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AIR-SOURCE HEAT PUMP INTEGRATION TO SUPPORT DISTRICT HEATING DECARBONIZATION IN LITHUANIAN CLIMATE

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Abstract. Many district heating (DH) systems in Eastern Europe continue to rely heavily on fossil fuels and ageing biomass boilers, limiting operational efficiency and slowing progress toward climate targets. As these systems face growing decarbonization pressures, there is a clear need to identify feasible technological pathways that can reduce emissions while maintaining a reliable heat supply. This study examines the integration of air-source heat pumps (ASHPs) and thermal energy storage (TES) into DH networks as an effective strategy for reducing fossil fuel use and supporting long-term decarbonization. Conducted within the framework of the SET_HEAT project, the pre-feasibility assessment focuses on identifying an optimal technological solution by evaluating end-user needs, technical constraints, environmental compliance, system performance, and potential modernisation pathways. Techno-economic modelling performed using the energyPRO software was applied to assess a modernisation concept that integrates two air-source heat pump (ASHP) units with a hot-water TES tank. Designed to operate efficiently down to –10 °C, the ASHP system provides a low-emission, electricity-driven alternative to conventional heat generation, while the TES enables load shifting, peak reduction, and improved operational flexibility, particularly during periods of favourable electricity pricing or high renewable generation. The modelling results show that this hybrid ASHP–TES configuration can substantially reduce dependence on fossil fuels, cutting natural gas consumption by nearly half. Overall, the findings indicate that integrating ASHPs with TES is a technically viable and environmentally beneficial modernisation pathway that enhances system resilience and supports district heating decarbonization objectives.

Keywords: air-source heat pump (ASHP), decarbonization, district heating (DH), Lithuanian climate, thermal energy storage (TES).

1. Introduction

District heating (DH) systems remain an important part of European heating supply, especially in Central and Eastern Europe, where existing heat production is still heavily dependent on fossil fuels and old biomass boilers (International Energy Agency, 2025). Achieving significant decarbonisation of such systems requires not only reducing heat carrier temperatures, but also integrating electricity-based heat production and thermal energy storage (Agyekum et al., 2025; Sollich et al., 2025). However, despite their importance, they face significant technical and operational challenges.

Electric heat pumps, especially air-source heat pumps (ASHPs), are increasingly being discussed as a suitable solution. They offer flexible control and require relatively low initial investment, making them ideal for retrofitting older networks. Reviews of the decarbonisation of the building sector show that heat pumps play a key role in reducing greenhouse gas emissions, especially when integrated with low-carbon electricity systems (Żelazna & Pawłowski, 2025). However, efficiency of ASHPs is highly dependent on outdoor weather conditions and heat carrier temperatures. Streckienė et al. (2024) highlighted that ASHPs experience a significant drop in efficiency at low outdoor temperatures, which is a serious drawback in cold climates. Similarly, Rogoža and Misevičiūtė (2022) point out that in order to improve heat pump efficiency, it is necessary to reduce the heat carrier temperature, which often requires network modernisation. Rugieniūtė and Bielskus (2024) agree with this view and point out that many existing networks cannot easily adapt to the low-temperature operation required for optimal heat pump performance. Streckienė et al. (2025) demonstrate that connecting the heating systems of apartment buildings to low-temperature DH networks can significantly increase

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the decarbonisation potential of the system, but the heating systems of the buildings themselves must also be adapted to this.

Another technology, thermal energy storage (TES), is widely recognised as essential for flexible DH operation. TES allows for the temporary separation of heat production from demand, thereby reducing peak load, shifting it, and better utilising renewable electricity (Rehman et al., 2024). Studies have evaluated short-term and seasonal TES configurations for their ability to reduce operating costs and emissions (Sornek et al., 2025; Tosatto et al., 2023). These studies show that combining TES with autonomous heat generators improves overall system efficiency and allows better exploitation of periods when electricity prices are lower, or the share of renewable energy production is high.

Techno-economic modelling is often used to compare different approaches to DH system modernisation. Optimisation and simulation studies show that hybrid ASHP-TES systems are more efficient than a single technology solution in terms of costs, emissions, and operational flexibility (Cheng et al., 2024; Sollich et al., 2025). Li et al. (2023) showed similar advantages when integrating borehole TES into a fifth-generation DH system.

In addition, reliable demand forecasting and life cycle assessment tools are very relevant in solution evaluation. Rieksta et al. (2025) showed that accurate forecasting improves the efficiency of the DH network, while Motuzienė et al. (2022) argued that when evaluating various energy conversion technologies, it is appropriate to take into account the life cycle of the system. Rehman et al. (2024) also note that technical and economic assessment alone cannot fully reveal the potential benefits of hybrid solutions, without taking into account the dynamics of the system itself and the interaction of storage.

