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# COMPARISON OF DISTRICT HEATING SYSTEMS AND DISTRIBUTED GEOTHERMAL NETWORK FOR OPTIMAL EXERGETIC PERFORMANCE

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**Abstract**

As part of the IEA ECB Annex 64, Low Exergy Communities, we investigate distributed heating and cooling systems using large campus infrastructures as baselines. The Princeton University system serves as a baseline with a 15 MW combined heat and power facility that supplies heating in winter and cooling in summer. This paper assesses a low temperature hot water combined heat and power system and a geothermal system as two alternatives to the current system. The heating period of 2013/2014 is investigated. To assess the primary energy and exergy input required to meet the campus heating demand of 132.8 GWh, the existing system and a theoretical geothermal system are modelled using the MATLAB/Simulink based toolbox CARNOT. The combined heat and power system needs 338.1 GWh of exergy to meet the heat demand and to produce 63.1 GWh of electricity. The geothermal system only needs 219.6 GWh of exergy to meet the heating demand and to provide the same amount of electricity using the electricity grid. The energy efficiency of both investigated systems is equal, but one third of the geothermal system's energy input is renewable geothermal heat. Also, the exergy efficiency of the geothermal system is 30.7 %, whereas the combined heat and power system has an exergy efficiency of only 19.9 %.

**Keywords:**

Exergy analysis; geothermal borehole heat exchangers; combined heat and power; campus heating system; CARNOT; LowEx

## 1 INTRODUCTION AND BACKGROUND

The built environment uses one third of the worlds end energy [1], of which more than fifty percent is used for room heating [2]. Room heating is a low exergy demand, but usually high exergy sources like fossil fuels are used to meet these heating demands. The International Energy Agency Annex 64 - LowEx Communities – Optimized Performance of Energy Supply Systems with Exergy Principles aims at providing the needed energy demand at the matching exergy level. The main focus of the Annex is the integration of low exergy thinking to facilitate the needed shift to renewable and greenhouse gas emission free energy systems in communities [3]. Tolga Balta et al. [4], analyse a "low exergy heating system from the power plant through the heat pump to the building envelope". They conclude that energy analysis alone is not sufficient to understand all factors of energy utilization processes. As another result, they identify the primary energy conversion as the largest exergy destruction of their system. Dalla Rosa et al. [5] present a low-temperature district heating concept. They show that a low-temperature operation has higher performance than a low-flow operation of a district heating system. Rosen et al. [6, 7] analyse combined heat and power (CHP) based district energy systems. The calculated energy and exergy efficiency is between 83 and

94 % and 28 and 29 %, respectively. Terés-Zubiaga et al. [8] analyse five different energy systems for a multifamily building in Spain. They identify combustion and resistance heating as biggest exergy losses. Lohani [9] analyses a condensing boiler and a ground and air source heat pump for a building for two different reference temperatures. Energy and exergy analyses show that the ground source heat pump with ambient reference temperature has the best performance. A good overview over the work on LowEx heating and cooling systems for buildings and communities can be found in Hepbasli [10]. The Princeton University is exploring a long-term plan for its campus heating system, which is currently a co-generation plant generating electricity and high-temperature steam. Alternatives include low temperature water distribution and switching to a geothermal heat pump. The historical data for campus energy demand and these future scenarios provide the context for this study.

## 2 METHODS

### 2.1 System Layout

The current Princeton University campus heating and cooling system has a central CHP plant which can be run using either natural gas or diesel fuel. The heating system is a steam system with temperatures and pressures up to 230 °C and 14 bar. Two auxiliary boilers are available to meet the heating peak demand. The total heat demand during the heating period in 2013/2014 is $E_{demand}$ = 132.8 GWh and the electricity production of the CHP plant during that period is 63.1 GWh.

In this work, the heating systems are modelled as heating hot water systems with a supply temperature $T_s$ of 50 °C and a return temperature $T_r$ of 35 °C. The systems are simulated using measured demand data in 15 min time steps. Further, the campus is modelled as one single load with one supply and one return pipe with a length of 21 km each, a diameter of 0.82 m and a heat loss coefficient of 1.3 W/(m$^2$K). For both systems, the energy needed to run the system pumps is neglected. The systems are modelled using the MATLAB/Simulink based toolbox CARNOT [11], which allows for a dynamic simulation of the heating period. Different couples of supply and return temperatures are developed for the simulation to explore effects on system operating conditions.

