VILNIUS TECH
Vilniaus Gedimino technikos universitetas

28-oji Lietuvos jaunųjų mokslininkų konferencijos „Mokslas – Lietuvos ateitis" teminė konferencija
Proceedings of the 28th Conference for Junior Researchers "Science – Future of Lithuania"

DARNI APLINKA / SUSTAINABLE ENVIRONMENT

2025 m. balandžio 24 d., Vilnius, Lietuva
24 April 2025, Vilnius, Lithuania

ISSN 2029-7157 / eISSN 2029-7149
eISBN 978-609-476-390-8
https://doi.org/10.3846/da.2025.030

Pastatų energetika / Energy for Buildings

https://vilniustech.lt/346238

SUSTAINABLE TRANSFORMATION OF DISTRICT HEATING NETWORKS: A CASE STUDY OF SALININKAI

Juozas BIELSKUS*, Abu Muhammad Mustakim REZA, Artur ROGOŽA

Department of Building Energetics, Faculty of Environmental Engineering, Vilnius Gediminas Technical University, Vilnius, Lithuania

**E-mail: juozas.bielskus@vilniustech.lt*

Received 24 February 2025; accepted 17 March 2025

Abstract: Global climate challenges, driven by rising greenhouse gas emissions and unsustainable energy practices, demand urgent action to transition toward cleaner and more efficient energy systems. The European Union has set ambitious targets to combat climate change, promoting renewable energy adoption and efficiency. Lithuania plays a crucial role in this transition with its cold winters and reliance on centralised heating systems. District Heating Networks (DHNs), which supply heat to residential and commercial buildings, are vital to achieving energy efficiency and sustainability in Lithuania's urban areas. The Salininkai DHN in Vilnius serves 46 buildings, including residential structures, a kindergarten, a supermarket, and small businesses. Powered by two 4.7 MW gas boilers with 85% efficiency, the system faces substantial heat losses due to its centralised heating point at one network corner and inefficiencies in many buildings with F and G energy class ratings and outdated radiator systems. This study evaluates Salininkai's energy production and distribution systems to improve efficiency and sustainability. Using EnergyPRO, the analysis simulates various scenarios, including integrating a 1 MW electric air-to-water heat pump, a 3,000 m^3 thermal storage system, and a solar park to reduce natural gas and commercial electricity dependency. Additionally, it explores repositioning the heating source to the network's centre and decentralising the network. The insights gained will guide recommendations to optimise heat distribution, reduce energy losses, and enhance the network's sustainability, which will be vetted by the Primary Energy Factor (PEF). These strategies could position the Salininkai DHN as a model for similar networks facing comparable challenges worldwide.

Keywords: distribution system optimisation of a DHN, integration of renewables in DHN, low temperature DHN, primary energy reduction in DHN, sustainable transformation of DHN.

1. Introduction

Climate change is one of the most pressing global challenges, driven by the rising concentration of greenhouse gases (GHGs) in the atmosphere. As a major contributor to these emissions, fossil fuel-based heating systems significantly impact the energy sector, exacerbating global warming (Dawson & Spannagle, 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 (International Energy Agency, 2022). District heating networks (DHNs) are critical to this transition, especially in colder regions where centralised heating provides substantial thermal energy to urban populations. However, ageing infrastructure, heat transmission inefficiencies, and reliance on fossil fuels hinder their sustainability and adaptability for renewable energy integration (Lund et al., 2010).

Lithuania, a Baltic nation characterised 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 (Eurostat, 2021). 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 up heat pumps, and different energy saving initiatives including building renovation, pipeline modification, etc.

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which perform optimally at lower temperatures (Villalobos et al., 2019; Stock et al., 2024).

District heating systems have long been a cornerstone of energy distribution in urban areas, particularly in Baltic countries. By centralising heat production and delivering it through insulated pipelines, these systems offer superior energy efficiency compared to decentralised systems. As Frederiksen and Werner (2013) highlighted, 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 decarbonisation (Dincer & Rosen, 2010).

However, ageing infrastructure poses a significant 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 ageing networks can lose 2–4 % of heat per kilometre (Werner, 2013; Werner, 2017), and modern insulation materials can reduce these losses by up to 50 % (Pan, 2015). These losses increase operational costs and 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 optimised network design and infrastructure upgrades.

Heat pumps harness ambient air or geothermal heat and are a promising solution for reducing fossil fuel dependence. Lund et al. (2010) and Sarbu et al. (2022) emphasise their potential to reduce GHG emissions and improve system efficiency. Research by Ochs et al. (2022) suggests that incorporating heat pumps can reduce annual gas consumption by 15–20 % (Ochs et al., 2022). When combined with TES, the heat pump systems can store surplus heat during peak demand, further enhancing sustainability (Dincer & Rosen, 2010).

Transitioning to low-temperature district heating (LTDH) is a key strategy for improving efficiency. LTDH operates at 50–55°C supply temperatures, compared to 70–90°C in traditional systems, reducing heat losses and enabling renewable integration (Sarbu et al., 2022). Nordic countries have demonstrated the success of LTDH in minimising energy consumption and emissions, providing a model for Lithuania (Lund et al., 2010). Decentralised networks can be modelled dynamically using tools like EnergyPRO, and Andersen (2019) highlights that such tools are essential for optimising operational parameters and reducing losses (Andersen, 2019; Marguerite et al., 2017).

Improving building energy efficiency is another critical aspect of modernisation. 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 can further promote energy-saving behaviours through awareness campaigns, flexible pricing, and incentives. Maghsoudi Nia et al. (2022) emphasise that targeted incentives can significantly reduce energy consumption and emissions.

Transforming the Salininkai DHN into a more efficient and sustainable system is a timely and necessary response to Lithuania's broader climate and energy challenges. As climate change accelerates due to rising greenhouse gas emissions, particularly from fossil fuel-based heating, modernising DHNs offers a practical pathway to reduce energy consumption, operational costs, and environmental impact. Salininkai, like many Lithuanian districts, relies heavily on ageing infrastructure and operates at high supply temperatures, limiting the integration of renewable energy technologies like heat pumps and thermal storage and resulting in significant heat losses. By transitioning to an LTDH model, upgrading pipelines, and improving building energy efficiency, Salininkai can serve as a benchmark for sustainable urban heating. Such transformation aligns with EU energy directives and demonstrates how thoughtful planning, modern technology, and consumer engagement can collectively drive decarbonisation and resilience in urban heating systems.

2. Current status and proposed alternatives of Salininkai DHN

The Salininkai DHN in Vilnius exemplifies these issues. Serving 46 buildings, including residential units, kindergarten, and commercial establishments, the network relies on two 4.7 MW gas boilers with 85 % efficiency to meet an annual heating demand of approximately 12,000 MWh (2021–2022 data). Its centralised heating point at one district corner exacerbates transmission losses (Figure 1). Suburban networks like Salininkai face even greater losses due to extended pipeline distances.

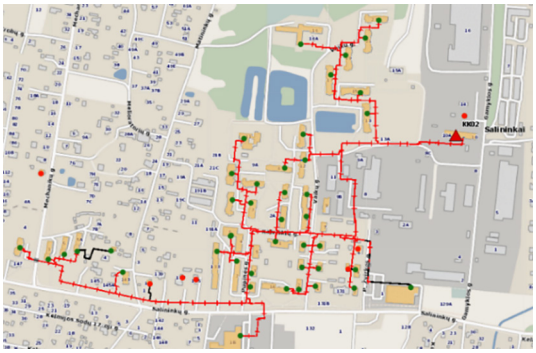


Figure 1. Salininkai DHN Map (Heat Source – Red Triangle)

Modernising the Salininkai DHN involves integrating renewable energy technologies, such as a 1 MW air-to-water heat pump and a 3,000 m³ thermal energy storage (TES) system. Solar photovoltaic systems are another proposed addition. They reduce reliance on primary heat sources like electricity by capturing solar energy to power heat pumps. A planned solar park in Salininkai will diversify the renewable energy portfolio, reducing carbon emissions and enhancing energy security. Optimising the Salininkai network's design includes repositioning the heating source to the network's centre and exploring decentralised nodes or secondary networks. Dynamic modelling tools like EnergyPRO can simulate heat flow, identify inefficiencies, and assess the feasibility of interventions.

