Technical analysis of using a multi-storage system for a university campus: A case study of a Norwegian district heating system

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Abstract. The building sector accounts for 40% of the total energy use in the European Union. 80% of this use comes from space heating and domestic hot water systems. District heating (DH) systems make it possible to supply those demands by renewable energies, waste heat, and fossil fuel in a more efficient and environmentally friendly way. Peak load has a significant impact on the investment and operation cost of a DH system. Therefore, DH companies introduce DH price models that motivate heat users to reduce their peak load by charging for the heat rate extraction. The DH bill is divided into two parts: fixed and variable. The fixed part is counting for the extracted heat rate in kW, while the variable part is counting for the heat use in kWh. Depending on DH companies, some additional elements for volume or other expanses may be introduced. In this study, the focused was only on the two elements for the extracted heat rate and for the heat use, because they are taking the highest share of the DH bill. As a result of the above introduced approach for DH pricing models, introduction of thermal storage is a straightforward way for heat users to decrease their peak load. A DH system at a university campus in Norway is chosen as the case study. The entire system consisting of buildings, connection to a DH system, waste heat from the data center, and a multi-storage water tank (WT) was modeled in Modelica. In this study, instead of modeling the entire campus in one component, buildings are clustered, and one component modeled for each cluster of buildings. These clusters are based on heat demand profile of buildings. This could help to evaluate the performance of WT thermal storage system for different type of buildings. Result showed thermal storage system has better performance when it is implemented in a building with more fluctuation in heat demand. The system's peak is lower with a multi-storage system compared to a single storage system. The main reason for this is reduced heat loss and improved adjustment in a multi-storage system.

1 Introduction

The rapid urbanisation has led to an increasing demand for energy in urban areas. The building sector consumes a significant portion of the energy used in urban areas, accounting

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for 30-40% of global energy use [1]. In Nordic countries, space heating (SH) and domestic hot water (DHW) systems, as essential parts of building energy systems, play an important role in buildings' energy use. District heating (DH) systems garnered attention for its energy efficiency and environmental benefits and can satisfy multiple buildings' heat demand.

DH systems are highly competitive when compared to other heating technologies, particularly in urban areas with high heat demand. In Europe, over four thousand DH systems are currently operating successfully [2], with some areas having a heat market share of up to 60% [3-5]. However, DH systems face challenges that hinder their competitiveness, including high distribution temperature leading to significant heat loss and a shrinking heat market due to improved building efficiency [4]. To remain competitive, the current second and third generation DH systems are evolving into the fourth and fifth generation DH systems [6-9]. By lowering distribution temperature and improving infrastructure, the transformation decreases heat loss and enables the utilization of additional free heat sources like renewables and waste heats.

DH utilises various heat sources, such as geothermal energy, biomass, solar and local waste heat, for sustainability [10]. Furthermore, technological advancements like smart grids and digital controls have played a vital role in enhancing the efficiency and flexibility of DH systems, resulting in reduced energy consumption [11]. Utilising diverse heat sources and advanced technologies is crucial for improving the environmental and energy efficiency of DH systems, as emphasised by these studies.

From an economic perspective, heating price models currently calculate the DH cost for buildings using both heat use and peak load. Therefore, to optimize the economic performance of heat users, two options are available: 1) increasing self-utilization of heat supply from users' DHSs to reduce reliance on the central DH system, and 2) shifting peak hour heat supply from the central DH system to non-peak hours to lower users' peak load. Thermal energy storages (TESs) are effective in accomplishing these goals. Using TESs can address the mismatch between heat supply and heat demand in DHSs and buildings. As a result, less heat is supplied to the central DH system when there is excess heat, leading to an increase in the self-utilization rate of heat supply from buildings' DHSs [12, 13]. Second, TESs may shift the central DH system's heat supply from peak hours to non-peak hours, by shaving the peak load [14, 15]. However, one challenge for integrating TESs into DHSs is determining the optimal size of tank(s) considering multiple heat demands of different buildings in a district [16].

