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Techno-economic analysis of implementing thermal storage for peak load shaving in a campus district heating system with waste heat from the data centre

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Abstract. Peak load has significant impacts on the economic and environmental performance of district heating systems. Future sustainable district heating systems will integrate thermal storages and renewables to shave their peak heat demand from traditional heat sources. This article analysed the techno-economic potential of implementing thermal storage for peak load shaving, especially for the district heating systems with waste heat recovery. A campus district heating system in Norway was chosen as the case study. The system takes advantage of the waste heat from the campus data centre. Currently, about 20% of the heating bill is paid for the peak load, and a mismatch between the available waste heat and heat demand was detected. The results showed that introducing water tank thermal storage brought significant effects on peak load shaving and waste heat recovery. Those effects saved up to 112 000 EUR heating bills annually, and the heating bill paid for the peak load could be reduced by 15%. Meanwhile, with the optimal sizing and operation, the payback period of the water tank could be decreased to 13 years. Findings from this study might help the heat users to evaluate the economic feasibility of introducing thermal storage.

1 Introduction

Peak load has significant impacts on a district heating (DH) system. Firstly, a higher peak load means more investment, since larger capacity heat sources and distribution systems are demanded [1]. Secondly, peak load causes higher operation cost, since the energy price for the peak load heat sources is usually higher than the basic load heat sources. Finally, DH systems with higher peak loads tend to be less environmentally friendly, since the peak load is usually supplied by non-renewable energies, meaning an increase in the CO_2 emission per unit of heat. Therefore, DH companies try to encourage heat users to decrease their peak load by providing incentives on heating bills. When considering the peak load, the heating bill may be divided into two parts: fixed and variable. The fixed part is charged based on the seasonal peak load and may consist of a significant part of the total heating bill [2].

Introducing thermal storages (TSs) is a straightforward way for heat users to decrease their peak load and gain economic benefits. Previous studies show it is economically feasible to introduce TSs into DH systems [3-8]. However, these TSs are used for storing the free heat (e.g., solar thermal energy), not for shaving the peak load. Some researchers demonstrate the economic feasibility of using TSs for load shifting [9-11]. However, the load referred to electricity load, and these TSs were applied to the building's level instead of the district level. There is a limited study to analyse the economic feasibility of using TSs for peak load shaving in DH systems. This study aimed to investigate the economically feasible to use TS for peak load shaving in DH systems. A campus DH system in Norway was chosen as the case study. Water tank (WT) systems with storage capacities ranged from two hours to one week were proposed. The energy and economic performance of the proposed WT systems were investigated.

2 Method

This study was conducted through numerical experiments. Firstly, a campus DH system in Norway was introduced as the case study. The system suffered from the high proportion of heating bill paid for the peak load, meanwhile, part of heat supply was lost due to the mismatch between waste heat feed-in and building heat demand. WTs were applied as the short-term TS to solve the above problems and the WTs' storage capacities range from two hours to one week. Afterwards, the way to achieve the optimal operation with the minimized peak load and heat loss was illustrated. Finally, the method to calculate the heating bill was described. Detailed information about the method is introduced as follows.

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2.1 Case study

A campus DH system in Trondheim, Norway, was chosen as the case study. The topology of the system is presented in Figure 1. The total campus building area is about 300 000 m^2, and the main building functions are education, office, laboratory, and sports. Currently, heat is delivered from the main substation (MS) and the data centre (DC). The MS obtains heat from the city DH system, and the DC recovers condensing heat from its cooling system. According to the measurements from June 2017 to May 2018, the total heat supply was 32.8 GWh. About 75% of the heat supply came from the MS and the other 25% came from DC. The measured heat use and heat supply from DC are presented in Figure 2.

