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Simultaneous Optimal Operation and Design of a Thermal Energy Storage Tank for District Heating Systems with Varying Energy Source

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Abstract

District heating systems based on industrial waste heat play an important role in using energy efficiently. Combined with a thermal energy storage technology, such as pressured-water tanks, they have the potential of significantly reducing greenhouse gas emissions as well. However, installing thermal energy storage requires capital and, therefore, it is important to find an optimal design that balances the benefits of energy storage with the costs of installing such system. In this work we formulate a dynamic optimization model for designing a thermal energy storage tank based on operational conditions and apply it to a case study using historical data from a district heating system that recovers heat from an industrial plant in Norway. We found that a relatively large tank (greater than 5000 m3) would be necessary to store all excess energy provided by the plant that cannot be immediately used for the period and input data considered. However, the results can be used to investigate uncertainties and their effects on the optimal tank volume and return of investment.

Keywords: Energy systems; thermal energy storage; optimal operation; optimal design.

1. Introduction

Environmental, energetic and climate issues of today require a shift from society's fossil fuel dependency to renewable energy sources. The pace of this change must accelerate, and significant measures are taken to increase the development and use of renewable-energy-based technologies (Mirandola and Lorenzini, 2016), and environmental policies implemented by governments. For such shifted scenario, decarbonized energy system, district heating (DH) systems and thermal energy storage (TES) can play a critical role and contribute significantly to Europe's 2050 emission goals (Connolly el al., 2014). An important DH system type is those utilizing industrial waste heat; however, due to the commonly high variation of the waste heat availability, its combination with TES is of interest to further reduce the use of peak-heating sources. Pressured-water tanks are the most suitable TES technology for DH systems, yet they can be very costly and space availability may be limited (Knudsen et al., 2021).

In this work we focus on the optimal *operation and design* of a TES tank for utilization in a DH system based on waste–heat recovery. Integrating operation into the sizing problem is important, as operational conditions have a significant impact on how efficiently the waste heat is utilized, which in turn can influence the size of the TES tank. We present an approach that formulates a single nonlinear dynamic optimization problem that accounts for optimal operation and sizing simultaneously, as opposed to combined optimization/simulation-based methods previously proposed, e.g., Knudsen et al., 2021; Li et al., 2021. We demonstrate this method on a historical data set from a DH plant in Norway that recovers heat from a ferrosilicon plant.

2. Case Study

We consider a case study for designing a TES tank for the heating plant of the DH system of Mo i Rana in Norway. The DH plant is located inside Mo Industry Park and receives waste heat from a ferrosilicon plant. The objective of the TES is to increase the waste-heat utilization and thereby reduce necessary peak-heating.

The DH system has 6 boilers heating up the water that is sent back to the city. Two of them use waste-heat from the industrial park and four of them are peak-heating boilers. They run primarily on electricity or CO-gas as energy source, the latter being a by-product from a manganese plant in the industry park and thus with varying availability. Since today waste-heat availability does not exactly match demand, excess heat is dumped, and deficit heat is supplied by the peak-heat boilers. Figure 1 shows a simplified diagram of the process with a TES tank; the waste-heat boilers (WHB) and peak-heat boilers (PHB) are lumped together and represented as one unit. Nodes A and B represent split or merging of the main water flow, depending on whether the TES tank is charging or discharging, since there is no variation of volume in the TES tank. A description of the variables is presented in the Modelling section.

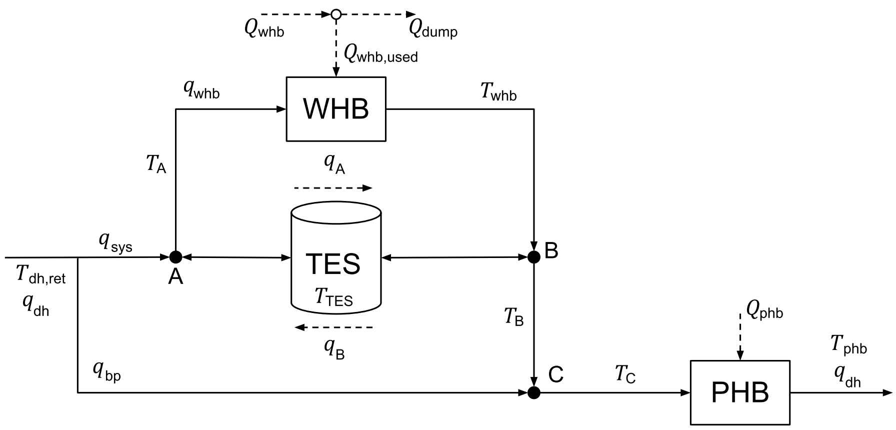

Figure 1. Flow diagram of the DH system of Mo i Rana.