*2.1.1 CHP System*

The low temperature heating hot water CHP system is modelled as a central CHP plant with 15 MW electric and 21 MW thermal output, (fig. 1). The electric and thermal efficiency of the CHP plant is set constant to 25.6 % and 36.9 %. An auxiliary boiler with an efficiency of 78 % is implemented to meet the heating peak demand. A thermal energy storage in the form of a hot water storage with a volume of 85 m$^3$ is used to prolong the running time of the CHP plant.

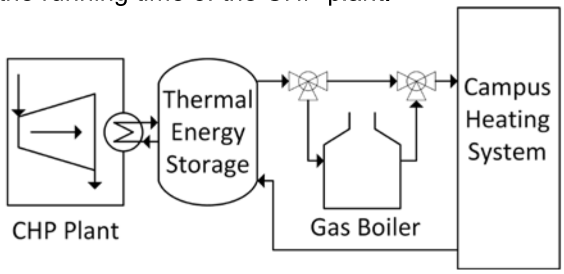


*Fig. 1: CHP System.*

*2.2.2 Geothermal System*

As a second alternative to the current system, a geothermal heat pump system is analysed, (fig. 2). It consists of a borehole field with vertical ground-source heat exchangers modelled as double-U-pipe heat exchangers with a depth of 96 m. To limit computing time, the borehole field and heat pump are modelled as a small system with a thermal power output of 121 kW. The nominal coefficient of performance (COP) of the heat pump is 3.6. In order to meet the demand of the campus heating system, the input and output energy and mass flows are scaled up in front of the thermal energy storage. The storage is used to even out demand peaks and is modelled as a hot water storage with a volume of 200 m$^3$.

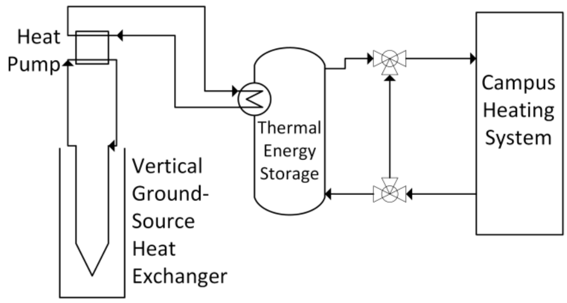


*Fig. 2: Geothermal System with Heat Pump.*

### 2.2 System Boundary and Reference State

The current outside air is chosen as reference environment according to the IEA Annex 49 guidebook [12]. In this paper the outside air temperature for the heating period 2013/2014 in Princeton, USA, is taken as reference temperature.

The system boundary is chosen according to the storability criterion developed by Jentsch [13]. The storability criterion demands that all energy forms are traced back to a storable form. The energy inputs crossing the system boundary are the gas needed for the CHP plant, the primary energy needed to run the heat pump and the geothermal energy. The energy needed to run the system pumps is not included in the analysis at this stage.

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### 2.3 Exergy Definition

*Exergy of natural gas*: The exergy of natural gas $L_{ex,NG}$ is defined as [14]:

$$L_{ex,NG} = \beta_{NG,LHV} LHV, \quad (1)$$

where $\beta_{NG,LHV}$ is the quality factor for natural gas ($NG$) and $LHV$ is the lower heating value for natural gas. In this work, $\beta_{NG,LHV} \approx 1.04$ is used [15].

*Exergy of geothermal heat*: The exergy equation for heat is used to calculate the exergy content of the heat input at the borehole:

$$-P_{ex} = \dot{Q}(1 - T_0/T_\infty), \quad (2)$$

where $P_{ex}$ is the exergy flow, $\dot{Q}$ is the heat flow from the geothermal heat source, $T_0$ is the reference temperature and $T_\infty$ is the undisturbed ground temperature in half of the depth of the borehole.

*Exergy demand of the campus*: The exergy demand of the campus is calculated using the exergy equation for heat:

$$-P_{ex} = \dot{Q}_C(1 - T_0/T_B), \quad (3)$$

where $P_{ex}$ is the exergy flow, $\dot{Q}_C$ is the campus heat demand, $T_0$ is the reference temperature and $T_B$ is the desired temperature inside the campus buildings, which is set to 21 °C.