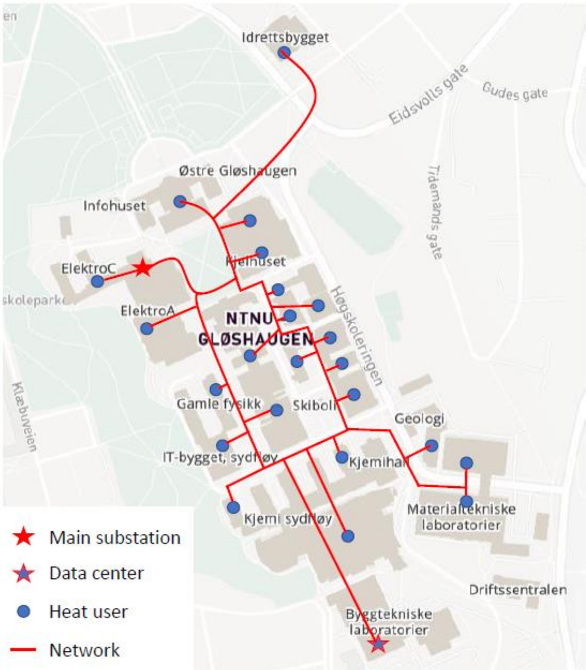

Figure 1. DH system of the university campus.

The main motivation for introducing a TS system was to reduce the heating bill. As mentioned in Section 1, a heating bill is divided into two parts: fixed and variable. The fixed part is related to the seasonal peak load (in kW). The variable part is charged based on the amount of heat use (in kWh). For the year 2017-2018, about 1.94 million EUR was paid for the heating bill, and 20% of it came from the fixed part, which was caused by the peak load. The heating bill paid for the peak load even dominated the total heating bill during the warm period from May to September. The average heating bill paid for the fixed part during this period was about eight times higher than the corresponding value for the variable part. Introducing a TS system is a straightforward way to shave the peak load and reduced the heating bill.

Another motivation for this work was to solve the mismatch between the waste heat feed-in and the building heat demand. According to the measurements, a mismatch between waste heat feed-in and building heat demand was observed during the warm period. The heat demand in warm periods came only from the domestic hot water system, and it showed an apparent daily fluctuation from 0.3 to 2.1 MW, while the amount of waste heat feed-in from the DC kept at a constant level, about 0.9 MW. Therefore, during the peak hours, the amount of waste heat feed-in was not enough to satisfy the heat demand, and the deficit would be supplemented by the MS. During the low demand hours, the amount of waste heat feed-in was higher than the demand, and the excess waste heat feed-in would become reverse heat flow to the city DH system. However, the university campus did not get any economic benefit from this reverse heat flow, because the local DH company has not yet adopted a method for charging the heating bill with bidirectional heat flow.

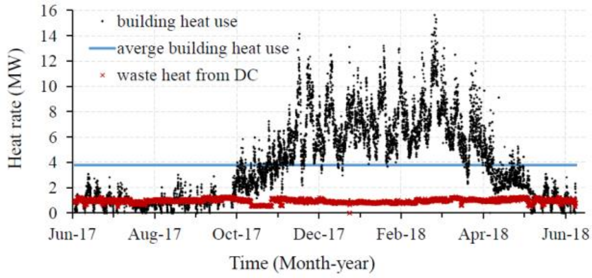

Figure 2. Building heat use and waste heat feed-in during the year 2017-2018.

2.2 Principles of WT sizing

In this study, the WT was chosen due to its easy application in different conditions. The simplified schematic of the campus DH system after integrating a WT system is illustrated in Figure 3. Before the economic study, the sizing of the WT was conducted and the operation strategy of the DH system was made.

The WT was sized based on the duration of the heat supply. The annual average building heat use was 3.79 MW. The storage capacity of the WT was quantified according to the heat supply at this heat flow rate. For example, if the WT was sized with two hours' capacity, it meant that the WT system could supply heat continuously for two hours with a discharging rate of 3.79 MW. In this study, the WT functioned as the short-term TS, and the investigated storage capacity ranged from two hours to one week. The detailed information on the WT sizing analysis is given in Table 1.

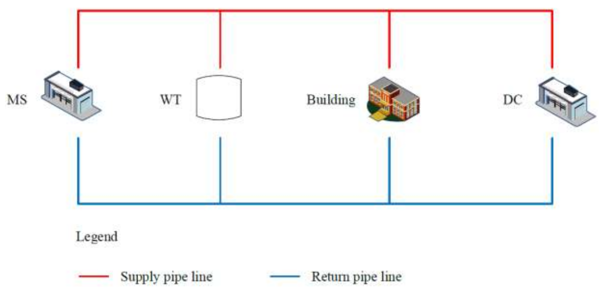

Figure 3. Schematic of the campus DH system after integrating a WT system.

Table 1. Information on the studied WTs.