2.1. Historical Data

For this case study, we selected March of 2019 as a representative month in which waste-heat availability oscillates from shortage to excess when compared against the heat demand from the city, as seen in Figure 2. This behaviour, usually seen during the transition months between summer and winter, has a potential for short-term savings, as opposed to long periods of shortage (winter) or excess (summer) of heat availability that would require long-term storage. From the DH system, we also have given the return and supply temperatures and mass flow rate of water for every hour available as input data; the temperatures are shown in the top Figure 3.

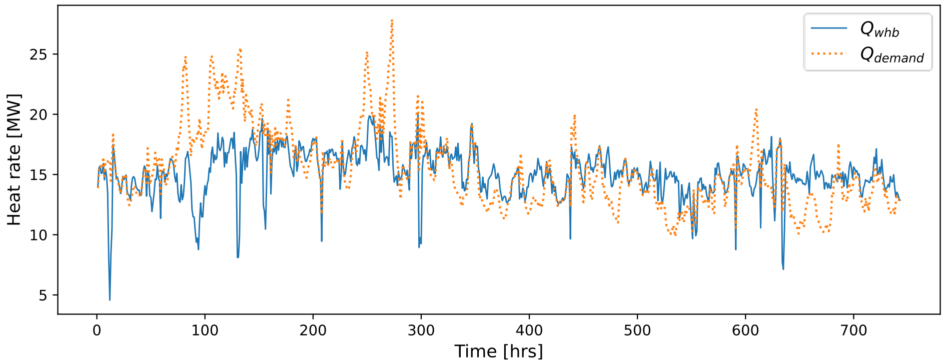

Figure 2. Historical waste-heat and heat demand data from Mo i Rana district heating system for March 2019.

3. Methodology

We formulate an optimization model to obtain the optimal volume of a TES tank for the Mo i Rana DH system taking operational conditions into account. For that, we need mass and energy balances of the process, as well as operational and cost functions that can be minimized to express our main goal. The mass and energy balances act as constraints in the model and are as follows

$$q_{\mathrm{dh}}(t) - q_{\mathrm{sys}}(t) - q_{\mathrm{bp}}(t) = 0 \tag{1a}$$

$$q_{\mathrm{sys}}(t) - q_{\mathrm{whb}}(t) - q_{\mathrm{A}}(t) + q_{\mathrm{B}}(t) = 0 \tag{1b}$$

$$q_{\mathrm{sys}}(t) C_p T_{\mathrm{dh,ret}}(t) + q_B(t) C_p T_{\mathrm{TES}}(t) - q_{\mathrm{whb}}(t) C_p T_A(t) - q_A(t) C_p T_A(t) = 0 \tag{1c}$$

$$q_{\mathrm{whb}}(t) C_p T_{\mathrm{whb}}(t) + q_A(t) C_p T_{\mathrm{TES}}(t) - q_{\mathrm{sys}}(t) C_p T_B(t) - q_B(t) C_p T_B(t) = 0 \tag{1d}$$

$$q_{\mathrm{bp}}(t) C_p T_{\mathrm{dh,ret}}(t) + q_{\mathrm{sys}}(t) C_p T_B(t) - q_{\mathrm{dh}}(t) C_p T_C(t) = 0 \tag{1e}$$

$$Q_{\mathrm{phb}}(t) - q_{\mathrm{dh}}(t) C_p \left(T_{\mathrm{phb}}(t) - T_C(t)\right) = 0 \tag{1f}$$

$$Q_{\mathrm{whb,used}}(t) - q_{\mathrm{whb}}(t) C_p \left(T_{\mathrm{whb}}(t) - T_A(t)\right) = 0 \tag{1g}$$

$$Q_{\mathrm{whb}}(t) - Q_{\mathrm{whb,used}}(t) - Q_{\mathrm{dump}}(t) = 0 \tag{1h}$$