The combination of high heat demand and diverse building types in a district result in a large water tank storage system, posing challenges for its location and increasing heat loss. As a result, in this study a multi storage water tank system was investigated.

2 Methodology

2.1 Gløshaugen campus

The case study case in this paper is a university campus in Trondheim, Norway. In the Gløshaugen campus, the system supplies heat to a total building area of 300,000 m^2, and the primary functions of these buildings are education, offices, laboratories, and sports. The campus district heating (DH) system is connected to the city DH system by the main substation (MS). Apart from the heat supply from the city DH system, part of the annual heat supply comes from waste heat recovered from the university's data center (DC) [16]. According to the measurements from June 2017 to May 2018, the total heat supply for the campus DH system was 32.8 GWh. About 80% of the heat supply came from the central DH system through the MS. The other 20% came from the waste heat recovery from the DC [16].

Map of the Gløshaugen campus is shown in Figure 1. There is a dataset for the campus DH demand for 2017, as shown in Figure 2.

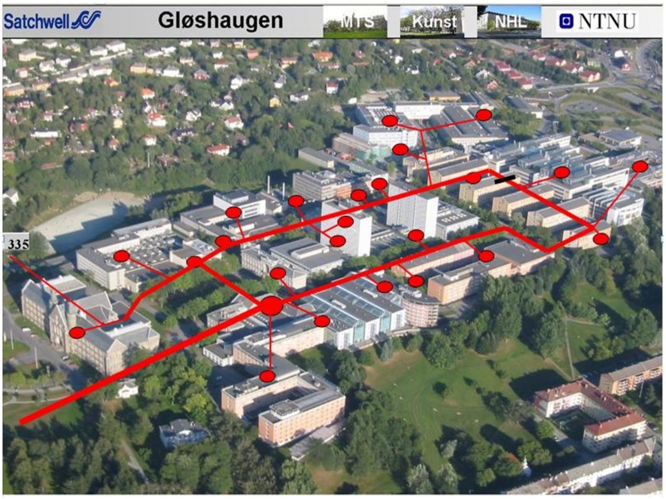

Fig. 1. Aerial image and building cluster for the Gløshaugen campus (red lines reperesent local district heating network on campus).

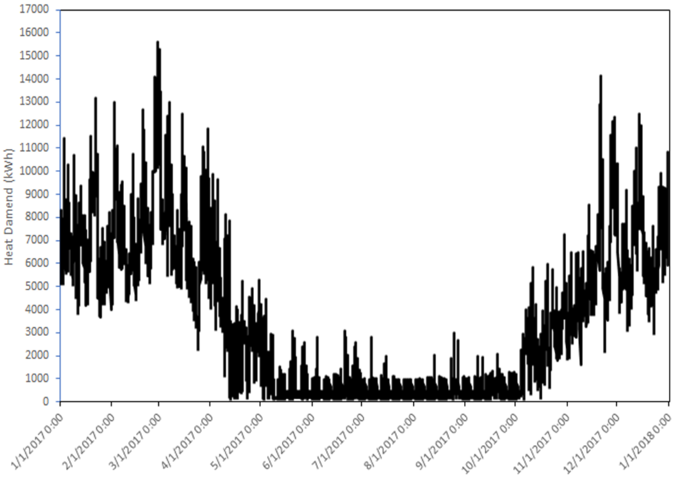

Fig. 2. Hourly building's heat demand for the year 2017

There are various types of buildings on campus. Buildings of the same type generally exhibit similar heat demand profiles. The performance of thermal storage systems relies on the heat demand profile, so campus buildings are grouped based on their heat demand characteristics. After investigating over 25 campus buildings, three main clusters were identified. One building from each cluster was chosen for evaluation in the model. Figure 3 illustrates the heat demand of a building throughout the year, with data collected over 24-hour intervals.
Three distinct behaviors can be observed among the buildings. There are no variations in thermostat setpoints in Building 302 during the day and all zones are heated continuously. Building 321 is programmed to warm up at 5 a.m. and continues until 4 p.m., resulting in a noticeable difference in heat demand between day and night. Building 239 also has a controller to regulate the temperature during work hours, but it has a smaller difference in

heat demand between day and night compared to building 321. This setpoint is specific to certain areas within the building. Rest of the buildings can be clustered based on one of these three buildings. As a representation of the entire campus, these three buildings were used to test the concept of a multi-storage system in this study.

