Geothermal power based ULTDH for cooling and heating purposes

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Abstract. Ultra-low temperature district heating systems facilitate use of waste and renewable heat sources. The article presents a possible scheme of operation and optimisation of small ultra-low temperature district heating system consisting of waste heat source, a number of heated individual dwellings and borehole thermal energy storage plant. Optimisation performed for typical meteorological year for Kraków indicate significant potential of decreasing energy amount discharged to the environment and total length of borehole heat exchangers, compared to individual heat/cold production from low-temperature geothermal resources. Meanwhile, satisfied is a set of constrains providing borehole thermal energy storage sustainability and fulfilling entire heating and cooling demands.

1 Introduction

Sufficient heating and cooling of buildings and industrial processes becomes one of the most crucial challenges in their proper design and realisation. Even more difficult is to meet requirements using environmentally friendly systems while keeping operation economically competitive. Especially, that the area and resources are usually limited. Common solution is an individual supplying in heat and cooling. It guarantees flexibility and potentially gives independency from external suppliers (which usually is illusive or no use is made of it). Simultaneously, such a solution entails entire variety of efforts including maintenance, optimal management, risk mitigation and other. Considering narrow specialisations of companies and regarding desire of comfortable and effortless maintaining internal temperature of flats and detached houses, many owners are likely to connect their buildings to the district heating. Therefore, some efforts are made to ease using district heating network not only for heating, but also for cooling [1]. Also, heat pumps in district heating gain in importance [2]. Among solutions prospective in this context, especially placed in not very densely built areas is ultra-low-temperature district heating (ULTDH) [3].

ULTDH is system, in which supply temperature is too low to prepare sanitary hot water (SHW) without an additional heat source [4]. Thus, it has potential to be both heat source and heat sink, as temperature in the pipeline may be low enough for heat discharge from many appliances [4]. Simultaneously, decreased temperature does not need to increase pipe's diameter compared to typical medium-temperature DH, as heat pumps operation may result

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in similar temperature differences between upstream and downstream nodes. It is important to notice, that energy loss in the pipeline may be decreased in comparison with medium-temperature DH and heat boosters may be used to meet end user's requirements [5–7].

The aim of this publication is to perform test and optimisation of ULTDH operating in conditions of Kraków city in Poland and compare results with stand-alone installations covering the same heating and cooling demands.

2 Problem description

The present article is to propose ultra-low-temperature district heating system used for cooling small industrial object, space heating and sanitary hot water preparation for citizens (this solution is already described and known from real-life conditions [4]) and energy gaining/storage from borehole heat exchangers (BHE), which constitute borehole thermal energy storage (BTES) (see Fig. 1.). The energy is recovered for utilisation with heat pumps installed individually at dwellings. As mentioned buildings may be easily heated and cooled using their own systems of borehole heat exchangers, comparison with such individual solution will be shown.
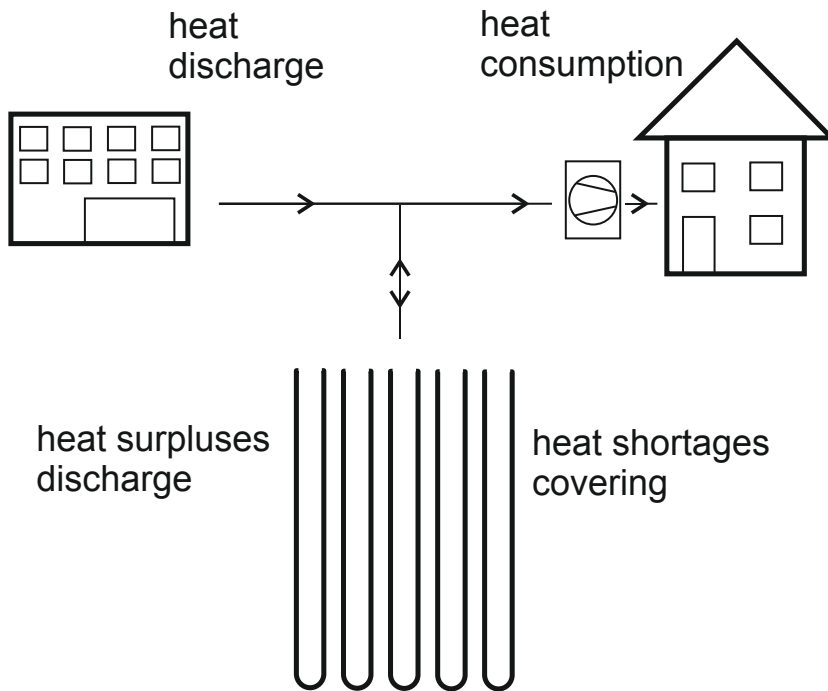

