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Optimization Strategies for Peak Load Reduction in District Heating Systems: A Case Study of Maribor

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Abstract: District heating systems play a vital role in sustainable urban energy management by providing centralized heat generation and efficient thermal energy distribution. They improve overall energy efficiency and reduce uncontrolled local emissions. However, their operation is increasingly affected by volatile energy prices, environmental policies, and the need for reliable performance during the heating season. Continuous operation of base-load units, combined with supplementary peak-load sources, often leads to system oversizing, higher operational costs, and reduced efficiency.

Heat consumption shifting is an effective strategy to address peak demand challenges. By redistributing energy use from high-demand to low-demand periods, it enables more uniform load profiles, improves system efficiency, and reduces the need for additional capacity. This approach can be implemented in existing district heating networks with minimal infrastructure modifications.

This paper examines the potential of load shifting in the district heating system of the City of Maribor through simulation-based analysis. Adjusted hourly consumption patterns were used to evaluate system performance under different scenarios. The results show that optimized energy distribution can improve operational stability, lower costs, and support the long-term sustainability of district heating networks.

Keywords: district heating; peak loads, efficient energy use; time-dependent consumption; production optimization

NOMENCLATURE

4GDH	Fourth-Generation District Heating
CHP	Combined Heat and Power
DHS	District Heating Systems
ENMB	public utility company Energetika Maribor
E_{saved}	saved energy
FTDHS	Flow-Through District Heating Substations
$G(k, \sigma)$	Gaussian function with offset k and standard deviation σ,
HTHP	High-Temperature Heat Pump
NFTDHS	Non-flow-Through District Heating Substations
$P(t)$	power at a given time interval
$P_{additional}$	additional power
$P_{increased}$	increased power profile
$P_{mod}(t)$	modified power profile
PP	production profile
$P_{reduced}$	reduced power
P_T	thermal power
SD	Sub-Databases
SG filter	Savitzky-Golay filter
SON	System Operating Instructions for the District Heating Distribution System
T_{OUT}	outdoor temperature
T_{RET}	return temperature
T_{SUP}	supply temperature
t_t	transport time
$\dot{V}$	volumetric flow rate

1 INTRODUCTION

District Heating Systems (DHS) play a crucial role in providing heat to urban areas by enabling efficient heat distribution and supply through centralized heat production. [1] In Europe, district heating could cost-effectively cover at least 50% of total heat demand by 2050, compared to around 10% today. Achieving this will require the development of 4th generation district heating, which is essential for enabling smart energy systems. [2] In the context of global warming and the urgent need for sustainable energy solutions, the efficiency of district heating systems has become increasingly important. The transition to market-based mechanisms in the heating sector introduces both opportunities and challenges for improving operational performance, sustainability, and customer satisfaction. Therefore, assessing the impact and effectiveness of such reforms is essential for policy development, strategic planning, and the modernization of district heating infrastructure. Comprehensive evaluation methods can enable better resource utilization, reduce carbon emissions, and improve economic benefits for both suppliers and consumers. Developing a methodological framework for evaluating DHS efficiency in the emerging market environment is thus a key step in determining the feasibility of transforming district heating into a more competitive, efficient, and environmentally sustainable system. [3]

Despite their numerous advantages, DHS face challenges related to fluctuating energy prices, environmental and climate issues, and ensuring reliable operation.

One of the biggest challenges for modern DHS is peak loads, which occur during periods of highest heat demand. The thermal power profile shows a characteristic daily consumption pattern, marked by pronounced peaks and periods of lower demand. In the early morning, there is a sharp increase in thermal power due to rising heating needs at the start of the day. This increase reaches a peak before gradually stabilizing at slightly lower levels throughout the morning and afternoon. The late afternoon often brings a second pronounced peak, linked to additional energy consumption before the system begins to settle in the evening. During the night, heat demand drops significantly as consumption decreases to a minimum due to lower requirements and the shutdown of certain systems. This daily cycle repeats consistently, with peaks aligning with periods of higher consumer activity. Such a pattern presents opportunities for optimization, such as peak shaving and a more even distribution of thermal power during periods of lower demand.

The DHS in the Municipality of Maribor ensures a reliable, sustainable, and energy-efficient heat supply. The system is managed by the public utility company Energetika Maribor d.o.o. (ENMB), which provides heating to households, public institutions, and commercial buildings through a modern distribution infrastructure. The operation of this complex system is governed by the System Operating Instructions for the District Heating Distribution System (SON). [4] The SON document regulates all aspects of system management, operation, and development, and defines the rights and obligations of all consumers, designers, and system operators. As the district heating provider, Energetika Maribor must continuously meet DHS requirements, ensuring that heat supply parameters such as temperature and pressure comply with agreed-upon standards, which prescribe specific temperature regimes. To manage peak loads, ENMB currently uses thermal storage units, which allow excess heat to be temporarily stored during low-demand periods and used during peak demand periods.

The main objective of this study is to explore options for smoothing production peaks in the DHS of ENMB. One potential solution is modifying the heating regime and implementing a continuous heating approach. To this end, a simulation of load shifting in the DHS of ENMB was conducted. The study examined an alternative heating pattern and its impact on heat production. The simulation was performed for three representative days during the heating season, selected based on historical outdoor temperature data:

- **Case *A*** represents a very cold day,
- **Case *B*** represents a moderately cold day, and
- **Case *C*** represents a warmer-than-average day during the heating season.

For each of these three cases, modified consumption profiles were created and compared with actual historical data. The adjusted heating regime is expected to reduce morning peaks, helping to lower the strain on production facilities during these periods, as the need for a sudden heat supply in the early hours will be diminished.