The modernisation of the Salininkai DHN presents an opportunity to address inefficiencies, integrate renewable energy technologies (Baxter, 2005; Dickson & Fanelli, 2013; Pakare et al., 2021), and improve overall system sustainability. The project offers a scalable framework for transforming traditional DHNs into resilient, low-carbon energy systems by leveraging advanced modelling tools, enhancing building efficiency, and fostering consumer participation. These efforts align with Lithuania's national energy goals and global climate objectives, positioning Salininkai as a model for similar systems worldwide.

2.1. Demand versus production and impact of outdoor temperature

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 most significant 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.

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.

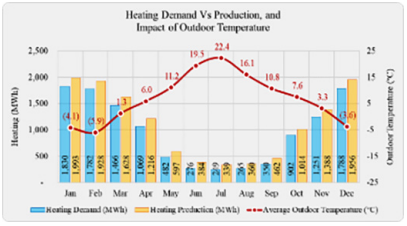


Figure 2. Demand Vs Production & Outdoor Temperature

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

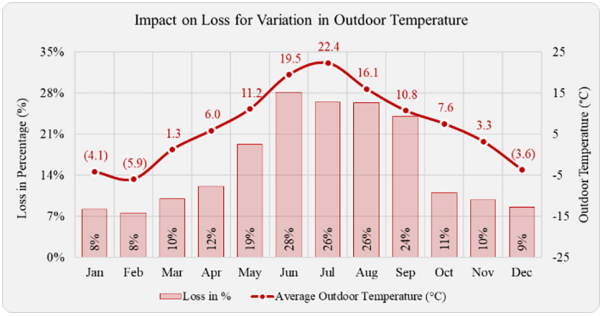


Figure 3. Variation of Loss over Outdoor Temperature

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

2.2. Focusing the loss in the Salininkai DHN system and yearly trend

The analysis of the Salininkai 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.

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 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

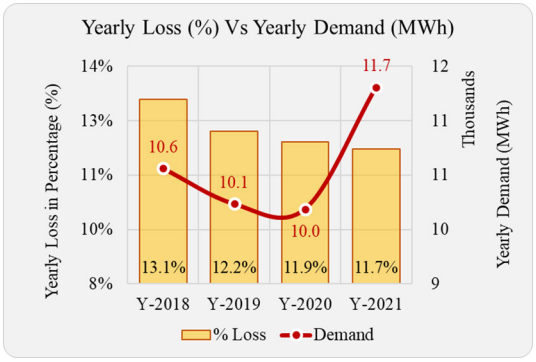


Figure 4. Loss Vs Demand (2018–2021)

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.

2.3. Segregation of heating demand for space heating and DHW

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 constant throughout the year, contributing 3,423 MWh annually, while space heating accounts for most demand variability. During summer (June to August), heating demand is negligible, but DHW demand sustains system operations. The following figure (Figure 5) represents monthly MWh demand for space heating and DHW.

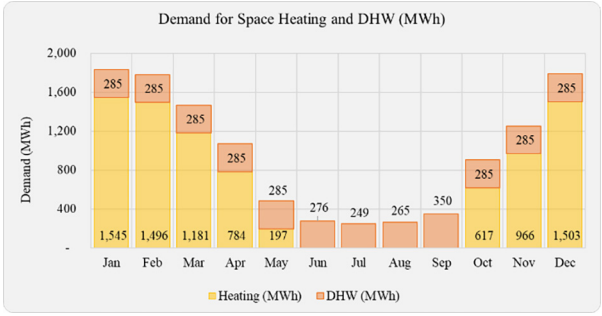


Figure 5. Space Heating and DHW (MWh)

It is noted that demand for DHW during the non-heating season is picked explicitly from the billing data and averaged for the rest of the months to calculate heating demand for space heating. While the percentage loss decreases, absolute heat loss remains substantial, especially during high-demand months. This underlines the critical impact of transmission inefficiencies on overall system performance. The rise in demand in 2021 and a reduction in loss percentage suggest 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 optimisation is necessary to minimise losses and achieve energy efficiency goals, particularly in addressing long-distance transmission inefficiencies and the ageing infrastructure serving poor energy-class buildings.

3. Goal and scope of the study

The study aims to evaluate the current state of the Salininkai 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 older buildings, and suboptimal boiler performance. The network's reliance on fossil fuels and limited integration of renewable energy further reduces its sustainability.

District heating systems are vital in Lithuania, where over 60 % of households depend on them. Modernising the Salininkai DHN will not only enhance its performance but also align with national energy goals and serve as a model for improving similar systems globally. The study uses EnergyPRO to simulate the current setup and evaluate potential upgrades, focusing on integrating renewable technologies like heat pumps with thermal storage and solar parks, optimizing heat distribution, and improving building-level energy efficiency. Cost-benefit and environmental impact analyses will support recommendations for sustainable and scalable solutions.

Key objectives of the study include:

- Analysing operational efficiency and addressing distribution losses.
- Exploring the integration of renewable energy technologies.
- Evaluating economic and environmental benefits of proposed upgrades.
- Developing actionable solutions for improving energy efficiency in buildings.

4. Methodology

The methodology for optimising the Salininkai DHN employs a systematic, data-driven approach, combining simulation modelling, sensitivity analysis, and scenario evaluation using tools like EnergyPRO and Microsoft Excel. Operational data, including hourly heating demand for 2021, outdoor temperature variations, historical heat production and loss data (2018–2020), and building energy classifications, is collected from the DHN authority. GIS tools (Yandex Mapping Tool, 2025) visualise the network's geographical layout to assess the

impact of pipeline distances on heat losses (Figure 6). This data forms the foundation for modelling and analysis.

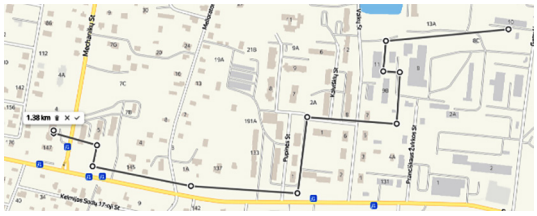


Figure 6. Distribution distance: through the GIS mapping tool, the distance of the distribution pipe from the heat generation point to the farthest site (Mechanikų g. 2) is measured, which is 1.38 km

EnergyPRO models the baseline system (Figure 7) to analyse gas boiler performance under varying load conditions. Outputs include heat loss patterns, boiler efficiency data, and mismatches between production and demand. Data is further analysed in Microsoft Excel to visualise performance and identify inefficiencies. The study evaluates an equivalent of 1 MW air-to-water heat pump and a 3,000 m³ thermal energy storage (TES) system along with a solar park (Figure 8).

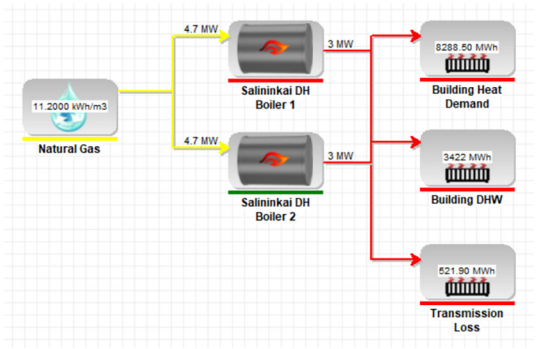


Figure 7. Baseline System (Existing Setup)

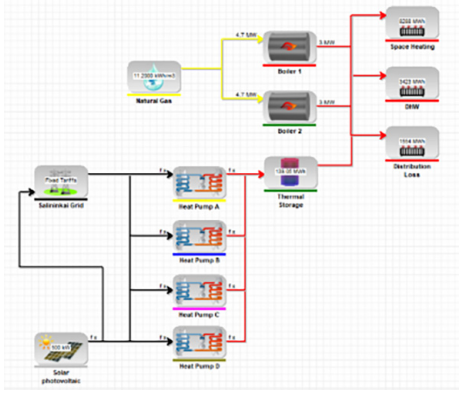


Figure 8. After the incorporation of HP, TES and Solar Park

EnergyPRO simulates fuel consumption reductions, load redistribution, and seasonal performance variations. Simulations assess the impact of improved pipeline insulation and lower supply-return temperatures on efficiency. Zoning scenarios, where the network is divided into two zones connected by a transmission line (**Error! Reference source not found.**), are modelled to evaluate reduced heat losses and pumping requirements.