Fig. 1. Scheme of proposed system operation. Heat is discharged in a small industrial facility, while it is consumed in a dozen of individual dwellings/multi-storey building. Excess heat and its shortages are managed with borehole thermal energy storage.

Operation of such a system has been optimised in regard to the size of BTES and number of citizens whose living space heating and SHW preparation may be provided by proposed ULTDH system cooperating with small industrial facility with cooling demand (heating power discharged) varying from 64 to 210 kW. Operation schedule may be observed on the graph Fig. 2.
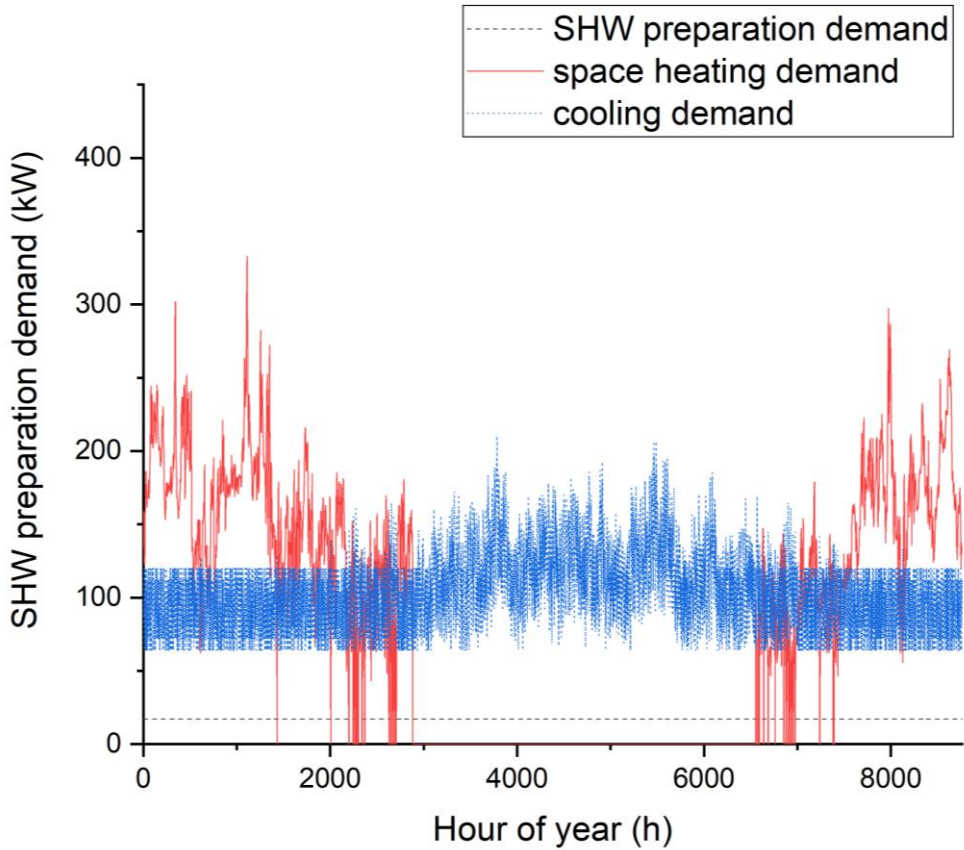
Fig. 2. Operation schedule of system receivers' demand for cold, heat and sanitary hot water preparation.