Recent scientific literature increasingly examines hybrid DH system configurations that combine ASHPs, TES, biomass, and other renewable heat sources to increase system resilience and reduce dependence on fuel price fluctuations (Li et al., 2023). Although the advantages of these systems are clear, there are still questions: standardised TES sizing methods for DH systems are lacking, and long-term operational data in cold climates are not available. This gap is particularly relevant for Eastern European DH systems. Furthermore, regulatory and policy integration (The European Parliament and the Council of the European Union, 2023) remains an area that requires further research.

In summary, there is a consensus among researchers that the integration of ASHPs with TES is technically feasible and beneficial. These solutions, carefully combined with low-temperature network operation, accurate modelling, and supportive pricing policies, can significantly reduce fossil fuel dependence, improve operational flexibility, and enhance the resilience of the DH system (Agyekum et al., 2025; Streckienė et al., 2025). This study aims to evaluate the modernisation potential of an existing district heating system in Vilnius, Lithuania, by integrating air-source heat pumps (ASHPs) and thermal energy storage (TES). The research seeks to determine whether this hybrid configuration can reduce fossil fuel consumption, improve operational flexibility, and support long-term decarbonization goals under Lithuanian climatic conditions.

2. Site analysis and modelled scenario

Site description

Naujoji Vilnia is among the most densely populated districts of Vilnius (Lithuania) (EBIZ.LT, 2024) and is one of seven areas currently undergoing pipeline renovation works. The analysis focuses on modernising the Naujoji Vilnia district heating (DH) system, which supplies thermal energy to a multi-apartment residential area and several public buildings.

The boiler house currently operates several biomass and gas-fired boilers. Two biomass boilers, each equipped with a flue gas condensing economiser, serve as the primary heat source. To illustrate the system layout, the schematic diagram of the main production equipment is presented in Figure 1. The total installed capacity of the boiler house is 84.78 MW, of which 15 MW corresponds to biomass boilers operating at full design capacity. Detailed capacities of the installed heat generation units and the types of fuel used are provided in Table 1.

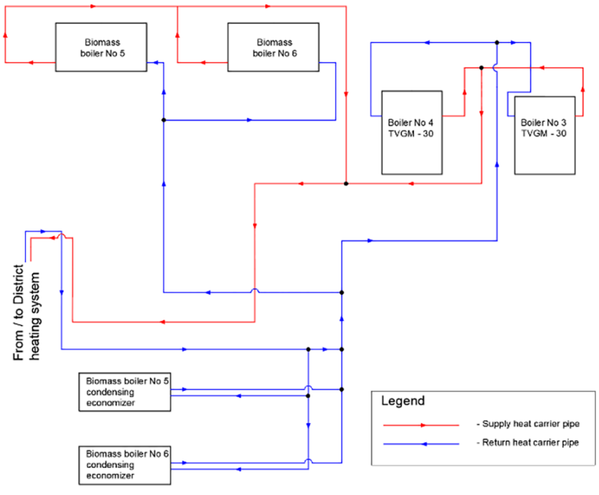


Figure 1. Principle diagram of a boiler house

However, operational challenges – such as outages and partial shutdowns caused by maintenance requirements or poor fuel quality – affect system reliability. As a result, gas boilers are occasionally activated to ensure an uninterrupted heat supply. As reported on March 20, 2024, the annual emissions attributable specifically to CO_2 from fossil-fuel combustion total 4,584 tCO_2e (Aplinkos apsaugos agentūra, 2023).

Table 1. Heat generation units in the district boiler house

Heat production unit	Year of installation / last major repair	Fuel	Installed capacity
Boiler No 1 (steam boiler)	1999	Natural gas	6.4 MW
Boiler No 2 (Boiler)	1965 (1997)	Natural gas	4.9 MW
Boiler No 3	1965 (1986)	Natural gas /liquid fuel	34.9 MW
Boiler No 4	1965 (1986)	Natural gas/liquid fuel	34.9 MW
Boiler No 5	2011 (2018)	Biomass	6.0 MW
Boiler No 6	2011 (2018)	Biomass	6.0 MW
Cond. economizer No 1	2011	Biomass	1.5 MW
Cond. economizer No 2	2011	Biomass	1.5 MW

Ambient conditions and actual data analysis

Vilnius (including Naujoji Vilnia) has a temperate climate, which is transitional between maritime and continental, so temperatures fluctuate seasonally. The average annual temperature is +6.6 °C. The coldest month is January, and the warmest month is July (Lietuvos hidrometeorologijos tarnyba, 2025). The actual ambient air temperature in 2023, during the analysis of boiler house operation, is presented in Figure 2.