*Exergy of electricity*: For electricity, its energy and exergy content is equal. Because of the storability criterion, electricity is traced back to the primary exergy input and the transformation losses are taken into account. Because the exergy and energy efficiency for various types of power plants is similar [16], the following equation is used to calculate the energy efficiency $\eta_{el}$ and exergy efficiency $\psi_{el}$ for electricity:

$$\eta_{el} = \frac{\Sigma_i \sigma_i \eta_i}{\Sigma_i \sigma_i} = \psi_{el} = \frac{\Sigma_i \sigma_i \psi_i}{\Sigma_i \sigma_i}, \quad (4)$$

where $\sigma_i$ are the percentages of the different kinds of electricity sources on the total electricity supply mix of the USA of the year 2014 [17]. $\eta_i$ and $\psi_i$ are the energy and exergy efficiency of the different kinds of electricity sources. In table 1, the values for $\sigma_i$, $\eta_i$ and $\psi_i$ are given.

It is assumed that natural gas and oil have the same transformation efficiency and that renewable energies have an efficiency of 100%. Other energy sources than the ones shown in table 1 are neglected. With table 1 and equation 4 $\eta_{el}$ and $\psi_{el}$ can be calculated to $\eta_{el}$ and $\psi_{el}$ = 0.48.

| | Renewable | Oil | Coal | Nuclear | Gas |
|---|---|---|---|---|---|
| $\sigma_i$ | 13 % | 1 % | 39 % | 19 % | 27 % |
| $\eta_i$/ $\psi_i$ | 100 % | 52.6 % | 36 % [16] | 30 % [16] | 52.6 % [18] |

*Table 1: Share on the electricity generation and efficiency values of different energy sources.*

### 2.4 Characteristic Numbers

The overall system energy efficiency $\eta_{system}$ is defined as:

$$\eta_{system} = \frac{E_{demand} + E_{el}}{E_{fossil} + E_{geothermal}}, \quad (5)$$

where $E_{fossil}$ is the fossil energy input into either the CHP and boiler or the heat pump, $E_{el}$ is the electricity produced by the CHP plant and $E_{geothermal}$ is the energy extracted from the boreholes. It is dependent on the system layout if $E_{geothermal}$ is applicable. The CHP system produces heat and electricity, whereas the geothermal system only produces heat. A comparison of the two systems is difficult since the output is not equal for both systems. This is due to the fact that the geothermal system cannot produce electricity and would therefore only have the produced heat in the numerator of equation 5. The following measure is taken to make the numerator of equation 5 equal for both systems.
The amount of electricity which the CHP plant produces is also used for the efficiency calculation of the geothermal system, so that the numerator is equal. Since the geothermal system cannot produce electricity it is assumed that the geothermal system pulls the amount of electricity which the CHP plant produces from the electricity grid. This electricity is named as compensated grid electricity. The compensated grid electricity is taken from the electricity grid and must therefore be traced back to the primary energy conversion using equation 4.
The overall system exergy efficiency $\psi_{system}$ is defined as:

$$\psi_{system} = \frac{EX_{demand} + EX_{el}}{EX_{fossil} + EX_{geothermal}}, \quad (6)$$

where $EX_{fossil}$ is the fossil exergy input into either the CHP or the heat pump system, $EX_{el}$ is the electricity produced by the CHP plant and $EX_{geothermal}$ is the exergy extracted from the boreholes. It is dependent on the system layout if $EX_{geothermal}$ is applicable. Again, as for equation 5, a compensated grid electricity for the geothermal system is calculated using equation 4.

## 3 RESULTS

In the energy and exergy efficiency comparison, the CHP and the geothermal system have a similar energy efficiency, but the geothermal system has a higher exergy efficiency (fig. 3).

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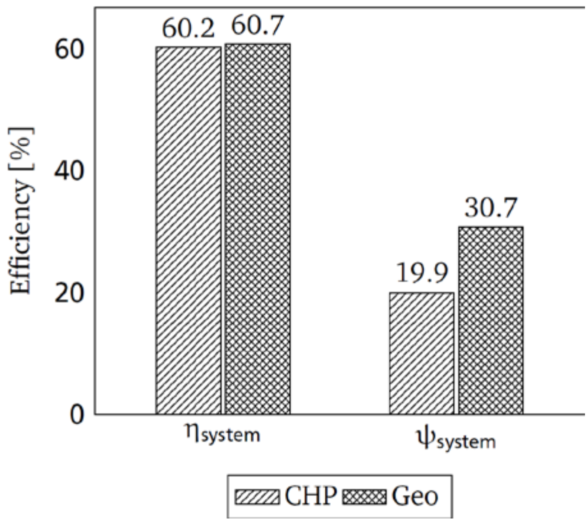


*Fig. 3: Energy and Exergy efficiency of the two systems.*

Although the CHP and the geothermal system have almost the same energy input into the system of 325.1 GWh and 322.4 GWh respectively, the geothermal system has one third of its energy input from geothermal heat, which is renewable, whereas the CHP system has only fossil fuel input (fig. 4).

