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Peak loads reduction optimizing strategies in district heating system – case study of Maribor

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Abstract: District heating systems provide centralised heat generation and efficient distribution in urban environments, enhancing energy efficiency and mitigating local uncontrolled emissions. Nonetheless, district heating is influenced heavily by fluctuations in energy prices, environmental and climate issues, and the necessity of maintaining reliable operations during the heating season. These systems often depend on continuously functioning equipment to meet fundamental heating requirements, while peak demands are addressed with supplementary flexible heat sources. This frequently results in system oversizing, elevating operating expenses and inefficiencies. An effective strategy to mitigate peak demand challenges is heat consumption shifting, which reallocates energy usage more uniformly over the day. Shifting heat demand from peak hours to times of lesser consumption enhances overall system efficiency and diminishes the necessity for extra peak-load capacity. This method can be very advantageous in current district heating networks without necessitating significant infrastructure modifications.
A simulation of heat load shifting was performed on the district heating system of the City of Maribor. The research employed altered heat consumption patterns to examine the viability of load shifting and its effects on system performance. The results indicate that optimised energy distribution may augment operational stability, decrease expenses, and boost sustainability.
Keywords:district heating system; energy efficiency; heating schedule; optimization

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. 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 exhibits a characteristic daily consumption pattern, marked by pronounced peaks and periods of lower demand. In the early morning hours, 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) [1]. The SON document regulates all aspects of system management, operation, and development while also defining 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 utilizes 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 within the heating season.

For each of these three cases, modified consumption profiles were created and compared with actual historical data.

It is expected that the adjusted heating regime will 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 District heating substations

District heating substations are a key component of DHS, as they serve as the connection between the distribution network and end users. A district heating substation consists of 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 dictated by their operation. In a way, a district heating substation can be seen as a mirror of 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, meaning that the temperature profile of the district heating substation closely matches that of the distribution network.

Non-flow-through district heating substations (NFTDHS), on the other hand, do not allow a constant flow and only activate flow at specific times. The term "activation" refers to the moment when the valve in the district heating substation opens, allowing the primary district heating water flow 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. The idea behind this study is to simulate a transition to an exclusively flow-through heating regime.

Figure 1 illustrates 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 presented profile represents the actual data for a typical day during the heating season.

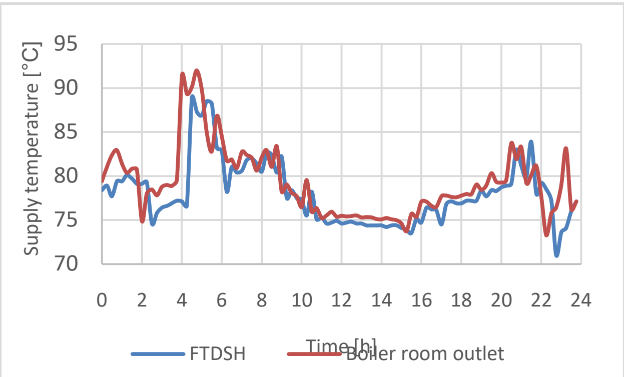

Figure 1 Temperature profile for a flow-through district heating substation

Figure 2 once again illustrates the supply temperature of the district heating substation and the water temperature at the heat source outlet. However, this time, it depicts a district heating substation operating in a non-flow-through heating regime. The data corresponds to the same day analysed in Figure 1, allowing for a direct comparison. The profile reveals a significant difference, with a distinct activation and deactivation moment clearly visible. This is expressed as a sharp temperature peak in the early morning hours, 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 in practice means that heating is entirely inactive during this period. As a result, users cannot adjust indoor temperatures using radiators or other heating devices during the deactivation period, as they do not reach the necessary operating temperature.

