Thermal energy storage for data centre waste heat recovery in district heating systems

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Abstract: A single data centre may consume as much electricity as a small city. Most of this electricity use will be converted into waste heat that is emitted into the environment. Recent studies have found that there is tremendous potential for using data centre waste heat for district heating (DH). Meanwhile, pilot projects being conducted around Europe have demonstrated the technical and financial feasibility of this concept. However, using data centre waste heat for DH systems still has a lot of space for improvement. Firstly, temporal mismatches between the data centre waste heat supply and DH heat demand usually exist. These mismatches result in surplus waste heat, which still needs to be emitted into the environment. Secondly, DH systems usually use fossil fuels to cover peak heat demand, meaning higher operating costs and more emissions at peak hours. To achieve better economic and environmental performance, the non-dispatchable waste heat supply should be shifted for peak load shaving. This article aimed to solve these problems by introducing thermal energy storage (TES). Three TES solutions were proposed, including a short-term water tank TES, a seasonal borehole TES, and both the short-term water tank and seasonal borehole TES, respectively. Detailed Modelica models were developed for these TES scenarios and a reference scenario before introducing any TES. The proposed method was tested on a campus DH system in Norway. Results showed that the water tank could shave the peak load by 30% and save the annual energy cost by 5%. The payback period was 12 years. However, it had no obvious benefits in terms of mismatch relief. In contrast, the borehole TES increased the waste heat utilization rate to 96%. However, the payback period was more than 17 years.

Keywords: District heating, thermal energy storage, waste heat recovery, data centre, heating costs

1. INTRODUCTION

One data centre can use as much electricity as a small city. Furthermore, it is estimated that the energy consumption of data centres worldwide equals that of Germany as a whole. The majority of the energy used by these data centres is converted into waste heat, resulting in a sizeable amount of waste heat that is continuously emitted into the environment all year round. One effective method for recycling data centre waste heat is for the district heating (DH) system. The DH system at the NTNU Gløshaugen campus offers a good example of this type of application. As shown in Figure 1, two heat pump units have been installed in the campus data centre to harvest waste heat and eventually reuse it to fulfil the heat demand of the campus buildings. Through the use of waste heat recovery, around 20% of the campus buildings' heating demands are met, saving NTNU about four million NOK in annual heating costs.

