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Exergoeconomic Optimization of Borehole Thermal Energy Storage in District Heating and Cooling Grids

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ABSTRACT

Detailed techno-economic assessment of Borehole Thermal Energy Storage (BTES) systems in District Heating and Cooling (DHC) grids is required for successful practical implementation of such systems. As there are many parameters that must be considered, a method has to be chosen so that all parameters affecting the combined system's performance can be assessed comprehensively and the ones with a higher impact can be identified and regulated. By utilizing the exergoeconomic analysis method, the thermoeconomic performance of different components and their interactions can be investigated. The main aim of this work is to assess the efficient integration of BTES systems into DHC grids by utilizing an exergoeconomic optimization method.

1. INTRODUCTION

In Germany, heating accounts for approximately two thirds of the end energy consumption in private households (AGEB, 2013). It is estimated that by about 2060 the amount of energy used worldwide in cooling will overtake that used in heating (Isaac and Van Vuuren, 2009). Therefore, there is a need to design efficient energy systems to supply heating and cooling loads simultaneously. The high surplus of produced heat that is generated in summer for example in cogeneration power plants, rejected heat of cooling cycles and solar thermal installations can be used for thermal purposes. To exploit this potential, the use of borehole thermal energy storage (BTES) systems has become increasingly popular in the past decades. Arrays of borehole heat exchangers (BHEs) are suitable thermal storages for fluctuating renewable energy sources and waste heat from industrial processes (Schulte et al., 2016).

An energy carrier's exergy is defined by its potential to interact with its environment. (Bejan et al. 2016). Exergoeconomics is the branch of engineering that combines exergy analysis and economic principles. It can provide information to a system designer which are not available through conventional energy analysis and economic evaluations, but crucial to the design and operation of a cost-effective system (Bejan et al.,1996). Because of the seasonal interaction of BTES systems with their environment, exergoeconomic analysis of such systems can be useful for practical designs.

Exergy and exergoeconomic assessments of BTES systems have been mainly conducted using static approach (Kizilkan and Dincer, 2015). However, when a system's operating temperature is close to the reference state (like in BTES-assisted heating and cooling system), the static approach cannot provide the required results and the utilization of a dynamic approach is necessary. Consequently, a dynamic exergoeconomic method allows for a comprehensive assessment of all parameters affecting the system's performance and enables the identification and regulation of relevant parameters regarding an improvement of the system.

2. METODOLOGY

2.1 Case study setup

To carry out the conceptual design, campus Lichtwiese of TU Darmstadt is considered as a case study. The supply and return temperatures of the district heating grid are given as hourly data. A grid temperature level reduction of 10 °C is considered, which would be possible with small adaptations on the heat transfer systems inside the buildings (Oltmanns et al., 2018). Consequently, the district heating supply and return temperatures in heating seasons, which are used for the conceptual system design, are set to 80˚C and 45 ˚C respectively. The TU Darmstadt district cooling grid operates with supply and return temperatures of 6 ˚C and 12 ˚C. It is assumed that a BTES supplies the heating load during 6 heating months and the buildings' cooling load for another 6 months. Therefore, the design heating and cooling loads are considered 19 GWh/a and 7.6 GWh/a.

The high grid temperature difference between heating seasons and cooling seasons and the ratio of heating to cooling load β are major challenges of using of one BTES system for both needs. BTES systems which are used both for heating and cooling should have a well-balanced β. This avoids an excessive increase or decrease in the storage temperature on the long term, which would ultimately impair the efficiency for either heating or cooling. Design should be conducted so that it remains an efficient heat sink as well as heat source during cooling and heating seasons.

The conceptual system design of the proposed DHC grid for the Campus Lichtwiese case study was chosen according to ASHRAE design recommendations for heating-dominated regions with integrated BTE, which based on it the ground heat exchanger is sized to meet the cooling load and a supplemental device meets the remaining heating load. These recommendations were already successfully implemented in Ontario (Kizilkan and Dincer, 2015), so this system is used as a reference case (Fig. 1). The reference case grid temperatures are 52 °C at the supply side and 41.3 °C at the return side during heating seasons and 5.5 °C and 14 °C during cooling season respectively. The reference case conceptual design and operational temperature levels were applied to the Lichtwiese case study. The resulting system design is then further optimized with respect to the heating-cooling ratio β.