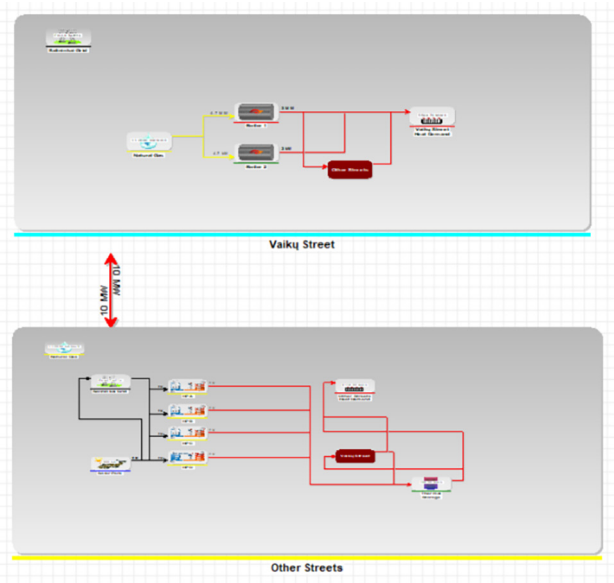


Figure 9. Distributed Heat Network (Recommended)

Sensitivity analysis examines the system's performance under varying temperatures, energy prices, and heat pump efficiencies. Results are plotted in Excel, and thresholds where solutions remain effective are identified. Cost-benefit analysis calculates energy consumption, payback periods, and emissions reductions for proposed upgrades. Environmental impact assessments quantify the decrease in greenhouse gas emissions and fossil fuel dependency.

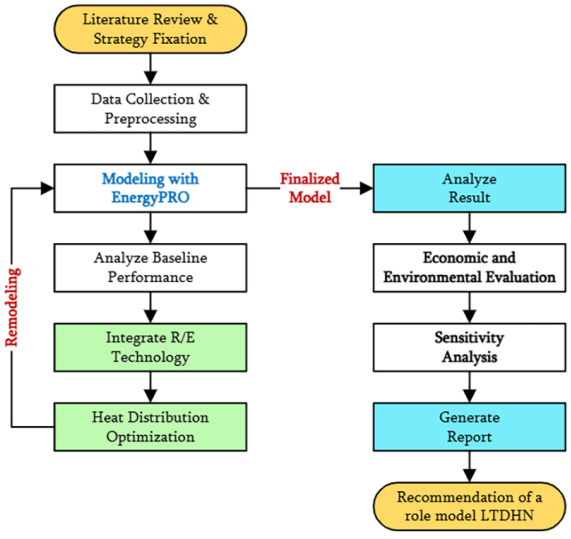


Figure 10. Methodology of the Study

EnergyPRO generates detailed reports, while Excel visualises efficiency and economic performance. Based on findings, recommendations focus on renewable integration, insulation upgrades, and optimised configurations to ensure cost-effective and sustainable solutions for the Salininkai DHN, which will be a role model LT-DHN (Figure 10).

5. Result of the study

This part presents the findings from the analysis of the Salininkai DHN. The results are derived from data analysis, simulations, and system modelling using EnergyPRO. These findings address the research objectives, including system performance, the impact of integrating an air-to-water heat pump, and potential optimisations in heat distribution.

5.1. EnergyPRO simulation results

The Salininkai DHN 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. This corresponds to a heat output of approximately 2.8 MW to 3.2 MW for these boilers. The peak delivery capacity of a single boiler of 3 MW is considered to simplify operations. 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, the EnergyPRO simulation is designed to get 3 MW heat output from each boiler, and the first boiler is prioritised over the second boiler. The following figure (Figure 11) represents the plotting of heat production by each of the boilers at every instance of heat consumption for the year.

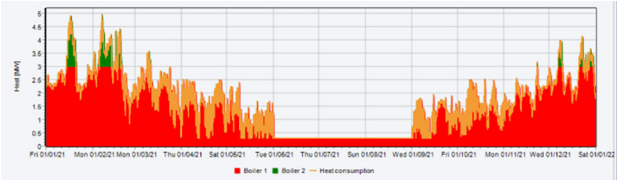


Figure 11. Heat Production (current status)

According to this report, boiler 1 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, boiler 2 comes into operation and delivers the required heat.

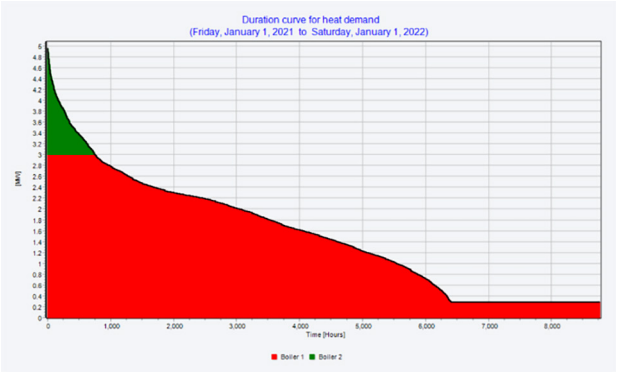


Figure 12. Boilers' Operations (current status)

The annual report of the EnergyPRO simulation shows that the maximum heat demand was 5.0 MW and the total heat demand was 13,265 MWh. The first boiler delivered 12,775.8 MWh, whereas the second boiler delivered only 489.2 MWh of total heat demand. The figure (Figure 12), i.e., the duration curve report, represents a comparison of the total operational period of the energy conversion units, in our case, two boilers.

From the above reports and short descriptions, it can be concluded that two boilers are currently operating to meet the heat demand for Salininkai DHN according to set priorities and other settings.

5.2. Incorporation of an electric air-to-water heat pump and the impact

Integrating renewable energy technologies into the district heating network of Salininkai represents a vital step toward achieving a sustainable and energy-efficient system. As part of this research, a 1 MW electric air-to-water heat pump has been selected for integration into the network. This system harnesses 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 carefully reviewing the market, several commercially available 1 MW air-to-water heat pump models can be considered, including the following models (Table 1).

For the EnergyPRO simulation, the RTXC XE-EC-R513A Air-to-Water Heat Pump (TRANE, n.d.) is selected, which is a high-efficiency unit with a Seasonal Coefficient of Performance (SCOP) ranging from 3.35 to 3.46. At maximum heating delivery, a single unit provides up to 798.7 kW of heating capacity, consuming approximately 252 kW of electric power. Four heat pumps are configured in a row to meet the 1 MW electric capacity requirement. The RTXC XE-EC-R513A uses R513A refrigerant, an environmentally friendly option with a lower global warming potential (GWP), aligning with sustainability goals and EU environmental

Table 1. Some Heat Pump Models available in Market (BOSCH, n.d.) (Daikin, n.d.) (Mitsubishi Electric, n.d.) (TRANE, n.d.)

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

standards. The faint sound power level ensures minimal disturbance to residential and business areas. Its compliance with Eco-design regulations guarantees optimal energy efficiency, making it an ideal solution for integrating renewable energy into the district heating network. 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 with only one unit if the demand is low. That will be seen in the EnergyPRO simulation, which will save further electricity.

When this heat pump is operated with the priority, with a thermal storage capacity of 3,000 m3 and an assumed loss of 5 %, the EnergyPRO simulation results are pretty interesting. The following figure (Figure 13) represents the EnergyPRO simulation plotting the heat production of each energy conversion unit at every instance of heat consumption.