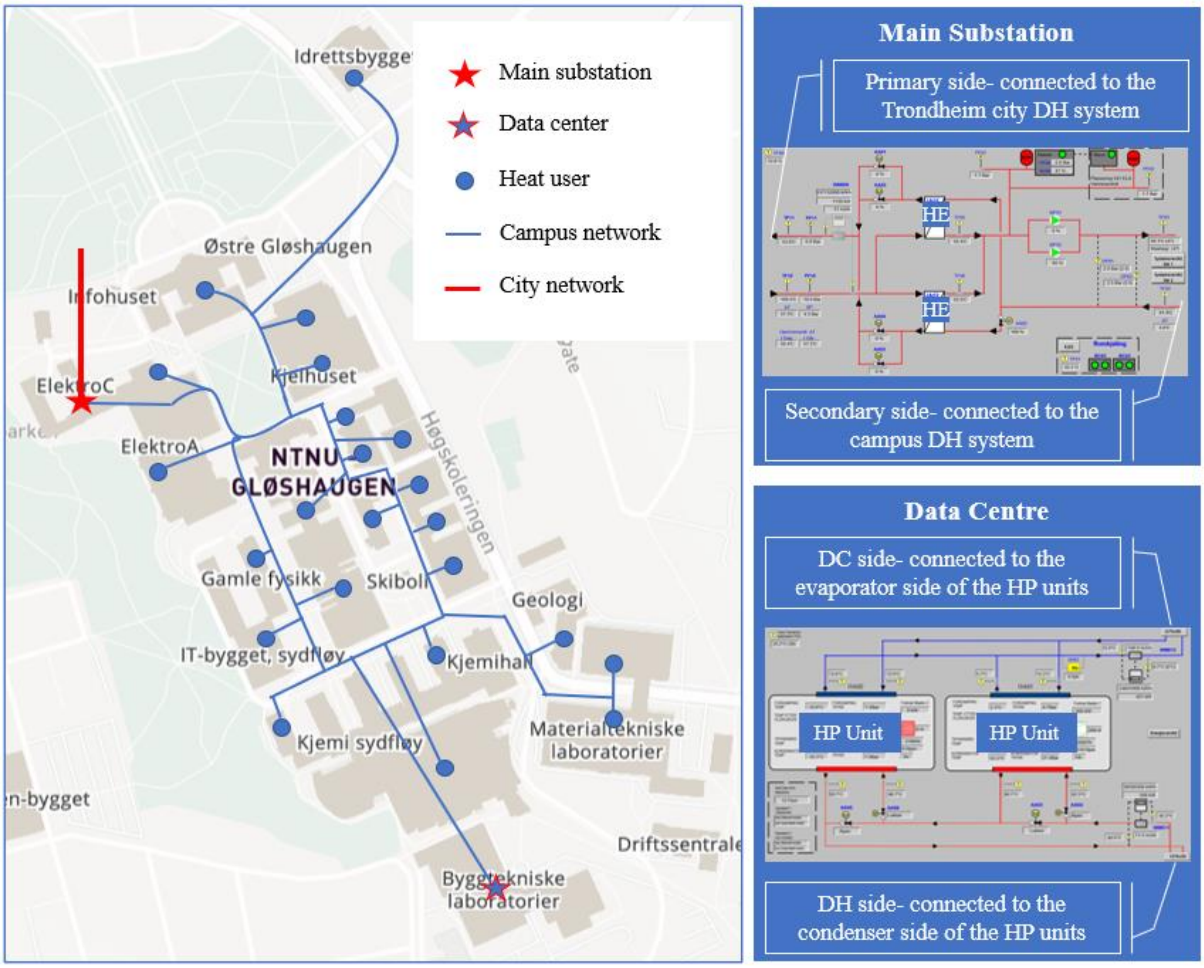

Figure 1: NTNU Gløshaugen campus DH system, the main substation connects the campus district heating system with the Trondheim city DH system by heat exchangers, meanwhile, the heat pump units recover the data centre waste heat.

The data centre waste heat recovery has a considerable positive effect on the energy system of the NTNU Gløshaugen campus in terms of energy, economy, and environment. However, there is still much room for improvement. Firstly, temporal mismatches between the data centre waste heat supply and DH heat demand usually exist. These mismatches result in surplus waste heat, which still needs to be emitted into the environment. Secondly, DH systems usually use fossil fuels to cover peak heat demand, meaning higher operating costs and more emissions at peak hours. To achieve better economic and environmental performance, the non-dispatchable waste heat supply should be shifted for peak load shaving. This study aimed to solve these problems by introducing thermal energy storage (TES). Step-by-step research is presented in this article to realize the smart design and operation of the campus DH system. In Section 2, three TES solutions were proposed, including a short-term water tank TES, a seasonal borehole TES, and both the short-term water tank and seasonal borehole TES, respectively. Moreover, Detailed Modelica models were developed for these TES scenarios and a reference scenario before introducing any TES. In Section 3, the simulation results before and after introducing TES are presented. Furthermore, conclusions are given in Section 4.

2. METHODOLOGY

Three types of candidate systems were developed to integrate TES into the campus DH systems. These candidate systems offered several TES solutions, including short-term TES, seasonal TES, and a combination of short-term and seasonal TES. Firstly, suitable TES technologies were identified through a literature review. As explained in the report from the International Energy Agency [1], the widely recognized and commonly used TES for DH systems are water tank TES, borehole TES, pit TES, and aquifer TES. In this study, the water tank was chosen as the short-term TES due to its merits such as:

- High storage efficiency with well-insulated envelopes [1].
- High performance on load shifting and peak shaving due to high charging and discharging heat flow rate [1].
- Small installation space because of the high specific heat capacity of water [1].
- Wide applicability that does not subject to geological conditions [2, 3].

Meanwhile, the borehole was chosen as the seasonal TES because of the following reasons:

- It can easily scale up its storage size to adapt to the expansion of DH systems [1].
- Low specific storage cost, especially for large-scale installations [1].
- It can be easily integrated with surroundings, e.g. being installed under playgrounds, under parks, and inside building foundations [4].