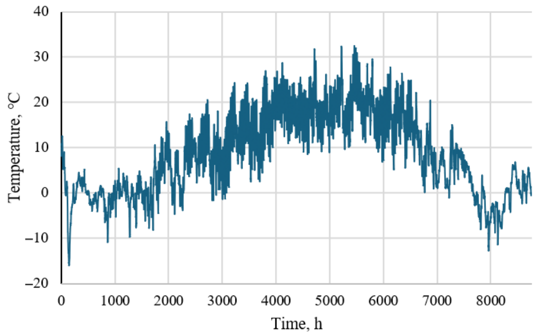


Figure 2. Ambient air temperatures, 2023

Depending on the outside air temperature the primary network regulation graph is used (see Figure 3).

Using hourly heat supply data for each day, the data were processed to show the actual supply and return temperatures of the heat carriers at corresponding outdoor air temperatures. The actual 2023 supply and return temperatures, in 1-hour time steps, are presented in Figure 4.

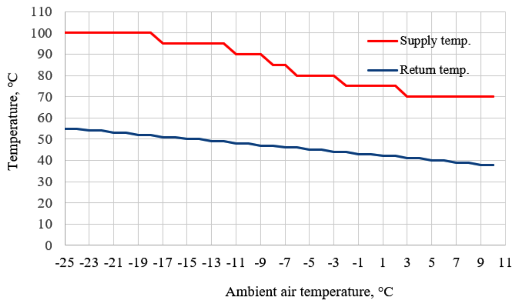


Figure 3. Schedule for the heating season in the territory of Naujoji Vilnia

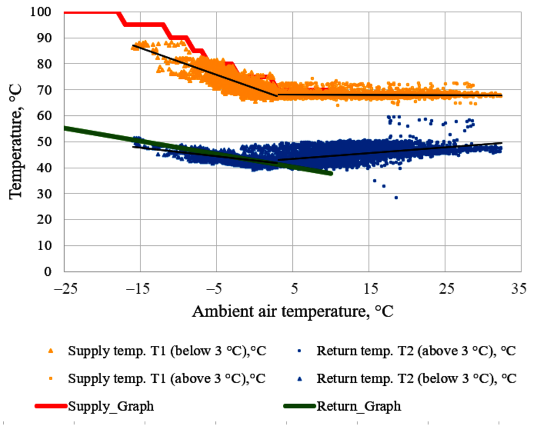


Figure 4. The actual dependence of the supply and return temperature of the boiler house on the outside air temperature

The temperature variation of the supply heat carrier can be divided into two ranges: when the outdoor air temperature is below 3 °C (orange triangles in Figure 4) and when it is above 3 °C (orange dots). For outdoor air temperatures above 3 °C, the supply heat transfer fluid temperature fluctuates by several degrees, and the regression line indicates that the dominant temperature is approximately 68 °C. When the outdoor air temperature falls below 3 °C, the data show that the heat transfer fluid temperature increases as the outdoor air temperature decreases.

The red line in Figure 4 represents the control graph for regulating the temperature of the supply heat transfer fluid. For outdoor air temperatures above 3 °C, the supply fluid temperature reaches approximately 70 °C, whereas for temperatures below 3 °C, the supply fluid temperature increases as the outdoor air temperature decreases. A comparison between the control graph and the actual measured temperatures shows that the actual values are lower (see regression lines). Figure 4 also presents the return fluid temperature, which, similar to the supply fluid, can be divided into two ranges depending on whether the outdoor air temperature is below 3 °C or above 3 °C.

At outdoor air temperatures of 3 °C and above, the return fluid temperature increases, while at temperatures below 3 °C, the increase is only slight. Considering the return heat graph, it can be observed that the temperature begins to rise from 10 °C onwards; however, the actual measurements show some deviations from these values. Notably, when the outdoor air temperature is below 3 °C, the actual regression line closely follows the reference graph. Table 2 presents the regression equations that describe the actual supply and return temperatures of the boiler house.

Table 2. Regression equations for supply and return heat transfer

Parameter	Outdoor temperature above 3 °C	Outdoor temperature below 3 °C
Supply heat carrier	y = –0.0179x + 68.33	y = –1.0368x + 70.414
Return heat carrier	y = 0.2258x + 42.14	y = –0.3304x + 42.753

Note: *In this table, x is the outdoor air temperature and y is the supply or return temperature; *during the cold period (when temperatures are below zero), the R^2 values of the equations range from 0.4 to 0.7.