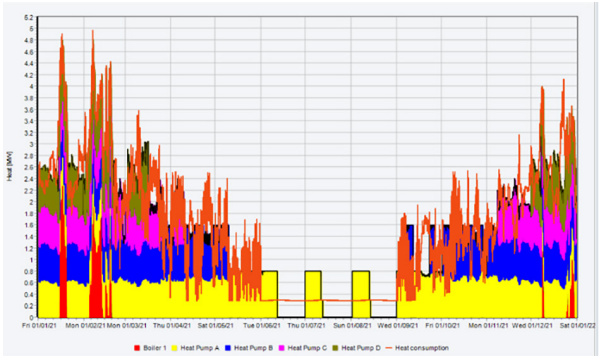


Figure 13. Heat Production (with Heat Pumps and Storage)

The EnergyPRO simulation's annual report found that the maximum heat demand was 5.0 MW and the total heat demand was 13,265 MWh. The heat pumps 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. Previously, no electricity consumption was there, but the incorporation of a heat pump incurs electricity consumption, and the following figure (Figure 14) represents electricity consumption from the EnergyPRO simulation. From the annual report, it is observed that heat pumps 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. However, the natural gas consumption dropped significantly from 1.86 million m3 to 0.15 million m3 only (Figures 15 and 16).

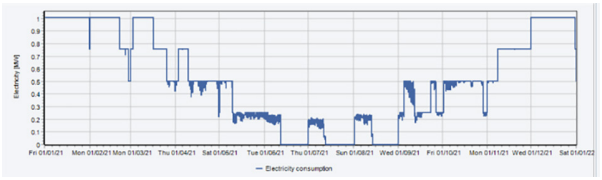


Figure 14. Electricity Consumption (with Heat Pumps)

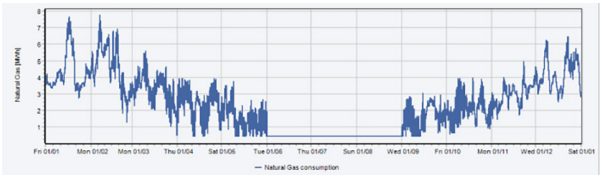


Figure 15. Natural Gas Consumption (Current Status)

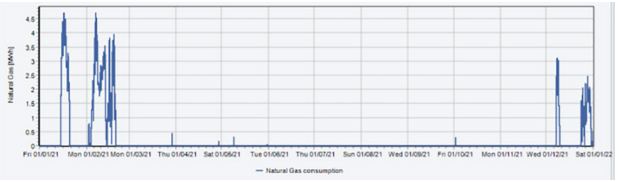


Figure 16. Natural Gas Consumption (with Heat Pumps)

5.3. Incorporation of a photovoltaic solar park and the impact

Integrating a solar park into the Salininkai DHN presents a valuable opportunity to enhance sustainability and reduce reliance on grid power. If 100 % of the required electricity for the heat pumps is to be taken from the solar park, the required solar park capacity (without tracking system) can be calculated using the following equation (Duffie et al., 2020).

$$E = P_{peak} \times H_{sun} \times \eta,$$

where

E = Yearly electricity generation in kWh = 4.584 MWh,

P_{peak} = Solar park peak capacity in kW_p,

H_{sun} = Annual solar irradiation = 1,144.5 kWh/m^2,

η = Overall system efficiency = 95%,

$$\therefore P_{peak} = \frac{E}{H_{sun} \times \eta} = \frac{4{,}584 \times 1{,}000}{1{,}144.5 \times 95\%} = 4{,}216\ kW_p.$$

However, considering the available space in the Salininkai DHN premises, it is possible to incorporate a 500 kWp solar park, and the EnergyPRO simulation will be done with it. While smaller in scale than utility-sized solar parks, this installation can still deliver meaningful energy contributions, particularly when paired with other renewable technologies like the proposed 1 MW air-to-water heat pump. A 500 kWp solar park can generate approximately 650–750 MWh of electricity annually, depending on solar irradiance in Vilnius and the efficiency of the installed photovoltaic (PV) panels.

To determine the peak demand, considering an optimistic design, it is assumed that the overall system will have 5 % total losses, including the inverter and wiring, in a calm and clean environment like Salininkai; hence, the overall system efficiency is considered 95 %.

This electricity could directly power the heat pump operations or other auxiliary systems in the DHN, reducing the system's reliance on grid-supplied electricity and fossil fuels. EnergyPRO simulations will evaluate how the solar park best complements the DHN infrastructure. The results will provide insights into operational efficiency, cost reductions, and emissions savings. From the simulation result, it is found that 500 kWp solar generated 730.9 MWh throughout the year, according to PVGIS (European Commission, 2024) data of solar irradiation and the electricity consumption from EnergyPRO simulation is represented in the following figure (Figure 17).

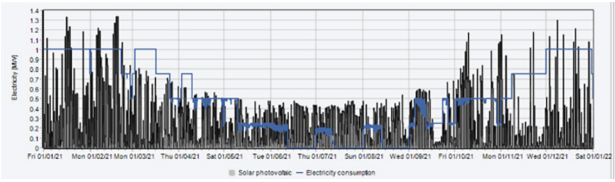


Figure 17. Electricity Consumption and PV Production

5.4. EnergyPRO simulation summary, energy demand flow and overall system efficiency

In the annual report, information related to annual heat demand, peak heat demand, heat production by each of the energy conversion units, hours of operation, fuel consumption, electricity consumption, peak electricity generation by solar park and overall energy consumption are summarised in the following table (Table 2).

5.5. Efficiency at the level of end users (analysing building class and user behaviour)

There are 46 buildings connected to this district heating network, which are of different energy classes. Of these, 44 buildings consume energy from this network. Their energy consumption varies from around 13 to 718 MWh, considering energy for heat and DHW. If the energy signature of the top five contributors of this network is plotted, it looks as follows (Figure 18).

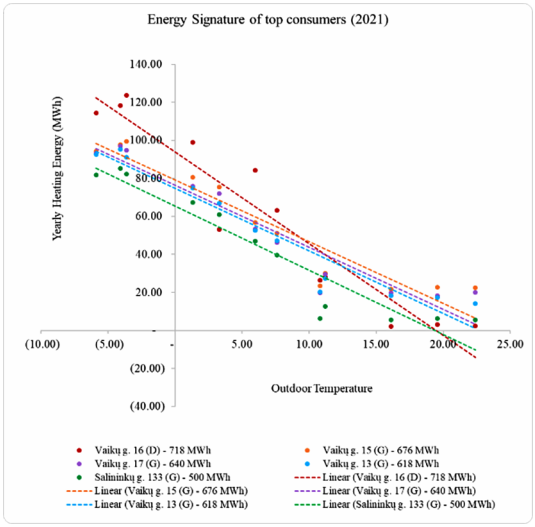


Figure 18. Energy Signatures of Top Contributors (2021)

The Energy Signatures clearly show that the building with a sharper slope (Vaikų g. 16) is of energy class D and consumes 718 MWh of energy. The other four buildings have a less sharp slope and are of energy class G, which indicates that it is possible to reduce energy consumption by updating the energy classes of the buildings.

5.6. Analysis of the thermal storage to maximise the gain

The designed thermal storage capacity (3000 m^3) supports around 139 MWh of energy to be stored and utilised during demand, which continues throughout the year. The benefits of thermal storage have already been blended with the previous analysis. However, it is understandable that thermal storage potentially contributed to reducing the running hours of heat pumps and boilers and thus reduced primary energy consumption.