Besides the above candidate systems, a reference system that presented the situation before introducing any TES was proposed. The reference system was used as a benchmark. Figure 2 illustrates the candidate systems and the reference system. A brief description of these systems is given as follows.

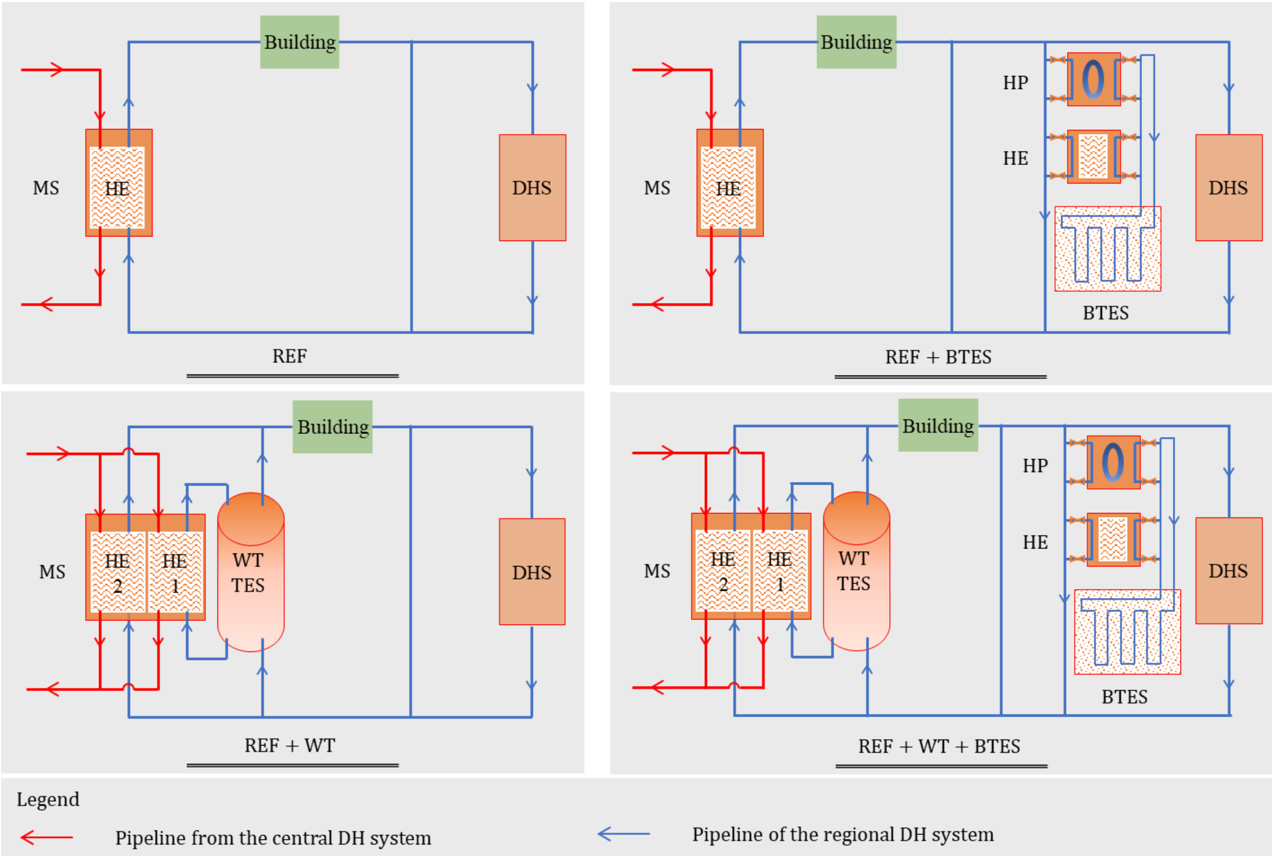

Figure 2: Schematic illustrates the candidate systems with TESs and the reference system.