Taking into account the capacity of the equipment and actual data on its efficiency, Figure 5 presents the real operation of the Naujoji Vilnia boiler house in meeting the required heat demand. In this figure, the black line represents the amount of heat produced and delivered to the buildings. Biomass boilers – primarily boiler No. 5 – have the highest priority during the heating season. If the first biomass boiler cannot meet the demand, the second biomass boiler (No. 6) is activated, and if additional capacity is still required, a gas boiler is started. During the warm season, when heat demand decreases, only biomass boiler No. 5 remains in operation, with the gas boiler compensating for any shortfall. The economiser of boiler 5 and boiler 6 in are blue and green, respectively.

It was found that the maximum capacity of the biomass boilers equipped with flue gas economisers was 4.5 MW. Boiler No. 5 operated year-round and consumes 37.3 GWh of biomass. Biomass boiler No. 6 was used only during the heating season, with a fuel consumption of 18.9 GWh. The gas boiler consumed 22.8 GWh of gas; however, diesel was also used in January and March, amounting to 2.6 GWh. This diesel consumption was subtracted from the gas total, resulting in an adjusted gas consumption of 20.2 GWh.

The calculated total biomass consumption is 1.24% higher, and the calculated gas consumption is 7.0% lower than the actual consumption. It was found that the calculation follows the same logic throughout the year, and for greater accuracy, each month needs to be treated separately. But in this case, the accuracy is sufficient and can indicate how the boilers would operate under normal conditions in the absence of boiler faults or other unforeseen malfunctions.

Scenario presentation

The proposed modernisation scenario aims to improve the efficiency and sustainability of heat supply by integrating two key technologies: air-source heat pumps (ASHPs) and a thermal energy storage tank. This approach retains the existing biomass boilers and one compliant gas boiler while reducing dependence on fossil fuels through electrification and thermal storage.

The type of heat pump analysed in this study is air-to-water. The main parameters for the selection of the heat pump are: type of compressors, number of units, number of stages, refrigerant, coefficient of performance (COP), maximum temperature out of the heat pump, minimum temperature into the heat pump, control range, noise emission, charging and discharging rates.

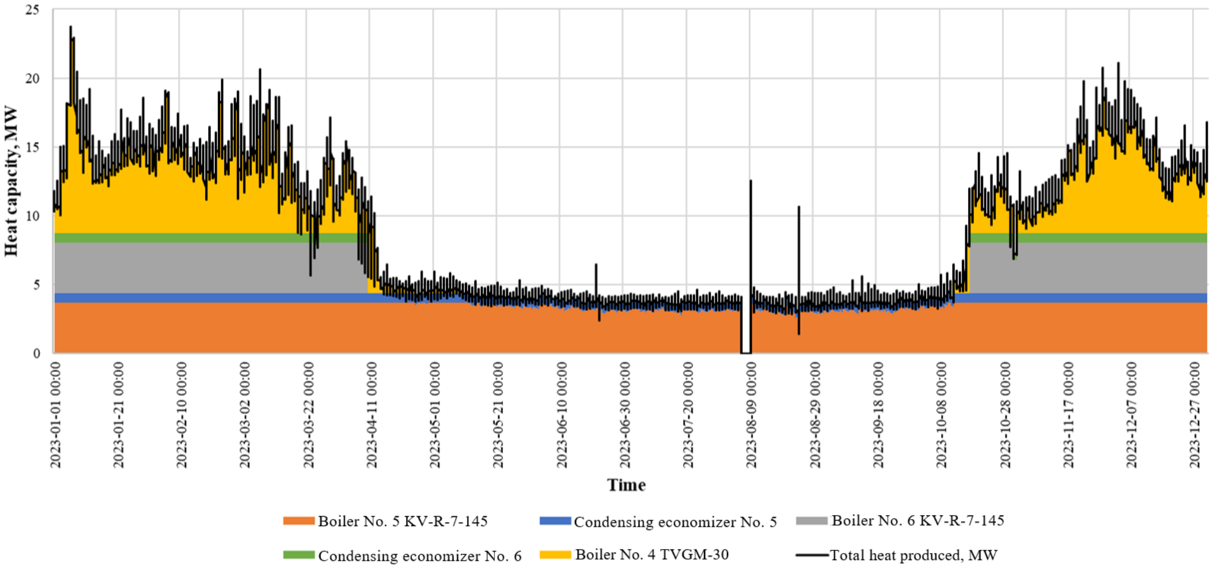


Figure 5. Actual operation of boilers at the boiler house

The heat pump is planned to operate down to an outdoor air temperature of –10 °C, if the outdoor air temperature drops below this, the heat pump will be switched off, and the existing biomass and gas water heating boilers will be connected.