Abbreviation	Sizing (m^3)
2h	163
4h	325
12h	975
1d	1 950
2d	3 900
3d	5 850
5d	9 750
1w	13 650

2.3 Operation strategy for the DH system with the WT

For the operation of the DH system, optimization was conducted to fully explore the potential of the WT system. An optimization problem was formulated to minimize the peak load and heat loss, the defined problem is presented as follows:

$$min \int \dot{Q}_{MS}{}^{2}\, dt \quad (1)$$

subject to

$$\dot{Q}_{MS} + \dot{Q}_{DC} - \dot{Q}_{WT} - \dot{Q}_{buil} = 0 \quad (2)$$

$$\dot{Q}_{WT} - \dot{Q}_{loss} - c \cdot \rho \cdot V_{WT} \cdot \frac{dT_{WT}}{dt} = 0 \quad (3)$$

$$\dot{Q}_{loss} = U_{WT} \cdot A_{WT} \cdot (T_{WT} - T_{envi}) \quad (4)$$

$$\dot{Q}_{up} = c \cdot \dot{m}_{char} \cdot \nabla T_{char} \quad (5)$$

$$\dot{Q}_{low} = c \cdot \dot{m}_{disc} \cdot \nabla T_{disc} \quad (6)$$

$$T_{low} \leq T_{WT} \leq T_{up} \quad (7)$$

$$\dot{Q}_{low} \leq \dot{Q}_{WT} \leq \dot{Q}_{up} \quad (8)$$

where $\dot{Q}_{MS}$ is the heat supply rate (positive value) or heat loss rate (negative value) from the MS. $\dot{Q}_{DC}$ is the waste heat feed-in from DC. $\dot{Q}_{WT}$ is the charging (positive value) or discharging (negative value) heat flow rate of the WT. $\dot{Q}_{low}$ and $\dot{Q}_{up}$ are the lower and the upper limit of $\dot{Q}_{WT}$. $\dot{Q}_{buil}$ is the heat use of the buildings at the campus. $\dot{Q}_{loss}$ is the heat loss from the WT to the environment. T_{WT} is the water temperature in the WT. T_{low} and T_{up} are the lower and the upper limit of T_{WT}. For these limits, the values of 40°C and 80°C were chosen, respectively. ∇T_{disc} and ∇T_{char} are the maximum temperature difference during the discharging and charging processes. The values of -40K and 40K were chosen, respectively. U_{WT} is the U-value of the WT walls. T_{envi} is the temperature of the environment. c is the specific heat capacity of water, of 4 187 J/(K·kg). ρ is the water density, of 995.6 kg/m^3.

2.4 Method for the DH heating bill calculation

As mentioned in the introduction, the heating bill includes usually two parts: the fixed and the variable, defined as follows:

$$B_{tot} = B_{fix} + B_{var} \quad (9)$$

where B_{tot} is the total heating bill, B_{fix} is the fixed part, and B_{var} is the variable part.

The fixed part was calculated as:

$$B_{fix} = \dot{Q}_{peak} \cdot p_{fix} \quad (10)$$

where $\dot{Q}_{peak}$ is the peak load, which is obtained by averaging the top three highest daily average heat uses. p_{fix} is the unit fixed cost, which was given by the local DH company Statkraft Varme [12] in Trondheim.

The variable part was calculated as:

$$B_{var} = \int \dot{Q} \cdot p_{var}\, dt \quad (11)$$

where $\dot{Q}$ is the heat demand. p_{var} is the variable heat price, which was given by the local DH company Statkraft Varme [12] in Trondheim.

3 Results

In this section, the reference scenario (Ref) without any TS together with the scenarios with the WT are investigated. The heat use and heating bill of these scenarios are presented. The peak load shaving, heating bill saving, and payback periods of the scenarios with the WT are analyzed. Detailed information about the results is presented as follows.

3.1 Peak load shaving and heat use saving

The peak load shaving and heat loss reduction could be derived from the difference between the heat demand of the reference scenario and the heat demand of the scenarios with the WT. The heat demand referred to the heat supply from the MS. Please note that the negative value meant the reverse heat flow to the city DH system, meaning the heat loss of the campus DH system. The results showed that introducing a WT could bring significant peak load shaving and heat loss reduction. Figure 4 gives an example of the impacts after introducing a WT with one day's capacity. As illustrated in Figure 4, the *Ref* scenario had higher peak loads compared with scenario *1d*. The peak load shaving effect was up to 3.3 MW, and it accounted for 23% of the annual maximum heat load. In addition, heat loss existed for the scenario *Ref* during the warm period from May to September. In contrast, the heat loss was almost eliminated for scenario *1d*. The annual heat loss reduction was about 362 MWh, which meant 82% of the heat loss was avoided.