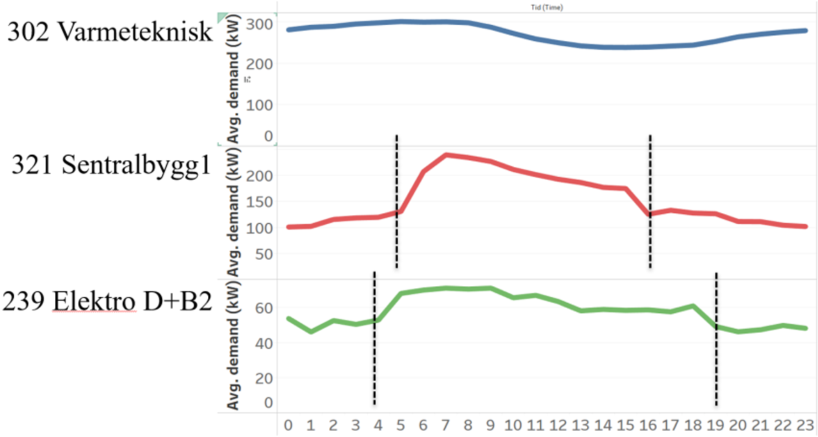

Fig. 3. Average 24-hour buildings heat demand over a year

2.2 Multi-storage system

Each district heating network contains buildings with various characteristics and heat demands. This means decisions can be specific to each user for enhancing the performance of the entire system, which is the key concept behind the multi-storage system. In such systems, instead of a large water tank, thermal storage for the entire network, small scale tanks can be used for just a few users to avoid excess heat loss and solve the space limitation problem. Figure 4 presents a visual representation of the idea, showcasing a local DH network connected to a main substation (MS). This network taps into the waste heat from a data center (DC) as a local heat source and accommodates various buildings with their own storage systems. This study investigated the performance of a similar system on a university campus.

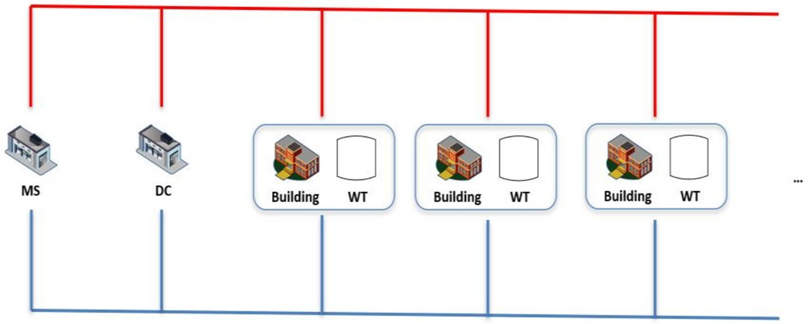

Fig. 4. Multi-Storage system schematic

2.3 Scenarios

The entire system comprising buildings, connection to a DH system, waste heat from the data center, and a multi-storage water tank (WT) was modeled in Modlica. As mentioned before, instead of the entire campus heat demand, just three representative buildings were modeled. To evaluate a multi storage system for a DH, three different scenarios were designed:

1. The reference scenario, Ref, presented the current campus DH system (figure 5). In this scenario, the city DH system acted as the basic heat source and supplied heat through the MS. Meanwhile, the DC functioned as an additional heat source. The condensing heat of the DC cooling system was fed into the return line of the campus DH ring. This scenario suffered from the mismatch and high peak load problems.
2. Ref + a single water tank thermal storage system (figure 6). This scenario integrated a WT into the reference scenario. The volume of the WT was chosen as 300 m³, which was able to supply heat to the system (three buildings) for one day. The WT functioned as the short-term TES. It aimed to relieve the mismatch between the DC waste heat supply and the building heat demand during the non-heating season. The WT operated in charging mode when the DC waste heat supply was higher than the building heat demand, otherwise, it operated in discharging mode. During the heating season, the WT was used to shave the peak load. It operated in discharging mode during the peak load hours, otherwise, it operated in charging mode.
3. Ref + a multi storage system where each building is connected to a water tank storage system (figure 7). the function of the system is just like scenario 2 where each water tank with a capacity of 100 m³, interacts with one building.

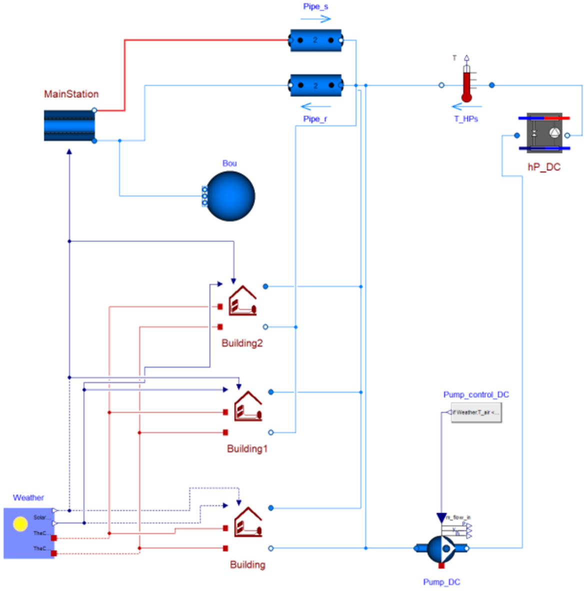

Fig. 5. Ref scenario

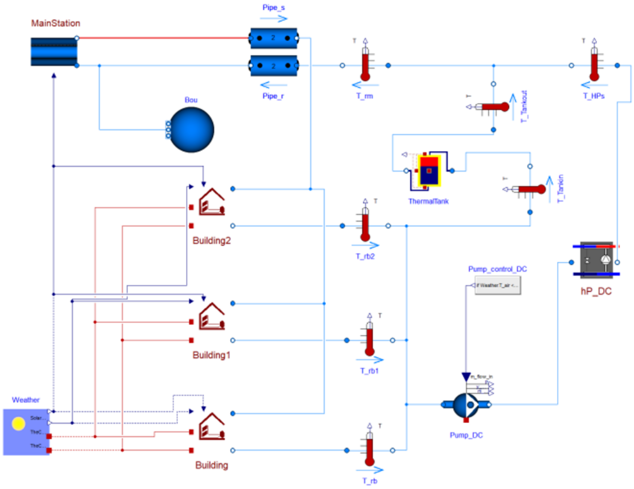

Fig. 6. Ref + water tank storage scenario

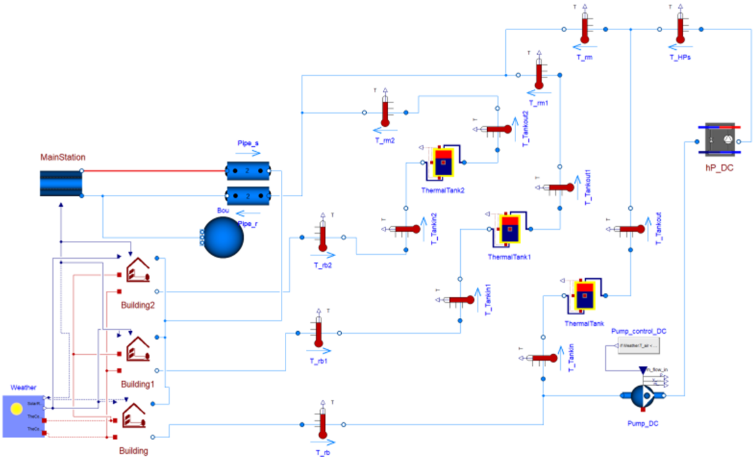

Fig. 7. Ref + multi storage scenario**.**

3 Result

This section first presents the model validation, then evaluates the three TES scenarios based on energy analyses.

