantly, adapting to changing technological, economic, and political landscapes.

Following independence from the Soviet Union, Lithuania faced an urgent need to modernize its energy systems, many of which were heavily reliant on imported fossil fuels, particularly natural gas from Russia (Nugent, 2022). Energy security became a national priority, prompting an ambitious transition toward renewable energy sources. One of the most striking examples of this transformation occurred in the DH sector: the share of biomass in district heat generation rose dramatically from just 2% in 2004 to around 68% by 2018 (LDHA, 2019). This transition not only decreased foreign energy dependence but also positioned Lithuania as a leader in renewable integration within the heating sector across the EU.

Despite such progress, persistent challenges hinder the full realization of an efficient, low-carbon DH infrastructure. Approximately 60% of Lithuania's population is connected to DH networks, many of which suffer from aging infrastructure, elevated distribution losses, and outdated control systems (LDHA, 2021). In Vilnius, the capital, substantial investments between 2002 and 2017 succeeded in reducing heat losses from 24% to 12%—a performance now comparable to Scandinavian benchmarks (Vilniaus Energija, 2025). However, these gains remain concentrated in core districts, with suburban and peri-urban zones lagging in modernization and efficiency.

The urgency for efficient heating systems is further underscored by Lithuania's harsh winters. From December through mid-March, average daytime temperatures in Vilnius typically range from -5°C to -10°C, with frequent snow cover and limited daylight hours (SeasonsYear.com, 2025; Weather Underground, 2025). In such conditions, uninterrupted and energy-efficient heating becomes essential to safeguard public health and quality of life. This makes the modernization of DH systems not just a technical imperative but a societal necessity.

The Salininkai district, located in the southern suburban area of Vilnius, exemplifies both the typical challenges and the untapped opportunities in decentralized DH modernization. Originally a sparsely populated suburb, Salininkai has experienced rapid urban development in recent years, leading to a growing and more diversified thermal energy demand. The district's DH network is primarily powered by two 4.7 MW natural gas boilers, each operating at approximately 85% efficiency. While the system currently supplies heat to a mix of residential buildings, a kindergarten, a supermarket, and several small businesses, its design—featuring a centralized heat source positioned at one corner of the network—contributes significantly to thermal losses. These are further compounded by the low energy efficiency of the receiving buildings, many of which fall into poor energy classes (F or G), and continue to rely on outdated cast iron radiator systems.

In light of these challenges, this study seeks to determine whether the Salininkai District Heating Network can be considered sustainable in its current form and, if not, what technological and operational improvements are needed to transition it toward long-term sustainability. Based on billing data from 2021 and 2022, the system has a reported annual heating demand of approximately 12 GWh. To improve system performance and reduce its dependency on fossil fuels, the local authority has outlined a modernization plan involving the integration of renewable energy sources and energy storage solutions. In alignment with standard 4G-LTDHN, proposed interventions include the installation of electric air-to-water heat pump, addition of a seasonal thermal energy storage (TES) system, and the establishment of a solar photovoltaic (PV) park to support electricity demand for the heat pump. These measures aim to improve overall system efficiency, reduce primary energy consumption, and enhance supply reliability.

In addition, the study explores spatial optimization strategies such as relocating the primary heat source to a more central position within the network and evaluating the feasibility of splitting the network into two segments, each with its own production or storage capacity, connected by a transmission line. These options aim to minimize distribution losses and adapt the network architecture to changing demand patterns.

To assess the technical, economic, and environmental viability of these proposed solutions, the study employs the EnergyPRO software suite. This professional-grade modeling tool enables simulation of multiple operating scenarios, loss quantification, and sensitivity analysis of each intervention. The outcomes will offer a data-driven basis for policy and investment decisions, not only for Salininkai but also for other similar networks across Lithuania and the Baltic region.

In summary, this research aims to explore sustainable modernization pathways for the Salininkai DHN through a comprehensive technical, economic and environmental evaluation. The following key objectives have been identified to guide the study:

- Analyze and interpret the operational and demand-side data of the existing network.
- Use professional simulation tools (EnergyPRO) to assess current performance and identify inefficiencies.
- Explore the technical feasibility and benefits of integrating renewable energy technologies, such as heat pumps, TES, and solar PV systems.
- Examine the potential for decentralizing the network by dividing it into two segments.
- Evaluate proposed solutions from multiple perspectives: technical feasibility, economic efficiency, environmental impact, and sensitivity to changing conditions.
- Develop a monitoring dashboard to track and visualize the system's sustainability index across various stages of intervention.
- Generate a set of actionable recommendations for achieving a more sustainable, resilient, and future-ready district heating network.

Through this structured approach, the study aims not only to optimize the performance of the Salininkai DHN but also to contribute to Lithuania's broader objectives for energy transition, decarbonization, and urban sustainability.

# 1. Relevance, current status and problem statement

In the context of the European Union's climate targets and Lithuania's national energy strategies, improving the efficiency of existing district heating networks is not only desirable but essential. The Salininkai district heating network in Vilnius represents a typical case of an older, conventional DHS that has not undergone significant modernization in recent decades. Studying and improving this network can provide actionable insights for policymakers, utility companies, and engineers to support the broader transition to sustainable and smart energy systems.

## 1.1 Relevance and importance of the study

Lithuania's energy sector has undergone significant transformation since regaining independence in 1990. One of the country's primary goals has been to reduce dependency on imported fossil fuels, particularly natural gas from non-EU countries. Historically, Lithuania was almost entirely reliant on Russian gas for heat and electricity generation, making its energy system vulnerable to geopolitical risks. In response, Lithuania initiated a strategic shift towards renewable energy sources (RES) to enhance its energy independence, security, and sustainability (IEA, 2021).

The district heating (DH) sector, which supplies over 60% of households with thermal energy, has been one of the central focuses of this transition. Although natural gas still accounts for a sizable portion of heat production, the integration of biomass, solar thermal, and heat pumps has grown rapidly in recent years. According to the Lithuanian District Heating Association, the share of biomass in DH rose from just 2% in 2004 to approximately 68% by 2018, marking one of the most successful renewable transitions in the Baltic region (LDHA, 2019). This transformation not only diversifies energy sources but also significantly reduces greenhouse gas (GHG) emissions and aligns with EU decarbonization targets under the European Green Deal.

In addition to environmental benefits, the shift to renewables in heating systems brings substantial economic advantages. Locally sourced biomass and renewable electricity reduce the outflow of capital and support domestic industries, such as forestry and clean energy technology providers. Furthermore, renewable-based DH systems can offer more stable and predictable prices compared to fossil fuel-based systems, which are extremely sensitive to global market fluctuations (European Commission, 2020b). As global natural gas prices have become increasingly volatile due to supply chain disruptions and geopolitical conflicts, renewable heating technologies provide a more resilient and cost-effective alternative for long-term planning.

Moreover, the transition to renewables is vital for meeting Lithuania's national climate commitments. Under its National Energy and Climate Plan (NECP), Lithuania aims to achieve at least 45% of energy from RES in its final energy consumption by 2030, with the heating sector playing a pivotal role in this objective (Ministry of Energy of the Republic of Lithuania, 2019). Converting fossil fuel-based systems, especially legacy district heating networks like Salininkai, into hybrid or fully renewable systems is essential to reach these goals. Technologies such as electric heat pumps, solar PV, and seasonal thermal storage offer scalable solutions that can be tailored to local demand patterns and infrastructure constraints.

In conclusion, transitioning fossil fuel-based heating systems to renewable energy in Lithuania is not only a necessity from an environmental and energy security standpoint but also a strategic move toward economic resilience and policy compliance. Continued investment, smart planning, and innovation in system design and operation are crucial for accelerating this transformation and ensuring a just, efficient, and sustainable energy future.

## 1.2 Salininkai DHN – existing system and available dataset

The current configuration of the Salininkai DH network consists of two 4.7 MW gas-fired boilers operating at around 85% efficiency, situated at one corner of the network. This layout leads to uneven heat distribution and significant transmission losses, especially to buildings located farther from the heat source. The system supplies approximately 12 GWh of thermal energy per year to a variety of consumers, including residential apartments, commercial facilities, and educational institutions. The majority of buildings connected to the system fall within low energy performance categories (D to G), indicating high heat demand and poor thermal insulation. In recent years, there has been a gradual improvement in operational performance; however, the system still suffers from seasonal inefficiencies, high peak-to-off-peak disparities, and outdated thermal infrastructure.

### *1.2.1 Existing DH system in Salininkai*

The map of the existing system is presented below (Figure 1). As mentioned earlier, existing system consists of two natural-gas driven boilers and these boilers' location is marked as the red triangle in the map. The lines represent transmission and distribution systems, and the small dots represent the end user connections.

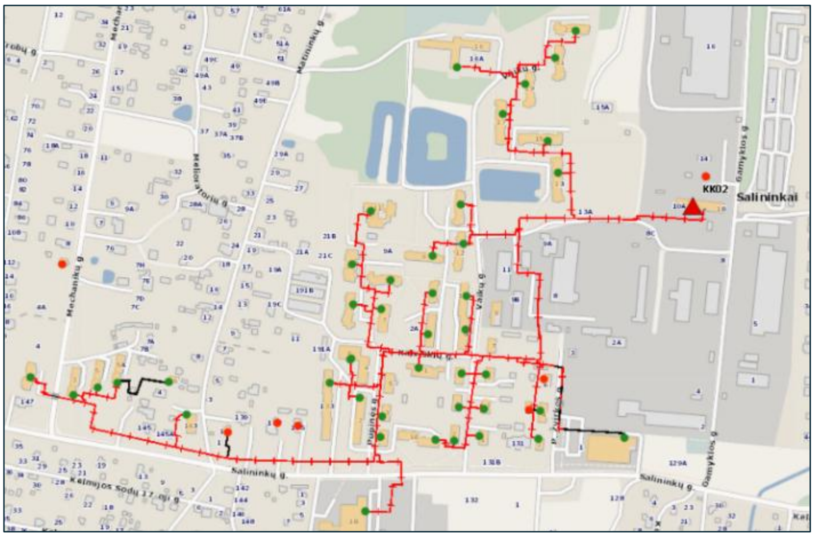


*Figure 1. Map of Salininkai District Heating Network*

### *1.2.2 Available dataset of the existing system (baseline system)*

The analysis benefits from a robust and comprehensive dataset covering both production-side and demand-side metrics. The following data points are available:

- Hourly heating demand data for the full year of 2021 at the heat generation point including distribution loss blended with space heating demand and DHW demand.
- Hourly outdoor temperature data corresponds to the same time period.

- Supply and return water temperature setpoints (ranging from 67°C to 90°C and 45°C to 60°C, respectively) linked to outdoor temperatures.
- Annual distribution losses for the years 2018, 2019, and 2020.
- Individual building-level heat consumption data for all 46 connected buildings.
- GIS-based spatial layout of the district heating network locating the central heat generation point, transmission & distribution lines and end user connection point.

This dataset allows for granular simulation of network behavior under different weather conditions, demand scenarios, and infrastructure setups. It also supports the calculation of key performance indicators such as system efficiency, loss percentages, and primary energy factors. Together, these data inputs provide a solid foundation for the EnergyPRO modeling and for generating realistic, data-driven modernization strategies.

## 1.3 Identification of key problems from available dataset

Although the Salininkai District Heating Network (DHN) is relatively insignificant compared to major urban DH systems, it exhibits many of the complex characteristics typical of low-temperature networks. The system supplies a variety of building types—residential, educational, and commercial—each with distinct energy consumption patterns and varying energy performance classifications. These buildings span across multiple energy classes, including several in the lower efficiency range (D to G), contributing to significant variation in thermal demand and loss behavior. The distribution network itself is a mix of older and newer pipeline segments, which likely results in inconsistent heat loss parameters across the system. Additionally, the heat exchangers in use may differ in material composition and functional design—some operating with automated regulators, while others rely on manual control or outdated technologies.

To better understand the existing inefficiencies, the available dataset was initially analyzed using Microsoft Excel. This allowed for the organization, visualization, and interpretation of key operational data such as hourly heat demand, temperature fluctuations, and loss metrics. Through this analysis, several critical problem areas were identified, which are further categorized and discussed in the subsequent sections.

### *1.3.1 Demand vs production and outdoor temperature*

Analyzing the variation between heat production and actual demand across the district heating network from 1st January 2021 to 31st December 2021. Investigating whether the heat production units' capacity is optimized for peak and off-peak demand periods and recommending strategies to minimize production inefficiencies.

The analysis reveals the monthly heating demand and production dynamics of the Salininkai District Heating Network across 2021. The total heating demand for the year was 11,711 MWh, while the heating production was 13,265 MWh, resulting in a total loss of 1,554 MWh or 11.71%. Loss percentages varied across the months, primarily influenced by outdoor temperature changes and distribution inefficiencies. The highest demand occurred in January (1,830 MWh) and December (1,788 MWh) due to colder outdoor temperatures, while the lowest demand was in July (249 MWh) during peak summer which was due to DHW. Monthly production exceeded demand in all months, with the largest production in January (1,993 MWh) and the lowest in July (339 MWh). The annual difference between production and demand indicates the extent of heat loss in the network, highlighting inefficiencies that should be addressed. The following figure (Figure 2) represents Demand Vs Production and Impact of Outdoor Temperature. It is also revealed that, during heating season average demand was 2.17 MW and during non-heating season average demand was 0.54 MW.

Outdoor temperatures directly influenced heat demand. The colder months (January, February, November, and December) had the highest heating requirements, correlating with outdoor temperatures averaging below 5°C. Losses were highest during the warmer months, peaking in June (28.20%) and

July (26.48%), primarily due to lower heat demand and reduced system efficiency during periods of minimal operation.

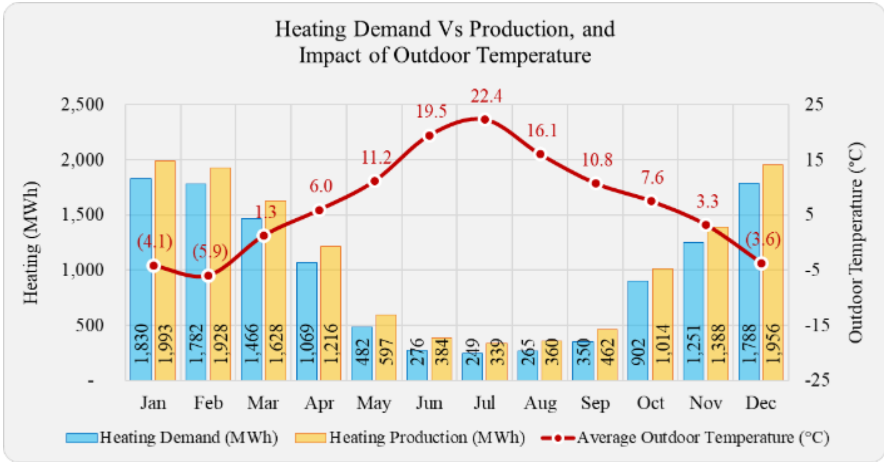


*Figure 2. Baseline System - Demand Vs Production*

During transitional months (e.g., March, April, October), heat losses decreased as the balance between demand and production improved, leading to better system efficiency. The following figure (Figure 3) represents the impact of outdoor temperature on monthly loss distribution.

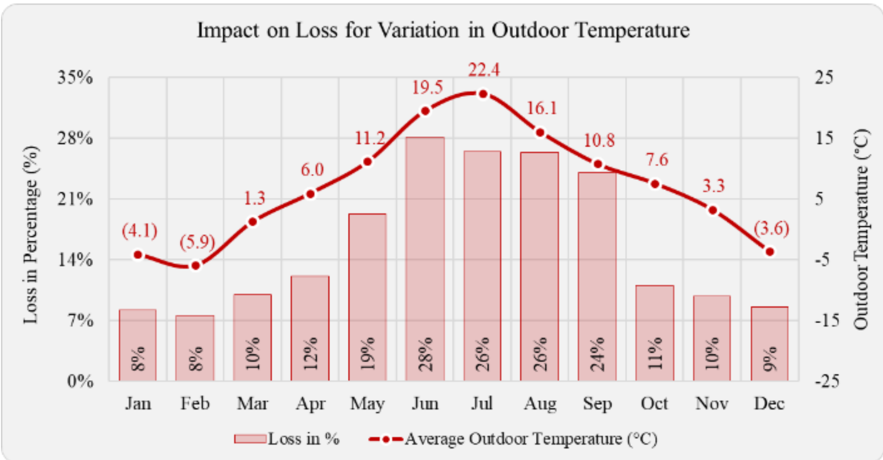


*Figure 3. Monthly Loss (2021) Variation with Outdoor Temperature*

An analysis of the Salininkai District Heating Network's monthly performance, as illustrated in Figure 3, reveals a notable trend: the percentage of heat loss is significantly higher during the summer months—exceeding average value with a peak at 22.4% in June, 19.5% in July, and 16.1% in August—despite an overall reduction in heating production and demand. This counterintuitive pattern is primarily due to the disproportionately low thermal energy demand during the summer, when space heating is largely inactive and the system operates mainly to meet domestic hot water (DHW) requirements. While the absolute value of thermal losses may not vary drastically throughout the year, these base losses represent a much larger fraction of the total energy delivered when the demand is low. For instance, a fixed distribution loss of 200 MWh constitutes only a small portion of winter production but becomes a dominant share when summer demand drops to around 300–400 MWh.

Furthermore, the system's operational efficiency tends to decline at partial load conditions common in warmer months. Boilers and circulation pumps, typically optimized for higher loads, may cycle frequently at lower loads, resulting in energy waste and reduced efficiency. Additionally, due to the extended length of the Salininkai network, maintaining continuous hot water circulation over long pipelines for a limited number of consumers leads to high relative heat losses. Compounding this issue, many older district heating systems lack advanced control mechanisms that can modulate supply temperatures or flow rates based on real-time demand. Consequently, the system may continue operating at unnecessarily hot temperatures, producing more heat than needed and increasing standby and transmission losses.

In summary, the elevated summer loss percentages are not caused by increased absolute losses but rather by a reduction in demand that magnifies the relative impact of baseline inefficiencies. This highlights the need for demand-responsive control strategies, seasonal operation adjustments, localized DHW production through heat pumps, and improved thermal storage solutions to enhance the system's year-round efficiency.

This analysis underscores the strong correlation between heating demand, outdoor temperature, and system performance, emphasizing the need for optimization measures, particularly during periods of low demand, to reduce energy losses and enhance overall efficiency.

### *1.3.2 Distribution losses*

The analysis of the Salininkai District Heating Network (DHN) reveals a consistent reduction in heat loss percentages over four years, from 2018 to 2021, indicating gradual improvements in system efficiency. The following figure (Figure 4) demonstrates the yearly loss in percentage against demand in MWh.

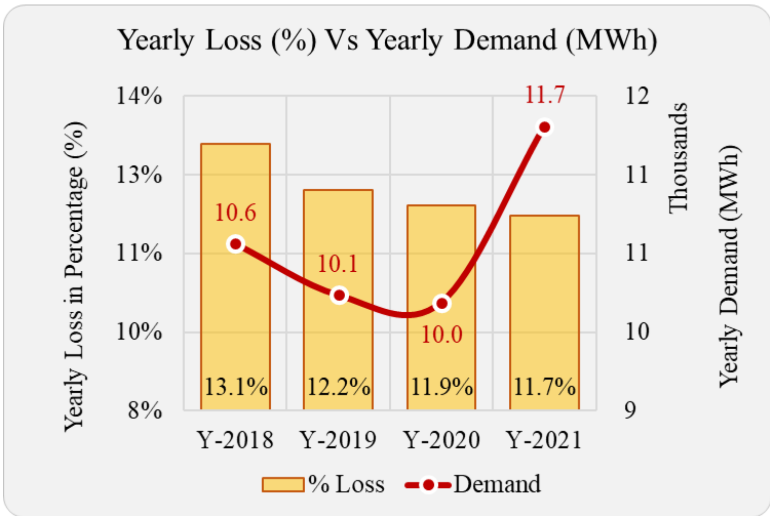


*Figure 4. Yearly Trend of Loss and Demand (2018-2021)*

In 2018, the network experienced a loss of 13.1% with a heating demand of 10,6 GWh. By 2019, the loss was reduced to 12.2%, with a slightly lower demand of 10,1 GWh. In 2020, the loss further decreased to 11.9%, correlating with a demand of 10,0 GWh. In 2021, the loss percentage dropped to its lowest at 11.7%, while the heating demand increased significantly to 11,7 GWh. This downward trend in percentage loss demonstrates incremental improvements in operational efficiency and reduced distribution losses over time.

The rise in demand in 2021, coupled with a reduction in loss percentage, suggests that operational adjustments and infrastructure improvements have positively influenced network efficiency. The yearly improvement in loss percentages is a positive indicator of enhanced DHN performance. However, with growing demand, further optimization is necessary to minimize losses and achieve energy efficiency goals, particularly in addressing long-distance transmission inefficiencies and the aging infrastructure serving poor energy-class buildings.

### *1.3.3 Space heating Vs DHW demand*

Seasonal heating demand varies significantly, with peak demand occurring in January (1,830 MWh) and December (1,788 MWh), primarily due to colder temperatures. Hot water demand (DHW) remains relatively constant throughout the year, contributing 3,423 MWh annually, while space heating accounts for the majority of demand variability. During summer months (June to August), heating demand is negligible, but DHW demand sustains system operations. The following figure (Figure 5) represents monthly demand for space heating and DHW in MWh.

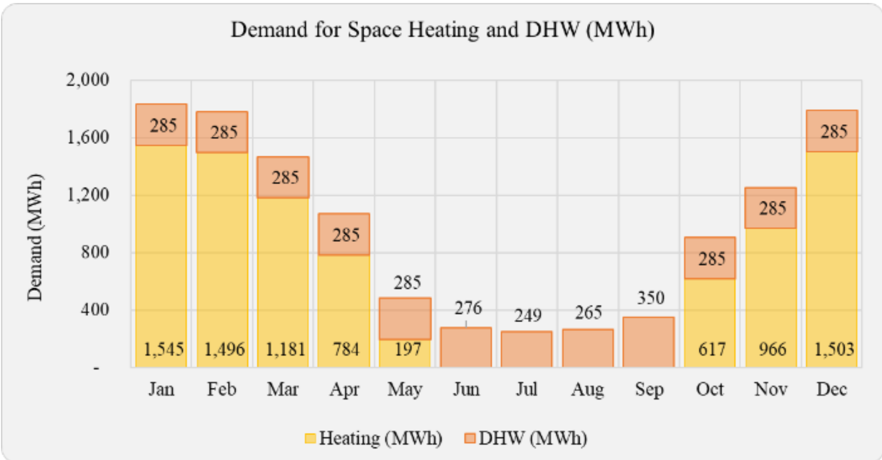


*Figure 5. Segregation of Demand - Space Heating and DHW (2021)*

This is to note that, demand for DHW for non-heating season is specifically picked from the billing data and averaged for the rest of the months to calculate heating demand for space heating. While the percentage loss is decreasing, absolute heat loss remains substantial, especially during high-demand months. This underlines the critical impact of transmission inefficiencies on overall system performance.

### *1.3.4 Long distribution network*

Examining the impact of the long-distance heat distribution on system performance, especially heat losses and pressure drops. Investigating the feasibility of dividing the network into two sections with a new transmission line to optimize heat distribution. From provided data and using GIS technology (Yandex, 2025), distance to source from every user can be measured. From the Fig-1 as presented above, the most distant point can be identified as, “Mechanikų g. 2” which is around 1.38 km far. The following figure (Figure 6) represents the approximate distance between the building and the heat production unit.


*Figure 6. Longest Distribution Length of the Salininkai DHN*

### *1.3.5 Energy signature - building level energy efficiency*

An Energy Signature (Eriksson et al., 2020) is a graphical representation that shows the relationship between a building's heating energy consumption and the corresponding outdoor temperature over a given period—typically a year. It helps visualize how heating demand changes with climatic conditions and provides insight into a building’s thermal performance. The energy signature is typically plotted by placing outdoor temperature on the x-axis and heating energy consumption (monthly or hourly) on the y-axis. A trend line, often linear for simplicity, is then fitted to the data points to show the overall correlation. The steepness of the slope indicates how sensitive the building's heating demand is to temperature changes—steeper slopes suggest higher energy loss and poor insulation. This method is widely used in energy audits and demand-side assessments to identify inefficiencies and prioritize buildings for retrofit or energy-saving interventions.

Investigating energy demand patterns of individual buildings, particularly those with low energy efficiency (F and G energy class). Analyzing their contribution to overall heat demand and recommending solutions for retrofitting or upgrading these buildings to reduce energy consumption. There are 46 buildings connected to this district heating network which are of different energy classes and among them 44 buildings consume energy from this network.

Their energy consumption varies from around 13 to 718 MWh including both space heating and DHW.

If the energy signature of the top five contributors of this network is plotted, it looks like follows (Figure 7)-

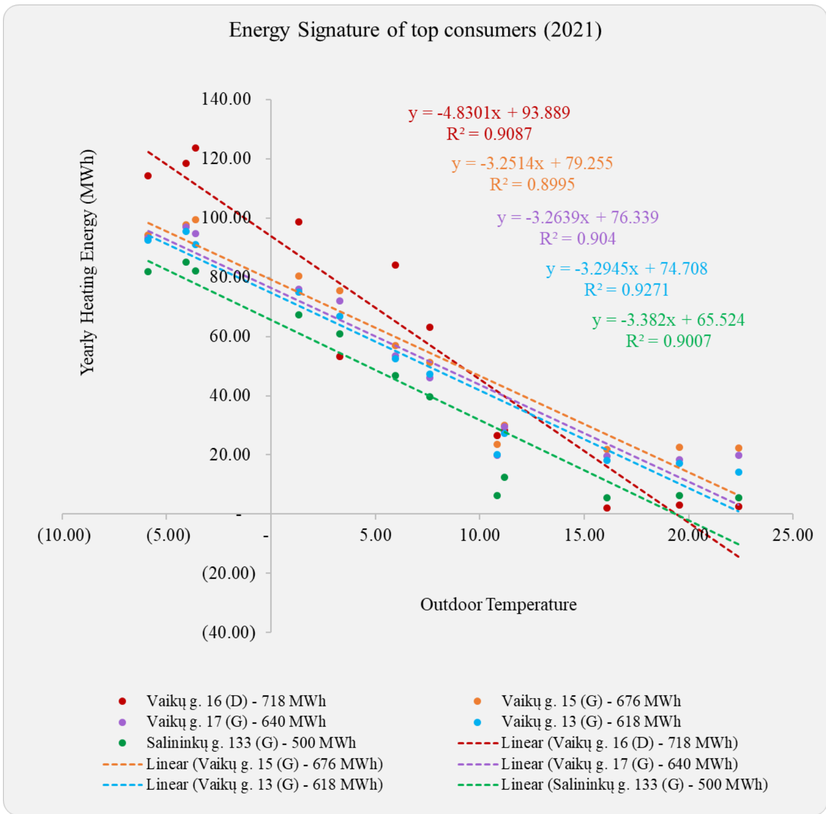


*Figure 7. Energy Signature of Top 5 Contributors (2021)*

Figure 7 presents the energy signatures of the top five heat-consuming buildings in the Salininkai District Heating Network for the year 2021, now enhanced with linear regression equations and $R^2$ values for each building. The equations describe the relationship between outdoor temperature (°C) and monthly heating energy consumption (MWh). Each equation follows the form $y = mx + c$, where the slope (m) indicates how sensitive the building's heating demand is to changes in outdoor temperature. The steepest slope is observed for Vaikų g. 16 (D class) with –4.8301, meaning its energy demand drops rapidly as temperature rises—highlighting poor insulation or high thermal losses. In comparison, Salininkų g. 133 (G class) has a less steep slope of –3.382, indicating a relatively lower temperature sensitivity and potentially better heat retention despite being in a lower energy class.