3 Mathematical description of the problem

Heat demand in hour n is described by the equation:

$$E_n^{heating} = E^{SHW} + E^{design} \cdot \frac{T_{designed}^{internal} - T_n^{external}}{T_{designed}^{internal} - T_{designed}^{external}} \tag{1}$$

Where $E^{design} \cdot \frac{T_{designed}^{internal} - T_n^{external}}{T_{designed}^{internal} - T_{designed}^{external}}$ part is used to calculate energy demand for space heating in an hour n ($E_n^{space\ heating}$).

$T_{designed}^{internal}$ has been assumed as 20°C, $T_{designed}^{external}$ as -20°C, $T_n^{external}$ is external temperature as given in typical meteorological year (TMY) for Kraków Balice meteorological station. Design heat load E^{design} equals 80W/m^2 and total heated area is optimised and amount to 27.6 m^2 of flat per capita, as mean for Poland (GUS). Space heating has been arbitrary disabled from May to September (no clear heating schedule is binding in Poland).

Heat energy required from ULTDH is calculated by the equation

$$E_n^{ULTDH\ heating} = (1 - \frac{1}{COP}) \cdot (E_n^{space\ heating} + E^{SHW}) \qquad (2)$$

Optimisation has been performed with objective function stated as

$$Z = \min(H) \qquad (3)$$

Where H is a total length of BHE.

With following constrains:

- Peak heating or cooling power cannot be higher than total BHE heat transfer rate potential
- BTES's energy content after an year of operation must be equal +/-10% to its initial state of charge
- In any hour, BTES state of charge cannot be lower than 0
- In any hour, ULTDH must provide entire energy demand

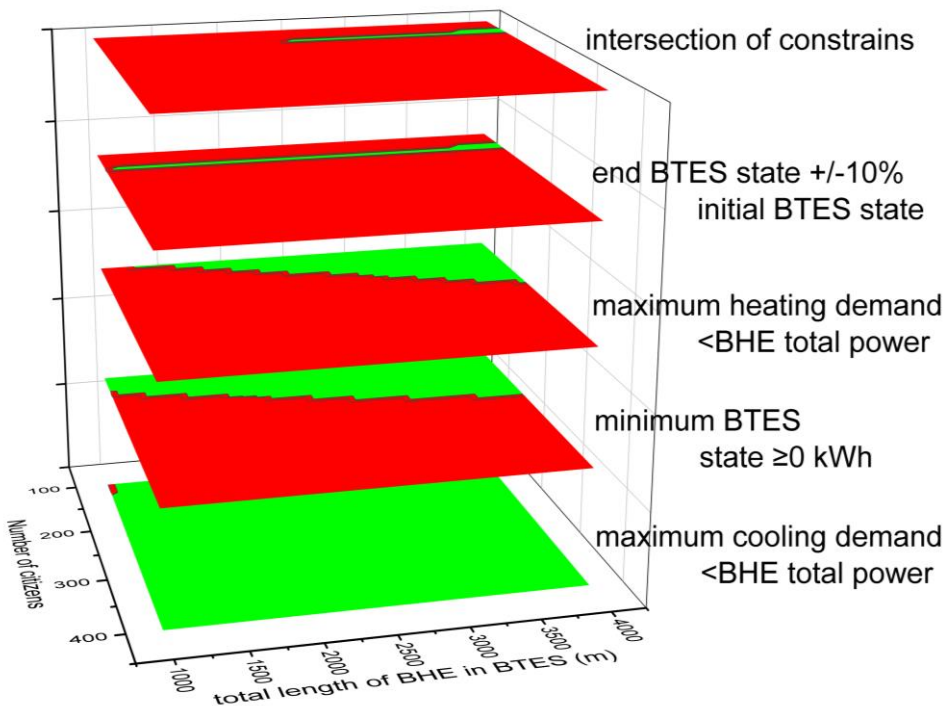An examined set of acceptable combinations is presented on Fig. 3.

Fig. 3. Parameters' constrains. Green areas represent sets of parameters which do not violate constrains e.g. are acceptable. Otherwise – red parts.