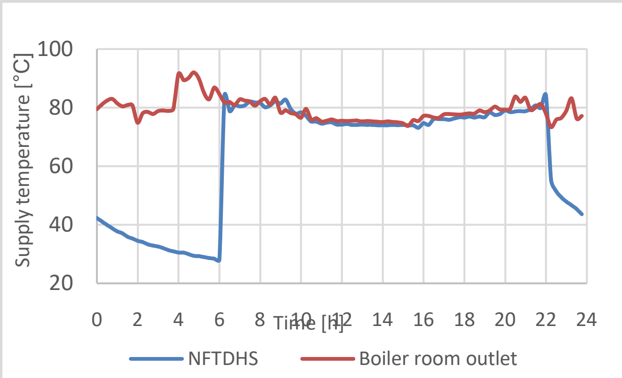

Figure 2 Temperature profile for a non-flow-through district heating substation

2 METHODS

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 also physically separated from the boiler plant on the left bank of the Drava River during this time. As a result, the analysis is focused 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 is 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 was 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 analysing 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.

2.1 Interdependencies between the analysed variables

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

To gain a better understanding of real-world system behaviour, one possible 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, where the relationships were quantified using the Pearson correlation coefficient, which ranges from -1 to 1. A value of 1 indicates a perfect positive correlation, meaning that 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 along with appropriate libraries to develop the necessary code [2][3][4][5]. This code calculates the Pearson correlation coefficient for every possible combination of variables in the dataset. Additionally, 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 also 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 reveals 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. On the other hand, outdoor temperature and thermal power exhibit a negative correlation, which is expected, as lower outdoor temperatures lead to an 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 in relation to outdoor temperature. Prior to data processing, a strong dependence of variables on outdoor temperature was anticipated. However, the resulting table did not indicate promising correlation values, as they were generally low and highly diverse. A similar variability was observed in a study [6] that focused on energy consumption forecasting. This variability was one of the key reasons why it was necessary to simplify the analysis with specific assumptions.

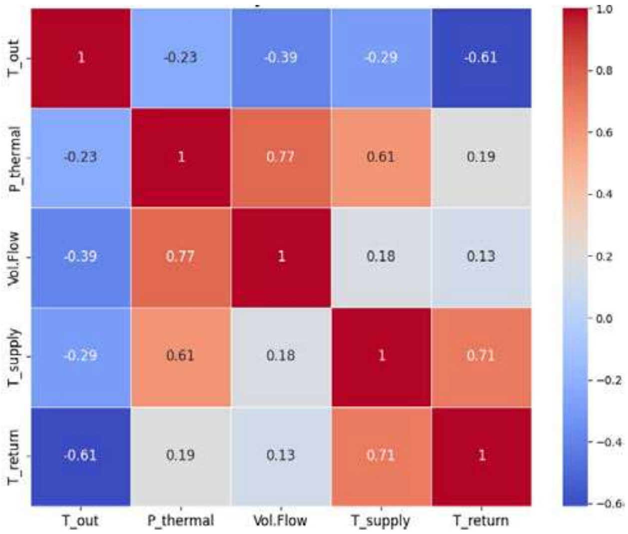

Figure 3 Correlation matrix for one of the district heating substations

Another important factor to highlight is the mutual influence of buildings. When multiple district heating substations serving neighbouring buildings activate simultaneously, it causes an increase in local heat demand, which can affect surrounding district heating substations in different ways. This is especially true for stations located toward the end of pipeline networks, where heat distribution may be less stable.

Table 1 presents Pearson correlation coefficients for the dependency 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 analysing 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 that flows 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}) represents the temperature of the medium as it exits the system, both expressed in degrees Celsius [°C].

Table 1 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

2.2 District heating water transport times

Determining transport times is crucial for analysing 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 with 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).

$$t_c = \frac{A * \rho * L}{\dot{m}} \quad (1)$$

Since the calculation of transport time based on flow rate depends on numerous external factors, such as pipeline branching and network complexity, the analysis employs a method that determines the delay between the temperature peaks at the heat source and the district heating substation. The 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, albeit with heat losses and a time delay. By identifying these temperature peaks, it is possible to determine the transport time. A graphical representation of this concept for analysing transport times is shown in Figure 4, with the transport time being labelled as Tt.