The $R^2$ values, ranging from 0.8995 to 0.9271, indicate extraordinarily strong correlations between outdoor temperature and heating demand, confirming that space heating dominates the energy consumption profile of these buildings. Vaikų g. 13, with an $R^2$ of 0.9271, exhibits the best fit, suggesting consistent and predictable heating behavior relative to outdoor temperature. These trendlines and statistical parameters reveal not only the total energy use but also the efficiency characteristics of each building. High consumption combined with a steep slope (e.g., Vaikų g. 16) flags buildings as ideal candidates for energy retrofits, while flatter slopes may suggest buildings with either partial efficiency improvements or lower thermal demand.

### *1.3.6 The problem statement*

Based on the analysis above, with the help of available data set and Microsoft Excel, we can state the problem statement as below:

"*The Salininkai District Heating Network, currently dependent on fossil fuels, faces operational inefficiencies from seasonal and distribution losses exceeding 22%, extended pipeline distances, and poor building-level energy performance, and it remains unclear whether the system is operating sustainably highlighting the need for a detailed assessment and modernization strategy.*"

In summary, the assessment of the current performance of the Salininkai District Heating Network has revealed multiple challenges related to heat loss, fossil fuel dependency, uneven demand distribution, and poor energy efficiency at the consumer level. When benchmarked against the principles of 4th Generation Low-Temperature District Heating Networks (4G-LTDHN), the system shows several critical gaps that hinder its transition toward sustainability. Addressing these deficiencies is essential for aligning the network with national energy goals and ensuring long-term operational efficiency. Therefore, in the subsequent sections of this document, focused attention will be given to evaluating technical, economic, and environmental solutions to guide the sustainable modernization of the Salininkai DHN.

## 2. Concept development and goal of the study

To determine the sustainability and future viability of the Salininkai District Heating Network (DHN), it is essential to benchmark its current operational performance against recognized international standards. The concept of $4^{th}$ Generation District Heating Networks (4G-LTDHN) represents a modern and sustainable approach to district energy systems, focusing on low-temperature operation, integration of renewable and surplus heat sources, improved efficiency, and intelligent control (Lund et al., 2014a). These systems are designed not only to reduce carbon emissions and energy waste but also to support sector coupling with electricity, cooling, and mobility infrastructures in the context of future smart energy systems.

Given the current challenges in Salininkai—including high fossil fuel dependency, fluctuating seasonal losses, and building-level inefficiencies—it is imperative to assess whether the existing system aligns with the core principles of 4G-LTDHN (Schmidt et al., 2017a). These principles emphasize low return temperatures, minimized heat losses, flexible integration of renewable energy sources (such as solar thermal and heat pumps), and advanced control systems capable of optimizing performance under varying demand profiles.

This chapter aims to map the operational parameters of the Salininkai DHN against the technical, environmental, and strategic criteria outlined for 4G-LTDHN, using both simulation outputs and available empirical data. Based on this comparative analysis, a set of goals will be defined to guide the sustainable transformation of the network. This includes determining temperature setpoints, distribution losses, primary energy factors, and evaluating readiness for renewable integration. The outcome will serve as a foundational benchmark for designing interventions and setting realistic, performance-based modernization targets.

### 2.1 Benchmarking with 4G-LTDHN – a sustainability concept development

To identify specific areas for improvement in the Salininkai District Heating Network, the following table (Table 1) presents a comparison between the key features of 4th Generation District Heating Networks (4G-LTDHN) and the current state of the Salininkai system, highlighting critical gaps and their relevance to planned modernization efforts.

*Table 1. Benchmarking of Baseline System with a Sustainable 4G-LTDHN*

| Feature | Description | Relevance to Salininkai DHN | Reference |
|---|---|---|---|
| **Low-Temperature Operation** | Supply ≤ 55°C, Return ≤ 25–30°C to reduce losses and enable renewable integration | Current supply (67–90°C) and return (45–60°C) temperatures are too high; need adjustment to enable efficient, low-exergy operation | (Lund et al., 2014a) |
| **Renewable Energy Integration** | Supports solar thermal, geothermal, heat pumps, and waste heat | Proposed addition of air-to-water heat pumps and a solar PV park directly supports this principle | (David et al., 2017) |
| **Thermal Energy Storage (TES)** | Short- and long-term storage enhances flexibility, renewable use, and peak load management | Proposed seasonal TES will help balance loads, reduce reliance on fossil fuels, and optimize system operation | (Schmidt et al., 2017a) |
| **Smart System Operation & Control** | Real-time demand management, weather-based forecasting, and intelligent flow temperature adjustment | The current system lacks advanced control and metering; high losses in summer show the need for automated, adaptive operation | (Pirouti et al., 2013) |
| **Sector Coupling** | Integration with electricity (heat pumps, solar PV), mobility (EVs), and cooling | Planned PV-powered heat pump is an example of electricity-heat coupling and paves the way for multi-energy integration | (Lund et al., 2014a) |
| **Compatibility with Energy-Efficient Buildings** | Designed for nearly zero energy building and low-demand buildings with balanced indoor comfort | Existing buildings are mostly low energy class (D–G); coordinated retrofitting is needed to reduce load and improve system-wide efficiency | (Persson & Werner, 2011) |

This comparison clearly illustrates that while the Salininkai DHN demonstrates the foundational structure of a centralized heating system, it falls short of meeting several essential 4G-LTDHN standards. These gaps serve as focal points for strategic interventions in the upcoming sections, where targeted technical and operational solutions will be explored to enable a sustainable transition of the network.

## 2.2 Sustainability indexing of baseline system (measuring PEF value)

A comprehensive understanding of the current energy performance of the Salininkai District Heating Network (DHN) is a critical prerequisite for planning sustainable modernization. The existing system, powered by two 4.7 MW natural gas boilers, requires careful evaluation in terms of primary energy consumption, overall operational efficiency, and Primary Energy Factor (PEF). The PEF serves as a key sustainability indexing measure, reflecting the environmental and resource-related efficiency of the system (Lund et al., 2014a). By calculating the energy input required to meet the annual heat demand of approximately 12 GWh and analyzing the efficiency losses across production and distribution, this study will identify the baseline against which future improvements can be measured. This performance benchmarking will serve as a foundation for assessing the necessity and potential of operational and technological interventions aimed at decarbonization and efficiency enhancement.

## 2.3 Integration of renewable technologies and seasonal thermal storage

In line with the transition toward 4th Generation District Heating (4G-DHN) systems, the proposed integration of renewable energy sources (RES) and thermal energy storage (TES) represents a key strategic pivot for Salininkai DHN. As proposed by the Salininkai DH Authority, the inclusion of a 1 MW electric air-to-water heat pump and a 3,000 m³ TES tank is expected to enable flexible load balancing and reduce dependency on fossil fuel-based heat generation. However, in the later sections of the study, justification of the proposed capacity of HP and TES will be derived. This intervention is projected to lower the network's primary energy requirement, improve overall system efficiency, and yield a more favorable PEF, thereby enhancing the environmental sustainability of the system (David et al., 2017).

Furthermore, the feasibility of incorporating a solar photovoltaic (PV) park with appropriate capacity will be evaluated to examine the benefits of electricity-heat sector coupling and increased renewable penetration. Such integration supports the strategic goals outlined in the European Union Energy Performance of Buildings Directive (EPBD) and Lithuania's National Energy and Climate Plan (NECP), which emphasize increased reliance on renewables in thermal energy systems (European Commission, 2020a).

## 2.4 Dynamic heat demand prediction and load balancing

Another crucial aspect of this investigation is the application of dynamic heat demand modeling and load balancing techniques. By analyzing hourly heat demand data from 2021, this study will develop a predictive model to better understand seasonal and intraday demand fluctuations. Accurate demand forecasting enables the optimization of heat production schedules and distribution strategies, significantly reducing system-level energy waste. Load balancing—particularly during low-demand periods—will be explored to improve boiler modulation, minimize cycling losses, and support integration of intermittent RES such as solar PV (Pirouti et al., 2013).

## 2.5 Environmental impact and economic model assessment

The study also undertakes a thorough environmental and economic impact assessment of the current system versus potential upgraded configurations. Carbon emissions associated with natural gas combustion will be quantified and compared with emissions reductions achievable through RES integration and TES. Primarily, environmental benefits will be evaluated through partial Life Cycle Assessment (LCA) by assessing $CO^2$ emission in some major phases. Further environmental assessments like a full-scale LCA or similar frameworks, will support a holistic view of system sustainability (Schmidt et al., 2017a).

Additionally, an OpEx comparison analysis will be conducted to evaluate operational cost savings, and long-term economic feasibility of interventions such as heat pump installation, TES, network reconfiguration, etc. Cost-benefit analysis, exploring different financial tools like LCCA, CBA, NPV, IRR, ROI, etc. can also be explored for further assessments. This will assist decision-makers in prioritizing investments based on both economic return and environmental benefit.

## 2.6 Modeling, sensitivity analysis and other factors

Currently, the Salininkai network relies solely on natural gas boilers for supplying heat and hot water, presenting an opportunity to significantly reduce fossil fuel dependency by integrating renewable alternatives. The proposed modernization strategy includes pairing the 1 MW heat pump with TES and solar PV infrastructure to diversify energy inputs, reduce peak-load boiler usage, and improve long-term system resilience. Shifting the heating source to a more central location or creating decentralized sub-networks is also under consideration to address high distribution losses in the extended pipeline. The use of advanced simulation software, such as EnergyPRO, will allow the modeling of heat flow, energy balance, and emissions under different operational scenarios, guiding the study toward evidence-based solutions (EMD International, 2018).

In summary, this phase of the study aims to critically assess whether the current Salininkai DHN is operating sustainably and how proposed interventions influence its technical, economic, and environmental performance. By simulating the existing and modified scenarios—including RES integration, TES deployment, and network segmentation—the study will evaluate the system's adaptability, efficiency, and carbon footprint. A detailed sensitivity analysis will also be conducted to evaluate the robustness of each solution under varying demand and pricing conditions; however, particular focus will be given on recent climate forecasts. These insights will form the basis for a comprehensive modernization roadmap, supporting the transition of the Salininkai DHN into a future-proof, low-carbon, and smart thermal energy system, in alignment with 4G-DHN principles (Lund et al., 2014a; Pirouti et al., 2013; Schmidt et al., 2017a).

## 2.7 Aim and objective of the study

The study aims to evaluate the current state of the Salininkai District Heating Network (DHN) and propose renewable energy-based solutions to improve its efficiency, reduce environmental impact, and ensure long-term sustainability. It addresses key challenges like mismatches between heat production and demand, high distribution losses, inefficiencies in overall system as well as the older buildings, and suboptimal boiler performance. Not only that, through EnergyPRO simulation required primary energy, overall system efficiency and PEF can be measured which will indicate whether the system is working sustainably or not beside mentioning system performance. The network's reliance on fossil fuels and limited integration of renewable energy further reduces its sustainability.

Addressing the problem statement in earlier section, aim of this study can be stated as:

"*This study aims to assess the sustainability of the existing Salininkai District Heating Network by examining its energy performance, fossil fuel dependency, and distribution losses, while exploring the potential of renewable energy integration, thermal energy storage, and network optimization strategies—supported by comprehensive technical, economic, and environmental evaluations, and validated through critical sensitivity analysis.*."

These key objectives, stated in the **Introduction**, will prescribe a 4-factor driven recommendation set based upon the 4-stage investigation through the key objectives. The 4-stage investigation set is:

- Baseline: Two gas boilers
- Stage 1: Addition of 1 MW electric heat pump and 3,000 m³ TES
- Stage 2: Integration of 500 kWp PV solar park
- Stage 3: Segregation into dual-site network

And, the 4-factor evaluation parameter set is:

- Demand and loss metrics
- Primary energy requirements
- Overall system efficiency
- Primary Energy Factor (PEF) as a sustainability index

## 3. Literature review

Climate change stands as one of the most pressing global challenges, driven by the rising concentration of greenhouse gases (GHGs) in the atmosphere. The energy sector, as a major contributor to these emissions, is significantly impacted by fossil fuel-based heating systems, which exacerbate global warming (Masson-Delmotte et al., 2021). Addressing these challenges requires a shift from fossil fuels to renewable energy sources and substantial improvements in energy efficiency, particularly in urban heating systems (IEA, 2022).

District heating networks (DHNs) are a critical part of this transition, especially in colder regions where centralized heating provides a substantial portion of thermal energy to urban populations. However, aging infrastructure, heat transmission inefficiencies, and reliance on fossil fuels hinder their sustainability and adaptability for renewable energy integration (Ravindra & Iyer, 2014).

Lithuania, a Baltic nation characterized by long, cold winters, heavily depends on DHNs to meet its heating demands. Over 60% of Lithuanian households are connected to these systems, making them integral to the country's energy landscape (Ministry of Energy of the Republic of Lithuania, 2019; Official Statistics Portal of Lithuania, 2022). Despite their widespread use, many DHNs in Lithuania face inefficiencies due to outdated infrastructure and elevated temperatures required by older buildings with poor energy performance. These inefficiencies not only increase energy consumption and operational costs but also limit the integration of renewable technologies such as heat pumps, thermal storage systems, solar PV for powering heat pumps, and various energy-saving initiatives including building renovation and pipeline optimization, which function optimally at lower temperatures (Stock et al., 2024; Villalobos et al., 2019).

District heating systems have long been a cornerstone of energy distribution in urban areas, particularly in Baltic countries. By centralizing heat production and delivering it through insulated pipelines, these systems offer superior energy efficiency compared to decentralized systems. As highlighted by scholars (Dinçer & Rosen, 2010;

Liu et al., 2007; Pellegrini & Bianchini, 2018), DHNs reduce carbon emissions and benefit from economies of scale, enabling better integration of renewable energy sources and waste heat—key pathways for urban energy decarbonization.

The concept of 4th Generation District Heating Networks (4G-LTDHN) represents the future of thermal energy systems. These networks are characterized by ultra-low supply and return temperatures, full integration of renewable and low-exergy heat sources, thermal storage, smart digital controls, and building-level interaction for demand-side flexibility (Lund et al., 2014b). The transition to 4G-LTDHN supports sector coupling (electricity, mobility, and heating), better energy efficiency, and decarbonization goals set by the European Union.

Heat pumps, particularly air-to-water and ground-source systems, are critical for decarbonizing heat supply in 4G-DHNs. The capacity of a heat pump is typically calculated based on peak heat demand, outdoor temperature profiles, and coefficient of performance (COP), which can be adjusted dynamically based on local climate data and building load requirements. Proper sizing is essential to balance efficiency with capital costs. According to Lund et al. (2010), the integration of heat pumps can reduce natural gas use by up to 20% annually in existing DHNs.

Thermal Energy Storage (TES) plays a vital role in supporting the seasonal interim heat demand. Material selection for TES tanks depends on pressure, temperature durability, and storage duration—ranging from steel tanks for short-term daily storage to pit or borehole storages for seasonal applications. The required TES volume is calculated using the formula (Schmidt et al., 2017a):

$$Q = \rho . V . c_p . \Delta T \qquad (Eq. 1)$$

Here,

$Q = Stored\ energy\ (kJ\ or\ MJ\ and\ often\ converted\ to\ MWh)$

$\rho = Density\ of\ water\ (for\ TES) = 1{,}000\ kg/m^3$

$V = Volume\ of\ the\ storage\ in\ m^3$

$c_p = Specific\ heat\ of\ water\ (for\ TES) = 4.18\ kJ/(kg°C)$

$\Delta T = Temperature\ difference\ between\ supply\ and\ return\ water\ in\ °C$

For sizing solar photovoltaic systems to support electric heat pumps in district heating networks, PVGIS (Photovoltaic Geographical Information System) is commonly used. This EU-endorsed tool helps estimate solar generation potential based on geographical data, system tilt, orientation, and local irradiance. By matching PV output profiles to daily and seasonal heating demand, planners can determine the optimal installed capacity for maximizing self-consumption and minimizing grid dependency (Huld et al., 2011).

Decentralization—i.e., dividing a network into smaller, localized segments—is increasingly seen as a strategic upgrade for large or elongated DHNs. In systems where the central heating source is located far from end users, decentralized sub-networks can reduce transmission losses, improve pressure balance, and enable localized integration of renewable sources. Studies by Werner (2013) and Marguerite et al. (2017) demonstrate that network segmentation significantly enhances operational flexibility, especially in suburban zones like Salininkai where pipeline distances and user density vary.

The performance of heat pumps and boilers within a DHN can be assessed using simulation tools such as EnergyPRO, which models system behavior based on hourly operational data. In this context, the Coefficient of Performance (COP) of a heat pump is calculated by dividing the thermal output (in MWh) by the electrical input (in MWh) over a given operational period. A higher COP indicates more efficient heat delivery per unit of electricity consumed. Similarly, the boiler efficiency is derived by dividing the useful thermal output by the fuel input (e.g., natural gas), which is also tracked hourly in EnergyPRO. These metrics, which can be averaged over seasonal or annual cycles, provide essential insights into energy conversion performance, cost-effectiveness, and emissions impact across multiple scenarios (EMD International, 2018).

However, aging infrastructure continues to pose a major challenge. Many buildings connected to DHNs in Lithuania fall under F and G energy classes, indicating poor insulation and high energy consumption (SSVA, 2025). Heat losses in Baltic DHNs typically range from 10% to 25%, depending on pipeline length and insulation quality (Werner, 2013). Studies show that poorly insulated pipelines in aging networks can lose 2–4% of heat per kilometer (Werner, 2013, 2017), and modern insulation materials can reduce these losses by up to 50% (Martin-Du Pan, 2015). These losses not only increase operational costs but also demand additional fuel, leading to higher GHG emissions. Long distribution networks often experience uneven heat delivery, with buildings closer to the heat source overheating while those farther away remain underheated. Addressing these inefficiencies requires optimized network design and infrastructure upgrades.

Improving building energy efficiency is another critical aspect of modernization. Retrofitting older buildings with better insulation, energy-efficient windows, and smart thermostats can reduce heat demand by 20–40%, according to Pérez-Lombard et al. (2008). Consumer engagement through awareness campaigns, flexible pricing, and incentives can further promote energy-saving behaviors. Maghsoudi Nia et al. (2022) emphasize that targeted incentives can lead to significant reductions in energy consumption and emissions.

Transforming the Salininkai District Heating Network (DHN) into a more efficient and sustainable system is both a timely and necessary response to the broader climate and energy challenges facing Lithuania. As climate change accelerates due to rising greenhouse gas emissions—particularly from fossil fuel-based heating—the modernization of DHNs offers a practical pathway to reduce energy consumption, operational costs, and environmental impact. Salininkai, like many Lithuanian districts, relies heavily on aging infrastructure and operates at comparatively higher supply temperatures, which not only limits the integration of renewable energy technologies like heat pumps and thermal storage but also results in significant heat losses. By modernizing to a sustainable district heating model, Salininkai can serve as a benchmark for sustainable urban heating. Such transformation aligns with EU energy directives and demonstrates how smart planning, modern technology, and consumer engagement can collectively drive decarbonization and resilience in urban heating systems.

# 4. Methodology of the study

The research on the Salininkai District Heating Network (DHN) adopts a structured methodology that integrates data analysis, simulation modeling, and scenario-based evaluation to assess the current system performance and explore viable pathways for sustainable modernization. This approach is designed to address technical inefficiencies, reduce fossil fuel dependency, and evaluate the feasibility of integrating renewable energy technologies within a low-temperature district heating (LTDH) framework.

## 4.1 Data collection and preprocessing

The study begins with the acquisition of essential datasets from the Salininkai DHN authority. The primary dataset includes hourly heat demand data for the year 2021, hourly outdoor air temperature, and the corresponding hourly supply and return water temperatures at the boiler plant. Additional data on annual heat production, network losses for the years 2018–2020, and building-specific heat consumption profiles enrich the system-level understanding. These datasets are analyzed using Microsoft Excel to identify trends in seasonal demand, production-demand mismatches, loss distribution, and segregation of heading demand for space heating and domestic hot water (DHW) (Figure 2, Figure 3, Figure 4, and Figure 5Figure 2). The physical layout of the distribution network is examined through GIS tools to assess the impact of long transmission lines (up to 1.38 km) on energy losses (Figure 6).

## 4.2 Baseline system modeling in EnergyPRO

Using EnergyPRO—a widely recognized software for modeling complex energy systems (EMD International, 2018) a detailed baseline model (Figure 8) is constructed to simulate the current gas boiler-based system. The existing setup comprises two 4.7 MW natural gas boilers, assumed to operate with a nominal seasonal efficiency of 85%, based on standard performance benchmarks (Sarbu & Sebarchievici, 2014). The energy content of natural gas is taken as 11.2 kWh/m³, which corresponds to the Lower Heating Value (LHV) typically used in EU energy accounting and billing

(Eurostat, 2020). This value allows conversion from gas volume to thermal energy input and supports accurate calculation of boiler fuel consumption and system losses.

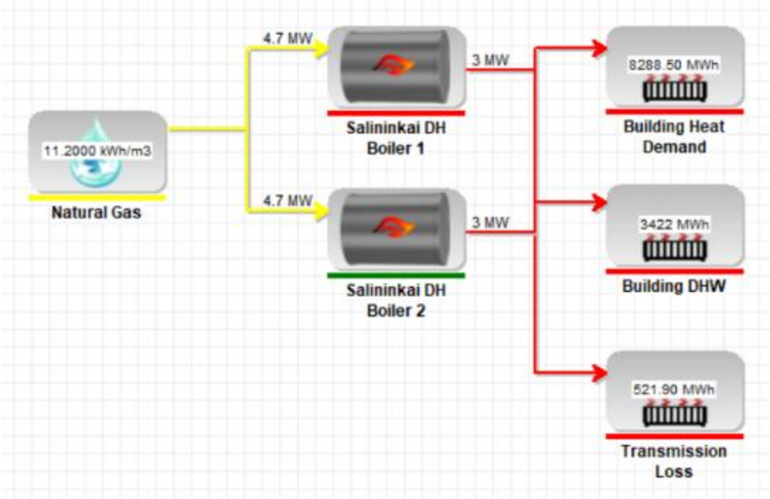


*Figure 8. Baseline System (Existing Setup)*

Respective data are then extracted from simulations like heat production, hours of operation, natural gas consumption, priorities, etc. With a peak demand of 4.7 MW, all data is presented and discussed in further sections. The graphical representation, as well as the annual report provided peak demand of the system which helps us to design alternative energy conversion units as planned to simulate in the following sections of the study.

In the Salininkai District Heating Network, two natural gas boilers, each rated at 4.7 MW, serve as the primary heat sources. These boilers are designed for high efficiency, operating with a nominal seasonal efficiency of approximately 85%. However, like most condensing gas boilers, their maximum efficiency is typically achieved when operating at 70–80% of full load, which translates to a thermal output of approximately 3.3–3.8 MW per unit (ASHRAE, 2016; CIBSE, 2016). Operating within this load range ensures optimal condensing conditions—especially when return water temperatures are kept below 55°C—allowing for latent heat recovery and minimizing fuel consumption (US Department of Energy). In the context of Salininkai, the average winter hourly demand ranges between 2.5 MW and 3.6 MW, meaning that operating a single boiler within this optimal load window covers a sizable portion of the base demand efficiently. For simplified modeling and planning, a peak effective delivery of 3.0 MW per boiler is assumed, which remains within the optimal efficiency envelope. This strategy not only ensures reliable system performance but also aligns with best practices for part-load operation of condensing boilers in 4th Generation District Heating (4GDH) systems. The following figure (Figure 9) represents input window of EnergyPRO simulation system where input scenario of Boiler-1 is displayed.

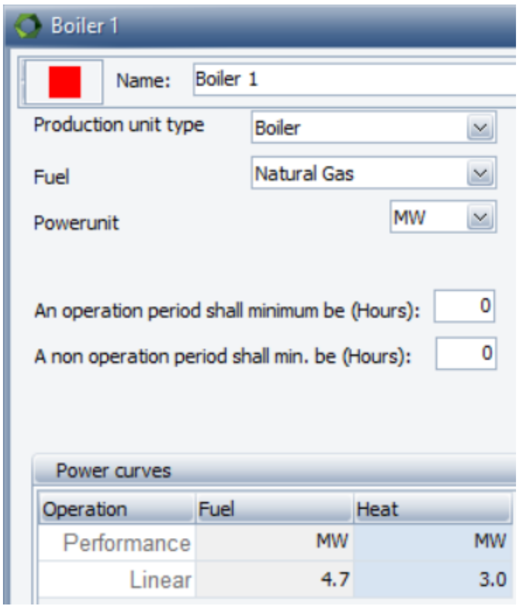


*Figure 9. EnergyPRO Simulation Input Window of Boiler-1*

## 4.3 Justification for electric heat pump capacity: Why 1 MW?

The hourly demand profile reveals that the maximum hourly heat demand during peak winter reaches approximately 3.6 MW. Again, EnergyPRO simulation for the baseline system reveals the same parameter as 4.7 MW. To support decarbonization without oversizing the system, a 1 MW electric air-to-water heat pump configuration is selected to cover about 25–30% of the peak load. This capacity ensures that the heat pump operates efficiently for most of the year, especially during summer seasons and average winter days. Given a Seasonal Coefficient of Performance (SCOP) ranging between 2.5 and 3.0, the selected 1 MW electric input corresponds to a thermal output of 2.5–3.0 MW (Sarbu & Sebarchievici, 2014). This sizing strategy balances capital investment, operational flexibility, and energy efficiency, allowing the gas boilers to remain as backup during extreme cold spells. However, selection of the best model and array is important, and it has been discussed in the later part of this study.

### *4.3.1 Selection of appropriate heat pump*

Integrating renewable energy technologies into the district heating network of Salininkai represents a vital step towards achieving a sustainable and energy-efficient modernization. As part of this research, electric air-to-water heat pump of 1 MW electric capacity has been chosen for integration into the network. This system processes ambient air as a renewable energy source, converting it into usable heat for water heating, thus reducing reliance on fossil fuel-based gas boilers. After careful review of the market, several commercially available 1 MW air-to-water heat pump models can be considered, including the following models (BOSCH, 2025; DAIKIN, 2025; Mitsubishi, 2025; RXTC Datasheet, 2025) (Table 2):

*Table 2. Some Heat Pump Models available in Market*

| Bosch Compress 5000 AW | Daikin Altherma Industrial Series | Mitsubishi Electric Ecodan CAHV-P500YA-HPB | RTXC XE-EC-R513A A2W HP |
|---|---|---|---|
| **Heating Capacity**<br>1 MW (at standard conditions)<br><br>**COP**<br>Up to 4.2 (depending on operating conditions)<br><br>**Maximum Flow Temperature**<br>60°C<br><br>**Refrigerant**<br>R290 (Propane)<br><br>**Additional Features**<br>Modular installation, remote control, and monitoring. | **Heating Capacity**<br>1 MW<br><br>**COP**<br>3.8–4.5 (varies with outdoor temperature)<br><br>**Maximum Flow Temperature**<br>70°C<br><br>**Refrigerant**<br>R32<br><br>**Additional Features**<br>Advanced inverter technology, compatibility with existing heating systems, and reduced refrigerant charge. | **Heating Capacity (Per Unit)**<br>500 kW<br><br>**Combined Capacity**<br>1 MW (2 units)<br><br>**COP**<br>Up to 4.2<br><br>**Maximum Flow Temperature**<br>65°C<br><br>**Refrigerant**<br>R410A<br><br>**Additional Features**<br>Scalable modular system, low noise levels, and high seasonal efficiency. | **Heating Capacity (Per Unit)**<br>252 kW<br><br>**Combined Capacity**<br>1 MW (4 units)<br><br>**COP**<br>3.35–4.6 (varies with outdoor temperature)<br><br>**Refrigerant**<br>R513A<br><br>**Additional Features**<br>Moderate efficiency, modular, low environmental impact, low noise level, compatible. |

For the EnergyPRO simulation, the RTXC XE-EC-R513A Air-to-Water Heat Pump (RXTC Datasheet) was selected due to its compatibility with low-temperature district heating applications and its superior seasonal efficiency. The unit delivers a maximum heating capacity of approximately 798.7 kW while consuming about 252.0 kW of electric power, yielding a seasonal coefficient of performance (SCOP) between 3.35 and 3.46 under standardized test conditions (CEN, 2022). These values are based on an outdoor air temperature of 7°C and hot water temperature of 45°C (supply) and 55°C (return), which are typical boundary conditions for low-temperature district heating systems (Directive 2009/125/EC, 2009; Regulation EU No 813/2013, 2010).