1.1 Implementing a Continuous Heating Approach

The concept of continuous heating refers to operating district heating systems (DHS) in a stable, constant mode throughout the day, rather than following the traditional pattern with pronounced peaks in the morning and evening. In the conventional peak-driven approach, production units and the distribution network must rapidly increase output at specific times to meet sudden demand surges. This peak-oriented operational logic requires higher supply temperatures, larger installed capacities, frequent equipment cycling, and greater pressure and thermal stress on system components.

In contrast, adopting a continuous heating approach smooths the thermal load profile over time. By eliminating or significantly reducing peak loads, the system can operate at lower and more stable temperatures, which is a core principle of fourth-generation district heating (4GDH). Several studies and reports indicate that lowering supply temperatures is directly associated with higher system efficiency, improved integration of renewable sources, and reduced heat losses in the distribution network. [5] When temperature fluctuations and steep load ramps are minimized, thermal stress on heat exchangers, pumps, and other components is reduced, which can extend equipment lifetime and lower maintenance costs.

Furthermore, continuous heating supports the transition to ultra-low temperature district heating networks, where typical supply temperatures can be reduced to 50–60°C or even lower, depending on building envelope performance and the share of low-temperature heat sources available. Lower supply temperatures also enable higher exergy efficiency and better integration of renewable and surplus heat sources, such as waste heat, industrial heat, data centres, and low-temperature geothermal sources.

1.2 District heating substations

District heating substations are a key component of district heating systems, serving as the connection between the distribution network and end users. A district heating substation includes heat exchangers, control valves, measuring devices, and circulation pumps, which ensure the transfer of heat from the high-temperature water network to the secondary circuit that heats the building's interior spaces. District heating substations play a crucial role in this study, as the entire heat production process is determined by their operation. In a sense, a district heating substation reflects consumer demand.

There are two operational modes for district heating substations: flow-through (continuous) and non-flow-through (intermittent) operation.

Flow-through district heating substations (FTDHS) maintain a constant flow of the heat transfer medium, specifically hot water. The water continuously circulates through the district heating substation, so the temperature profile of the district heating substation closely matches that of the distribution network.

Non-flow-through district heating substations (NFTDHS), in contrast, do not maintain a constant flow and only activate flow at specific times. "Activation" refers to the moment when the valve in the district heating substation opens, allowing the primary district heating water to pass through the heat exchanger. This typically occurs between 5:30 and 6:30 AM. As a result, the temperature profile of a non-flow-through district heating substation shows a distinct peak, reflecting the sudden increase in temperature when heating begins.

In the DHS of ENMB, the number of flow-through and non-flow-through stations is approximately equal. This study aims to simulate a transition to an exclusively flow-through heating regime.

Figure 1 shows the temperature profile for a flow-through district heating substation's supply temperature and the corresponding temperature at the heat source outlet. The district heating substation's profile follows that of the heat source, but with a slight time lag and lower temperature values. The time lag is caused by heat transport delays, while the lower temperatures result from heat losses in the distribution network. The profile shown represents actual data for a typical day during the heating season.

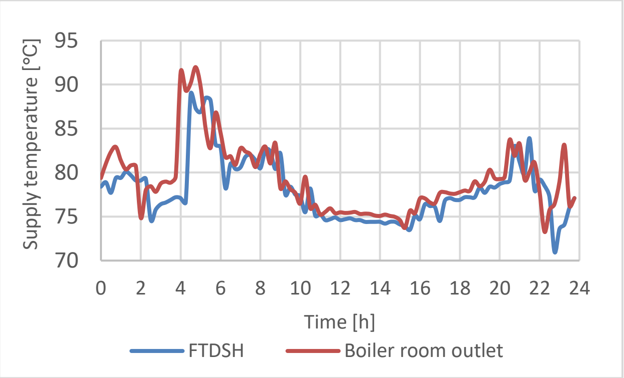

Figure 1. Temperature profile for a flow-through district heating substation.

Figure 2 again shows the supply temperature of the district heating substation and the water temperature at the heat source outlet. This time, it depicts a district heating substation operating in a non-flow-through heating regime. The data corresponds to the same day analyzed in Figure 1, allowing for direct comparison. The profile reveals a significant difference, with distinct activation and deactivation moments clearly visible. This is shown as a sharp temperature peak in the early morning, when the district heating substation is activated, followed by a steep drop in the evening, when the system is deactivated.

In non-flow-through heating systems, buildings operating under this regime maintain a reference temperature of 0 °C overnight, which means that heating is completely inactive during this time. As a result, users cannot adjust indoor temperatures using radiators or other heating devices during the deactivation period, as these do not reach the required operating temperature.

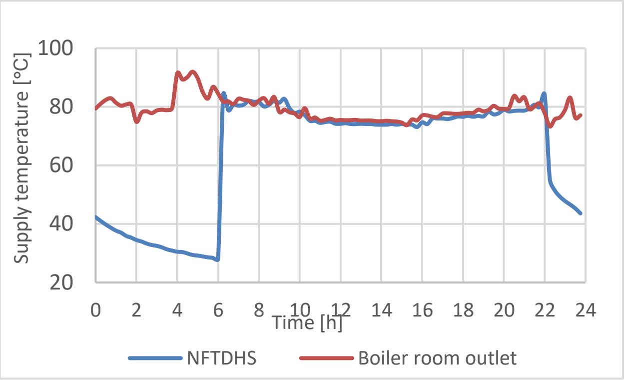

Figure 2. Temperature profile for a non-flow-through district heating substation.