5.7. Economic and environmental evaluation

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 (*Tarifas*, n.d.). This model will be performed in the second phase of this study. The following figure (Figure 19) elaborates the total yearly energy cost in Euro

Table 2. Simulation Summary (Current Status | After Addition of HP and TES | After Addition of Solar Park)

Current Status			`+ Heat Pumps + Thermal Storage			`+ Solar Park		
Heating Demand (MWh)			**Heating Demand (MWh)**			**Heating Demand (MWh)**		
Space Heating	8,288	62.5%	Space Heating	8,288	62.5%	Space Heating	8,288	62.5%
DHW	3,423	25.8%	DHW	3,423	25.8%	DHW	3,423	25.8%
Distribution Loss	1,554	11.7%	Distribution Loss	1,554	11.7%	Distribution Loss	1,554	11.7%
Total	**13,265**	**100.0%**	**Total**	**13,265**	**100.0%**	**Total**	**13,265**	**100.0%**
Peak Load	**5.00**	**MW**	**Peak Load**	**5.00**	**MW**	**Peak Load**	**5.00**	**MW**
Heat Production (MWh)			**Heat Production (MWh)**			**Heat Production (MWh)**		
Heat Pump A	-	0.0%	Heat Pump A	5,151.4	38.8%	Heat Pump A	5,151.4	38.8%
Heat Pump B	-	0.0%	Heat Pump B	3,630.4	27.4%	Heat Pump B	3,630.4	27.4%
Heat Pump C	-	0.0%	Heat Pump C	2,133.2	16.1%	Heat Pump C	2,133.2	16.1%
Heat Pump D	-	0.0%	Heat Pump D	1,362.2	10.3%	Heat Pump D	1,362.2	10.3%
Boiler 1	12,775.8	96.3%	Boiler 1	1,048.2	7.9%	Boiler 1	1,048.2	7.9%
Boiler 2	489.2	3.7%	Boiler 2	-	0.0%	Boiler 2	-	0.0%
Storage Tank Loss	-	0.0%	Storage Tank Loss	(60.5)	-0.5%	Storage Tank Loss	(60.5)	-0.5%
Total	**13,265**	**100.0%**	**Total**	**13,265**	**100.0%**	**Total**	**13,265**	**100.0%**
Hours of Operation (Hours)			**Hours of Operation (Hours)**			**Hours of Operation (Hours)**		
Heat Pump A	-	0.0%	Heat Pump A	7,437.0	84.9%	Heat Pump A	7,437.0	84.9%
Heat Pump B	-	0.0%	Heat Pump B	5,441.0	62.1%	Heat Pump B	5,441.0	62.1%
Heat Pump C	-	0.0%	Heat Pump C	3,429.0	39.1%	Heat Pump C	3,429.0	39.1%
Heat Pump D	-	0.0%	Heat Pump D	2,281.0	26.0%	Heat Pump D	2,281.0	26.0%
Boiler 1	8,760.0	100.0%	Boiler 1	793.0	9.1%	Boiler 1	793.0	9.1%
Boiler 2	746.0	8.5%	Boiler 2	-	0.0%	Boiler 2	-	0.0%
Solar		0.0%	Solar		0.0%	Solar	4,282.0	48.9%
Total	**8,760**		**Total**	**8,760**		**Total**	**8,760**	
Gas Consumption (m^3)			**Gas Consumption (m^3)**			**Gas Consumption (m^3)**		
Boiler 1	1,787,095.9	96.3%	Boiler 1	146,629.5	100.0%	Boiler 1	146,629.5	100.0%
Boiler 2	68,425.0	3.7%	Boiler 2	-	0.0%	Boiler 2	-	0.0%
Total	**1,855,521**		**Total**	**146,630**		**Total**	**146,630**	
Electricity Consumption (MWh)			**Electricity Consumption (MWh)**			**Electricity Consumption (MWh)**		
Heat Pump A	-		Heat Pump A	1,785.6	39.0%	Heat Pump A	1,785.6	46.3%
Heat Pump B	-		Heat Pump B	1,359.2	29.7%	Heat Pump B	1,359.2	35.3%
Heat Pump C	-		Heat Pump C	864.1	18.9%	Heat Pump C	864.1	22.4%
Heat Pump D	-		Heat Pump D	574.8	12.5%	Heat Pump D	574.8	14.9%
Boiler 1	-		Boiler 1	-	0.0%	Boiler 1	-	0.0%
Boiler 2	-		Boiler 2	-	0.0%	Boiler 2	-	0.0%
Solar			Solar		0.0%	Solar	(730.9)	-19.0%
Total	-	**MWh**	**Total**	**4,584**	**MWh**	**Total**	**3,853**	**MWh**
Peak Solar Output	-	**kW**	**Peak Solar Output**	-	**kW**	**Peak Solar Output**	**1,336.80**	**kW**
Neat Energy Consumption (MWh)			**Neat Energy Consumption (MWh)**			**Neat Energy Consumption (MWh)**		
Heat Pump A		0.0%	Heat Pump A	1,785.6	28.7%	Heat Pump A	1,785.6	32.5%
Heat Pump B		0.0%	Heat Pump B	1,359.2	21.8%	Heat Pump B	1,359.2	24.7%
Heat Pump C		0.0%	Heat Pump C	864.1	13.9%	Heat Pump C	864.1	15.7%
Heat Pump D		0.0%	Heat Pump D	574.8	9.2%	Heat Pump D	574.8	10.5%
Boiler 1	20,015.5	96.3%	Boiler 1	1,642.2	26.4%	Boiler 1	1,642.2	29.9%
Boiler 2	766.4	3.7%	Boiler 2	-	0.0%	Boiler 2	-	0.0%
Solar		0.0%	Solar	-	0.0%	Solar	(730.9)	-13.3%
Total	**20,782**	**MWh**	**Total**	**6,226**	**MWh**	**Total**	**5,495**	**MWh**
Primary Energy	**20,781.90**	**MWh**	**Primary Energy**	**11,267.99**	**MWh**	**Primary Energy**	**10,537.09**	**MWh**
System Efficiency	**56%**		**System Efficiency**	**104%**		**System Efficiency**	**111%**	
PEF Calculation (Sustainability Index)			**PEF Calculation (Sustainability Index)**			**PEF Calculation (Sustainability Index)**		
Primary Energy Input	20,781.9	MWh	Primary Energy Input	11,268.0	MWh	Primary Energy Input	10,537.1	MWh
Useful Energy Output	13,265.0	MWh	Useful Energy Output	13,265.0	MWh	Useful Energy Output	13,265.0	MWh
PEF	**1.57**		**PEF**	**0.85**		**PEF**	**0.79**	

for the current status after integrating heat pumps and thermal storage, incorporating a solar park, and distributing the network into two segments.

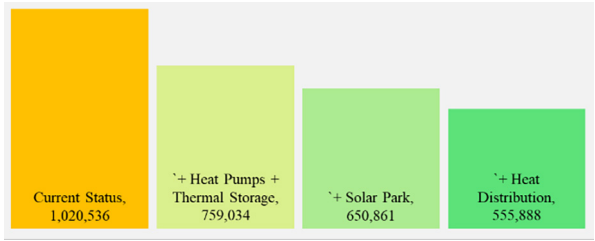


Figure 19. Yearly Energy Cost (Euro)

5.8. Dividing the DHN into two sites to reduce distribution losses

Heat distribution network is carefully observed to distribute the heat load into two segments (sites) where in the first segment, named as Vaikų Street, contains 17 connected buildings with a total energy demand of yearly 5,594.74 MWh and the second segment, named as Other Streets, contains 19 buildings with a total energy demand of yearly 6,116.48 MWh. While dividing, as the existing boiler is near to the Vaikų Street, the heat pumps including the thermal storage is installed in the Other Streets and result gives us a significant savings keeping both the boilers out of operation through priorities and increasing the heat production of the heat pumps with an overall system efficiency of 135%. The result is summarised in the following table (Table 3).

The analysis shows that the total energy requirement remains the same, but the heat production of energy conversion units changed dramatically. Heat pumps increased production, but the boilers reduced their operation to zero, meaning the natural gas consumption turned to zero. As a result, the total required primary energy reduced from 10.54 GWh to 8.69 GWh, and the overall system efficiency increased from 111 % to 135%. In contrast, the overall system efficiency of the existing scenario is only 56 %.

Segmentation of the network into two segments helped it maximise its resources, taking 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 and proper prioritisation.

5.9. Sensitivity analysis

Different levels of sensitivity analysis can be done, including heat pump capacity, TES capacity, transmission line capacity, distance of heat sources, outdoor temperature variation, solar irradiation variation, etc. Due to the scope of the analysis and keen focus on the transformation of the DHN, this study's sensitivity analysis is limited. However, it can be done in the future.

6. Discussion

The Salininkai DHN study presents a detailed investigation into optimising its operational efficiency and integrating renewable energy technologies. This discussion examines the key findings from simulations, renewable technology integration, and the economic and environmental implications of the proposed changes.