The selected model uses R513A refrigerant, known for its lower Global Warming Potential (GWP) compared to traditional refrigerants, aligning with EU sustainability targets. The unit is Eurovent and Ecodesign certified (Eurovent Certificate), ensuring compliance with the highest efficiency and environmental standards across operating conditions. To achieve the target 1 MW of electric input capacity, four heat pumps are configured in parallel. This configuration allows flexibility, redundancy, and modulation according to variable heat demand while supporting grid-responsive operation.

Furthermore, the system operates effectively even in low ambient conditions, capable of delivering hot water up to 55°C, at outdoor temperatures as low as –12°C. The relatively faint sound power level (LwO ≈ 134.5 dB(A)) makes the RTXC suitable for deployment in residential and semi-urban environments. These detailed parameters (RXTC Datasheet, 2025) such as SCOP, COP, inlet and outlet water temperatures, and part-load performance—are all input into the EnergyPRO model to ensure realistic simulation outcomes that reflect the seasonal performance and environmental compatibility of the proposed system.

*Table 3. Important Parameters of RTXC XE-EC-R513A Air-to-Water Heat Pump*

| Parameter | Value / Condition | Source |
|---|---|---|
| **SCOP range** | 3.35 – 3.46 | RXTC Datasheet |
| **COP (nominal at 7°C)** | ~3.10 – 3.24 | |
| **Electric input per unit** | 252.0 kW | |
| **Heating capacity per unit** | 798.7 kW | |
| **Max outlet water temperature** | 55°C, at –12°C ambient | |
| **Sound power level (LwO)** | 134.5 dB(A) | |
| **Refrigerant** | R513A | |

This configuration ensures effective performance during peak demand while supporting the transition toward sustainable energy systems. Another strong logic behind considering this model of heat pump is its modular connectivity, i.e., four units will combine a total capacity of 1 MW, but it can be run only one unit if the demand is low.

### 4.3.2 Setting conservative value of COP in EnergyPRO simulation

In the EnergyPRO simulation, all the four heat pumps are set with a COP value of 3.0 which means, for a given electric power of 252 kW, each heat pump will deliver 756 kW of heat with that COP. The following figure (Figure 10) shows about heat pumps input parameters. Supply and return temperatures are set at 55°C and 45°C respectively and inlet and outlet air temperature are considered as 10°C and 7°C; however, during operation the inlet air temperature will be same as the ambient temperature, but outlet temperature will be 3°C less than inlet temperature.

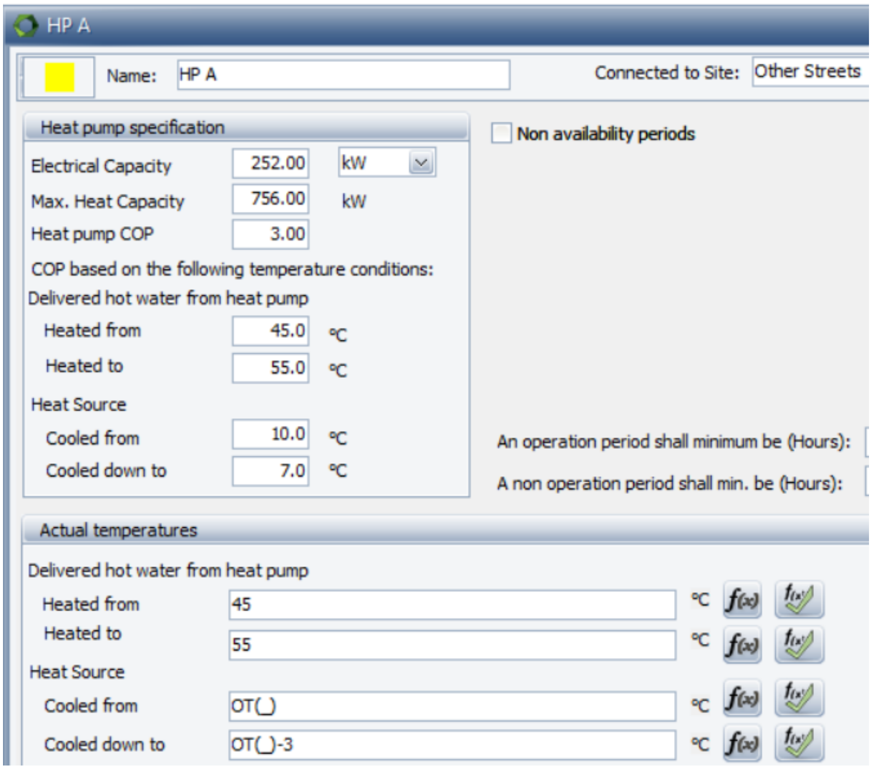


*Figure 10. EnergyPRO Input Parameters for Heat Pumps*

### 4.3.3 Setting priority of heating systems

In the EnergyPRO simulation mechanism, four heat pumps are given priorities from 1 to 4 and two boilers are prioritized then which will enable heat pumps to operate first and one-by-one. And then, depending upon the demand, boilers will come into operation.

## 4.4 Defining thermal energy storage sizing

The required storage capacity can easily be calculated using an equation ($Eq. 1$), however, at the beginning it is needed to define the amount of thermal energy is required or planned to be stored. In the following parts of the document, we shall go step-by-step towards defining the capacity of thermal energy storage.

### *4.4.1 Purpose of TES in the system*

In designing Thermal Energy Storage (TES) systems for 4th Generation District Heating (4GDH) networks, the duration for which the TES should supply heat during peak demand is a critical consideration. The size of TES is typically based on the desired load coverage during peak periods, which can range from a few hours to several days, depending on the specific objectives of the system. The exact duration for which this TES can supply heat during peak demand depends on the network's specific load profile and operational strategies.

Studies have shown that integrating TES into district heating systems can significantly reduce peak loads and improve overall system efficiency. For example, in a study by van der Heijde et al. (2019), an integrated optimal design and control algorithm was applied to a district heating network, demonstrating the benefits of TES in managing peak demands and integrating renewable energy sources.

Furthermore, the duration for which TES should supply heat during peak demand is influenced by factors such as the variability of renewable energy sources, the thermal inertia of connected buildings, and the economic considerations of storage sizing. Therefore, a comprehensive analysis of the specific district heating network's characteristics is essential to determine the optimal TES capacity and its operational duration during peak demand periods.

### *4.4.2 Calculation of required thermal energy to be stored*

For instance, in the Salininkai District Heating Network, a consideration of 60 hours of preservation at an average demand during heating season (2.17 MW) is considered with EnergyPRO calculated system loss for 20.5 m of height and 300 mm of thick insulation. According to this consideration, storage capacity ($Q$) can be calculated as:

$$Q = Demand \times Duration = 2.17 \times 60 = 130.2\ MWh \qquad (Eq.2)$$

### *4.4.3 Calculation of thermal storage capacity*

Using $Eq.1$ and $Eq.2$, we can calculate the volume ($V$) of the TES according to the following calculation:

$$\begin{aligned} V &= \frac{Q}{\rho . c_p . \Delta T} \\ &= \frac{130.2\ MWh}{\left(1000 \frac{kg}{m^3}\right) \times (4.18 \frac{kJ}{kg°C}) \times (40°C)} \\ &= \frac{130.2 \times 10^6 \times 3600}{1000 \times 4.18 \times 10^3 \times 40} m^3 = 2803.35\ m^3 \end{aligned}$$

Considering some losses, a 3,000 m³ TES unit is proposed to store approximately 139 MWh of thermal energy. This capacity is designed to cover peak demand periods and enhance operational flexibility. The exact duration for which this TES can supply heat during peak demand depends on the network's specific load profile and operational strategies.

The proposed TES system is designed to support daily load balancing and reduce the frequency of boiler start-stop cycles, which in turn improves operational stability and efficiency. By storing excess thermal energy, particularly from renewable sources like solar PV, the system maximizes the use of clean electricity and minimizes fossil fuel dependency. Acting as a flexible thermal buffer, the TES enhances the overall system’s coefficient of performance (COP), lowers greenhouse gas emissions, and contributes to greater grid resilience. This approach to TES sizing and integration is consistent with best practices recommended for 4th Generation District Heating Networks (Schmidt et al., 2017b).

## 4.5 Stage-1: EnergyPRO modeling for addition of HP and TES

After finalizing the required specifications of heat pump and TES, a detailed modeling is done in EnergyPRO, and simulation circuit is as below (Figure 11):

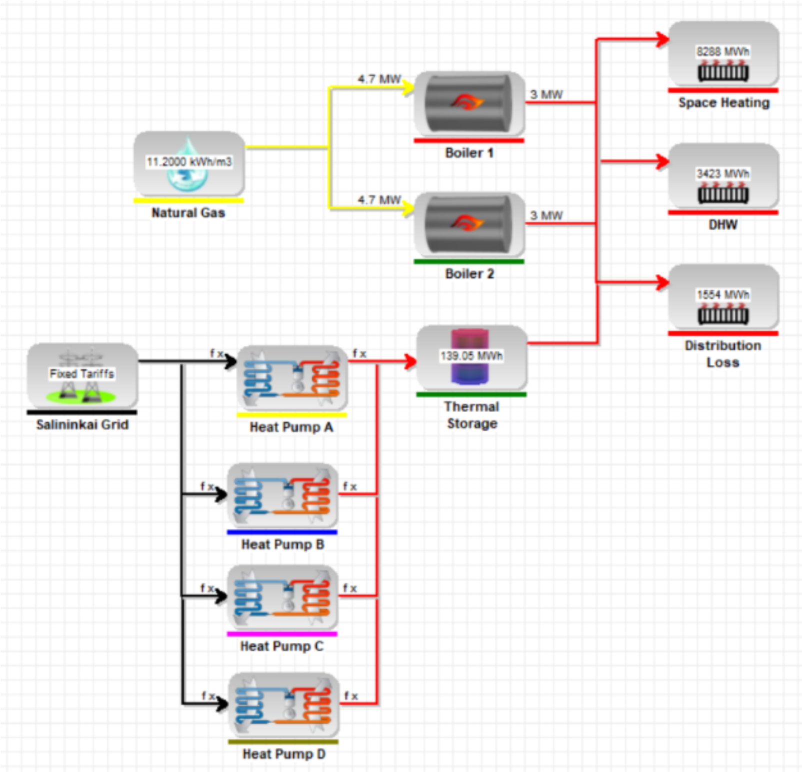


*Figure 11. Baseline System + HP + TES*

In the design of the Salininkai District Heating Network (DHN), the thermal energy storage (TES) unit is deliberately connected only to the electric air-to-water heat pump system, excluding the natural gas boilers. This decision offers multiple advantages from both an energy efficiency and sustainability standpoint, especially in the context of transitioning to a 4th Generation District Heating (4GDH) model.

Primarily, coupling TES exclusively with heat pumps ensures that the stored heat originates from a low-carbon or renewable energy source. The proposed heat pumps in Salininkai are partly powered by a 500 kWp solar photovoltaic system, and the electricity grid in Lithuania already has a significant share of renewables. As a result, the TES effectively serves as a buffer for clean energy, enhancing the renewable share in the heating mix and supporting national decarbonization goals. This aligns with the smart energy system concept, which emphasizes the integration of flexible thermal storage with low-carbon generation technologies (Lund et al., 2017).

Moreover, excluding boilers from the TES connection helps to avoid operational inefficiencies commonly associated with gas-fired systems. Boilers, particularly condensing types, achieve optimal efficiency at 70–80% of their rated capacity. Charging a TES with gas boilers often leads to low-load cycling, which reduces efficiency, increases wear and tear, and elevates $CO_2$ emissions. In contrast, heat pumps operate best at steady-state conditions, making them more suitable for charging storage tanks in a way that maintains both energy efficiency and system reliability (Schmidt et al., 2017b).

Another critical advantage of this configuration is the ability to shift the heat pump's operation to off-peak electricity hours—typically during nighttime—when outdoor temperatures are slightly higher and electricity costs are lower. This not only improves the coefficient of performance (COP) of the heat pump but also enables load shifting, allowing stored heat to be discharged during peak demand periods in the morning and evening. This effectively reduces the need to activate the gas boilers at peak times, thereby decreasing fossil fuel use and operational costs (Arteconi et al., 2013).

Additionally, restricting TES usage to heat pumps simplifies the overall control and dispatch strategy. The system can be programmed to prioritize charging from renewable sources and discharging to meet demand before activating fossil-based heating. This operational logic reduces complexity, supports modular planning, and enhances transparency in sustainability reporting (Lund et al., 2017). By enabling the heat pump to operate consistently and allowing the boilers to serve as backup units, the system gains both resilience and flexibility.

In conclusion, in the Salininkai DHN design, thermal energy storage (TES) is connected only to the air-to-water heat pump system and not to the gas boilers. This strategy ensures that the stored heat originates from a renewable, low-carbon source, improving the overall sustainability of the network. It avoids inefficiencies associated with boiler cycling and ensures that TES supports peak shaving and load balancing without increasing fossil fuel use. Additionally, it enhances heat pump performance by enabling operation under stable conditions and simplifies system control, aligning with 4GDH principles and EU decarbonization goals.

## 4.6 Defining photovoltaic solar park capacity

From the Stage-1 EnergyPRO simulation, i.e., after adding the HP and TES to the Salininkai DHN, we came to know that the heat pumps consumed 4,584 MWh of electricity (detailed result is shown in the further sections) and the integration of a solar park into the Salininkai District Heating Network (DHN) presents a valuable opportunity to enhance sustainability and reduce reliance on grid power. Step-by-step methodologies are followed to determine the solar park capacity.

### *4.6.1 Calculating maximum solar capacity demand*

If we plan to take 100% of the required electricity for the heat pumps from the solar park, we can calculate the required solar park capacity (without tracking system) through the following equation (Duffie et al., 2020):

$$E = P_{peak} \times H_{sun} \times \eta \qquad (Eq. 3)$$

Here,

$E = Yearly\ electricity\ generation\ in\ kWh = 4.584\ MWh$

$P_{peak} = Solar\ park\ peak\ capacity\ in\ kWp$

$H_{sun} = Annual\ solar\ irradiation = 1{,}144.5\ kWh/m^2\ (PVGIS)$

$\eta = Overall\ system\ efficiency = 95\%$

$$From\ Eq. 3, P_{peak} = \frac{E}{H_{sun} \times \eta} = \frac{4{,}584 \times 1{,}000}{1{,}144.5 \times 95\%} = 4{,}216\ kWp$$

From the above calculation it is seen that, for an ideal case scenario, considering solar energy generation efficiency as 95%, 4.216 $MW_p$ PV solar capacity is needed to meet 100% of electricity demand of heat pump operation. Therefore, 4,216 kWp is the maximum PV solar capacity demand.

Achieving full electrification through solar would also necessitate an appropriately sized battery energy storage system (BESS) capable of shifting several hours to days' worth of electricity. While technically feasible, this approach requires significantly higher capital investment and careful operational planning to ensure load balancing and storage cycling without overdesigning the system (Arteconi et al., 2013; Dinçer & Rosen, 2010).

To install a 4,216 kWp ground-mounted fixed-tilt solar PV system in Salininkai, an estimated 27,400 square meters (or 2.74 hectares) of open land would be required. This estimate is based on a typical land use factor of 6.5 $m^2$ per kWp, accounting for panel spacing, maintenance access, and shading minimization (IRENA, 2019).

### *4.6.2 Limiting the photovoltaic solar park capacity to 500 kWp*

This sizing is strategically selected based on regional solar resource availability, system demand characteristics, and alignment with renewable energy integration principles. According to PVGIS estimates, a 500 kWp system in Vilnius can produce approximately 650–750 MWh annually (Huld et al., 2011). With the heat pump expected to consume around 4,584 MWh annually under a 2.85 COP assumption, this PV setup can supply nearly 15% of its energy needs, especially during spring and autumn when solar availability and heating demand moderately overlaps, which serves the purpose of getting simulation result and study the outcome.

From a planning perspective, a 500 kWp installation presents a practical balance between land use, cost, and contribution to decarbonization. It avoids excessive curtailment losses, fits well within the spatial constraints of typical municipal land parcels, and is easily scalable. Integrating this PV capacity improves the system's sustainability by reducing dependence on grid electricity—particularly during daylight hours—and supports Lithuania's National Energy and Climate Plan (NECP), which emphasizes increasing the share of renewables in the thermal energy sector (Ministry of Energy of the Republic of Lithuania, 2019). Furthermore, the PV-powered system complements the proposed thermal energy storage (TES), allowing excess electricity to be stored as heat during low demand hours for later use.

### *4.6.3 Collection of solar irradiation data for the year 2021*

For the purpose of this study, location of photovoltaic solar park is selected inside existing DH setup of Salininkai where an area of 3,200 $m^2$ is available. The area can accommodate the heat pump setup along with a 500 kWp photovoltaic solar park. Though this is not the only reason for limiting solar park's capacity at 500 kWp, it will also help us to get the solar irradiation data for any particular location. The following picture gives a glimpse of the selected area (Figure 12):

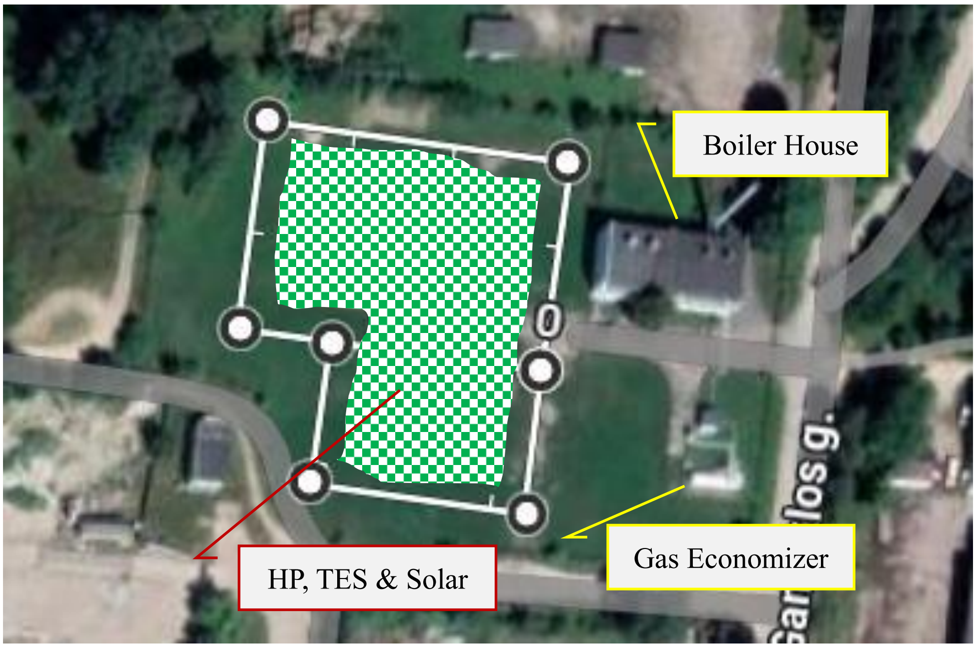


*Figure 12. Salininkai DHN Premises for HP, TES and Solar Park*

The latitude and longitude of this area is 54.6101° N and 25.2678° E and using PVGIS (Figure 13) solar irradiance for the year 2021 is found. The solar irradiance values are plotted in EnergyPRO as a time series. The solar irradiance profile for Salininkai in 2021, based on PVGIS hourly data, reveals significant seasonal variation (Figure 14).


*Figure 13. Using PVGIS to collect Solar Irradiation (2021)*

Maximum irradiance peaks of over 1,000 W/m² occur from April to August, aligning with the optimal generation window for solar PV. In contrast, irradiance during winter months drops below 200 W/m², with frequent periods of low or zero output. This emphasizes the importance of combining PV systems with thermal or battery storage to ensure supply stability, especially in colder months when heating demand is highest but solar input is lowest.

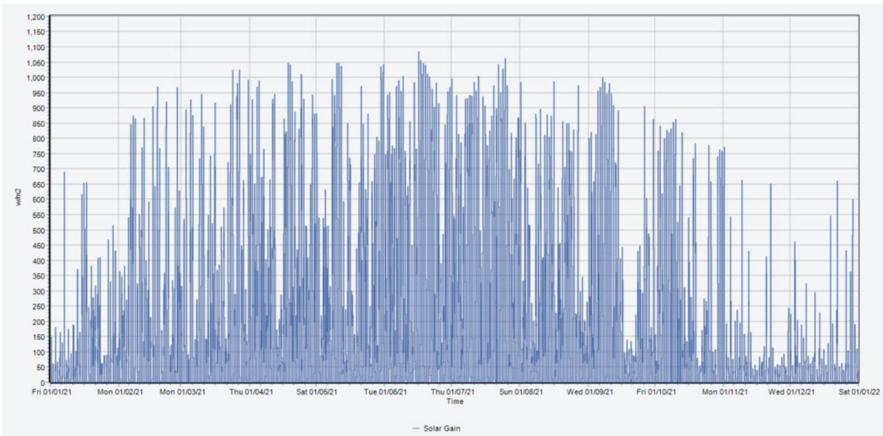


*Figure 14. EnergyPRO plotting of Solar Irradiation (2021) of Salininkai*

### *4.6.4 Inclination and orientation for PV in Salininkai*

Salininkai, located just south of Vilnius, Lithuania (latitude ~54.6°N), benefits from moderately good solar radiation during spring, summer, and early autumn. For fixed-tilt photovoltaic systems in this region, the optimal inclination angle is typically close to the site's latitude, which is about 35–37 degrees. This tilt angle ensures a balance between maximizing annual energy yield and avoiding excessive winter shading or summer overexposure. According to PVGIS and other European PV system design tools, the best annual performance in Salininkai is achieved with a south-facing orientation (azimuth of 0°) and a tilt between 30° and 40°, depending on specific site constraints and seasonal generation targets (Huld et al., 2011; Solargis, 2021).

For example, a tilt of 35° with azimuth 0° (true south) results in the highest yearly output, while a steeper tilt (40–45°) can favor winter production—useful for heating applications, albeit with a slight annual energy penalty. Tracking systems can improve output but at significantly higher cost and complexity, which may not be justified for small to mid-size district-scale applications. However, in EnergyPRO simulation, 45° tilt (inclination) is used along with an azimuth (orientation) of 0°.

#### *4.6.5 Temperature coefficient of power and NOCT*

Photovoltaic panel efficiency decreases with rising cell temperature. This behavior is quantified by the temperature coefficient of power, typically expressed as a percentage loss per degree Celsius above standard test conditions (25°C). For most crystalline silicon modules, this coefficient ranges between –0.35% to –0.45% per °C. For example, a panel with a coefficient of –0.40%/°C will lose 4% of its output for every 10°C rise in temperature. This effect becomes relevant in summer months or under low ventilation conditions. In the case of Salininkai, we set the value as -0.380% /°C.

The Nominal Operating Cell Temperature (NOCT) represents the expected module temperature under specific reference conditions: 800 W/m² irradiance, 20°C ambient temperature, 1 m/s wind speed, and open-circuit operation. For standard crystalline silicon panels, NOCT is typically between 42°C and 48°C. Panels with lower NOCT values tend to perform better in warm environments and contribute to higher effective system yields. For Salininkai, where ambient temperatures are generally moderate to cool, the temperature-related losses are relatively low. However, panel selection should still consider the temperature coefficient to optimize annual output, particularly during high-solar summer periods. In this study, this value is considered as 45°C in EnergyPRO simulation.

## 4.7 Stage-2: EnergyPRO modeling for addition of PV solar park

After finalizing the required specifications of photovoltaic solar park, a detailed modeling is done in EnergyPRO, and simulation circuit is as below (Figure 15):

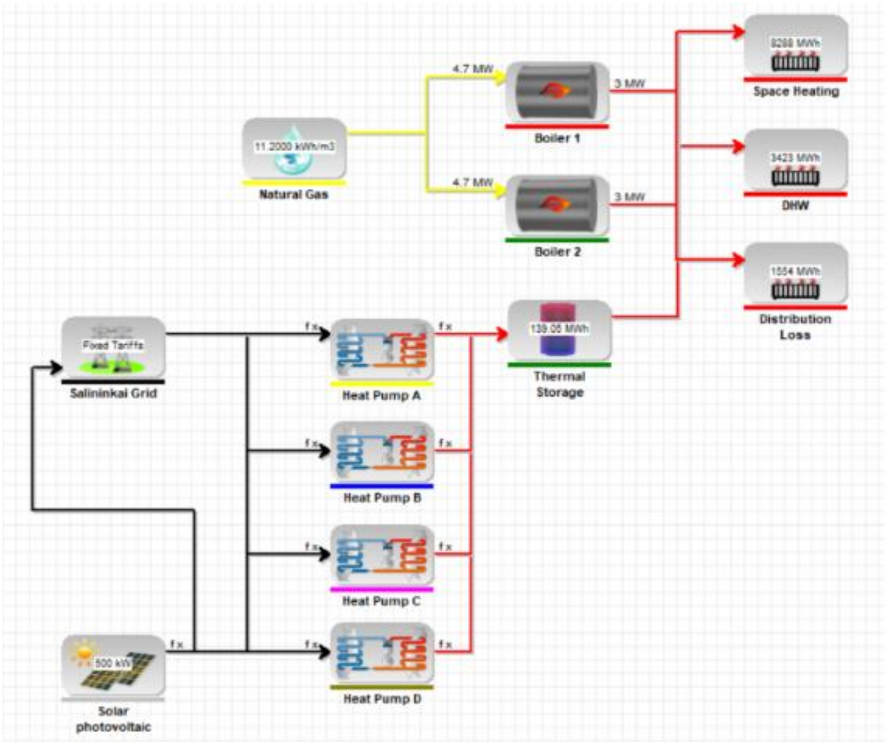


*Figure 15. Baseline System + HP + TES + PV Solar Park*

Following the completion of Stage 2, the Salininkai District Heating Network (DHN) demonstrates noteworthy progress toward sustainable modernization. The integration of 1 MW electric air-to-water heat pump and 3,000 $m^3$ thermal energy storage (TES) system in Stage 1 introduced renewable flexibility into the network, enabling base-load heating through electricity, supported by operational strategy and priorities. The subsequent addition of a 500 kWp solar photovoltaic (PV) system in Stage 2 should further improve the system's environmental performance by partially offsetting the electricity needs of the heat pump. Together, these interventions should measurably reduce the system's fossil fuel dependency, improve its primary energy factor (PEF), and enhance the overall operational efficiency, particularly during the shoulder seasons (autumn and spring) when solar generation and heating demand align. Lastly, in the operation strategy, heat pumps are prioritized than boilers and all the energy conversion units are allowed to operate at partial loading.

Despite these improvement opportunities, heat losses associated with long-distance transmission pipelines and uneven heat distribution remain significant challenges—especially given the current location of the main heating source at one end of the network. This inefficiency is exacerbated during peak demand periods and in low-demand summer months, where loss percentages rise disproportionately. As such, the focus now shifts to Stage 3, where the feasibility and impact of dividing the network into two operational zones connected by a transmission line will be examined. This step aims to minimize distribution losses, improve pressure balancing, and enable modular expansion or decentralization of heat generation sources in the future.

## 4.8 Dividing the network – is it a solution to reduce system loss?

Despite the successful integration of renewable energy technologies such as 1 MW electric heat pump, 3,000 m³ thermal energy storage (TES), and a 500 kWp solar photovoltaic (PV) system, the Salininkai District Heating Network (DHN) still faces significant structural challenges that limit its overall efficiency. Prime among these is the system's linear, single-source heat distribution configuration, where the main heat production unit is located at one extreme end of the network. Consequently, hot water must travel long distances—up to 1.38 km to reach the most remote consumers (e.g., Mechanikų g. 2). This extended transmission path leads to elevated distribution losses, increased hydraulic head requirements, and inconsistent temperature delivery, especially at system extremities.