2 METHODS

This chapter presents the research approach, which examines strategies to reduce peak loads in the district heating system of the Municipality of Maribor. The study began with problem definition and a literature review to gain a deeper understanding of the topic. This was followed by data acquisition and collection, involving large datasets from thermal stations, including temperature, flow rates, energy consumption, and pressure measurements.

Based on historical data, key assumptions were formulated, and thermal stations were classified into subgroups. The study then analyzed the additional heat consumption associated with different heating regimes. An interactive tool for modifying thermal power profiles was developed, enabling the creation of a customized boiler operation plan. Finally, a comparative analysis of the results was conducted, covering both energy and economic aspects. These insights formed the basis for the study's final conclusions.

2.1 Data

To reduce complexity, the analysis is limited to the heating season, covering the months from November to March. This period is characterized by low temperatures, during which the primary heat source is the Jadranska boiler plant, which is physically separated from the boiler plant on the left bank of the Drava River during this time. As a result, the analysis focuses solely on this boiler plant, as it dictates heat production during the specified period.

The database includes 251 district heating substations, comprising all stations for which relevant data are available for the analysis. The key variables considered in the study are outdoor temperature, thermal power, supply temperature, return temperature, and thermal energy, all of which were continuously monitored throughout the analysis. Historical data were collected at 30-minute intervals over the past two years, ensuring a comprehensive dataset for evaluation.

Due to the large volume of data, the district heating substations were grouped into logical categories based on their location within the city. Instead of analyzing each station individually, they were organized into data subsets – sub-databases (SD). In total, 12 groups were formed, but only 11 were considered relevant for the analysis.

2.2 Interdependencies between the analysed variables

Determining the interdependencies among the analyzed variables is crucial for understanding the behavior of the entire district heating distribution system. Theoretically, the correlations between these variables can be described mathematically using established equations from heat transfer and fluid mechanics. However, in practice, these relationships often do not hold precisely due to multiple influencing factors that affect each variable differently. As a result, the interactions between variables are not always constant.

To better understand real-world system behavior, one approach is to construct a correlation matrix of influencing factors, which provides a structured representation of these interdependencies. A correlation matrix is a table that displays the correlations between multiple variables within a dataset. The correlation analysis was conducted using a correlation matrix, with relationships quantified by the Pearson correlation coefficient, which ranges from -1 to 1. A value of 1 indicates a perfect positive correlation, meaning an increase in one variable results in a proportional increase in another. Conversely, a value of -1 represents a perfect negative correlation, where an increase in one variable leads to a proportional decrease in the other. A value of 0 signifies the absence of a linear relationship between variables.

To generate the correlation matrix, we used the Python programming language and relevant libraries to develop the required code [6] [7] [8] [9]. This code calculates the Pearson correlation coefficient for every possible combination of variables in the dataset. Two filtering constraints were applied to improve data quality. First, missing and anomalous values were excluded from the calculations. Second, rows containing values that deviated by more than three standard deviations from the mean were removed, as these outliers often result from data entry errors or anomalies during data collection.

The correlation matrix for one of the district heating substations is shown in Figure 3. Each field in the matrix represents the Pearson correlation coefficient for a specific pair of variables, determined at the intersection of a column and a row. For example, Figure 3 shows that the Pearson coefficient between flow rate and thermal power is 0.77, indicating a strong positive correlation: as the flow rate increases, thermal power also increases. In contrast, outdoor temperature and thermal power exhibit a negative correlation, which is expected, as lower outdoor temperatures lead to increased demand for thermal power, consistent with the fundamental equation for calculating thermal energy.

Correlations vary more than expected for each district heating substation, especially regarding outdoor temperature. Before data processing, a strong dependence of variables on outdoor temperature was anticipated. However, the resulting table did not show promising correlation values, as they were generally low and highly diverse. Similar variability was observed in a study [10] focused on energy consumption forecasting. This variability was one of the main reasons it was necessary to simplify the analysis with specific assumptions.

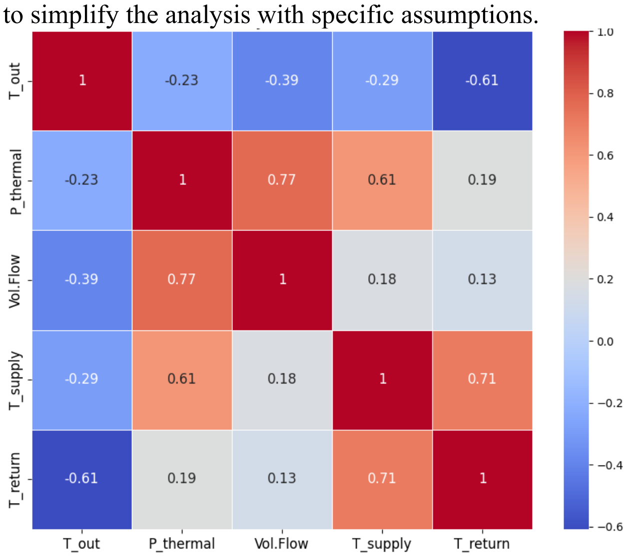

Figure 3. Correlation matrix for a district heating substation.

Another important factor to consider is the mutual influence of buildings. When multiple district heating substations serving neighboring buildings activate at the same time, local heat demand increases, which can affect surrounding district heating substations in various ways. This is especially true for stations located at the ends of pipeline networks, where heat distribution may be less stable.