6.1. System Performance Analysis

To meet the demand of 11,711 MWh of heat, the existing two boilers consumed 20,783 MWh of energy from fuel (natural gas), which is primary energy, giving an overall system efficiency of 63.8 %. Whereas, 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, it is found that the total energy requirement to produce the demanded heat is 11,268 MWh, considering energy from fuel and electricity together, which results in an overall system efficiency of 104 %. To convert the consumed energy from electricity to primary energy, the value of the primary energy factor is used as 2.1 (European Commission, 2016). Not only that, after incorporating the solar park, the total demand for primary energy is reduced to 10,537 MWh, which results in an overall system efficiency of 111 %. The comparison can be displayed in the following figure (Figure 20).

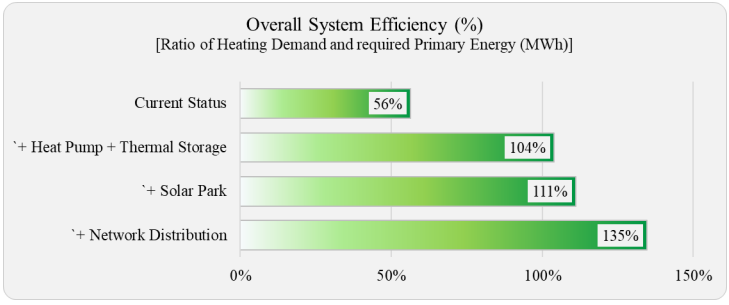


Figure 20. Overall System Efficiency (%)

Table 3. Simulation Result (Current Status | After Addition of HP and TES | After Addition of Solar Park | After Heat Distribution)

Current Status			`+ Heat Pumps + Thermal Storage			`+ Solar Park			`+ Heat Distribution		
Heating Demand (MWh)			**Heating Demand (MWh)**			**Heating Demand (MWh)**			**Heating Demand (MWh)**		
Space Heating	8,288	62.5%	Space Heating	8,288	62.5%	Space Heating	8,288	62.5%	Space Heating	8,288	65.8%
DHW	3,423	25.8%	DHW	3,423	25.8%	DHW	3,423	25.8%	DHW	3,423	27.2%
Distribution Loss	1,554	11.7%	Distribution Loss	1,554	11.7%	Distribution Loss	1,554	11.7%	Distribution Loss	876	7.0%
Total	**13,265**	**100.0%**	**Total**	**13,265**	**100.0%**	**Total**	**13,265**	**100.0%**	**Total**	**12,587**	**100.0%**
Peak Load	**5.00**	**MW**	**Peak Load**	**5.00**	**MW**	**Peak Load**	**5.00**	**MW**	**Peak Load**	**5.00**	**MW**
Heat Production (MWh)			**Heat Production (MWh)**			**Heat Production (MWh)**			**Heat Production (MWh)**		
Heat Pump A	-	0.0%	Heat Pump A	5,151.4	38.8%	Heat Pump A	5,151.4	38.8%	Heat Pump A	5,924.7	47.1%
Heat Pump B	-	0.0%	Heat Pump B	3,630.4	27.4%	Heat Pump B	3,630.4	27.4%	Heat Pump B	5,741.3	45.6%
Heat Pump C	-	0.0%	Heat Pump C	2,133.2	16.1%	Heat Pump C	2,133.2	16.1%	Heat Pump C	979.0	7.8%
Heat Pump D	-	0.0%	Heat Pump D	1,362.2	10.3%	Heat Pump D	1,362.2	10.3%	Heat Pump D	-	0.0%
Boiler 1	12,775.8	96.3%	Boiler 1	1,048.2	7.9%	Boiler 1	1,048.2	7.9%	Boiler 1	-	0.0%
Boiler 2	489.2	3.7%	Boiler 2	-	0.0%	Boiler 2	-	0.0%	Boiler 2	-	0.0%
Storage Tank Loss	-	0.0%	Storage Tank Loss	(60.5)	-0.5%	Storage Tank Loss	(60.5)	-0.5%	Loss (Storage + Tx)	(57.6)	-0.5%
Total	**13,265**	**100.0%**	**Total**	**13,265**	**100.0%**	**Total**	**13,265**	**100.0%**	**Total**	**12,587**	**100.0%**
Hours of Operation (Hours)			**Hours of Operation (Hours)**			**Hours of Operation (Hours)**			**Hours of Operation (Hours)**		
Heat Pump A	-	0.0%	Heat Pump A	7,437.0	84.9%	Heat Pump A	7,437.0	84.9%	Heat Pump A	8,760.0	100.0%
Heat Pump B	-	0.0%	Heat Pump B	5,441.0	62.1%	Heat Pump B	5,441.0	62.1%	Heat Pump B	8,562.0	97.7%
Heat Pump C	-	0.0%	Heat Pump C	3,429.0	39.1%	Heat Pump C	3,429.0	39.1%	Heat Pump C	1,910.0	21.8%
Heat Pump D	-	0.0%	Heat Pump D	2,281.0	26.0%	Heat Pump D	2,281.0	26.0%	Heat Pump D	3.0	0.0%
Boiler 1	8,760.0	100.0%	Boiler 1	793.0	9.1%	Boiler 1	793.0	9.1%	Boiler 1	5.0	0.1%
Boiler 2	746.0	8.5%	Boiler 2	-	0.0%	Boiler 2	-	0.0%	Boiler 2	27.0	0.3%
Solar		0.0%	Solar		0.0%	Solar	4,282.0	48.9%	Solar	4,282.0	48.9%
Total	**8,760**		**Total**	**8,760**		**Total**	**8,760**		**Total**	**8,760**	
Gas Consumption (m^3)			**Gas Consumption (m^3)**			**Gas Consumption (m^3)**			**Gas Consumption (m^3)**		
Boiler 1	1,787,095.9	96.3%	Boiler 1	146,629.5	100.0%	Boiler 1	146,629.5	100.0%	Boiler 1	-	0.0%
Boiler 2	68,425.0	3.7%	Boiler 2	-	0.0%	Boiler 2	-	0.0%	Boiler 2	-	0.0%
Total	**1,855,521**		**Total**	**146,630**		**Total**	**146,630**		**Total**	-	
Electricity Consumption (MWh)			**Electricity Consumption (MWh)**			**Electricity Consumption (MWh)**			**Electricity Consumption (MWh)**		
Heat Pump A	-		Heat Pump A	1,785.6	39.0%	Heat Pump A	1,785.6	46.3%	Heat Pump A	2,054.4	54.7%
Heat Pump B	-		Heat Pump B	1,359.2	29.7%	Heat Pump B	1,359.2	35.3%	Heat Pump B	2,003.8	53.3%
Heat Pump C	-		Heat Pump C	864.1	18.9%	Heat Pump C	864.1	22.4%	Heat Pump C	431.1	11.5%
Heat Pump D	-		Heat Pump D	574.8	12.5%	Heat Pump D	574.8	14.9%	Heat Pump D	-	0.0%
Boiler 1	-		Boiler 1	-	0.0%	Boiler 1	-	0.0%	Boiler 1	-	0.0%
Boiler 2	-		Boiler 2	-	0.0%	Boiler 2	-	0.0%	Boiler 2	-	0.0%
Solar			Solar		0.0%	Solar	(730.9)	-19.0%	Solar	(733.3)	-19.5%
Total	-	**MWh**	**Total**	**4,584**	**MWh**	**Total**	**3,853**	**MWh**	**Total**	**3,756**	**MWh**
Peak Solar Output	-	**kW**	**Peak Solar Output**	-	**kW**	**Peak Solar Output**	**1,336.80**	**kW**	**Peak Solar Output**	**1,335.60**	**kW**
Neat Energy Consumption (MWh)			**Neat Energy Consumption (MWh)**			**Neat Energy Consumption (MWh)**			**Neat Energy Consumption (MWh)**		
Heat Pump A		0.0%	Heat Pump A	1,785.6	28.7%	Heat Pump A	1,785.6	32.5%	Heat Pump A	2,054.4	54.7%
Heat Pump B		0.0%	Heat Pump B	1,359.2	21.8%	Heat Pump B	1,359.2	24.7%	Heat Pump B	2,003.8	53.3%
Heat Pump C		0.0%	Heat Pump C	864.1	13.9%	Heat Pump C	864.1	15.7%	Heat Pump C	431.1	11.5%
Heat Pump D		0.0%	Heat Pump D	574.8	9.2%	Heat Pump D	574.8	10.5%	Heat Pump D	-	0.0%
Boiler 1	20,015.5	96.3%	Boiler 1	1,642.2	26.4%	Boiler 1	1,642.2	29.9%	Boiler 1	-	0.0%
Boiler 2	766.4	3.7%	Boiler 2	-	0.0%	Boiler 2	-	0.0%	Boiler 2	-	0.0%
Solar		0.0%	Solar	-	0.0%	Solar	(730.9)	-13.3%	Solar	(733.3)	-19.5%
Total	**20,782**	**MWh**	**Total**	**6,226**	**MWh**	**Total**	**5,495**	**MWh**	**Total**	**3,756**	**MWh**
Primary Energy	**20,781.90**	**MWh**	**Primary Energy**	**11,267.99**	**MWh**	**Primary Energy**	**10,537.09**	**MWh**	**Primary Energy**	**8,694.23**	**MWh**
System Efficiency	**56%**		**System Efficiency**	**104%**		**System Efficiency**	**111%**		**System Efficiency**	**135%**	
PEF Calculation (Sustainability Index)			**PEF Calculation (Sustainability Index)**			**PEF Calculation (Sustainability Index)**			**PEF Calculation (Sustainability Index)**		
Primary Energy Input	20,781.9	MWh	Primary Energy Input	11,268.0	MWh	Primary Energy Input	10,537.1	MWh	Primary Energy Input	8,694.2	MWh
Useful Energy Output	13,265.0	MWh	Useful Energy Output	13,265.0	MWh	Useful Energy Output	13,265.0	MWh	Useful Energy Output	12,587.3	MWh
PEF	**1.57**		**PEF**	**0.85**		**PEF**	**0.79**		**PEF**	**0.69**	