According to operational data from 2021, the network produced 13,265 MWh of thermal energy, while the total consumer-side demand was 11,711 MWh, resulting in a distribution loss of 1,554 MWh, or 11.7% of total production. These losses are not evenly distributed throughout the year. During the summer, when domestic hot water (DHW) demand dominates and heat flows are minimal, the loss percentage rises sharply—up to 28.2%, as the system continues circulating heat over long distances with minimal withdrawal, increasing standby and conductive losses. These patterns are in line with findings in other district heating systems, where heat losses typically range from 10–25%, influenced by factors such as pipe length, diameter, insulation quality, and network topology (Chicherin et al., 2020; Çomaklı et al., 2004; El Mrabet et al., 2024; Gadd & Werner, 2015).

To address these persistent inefficiencies, dividing the network into two operational segments—with a connecting transmission line—emerges as a technically sound and forward-looking solution. By localizing generation or storage points nearer to concentrated demand zones, the effective heat transmission distance is reduced, lowering the cumulative thermal loss across the network. According to Schmidt et al. (2017b), low-temperature district heating systems with optimized supply-return temperatures and loop distances below 1 km can limit heat losses to under 8%, especially when high-performance pipe insulation is employed.

From a hydraulic perspective, the benefits of segmentation are equally compelling. Long, branched networks often suffer from imbalanced pressure zones, requiring higher pump heads and flow rates to maintain adequate delivery at distal nodes. This not only increases electricity consumption in the pump system but also raises return temperatures, reducing overall system efficiency. A dual-segment model would allow for independent pressure control in each zone, enabling more stable and responsive hydraulic balancing. Furthermore, it simplifies flow optimization, particularly in buildings of poor energy class (many in D to G), where variable demand leads to localized flow mismatches. Moreover, no booster is needed in all aspects.

Operationally, dividing the network increases resilience. In the event of pump failure, pipe rupture, or maintenance work in one segment, the other can continue functioning independently. Additionally, it facilitates modular expansion and easier integration of decentralized heat sources such as secondary heat pumps, biomass micro-boilers, or solar thermal systems, consistent with the modularity and smart-grid philosophy of 4th Generation District Heating (4GDH) (Lund et al., 2014b). While capital investment is needed for additional piping, flow control units, and supervisory control systems, these costs are often outweighed by long-term gains in energy savings, emission reduction, and maintenance avoidance (Guelpa & Verda, 2021). Thus, the solution of dual zone is proposed where the heat pumps and TES will not be connected at the same point boilers are connected, but in somewhere center so that distance to the far most building becomes nearly half of present value from the boiler room.

In conclusion, the proposed dual-zone configuration represents a logical progression in the sustainable transformation of the Salininkai DHN. By shortening heat delivery paths, improving hydraulic pressure regulation, enabling demand-driven flow control, and supporting decentralized energy integration, this stage addresses both thermal and hydraulic inefficiencies. The result is a more robust, efficient, and future-ready network that aligns with Lithuania’s broader energy transition goals.

## 4.9 Stage-3: EnergyPRO modeling after dividing the network

To implement the dual-zone configuration of the Salininkai District Heating Network (DHN), the existing heat distribution layout was carefully analyzed with a focus on optimizing thermal performance while minimizing physical infrastructure changes. The network was divided into two operational segments—strategically named based on their geographical layout. The first segment, referred to as the “Vaikų Street” zone, encompasses 17 buildings located primarily along and around Vaikų g., with a total annual energy demand of 5,594.74 MWh. The second segment, named “Other Streets”, consists of 19 buildings spread across adjacent locations, with a combined yearly energy demand of 6,116.48 MWh. This near-equal distribution of thermal loads ensures that hydraulic and thermal balancing between the two zones remains feasible, even if exact parity is not achieved.

One of the core design principles in this methodology was to avoid the need for new or extended consumer-side piping, which would significantly increase capital and operational complexity. Therefore, the division was conducted in such a way that existing pipeline corridors are retained, and all connected buildings remain served by their current branch lines. This was achieved by identifying a logical branching point within the distribution network, from where a connecting transmission line between the two zones can be introduced if needed for backup or load redistribution. Care was also taken to respect the natural hydraulic flow paths and existing pressure zones, ensuring minimal disruption to the network's current operational integrity.

In terms of equipment placement, the 1 MW electric heat pump and the 3,000 m³ thermal energy storage (TES) unit—introduced in earlier stages—were positioned such that their heat injection points serve buildings within the “Other Streets” segment without the need for bypassing or re-routing existing supply pipelines. The main gas boilers, which serve as peak-load or backup sources, remain connected to the “Vaikų Street” segment, ensuring that both zones are independently operational and capable of responding to load fluctuations. This distribution also facilitates modular energy management and decentralized control strategies, consistent with 4th Generation District Heating (4GDH) principles. The EnergyPRO simulation circuit is shown in the following figure (Figure 16):

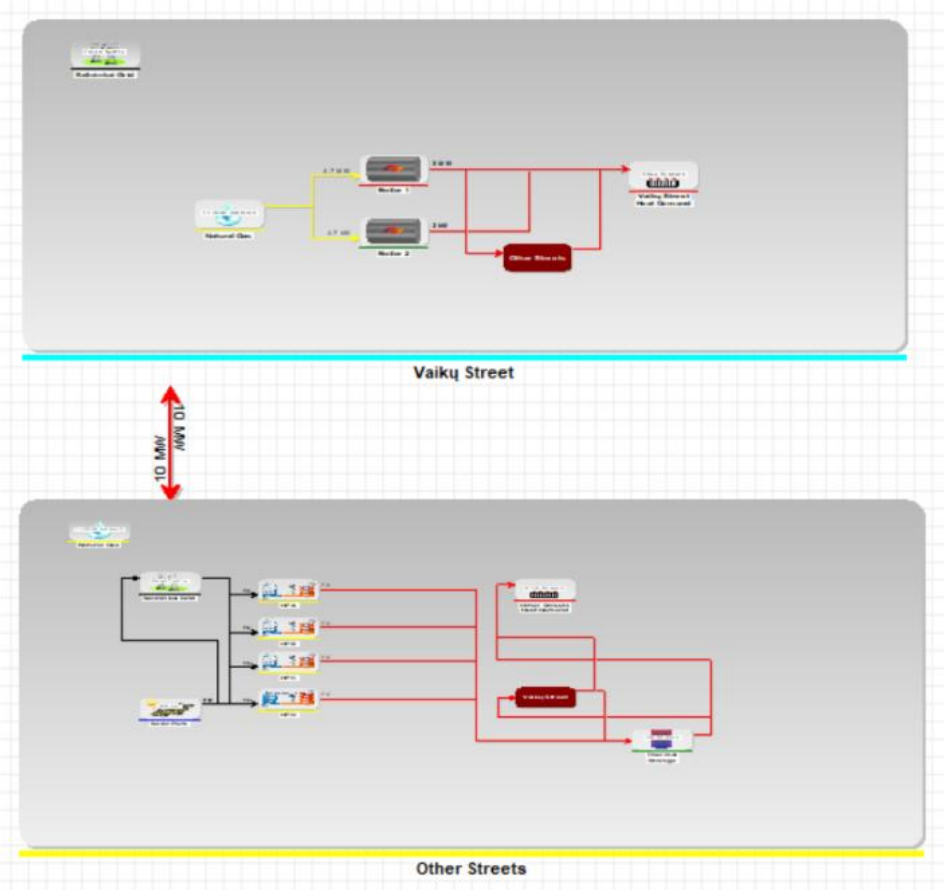


*Figure 16. Baseline System + HP + TES + PV Solar Park + Network Division*

This is to be noted that, in the EnergyPRO simulation circuit, the transmission line capacity is set as maximum as 10 MW to support required heat transfer through the transmission line though the length will be too short compared to the real world. Transmission loss is considered as 1% of transmission capacity (100 kW) in the simulation in addition to the existing transmission and distribution losses blended with the demand at heat generation end.

## 4.10 EnergyPRO simulation data collection and processing

The EnergyPRO software produces a comprehensive range of simulation outputs that are essential for evaluating the technical, economic, and environmental performance of complex energy systems like the Salininkai District Heating Network (DHN). After configuring the model with accurate inputs—such as hourly demand profiles, technology capacities, fuel types, operating schedules, and environmental conditions—the software generates hourly, daily, monthly, and annual data on several key performance metrics. These include but are not limited to heat production and consumption, boiler efficiency at varying loads, fuel consumption by type, electricity usage and generation, thermal energy storage (TES) charge/discharge cycles, $CO_2$ emissions, and overall system efficiency.

The simulation results can be exported in tabular form (typically as Excel or CSV files) and visualized using EnergyPRO's built-in graphical tools or external platforms like Microsoft Excel or MATLAB for advanced analysis. These outputs allow researchers to assess system behavior under varying operational strategies, compare multiple scenarios side by side, and perform sensitivity analyses. Key sustainability indicators—such as the Primary Energy Factor (PEF) and $CO_2$ savings—can be calculated directly from the output data. For the Salininkai DHN study, such output metrics are critical in identifying system bottlenecks, quantifying the benefits of heat pump and TES integration, and justifying the design of a dual-zone network.

### *4.10.1 Simulation data collection*

As there are a lot of analysis options in EnergyPRO, however, in this study, performing thermal analysis using EnergyPRO was the key focus. Therefore, the data input and simulated data collection is emphasized on mostly the thermal part. There are two major types of data those were collected and considered – the graphical representations and hourly raw data for every hour of the designated period, i.e., the year 2021.

In the graphical part, we collected generated charts for heat production, electricity consumption and natural gas consumption from the option ***Reports >***

***Production, graphic*** option (Figure 17). In these graphical content, instantaneous (at every hour) heat production or electricity / natural gas consumption is plotted for the total period in an hourly duration.

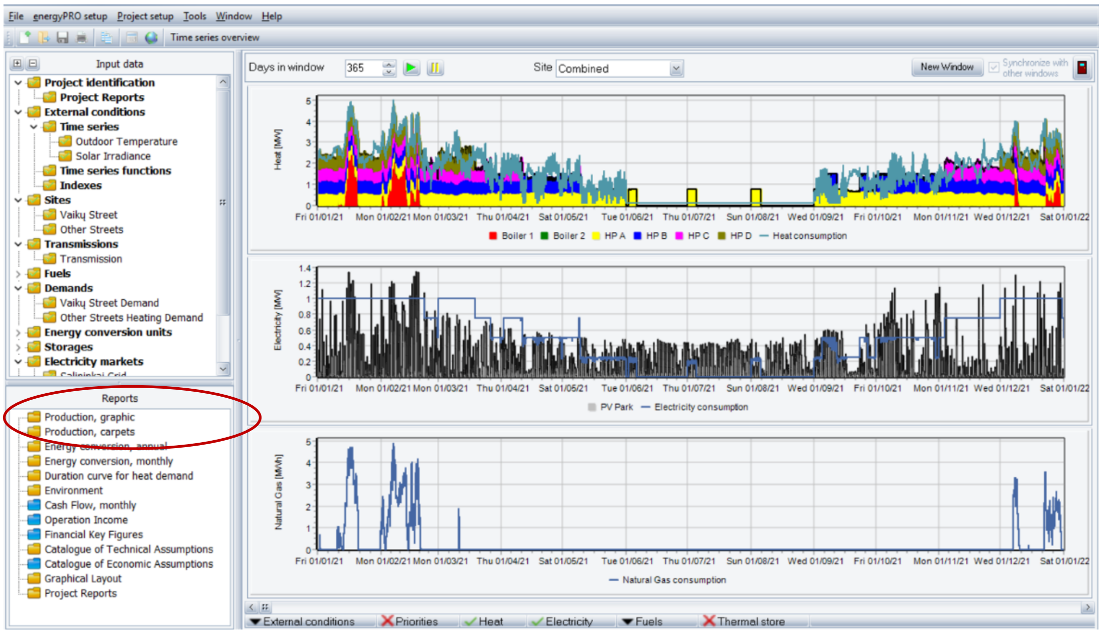


*Figure 17. EnergyPRO Reports (Graphical Representation)*

Similarly, from ***Reports > Duration curve for heat demand***, another graphical representation is collected which represents – for how many hour each unit operated with operating duration (Figure 18).

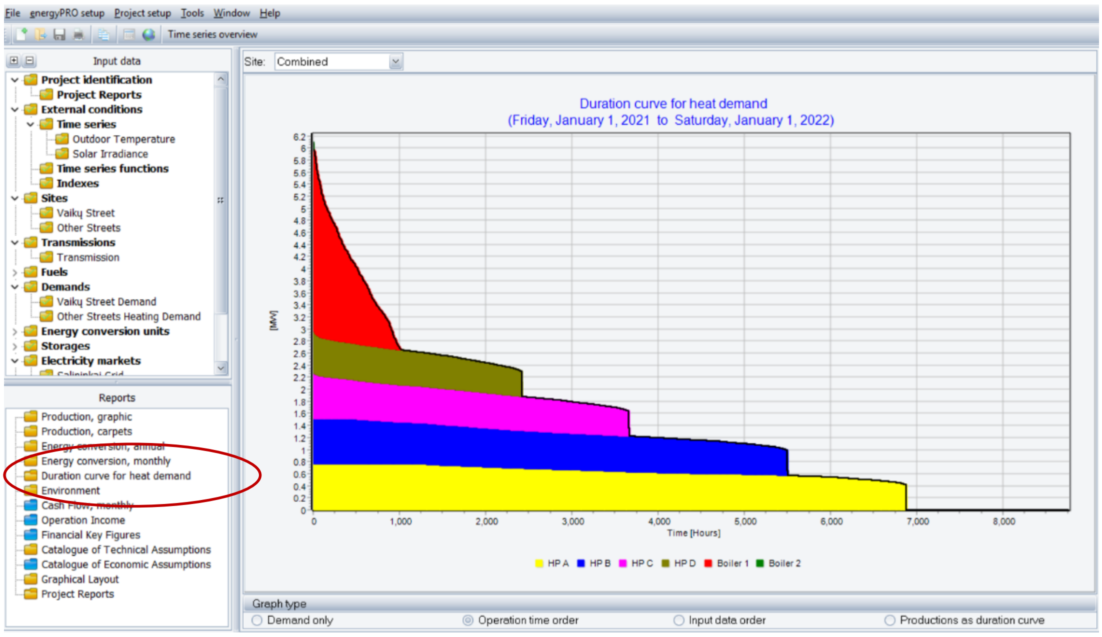


*Figure 18. EnergyPRO Reports (Duration Curve)*

By right clicking on each graphical representation, we can get "Edit Graphics" option which will guide us to various information including detailed dataset (Figure 19) for further processing through different applications like Microsoft Excel.

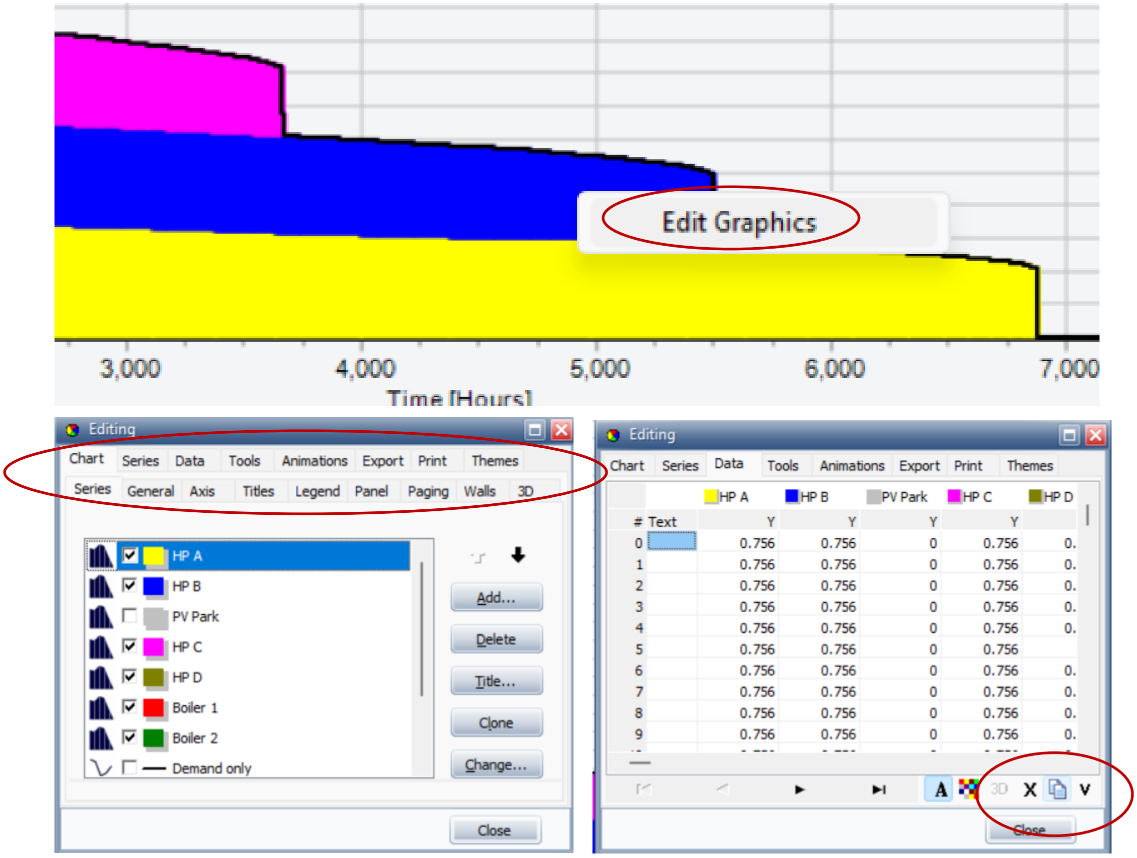


*Figure 19. Data Collection from EnergyPRO*

Important dataset categories for further analysis are as below but not limited to:

- Hourly heat consumption in MWh.
- Hourly heat production by each boiler and HP in MWh.
- Hourly content of TES in MWh.
- Hourly natural gas consumption by each boiler in MWh.
- Hourly electricity consumption by each heat pump in MWh.
- Hourly solar electricity production in MWh.
- Hourly run-duration for every energy conversion units in hours.
- Annual report for gas consumption in $m^3$, total turn-on's, etc.

### *4.10.2 Boiler performance evaluation – calculating efficiency*

From the collected simulation data, it is possible to calculate instantaneous (hourly) or yearly average value of boiler efficiency, for each boiler as well as for combined boiler system. The following formula ($Eq. 4$) is used to calculate boiler efficiency:

$$Boiler\ efficiency = \frac{Heat\ production\ (MWh)}{Natural\ gas\ consumption\ (MWh)} \qquad (Eq. 4)$$

### *4.10.3 Heat pump performance evaluation – calculating COP*

From the collected simulation data, it is possible to calculate instantaneous (hourly) or yearly average value of heat pumps' COP, for each heat pump as well as for combined heat pump system. The following formula ($Eq. 5$) is used to calculate heat pump COP:

$$Heat\ pump\ COP = \frac{Heat\ production\ (MWh)}{Electricitey\ consumption\ (MWh)} \qquad (Eq. 5)$$

### *4.10.4 Calculation of primary energy*

To evaluate the primary energy performance of the Salininkai District Heating Network, both natural gas and electricity consumption must be converted into their respective primary energy equivalents using standard Primary Energy Factors (PEFs). According to the directives of ISO 52000-1 (2017) and European Commission (2023), natural gas has a PEF of 1.0, reflecting direct usage with minimal upstream losses, while grid electricity typically carries a PEF of 1.8 to 2.1, depending on the national energy mix. For Lithuania, a representative value of 1.8 can be assumed based on the country's renewable share and grid composition, however, in this study this value is assumed as 2.1 for a conservative approach. Thus, 1 MWh of electricity consumed by the heat pump corresponds to 2.1 MWh of primary energy, while 1 MWh of natural gas input remains unchanged. This conversion enables consistent assessment of system sustainability, overall efficiency, and benchmarking against EU decarbonization targets (Latõšov et al., 2017).

For on-site solar photovoltaic systems, the Primary Energy Factor (PEF) is typically considered 1.0, as the electricity is generated directly from a renewable source without conversion losses, aligning with EU sustainability accounting standards (European Commission, 2023; ISO 52000-1, 2017). As the generated solar power will be in offset-effect with consumed grid power, beside considering these points, following formula ($Eq. 6$) is used to calculate primary energy requirement for the overall system:

$$\begin{gathered} Primary\ energy = Natural\ gas\ consumption\ in\ MWh \\ +\{(Electricity\ \text{consumption} - Solar\ power\ generation) \times 2.1\} \\ +Solar\ power\ generation \end{gathered} \qquad (Eq. 6)$$

### *4.10.5 System performance evaluation – calculating system efficiency*

Overall system efficiency represents the ratio of actual heating demand, i.e., the added value of DHW heating demand with space heating demand and required primary energy. Therefore, the following formula ($Eq. 7$) is used to calculate the overall system efficiency:

$$System\ efficiency = \frac{(Space\ heating\ demand + DHW\ demand)\ in\ MWh}{Required\ primary\ energy\ in\ MWh} \qquad (Eq. 7)$$

### *4.10.6 Calculation of overall system PEF*

Overall system PEF is the ratio of primary energy input to the system and useful heat delivered to the system. In the system PEF calculation, it is needed to consider the distribution and transmission loss with the space heating demand and DHW demand. Therefore, the following formula ($Eq. 8$) is used to calculate the overall system PEF:

$$System\ PEF = \frac{Primary\ \text{energy}\ input\ to\ the\ system\ in\ MWh}{Demand\ of\ (Space\ heating + DHW + T\&D\ Loss)\ in\ MWh} \qquad (Eq. 8)$$

## 4.11 Economic evaluation methodology

In this study, the economic evaluation of the Salininkai District Heating Network (DHN) is approached through a comparative analysis of energy-related operational costs across different system configurations. Rather than conducting a full life-cycle cost analysis or detailed investment appraisal, the methodology focuses on the variable cost of energy consumption—specifically comparing the cost implications of natural gas usage, electricity consumption for heat pumps, and electricity generation from solar photovoltaic (PV) systems.

For each scenario modeled in EnergyPRO (e.g., baseline with gas boilers, integration of 1 MW electric heat pump and 3,000 $m^3$ TES, addition of 500 kWp solar PV, and dual-site segmentation), the annual energy consumption by source is extracted and multiplied by corresponding unit prices to estimate total energy costs. The prices used are based on average Lithuanian energy tariffs. Though the energy tariffs are variable for both natural gas and electricity, however, at the time of analysis cost of natural gas was at approximately €0.55/$m^3$ and electricity at €0.148/kWh (Tarifas, 2025) inclusive of VAT, adjusted where applicable for PV self-consumption or offsetting. This cost comparison allows the identification of scenarios that offer the lowest operational energy expenses, thus supporting decisions on system upgrades from both technical and financial sustainability perspectives. Although capital investment and payback periods are not evaluated in this scope, this cost-based methodology offers an essential first-layer economic insight into the benefits of transitioning toward a renewable-integrated DHN.

## 4.12 Environmental impact assessment methodology

It is important to highlight that the modernization of the Salininkai District Heating Network has not only brought about significant technical and economic improvements but also carries substantial implications for environmental sustainability. As energy systems shift away from fossil fuel dependency toward renewable and low-carbon alternatives, evaluating their environmental impact becomes critical. The following part of the document will analyze the comparative environmental performance of the existing gas-based system versus the proposed renewable-integrated configuration, with a focus on emissions, primary energy usage, and long-term sustainability metrics.

Life Cycle Assessment (LCA) is critically important for conducting a comprehensive Environmental Impact Assessment (EIA)—especially for energy systems like solar, heating networks, or buildings. While traditional EIA methods often focus only on local and operational emissions, LCA expands the boundary by including raw material extraction, manufacturing, transportation, usage, and end-of-life disposal or recycling. This holistic approach allows stakeholders to understand the total environmental burden of a system or product over its full lifespan.

However, in this study, Salininkai DHN is not swapping entire heating system or elements, rather it emphasizes on incorporating renewable technologies, storage systems and operational excellence to become a sustainable system. Therefore, while performing an LCA of the total scenarios, it will become complex and large in the context of this study. Still, without performing a proper LCA it won't be possible to holistically enlighten the field for EIA. Therefore, the LCA shall be performed in a customized manner.

#### *4.12.1 Important GHG emissions*

In Life Cycle Assessment (LCA) of energy systems—including solar PV, district heating, and fossil fuel-based technologies—carbon dioxide ($CO_2$) is consistently the dominant contributor to greenhouse gas (GHG) emissions. This is primarily because $CO_2$ is released directly during fuel combustion, electricity generation, and manufacturing processes such as steel, aluminum, and cement production. According to the IPCC's Sixth Assessment Report (IPCC, 2023), and standardized methodologies outlined in ISO 14067 (2018), the most commonly reported GHGs in LCA include $CO_2$, methane ($CH_4$), nitrous oxide ($N_2O$), and various industrial gases (e.g., $SF_6$, HFCs). However, the global warming potential (GWP) of $CO_2$ is used as the baseline (GWP = 1), and its proportional contribution to total emissions is typically above 95% in most energy-related LCAs. For instance, studies by Fthenakis & Kim (2011) show that $CO_2$ accounts for 97–99% of all life cycle emissions in solar photovoltaic systems. Similarly, Gadd & Werner (2014) report that in district heating systems, particularly those dependent on fossil fuels or electricity from mixed grids, $CO_2$ contributes approximately 96–98% of the total life cycle GHG emissions, with $CH_4$ and $N_2O$ playing a minimal role.

The remaining impact—usually less than 3%—is attributed to high-GWP gases such as $CH_4$ (with GWP ~27–30) and $N_2O$ (~265–273), which may become more relevant in specific contexts like biogas or agriculture but are negligible in solar and conventional heating systems. Therefore, $CO_2$ is the principal focus in environmental impact calculations, and its reduction forms the cornerstone of climate mitigation strategies in energy infrastructure. Hence, in this study, we shall perform an LCA to calculate ton $CO_2$ equivalent GHG emissions.

### *4.12.2 Goal and scope of LCA*

In most LCA studies of energy technologies such as solar photovoltaic (PV) parks, heat pumps, and district heating systems, the operational phase and the manufacturing phase are the primary contributors to total environmental impact, especially in terms of greenhouse gas (GHG) emissions. For fossil fuel-based systems (like gas boilers or traditional district heating networks), the operational phase dominates—often contributing 80–90% or more of the total emissions—due to continuous combustion of fuels over the system's lifetime (Gadd & Werner, 2014; IPCC, 2023).

Conversely, in renewable-based systems such as solar PV parks, the manufacturing phase accounts for the majority of the environmental impact. This is primarily due to energy-intensive processes involved in producing silicon wafers, module frames, inverters, and mounting structures. Studies by Fthenakis & Kim (2011) and the Brivio et al. (2024) show that for modern PV systems, the manufacturing stage accounts for 60–80% of the total life cycle $CO_2$-equivalent emissions, while operation contributes close to zero, and end-of-life (EoL) and maintenance together account for less than 10%.

Transportation (both for manufacturing and decommissioning) generally has a minor contribution, usually less than 5% of the total life cycle impact, unless the system components are shipped over large distances or by high-impact methods (e.g., air freight). The decommissioning/destruction phase, including recycling or disposal of modules or steel components, contributes slightly to emissions but is increasingly mitigated by circular economy practices. According to the IRENA-IEA-PVPS (2016), recycling PV modules can offset more emissions than it generates, further reducing the end-of-life impact. Maintenance emissions (e.g., for inverters or pumps) are also low, typically under 5%, and often modeled as recurring material or energy inputs. Therefore, in this study, we shall perform an LCA to calculate ton $CO_2$ equivalent GHG emissions only in manufacturing including related transportation, operation and maintenance phases of life cycle.