$$\frac{d}{dt}\left(\rho V_{\mathrm{TES}} C_p T_{\mathrm{TES}}(t)\right) = q_A(t) C_p \left(T_{\mathrm{TES}}(t) - T_A(t)\right) - q_B(t) C_p \left(T_{\mathrm{TES}}(t) - T_B(t)\right) \tag{1i}$$

where $q_.$ are flow rates in kg/s, $T_.$ corresponds to the temperature at the outlet of the subscript reference in °C, C_p is the specific heat capacity of the water in kJ/(kgK), $Q_.$ are heat rates in W, ρ is the density of the water in kg/m^3, and V_{TES} is the volume of the TES tank in m^3. It is important to point out that q_A and q_B correspond to the same flow but in opposite direction. For example, when the TES tank is charging, $q_B > 0$ and q_A must be zero, and vice versa. If we enforced this condition in the optimization model, we would get a mathematical program with complementarity constraints, which is a class of nonconvex optimization models that can be particularly challenging to solve. To avoid that, we rely on information we have available; we enforce that, if the waste-heat available is higher than the city demand, then the tank can only be charged, i.e., $q_A = 0$ while q_B is a free positive variable. The opposite is also added as constraint to the model.

For the operational term in the objective function, we choose to minimize dumped waste-heat that could be later used during periods of low waste-heat availability. Peak-heat use, which we also wish to minimize, is considered in operational costs. The economic term in the objective function to be minimized is the payback period since it is one of the most relevant economic aspects in designing a tank. It relates both investment and operational costs, allowing for one term to account for them simultaneously and avoiding tuning separate weights.

The dynamic optimization model is then given by

$$\min_{q, V_{\text{TES}}} \quad N + C \int_0^T Q_{\text{dump}}(t) dt + 10^{-7} \int_0^T q_{\text{whb}} dt + 10^{-5} \int_0^T q_{\text{bp}} dt \tag{2a}$$

$$\text{s.t.} \quad N = \frac{ln(S/(S - I\{V\}r))}{ln(1+r)} \tag{2b}$$

$$S = n\, C \int_0^T \left(Q_{\text{phb,noTES}}(t) - Q_{\text{phb}}(t) \right) dt \tag{2c}$$

$$I(V) = 4.7 V^{0.6218} \tag{2d}$$

$$q_A(t) = 0 \quad \text{if } Q_{\text{whb}}(t) < Q_{\text{demand}}(t) \tag{2e}$$

$$q_B(t) = 0 \quad \text{if } Q_{\text{whb}}(t) \geq Q_{\text{demand}}(t) \tag{2f}$$

$$x_{\text{lb}} \leq x \leq x_{\text{ub}} \tag{2g}$$

The model in Eq. (1)

where N is the payback period in years, T is the total length of the considered period in hours, $I(V)$ is an expression describing initial investment cost in 10^3 euros as a function of the volume of the tank in m^3 (Li et al., 2021), r is the annual interest rate, S is financial savings in 10^3 euros/year, n is the number of representative periods in a year, C is the cost of heat composed by the price of the energy source (in this case, C_{CO} or C_{elect}) and associated tax emissions (C_{CO_2} and C_{NO_x}), x is a vector containing all variables in the model, and x_{lb} and x_{ub} are the corresponding lower and upper bounds, respectively. The extra two terms in the objective function are regularization terms, which help the solver converge to a local solution, since the flow distribution within the DH system is not necessarily unique for some Q profiles and V_{TES}. Note that, here, C is also used as a weighting parameter for the waste-heat dump term.

Eq. (2) was discretized using implicit Euler with time step of one hour and implemented in Julia using JuMP as the mathematical modelling language (Dunning et al., 2017) and IPOPT as the nonlinear programming solver (Wächter and Biegler, 2006). Table 1 shows the values of parameters and variable bounds used for the calculation.

Table 1. Parameters and variable bounds for Eq. (2) (The cost of CO-gas is confidential).