3.1 Model validation

The building models were validated by the measured data from the campus energy management platform. The validation of the one of the building models is presented in Figure 8 and 9. The simulated and measured hourly building heat demands exhibited a similar pattern. During the heating season, the building heat demand was negatively correlated with the outdoor temperature. However, this correlation disappeared during the non-heating season. In addition, the median of the simulated building heat demand matched the measured value at the same interval. The CV(RMSE) criteria of building models and measured data were presented in Table1. The validation criteria required in ASHRAE Guideline 14-2014 is within ±30% for CV(RMSE). As shown in Table1, the values of this indicator satisfied the requirements.

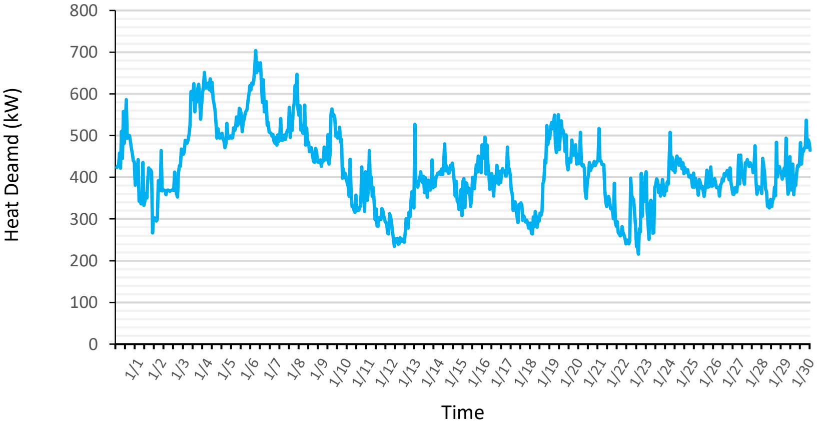

Fig. 8. heat demand of model output for building 302

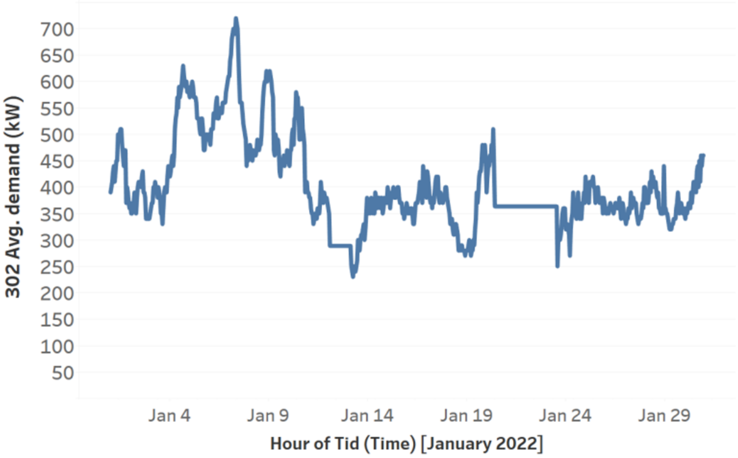

Fig. 9. Actual heat demand of building 302

Table 1. CV(RMSE) values for building models.

Building 302	Building 321	Building 239
15.4%	23.6%	18%

3.2 Evaluating the TES scenarios by energy analysis

To better understand the impact of adding a storage system to the model, the result for each scenario is reported as heat demand for one month in the cold season (January).