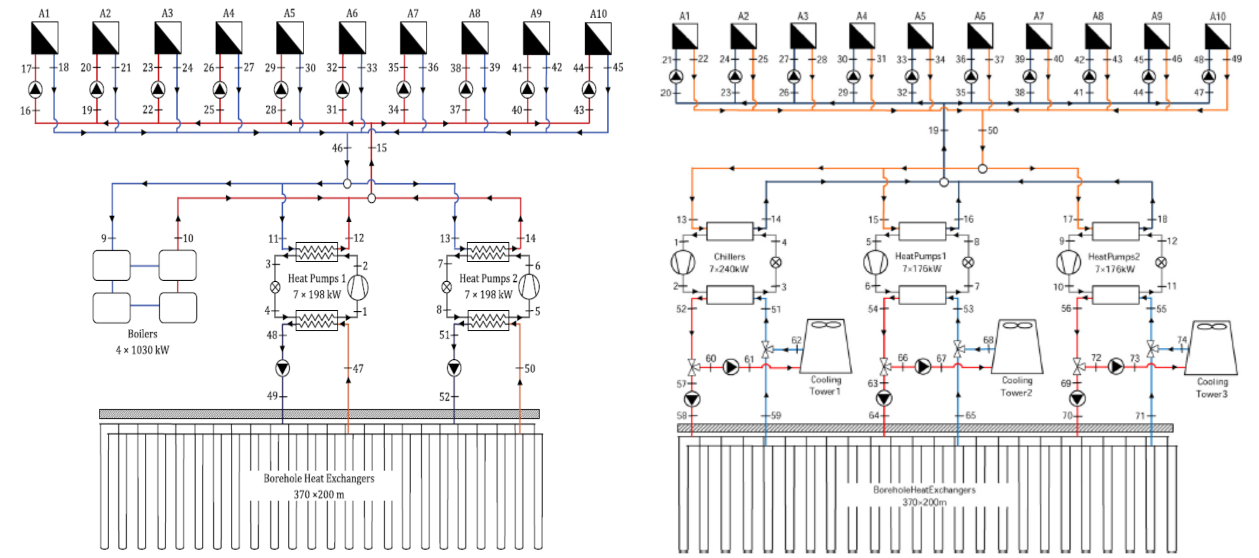

Figure 1: Reference case in heating (left) & cooling seasons (right) (Kizilkan and Dincer, 2015)

2.2 Performance analysis

2.2.1 Dynamic exergy definition

Exergy is a measure of the departure of the state of the system from that of the environment (Bejan et al., 1996). For thermal systems, this corresponds to the temperature difference between the heat carrier medium and a predefined reference temperature. The definition of this reference temperature is thus a fundamental issue in exergy analysis for thermal systems. A variation of the reference temperature does not affect the result of an exergy analysis significantly for systems with operating temperatures on a much higher level (e.g. power plants) (Rosen and Dincer, 2004). On the contrary, when operation temperatures of a system are close to the one of the reference temperature (e.g., in heating and cooling systems), the results of an exergy analysis undergoes strong variations depending on the definition of the reference environment (Torío et al., 2009). The reference temperature for a steady-state exergy analysis must be chosen as a fixed temperature, such as the seasonal mean temperature, the annual mean temperature, the design temperature, etc.(Sayadi et al., 2016). For the dynamic analysis, however, several possible reference temperatures like the indoor air temperature, the undisturbed ground temperature and the outdoor temperature are discussed (Schmidt and Torio, 2011).
Considering the mentioned features, thermal exergies of different components and overall district heating and cooling grid is calculated dynamically (Eq. 1). The dynamic exergy calculation approach of the heat pump, as one of the major components, can be seen as a sample in Fig. 2.