The initial (in hour n = 1) BTES value has been set as 80 kWh per meter of the borehole heat exchanger (BHE), which is moderate value for its energy content [8]. For each and every hour, energy provided by industrial facility is compared with energy demand decreased by 25%, as heat pumps (HP) coefficient of performance (COP) equal to 4.0 has been assumed. Heat transfer rate of BHEs is assumed to be 40W/m. If any excess occur, energy is stored in BTES of 40% efficiency [9]. Otherwise, lack of energy for space heating and domestic hot water preparation (50 kg per 24 h per person, temperature shift 50°C, demand distributed steadily and equal in every hour) is covered by heat pump from BTES. For every hour n > 1, BTES energy content is described as:

$$E_n^{BTES} = E_{n-1}^{BTES} + 0.4 \cdot E_n^{cooling} - (1 - \frac{1}{COP}) \cdot (E_n^{space\ heating} - E^{SHW}) \qquad (4)$$

Every hour, when

$$\frac{E_n^{cooling}}{1 - \frac{1}{COP}} > E_n^{space\ heating} + E^{SHW} \qquad (5)$$

BTES is charged with excessing energy, otherwise – energy is extracted from BTES with 40% efficiency and extracted heat is calculated as:

$$E_n^{BTES\ extracted} = (1 - \frac{1}{COP}) \cdot \left(E_n^{space\ heating} + E^{SHW} \right) - \frac{E_n^{cooling}}{1 - \frac{1}{COP}} \qquad (6)$$

ULTDH transport heat loss has been neglected, as temperature difference between medium and ground would be small, supposedly less than 15°C. Similarly, circulation pumps and heat capacity of DH medium is neglected.

4 Results

For given initial conditions, BTES consisting of about 2400 m of BHE is supposed to meet expectations. In its lowest energy content is 90 MWh, which is 47% of its initial state, while in its highest is 249 MWh and 129.5% of BTES initial energy content. In total, for typical meteorological year BTES provided 430 MWh of cooling and 180 MWh for heating purposes. Simultaneously, receivers discharged 909 MWh in cooling process and consumed 880 MWh for space heating (note: 220 MWh was produced from electricity in heat pump compressor, so total energy consumption was 880 MWh). Thus, significant amount of waste heat has been recovered and reused instead of being directly discharged into the environment, significantly reducing environmental burden. State of charge is presented in Fig. 4.

Over 8760 analysed hours, 780 BTES charging/discharging switching events occurred. The transient periods during which system is close to balance and BTES is hardly used are especially interesting, as represent system's highest efficiency. The final BTES state of charge indicates long-lasting system's durability and reliability, as its natural resource is not depleted. This leads to the conclusion that BHE might be even smaller, if its finite lifetime was assumed.

The simulation suggests that space heating and SHW preparation might be provided for 150 people. There is not a single hour in which heating and cooling demand would not be covered (what was one of the assumptions).