The reference system REF presented the campus DH system without any TES. The key components were the main substation, data centre, and buildings. The main substation connected the campus DH system with the central city DH system, meanwhile, it separated the hydraulic conditions of these two systems. The main substation had two functions. Firstly, it supplemented the heat supply from the data centre. Secondly, it boosted the supply temperature of the campus DH system to the required level. The data centre was integrated into the campus DH system by the R2R mode, i.e., extracts the water from the return line and then feeds it back to the return line after the heating process. The R2R mode was used because it is preferable for low-temperature heat sources [5].

The candidate system REF+WT integrated a water tank TES into the reference system. The water tank functioned as the short-term TES. It aimed to relieve the mismatch between buildings' heat demand and the data centre's heat supply, meanwhile, it was serviced for the peak load shaving.

The candidate system REF+BTES integrated a borehole TES system, including a heat pump, a heat exchanger, and a borehole field, into the reference system. The borehole TES system functioned as the seasonal TES and it aimed to transfer the data centre's surplus heat from the non-heating season to the heating season. The heat exchanger was used to charge the surplus heat into the borehole field during the non-heating season, while the heat pump was used to discharge the stored heat from the borehole field during the heating season.

The candidate system REF+WT+BTES integrated both a water tank and a borehole field into the reference system. It took advantage of the two types of TES. The following functions were achieved by this system: relieving the short-term mismatch, shaving the peak load, and transferring the surplus heat from the non-heating season to the heating season.

Modelica language was chosen as the modelling language, and Dymola was selected as the modelling and simulation environment. Meanwhile, the open-source libraries Modelica Standard Library and Modelica IBPSA Library were used to build the system model. Detailed Modelica models were developed for the candidate systems and the reference. These models were obtained by connecting model components, including the main substation, buildings, data centre, water tank TES, and borehole TES. Detailed information on the modelling, operation and simulation processes are given in the article [6] and the PhD thesis [7].

3. RESULTS

This section summarizes the key findings of the research. To begin, the peak loads and energy uses of the four scenarios are compared. Following this, the results of the economic performance are investigated, assisting the analysis of the impacts of the TES solutions on the performance of the campus DH systems. More detailed results can be found in the article [6], and the economic background regarding the heating price models can also be found in the articles [8-11].

3.1. Energy performance on peak load and energy use

Figure 3 presents the heat load duration curves for the four scenarios, which are used for the analysis of the peak load. From Figure 3, it can be found that compared with the reference scenario (Ref), the scenario that introduced a water tank TES (Ref+WT) shaved the peak load significantly from 11.7 MW to 8.2 MW, a shaving of 30%.

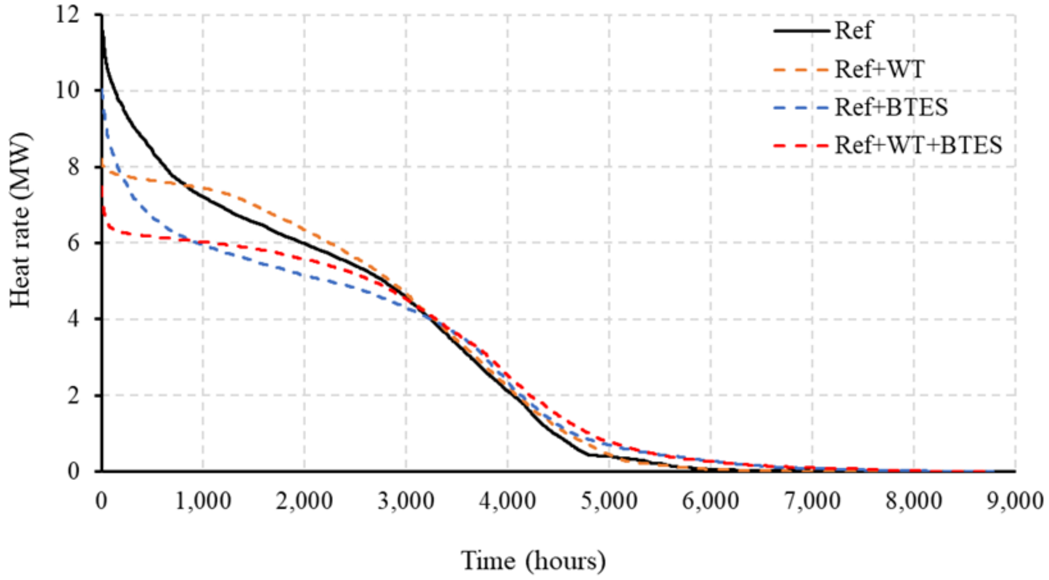

Figure 3: Heat load duration diagram for the four scenarios.