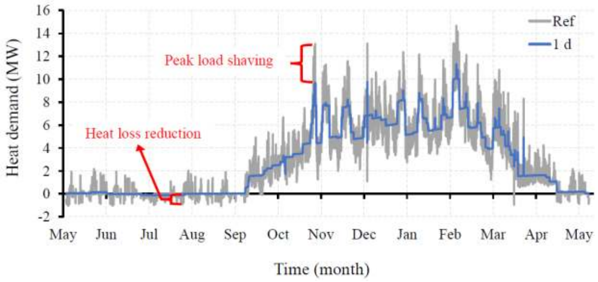

Figure 4. Example of peak load shaving and heat loss reduction after introducing WT.

The seasonal peak load shaving effect of the scenarios with the WT is presented in Figure 5. From Figure 5, it may be observed that the larger WT brought higher seasonal peak load shaving. For the scenario *2h* when the storage capacity was two hours, the seasonal peak load shaving was 10 kW in the winter season and 5 kW in the summer season, see Figure 5 the column filled with the black colour. For scenario *1w* when the storage capacity increased to one week, the corresponding reduction increased to 3.2 MW and 2.2 MW, respectively, see Figure 5 the column filled with the red colour.

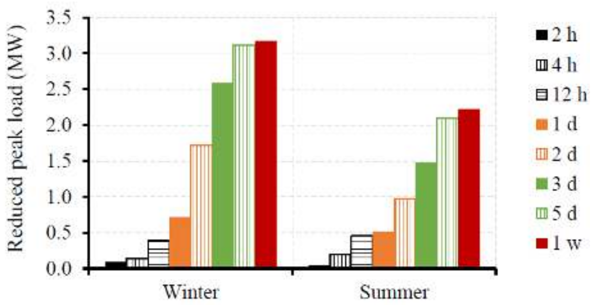

Figure 5. Seasonal peak load shaving for the scenarios with different storage capacity.

The heat demand saving effect of the scenarios with the WT is presented in Figure 6. From Figure 6, it can be observed that the scenario *1d* with one day's storage capacity showed the best performance regarding heat demand saving. The reason was that the total heat loss was minimized for scenario *1d*. The total heat loss included two parts: the heat loss through the MS (reverse heat flow to the central DH system), and the heat loss from the WT to the environment. The larger WT reduced the heat loss from the MS because the short-term mismatch between the waste heat feed-in and building heat demand could be relieved. However, the larger WT suffered from more heat loss to the environment, because of the larger heat transfer area. The size of the WT in scenario *1d* was at the optimal point considering these two parts of heat loss.

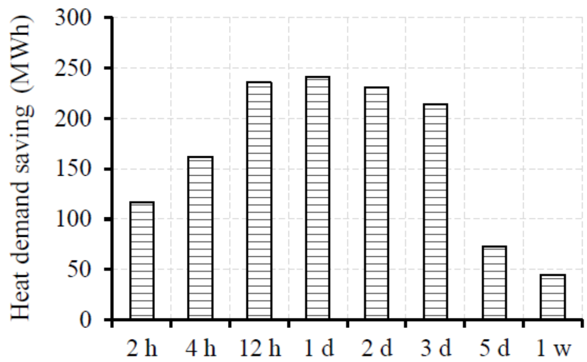

Figure 6. Heat demand saving for scenarios with different storage capacity.

3.2 Heating bill saving and payback period

The heating bill considering the share between the fixed and variable parts for the proposed scenarios is presented in Figure 7. The two impacts could be observed due to introducing the WT: 1) the total heating bill was decreased, 2) the share of the fixed part in the total heating bill was reduced. For the reference scenario *Ref*, the total bill was 1.94 million EUR, and 20% of it came from the fixed part. After introducing the WT system, the total bill could decrease to 1.83 million EUR, and only 15% of it came from the fixed part.