In comparison with individual sources of heat and cold for the same conditions, the BHE size is reduced by more than 5 times, bringing significant limitation on required space and capital costs. For typical conditions in Poland, about 60% of heat injected to BTES from cooling is dissipated in the environment. It is still not sufficient enough, yet significantly less than in case of traditional dry-coolers discharging heat into the atmosphere. Meanwhile, the heat discharged to ULTDH during space heating demand is consumed and significantly decreases conventional heat demand. Thus, heat is used efficiently, not susceptible for exergy decrease or heat storage inefficiency loss. For presented optimal conditions fulfilling all the constrains, share of heat discharged to ULTDH and directly used by heat pumps in overall heat demand is never lower than 50% (Fig. 5).
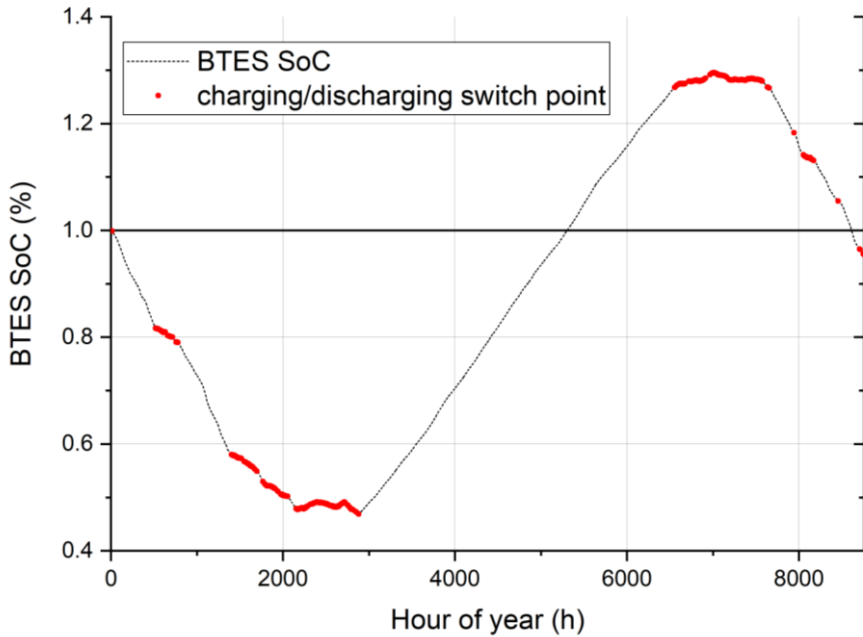
Fig. 4. State of charge of BTES. Red dots represent transient conditions, for which heat exchange in BTES occur in a very limited range, while entire ULTDH system's efficiency is highest.
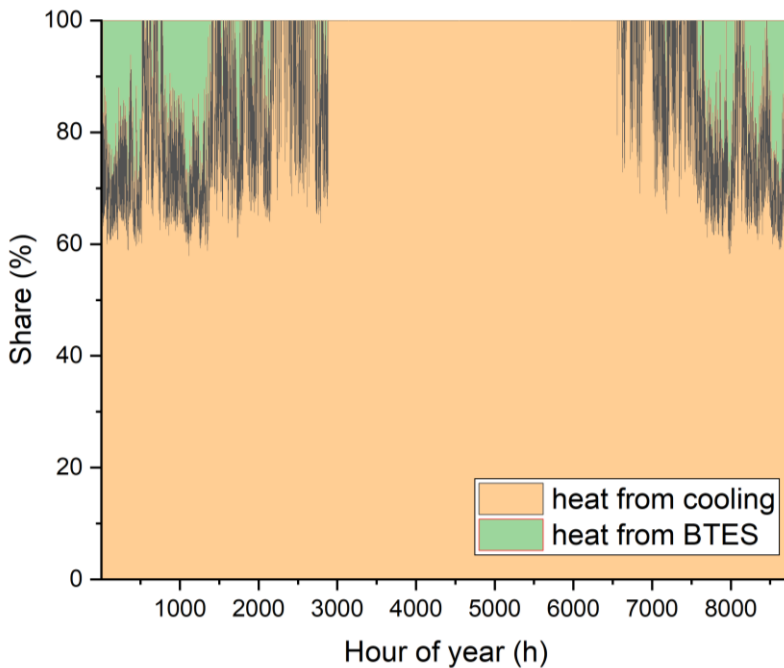

Fig. 5. Proportions of heat provided directly from cooling and from BTES.

5 Summary

The optimisation and operation mode of the geothermal power based ULTDH for cooling and heating purposes has been presented. Obtained results indicate significant benefits derived from the ULTDH system operation connecting heat sources and heat sinks, which nominally are not dependent of each other. Low temperature of used medium brings benefits in limited heat losses and increased heat sink effectiveness. Total BHE length may be reduced 5 times compared to individual heat and cold sources while satisfying entire demands during the typical meteorological year. Simultaneously, less energy is dispersed in the environment, what has a potential in reducing negative effects like urban heat islands. Use of heat pumps at dwellings has potential to facilitate use of energy-efficient low temperature heating in houses (e.g. floor heating).

Presented results are valid for assumed situation during the typical meteorological year. Yet, the methodology is applicable in real-life considerations, where more complex and diversified data would be provided. For the future work, including DH system's heat capacity and performing sensitivity analyses for longer time periods is planned.

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