Table 1 presents Pearson correlation coefficients for the relationships between various variables and the thermal power output of selected district heating substations (101, 105, 305, 405, 510, 712). The thermal power (P_T) represents the amount of thermal energy delivered to consumers over a given period, expressed in megawatts [MW]. It is a key parameter in analyzing district heating substation loads and optimizing heat distribution. The demand for heating is strongly influenced by outdoor temperature (T_{OUT}), expressed in degrees Celsius [°C]. Lower outdoor temperatures increase the demand for thermal power, as more energy is required to maintain the same indoor heating levels.

Another crucial parameter in heat transfer is the volumetric flow rate ($\dot{V}$), which represents the amount of water flowing through the system per unit time [m³/h]. A higher volumetric flow rate enables the transfer of a larger amount of heat at the same temperature difference. The supply temperature (T_{SUP}) refers to the temperature of the heat transfer medium as it enters the heating system, while the return temperature (T_{RET}) is the temperature of the medium as it exits the system, both expressed in degrees Celsius [°C].

Table 2. Pearson correlation between variables and thermal power.

P_T	101	105	305	405	510	712
T_{OUT}	-0.23	-0.2	-0.096	-0.15	-0.43	-0.72
$\dot{V}$	0.77	0.82	0.92	0.97	0.25	0.55
T_{SUP}	0.61	0.64	0.6	0.67	0.74	0.47
T_{RET}	0.19	-0.8	-0.76	-0.014	-0.77	-0.98

2.3 District heating water transport times

Determining transport times is crucial for analyzing the connection between the heat source and district heating substations. The most pronounced response of district heating substations occurs during the morning peak, when the heat source must rapidly supply the required thermal energy. At this time, a sharp increase in temperature at the heat source profile is clearly visible, and, after a delay, the peak also appears in the district heating substation profile. This delay represents the transport time, which is the time it takes for a unit of heat to travel from the source to the station. Analytically, transport time can be calculated if the pipe cross-section, hot water density, pipeline length, and mass flow rate are known, as derived from Equation (1).

$$t_t = \frac{A * \rho * L}{\dot{m}} \tag{1}$$

Since calculating transport time based on flow rate depends on various external factors, such as pipeline branching and network complexity, the analysis uses a method that determines the delay between temperature peaks at the heat source and the district heating substation. This approach assumes that the heat unit reaching its maximum at the source is the same unit that later reaches its maximum at the district heating substation, though with heat losses and a time delay. By identifying these temperature peaks, the transport time can be determined. Figure 4 provides a graphical representation of this concept for analyzing transport times, with the transport time labelled as t_t.

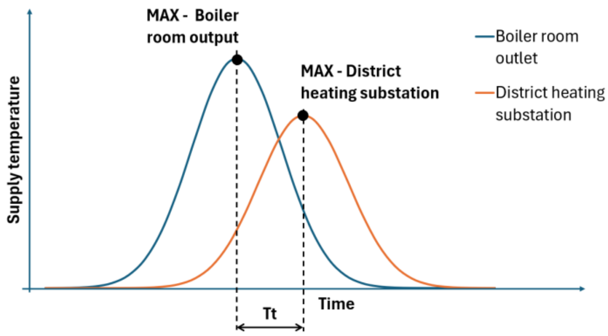

Figure 3. A graphical representation of the transport time concept.

For more precise analysis, time-series data are often smoothed. Traditional filters, such as the moving average and moving median, reduce noise but also truncate peaks, which can affect results. Therefore, this analysis uses the Savitzky-Golay filter (SG filter), which is based on polynomial approximation using the least squares method. This filter effectively preserves the shape of the temperature profile while reducing noise without losing important information, making it widely used in spectroscopy, audio processing, medical analyses (ECG, EEG), and other fields.

After smoothing the profiles, the next step was to determine transport times. For this purpose, a custom script was developed that uses a function to identify local maxima in the signal, i.e., in the temperature profile. The script detects the peak as the point where the value is higher than its neighboring points in both directions. The process was adapted to calculate only one transport time per day, specifically the most prominent one, ensuring comparability between flow-through and non-flow-through thermal stations. Non-flow-through stations typically have only one pronounced peak, which occurs in the morning when the station is activated.

2.4 Heat consumption time shift

Energy flexibility is the ability to shift energy flows over time to adapt to operational constraints and objectives. [11] Lowering temperature levels in the network reduces peak loads, mitigating temperature peaks and allowing the system to operate more efficiently in a base load mode.

Base load operation of heating equipment is the most favorable heat production regime, as boilers and heating plants operate at a relatively constant load without sudden power fluctuations. This results in lower maintenance costs and extends equipment lifespan. At the same time, it creates an opportunity to integrate continuous heating and heat load shifting within the network.

The goal of continuous heating is to ensure more stable heat production while reducing sudden peaks in heat demand. If buildings are heated continuously, the system experiences a smaller temperature difference during peak demand periods, which reduces the amount of heat that must be supplied at those times.

To maintain thermal comfort for consumers, the same total amount of heat must still be delivered, so heat must be stored or supplied during periods of lower demand. This process is known as heat load shifting. The approach is to increase thermal power during low-demand periods (before the morning peak) and reduce it during high-demand periods, ultimately lowering the maximum daily power requirement for production facilities. This redistribution of load from peak-demand to low-demand periods is illustrated in Figure 5. [12]

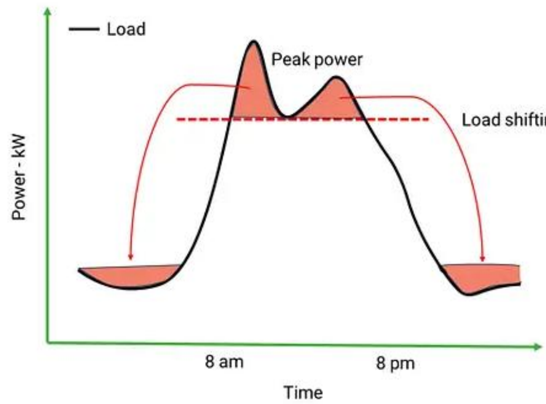

Figure 4. The redistribution of load from peak-demand to low-demand periods.