A ground-based thermal energy storage (TES) tank with a working (usable) storage volume of ~3000 m^3 is selected. The thermal insulation of the tank is 300 mm thick.

The basic connection layout of the scenario is illustrated in the schematic diagram (Figure 6). Two air-source heat pumps are analysed as part of the heating system support. These units are connected to a hot-water thermal storage tank, which helps balance heat production and demand.

Figure 6 includes these main interconnections:

- Air-source heat pumps – the primary heat generation units.
- TES tank – used to buffer and store hot water to optimise system performance and reduce peak loads.
- Hydraulic connections – showing the flow of heated water between the heat pumps, storage tank, and the existing heating network.

It is assumed that the TES tank and two heat pumps will be integrated into the existing district heating system so that the return line flows through the heat pump condenser. The resulting higher-temperature water will then be directed to the supply line, where it can be mixed with higher-temperature water from the existing boilers if needed to meet the network's temperature requirements.

The sizing of the heat pumps, as a new base heat generation source in the network, was carried out based on historical summer heat demand profiles. The assessment also considered potential future increases in heat demand, a flexibility margin to accommodate fluctuations in electricity market prices, and the objective of replacing a larger share of heat produced from natural gas and biomass with combustion-free technologies. The ASHP was selected for a temperature regime that does not exceed its capacity (70–75 °C), assuming that peak-load boilers will not only supply the additional required heat but also raise the thermal carrier temperature to meet the required level for the district heating network. At an outdoor air temperature of 0 °C, two ASHP units will generate approximately 4.9 MW of thermal power. These parameters will be used in the EMD energyPRO model, i.e., the supply and return heat carrier temperatures are 80 °C and 45 °C, respectively, when the outdoor air temperature is 0 °C, and the COP is 2.5 (Fenagy, 2025).

Two FENAGY 2×H-2600 heat pumps were selected for the analysis. Their heating capacity increases significantly with rising ambient temperatures – from 3,606 kW at –10 °C to 6,380 kW at +20 °C. Similarly, the COP improves from 2.10 to 3.05, indicating more efficient operation under milder conditions. This demonstrates that the units are well-optimised for moderate climates while remaining functional even in severe cold.

3. System modelling

The boiler house modernisation scenario is modelled using the energyPRO software, which is designed for planning, simulation, and optimisation of energy systems. It enables the analysis of technical and economic performance for projects such as district heating, CHP plants, renewable energy integration, and thermal storage solutions (EMD International, 2025).

The following main assumptions were adopted in the model:

- A complex of two heat pumps is used.
- The total maximum capacity of the heat pumps is

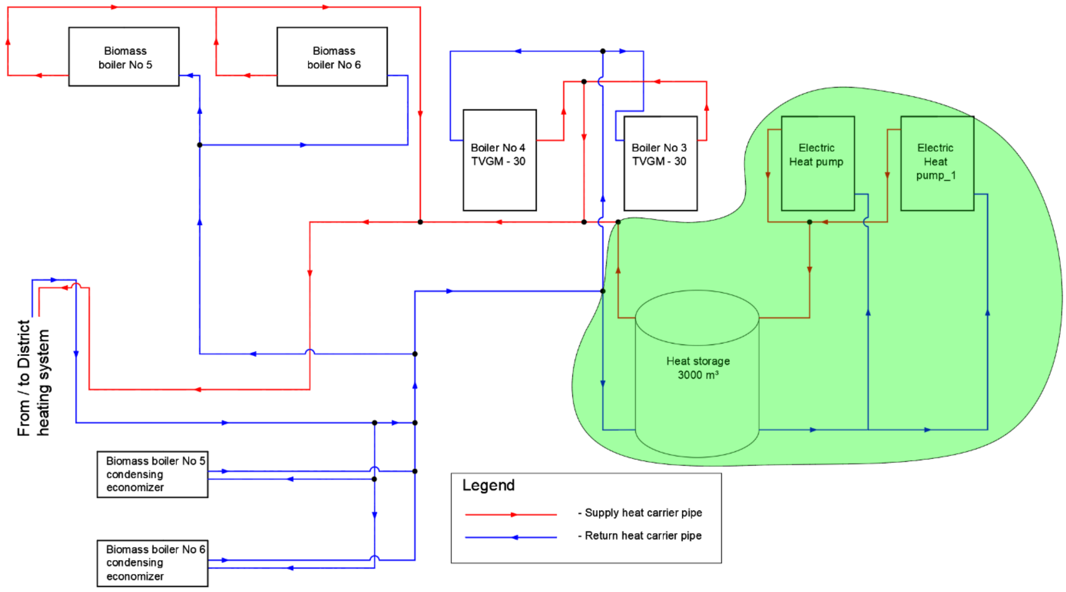


Figure 6. Scenario with heat pumps and thermal storage tank

4.9 MW at a water inlet temperature of 45 °C and outlet temperature of 80 °C, when the ambient temperature is 0 °C.

– The maximum electrical power is 2.018 MW.