Parameter	Value	Bounds	Value
Electricity cost, C_{elect}	€ 0.087/kWh	T lower bound	40 °C
CO_2 emission tax, C_{CO_2}	€ 58.82/t CO_2	T upper bound	120 °C
NO_x emission tax, $C_{\text{NO\_x}}$	€ 2,340.9/t NO_x	$Q_{\text{whb,used}}$ upper bound	22 MW
Annual interest rate, r	5 %	Q and q lower bound	0
Initial tank temp., $T_{\text{TES}}(0)$	95 °C	q_{whb} upper bound	333 kg/s

4. Results

The results for operational conditions considering electricity and CO-gas as peak heating were the same. In both cases, the optimal volume was 6323 m^3 and Figure 3 shows some of the optimal operational conditions. The bottom plot shows peak heating and waste heat used, as well as the peak heating use without a TES tank. The total peak heating originally used during the period considered was 876.4 MWh. With the implementation of a TES tank of the optimal volume, this consumption is reduced in 48 % in total for the period. The top plot shows the TES tank, the supply temperatures to the DH system, and the corresponding return temperature. Initially during this the month, up to around 300 h, heat demand from the city is mostly greater than waste-heat supply, so the energy initially stored in the tank is consumed. Then, the TES tank temperature increases as excess waste-heat is available and reaches the maximum temperature at the end of the period.

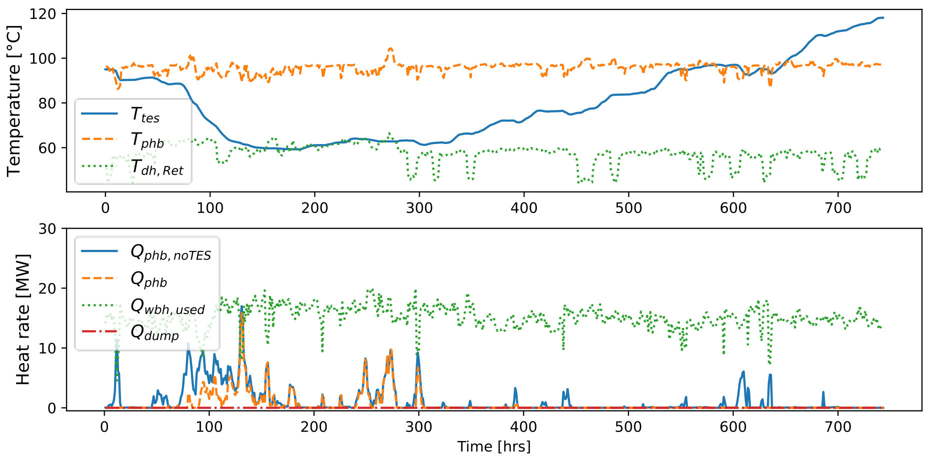

Figure 3. Optimal operation conditions for the optimal TES tank.

Regarding the economic aspect, if we consider that there are 3 months such as the representative period per year, and that the remaining months are not able to induce significant savings, the payback time for electricity as peak-heating source would be 13.7 years. Since in Norway, electricity is mainly from hydropower, the corresponding emission tax is lower. Consequently, for the case with CO-gas as peak-heating source the payback period is reduced to 12.2 years. Although these values imply large investment costs, uncertainties in the cost parameters, such as varying electricity price and emission taxes, the latter expected to increase in the next years (Klima- og Miljødepartementet, 2021), can reduce the payback time. Indeed, if the CO_2 tax is increased to the value expected by the Norwegian government in 2030, the payback time is reduced in about half for CO-gas as peak-heating source.

Since the investment cost of the TES tank is directly related to its volume, the payback period is also dependent on it. The bottom plot of Figure 3 shows that no waste heat is discarded, i.e., $Q_{\text{dump}} = 0$, and the large volume obtained for this TES tank is due to minimizing heat dump. The weighting parameter C can be seen as a cost for dumping heat and, in this case study, we used the actual cost of peak-heating. Decreasing its value could potentially allow for some excess waste-heat to be discarded, which, in turn, could reduce the tank volume. However, that would also increase peak heating and a balance should be found.

5. Conclusions and Future Work

The results show that using a single dynamic optimization model based on operation conditions can indeed be applied to design a TES tank and systematically investigate the influence of parameters subjected to uncertainties. The calculated TES tank volume for the case study is relatively large, which is a result from the selected input data (one month), and the available price parameters. For future work, we seek to apply this optimization model to a longer horizon that can comprehend an entire season and find a systematic approach to balance storing enough heat to obtain significant savings while keeping the tank as small as possible to reduce investment costs.

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