2.5 Additional energy demand

Peak loads cannot be reduced solely by shifting heat consumption; it is also necessary to consider that continuous heating results in higher overall energy use. While the peak load is lower, continuous heating causes constant heat losses, leading to increased total thermal energy consumption for space heating.

To estimate the magnitude of this additional energy demand, an analysis was conducted on two identical residential buildings with the same architecture and a connected heating capacity of 175 kW. These buildings were selected as ideal candidates for evaluating additional energy consumption, as one operates under a continuous heating regime and the other under an intermittent heating regime.

The analysis used two identical buildings located in the same area with the same connected power capacity, allowing for a reliable comparison of heat consumption. This comparison provides a solid estimate of additional energy use, though final consumption figures are also influenced by occupant behavior, renovation levels, and other factors that are difficult to quantify precisely.

A historical consumption analysis based on data from 2023 and 2024 showed that over one month, specifically January, the building with continuous heating consumed 20% more thermal energy. The difference was particularly pronounced toward the end of the month, when outdoor temperatures dropped further. This significant increase in consumption exceeded initial expectations set before the analysis. Consequently, this additional energy consumption was accounted for in the modification of heating profiles and served as one of the key assumptions in further simulations.

2.6 Assumptions

Before modifying the consumption profiles, it was necessary to establish a set of assumptions and simplifications that apply to all district heating substations and all analyzed cases. These assumptions are based on historical operational data and relevant findings from scientific literature. The analysis is limited exclusively to the heating season, defined in this work as the period from November to March, as this is the period characterized by the highest thermal energy demand, maximum heat production, and continuous operation of all district heating substations. The analysis considers only energy for space heating. Energy used for domestic hot water preparation is not included, as it is not relevant for the purpose of this evaluation.

The district heating substations in the Municipality of Maribor are divided into 12 subgroups according to their geographical location and characteristic heat demand. The number of substations in each subgroup varies according to the size and nature of each district. Three representative scenarios were defined, each representing a typical day during the heating season. These representative days are used as a basis to analyze the effects of modification and heat demand redistribution:

- **(*A*) a very cold day** with the lowest average outdoor temperature,
- **(*B*) a cold day** with an average outdoor temperature around 0°C,
- **(*C*) a milder day** with an above-season-average outdoor temperature.

These representative days adequately describe the typical operating regimes of the heating season and enable analysis of the effects of profile modification under different climatic conditions. During profile modification, increased energy consumption was taken into account. In the assumed continuous heating operation, indoor room temperatures are expected to be higher during low-demand periods compared to the traditional intermittent regime, resulting in higher thermal losses at the building level. To maintain equal comfort conditions for consumers, additional energy must be supplied. For each subgroup, average energy efficiency indicators [kWh/m²] were available and used to determine the magnitude of additional consumption. The reduction of peak loads and the amount of thermal energy redistributed into low-demand periods depended on the technical characteristics of each profile. Not all profiles allow the same degree of peak reduction, so realistic upper limits were applied to ensure plausible results. In general, the goal was to minimize the peak while preserving realistic system behavior.

Redistribution of thermal energy demand also results in a change in the operating mode of substations. Because energy is shifted to low-demand periods, substations must allow continuous flow of the heat transfer medium. Flow-through substations already provide this capability, while non-flow-through substations do not. Therefore, all non-flow-through substations were converted to flow-through operational mode in the modified profiles. As a result, the modified profile shows a gradual increase in thermal power before the peak, whereas the original profile shows zero before activation. Transport times were determined only for flow-through substations, as these enable continuous flow and thus accurate determination of heat transport time. Non-flow-through substations interrupt the primary flow when inactive, making them unsuitable for estimating transport time. After modifying each subgroup profile, all profiles were aggregated into a total modified daily demand. During aggregation, transport times for each subgroup were incorporated through appropriate time shifts.

Transport times were determined based on flow-through substations, as they provide a more accurate representation of heat transfer dynamics. Non-flow-through substations interrupt the primary flow, making it more difficult to estimate transport times. When aggregating modified profiles, transport times were adjusted with appropriate time shifts for each subgroup. The principle of maintaining the total amount of heat delivered was upheld in the profile modification process. While peak loads were reduced, the heat was redistributed, and additional heat losses due to the changed regime were incorporated into the modified profile. As a result, the modified profile includes a higher total energy consumption compared to the original.

Some substations had incomplete, missing, or invalid data. Missing substations were replaced with virtual substations to obtain correct total daily demand and ensure realistic heat production requirements. The total thermal energy at substations was then adjusted to match the annual system efficiency of 86.5%, which represents the actual average annual efficiency of the district heating system operated by ENMB. Since the ratio between total delivered heat at substations and total heat produced at the source was initially lower due to missing substations, additional virtual substations were added to achieve the required efficiency ratio of 86.5%.