Figures 10 to 12 demonstrate the combined heat demand of three buildings in a DH system over a month. It can be used as a benchmark for evaluating the thermal energy storage system across the entire campus. Fewer number of peaks in scenarios 2 and 3 result from adding a storage system. The combination of three scenarios in Figure 13 allows for a more effective comparison and the smoothest trend is observed in scenario 3 (green line) when it comes to heat demand.

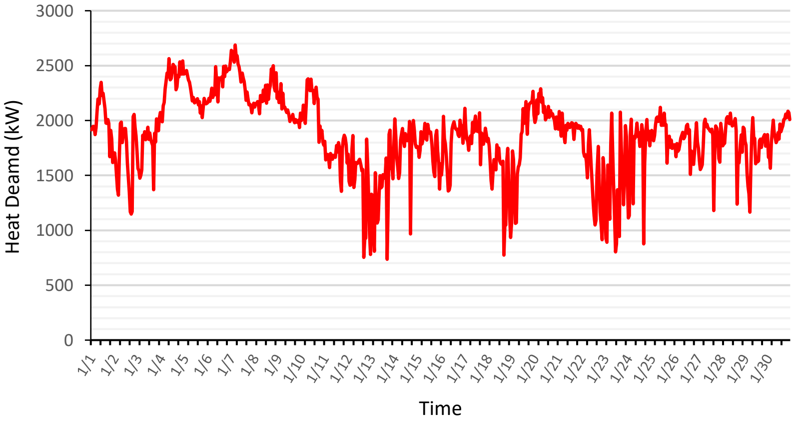

Fig. 10. Heat demand of model in Ref scenario

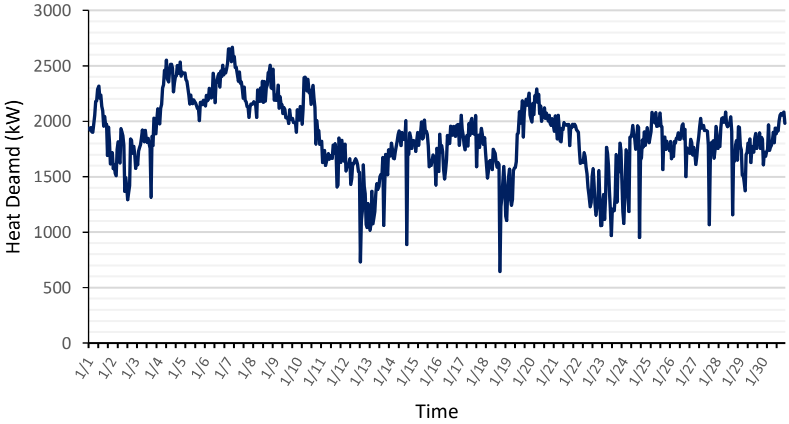

Fig. 11. Heat demand of model in Ref + Single WT scenario

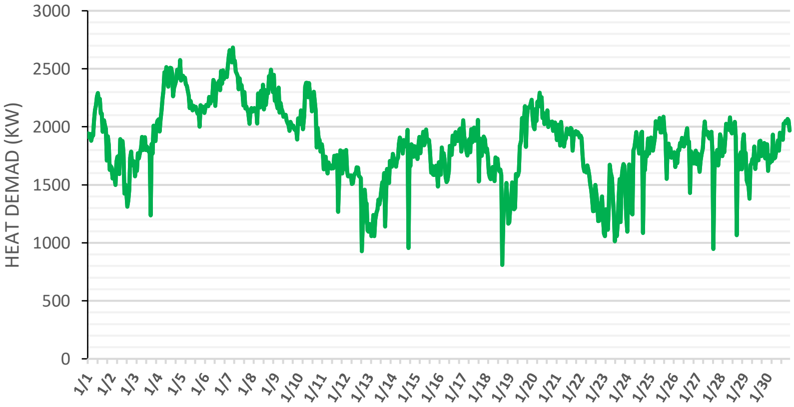

Fig. 12. Heat demand of model in Ref + multi-storage scenario

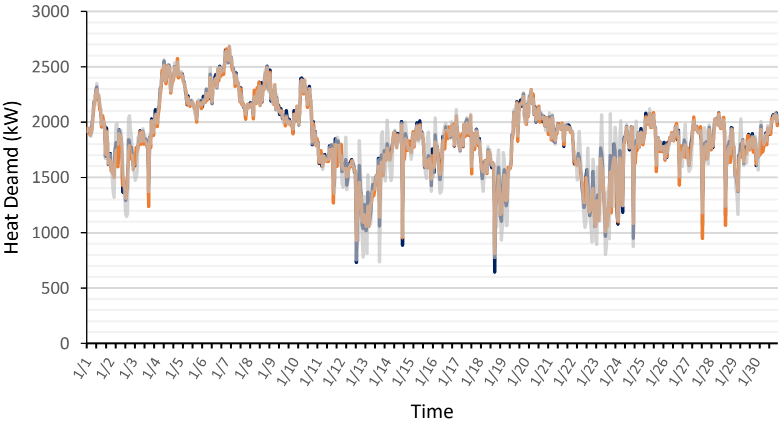

Fig. 13. Heat demand of model in 3 scenarios (red: scenario1, blue: scenari2, grey: scenario3)

The difference between scenarios is shown in detail over a 72-hour period in Figure 14. Heat demand shows greater fluctuations in scenario 1 (red line) when there is no storage device in the DH network. This results in higher peaks and increased costs for DH throughout the campus. Adding a single water tank storage in scenario 2 (blue line) can eliminate most of these peaks. In certain situation this reduction was 10% comparing to the reference scenario. Scenario 3 (green line) also