Based on the above arguments and facts, the goal and scope of this LCA analysis can be stated as:

"*By performing this customized Life Cycle Assessment (LCA) it is expected to get the interpreted result which will give clear indication of Environmental Impact Assessment (EIA) of Salininkai District Heating Network for all the stages, i.e., Baseline, Stage-1, Stage-2 and Stage-3, of $CO_2$ emission data considering manufacturing, related transportation, operation and maintenance phases of every elements' lifespan.*"

### *4.12.3 Inventory analysis for boilers, heat pumps, TES and PV*

The following inventory table (Table 4) is used for LCA inventory analysis from another study (Reza & Rogoža, 2024). A scaling factor is used to get the estimate on amount of material used in the study. This table represents required materials for each individual element undergo LCA in every stage of sustainable modernization of Salininkai DHN. Each material has its own lifespan, and individual GHG emission values at every phase of lifecycle. However, only $CO_2$ emission for manufacturing including related transportation, energy usage during operation and required maintenance for particular element is planned to be calculated. For photovoltaic, rather doing detailed inventory analysis, it is preferred to follow previous scholars. Life-cycle emissions of solar panels in Europe are about 1.2 ton $CO_2$ /kWp equivalent (Heath et al., 2016) and maintenance is assumed 1% of manufacturing emission over 20 years. LCA is calculated based on 20 years lifespan of overall system.

*Table 4. LCA Inventory Analysis (Material Used)*

**Baseline:** Only boilers are in operation
**Stage-1**: Boilers + HP + TES in operation
**Stage-2:** Boilers + HP + TES + PV in operation
**Stage-3:** HP + TES + PV in operation

| Inventory Analysis | | Production | | | | Operation | | | | Maintenance | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Boiler | Heat Pump | Thermal Storage | Photovoltaic | Boiler | Heat Pump | Thermal Storage | Photovoltaic | Boiler | Heat Pump | Thermal Storage | Photovoltaic | Baseline | Stage-1 | Stage-2 | Stage-3 |
| ABS | kg | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 1,101 | 1,101 | 1,101 | - |
| Aluminium | kg | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 1,791 | 1,791 | 1,791 | - |
| Brass | kg | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 3,022 | 3,022 | 3,022 | - |
| Copper | kg | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 2,153 | 9,410 | 9,410 | 7,258 |
| Electronics | kg | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | 233 | 233 | 233 | - |
| EPDM | kg | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 60 | 60 | 60 | - |
| Low alloyed steel | kg | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 21,506 | 27,957 | 27,957 | 6,451 |
| Electricity | MJ | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 75,106 | 176,712 | 176,712 | 101,606 |
| Natural gas | MJ | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 109,604 | 391,844 | 391,844 | 282,240 |
| PVC | kg | ● | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 5 | 327 | 327 | 323 |
| Silicone | kg | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 108 | 108 | 108 | - |
| Stainless steel | kg | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 6,332 | 6,332 | 6,332 | - |
| Cabling | kg | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 350 | 350 | 350 | - |
| Elastomer | kg | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | - | 3,226 | 3,226 | 3,226 |
| HDPE | kg | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | - | 101 | 101 | 101 |
| Lubricating oil | kg | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | - | 544 | 544 | 544 |
| R-134a | kg | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | ○ | ○ | - | 988 | 988 | 988 |
| Reinforcing steel | kg | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | - | 24,192 | 24,192 | 24,192 |
| TES Material | kg | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ | - | 183,200 | 183,200 | - |
| PV System | | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● | | | | |
| Electricity | kWh/y | ○ | ○ | ○ | ○ | ● | ● | ○ | ● | ○ | ○ | ○ | ○ | 20,586 | 4,604,586 | 3,874,586 | 3,756 |
| Natural gas | $m^3$/y | ○ | ○ | ○ | ○ | ● | ○ | ○ | ○ | ○ | ○ | ○ | ○ | 1,855,521 | 146,630 | 146,630 | - |

### *4.12.4 GHG emission data collection*

GHG emission data is collected using the SimaPro 9.4.0 software platform, applying the IMPACT 2002+ method, which integrates midpoint and endpoint approaches to assess climate change, human health, ecosystem quality, and resource depletion. The data inventory for this Life Cycle Assessment (LCA) includes all material, energy, and emission-related flows associated with the various system components of the Salininkai District Heating Network (DHN) across four operational scenarios: Baseline, Stage-1, Stage-2, and finally Stage-3.

The process begins with the Baseline, which involves only the operation of two natural gas boilers. Emission data for each material listed in Table 1 (e.g., steel, copper, brass, ABS, electronics) is collected based on the quantities used in boiler production, installation, and operation. Fuel consumption and electricity usage for boiler operation are included, along with relevant maintenance materials like lubricating oil and cabling. The primary energy carriers are natural gas ($m^3/y$) and electricity (kWh/y), used exclusively for boiler control systems.

For Stage-1, both boilers and heat pumps are in operation, along with the newly introduced thermal energy storage (TES) system. In this phase, additional materials such as R-134a refrigerant, reinforcing steel, and TES insulation materials are included in the inventory. Emission factors are applied to production, operational, and maintenance data. Since both natural gas and electricity are consumed for heating in this hybrid configuration, their environmental burdens are calculated accordingly. Equipment like electronics and elastomers is added for the heat pump assemblies and TES control systems.

In Stage-2, a 500 kWp photovoltaic (PV) system is integrated while both boilers and heat pumps remain in use. Additional material flows are incorporated for PV panel production, mounting structures (aluminum and stainless steel), and HDPE conduits. This stage reflects increased electricity use but partially offsets it through renewable generation. SimaPro is used to allocate PV-related emissions over the 25-year operational life. Cable and electronic components are adjusted to reflect additional control and inverter systems. The PV system is assumed to have negligible operational emissions, though maintenance and inverter replacement are modeled.

Finally, in Stage-3, only the heat pumps, TES, and PV system remain in operation, completely replacing the gas boilers. Accordingly, emissions from natural gas combustion are excluded in this stage. Material use from boiler production and maintenance phases are removed, while the usage of TES and PV systems remains unchanged from Stage-2. The emission data for Stage-3 focuses on electricity consumption for heat pumps, PV contribution, and ongoing maintenance materials like R-134a and elastomers. This scenario reflects the lowest fossil fuel dependency and thus provides the benchmark for sustainable modernization.

For each stage, inputs are categorized by life cycle phase—production, operation, and maintenance—and matched with material- and energy-specific emission factors from the Ecoinvent 3.8 database (Wernet et al., 2016) integrated into SimaPro. This structured approach ensures the comparability and consistency of GHG emission calculations across all system transformation stages.

### *4.12.5 GHG emission data calculation methodology*

After completing the data collection using SimaPro 9.4.0 and the IMPACT 2002+ methodology, all life cycle inventory (LCI) data—covering material usage and energy consumption—were exported and processed in Microsoft Excel. Since the study focuses on the climate change impact category, all data were converted to a unified metric of tons of $CO_2$-equivalent (t $CO_2$ eq). This approach ensured consistent comparison across all four operational scenarios: Baseline, Stage-1, Stage-2, and Stage-3.

For each of these scenarios, the total $CO_2$ emissions from manufacturing were calculated first. This included emissions associated with the production and delivery of major system components such as natural gas boilers, heat pumps, thermal energy storage (TES), and photovoltaic (PV) systems, based on the quantities listed in the LCA inventory table. The environmental impact of each material was traced back to its origin using emission factors sourced from the Ecoinvent 3.8 database. Next, annual operational emissions were assessed for each stage. These were based on actual or modeled energy use, namely natural gas ($m^3$/year) and electricity (kWh/year), as reported in the respective scenarios. The emission intensity of each energy type was applied to calculate yearly operational emissions.

To complete the life cycle scope, maintenance-related emissions were estimated over a 20-year system life. This included recurring use of lubricants, refrigerants, and electronics, as well as potential part replacements such as inverters or control systems. The same emission factors and material quantities were used to ensure consistency. Finally, the emissions from manufacturing, operation, and maintenance were summed for each stage. This allowed for a full life cycle comparison of all four scenarios, enabling an evaluation of how each modernization phase reduces or shifts the environmental burden of the Salininkai District Heating Network.

### 4.13 Sensitivity analysis assumptions and methodology

A critical component of this study involves conducting a sensitivity analysis to evaluate the system's performance under varying ambient temperature conditions, which directly and indirectly affect several operational parameters of the Salininkai District Heating Network (DHN). The analysis is particularly important in assessing the adaptability of the proposed modernization stages—including gas boilers, heat pumps, thermal energy storage (TES), and photovoltaic (PV) systems—under realistic seasonal fluctuations.

Firstly, outdoor temperature is a primary determinant of space heating demand. For example, analysis of 2021 hourly data from the Salininkai DHN shows that when average outdoor temperatures dropped below -5 °C in January, daily heating demand peaked around 6.2 MWh/day, whereas in milder conditions (e.g., March, +4 °C), demand dropped to under 2.5 MWh/day. This significant variation requires heating systems to be responsive across a wide load range. Boiler performance is known to be nonlinear under part-load conditions; condensing gas boilers typically achieve peak efficiency (~80%+) when operating at 70–80% load with return temperatures below 57 °C, but their efficiency declines at lower loads due to increased cycling and thermal losses (Bastero & Paepe, 2021; Gadd & Werner, 2014).

Heat pump performance, particularly that of air-to-water systems, is even more temperature-sensitive. The Coefficient of Performance (COP) decreases with lower ambient temperatures due to the increased energy required for heat extraction and compression. For instance, according to the RTXC XE-EC-R513A performance datasheet used in this study, the COP drops from 3.5 at +7 °C to approximately 2.1 at -7 °C. This variation affects both electricity demand and the system's primary energy consumption, which must be captured in a dynamic modeling environment like EnergyPRO to assess seasonal system resilience (Sarbu & Sebarchievici, 2014).

Moreover, solar PV system performance is directly influenced by both solar irradiance and ambient temperature. In Salininkai, solar irradiance varies significantly throughout the year—from monthly averages of 20–30 kWh/m² in December to 150–160 kWh/m² in June, based on PVGIS 2021 data. Although solar output increases with irradiance, PV module efficiency decreases by ~0.4–0.5% per °C above standard test conditions (STC), according to Huld et al. (2011). Indirectly, reduced solar production in colder months coincides with peak heating demand, creating a supply–demand imbalance that underscores the importance of hybrid system flexibility and TES sizing.

However, Climate projections indicate that Lithuania is expected to experience a significant rise in average temperatures over the 21st century. Depending on global greenhouse gas emission scenarios, the anticipated increase in annual mean temperature by the end of the century ranges from approximately 1.2°C under optimistic scenarios to about 4.0°C under high-emission scenarios (Lithuanian Hydrometeorological Service under the Ministry of Environment, 2025).

Notably, the most substantial warming is projected during the winter months. For instance, average winter temperatures in Lithuania could rise by 3°C to over 7°C by 2071–2100 compared to 1961–1990, depending on the emission scenario and climate model used (ClimateChangePost, 2025). These temperature increases are expected to lead to more frequent heatwaves, with days exceeding 30°C becoming more common, particularly in southern and southeastern regions of Lithuania. Conversely, cold spells with temperatures below -15°C are projected to become less frequent, especially in urban areas like Vilnius (Hydrometeorological, 2023).

Based on these studies, we can predict that the possibility of decreasing the yearly average temperature in Salininkai is exceptionally low or zero, however, it may increase. Though it is a grave concern and a growing matter of fear to have warmer world, from the view of design perspective, in the modernized system with heat pumps, TES and photovoltaic integration we shall lessen the dependency on electricity even at a warmer air temperature.

In that regard, sensitivity analysis with a risen average temperature will certainly deliver output towards more sustainable system. Still, for the sake of design, a sensitivity analysis will be performed considering a -1°C reduction in average yearly temperature. A study published in Applied Energy indicates that a 1°C decrease in average outdoor temperature can lead to an approximate 3.7% increase in annual energy consumption for heating systems (Fikru & Gautier, 2015).

#### *4.13.1 Changed parameters for sensitivity analysis*

From hourly outdoor temperature data, 1°C will be deducted from every hourly value throughout the year 2021, and the time series for outdoor temperature will be replaced with the new temperature keeping all other parameters same.

#### *4.13.2 Probable impacts on network and interpretation*

Though this change is not practical because 1°C deduction from summer air temperature will not have any visible impact rather it will shift heat pumps operation by 1°C laterally. It can be predicted that the change will not be able to trigger boilers to run during summer. This change will take the winter season towards colder weather condition which may reduce heat pumps' COP to inoperative level and as a result boilers may get started. This may cause inefficient operation of heat pumps and variation of COP may be visible. This change will bring the autumn early and end the spring lately. This may cause toggle the system load on boiler and heat pumps which may cause lower boiler efficiency and heat pump COP. TES utilization can become inefficient as well.

### 4.14 Recommendation matrix

From the aforementioned part of the study, we can conclude that, the investigation of sustainable modernization options for Salininkai DHN is related to much more complex matters and after focusing on every single issue the indicators have been identified for the goal to achieve. In the following part of the document, the following matrix (Table 5) will guide us to choose the options for sustainable modernization of Salininkai DHN:

*Table 5. Sustainable Modernization Matrix*

| | Baseline → Stage-1 | Stage-1 → Stage-2 | Stage-2 → Stage-3 |
|---|---|---|---|
| Loss | ↓ Sustainable | ↓ Sustainable | ↓ Sustainable |
| Required Primary Energy | ↓ Sustainable | ↓ Sustainable | ↓ Sustainable |
| Overall System Efficiency | ↑ Sustainable | ↑ Sustainable | ↑ Sustainable |
| System PEF | ↓ Sustainable | ↓ Sustainable | ↓ Sustainable |

Based on the analysis presented in the Sustainable Modernization Matrix, each transition stage—from the existing baseline system through to Stage-3—has been evaluated across four key sustainability indicators. While all transitions are marked as "Sustainable," the matrix also includes directional arrows that reflect relative performance changes in specific areas. While all stages support a sustainable modernization path, the matrix highlights that sustainability is multi-dimensional improvements in one area may lead to challenges in another. Therefore, a balanced, data-driven approach is essential in guiding Salininkai DHN’s transition to a low-carbon, efficient, and resilient energy system. Further refinements—especially in thermal storage, control strategies, and load-balancing—are key to optimizing performance in Stage-3 and beyond.

This chapter has outlined a comprehensive and structured methodology for evaluating the current state and proposed modernization of the Salininkai District Heating Network. Through a combination of real operational data, professional simulation using EnergyPRO, and environmental evaluation via SimaPro and the IMPACT 2002+ method, each stage of system transformation—from the baseline gas boiler setup to hybrid and fully renewable configurations—has been systematically modeled and analyzed. The methodology ensures accuracy by integrating both engineering principles (e.g., heat loss analysis, COP variation, TES sizing) and life cycle thinking (e.g., material and emission tracking, primary energy equivalence). Sensitivity analysis further strengthens the robustness of the evaluation by capturing the influence of external variables such as ambient temperature on system demand, efficiency, and renewable performance. This well-rounded approach lays a solid foundation for the upcoming Results and Discussion chapters, where technical, economic, and environmental outcomes of each scenario will be critically compared to guiding sustainable decision-making for district heating modernization.

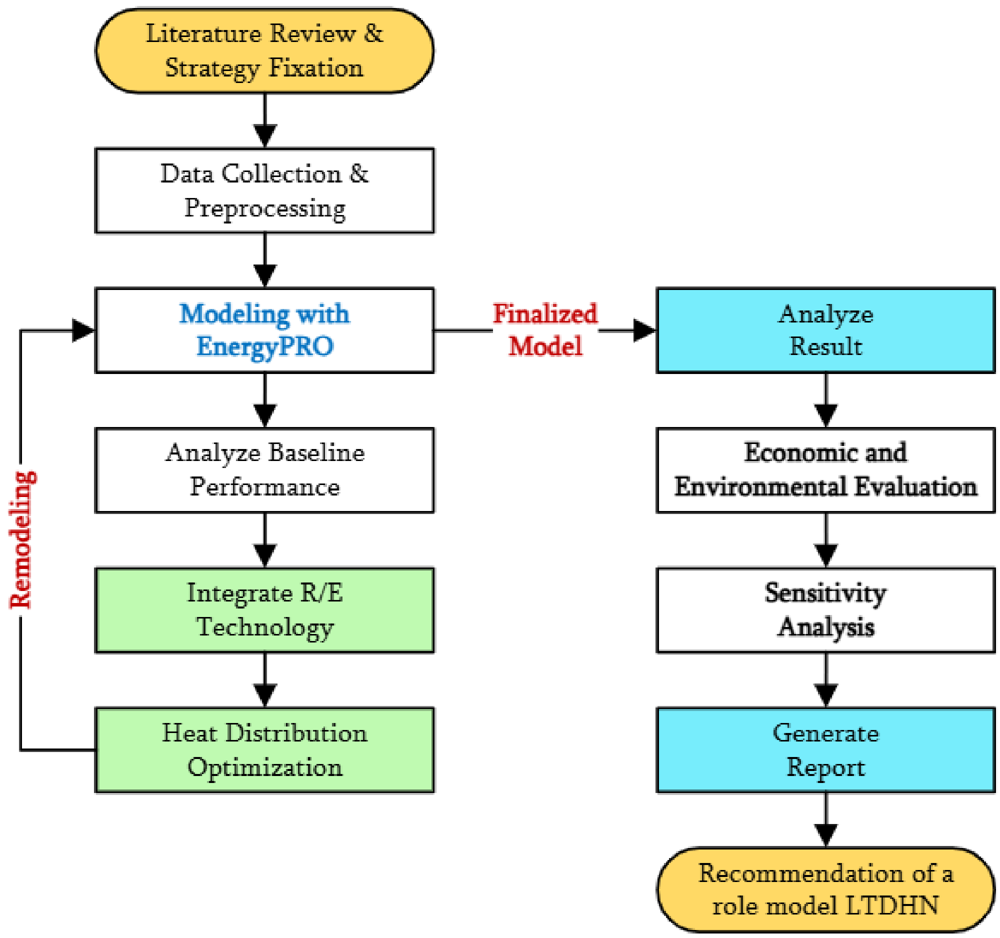


*Figure 20. Methodology of the Study*

This comprehensive methodology (Figure 20) ensures that the research not only identifies current challenges but also provides actionable insights for long-term sustainability. EnergyPRO generates detailed reports, while Excel visualizes efficiency and economic performances. Based on findings, recommendations focus on renewable integration, insulation upgrades, and optimized configurations to ensure cost-effective, environment friendly and sustainable solutions for the Salininkai DHN which will be a role-model LTDHN.

# 5. Results of the Study

This part presents the findings from the analysis of the Salininkai District Heating Network (DHN). The results are derived from data analysis, simulations, and system modeling using EnergyPRO and finally different plotting through Microsoft Excel. These findings address the research objectives, including system performance, the impact of integrating an electric air-to-water heat pump, thermal energy storage, solar park, and potential optimizations in heat distribution.

## 5.1 EnergyPRO simulation results of baseline system

The Salininkai District Heating Network operates two natural gas boilers, each with a capacity of 4.7 MW and an efficiency of 85%. Based on efficiency versus load curves, boilers generally achieve optimal efficiency when operating at 70–80% of their full load. For these boilers, this corresponds to a heat output of approximately 2.8 MW to 3.2 MW. To simplify operations, the peak delivery capacity of a single boiler as 3 MW is considered as discussed in Methodology section (sub-section 4.2).

Under normal conditions, one boiler efficiently manages heat demands up to 3 MW. However, during colder winter months, when the heat demand exceeds 3 MW due to low outdoor temperatures and high energy consumption in poorly insulated buildings, the second boiler is activated to meet the additional demand. Hence, in the EnergyPRO simulation it is designed to get 3 MW heat output from each boiler and the first boiler is prioritized over the second boiler. The following figure (Figure 21) represents the plotting of heat production by each of the boilers at every instance of heat consumption for the year.

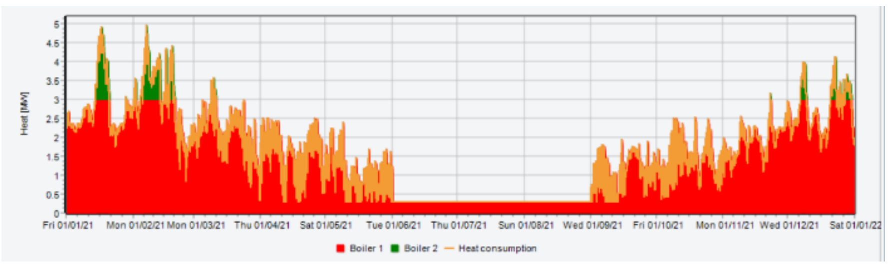


*Figure 21. Baseline Heat Production*

According to this report, boiler 1(red one) supplies the majority of the required heat as it was set as priority one. In any particular instance, when the required load is more than 3 MW, the boiler 2 (green one) came into operation and delivered the required heat. From the annual report of the EnergyPRO simulation, it is observed that the maximum heat demand was 5.0 MW and total heat demand was 13,265 MWh. The first boiler delivered 12,775.8 MWh after running for the whole year (8,760 hours) whereas the second boiler delivered only 489.2 MWh of total heat demand and it ran 746 hours (8.5% of the year). The figure (Figure 22), i.e., the duration curve report represents comparison of total operational period of the energy conversion units

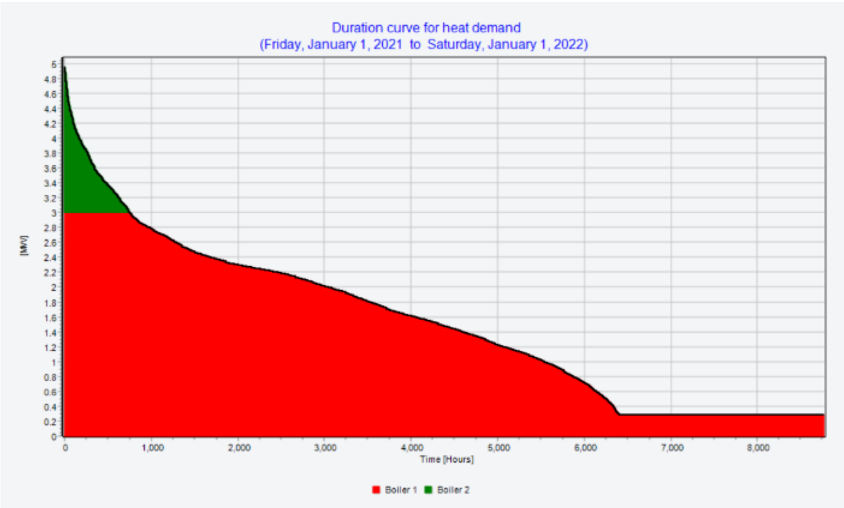


*Figure 22. Baseline Duration Curve*

From these reports and short descriptions, it can be concluded that currently two boilers are in operation to meet the heat-demand for Salininkai District Heating Network according to set priority and other settings. The following figure (Figure 23) shows the natural gas consumption over the year. It is found that, during non-heating season, there is nearly a steady consumption throughout the period and that is due to DHW and related circulation loss.

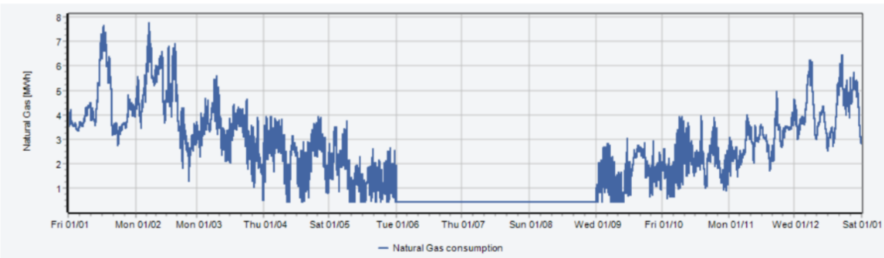


*Figure 23. Baseline Natural Gas Consumption*

From the annual report, we also found that natural gas consumption for the boiler 1 is around 1,787,096 $m^3$ and for the boiler 2 is 68,425 $m^3$. In total 1,855,521 $m^3$ natural gas is consumed throughout the year by both of the boilers which is equivalent to 20,782 MWh of primary energy. Therefore, this can be stated that, 20.782 GWh primary energy is used to meet 11.711 GWh of heat demand for space heating and DHW which resulted in an overall system efficiency value of 56% ($Eq. 7$). Again, using the same primary energy, these boilers delivered 13,265 GWh of heat to the overall system including 1,554 GWh of transmission and distribution loss which resulted in a PEF value of 1.57 ($Eq. 8$) (Figure 24).

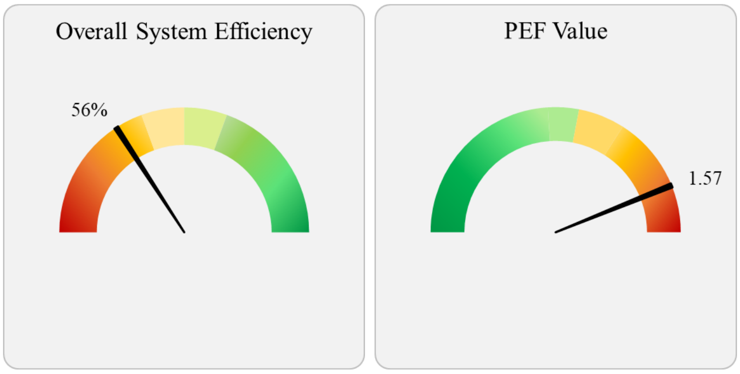


*Figure 24. Baseline - Overall System Efficiency and PEF*

In this calculation, the ratio of demand (required heat for space heating and DHW) and production represents the overall system efficiency ($Eq. 7$). And, the PEF represents the ratio of required primary energy and usable energy, i.e., demand for space heating and DHW, and the loss ($Eq. 8$). The Primary Energy Factor (PEF) is a critical metric in evaluating the sustainability of energy systems, including district heating networks (DHNs). A lower PEF indicates that less primary energy is required to deliver a unit of usable energy, signifying higher efficiency and reduced environmental impact. Therefore, reducing the PEF of a DHN is directly associated with enhancing its sustainability. Latõšov et al. did a study in 2017, and the study clearly revealed this information. From the above scenario (Figure 24), it can clearly be stated that the system is very inefficient and very unsustainable.

Boiler efficiency is calculated following equation $Eq. 4$ and found 64% for both the boilers and in combined situation as well. The hourly frequency also remained 64%

for individual and combined scenario. Combined heat production and frequency is plotted in the following picture (Figure 25).

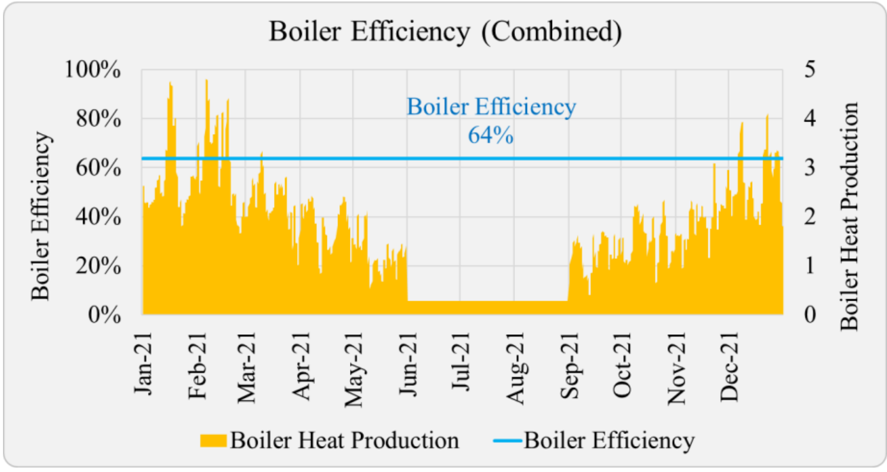


*Figure 25. Baseline - Boiler (Combined) Heat Production and Efficiency*

The data suggests that the current boiler configuration is suboptimal for year-round performance, especially given the seasonal variation in load. It strongly supports the case for integrating thermal energy storage (TES) and heat pumps, which can handle low-demand periods more efficiently and stabilize load profiles, ultimately improving system-wide energy performance and reducing fuel consumption.