2.7 Profile modification

A dynamic model was developed in Python using the Dash module, which enables visualization and interactive manipulation of graphs for heat consumption redistribution. The model allows users to define the start and end times (hh:mm) for two peak demand periods and two reduced demand periods. One period is designated for morning peaks, while the other accounts for potential increases in afternoon consumption. For each period, peak loads can be reduced by a specified percentage. The model lowers values in the selected time intervals based on the defined percentage reduction. If the power at a given time interval is represented by *P(t)*, then the reduced power, $P_{reduced}(t)$, at a specified reduction level (expressed as a percentage), is defined as shown in Equation (2).

$$P_{reduced}(t) = P(t) * \left(1 - \frac{z}{100}\right) \quad (2)$$

If a time point falls within a peak demand period, the corresponding heat consumption value is reduced. The amount of energy reduced is stored and summed, then evenly redistributed across the selected low-demand period. Thus, if a time point is within a high-demand period, the corresponding thermal power value is decreased. Conversely, during low-demand periods, the power is increased by the redistributed amount. When thermal power is reduced, the saved energy is calculated and allocated to intervals with lower heat consumption. The energy savings can be expressed mathematically as shown in Equation (3).

$$E_{saved} = \sum_{t \in peaks} \left(P(t) - P_{mod}(t)\right) * \Delta t \quad (3)$$

The saved energy must be redistributed during low-demand periods to achieve a smoother, more balanced profile. Redistribution is performed linearly based on the total duration of the low-demand periods. If the low-demand periods contain n intervals, the additional power $P_{additional}$ is defined as shown in Equation (4).

$$P_{additional}\,(t) = \frac{E_{saved}}{n * \Delta t},\ t \in reduced\ demand \quad (4)$$

$P_{additional}$ represents the power added to the thermal power values during low-demand periods, resulting in the increased power profile $P_{increased}(t)$.

Additionally, a Gaussian mathematical filter was implemented to further smooth the modified profile, as shown in Equation (5). Without filtering, sudden fluctuations were observed because noise from the original profile was transferred to the modified profile. To achieve a cleaner and more refined result, this filter was applied. In this case, a Gaussian filter was chosen instead of the previously used Savitzky-Golay (SG) filter. The Gaussian filter proved to be simpler and more effective, primarily due to its easier control of smoothing intensity using the parameter σ, which defines the width or intensity of smoothing. With the Gaussian filter, the smoothing intensity can be adjusted more directly, whereas the SG filter requires manipulation of two parameters, making fine-tuning more complex.
The final modified profile, denoted as $P_{mod}(t)$, consists of the reduced power profile $P_{reduced}(t)$ and the increased power profile $P_{increased}(t)$, which appear within their respective periods. This profile is then smoothed using the SG filter, as shown in Equation (5).

$$P_{smoothed}(t) = \sum_k P_{mod}(t-k) * G(k,\sigma) \quad (5)$$

$G(k, \sigma)$ denotes the Gaussian function with offset k and standard deviation σ, as defined in Equation (6).

$$G(k,\sigma) = \frac{1}{\sqrt{2\pi\sigma}} * e^{\left(-\frac{k^2}{2\sigma^2}\right)} \quad (6)$$

3 RESULTS

Profile manipulation is performed using a custom-developed tool that operates according to the described equations. The software is supported by libraries that provide existing code functionalities. To use the tool, the user must upload a file containing thermal power data for the selected day. The file is structured so that each column contains data for a specific SD subgroup. The user must define four time intervals: two peak demand periods and two low-demand periods. For each period, both the start and end times must be specified. Additionally, the percentage reduction of peak demand (z) must be defined, which can vary between the two peak periods.

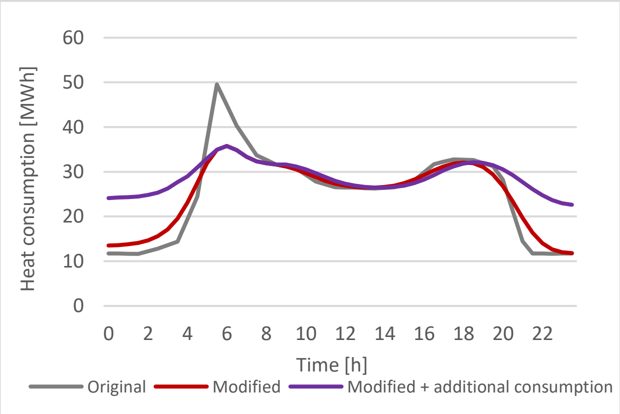

Figure 5. The modification process.

Figure 6 shows the modification process applied to the hourly thermal power profile. The original and modified profiles have the same total heat consumption over a single day, meaning they have the same area under the curve. The total heat consumption increases only when the modified profile includes additional energy consumption, which is added exclusively during low-demand periods. This approach best describes the transition from mixed heating regimes to a fully flow-through heating regime. It is important to note that this represents only a modified heat consumption profile, not the heat production profile, which is discussed in the following chapter.

3.1 Profile modification

For each analyzed day, a modified production profile was generated to match the adjusted and redistributed heat consumption pattern derived from the modification methodology. The construction of the new production profile relied entirely on the assumptions, simplifications, and boundary conditions defined in the previous sections of this paper. First, the total amount of thermal energy required under each scenario (*A*, *B*, and *C*) was determined. To maintain consistency between the thermal energy measured at district heating substations and the energy produced at the source, the total supplied heat had to represent 86.5% of the thermal energy injected into the system, reflecting the annual average system efficiency of the local district heating system. However, in the initial state, the total thermal energy of all district heating substations did not meet this condition, either due to incomplete datasets or missing substations. Therefore, virtual district heating substations were introduced. These represent theoretical thermal loads, added solely to achieve the correct balance between total consumption and production, thereby ensuring the correct efficiency factor at the system boundary.