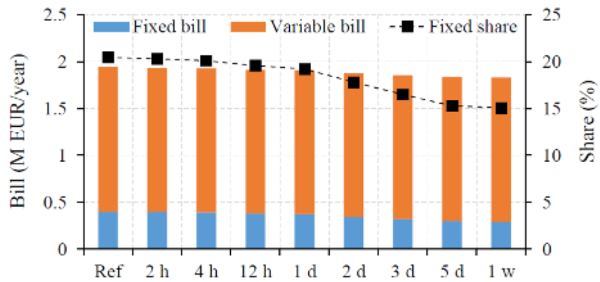

Figure 7. Annual heating billing for the scenarios before and after introducing a WT system.

The detailed information on heating bill saving is presented in Figure 8. The saving from the fixed part increased as the storage capacity increased, as shown in Figure 8. The reason was that larger WT brought higher seasonal peak load reduction. The variable part of the heating bill achieved a higher saving for the scenarios with medium storage capacities, as shown in Figure 8. This can be explained by the higher heat demand saving for those scenarios with medium storage capacities.

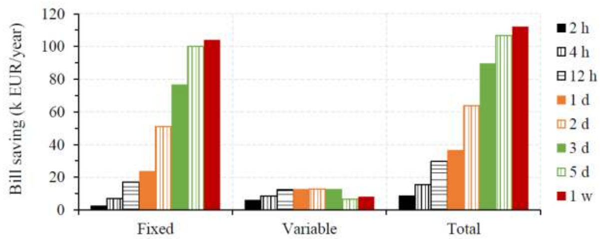

Figure 8. Annual heating billing saving for the scenarios after introducing a WT system.

The payback periods for the scenarios with different storage capacities are presented in Figure 9. As shown in Figure 9, the payback periods ranged from 13 years to 19 years. Further, the two optimal WT sizes could be observed: the storage capacities with four hours and three days. The payback periods of the WT may be explained by the indicator *unit bill saving*, which was obtained by dividing the heating bill saving by the WT size. As shown in Figure 10, the value of *unit bill saving* ranged from 8 EUR/m^3 to 55 EUR/m^3, it decreased as the WT size increased. This meant the larger WT had less heating bill saving effect. A two order polynomial trend line could be drawn to show the relationship between the unit bill saving and the WT size. The WT capacity with the unit bill saving above the trend line tended to have shorter payback periods, see Figure 10 the dots filled with the red colour. In contrast, the WT capacity with the unit bill saving below the trend line tended to have longer payback periods, see Figure 10 the dots filled with the black colour.

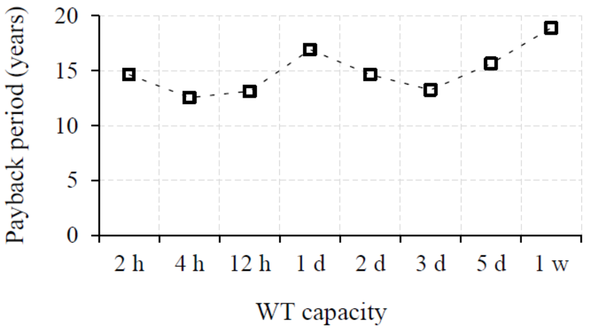

Figure 9. The payback period for the scenarios with different storage capacity.

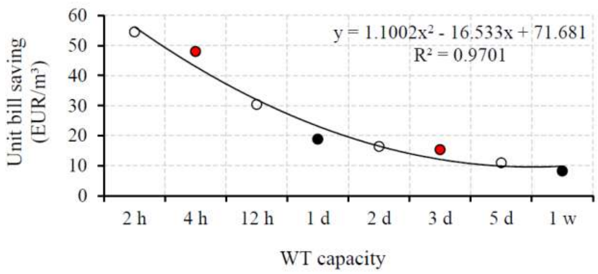

Figure 10. Unit heating bill saving for the scenarios with different storage capacity.

4 Conclusions

In this study, the economic analysis of using WT for peak load shaving in a DH system with waste heat feed-in was conducted. A campus DH system in Norway was chosen as the case study. WTs with storage capacities ranged from two hours to one week were tested. The peak load shaving, heat use saving, heating bill saving, and payback period for the WT system were investigated.

The results showed that WT had significant effects on peak load shaving and heat use saving. Those effects brought up to 112k EUR annual heating bill saving, which accounted for 6% of the total heating bill. Meanwhile, the payback periods of WT ranged from 13 years to 19 years.

Finding from this study may help heat users to evaluate the economic feasibility of introducing a WT system.

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