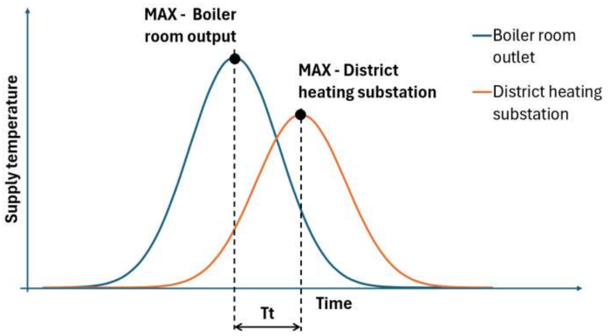

Figure 4A graphical representation of the transport time concept

For a more precise analysis, time-series data is 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, and other fields.

2.3 Heat consumption time shift

Energy flexibility can be defined as the ability to shift energy flows over time to adapt to operational constraints and objectives [7]. Lowering temperature levels in the network reduces peak loads, meaning temperature peaks are mitigated, allowing the system to operate more efficiently in a base load operation mode.

Base load operation of heating equipment is the most favourable heat production regime, as boilers and heating plants operate at a relatively constant load without being subjected to sudden power fluctuations. This results in lower maintenance costs and extended equipment lifespan. In parallel, this presents 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 encounters a smaller temperature difference during peak demand periods, which in turn reduces the amount of heat that needs to be supplied at those times.

To maintain thermal comfort for consumers, the same total amount of heat must still be delivered, meaning that heat must be stored or supplied during periods of lower demand. This process is known as heat load shifting. The idea is to increase thermal power during low-demand periods (before the morning peak) and reduce it during high-demand periods, ultimately leading to a lower maximum daily power requirement for production facilities. This redistribution of load from peak-demand to low-demand periods is illustrated in Figure 5 [8].

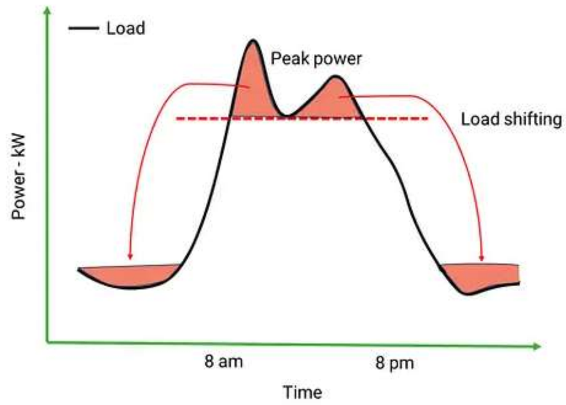

Figure 5 Theredistribution of load from peak-demand to low-demand periods

2.4 Additional energy demand

Peak loads cannot be reduced solely by shifting heat consumption; it is also necessary to consider the fact that continuous heating results in higher overall energy use. While the peak load itself is lower, the assumption of continuous heating means that heat losses always occur, leading to an increase in 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. These buildings share identical architecture and a connected heating capacity of 175 kW. These buildings were chosen as ideal candidates for evaluating additional energy consumption, as one building operates under a continuous heating regime, while the other follows an intermittent heating regime.

The analysis utilized 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 the final consumption figures are also influenced by occupant behaviour, renovation levels, and other factors that are difficult to quantify precisely.

A historical consumption analysis based on data from 2023 and 2024 revealed that over the course of one month, specifically January, the building with continuous heating consumed 20 % more thermal energy. The difference was particularly pronounced towards 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, serving as one of the key assumptions in further simulations.

2.5 Assumptions

Before modifying the profiles, it was necessary to define key assumptions and simplifications applicable to all cases. These assumptions are based on historical data and relevant literature. The analysis is limited to the heating season, covering the period from November to March, as this is when heat production is at its peak and all district heating substations are actively consuming heat. The study focuses exclusively on energy for space heating, while energy for domestic hot water preparation is excluded, as it is not relevant for this analysis.