After achieving the correct energy balance, the profiles of individual subgroups were modified. These modifications ensured that thermal power demand was redistributed from peak hours to periods characterized by low thermal loads, in accordance with the adopted continuous heating principles. Each subgroup's modified profile was then summed, resulting in an aggregated daily profile. At this stage, the aggregated profile already included the increased energy consumption due to higher thermal losses arising from higher assumed indoor temperatures during periods of lower demand. Since different district heating substation groups are located at varying geographical distances from the main heat source and consequently exhibit different dynamic heat transport delays, each subgroup profile was shifted in time according to the previously determined transport times, ensuring realistic alignment between production and consumption.

In the final step, the overall system efficiency was applied once more to ensure that the aggregated and time-shifted modified profile reflected the actual necessary production levels. This was done by dividing the modified and aggregated consumption profile by the efficiency factor of 0.865. The result of this procedure was a new, fully adjusted production profile *PP (1)*, which represents the required production power curve for the respective representative day. This modified production profile then served as the basis for defining the operation strategy of the production units and the new target baseload generation regime within the heating plants. The entire process of constructing this modified production profile is illustrated schematically in Figure 7.

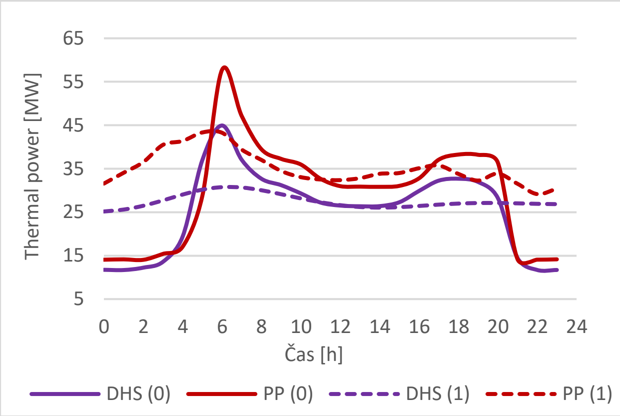

Figure 6. Process of determining the new thermal power profile for the production.

3.2 Heat production

The production structure of the Energetika Maribor group includes hot water boilers, combined heat and power (CHP) units, solar collectors, and a high-temperature heat pump (HTHP) located at the Pristan boiler plant. However, the solar collectors and HTHP were not considered in this analysis. In the previous sections, we defined the new heat demand profile. Based on this profile, an operational plan was developed to ensure that the heating plants meet the revised thermal requirements. As a result, three operational plans were created, one for each analyzed scenario representing a different typical heating day.

At the Jadranska unit, various heat and power generation devices are installed, including hot water boilers, gas engines, and solar collectors. The thermal energy supply is provided by four hot water boilers:

- LOOS 12 has a total thermal capacity of 12 MW,
- LOOS 18 has a thermal capacity of 18 MW,
- UT-HZ 1 and UT-HZ 2 each have a thermal capacity of 26 MW.

For combined heat and power (CHP) generation, gas engines are used:

- TOM 1 (one gas engine) provides 2.58 MW of thermal power and 3 MW of electrical power,
- TOM 2 (four gas engines) provides a total of 8.904 MW of thermal power and 9.859 MW of electrical power.

Thermal storage tanks also play a crucial role, as they can increase base load energy production and manage peak loads. In Figures 8 and 9, these storage tanks are labeled with H and indexed with "in" and "out," indicating charging or discharging operations.

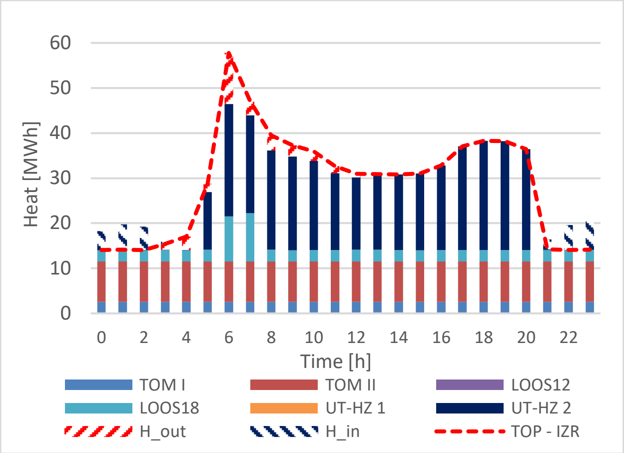

Figure 7. Original operational regime.

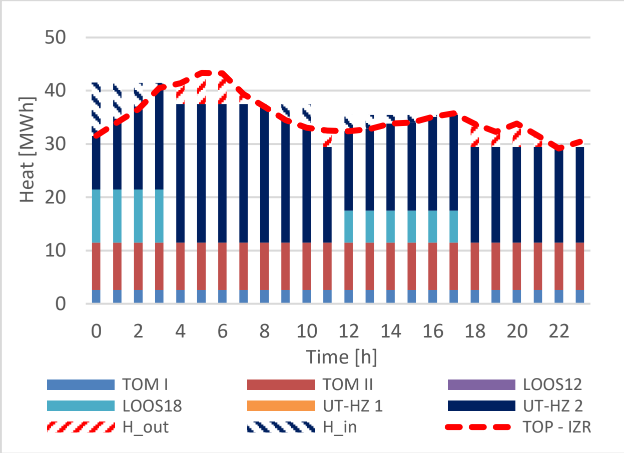

Figure 9. Operational plan for the modified heat consumption profile.

Figure 8 shows the original operational regime. The red dashed line (TOP-IZR) indicates the heat demand profile that must be met to comply with the System Operating Instructions (SON). This profile displays a distinct morning peak, which was primarily covered by the UT-HZ 2 boiler. The required thermal power ranges from 10 MW to 57 MW.