– The COP is 2.5.

– The heat pumps operate through a storage tank, which enables more efficient utilisation of the produced heat and helps balance electricity consumption.

Figure 7 presents the layout of the modelled boiler house modernisation scenario within the energyPRO environment. It illustrates the configuration of the main system components, their interconnections, and the integration of new technologies into the existing district heating infrastructure.

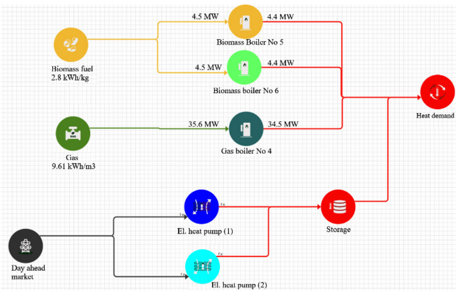


Figure 7. Model of the modernisation scenario

Figure 7 shows that the boilers deliver energy directly to the network, while the heat pump operates through a storage tank. Although hydraulically integrated, all technologies can simultaneously supply heat to the network and charge the thermal storage tank.

The system is configured so that the heat pump ceases operation when the ambient temperature falls below −10 °C. In such cases, heat demand is automatically met by biomass and natural gas boilers. This control strategy ensures an uninterrupted heat supply under extreme weather conditions and provides a realistic assessment of the operational limits of the heat pump.

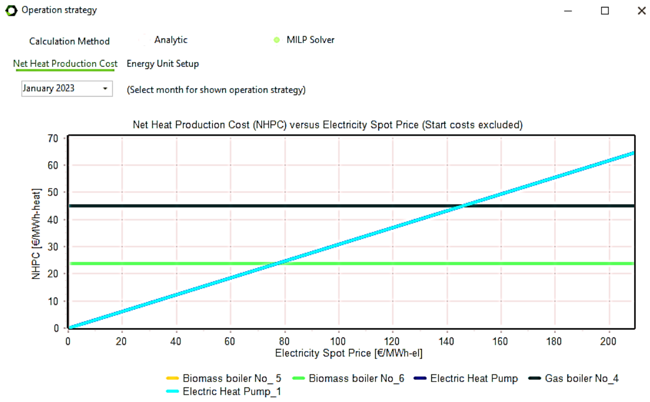
According to the statistics, the average actual biomass price in 2023 ranged between 20–25 €/MWh (Baltpool, 2024). Considering the calorific value of the biomass used (2,405.7 kcal/kg ≈ 2.8 MWh/t), this corresponds to a price range of 0.056–0.070 €/kg. For the EMD energyPRO model, an average value of 0.065 €/kg was selected, which accurately reflects the real supply conditions. This price was entered as a fixed value, as the model covers a one-year period and seasonal effects are represented through temperature-based heat demand variations. For natural gas, assuming a typical lower heating value of 10.5 kWh/m^3, the price range was estimated at 0.19–0.47 €/m^3. In the model, a fixed value of 0.42 €/m^3 was selected to represent a realistic and slightly conservative estimate

For modelling the modernisation scenario strategy, hourly electricity prices from the Nord Pool exchange for Lithuania for the entire year were imported into the EMD energyPRO environment (Nord Pool, 2025). These prices were used to calculate the operating costs of electricity-driven equipment (heat pumps) and to compare them with other heat production sources.

4. Results and discussion

Operating strategy is crucial in a boiler house because it determines how different units – especially renewable energy technologies – are dispatched to meet heat demand efficiently and cost-effectively. A well-designed strategy minimises fuel costs, reduces emissions, and ensures reliability by prioritising renewable sources while maintaining backup capacity. In energyPRO model, this strategy is implemented through detailed hourly simulations. The software uses demand profiles, fuel prices, and technical constraints to optimise unit operation, storage utilisation, and interactions with the electricity market, ensuring the most economical and sustainable performance under varying conditions.