## 5.2 EnergyPRO simulation results for Stage-1

When this heat pumps are given in operation with the earlier priority than the boilers, and with a thermal storage of 3,000 m$^3$ capacity with some storage loss, the EnergyPRO simulation results are quite interesting to see. The following figure (Figure 26) represents the EnergyPRO simulation plotting of heat production of each of the energy conversion units at every instance of heat consumption.

According to set priority, first HP-A (the first heat pump) came in operation and delivered its maximum. As the demand rose, HP-B came in operation and gradually reached its peak. Similarly HP-C and HP-D, i.e., all four heat pumps came in operation. When demand rose above their combined production, B-1 (the first boiler) came in operation and delivered its maximum. The report says that B-2 didn't come in operation which means combined production of four heat pumps and B-1 was sufficient enough to meet the demand and also had opportunity to fill TES with the remaining hot water. Thus the system came in operation.

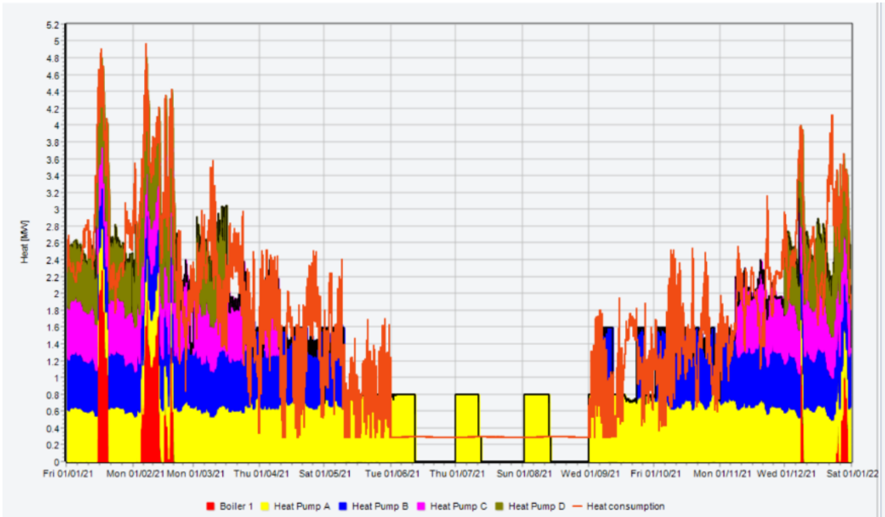


*Figure 26. Stage-1 Heat Production*

In the annual report (Figure 27) of the EnergyPRO simulation, we found that the maximum heat demand was 5.0 MW and total heat demand was 13,265 MWh where demand for space heating was 8,288 MWh, demand for DHW was 3,423 MWh and loss was 1,554 MWh. The heat pump A, B, C and D delivered 5,151.4 MWh, 3,630.4 MWh, 2,133.2 MWh and 1,362.2 MWh respectively whereas the first boiler delivered only 1,048.2 MWh and the second boiler did not deliver any heat to the network.

**Calculatedperiod:** 01/2021 - 12/2021

| | |
|---|---|
| **Heatdemands:** | |
| Space Heating | 8,288.0 MWh |
| DHW | 3,423.0 MWh |
| Distribution Loss | 1,554.0 MWh |
| Total | 13,265.0 MWh |
| Max heat demand | 5.0 MW |
| **Heatproductions:** | |
| Boiler 1 | 1,048.2 MWh/year |
| Boiler 2 | 0.0 MWh/year |
| Heat Pump A | 5,151.4 MWh/year |
| Heat Pump B | 3,630.4 MWh/year |
| Heat Pump C | 2,133.2 MWh/year |
| Heat Pump D | 1,362.2 MWh/year |
| Heat Storage Loss (total for site) | -60.5 MWh/year |
| Total | 13,265.0 MWh/year |

*Figure 27. Stage-1 Annual Report*

The following figure (Figure 28), i.e., the duration curve report represents a comparison of the total operational period of all the energy conversion units.

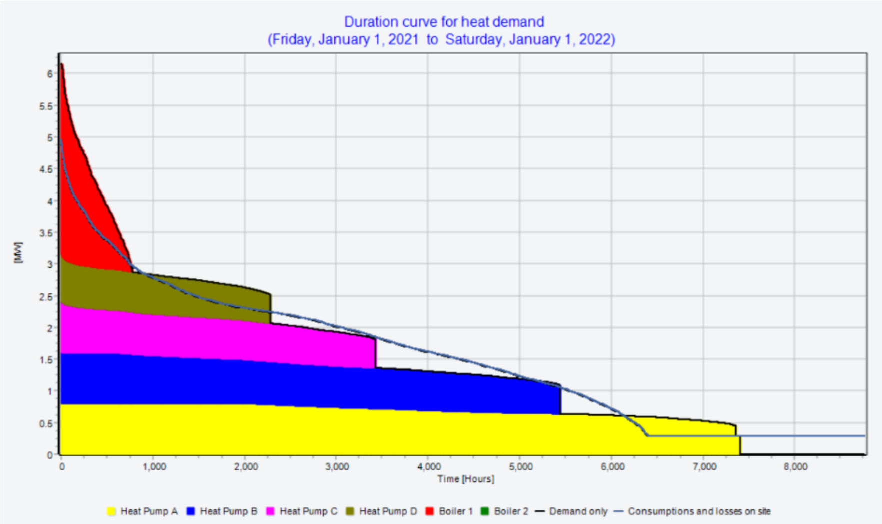


*Figure 28. Stage-1 Duration Curve*

The duration curve explains the set priority in the EnergyPRO simulation clearly. We did the priority setup in sequence HP-A>HP-B>HP-C>HP-D>B-1 >B-2 from left to right, i.e., in response to demand the Heat Pump A (HP-A) will response first, B-2 (Boiler 2) will response at the last, and so on. We found that, HP-A ran maximum for 7,437 hours (84.9% of the year), then HP-B ran for 5,441 hours (62.1%) and then HP-C (3,429 hours, 39.1%) and HP-D (2,281 hours, 26%). B-1 ran for 793 hours (9.1%) and B-2 didn't run. It is pretty visible that boiler run hours decreased significantly (92% less) from the baseline situation.

If we compare the natural gas consumption before and after incorporation of heat pumps, we shall get noticeable changes which are represented in the following figures (Figure 23 and Figure 29).

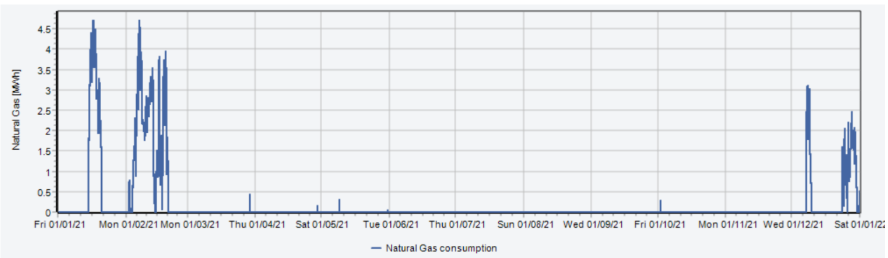


*Figure 29. Stage-1 Natural Gas Consumption*

But previously no electricity consumption was there but incorporation of heat pump incurs electricity consumption, and the following figure (Figure 30) represents electricity consumption from EnergyPRO simulation. From the annual report, we observed that heat pump A, B, C and D would require 1,785.6 MWh, 1,359.2 MWh, 864.1 MWh and 574.8 MWh respectively, i.e., a total of 4,584 MWh of electricity would be required.

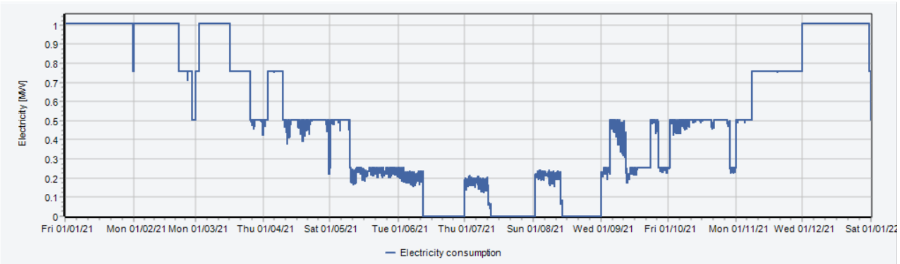


*Figure 30. Stage-1 Electricity Consumption*

After incorporating the heat pumps and thermal storage, these boilers consumed 1,642 MWh of energy from fuel and the heat pumps consumed only 4,584 MWh of electricity. Converting energy from electricity to primary energy using $Eq. 6$, it is found that total energy requirement to produce demanded heat is 11,268 MWh considering energy from fuel and electricity together which results in an overall system efficiency of 104% (using $Eq. 7$) (Figure 31). Similarly, the PEF value reduced down to 0.85 (using $Eq. 8$) (Figure 31) from the existing value of 1.57 which indicates the overall system is now converted from unsustainable to sustainable (European Commission, 2023; ISO 52000-1, 2017).

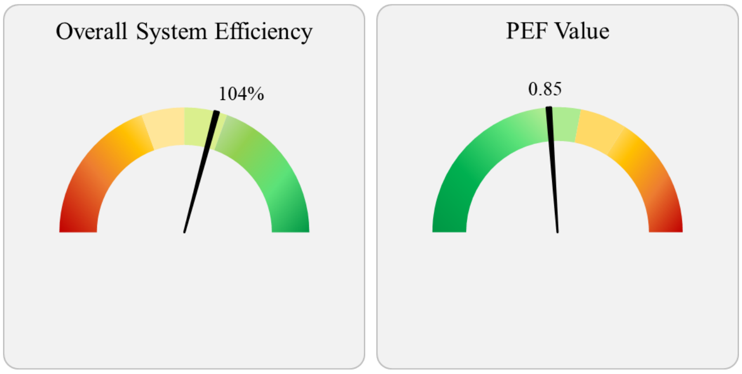


*Figure 31. Stage-1 Overall System Efficiency and PEF*

## 5.3 EnergyPRO simulation result for Stage-2

From the simulation result, we found that 500 kWp solar generated 730.9 MWh throughout the year according to PVGIS data of solar irradiation and the electricity consumption from EnergyPRO simulation is represented in the following figure (Figure 32) where solar output and electricity consumption is shown.

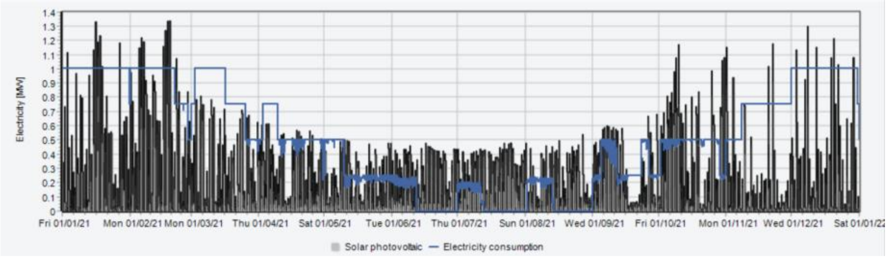


*Figure 32. Stage-2 Electricity Consumption*

For further analysis purpose same data is collected – hourly electricity demand, at the same instant photovoltaic solar output and number of HP operated at that particular time as an additional one. Those three are plotted (Figure 33):

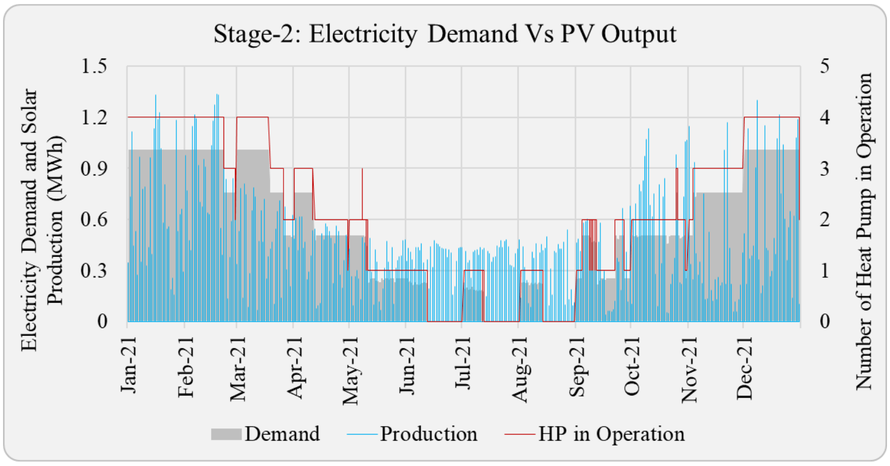


*Figure 33. Stage-2 Electricity Demand, PV Output & Running HP Number*

The chart illustrates the dynamic interaction between the Salininkai District Heating Network’s electricity demand, solar photovoltaic (PV) generation, and heat pump operation throughout the year 2021. The grey area represents the hourly electricity demand from heat pumps, the blue vertical lines indicate hourly solar electricity production from the 500 kWp PV system, and the red stepped line shows the number of heat pumps in operation on any given hour. During the cold months—particularly in January, February, and December—electricity demand peaks as all four heat pumps operate to meet the high heating requirements. However, solar PV output remains very low during this period due to limited irradiance and short daylight hours, which results in a high dependency on grid electricity. In contrast, during spring and summer (May through August), the demand for heating drops significantly, reducing the operational load on the heat pumps. During these months, solar PV output increases, frequently exceeding the electricity demand, and offering potential for grid export or storage utilization. This seasonal mismatch clearly highlights that PV production is highest when heat demand is lowest, and vice versa.

As the system transitions from autumn into winter, there is a steady increase in demand due to dropping outdoor temperatures, and the staged activation of heat pumps is clearly visible through the stepped red line. However, the reduction in solar production during this period creates an increasing gap between renewable supply and electricity demand. In summary, this chart emphasizes both the benefits and limitations of integrating PV into a heat pump-driven district heating system. While Stage-2 significantly improves sustainability through renewable electricity generation, the temporal mismatch between supply and demand underscores the need for supplementary storage systems, intelligent control strategies, or expanded PV capacity to enhance self-sufficiency, especially during high-demand, low-generation winter months.

After incorporation of solar park, electricity consumption has reduced down to 3,853 MWh and primary energy consumption has reduced down to 10,537 MWh to meet the same heating demand and as a result overall system efficiency has jumped to 111% ($Eq.7$) (Figure 34) and PEF value further decreased down to 0.79 ($Eq.8$) (Figure 34). Thus the Salininkai DHN is transforming towards a more sustainable one. Heat production and operating hour of every energy conversion element were same as the previous stage, i.e., similar to Stage-1.

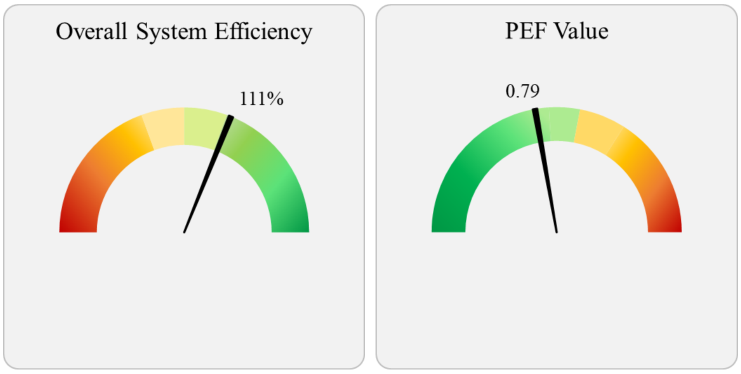

*Figure 34. Stage-2 Overall System Efficiency and PEF*

## 5.4 EnergyPRO simulation result for Stage-3

After EnergyPRO simulation, the data shows that total energy requirement reduced by a portion due to reduced transmission loss, and the heat production of energy conversion units changed dramatically. Heat pumps increased their production, but the boilers stopped their operation which means the natural gas consumption turns to zero.

Exactly same as Stage-1, in Stage-2, heat is generated through a combination of four electric air-to-water heat pumps (A, B, C, and D) and one auxiliary natural gas boiler (Boiler 1). Heat Pump A is the dominant source, producing 5,151.4 MWh (38.8% of total output), followed by Heat Pump B with 3,630.4 MWh (27.4%), Heat Pump C with 2,133.2 MWh (16.1%), and Heat Pump D contributing 1,362.2 MWh (10.3%). Boiler 1 supplements the system with 1,048.2 MWh, accounting for 7.9% of the total. Overall, total heat production for the year reaches 13,265 MWh.

In contrast, Stage-3 reflects a significant system evolution, with the network operating entirely on electricity-based generation—no gas boilers are used. Heat Pumps A and B now cover the bulk of the demand, producing 5,924.7 MWh and 5,741.3 MWh, respectively, accounting for over 92% of total heat production. Heat Pump C delivers a reduced 979.0 MWh (7.8%), while Heat Pump D is no longer in use. The total heat production slightly decreases to 12,587 MWh which is mainly for reduction of overall system loss from 1,554 MWh to 876 MWh which is a 44% reduction.

This comparison highlights that Stage-3 achieves full decarbonization of heat production while maintaining system performance, albeit with higher reliance on electricity and potentially increased peak load on the grid. The removal of boilers simplifies operation but requires careful management of electricity availability and heat pump efficiency—especially under cold weather conditions. This shift aligns with 4th Generation District Heating (4GDH) goals of full electrification and renewable integration.

If we graphically compare heat pumps' operation for Stage-2 and Stage-3, the following figure (Figure 35) says it all:

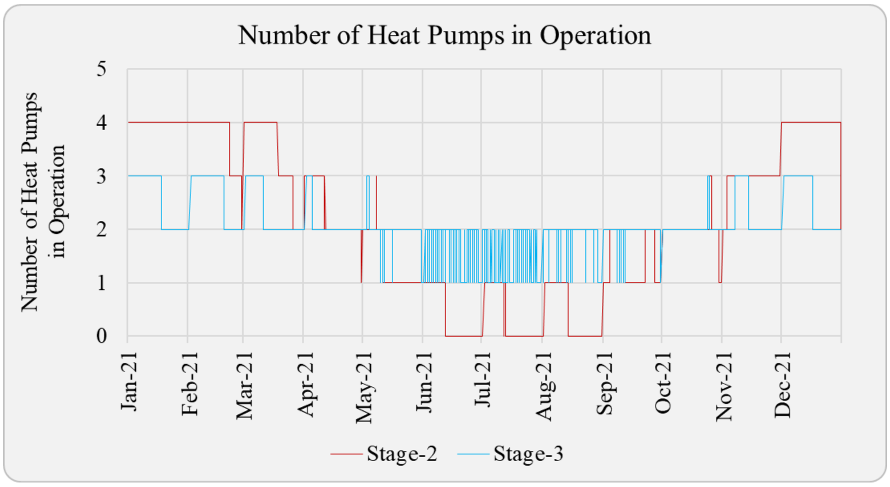


*Figure 35. Comparison of Stage-2 and Stage-3 (Heat Pumps' Operation)*

As a result total required primary energy reduced from 10.54 GWh to 8.69 GWh and the overall system efficiency increased from 111% to 135% ($Eq. 7$) (Figure 36) whereas the overall system efficiency of existing scenario is only 56%. The PEF value reduced further from 0.79 to 0.69 ($Eq. 8$) (Figure 36).

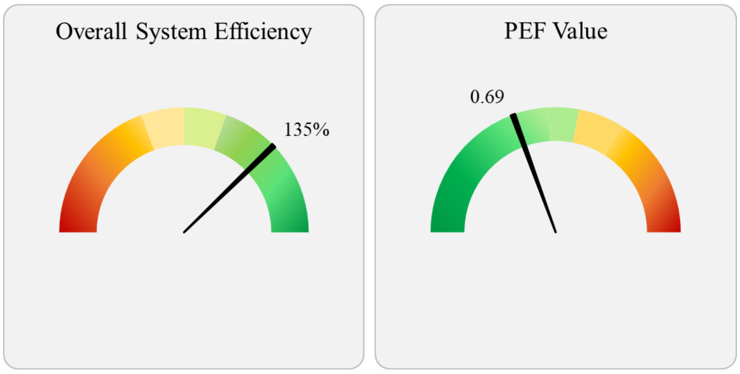


*Figure 36. Stage-3 Overall System Efficiency and PEF*

Segmentation of network into two segments helped the network to utilize their resources up to maximum utilization taking the support from TES. Planned heat pumps and the TES are installed in the second segment, which has become the leading heat producer in the total system through EnergyPRO simulation circuits by proper prioritization.

## 5.5 Result – SUSTAINABLE MODERNIZATION DASHBOARD

The following figure (Figure 37) represents the "Analysis Dashboard" which contains the results of the analysis in all the stages (4-stage investigation set) and prepared in Microsoft Excel-

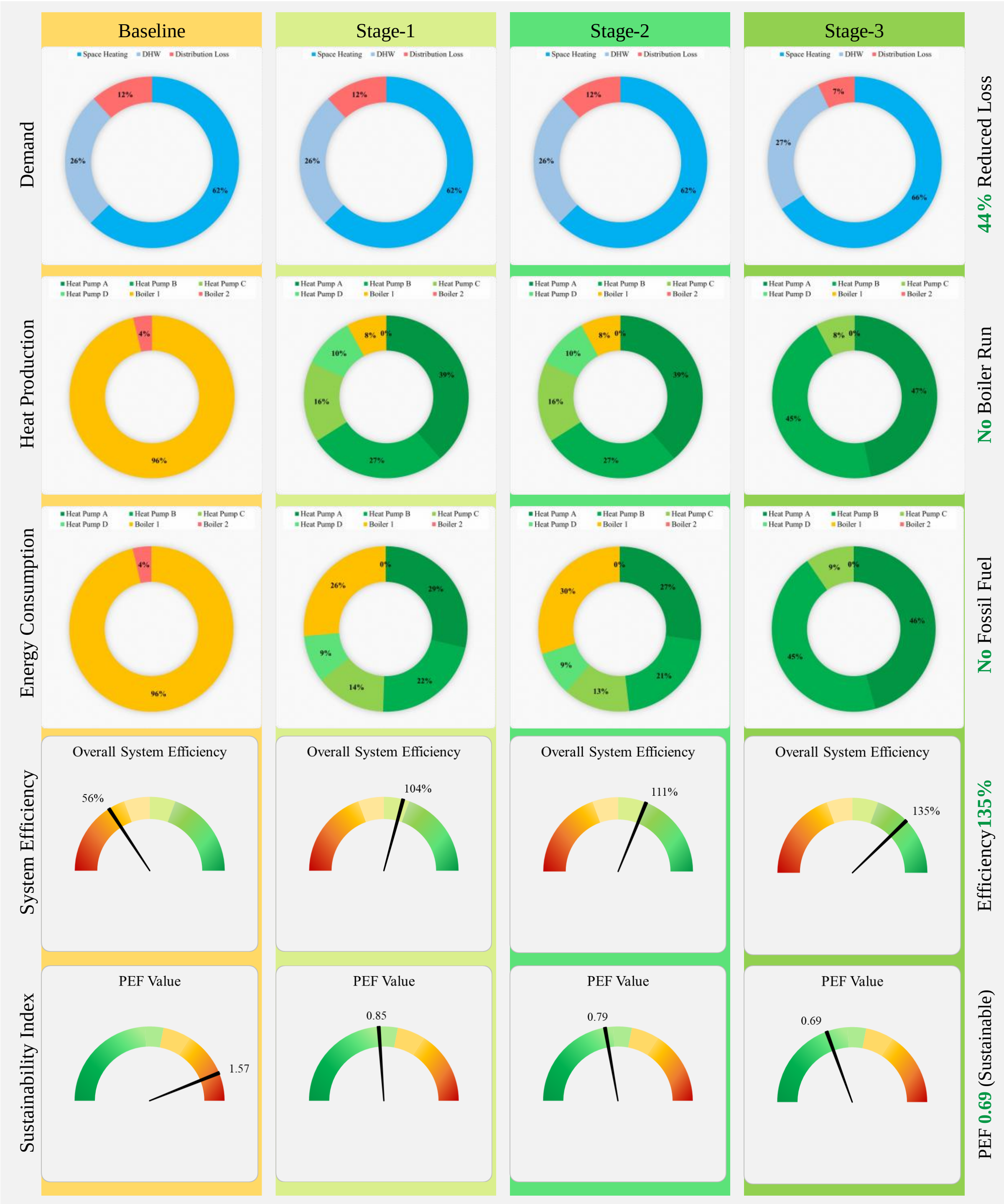


*Figure 37. Sustainable Modernization Dashboard*

The dashboard (Figure 37) developed for the Salininkai District Heating Network (DHN) offers a comprehensive visual representation of how sustainable transformation can be achieved through four distinct modernization stages. Each stage reflects a progressive shift from a conventional fossil fuel-based heating model toward a highly efficient, renewable-integrated, and decentralized energy system. By examining demand characteristics, heat production sources, energy consumption profiles, system efficiency, and the sustainability index measured via the Primary Energy Factor (PEF), the dashboard provides an insightful basis for discussing the strategic impacts of each modernization phase.

In the current status, the DHN relies entirely on two natural gas-fired boilers, resulting in a conventional setup with limited flexibility and high energy dependency. The demand structure is typical for urban Lithuanian heating networks, where space heating comprises the majority at 64%, followed by domestic hot water (DHW) at 24%. A concerning 12% of total production is lost due to distribution inefficiencies likely exacerbated by the fact that the heating plant is situated at one corner of the network, creating long transmission distances to many buildings.

The heat production is dominated by Boiler 1, contributing 96% of the supply, while Boiler 2 provides the remaining 4%. This over-reliance on a single boiler also indicates a lack of redundancy and operational resilience. Consequently, energy consumption aligns fully with fossil fuel usage, as 100% of the heat input derives from natural gas combustion. The system's overall efficiency stands at a low 56%, demonstrating that nearly half the energy input is lost or not usefully utilized. The PEF value in this scenario is 1.57, indicating that for every unit of usable thermal energy delivered, 1.57 units of primary energy are consumed—an unsustainable ratio in the context of current EU energy and climate directives.

The second stage of transformation integrates 1 MW electric air-to-water heat pump system paired with a 3,000 $m^3$ thermal energy storage (TES) unit. This marks a significant transition from fossil-based to electrically driven heating, with flexibility introduced through TES. The overall heat demand profile remains unchanged, maintaining the same proportions of space heating, DHW, and distribution loss. However, the heat production matrix shifts substantially. Four heat pumps, designated

A through D, now contribute a combined 91% of the total heat output, with the largest share (39%) coming from Heat Pump A.

Boiler 1's contribution drops dramatically to only 9%, and Boiler 2 is rendered inactive. The system becomes predominantly electric in its energy consumption, with the majority now attributed to the operation of heat pumps. This shift not only reduces gas dependency but also leverages the higher efficiency of electrically driven systems with favorable coefficients of performance (COPs), especially under low-temperature conditions suitable for modern district heating. System efficiency rises sharply to 104%, crossing the critical 100% threshold due to the effective use of ambient energy by the heat pumps. Correspondingly, the PEF improves to 0.85, reflecting a major leap in primary energy efficiency and sustainability.

The third modernization step builds upon the previous by adding a 500 kWp solar photovoltaic (PV) system, which directly supplies renewable electricity to the heat pumps. This move addresses not just the decarbonization of heat production but also that of the electricity used for heating. With solar power now contributing to the energy mix, the dependency on commercial grid electricity reduces further. While the overall demand structure remains static, heat production sees minor redistribution, with heat pumps continuing to dominate and Boiler 1 operating only intermittently to cover peak demand or extremely wintry conditions. Energy consumption patterns evolve further: while the absolute consumption by the heat pumps remains high, a portion of it is now met via solar-generated electricity, thus reducing reliance on grid-based, and possibly fossil-derived, power. The effect on performance is evident—overall system efficiency improves to 111%, and the PEF value decreases further to 0.79. This demonstrates that the integration of local renewable electricity enhances both energy autonomy and environmental performance without compromising thermal comfort or supply reliability.