Figure 4 illustrates the energy use of the four scenarios. As shown in Figure 4, introducing a water tank TES did not bring any benefit to energy use saving, as observed that there was no obvious difference in annual heat use and electricity use between Scenario Ref+WT and Ref. In contrast, it can be found that introducing a borehole TES system reduced the annual heat use from 25.1 GWh to 22.8 GWh, a saving of 9% when comparing Scenario Ref+BTES to Scenario Ref. However, Scenario Ref+BTES achieved less peak load shaving effect than Scenario Ref+WT, with a peak load shaving of 14% from 11.7 MW to 10.0 MW. Moreover, introducing the BTES system caused an extra electricity use of 0.9 GWh per year due to the introduction of the ground source heat pump. In addition, Scenario Ref+WT+BTES achieved high performance on both the peak load shaving and heat use saving. Compared to Scenario Ref, it shaved the peak load from 11.7 MW to 7.5 MW, a shaving of 36%, which was the best peak load shaving effect among all the scenarios with TES. Meanwhile, it reduced the annual heat use from 25.1 GWh to 23.0 GWh, a saving of 9%, which was the second-best heat use saving effect after Scenario Ref+BTES. However, same as Scenario Ref+BTES, introducing the BTES system increased the annual electricity use by 0.9 GWh due to the introduction of the ground source heat pump.

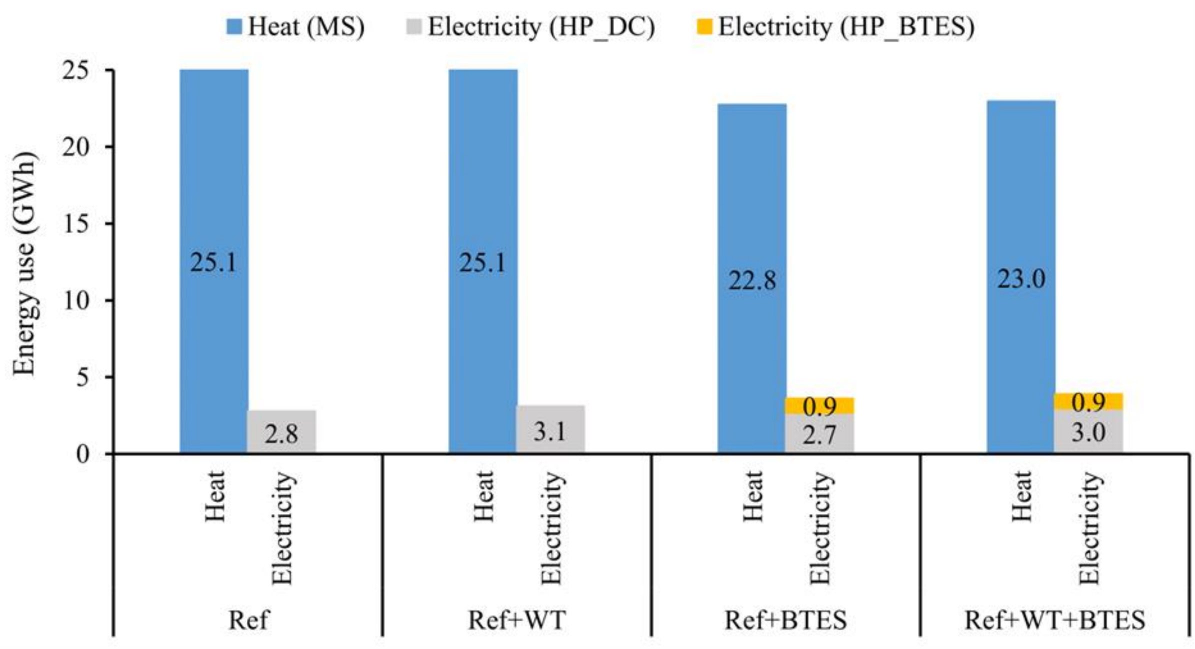

Figure 4: Annual heat and electricity use for the four scenarios.