6.2. Impact of Renewable Integration on Primary Energy Demand

The transition to a renewable-integrated system reduced annual natural gas consumption from 1,855,521 m^3 to 146,630 m^3, achieving significant primary energy savings. However, this shift incurred an annual electricity consumption of 4,584 MWh, which the study proposed to offset through a 500 kWp solar park. The solar park could generate 730.9 MWh annually, covering a vast portion of the heat pump's electricity demand and reducing the environmental footprint. The following figure (Figure 21) represents changes in primary energy demand.

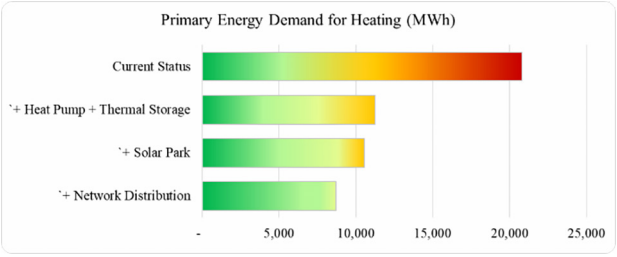


Figure 21. Primary Energy Demand (MWh)

6.3. Boilers' Performance and Efficiency

After the integration of the heat pump and thermal storage system, the performance and operational dynamics of the boilers in the Salininkai District Heating Network underwent significant changes. Renewable technologies significantly reduce reliance on boilers, especially during moderate outdoor temperatures.

Boiler 2 was eliminated from operation after integrating the heat pump and thermal storage, as the combined capacity of the renewable systems was sufficient to meet the heating demand under most conditions. This marked a substantial improvement in system efficiency and reduced fossil fuel dependency. Boiler 1, however, remained essential during colder periods when the outdoor temperature dropped below −2.1°C. The heat pump reached its maximum capacity at this threshold, necessitating additional heat production to meet the rising total heat demand. Boiler 1 supplemented the system during these periods, ensuring a reliable heating supply during peak demand.

This operational adjustment highlights the enhanced flexibility and efficiency of the network after renewable integration. By reducing the runtime of the boilers, particularly Boiler 2, the system achieved significant reductions in fuel consumption, emissions, and operational costs, while maintaining the ability to handle peak demands effectively. This approach underscores the potential for balancing renewable and conventional heating systems to optimise energy use and sustainability. The following figure (Figure 22) will give insight into the overall operational mechanism.

Three significant insights are observed in this figure. The first one is the boiler's heat production. The boiler produces heat only when the temperature goes below −2.1 °C, indicating that the overall system demand also rises above the heat pumps' capacity at that point. The second insight is that the boiler ran constantly at an efficiency of 64 %, regardless of the production, up to 3 MW. The final insight is about heat pumps' operation. They ran from the extremely low temperature to the high temperature in summer. For any particular point, heat pumps' produced heat has different values, i.e., at 0 °C four types of production are found which is due to two main reasons – operational flexibility for modular nature as four heat pumps work in series connection to increase capacity and another important reason is the flexibility due to the thermal storage's supply during peak demand. When TES's supply was available, not all heat pumps went into operation, but when it was not available, more heat pumps went into operation.

6.4. Variation of Heat Pumps' COP with Outdoor Temperature

The Coefficient of Performance (COP) of heat pumps exhibits an apparent variation with outdoor temperature, reflecting the relationship between environmental conditions and system efficiency. At lower outdoor temperatures, the COP is significantly reduced, typically below 2.0 when temperatures drop below −10°C. This decline is due to the increased energy required to extract heat from colder air, which decreases the heat pump's efficiency. The following figure (Figure 23) represents the variation of heat pumps' COP with outdoor temperature.

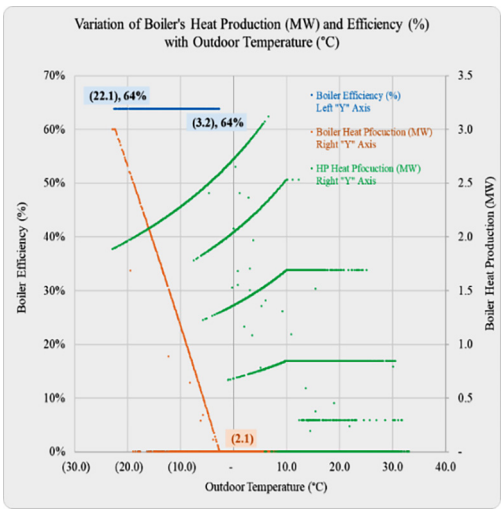


Figure 22. Boiler Performance and Efficiency

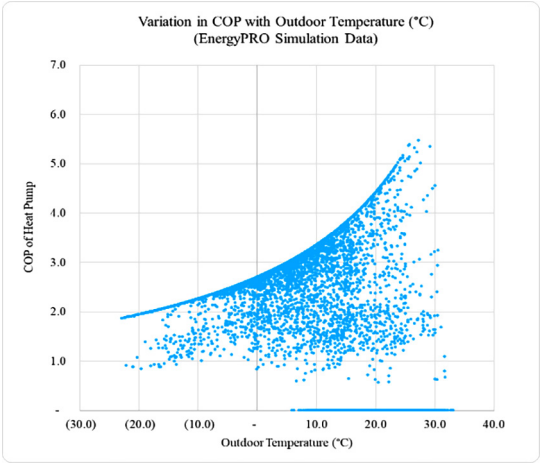


Figure 23. Variation in COP with Outdoor Temperature

As outdoor temperatures rise, the COP improves substantially. Around 0°C, the COP typically ranges between 3.0 and 4.0, indicating a more efficient operation. This trend continues, with the COP reaching values of 5.0 to 6.5 as outdoor temperatures climb to 20°C or higher. This improvement occurs because the heat pump requires less energy to transfer heat when the temperature difference between the source and the supply is smaller.

This variation in COP underscores the heat pump's suitability for milder weather conditions, where its efficiency is maximized. However, supplementary heating sources, such as boilers, may be necessary during icy conditions to effectively meet heating demand. Optimising the operation of heat pumps during varying outdoor temperatures is crucial for achieving overall energy efficiency and minimising operational costs in district heating networks.

6.5. Heat Distribution Optimisation

As elaborated in the following representation, this challenging part of the DHN's complete transformation process will be most attractive if natural gas consumption is turned null (Figure 24).