$$\dot{E}_j = \dot{m}c_p((T_j-T_0)-T_0\ln\frac{T}{T0}) \qquad (1)$$

Temperature	Exergy of Fuel and Product
$T_0>T_2$	$\dot{E}_p = \dot{W} + (\dot{E}_1-\dot{E}_2)$ $\dot{E}_p = (\dot{E}_4-\dot{E}_3)$
$T_1<T_0<T_2$	$\dot{E}_F = \dot{W} + \dot{E}_1$ $\dot{E}_p = \dot{E}_2 + (\dot{E}_4-\dot{E}_3)$
$T_3<T_0<T_1$	$\dot{E}_F = \dot{W}$ $\dot{E}_p = (\dot{E}_2-\dot{E}_1) + (\dot{E}_4-\dot{E}_3)$
$T_4<T_0<T_3$	$\dot{E}_F = \dot{W} + \dot{E}_3$ $\dot{E}_P = (\dot{E}_2-\dot{E}_1) + \dot{E}_4$
$T_0<T_4$	$\dot{E}_F = \dot{W} + (\dot{E}_3- \dot{E}_4)$ $\dot{E}_p= (\dot{E}_2-\dot{E}_1)$

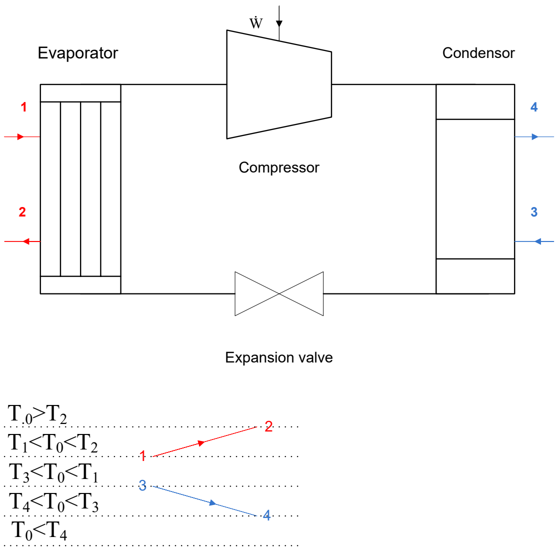

Figure 2. Dynamic exergy calculation of a heat pump

2.2.2 Exergoeconomic analysis

The exergoeconomic performance of the proposed conceptual design is assessed by its exergetic efficiency (η_{exe}) and levelized cost of supplied exergy (LCOE). The exergetic efficiency of a system is the ratio of the product exergy rate ($\dot{E}_p$) to the used fuel exergy rate ($\dot{E}_f$) (Eq. 2) (Bejan et al., 1996). The product represents the desired outputs produced by the system and the fuel represents the resources expended to generate this product (Bejan et al., 1996). The LCOE of a system is defined by the ratio of the cost associated with the product exergy of the system (C_p) to the product exergy ($E_{p,lev}$) (Eq. 3). C_p equals the total expenditures made to generate the product, namely the fuel cost per year ($\dot{C}_f$) and the cost rate associated with capital investment ($\dot{Z}^{CI}$) and operating and maintenance ($\dot{Z}^{OM}$) (Eq. 4). The system lifetime n_{end} is assumed to be 30 years and the discount rate i 10 %.

$$\eta_{exe}=\frac{\dot{E}_p}{\dot{E}_F} \tag{2}$$

$$LCOE_j=\frac{Cp}{Ep,lev} \tag{3}$$

$$C_p=\sum_{n=0}^{n_{end}}(\dot{C}_{f,n}+\dot{Z}^{CI}{}_n+\dot{Z}^{OM}{}_n).\left(\frac{1}{(1+i)^n}\right) \tag{4}$$

$$E_{p,lev}=\sum_{n=0}^{n_{end}}(\dot{E}p).\left(\frac{1}{(1+i)^n}\right) \tag{5}$$

2.3 Computational procedure

The proposed conceptual design is modeled and parameterized in TRNSYS 18 (Klein et al., 2017), Because of the standard equipment units, this software can be used for simulation of complex energy systems. The optimization is carried out using generic optimization tool, GenOpt (Wetter M., 2011). Moreover, sensitivity analysis of the most optimal solution is done using TRNedit. Figure 3 shows the overall work procedure.