3.2. Economic performance on energy cost and payback period

The initial investment of different TES solutions is shown in Figure 5. From Figure 5, it can be found that introducing a water tank TES had the lowest investment of 11.9 million NOK[1]. Introducing a borehole TES system would increase the investment to 18.6 million NOK, an increase of 56% compared to the water tank TES. The scenario with both the water tank TES and the borehole TES system had the highest investment of 30.6 million NOK, an increase of 156% compared to the water tank TES scenario.

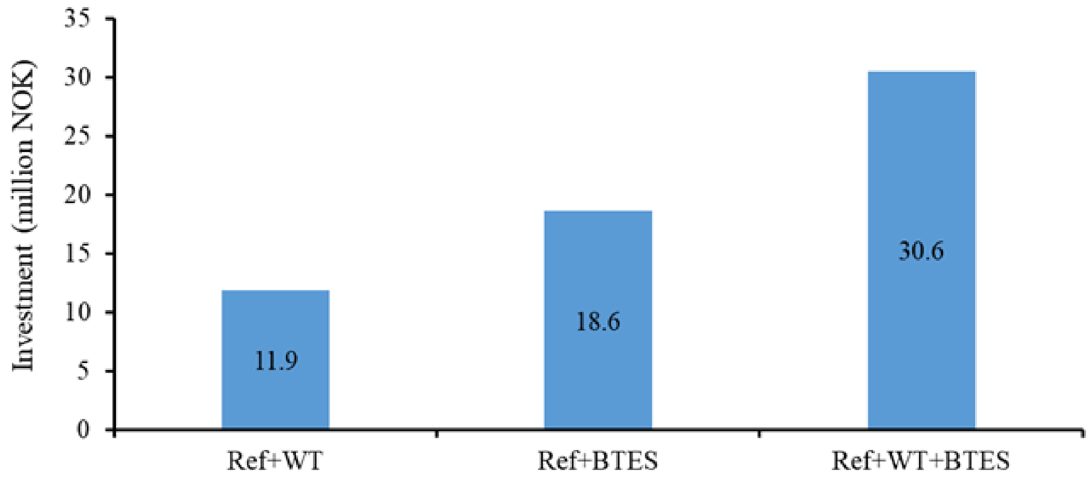

Figure 5: Investment for TES scenarios.

[1] The currency rate between NOK and EUR can be found from https://www.xe.com/, in this study 1 EUR=10 NOK.

The resulting energy bills of the four scenarios are presented in Figure 6. As shown in Figure 6, both the water tank TES and the borehole TES system could save energy bills. Scenario Ref+WT saved 5% of the annual energy bill compared to the reference scenario (Ref). This saving arose only due to the reduction of the load-related heating cost, which was brought by the peak load-shaving effect of the water tank TES. Similarly, Scenario Ref+BTES saved 6% of the annual energy bill. This bill saving came from the reduction in both the load-related and heat use-related heating cost, which was caused by the peak load shaving and mismatch relieving effects of the borehole TES system, respectively. Moreover, Scenario Ref+WT+BTES achieved the highest energy bill saving, reducing the bill by 8%, due to the full use of the advantages of both the water tank TES and the borehole TES system.