Figure 8 illustrates the operating strategy, indicating which technology is utilised under different conditions. In this scenario, biomass boilers are used exclusively during the heating season, when heat demand is high, including January. Heat pumps are employed during the warmer season and are activated only when electricity prices are sufficiently low to ensure cost-effective operation. The natural gas boiler (Boiler No. 4) serves as a


Operation strategy

Calculation Method ○ Analytic ● MILP Solver

Net Heat Production Cost | Energy Unit Setup

January 2023 (Select month for shown operation strategy)

Figure 8. Net Heat Production Cost (NHPC) versus Electricity Spot Price for different heat generation technologies in January

Figure 9. Annual operation of the heat generation system and storage dynamics (top section: heat flow [MW], light and dark blue indicate heat pump operation, yellowish and greenish tones represent biomass boilers, grey denotes the natural gas boiler; middle section: electricity consumption [MW]; bottom section: thermal storage operation [MWh], orange shows storage content, and blue indicates storage capacity)

backup or balancing unit, typically engaged when other technologies are insufficient or temporarily unavailable.

The core objective of this strategy is to minimise heat production costs by optimally combining different technologies based on market conditions. Figure 8 shows that the normalised heat production cost (NHPC) of biomass boilers remains constant and lower than that of heat pumps when electricity prices are high, making biomass the primary heat source during January.

Figure 9 presents simulation results for the entire year, including the dynamics of heat generation, electricity consumption, and thermal storage operation. From the upper part of the figure, it can be observed that biomass boilers (yellow and green colours) provide the primary heat supply during the cold season. Heat pumps operate throughout the year (light and dark blue), particularly during warmer periods when their COP is higher. The gas boiler is activated for short intervals in winter when heat pumps are automatically shut down due to low ambient temperatures. It should be noted that the model does not account for biomass boiler maintenance (e.g., cleaning), which in practice may require shutting down the boilers for several days or even up to a week – a factor that is difficult to predict and accurately simulate.

The middle section of Figure 9 illustrates electricity consumption by heat pumps and day-ahead market imports. The pronounced fluctuations reflect the dynamic control of heat pumps in response to variations in electricity price and demand. The lower part of the figure depicts storage content and capacity levels. It can be observed that storage content depends on heat demand and the availability of surplus heat. During the warmer season, active charging and discharging of the storage occur, which helps balance the system and reduces boiler cycling.

Figure 10 presents the operating hours of different heat generation units along with the amount of heat produced. Biomass boilers accounted for 47.4% of the total annual heat demand (36,998.4 MWh out of 76,752.9 MWh), heat pumps supplied 39.7% (a combined 30,524.6 MWh), and the natural gas boiler contributed 13.2% (10,132.6 MWh). This outcome demonstrates an effective balancing strategy, in which biomass boilers remain the primary heat source, while heat pumps operate efficiently when electricity prices and ambient temperatures are favourable. The gas boiler serves mainly as a backup during periods when heat pumps are offline due to low outdoor temperatures.

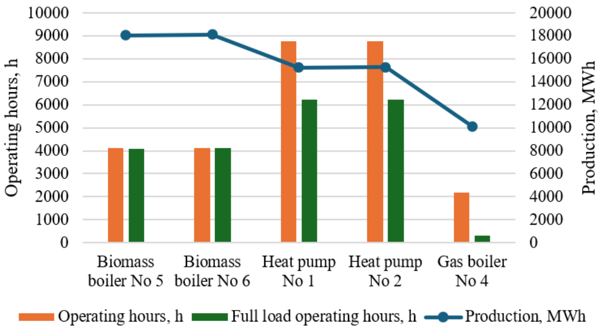


Figure 10. Units' operation characteristics and heat production

The simulation results indicate that the heat pumps can operate continuously throughout the entire year, particularly when the winter season is relatively mild (temperatures above –10 °C, as was the case during the years analysed). Under such conditions, each heat pump would operate without interruption over the full year. Their utilization factors were 71.82% and 71.83%, respectively, with a high number of full-load operating hours (approximately 6,240 hours). The overall efficiency exceeded 324%, demonstrating highly efficient performance under favourable conditions.

The biomass boilers operated for approximately 4,100–4,120 hours per year, corresponding to roughly half the year or the heating season. Their utilisation factors were around 47%, with nearly the same number of full-load hours (about 4,100 hours), confirming their role as the primary heating source during colder months. The overall efficiency of the biomass boilers reached approximately 97.8%, which is exceptionally high for this type of equipment. The gas boiler was activated 94 times but operated for only 2,176 hours over the year. Its full-load operation time was just 293.7 hours, resulting in a low utilisation factor of 3.35%.

The analysis of the model results shows that the installation of heat pumps and a thermal storage tank reduces annual natural gas consumption to 10.46 GWh. Compared to the previous real-life consumption of 21.9 GWh/year, this represents a reduction by approximately a factor of 2.1. Biomass boiler fuel consumption amounts to 37.0 GWh/year, corresponding to 13.2 thousand tonnes of biomass. The annual electricity demand of the heat pumps is 9.4 GWh_e, evenly distributed between the two units.