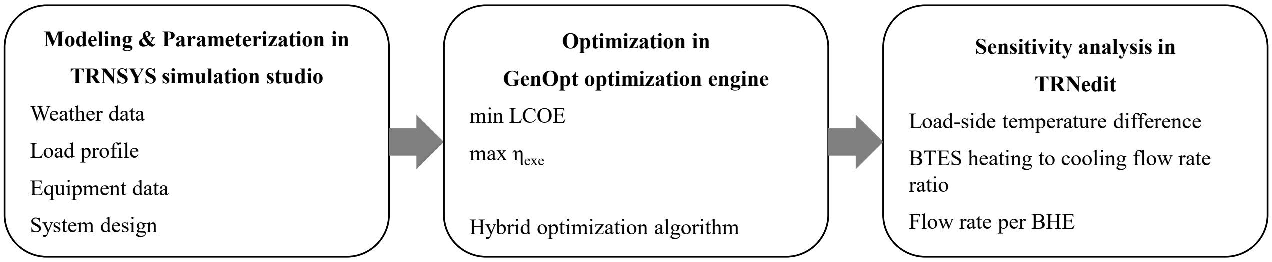

Figure 3: Computational model procedure

2.3.1 Exergoeconomic optimization

To simultaneously minimize the levelized cost of exergy product and maximize exergetic efficiency of the case study, the weighted sum method was used (Ehrgott, 2017). Considering the mentioned importance of is the ratio ß of BTES usage in heating seasons to cooling seasons, it is taken as the first optimization variable. Moreover, by keeping the length of borehole heat exchangers (L_{BHE}) constant at 200 meters, like the reference case, the number of BHEs (N_{BHE}) is considered as the second optimization variable. Other BTES parameters can be seen in Table 1.

$$\min\,(LCOE, F\eta_{exe}),\;\; F\eta_{exe}=1-\eta_{exe} \tag{6}$$
$$\text{s.t. } \beta_{min}\le\beta\le\beta_{max},\; N_{BHEmin}\le N_{BHE}\le N_{BHEmax}$$

$$\min\, WS=(1-\lambda)\,\overline{LCOE}\,(N_{BHE},\beta)+\lambda\,\overline{F\eta_{exe}}(N_{BHE},ß) \tag{7}$$
$$\text{s.t.} 1\le\beta\le 3,\; 54\le N_{BHE}\le 192$$
$$0\le\lambda\le 1$$

$\overline{LCOE}$ and $\overline{F\eta_{exe}}$ are normalized objectives and λ is the normalization weight. Generally, a normalized objective function ($\overline{f(x)}$) can be calculated as below. UT and PN are utapia and pseudo nadir points (Ehrgott, 2017).

$$\bar{f}(x)=\frac{f(x)-f(UT)}{f(PN)-f(UT)} \tag{8}$$

The optimization variables and their constrains are set according to the reference case (Kizilkan and Dincer, 2015) standards (ASHRAE, 2015). A hybrid algorithm, which combines Particle Swarm Optimization (PSO) for global search and Hooke-Jeeves Generalized Pattern Search (GPS) algorithms for local search is used to optimize the objective function using the GenOpt engine (Wetter M., 2011).