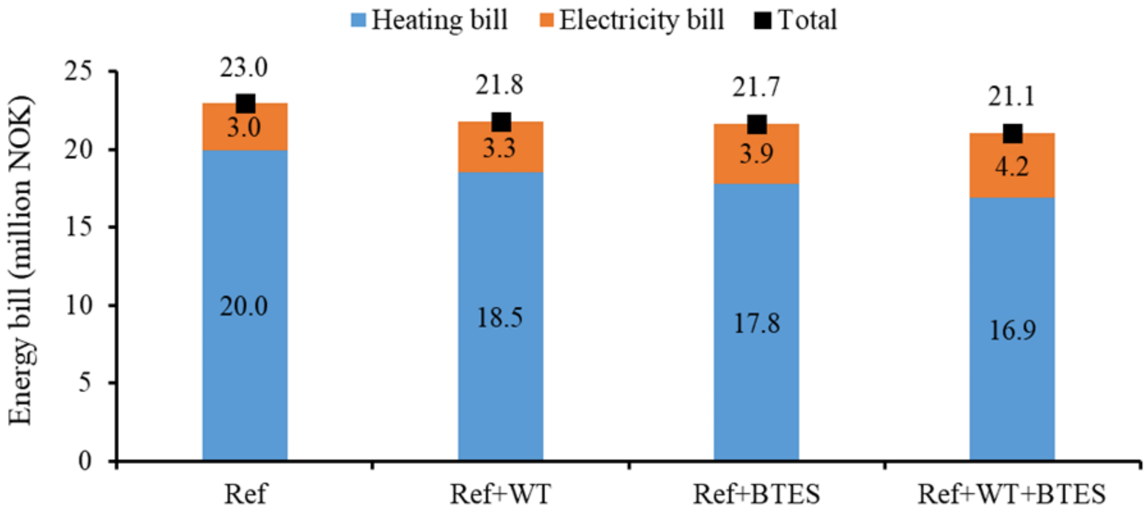

Figure 6: Annual heat and electricity bills for the four scenarios.

The payback periods for different TES solutions are shown in Figure 7. As shown in Figure 7, Scenario Ref+WT had the shortest payback period of 12 years. In contrast, Scenario Ref+BTES and Ref+WT+BTES had longer payback periods of 17 and 20 years, respectively, although they had better annual energy bill savings. These long payback periods were due to the high initial investment of the BTES system.

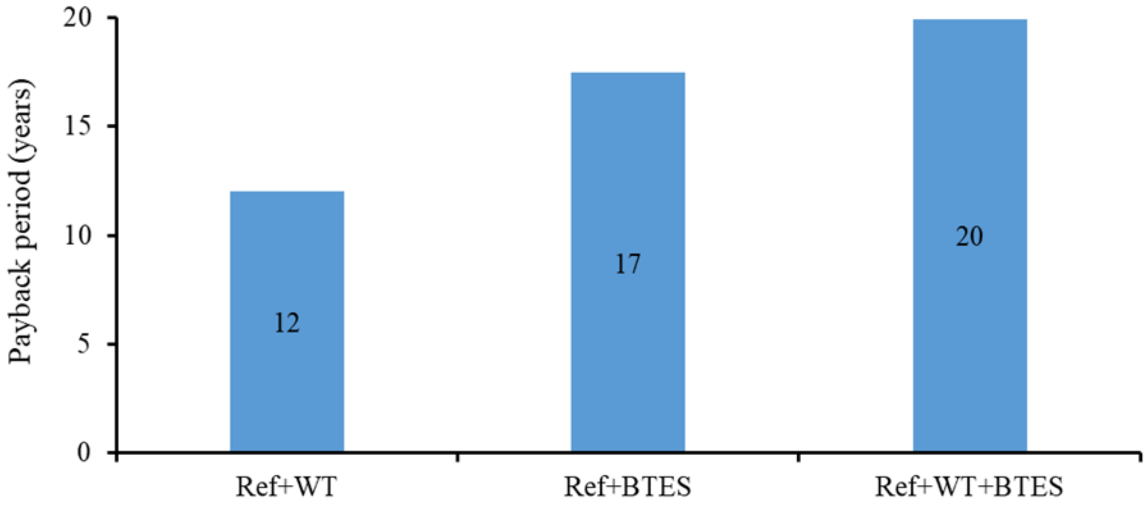

Figure 7: Payback period for the three TES scenarios.

4. CONCLUSION

Based on the above findings, the following conclusion can be reached. The superior TES solution is determined by the economic conditions as well as the economic strategies of the campus DH system. For a situation with limited investment and a propensity for a short payback period, introducing a water tank TES may be a superior TES solution. However, for a situation with ample investment and a propensity for low operating costs, introducing both a water tank TES and a borehole TES system may be a superior TES solution. Moreover, introducing a borehole TES system may be a compromised solution that could reduce the energy cost considerably, while demanding a moderate amount of investment and recovering the investment within 20 years as well.

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