The district heating substations are grouped into 12 subgroups, each representing a specific district within the Municipality of Maribor. The number of district heating substations in each subgroup varies based on geographical location and the specific heating demands of each area.

For the simulation, three representative scenarios were defined, corresponding to typical days during the heating season:

- **A very cold day** (A) with the lowest average outdoor temperature (T_{OUT}),
- **A cold day** (B) with an average T_{OUT} around 0°C, and
- **A milder day** (C) where T_{OUT} is higher than the seasonal average.

During the modification of profiles, the increased energy consumption caused by higher indoor temperatures during low-demand periods was accounted for, as it leads to greater heat losses. Peak reduction and load redistribution were adjusted based on the specific characteristics of each profile, ensuring realistic adaptations.

By redistributing heat demand, the operating mode of district heating substations also changes. Flow-through stations allow for a continuous flow, whereas non-flow-through stations do not, requiring their profiles to be adjusted to a flow-through regime. As a result, the modified profile shows a gradual increase in power before the peak, while the original profile shows zero thermal power before activation.

Transport times were determined based on flow-through stations, as they provide a more accurate representation of heat transfer dynamics. Non-flow-through stations 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 one.

Since some stations had incomplete or unavailable data, missing power values were replaced with virtual district heating substations to enable accurate total load calculations and ensure realistic heat production estimations. The total heat supplied by the district heating substations was adjusted to match the system's annual efficiency rate of 86,5%, which is the efficiency standard for the district heating system operated by ENMB.

2.6 Profile modification

A dynamic model was developed in the Python programming language using the Dash module, which enables visualization and interactive graph manipulation 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 separately, it is possible to reduce peak loads by a specified percentage. The model lowers values in the selected time based on the defined percentage reduction. If 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).

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

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

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

The saved energy must be redistributed during low-demand periods to achieve a smoother and more balanced profile. The 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).

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

$P_{additional}$ 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, Equation (5). Without filtering, sudden fluctuations were observed, as 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 sing SG filter as shown in Equation (5).

$$P_{smoot\ hed}(t) = \sum_k P_{mod}(t-k) * G(k,\sigma) \tag{5}$$

G(k,σ) represents the Gaussian function with an offset □ and a standard deviation □, as defined in Equation (6).

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

3 RESULTS

Profile manipulation is performed using a custom-developed tool that operates based on the described equations. The software tool is supported by libraries that enable the use of 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 4 time intervals, specifically: two peak demand periods and two low-demand periods.

For each period, both 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.

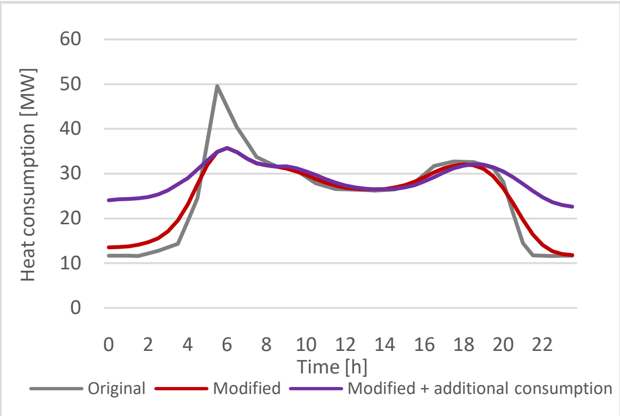

Figure 6 The modification process

The graph in Figure 6 illustrates the modification process applied to the hourly thermal power profile. The original and modified profiles contain the same total amount of consumed heat over a single day. From a mathematical perspective, this means they have the same area under the curve. The total heat consumption increases only when the modified profile incorporates 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 emphasize 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 analysed day, it was necessary to generate a modified production profile that corresponded to the adjusted heat consumption profile. The modified profile was based on the assumptions outlined previously in this paper. Based on this, the total amount of heat for each scenario was determined. The total heat supplied needed to be 86.5% of the energy produced at the source, reflecting the system's efficiency. However, since the sum of the thermal energy of all district heating substations did not meet this condition, virtual district heating substations were introduced to achieve the correct balance between production and consumption.