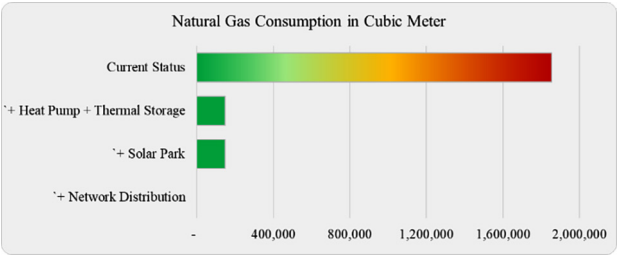


Figure 24. Natural Gas Consumption (m^3)

Taking measures on buildings' energy classes to bring efficiency (as described in section 5.5) and consumer behaviour, significant gains can be achieved, which is common in all DHNs. Further economic analysis can be done by considering the need for investment, pay-back period, and internal rate of return. Moreover, life cycle assessment of existing scenarios versus proposed scenarios will give deep insight into the environmental assessment part and outcomes of the final scenario with changed parameters in fuel and grid prices, outdoor temperatures, solar irradiations, etc., will give complete insight into the analysis by inclusion of sensitivity analysis.

6.6. Sustainability Index (PEF) of the Overall System

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. (2017) did a study in 2017, which revealed this information. The PEF is measured in this study and can be represented according to the following figure (Figure 25).

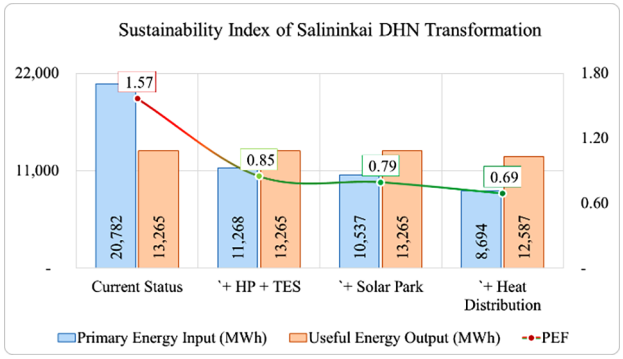


Figure 25. Sustainability Index (PEF) of DHN Transformation

The current scenario requires 20,782 MWh of primary energy to generate 13,265 MWh of heat as output. In contrast, after installing the Heat Pump and TES, the required primary energy is reduced to 11,268 MWh, and after incorporating the solar park, it is further reduced to 10,537 MWh. When the network is segregated into two parts, distribution loss reduces from 1,554 MWh to 876 MWh, a reduction of around 44 %, resulting in 12,587 MWh of heat as output from 8,694 MWh of primary energy input. Similarly, the Primary Energy Factor (PEF) reduced from 1.57 to 0.69 at the final stage of the recommended transformation proposals. The above chart (Figure 24) plots the PEF against all four primary stages of the transformation.

7. Recommendation for sustainable transformation and indication towards future studies

Low-Temperature District Heating Networks (LTDHNs) in Lithuania and regions with similar climates face 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:

- **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 extremely low temperature levels, one boiler will be activated. In this study, integrating a heat pump and thermal storage reduced 46 % of primary energy consumption.

- **Stage-2: Integration of Solar Park (Electricity Focused Renewable Technologies):** Deployment of a solar park will significantly reduce dependency on electricity. This study proposes a 500 kWp solar park based on available space, reducing primary energy consumption by a further 4 %.
- **Stage-3: Distributed Heating Network:** Segmentation of the heat distribution network optimises boiler operation to nullity, ensuring this DHN's reduced primary energy consumption, dependency on natural gas and energy security. In this study, segregation of the heating network and centralised heat source design has reduced the primary consumption by a further 9 %, resulting in a total of 58 % from the current scenario.
- **Stage-4: Other Recommendations:** Other recommendations may include, but are 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 behaviour 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 environmental impact analysis, LCA, sensitivity analysis, etc., which may include further assessment of ornamentation to escalate the recommendations to the 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 in Lithuania to maximise the nation's gain in the heating sector, which will ensure national energy security.

8. Conclusion

The study of the Salininkai DHN presents a comprehensive framework for transitioning conventional district heating systems toward sustainable, low-temperature configurations. The research significantly improved energy efficiency and environmental performance by integrating renewable technologies, particularly the 1 MW air-to-water heat pump, a 3,000 m^3 thermal storage unit, and a 500 kWp solar park. These measures reduced natural gas dependency, minimised 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 63.8 % in the baseline scenario to 111 % in the optimised configuration. Integrating 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 peak demand could be met during extreme conditions. This operational adjustment highlighted the importance of renewable integration in optimising system performance and reducing fossil fuel consumption. Segregation of the heat distribution network nullifies the requirement of the boiler. This final recommendation brings the sustainability index (PEF) from 1.57 to 0.69, indicating a sustainable transformation.

Additionally, the study provided actionable recommendations for improving LTDHNs in Lithuania and similar climates. Key measures include enhancing pipeline insulation to minimise heat losses, retrofitting low-efficiency buildings to reduce energy demand, and adopting innovative grid technologies for dynamic load management. Consumer engagement through flexible pricing models and awareness campaigns was also emphasised to promote energy-saving behaviours and increase the adoption of renewable energy solutions.

In conclusion, the Salininkai DHN is a model for modernising district heating systems through renewable integration, operational optimisation, 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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TVARI CENTRALIZUOTO ŠILUMOS TIEKIMO TINKLŲ TRANSFORMACIJA: SALININKŲ ATVEJO ANALIZĖ

A. M. M. REZA, J. BIELSKUS, A. ROGOŽA

Santrauka. Globalūs klimato iššūkiai, kylantys dėl didėjančio šiltnamio efektą sukeliančių dujų kiekio bei netvarių energijos vartojimo įpročių, skatina skubius veiksmus pereinant prie švaresnių ir efektyvesnių energijos sistemų. Europos Sąjunga yra išsikėlusi ambicingus tikslus kovai su klimato kaita, skatindama atsinaujinančių energijos šaltinių naudojimą ir energijos vartojimo efektyvumą. Lietuva, pasižyminti šaltomis žiemo-

mis ir priklausomybe nuo centralizuotų šilumos tiekimo sistemų, šiame kontekste atlieka svarbų vaidmenį. Centralizuoto šilumos tiekimo tinklai (CŠTT), kurie tiekia šilumą gyvenamiesiems ir komerciniams pastatams, yra kertiniai elementai siekiant energinio efektyvumo ir tvarumo Lietuvos miestuose. Salininkų CŠTT šiuo metu Vilniuje aptarnauja 46 pastatus: gyvenamuosius namus, vaikų darželį, prekybos centrą ir mažas įmones. Sistemą sudaro du 4,7 MW galios dujiniai katilai, kurių naudingumo koeficientas siekia 85 %, tačiau ji susiduriama su keliais iššūkiais: šilumos šaltinis įrengtas viename tinklo kampe, dėl to fiksuojami dideli šilumos nuostoliai, o daugelio pastatų energinio naudingumo klasė yra F arba G. Be to, naudojamos pasenusios radiatorinės sistemos. Šiame tyrime vertinama Salininkų energijos gamybos ir paskirstymo sistema, siekiant padidinti jos efektyvumą ir tvarumą. Naudojant „EnergyPRO“ programinę įrangą, buvo simuliuoti įvairūs scenarijai, įskaitant 1 MW galios elektrinio oro-vandens šilumos siurblio integravimą, 3,000 m^3 talpos šilumos akumuliacinę talpyklą ir saulės parką, siekiant sumažinti priklausomybę nuo gamtinių dujų ir komercinės elektros energijos. Taip pat vertinamos galimybės perkelti šilumos šaltinį į tinklo centrą ir decentralizuoti sistemą. Gautos įžvalgos padės formuluoti rekomendacijas, kaip optimizuoti šilumos paskirstymą, sumažinti energijos nuostolius bei padidinti tinklo tvarumą, atsižvelgiant į pirminės energijos faktorių (PEF). Įgyvendinus šias strategijas, Salininkų CŠTT galėtų tapti pavyzdys panašiems tinklams visame pasaulyje.

Reikšminiai žodžiai: centralizuoto šilumos tiekimo tinklo optimizavimas, atsinaujinančių energijos šaltinių integravimas į CŠT, žemos temperatūros CŠT, pirminės energijos mažinimas CŠT, tvari CŠT transformacija.