The final stage represents the most advanced transformation: the division of the district heating network into two operational segments connected via a transmission line. This spatial restructuring resolves one of the most persistent inefficiencies of the system—distribution losses—by localizing heat generation closer to the demand points.

The benefits are immediate and significant. Distribution losses drop from 12% to just 7%, which is a direct result of reduced transmission distances and better zonal control.

The heat production configuration reveals an even stronger role for the heat pumps. With the network decentralized, the load is redistributed more evenly, and all heating needs are met without any contribution from the gas boilers. In effect, the boiler system is decommissioned or retained only for emergency backup. Energy consumption is now fully electrical and met by heat pumps supported by thermal storage and solar power. This results in an exceptionally high overall system efficiency of 135%, indicating that the majority of primary energy input—now largely renewable or low-exergy—is converted into useful thermal energy. The PEF drops to 0.69, placing the system well within the range of what is considered a fully sustainable heating solution under European benchmarks.

This four-stage transition, as illustrated in the dashboard, paints a clear picture of how deliberate, phased modernization can convert a conventional, carbon-intensive DHN into a model of sustainable urban heating. The combination of electrification through heat pumps, buffering via thermal storage, renewable integration with solar PV, and network decentralization results in a robust, efficient, and resilient energy system. Each stage not only improves numerical performance metrics but also reflects deeper operational and strategic shifts—from rigid, supply-driven models to flexible, demand-responsive and environmentally optimized configurations. In doing so, the Salininkai District Heating Network sets an example of how legacy infrastructure in post-Soviet urban areas can be repurposed and future-proofed through data-driven planning and sustainable engineering interventions.

# 6 Discussion

The results of this study reveal an extensive transformation pathway for the Salininkai District Heating Network (DHN), transitioning it from a conventional, centralized fossil fuel-based system to a sustainable, decentralized, and renewable-integrated model. Through EnergyPRO simulations and staged interventions, unmistakable evidence emerges of significant improvements in energy efficiency, reduction in primary energy usage, and overall system sustainability. The discussion here focuses on the interpretation of those findings, the implications of each modernization step, and how they align with broader energy policy objectives.

## 6.1 Technical evaluation of the sustainable modernization solutions

The technical assessment of the Salininkai District Heating Network (DHN) across four transformation stages reveals a profound shift from a rigid, gas-dependent infrastructure to a dynamic, sustainable energy system. Initially, the network operated with two 4.7 MW natural gas boilers, delivering 13,265 MWh of heat annually using 20,782 MWh of primary energy, resulting in a low system efficiency of 56% and a Primary Energy Factor (PEF) of 1.57. Boiler 1 supplied 96.3% of the heat, indicating limited operational flexibility. Distribution losses stood at 11.7%, due primarily to the network's configuration, with the heating plant located at one corner, leading to extended heat transmission distances.

The first phase of transformation integrated 1 MW electric air-to-water heat pump system paired with a 3,000 $m^3$ thermal energy storage (TES) unit. This significantly altered the system's dynamics. The four heat pumps contributed over 92% of the total heat production, displacing reliance on natural gas and reducing gas consumption by more than 90%. This transformation raised system efficiency to 104%, while PEF improved to 0.85, a substantial leap toward sustainability. These improvements reflect the superior efficiency of heat pumps, especially when ambient temperatures are moderate, as evidenced by the chart showing COP variation with outdoor temperature (Figure 38).

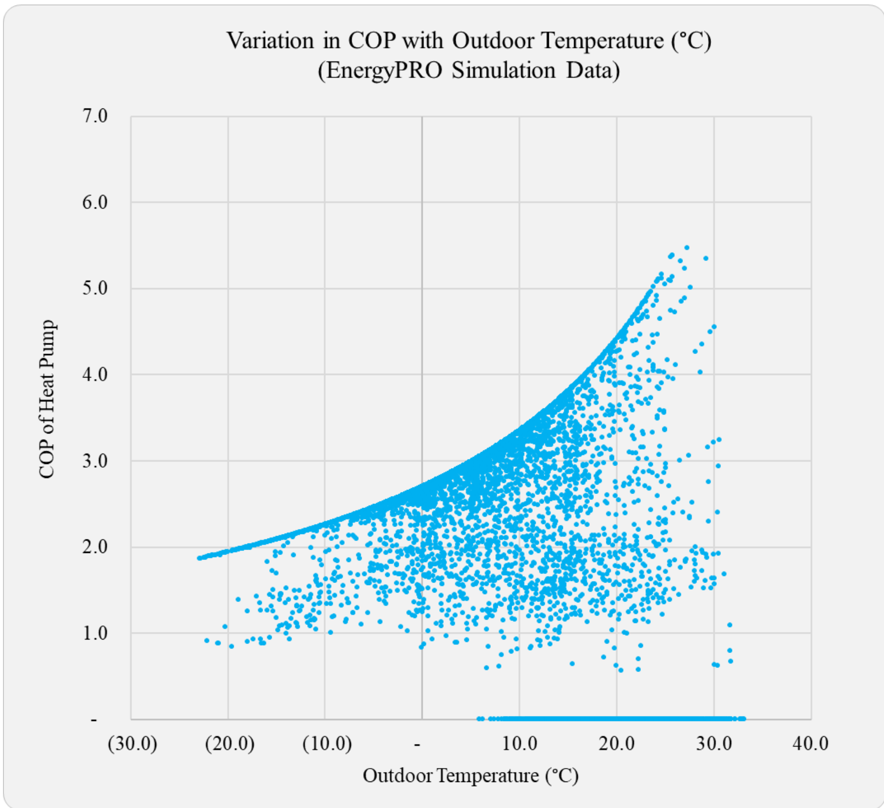


*Figure 38. Stage-1 Variation of Heat Pumps' COP*

This chart (Figure 38) illustrates the variation of the Coefficient of Performance (COP) of heat pumps with respect to hourly outdoor temperature during Stage-1. Hourly heat generation and corresponding electricity consumption data were extracted from EnergyPRO simulation results. Using $Eq.$ 5, the COP for each hour was calculated as the ratio of thermal energy output to electrical energy input. These values were then plotted in Microsoft Excel, with COP on the y-axis and the corresponding hourly outdoor temperature on the x-axis.

As outdoor temperatures rose, heat pump COP values increased significantly, often exceeding 5.0, confirming their suitability for low-temperature district heating applications. Boiler 1 operated only when the temperature fell below -2.1°C till the coldest temperature of -22.1°C with a constant efficiency of 64%. The following figure (Figure 39) illustrates the scenario. In this chart, the operational characteristics of both heat pumps (HPs) and boilers during Stage-1 of the simulation are plotted. It combines three datasets on a dual-axis graph to illustrate how outdoor temperature influences boiler efficiency as well as the heat production of both technologies.

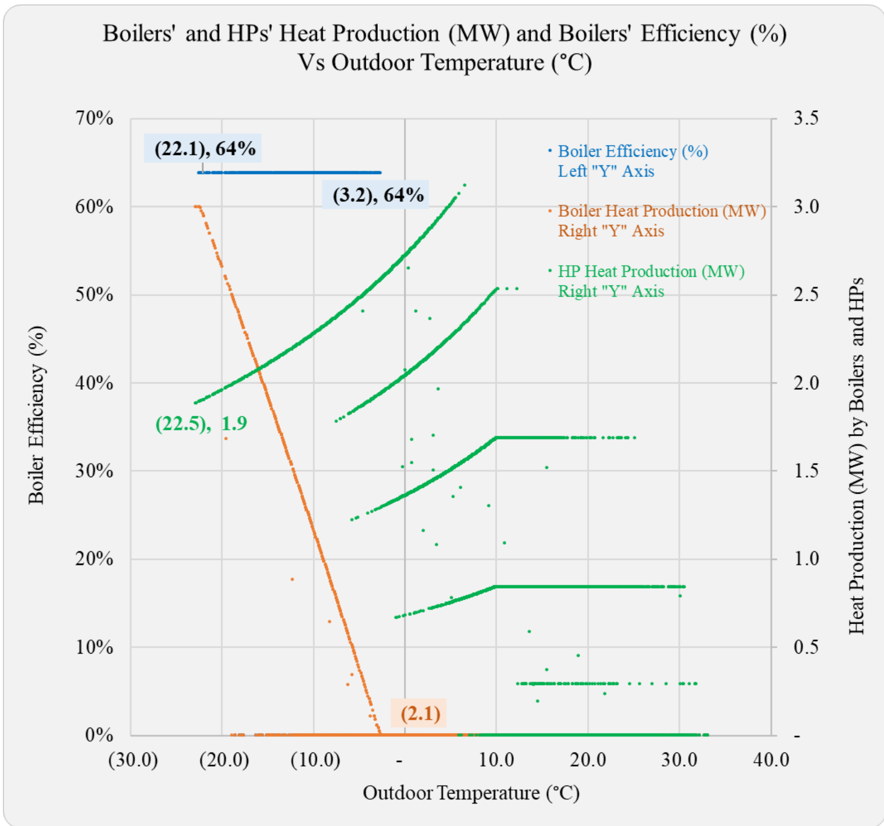


*Figure 39. Stage-1 Heat Production (MW) by Boilers & HPs, and Boiler Efficiency Vs Outdoor Temperature*

On the x-axis, hourly outdoor temperature (in °C) is plotted, ranging from approximately -30°C to +35°C. The left y-axis corresponds to boiler efficiency, expressed in percentage, while the right y-axis shows the thermal energy production of both boilers and heat pumps, measured in megawatts (MW).

Boiler efficiency is shown with blue dots, and it remains fairly consistent at around 64% when the boiler is operating, regardless of outdoor temperature. However, this efficiency trend is only visible over a limited temperature range, indicating that boilers primarily operate during colder periods (from -2.1°C to -22.1°C). The boiler heat production, plotted with orange dots, shows a significant contribution at low outdoor temperatures (particularly from -2.1°C), reaching up to around 3 MW when the outdoor temperature drops to approximately -22.1°C. As the temperature increases, boiler operation diminishes, eventually ceasing altogether when ambient conditions are warm enough for heat pumps to meet the demand.

In contrast, heat pumps' heat production, represented by green dots, increases with rising outdoor temperature. These dots show the amount of heat produced by the heat pumps at each instance when a particular outdoor temperature was recorded temperatures that may have occurred multiple times throughout different periods of the year. At each of these temperature points, the number of operating heat pumps varied depending on the system's demand and control logic. Sometimes only one heat pump was running, while at other times two, three, or all four units were in operation. This variation results in distinct stepped lines of green dots on the graph. Notably, at any given vertical slice (i.e., a specific outdoor temperature), no more than four distinct levels of heat output are visible corresponding to the maximum of four heat pumps while 1, 2, 3, or 4 levels are clearly distinguishable across the temperature range. This pattern illustrates the staged operation of the heat pump units and their increasing contribution as outdoor temperatures rise.

This chart (Figure 39) effectively captures the complementary operation between boilers and heat pumps. Boilers support the heating demand during colder periods when heat pump performance is limited, while heat pumps become the primary source of heating as ambient temperatures rise, improving their Coefficient of Performance (COP) and output.

Subsequent integration of a 500 kWp solar photovoltaic (PV) system further optimized the system in Stage-2. Solar energy offset 730.9 MWh of grid electricity, reducing net electric consumption to 3,853 MWh. Heat pumps continued to dominate production, and the boiler was relegated to a backup role. As a result, system efficiency rose to 111% and PEF fell to 0.79. Though designed photovoltaic park contributes only 8% of total electricity requirement, produced solar power over the year can be represented by the following figure (Figure 40). In the above figure (Figure 40), solar power production over instantaneous demand on every day is plotted. In most of the days 500 kWp photovoltaic park is incapable of supplying daily demand but in some days it can support even 250% or more of daily demand. Each vertical bar represents a moment in time when solar output was compared with demand. Green bars indicate instances when solar power generation exceeded the instantaneous electricity demand, meaning there was surplus generation at that moment. Conversely, red bars represent instances where solar generation was insufficient to meet the demand, and additional power sources would be required to fill the gap.

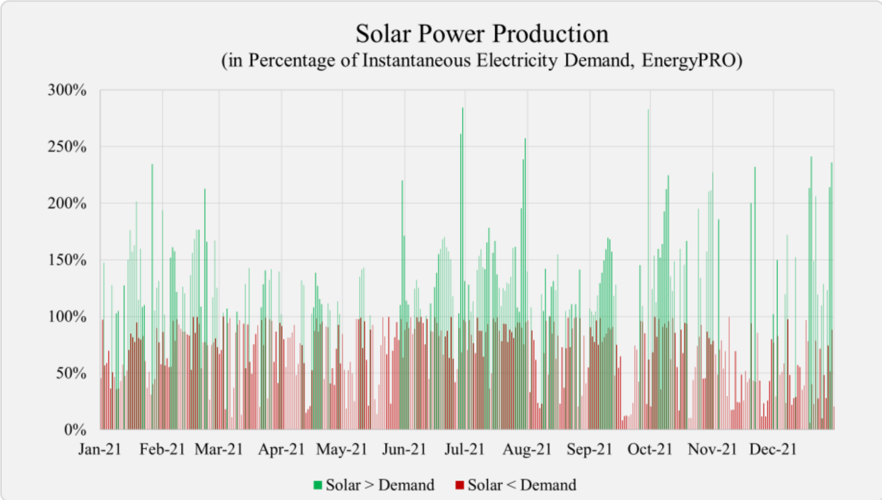


*Figure 40. Stage-2 Hourly PV Solar Power Production for 2021 (Compared with Electricity Demand)*

From the chart, it is evident that there were frequent occurrences—especially during spring and summer months—where solar power production surpassed demand, with peaks exceeding 250% of the instantaneous requirement. This reflects the high potential of solar energy during periods of strong sunlight. On the other hand, during winter and cloudy months, the chart is dominated by red bars, showing a consistent shortfall of solar energy relative to demand. Overall, this chart highlights the variability and intermittency of solar energy production in relation to electricity demand across the year, reinforcing the need for storage solutions or backup systems to ensure a reliable and balanced power supply.

The final technical transformation involved dividing the network into two zones (Stage-3), effectively reducing distribution losses from 11.7% to 7.0% which is a 44% of reduction in distribution losses. Heat production was fully managed by the heat pumps, and natural gas use was eliminated. With this spatial optimization, overall system efficiency peaked at 135%, and PEF dropped to 0.69 which is one of the lowest and most sustainable levels observed in European DHN standards.

Considering different stages in terms of energy source dependency on the same page, all the stages are plotted in terms of energy source in the following figure (Figure 41):

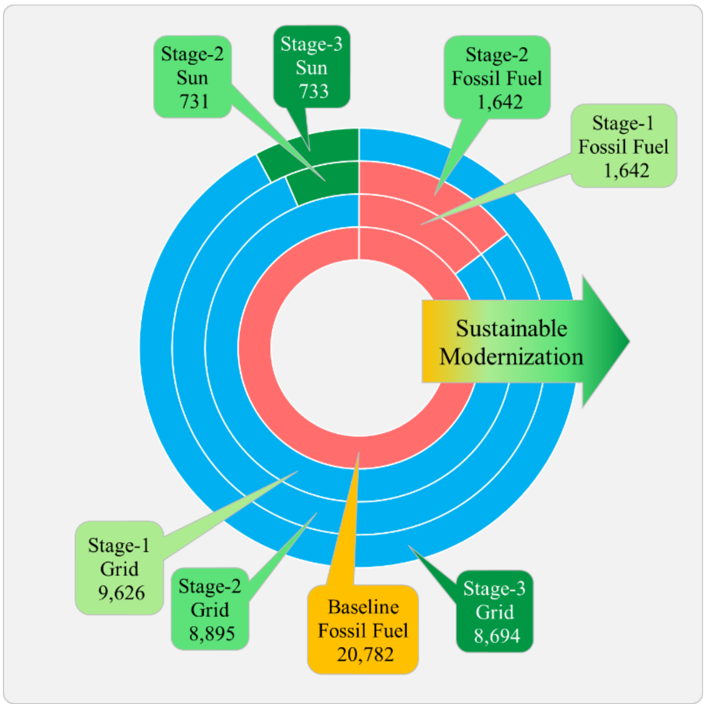


*Figure 41. Stage-3 Dependency of Energy Source at different stages of Sustainable Modernization*

The ring diagram (Figure 41) illustrates the transition in energy source dependency across different stages of Sustainable Modernization, achieving in Stage-3. The ring diagram is segmented to represent energy supply from three major sources—Fossil Fuel, Grid, and Solar (Sun)—across three sequential stages: Stage-1, Stage-2, and Stage-3. At the center lies the Baseline Fossil Fuel usage, which is significantly high at 20,782 MWh, indicating a heavy initial reliance on fossil fuels.

As the system transitions from the baseline to Stage-1, fossil fuel dependency drops sharply to 1,642 MWh, while the grid contributes 9,626 MWh. Notably, solar energy is not yet utilized in Stage-1. Moving into Stage-2, fossil fuel usage remains constant at 1,642 MWh, but there's a marked increase in renewable contribution, with solar energy entering the mix at 731 MWh, and a slight drop in grid dependence to 8,895 MWh. Finally, in Stage-3, fossil fuel reliance is entirely eliminated, while solar energy marginally increases to 733 MWh, and grid usage stabilizes around 8,694 MWh.

The diagram clearly demonstrates a strategic and structured move toward sustainability. Over the three stages, fossil fuels are phased out completely, and renewables (particularly solar) begin to supplement energy needs alongside the grid.

This visual representation emphasizes the effectiveness of gradual energy transition in achieving a more sustainable and modernized energy mix.

In Lithuania, DH systems exhibit a range of efficiencies and PEFs, influenced by factors such as fuel sources, system configurations, and the extent of renewable energy integration. A study analyzing 35 DH producers in Lithuania found that PEF values varied significantly, reflecting the diversity in system designs and energy sources. However, this study says, Lithuania has a country average PEF value of 0.91 (Latõšov et al., 2017). Across the EU, the PEF for DH systems also vary. For instance, the default PEF for DH networks utilizing efficient combined heat and power (CHP) systems is approximately 0.19, while systems relying solely on waste heat have a default PEF of 1.0 . These values are calculated in accordance with standards such as EN 15316-4-5 (2014).

The European Commission's Energy Efficiency Directive (EED) provides a framework for assessing the efficiency of DH systems. Under this directive, a DH system is considered efficient if it meets certain criteria, such as utilizing a significant share of renewable energy, waste heat, or CHP. This directive also emphasizes the importance of reducing primary energy consumption and greenhouse gas emissions (Toleikyte et al., 2023).

The enhancements achieved in the Salininkai DH network are notable when compared to these benchmarks. An increase in system efficiency from 56% to 135% suggests a transition from traditional heating methods to more advanced technologies, possibly incorporating high-efficiency heat pumps or CHP systems. Similarly, the reduction in PEF from 1.57 to 0.69 indicates a significant decrease in primary energy consumption per unit of delivered heat, aligning with the EU's goals for sustainable energy systems. These improvements not only demonstrate the potential for energy savings and emission reductions in DH systems but also highlight the effectiveness of integrating renewable energy sources and advanced technologies in achieving energy efficiency targets. For a more comprehensive understanding of DH system efficiencies and PEFs across different EU member states, refer to the detailed analyses provided in the studies cited above.

The improvement is also evident in the COP comparison chart, where post-division heat pump operations consistently show higher COPs across varying loading conditions. This indicates better part-load performance and reduced inefficiencies, likely due to shortened pipe lengths and better control of supply-return temperature differentials. The following figure (Figure 42) plots COP of divided network over the COP of non-divided network, i.e., after incorporation of heat pumps and thermal energy storage (Figure 38). This plotting clearly says that after network division, the heat pumps worked at their best efficiency with a constant COP value at every specific temperature. When temperature falls below -3.2°C, they sacrificed COP but didn't allow boilers to run and in return overall system efficiency goes to its peak.

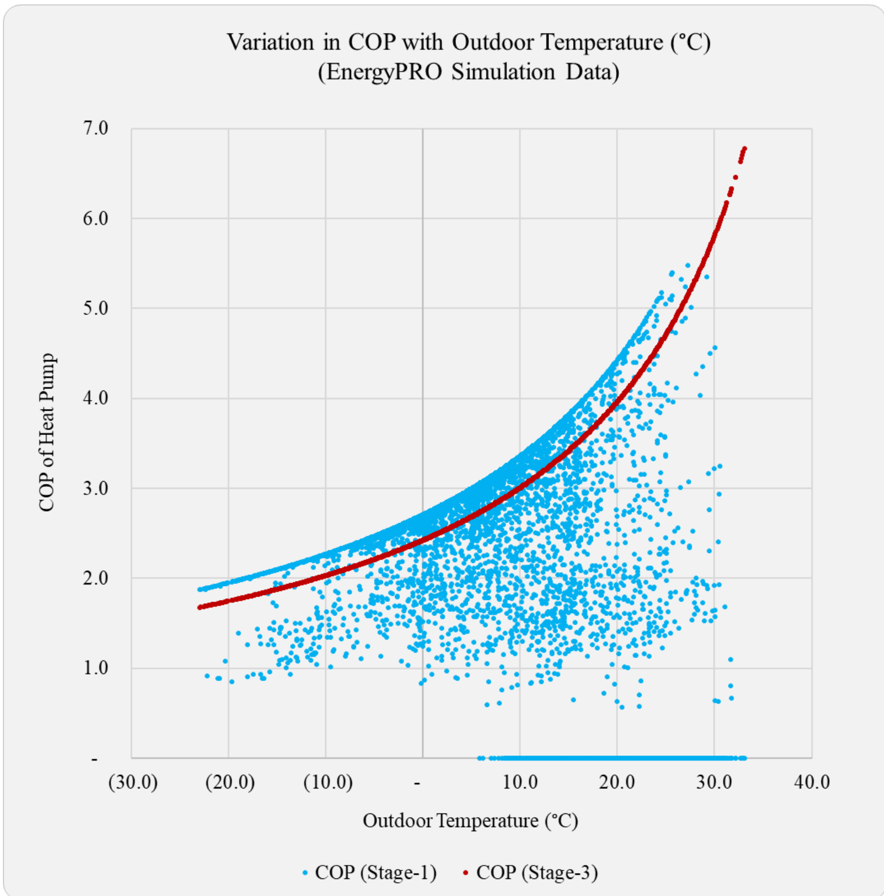


*Figure 42. Comparison of HPs' COP (Before Vs After Network Division)*

This comparison clearly illustrates the impact of network optimization and restructuring—following the division of the heating network—on heat pump efficiency. The more stable COP values in Stage-3 indicate that the system is now operating under more favorable and controlled conditions, leading to improved energy efficiency and reduced operational costs.

The key reason for the consistent COP values at each temperature point in Stage-3, as shown by the smooth red curve, lies in the absence of boilers and the controlled operation of heat pumps in a simplified network structure. After the network division in Stage-3, the heat pumps were the sole source of heat production, and they operated under well-defined and optimized conditions. Because of this, for each outdoor temperature, the system maintained a fixed set of internal return temperatures and flow conditions, resulting in a predictable and repeatable COP value for each outdoor temperature level. Hence, each temperature point corresponds to a single, clean COP value, forming the smooth curve seen in the chart.

In contrast, during Stage-1, the system involved both heat pumps and boiler operation in parallel, often leading to fluctuating return water temperatures, variable load distribution, and more dynamic system behavior. For a given outdoor temperature, the heat pump might have faced different internal operating conditions—such as return water temperature, part-load ratio, or interaction with the boiler. These variations introduced multiple COP values for the same outdoor temperature, as seen in the scattered blue points. Essentially, the presence of the boiler and less optimized control strategies in Stage-1 led to less stable operating conditions, resulting in a spread of COP values even at the same ambient temperature.

Moreover, if the COP is plotted against percentage loading of heat pump (Figure 43), an interesting insight comes out.

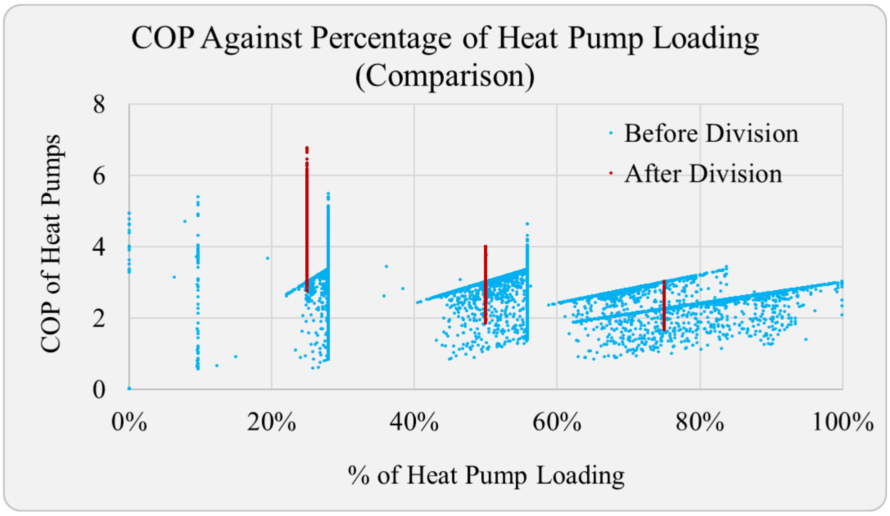


*Figure 43. Comparison of COP on HP Loading (Before Vs After Network Division)*

Before network division, all four heat pumps needed to be run along with the first boiler. Therefore, heat pumps had four types of loading like 25% loading for running of HP-A only, 50% for running of both HP-A and HP-B, 75% for running of HP-A, HP-B and HP-C, and 100% for running of all four heat pumps. Except for the minimal loading condition, i.e., except when only the first heat pump needed to be run, in all the loading conditions, heat pumps worked at variable COP which indicates that heat pumps needed to be run but the demand is lower than heat pumps given output.

However, after network division, no boilers needed to run, even the fourth heat pump didn't need to run. As a result, heat pumps had to run with loading percentages of 25% (for HP-A), 50% (for HP-A and HP-B) and 75% (for HP-A, HP-B and HP-C). Due to proper loading conditions and perfect utilization of TES, heat pumps ran at their peak efficiency for every loading conditions and as a result they ran at constant COP values. Combining heat pumps' operations with Figure 39, we will get a noticeably clear idea in the Figure 44 where the violet lines represent heat pumps operations after network division.

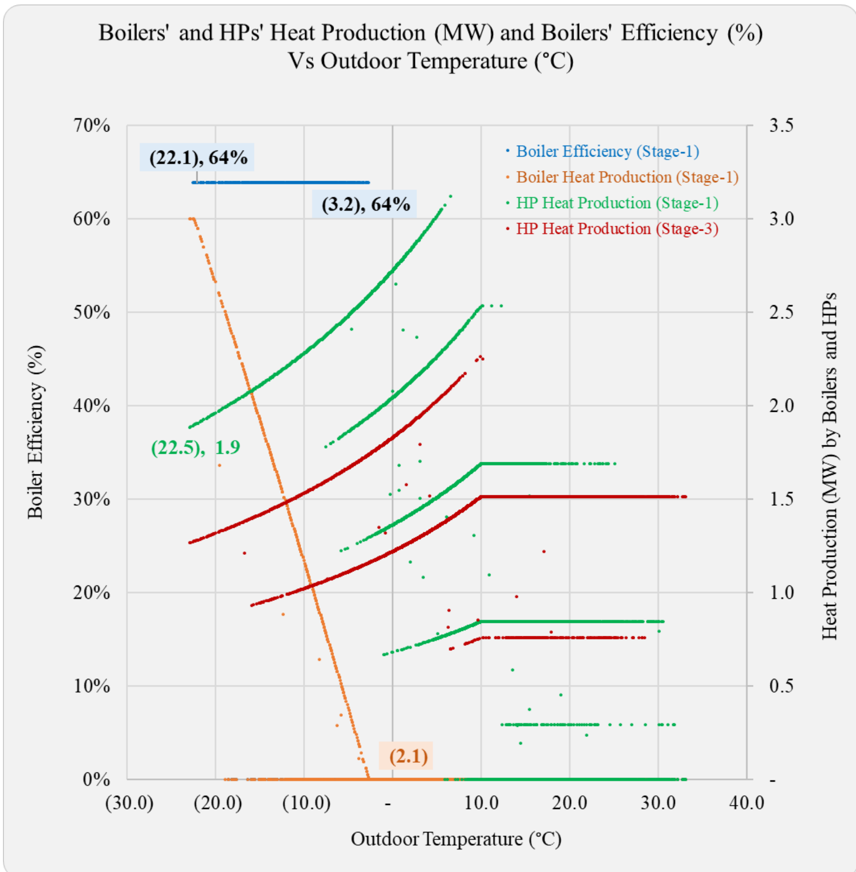


*Figure 44. Comparison of Heat Production (Stage-1 Vs Stage-3)*

Stage-1 is described just below the Figure 39. In Stage-3, as shown by the red markers, the system operated without any boilers, relying entirely on heat pumps. The red lines reflect the heat production from the HPs, which also shows a stepped behavior similar to Stage-1 but at a generally lower level of production. This suggests more optimized or controlled operation, with no overlapping boiler usage. The distinct and smoother operation in Stage-3 demonstrates the result of system simplification following the network division—leading to a clearer, more consistent thermal load distribution handled exclusively by heat pumps. Overall, this chart highlights the contrast in system behavior and component contribution before and after network optimization. The removal of boilers in Stage-3 significantly altered the heat production profile and stabilized system operation, pointing to a shift toward a more sustainable and streamlined heat supply strategy.