Figure 9 presents the operational plan developed for the modified heat consumption profile. This plan was manually designed to meet the hourly heat demand specified by the modified profile. The most notable difference is in boiler operations– in the modified scenario, the boilers would produce 44% more MWh of thermal energy. As a result, internal electricity consumption and natural gas usage would increase. The rise in thermal energy production is due to both the higher overall heat consumption described in previous sections and the redistribution of demand over time.

A key achievement of the modification is the reduction of peak power, which was successfully lowered by 14 MW. However, the average and minimum achieved thermal power levels are higher in the modified operational plan. A similar effect was observed in the other two scenarios, where peak reduction was also achieved but required higher average and minimum thermal power levels. Additionally, peak reduction was influenced by outdoor temperature. At higher outdoor temperatures, the reduction in peak load was smaller. This is because peak loads tend to be more pronounced at lower temperatures, as heat demand rises more sharply in colder conditions.

The characteristics of the newly modified operational plans, compared to the original ones, can be analyzed using a load duration diagram. These diagrams clearly visualize peak loads, which, although infrequent, have a significant impact on the system. Ideally, a more uniform distribution of loads over time is desirable. The diagram shows load curves for all scenarios, indicating a substantial reduction in peak loads and a much more balanced profile. In the original load curves, the direct influence of outdoor temperature on system load is evident. Scenario *C* (the warmest day) places significantly less strain on the system than Scenario *A* (the coldest day), when heat demand was highest. In the diagram shown in Figure 10, dashed lines represent modified operational regimes, while solid lines depict the original (actual) profiles.

In the economic comparison of individual scenarios, the primary focus was on the daily financial outcome, determined by costs (as described in the previous subsection) and revenues. Revenues consist of sold heat, electricity, and operational support received for CHP (SPTE) units. Although the modified operational regime resulted in a better financial outcome, this was achieved at the cost of additional energy consumption supplied to consumers. The key question of the master's thesis is whether the additional revenue was sufficient to at least offset the increased heating costs. For CHP units (SPTE), there were no significant differences, as both scenarios operated within the base load range, supporting this conclusion.

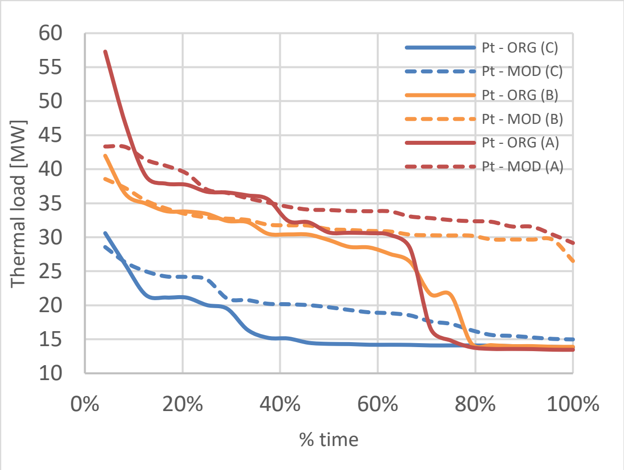

Figure 8. Load duration diagram.

However, at the boiler plant, more heat was produced to compensate for additional losses caused by continuous consumption. The extra heat generated represents a cost that must be covered. Although consumers pay for the heat produced, it would not be justified to pass the cost of additional heat generation directly to them, as they do not benefit from it directly. From this perspective, the extra heat produced can be considered an additional expense. Therefore, it is important to examine production savings that could potentially be used to reduce or offset this additional cost. A notable difference was observed at the boiler plant, where the modified operational regime resulted in a slightly better outcome, as the boilers produced a higher amount of heat.

4 DISCUSSION

As part of this study, a method for peak load smoothing was examined using heat load shifting and the creation of new operational regimes, assuming continuous heating. The analysis included a literature review, data acquisition and processing for thermal stations, data analysis, and the formulation of assumptions based on the collected data.

The main challenges in data processing were handling missing and erroneous values, visualizing data graphically, and determining transport times. Python programming was used throughout the calculation and analysis process, enabling automated data processing and complex calculations. After data analysis, new heat consumption profiles were created based on existing thermal power profiles and the adopted assumptions. Using these modified consumption profiles, corresponding operational plans were developed and compared with the existing ones from both technical and economic perspectives.

In the modified profiles, additional heat consumption was assumed based on an analysis of two identical buildings with different heating regimes. It was determined that during the heating season, a flow-through system requires an average of 20% more thermal energy. This additional energy consumption was incorporated into the profile modifications, resulting in a greater amount of heat being produced.

From an economic standpoint, this benefits the boiler plant, as more heat is sold, leading to better daily financial results. However, the additional energy also results in increased emissions and higher heating costs for consumers. While the final analysis confirmed an expected cost increase for consumers, the study also explored the possibility of cost compensation.

The compensation mechanism consisted of additional revenue from heat sales and savings due to lower peak loads. However, the results indicate that the achieved compensation was not sufficient to fully cover the increased consumer costs. The cost increase could only be reduced by approximately one-quarter.

This leads to the conclusion that a direct switch to continuous heating regimes would not be economically justified. One possible alternative is the integration of renewable-based heating technologies with lower production costs, such as biomass boilers or heat pumps. These would provide the additional heat from sustainable and environmentally friendly primary sources while simultaneously reducing peak loads in the district heating system.

It is anticipated that such simulations will become increasingly relevant in the future due to ongoing transformations in the energy sector, including changes to network regulations, the transition to renewable energy sources, digitalization, and potential legislative adjustments, all of which may introduce new challenges for the energy industry.

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