Table 1: BTES parameters

Parameter	Value	Parameter	Value
Length of BHEs	200 m	Grout thermal conductivity	2 W/(m K)
Insulation height fraction	1 %	Grout thermal capacity	1300 J/(kg K)
Number of boreholes in series	6	Outer pipe outer radius	63.5 mm
BHE type	coaxial	Outer pipe inner radius	57.9 mm
Storage heat capacity	2300000 J/(m^3K)	Inner pipe outer radius	37.5 mm
Geothermal gradient	0.03 K/m	Inner pipe inner radius	30.7 mm
Reference volume flow per BHE	4 l/s	Pipe thermal conductivity	54 W/(m K)

3. RESULTS

After running 1058 simulations by the optimization algorithm, the final optimization results consist of Pareto fronts, which are loci of the most optimal solutions (Fig. 4). To select the best possible designs, decision criteria are selected according to technical and legal limitations in standards (ASHRAE, 2015 - VDI, 2010). The most important ones include the temperature range of the heat carrier fluid returning to the borehole heat exchanger compared to the undisturbed ground temperature, minimum allowable storage temperature after one cycle of charge and discharge and maximum pump's power consumption of the ground loop as a ratio of the system total demand. Figure 5 shows the remained points after implementation of the selection criteria and the resulted new Pareto front for all simulations (red dots).

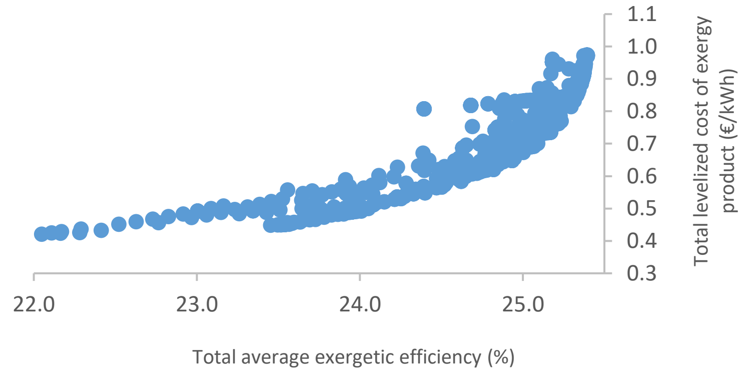

Figure 4: Initial pareto fronts

By moving from right to left in the figure, a small change in exergetic efficiency causes a large increase in cost. Consequently, the selected optimal point could be selected from the left side of the front with a β of 2.05 and N_{BHE} of 110. The green point, with a β of 1.75 and N_{BHE} of 114, is the design point of the reference case. Therefore, the proposed exergoeconomic approach can determine the reference case system design among the final points and specify more efficient designs with lower costs after implementation of all technical and practical constraints and limitations. Moreover, the higher number of β in comparison with reference case design shows that the BTES system can provide more heating load with the same amount of cooling load in comparison to the reference case design, which is in favor of heating-dominated regions and reduces the required amount of heat from other resources.

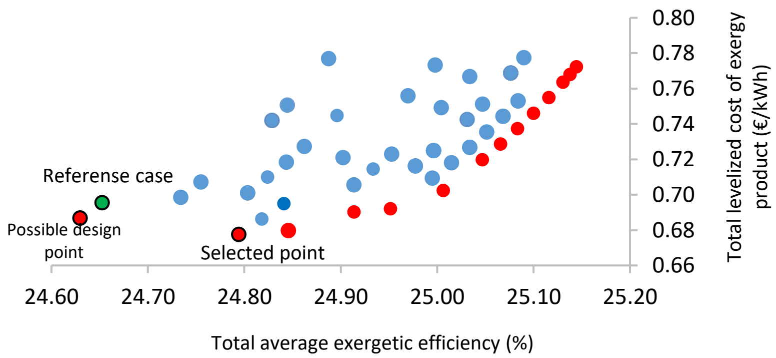

Figure 5: Possible design points

As mentioned earlier, the difference between supply and return temperatures which could be easily realized at the Campus Lichtwiese DHC grid is more than three times higher than that of the reference case in heating seasons. Consequently, effects of an increase of the temperature difference to the maximum possible amount, which still satisfies the optimal β, determined during optimization, should be investigated. Therefore, a parametric study is carried out. As it can be seen in Fig. 6, an increase of the temperature difference increases the overall exergetic efficiency while levelized costs of exergy decrease. This makes setting the operating temperature range on the maximum possible number, 20°C, reasonable. However, both heating and cooling seasonal performance factors (HSPF &CSPF) of the heat pump decrease, which necessitates the utilization of heat pumps with a higher reference temperature shift. It can be also concluded that it is not possible to supply the heating design temperature difference at the Campus with one BTES, which supplies both heating and cooling load optimally.