The TES played a crucial role by buffering excess solar energy and supporting demand during peak periods. Improved TES utilization after network division is clearly shown in the TES utilization chart (Figure 45), which highlights consistent storage cycling and increased operational effectiveness. Before network division (blue line), boiler did run and as a result TES got opportunity to fill quickly and when it started to become empty it couldn't support the complete heating demand and as a result heat pumps had to run but with partial loading which caused COP to drop. On the contrary, after network division (red line), boilers didn't run, and heat pumps' operation was not adequate enough to fill the TES as fast as boiler did and as a result heat pumps ran at their best efficiency with a constant COP and thus the overall system became more efficient.

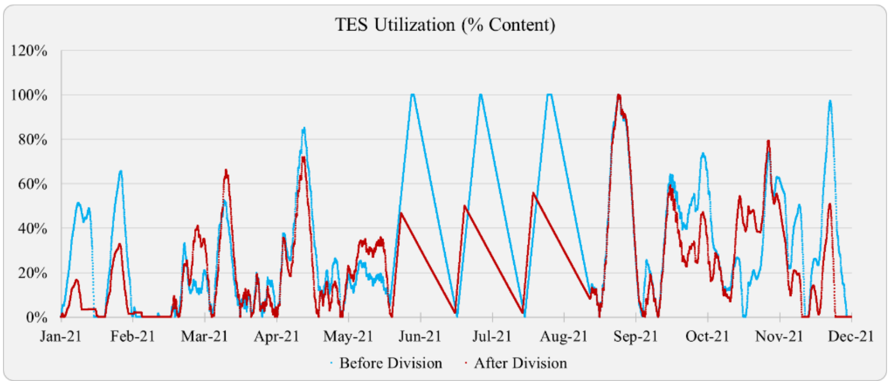

*Figure 45. TES Utilization (Before and After Network Division)*

The staged modernization of the Salininkai DHN demonstrates a compelling technical success story of transitioning from a conventional, carbon-intensive system to a highly efficient, renewable-integrated, and intelligent thermal infrastructure. Each stage of transformation—heat pump and TES integration, solar PV deployment, and network segmentation—delivered quantifiable performance gains while resolving core inefficiencies related to energy losses, boiler over-dependence, and seasonal mismatches in load versus generation. The increasing system efficiency from 56% to 135% and the sharp decline in PEF from 1.57 to 0.69 provide convincing evidence that thoughtful engineering design, combined with advanced simulation tools like EnergyPRO, can unlock deep decarbonization opportunities even in legacy heating networks. Improvements in heat pump COPs, optimization of part-load operations, and strategic TES utilization further enhanced the technical resilience of the system. The synergy between component-level upgrades and network-level restructuring in the final stage not only eliminated fossil fuel dependency but also created a framework adaptable to future grid interaction, demand response, or sector coupling strategies. This transformation provides a replicable and scalable model for other low-temperature district heating systems across Lithuania and the broader Baltic and Nordic regions.

## 6.2 Economic evaluation of the sustainable modernization solutions

For the economic analysis, the study selected a simple yearly energy cost comparison model which considered gas price per m$^3$ and electricity price per kWh from Tarifas (2025). The following table (Table 6) represents a clear economic evaluation of the annual energy cost associated with four progressive stages of sustainable transformation for the Salininkai District Heating Network (DHN).

*Table 6. Comparison of Yearly Energy Consumption and Cost*

| | Natural Gas (m$^3$) | | Electricity (MWh) | |
|---|---|---|---|---|
| | **Consumed** | **Cost (EUR)** | **Consumed** | **Cost (EUR)** |
| **Baseline** | 1,855,521 | 1,020,536 | - | - |
| **Stage-1** | 146,630 | 80,646 | 4,584 | 678,388 |
| **Stage-2** | 146,630 | 80,646 | 3,853 | 570,214 |
| **Stage-3** | - | - | 3,756 | 555,888 |
| **Tariff (EUR)** | **0.55** | **/ m3** | **0.148** | **/ kWh** |

Under the current status, where heat is entirely generated by natural gas boilers, the yearly energy cost amounts to €1,020,536. With the integration of heat pumps (HP) and thermal energy storage (TES), the energy cost drops significantly by 26% (Figure 46) to €759,034, reflecting improved system efficiency and reduced gas consumption. Further enhancement with the addition of a 500 kWp solar park leads to a 36% total cost reduction, bringing the annual expense down to €650,861, as solar power partially replaces grid electricity. The most substantial savings 46% compared to the baseline are realized when the network is divided into two segments, minimizing distribution losses and eliminating gas usage, resulting in a final yearly energy cost of €555,888. These evaluations are based on energy prices of €0.55/m³ for natural gas and €0.148/kWh for electricity, clearly demonstrating the financial viability of transitioning to a renewable and decentralized district heating system.

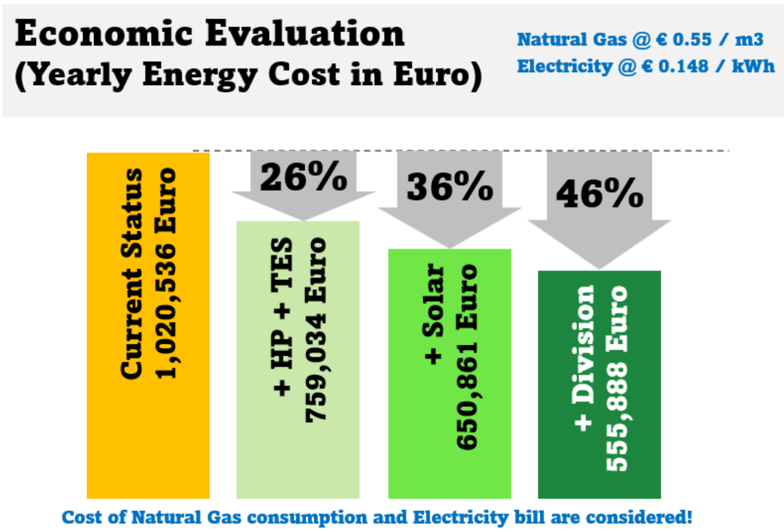


*Figure 46. Comparison of Yearly Energy Cost*

Beyond the current energy cost evaluation, several other economic models could be incorporated to deepen the understanding of the financial viability of modernizing the Salininkai District Heating Network. Life Cycle Cost Analysis (LCCA) could be employed to assess the long-term investment payback considering capital expenditures, maintenance, operational costs, and replacement costs over the system's lifetime. Net Present Value (NPV) and Internal Rate of Return (IRR) analyses could provide insights into the profitability and economic feasibility of each modernization phase under various discount rate scenarios. Additionally, a Cost-Benefit Analysis (CBA) could evaluate the broader economic advantages. While these comprehensive assessments are essential for a holistic understanding, they are beyond the scope of this current work and are thus reserved for future research.

## 6.3 Environmental evaluation of the sustainable modernization solutions

In the methodology chapter (Section 4.12), we did in detailed discussion on LCA we performed in this study. We already completed defining the goal and scope and also the inventory analysis. At the impact assessment, we found the following table (Table 7):

*Table 7. Environmental Impact Assessment of Sustainable Modernization Solution*

| Category | Baseline | Stage-1 | Stage-2 | Stage-3 |
|---|---|---|---|---|
| Manufacturing Emissions (t CO2 e) | 108 | 474 | 1,074 | 965 |
| Annual Operating Emissions (t CO2 e) | 3,668 | 865 | 774 | 470 |
| Maintenance (20 years) (t CO2 e) | 7 | 17 | 23 | 16 |
| **20-Year LCA Total (t CO2 e)** | **73,485** | **17,796** | **16,574** | **10,371** |
| **$CO_2$ Reduction (t CO2 e)** | - | **55,689** | **56,911** | **63,113** |
| **% Reduction** | - | **76%** | **77%** | **86%** |

The table presents a comprehensive 20-year Life Cycle Assessment (LCA) comparing the baseline scenario with three progressive stages (Stage-1, Stage-2, and Stage-3) of sustainable modernization of Salininkai DHN. It evaluates carbon emissions from three components: manufacturing, annual operations, and maintenance, all measured in tons of $CO_2$ equivalent (t $CO_2$ e).

In the baseline scenario, the total LCA emissions over 20 years amount to 73,485 t $CO_2$ e, driven primarily by high annual operating emissions (3,668 t $CO_2$ e). In contrast, the staged modernization significantly reduces life cycle emissions. Stage-1 achieves a 76% reduction, lowering total emissions to 17,796 t $CO_2$ e, mainly due to a substantial drop in operating emissions to 865 t $CO_2$ e per year, despite an increase in manufacturing and maintenance emissions. Stage-2 performs slightly better, reducing the total to 16,574 t $CO_2$ e (a 77% reduction), though it shows higher manufacturing and maintenance emissions than Stage-1, indicating more material-intensive upgrades.

The most significant improvement is observed in Stage-3, which reduces the 20-year LCA emissions to just 10,371 t $CO_2$ e, resulting in an 86% reduction compared to the baseline. This outcome is primarily driven by the lowest operational emissions (470 t $CO_2$ equivalent per year), demonstrating the long-term climate benefits of the final modernization stage, even though manufacturing emissions remain high due to system overhaul.

Overall, the LCA results highlight a clear trade-off: while modernization increases upfront (manufacturing) and maintenance emissions, the dramatic cut in operating emissions results in substantial long-term environmental benefits. Stage-3 emerges as the most sustainable configuration, balancing system performance with the highest overall carbon reduction across the life cycle. The modernized scenario, therefore, aligns with EU Green Deal goals, Lithuania's energy strategy, and global climate commitments for low-carbon and resilient urban energy systems (Lake et al., 2017).

## 6.4 Sensitivity analysis

A detailed discussion on sensitivity analysis is done in the Methodology chapter (Section 4.13). A sensitivity analysis methodology was developed there to check the heat production and network performance with a reduced annual average outdoor temperature. Accordingly, we reduced annual average outdoor temperature by 1°C by deducting 1°C from every value of hourly outdoor temperature and the input is given to EnergyPRO software (external conditions).

A study published in Applied Energy indicates that a 1°C decrease in average outdoor temperature can lead to an approximate 3.7% increase in annual energy consumption for heating systems (Fikru & Gautier, 2015) which is reflected in EnergyPRO simulation also (Figure 47). This relationship underscores the sensitivity of heating demand to temperature variations, emphasizing the importance of accurate climate considerations in energy planning. Both boilers needed to run to support the peak, however, the Boiler-1 delivered 1,320 MWh (around 12% of annual demand) and Boiler-2 delivered only 0.2 MWh.

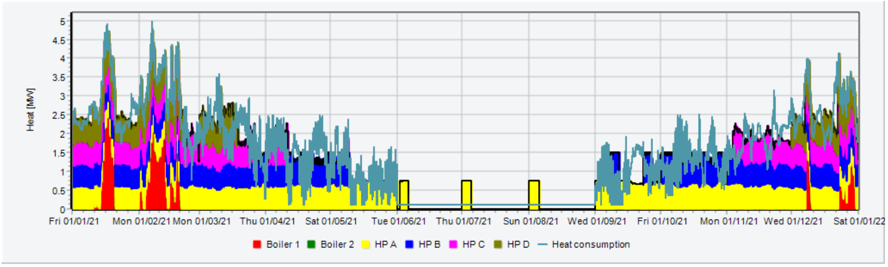


*Figure 47. Sensitivity Analysis Outcome (Heat Production)*

Boilers started operating from -2°C and constantly worked with 64% efficiency (Figure 48) similar as Figure 39 and Figure 44. However, heat pumps have variable outputs at this time.

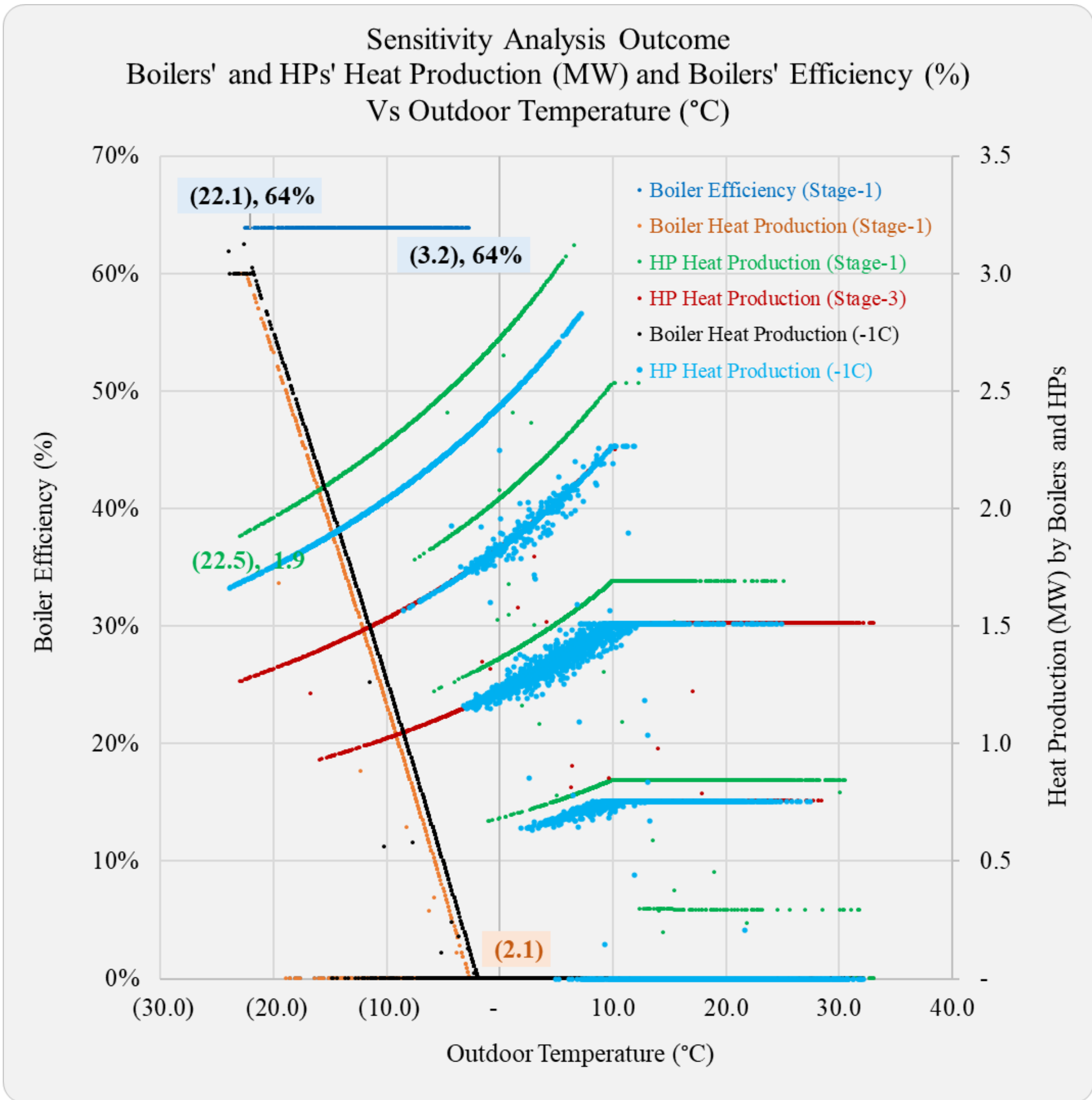


*Figure 48. Sensitivity Analysis Outcome (System Performance)*

Figure 48 presents the outcome of a sensitivity analysis performed on Stage-3 of the district heating system to evaluate its resilience under slightly colder climate conditions. Specifically, the analysis simulates a uniform reduction of 1°C in hourly outdoor temperatures over the entire year. The graph compares heat production from boilers and heat pumps (HPs), as well as boiler efficiency, against outdoor temperature for both the original and modified weather scenarios.

In addition to the previously recorded Stage-1 (Figure 39) and Stage-3 (Figure 44) data, the chart introduces new sensitivity case data, represented by light blue (HP Heat Production under -1°C) and black (Boiler Heat Production under -1°C). The results show that while heat pumps continue to serve as the main source of heating, the colder ambient conditions shift more load to the boilers, especially in lower temperature ranges. This is reflected in the increase in black data points at sub-zero temperatures, indicating that auxiliary boiler support is engaged earlier and more frequently.

Despite this, the system shows strong adaptability and stability. Heat pumps still maintain a substantial role, even in a colder climate, with only moderate increases in boiler support. Interestingly, the heat pump production appears as discrete steps at each temperature level. This is due to the modular operation of up to four heat pump units, which activate in stages depending on system demand. At a given outdoor temperature, one, two, three, or all four heat pumps may be operating, resulting in distinct horizontal clusters of production levels. This stepped pattern is typical of multi-unit systems with staged control strategies, ensuring optimal efficiency and flexibility in response to varying thermal loads.

Overall, this analysis demonstrates that even under slightly harsher climate conditions, the Stage-3 configuration remains robust and continues to prioritize clean, electric-driven heating. The system design—featuring modular heat pumps and minimized boiler dependency—proves to be a resilient and future-ready solution capable of absorbing climate variations while maintaining performance and sustainability.

Since the outputs of heat pumps vary in some points, the COP is also plotted to see what it looks like (Figure 49). The COP is almost aligned on the COP scenario after network division (Stage-3), however, in some points there are discrete COP values which are a direct result of average annual temperature deviation by -1°C.

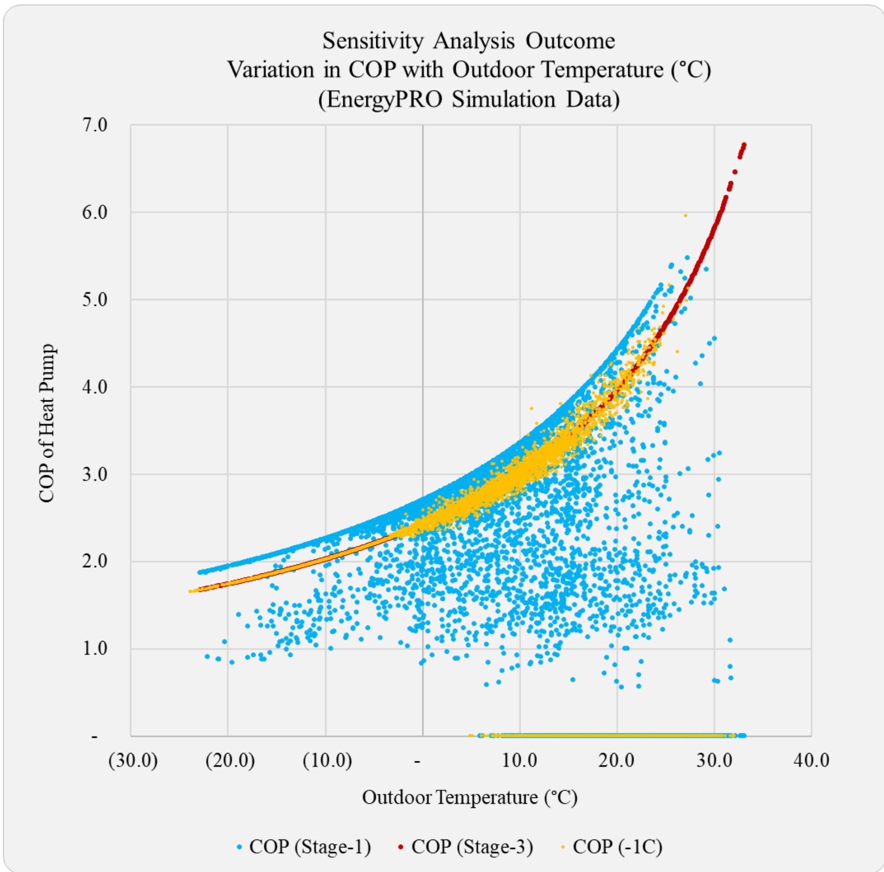


*Figure 49. Sensitivity Analysis Outcome (Heat Pump Performance)*

These observations underscore that while the Salininkai District Heating Network (DHN) exhibits significantly improved sustainability under typical and warmer weather conditions, ensuring long-term performance demands robust operational strategies and contingency planning. Even with enhanced system design, colder-than-expected climate events can introduce efficiency losses and increase reliance on fossil-based backup systems. Therefore, this sensitivity analysis not only confirms the resilience of the modernized Salininkai DHN but also highlights the critical importance of adaptive and flexible system architecture to maintain carbon savings and operational efficiency across a range of potential future climate scenarios.

Importantly, climate change is not only warming the atmosphere but also extending transitional seasons such as spring and autumn, effectively lengthening periods with moderate outdoor temperatures. As noted by the professor, this trend results in longer durations of favorable ambient conditions for technologies like heat pumps and solar photovoltaics. In parallel, average solar radiation is increasing, further enhancing the viability of renewable-based systems. These evolving climate patterns strengthen the case for investments in systems that can capitalize on milder conditions and shifting seasonal dynamics.

To build on the current findings, further sensitivity analyses are recommended to strengthen the robustness of the modernization strategy. Key parameters for future study include fluctuations in electricity prices, which directly affect the cost-effectiveness of heat pump operation; variations in natural gas tariffs, particularly relevant in volatile geopolitical contexts; and changes in the primary energy factor (PEF) as Lithuania's electricity grid becomes greener. Additionally, evaluating year-to-year solar irradiance variability can assess the reliability of photovoltaic contributions, while examining thermal energy storage (TES) sizing can determine the optimal buffer capacity for diverse load profiles. Investigating heat pump capacity scaling, COP degradation over time, and maintenance cycle intervals will also be valuable in refining both technical design and economic forecasts.

Although these extended analyses lie beyond the scope of the current study, they are highly recommended for future research. Together, they will offer deeper insight for strategic investment planning and operational resilience. In conclusion, the results of the technical and environmental assessments strongly support a phased modernization approach for the Salininkai DHN. Each progressive stage delivers measurable performance and sustainability benefits, while the final configuration positions Salininkai as a model for resilient, low-carbon, and climate-adaptive district heating systems in the Baltic region and beyond.

# 7 Recommendation

Low-Temperature District Heating Networks (LTDHNs) in Lithuania and regions with similar climates face challenges such as extreme temperature variations, high heat losses, and reliance on fossil fuels. Based on the analysis of the Salininkai DHN, several actionable recommendations can enhance the performance, sustainability, and resilience of LTDHNs.

These recommendations address both technical and operational aspects to ensure efficient energy delivery while minimizing environmental impact:

## 7.1 Recommendation set: Stage-1

Integration of Renewable Energy Technologies (Heat Focused): Deploy heat pumps and thermal storage systems to reduce reliance on fossil fuels and optimize energy efficiency, especially during moderate temperatures. At extreme low temperature levels, one boiler will be activated. In this particular study, integration of heat pump and thermal storage reduced 46% of primary energy consumption.

## 7.2 Recommendation set: Stage-2

Integration of Solar Park (Electricity Focused Renewable Technologies): Deployment of solar park will significantly reduce dependency on electricity. In this particular study, a 500 kWp solar park is proposed based on available space which reduced primary energy consumption by further 4%.

## 7.3 Recommendation set: Stage-3

Distributed Heating Network: Segmentation of heat distribution network optimizes boiler operation to nullity which will ensure this particular DHN's reduced primary energy consumption, dependency on natural gas and as a result energy security. In this particular study, segregation of heating network and centralized design of heat-source has reduced the primary consumption by further 9% with a result of 58% in total from the baseline scenario.

## 7.4 Recommendation set: Stage-4

Other recommendations may include but not limited to-

- Enhanced pipeline insulation to reduce heat loss and pumping requirements.
- Retrofit buildings with poor energy performance (F and G classes) and provide incentives for upgrades to lower heat demand.
- Use predictive models and smart grids to optimize heating supply based on real-time demand and outdoor conditions.
- Incorporating models to evaluate user behavior and its impact on heat demand patterns. Designing strategies to engage consumers in energy-saving practices, such as flexible pricing mechanisms and public awareness programs.
- Future studies may include full-scale environmental impact analysis (LCA), full-scale economic evaluation (LCCA) and some suggested models appropriate for such cases, different sensitivity analysis, etc. which may include further assessment ornamentation to escalate the recommendations to national level.

These strategies aim to create a balanced, efficient, and future-ready heating system that supports Lithuania's national energy goals and aligns with EU sustainability directives. The transformation of Salininkai DHN can be prototyped to other small-scale DHNS of Lithuania to maximize nation-wide gain in heating sector which will ensure national energy security.

# Conclusion

The study of the Salininkai District Heating Network (DHN) presents a comprehensive framework for transitioning conventional district heating systems toward sustainable, low-temperature configurations. By integrating renewable technologies, particularly the 1 MW air-to-water heat pump, a 3,000 m³ thermal storage unit, and a 500 kWp solar park, the research achieved significant improvements in energy efficiency and environmental performance. These measures reduced natural gas dependency, minimized greenhouse gas emissions, and aligned the DHN with global renewable energy goals.

Through advanced EnergyPRO simulations, the study captured key insights into the operational dynamics of the Salininkai DHN under various scenarios. Results highlighted a marked transformation in system efficiency, with a reduction in primary energy demand and emissions. The system's efficiency improved from 56% in the baseline scenario to 135% in the modernized configuration. The integration of thermal energy storage played a pivotal role in balancing peak and off-peak demand, further enhancing system reliability and operational flexibility.

The analysis also revealed the critical role of heat pumps in reducing reliance on boilers during moderate outdoor temperatures. Boiler 2 was entirely decommissioned, while Boiler 1 operated only when outdoor temperatures fell below -2.1°C, ensuring that peak demand could be met during extreme conditions before network division. However, after network division Boiler 1 stopped production and heat pumps could support the demand with a higher system efficiency level. This operational adjustment highlighted the importance of renewable integration in optimizing system performance and reducing fossil fuel consumption. Segregation of heat distribution network nullifies the requirement of boiler and through this final recommendation it brings sustainability index (PEF) from 1.57 to 0.69 only which clearly indicates a sustainable transformation.

Additionally, ornamented by technical evaluation, economic justification, environmental impact assessment and sensitivity analysis, the study provided actionable recommendations for improving low-temperature district heating networks (LTDHNs) in Lithuania and similar climates. Key measures include enhancing pipeline insulation to minimize heat losses, retrofitting low-efficiency buildings to reduce energy demand, and adopting smart grid technologies for dynamic load management. Consumer engagement through flexible pricing models and awareness campaigns was also emphasized to promote energy-saving behaviors and increase the adoption of renewable energy solutions.

In conclusion, the Salininkai DHN serves as a model for modernizing district heating systems through renewable integration, operational optimization, and energy efficiency improvements. These findings provide a scalable and adaptable framework for other systems facing similar challenges, supporting national and global efforts toward a sustainable, low-carbon future.

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