Once the balance was properly adjusted, the next step was the modification of individual subgroups, ensuring that heat consumption was properly redistributed. The modified subgroups were then summed, resulting in an overall increase in total heat consumption due to the additional energy use incorporated in the assumptions. The final summed profile of the modified subgroups thus represented the new thermal power demand profile. Since different district heating substation groups have different transport times, their profiles needed to be shifted accordingly to account for heat transport delays to the consumption points.

In the final step, system efficiency between the production sources and district heating substations was accounted for. The modified profiles were divided by the efficiency factor, ensuring that the necessary production values were correctly reflected. The total sum of the modified profiles ultimately represented the new production profile PP (1), which served as the foundation for planning the new base load operation of the heating plants. The process is visually represented in Figure 7.

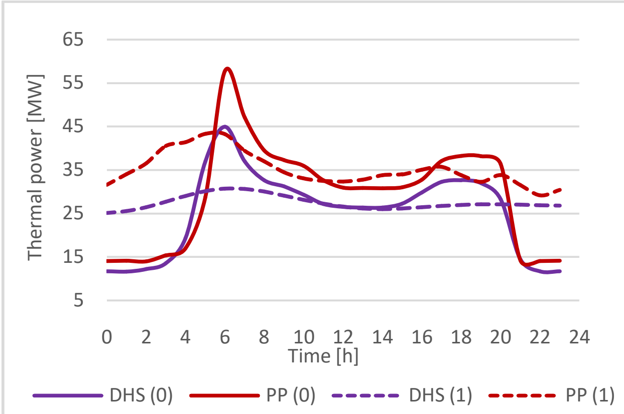

Figure 7 Process of determining the new thermal power profile for the production

3.2 Heat production

The production structure of the Energetika Maribor group consists of 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 new 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 analysed 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 with a total thermal capacity of 12 MW,
- LOOS 18 with a thermal capacity of 18 MW,
- UT-HZ 1 and UT-HZ 2, each with a thermal capacity of 26 MW.

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

- TOM 1 (one gas engine) with 2,58 MW of thermal power and 3 MW of electrical power,

- TOM 2 (four gas engines) with total 8,904 MW of thermal power and total 9,859 MW of electrical power.

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

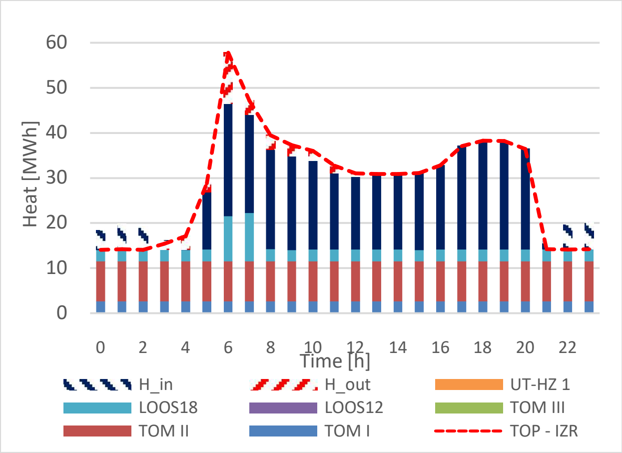

Figure 8 Original operational regime

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

Figure 9 illustrates the operational plan developed for the modified heat consumption profile. This plan was manually designed, with a focus on meeting the hourly heat demand specified by the modified profile. The most notable difference appears in boiler operations—in the modified scenario, the boilers would produce 44% more MWh of thermal energy. Consequently, this would lead to higher internal electricity consumption and increased natural gas usage. The rise in thermal energy production is a result of 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 can be attributed to the nature of peak loads, which tend to be more pronounced at lower temperatures, as heat demand rises more sharply in colder conditions.