Figure 11 illustrates the annual duration curve of heat demand, enabling an assessment of how different heat generation technologies contribute across varying load durations – from peak demand to the lowest load levels. During peak heat demand periods (up to 24 MW), all generation units are activated, including the gas boiler (No 4), which operates only briefly when heat pumps cannot meet demand due to unfavourable outdoor temperatures. This limited operation is clearly visible on the left-hand side of the graph.

Biomass boilers (yellowish and greenish tones) cover medium- to high-demand periods, with their operation concentrated in the first half of the year, corresponding to the heating season. Heat pumps (light and dark blue tones) operate throughout the entire year but dominate during periods of lower heat demand, as seen on the right-hand side of Figure 11. This confirms their role as base-load units when ambient conditions allow for efficient operation.

The duration curve clearly distinguishes the operational intervals of each technology and provides insights into their effective load distribution. Such analysis is particularly useful for planning operational strategies and optimising the heat generation mix in terms of cost and energy efficiency.

The proposed modernisation scenario – based on air-source heat pumps (ASHPs), thermal energy storage, and integration with the existing biomass boiler house – demonstrates strong potential for adaptation and replication in district heating (DH) networks, particularly in regions transitioning to cleaner and more flexible energy sources. This applies both to the utilisation of local biomass fuel and to the shift toward non-combustion technologies. It could be relevant for urban or suburban zones with medium to high heat demand densities.

5. Conclusions

This study evaluates the modernisation potential of the Naujoji Vilnia district heating (DH) system in Vilnius, Lithuania, through the integration of air-source heat pumps (ASHPs) and a thermal energy storage tank. The proposed system enables ASHPs to meet summer heat demand, while biomass and gas boilers cover peak winter loads. This hybrid configuration ensures higher efficiency, faster responsiveness to grid conditions – particularly during periods of excess renewable electricity – and reduced emissions. The solution aligns with EU and national targets for achieving climate neutrality by 2050 and supports the DH company's development strategy.

The results indicate that the thermal storage tank significantly enhances system flexibility by allowing heat to be stored when electricity prices are low and utilised during peak demand, thereby improving efficiency and reducing boiler cycling. The integration of heat pumps and thermal storage substantially decreases reliance on fossil fuels. Natural gas consumption drops from 21.9 GWh/year to 10.46 GWh/year – nearly halved – while biomass demand is estimated at approximately 37 GWh/year.

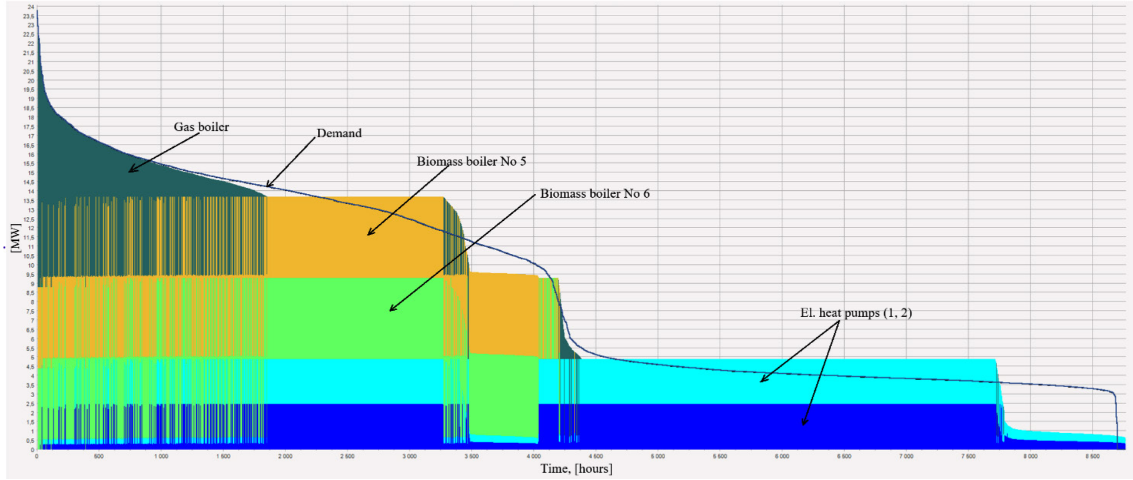


Figure 11. Duration curve of heat demand and heat generation technologies during one year (light and dark blue indicate heat pump operation, yellowish and greenish tones represent biomass boilers, grey denotes the natural gas boiler)

Future work should focus on incorporating real-world operational constraints, such as maintenance schedules and potential system outages, as well as examining relevant economic indicators, and exploring the integration of additional renewable energy sources and advanced control strategies to further optimize overall performance and cost-efficiency.

Acknowledgements

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