shows similar effect with better performance in a same capacity of storage, which leads to 2.5% more reduction in peak load in the same condition. The main reason for this is the reduced heat loss and the ability to charge and discharge the tanks separately based on each building's specific conditions, which is not possible in scenario 2.

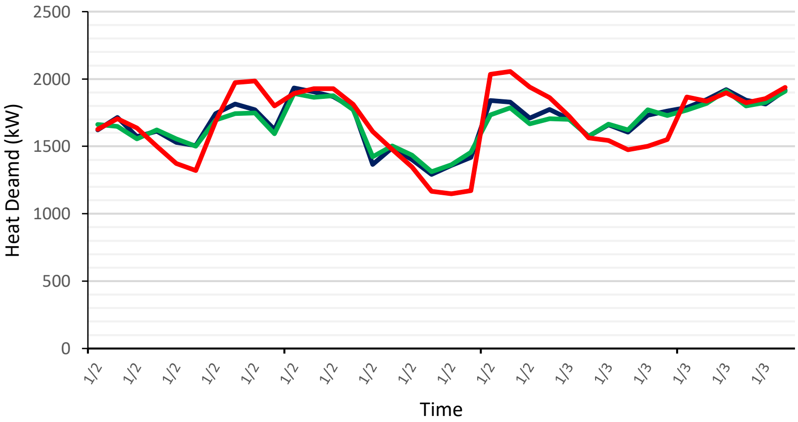

Fig. 14. Heat demand of model in 3 scenarios (red: scenario1, blue: scenari2, green: scenario3).

4 Conclusion

This study aimed to evaluate a multi-storage system performance in a DH network. A university campus was chosen as a case study and after clustering campus buildings, three main clusters of buildings were identified. For each cluster, one reference building was modeled in Modelica as well as other components of DH network. Three TES scenarios were proposed to address the mismatch problem and shave the peak load for the DH system, where the waste heat from data centre was available: without storage, with single water tank storage and with a multi-storage system. Energy indicators were used to evaluate the system performance. Adding a storage device to the system resulted in lower peak loads. Furthermore, a multi-storage system outperformed a single water tank storage system of the same capacity, mostly due to its added flexibility.

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