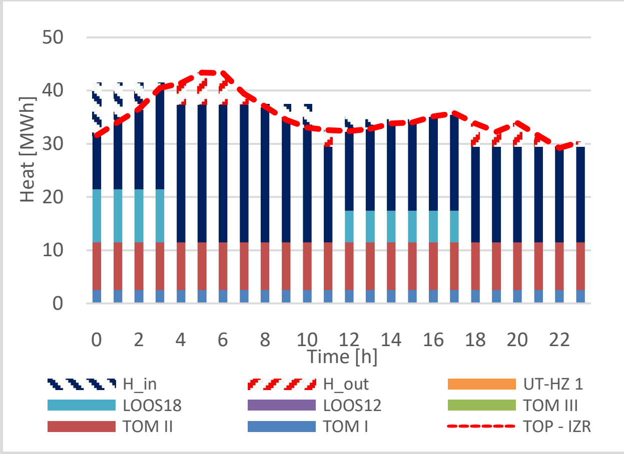

Figure 9 Operational plan developed for the modified heat consumption profile

The characteristics of the new modified operational plans, compared to the original ones, can be analyzed using a load duration diagram. These diagrams provide a clear visualization of peak loads, which, although infrequent, have a significant impact on the system. Ideally, we aim for a more uniform distribution of loads over time. The diagram illustrates load curves for all scenarios, showing 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 compared to Scenario A (the coldest day), where heat demand was highest. In the diagram shown in Figure 10, dashed lines represent modified operational regimes, while solid lines depict the original (real) profiles.

In the economic comparison of individual scenarios, the focus was primarily on the daily financial outcome, which is determined by costs (as described in the previous subsection) and revenues. Revenues consist of sold heat, electricity, and received operational support 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, which was 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, justifying this conclusion.

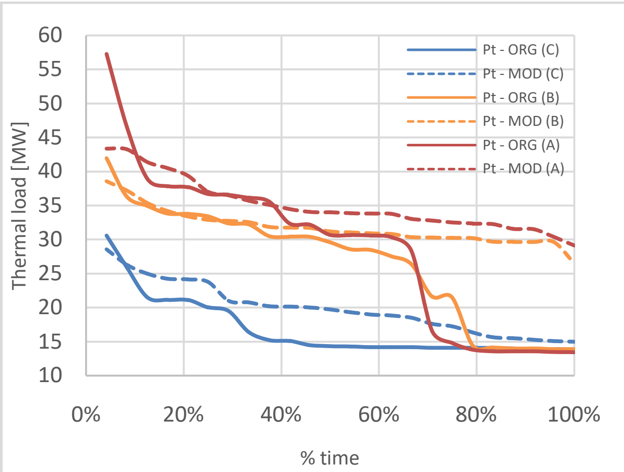

Figure 10 Load duration diagram

However, at the boiler room, a higher amount of heat was produced to compensate for additional losses caused by continuous consumption. The additional heat produced represents a cost that must somehow be covered. Although consumers pay for the produced heat, it would not be justified to pass the cost of additional heat generation directly onto them, as they do not benefit from it directly. From this perspective, the extra produced heat could be considered an additional expense. Therefore, it is crucial to examine the savings in production, which could potentially be leveraged 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 quantity 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, where continuous heating was assumed. The analysis steps included a literature review, data acquisition and processing for district heating substations, data analysis, and the formulation of assumptions based on the collected data.

The main challenges in data processing involved handling missing and erroneous values, visualizing data graphically, and determining transport times. Throughout the calculation and analysis process, Python programming was used, enabling automated data processing and complex calculations. Following the 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. These were then compared with the existing ones from both a technical and an economic perspective.

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 is beneficial for the boiler plant, as it means 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.

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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