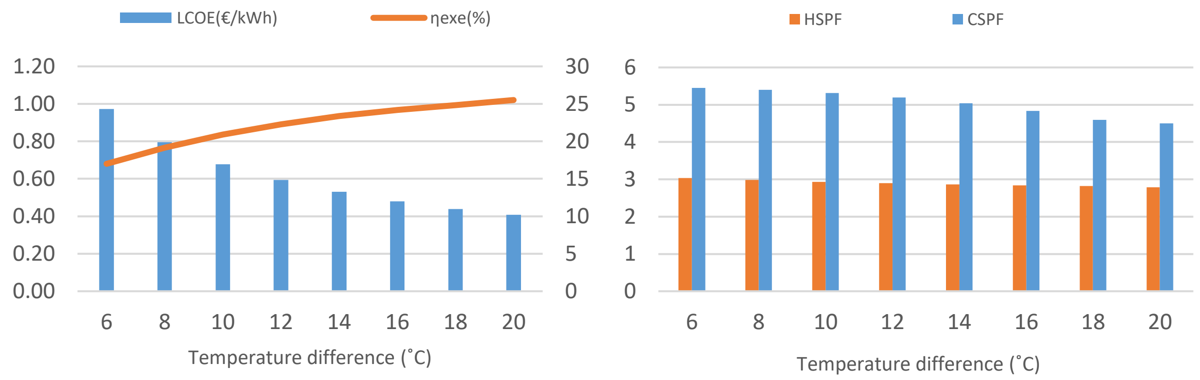

Figure 6: Effect of the difference between supply and return temperatures

In addition to the operational temperature level several parameters of BHEs, like the ratio of pump's flow rate in heating to cooling and the flow rate per heat exchanger, show to have significant effects on the system performance. To assess their impact parametric studies were conducted. As it can be seen the optimum ratio of pump's flow rate during heating and cooling season can be considered 1.4 and the flow rate of each BHE can be taken as 3 l/s.

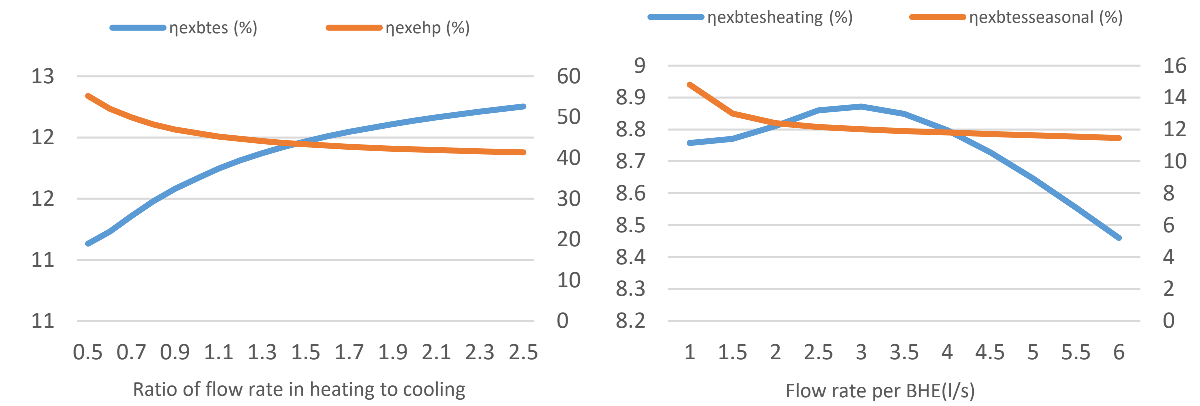

Figure 7: Sensitivity analysis of BTES operational parameters

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