Since geothermal heat is a low exergy heat source, the exergy input into the geothermal system at 218.7 GWh is lower than its energy input. The grey bar "Comp. Electricity" (fig. 4) is the compensated grid electricity introduced in section 5 in order to make a comparison of the two investigated systems possible, calculated with equation 4. The exergy input into the CHP system is 338.1 GWh.

The influence of different supply and return temperatures is investigated (fig 5). The couples of supply and return temperatures were determined to be 50/35 °C, 60/45 °C, 70/50 °C and 90/70 °C.

The pipe losses increase with increasing system temperatures (fig 5). The electricity production of the CHP plant decreases slightly with increasing system temperatures because of the control strategy of the thermal energy storage. The energy input into the CHP system does not increase as much as the pipe losses with increasing temperature. Since the CHP plant produces less electricity due to the chosen storage control strategy, it also produces less heat. In order to cover the heat demand, the auxiliary boiler produces more heat.

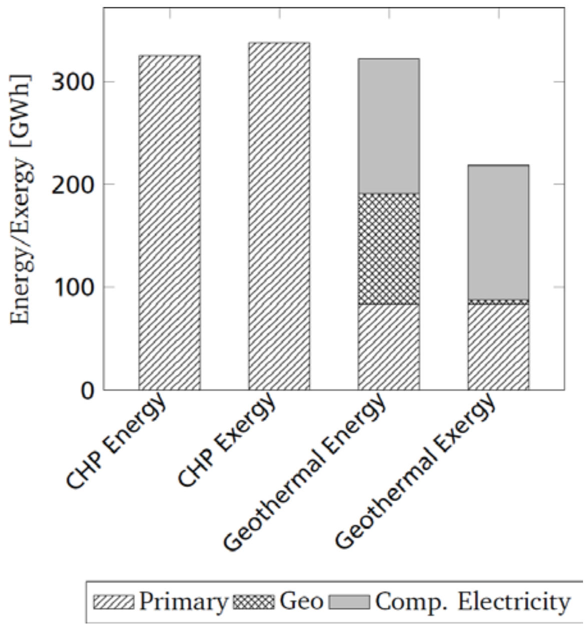


*Fig. 4: Energy and Exergy Input of the two Systems.*

The auxiliary boiler has a higher energy efficiency than the CHP plant. This leads to a smaller increase of energy input with increasing temperatures compared to the increase of pipe losses. The energy input into the heat pump increases more than the pipe losses, because the heat pump's COP decreases from 3.6 at 50 °C to 2.9 at 60 °C when the heat pump has to cover a higher temperature spread. The total energy input into the geothermal system also increases. The compensated grid electricity of the geothermal system is not included in the total energy input (fig. 5).

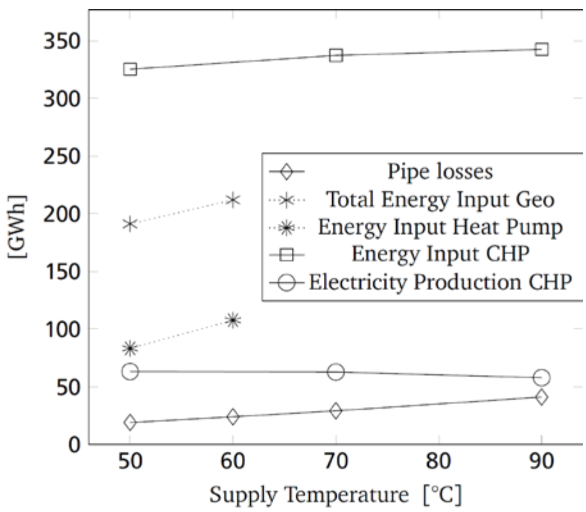


*Fig. 5: Influence of Supply Temperature.*

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## 4 DISCUSSION

Since the CHP and the geothermal systems have different energy products as an outcome, a compensated grid electricity of the geothermal system is calculated to make the two systems comparable. The results show better performance for the geothermal system, but the energy needed to run the system pumps is not taken into account. The pump energy needed to run the geothermal system is higher than for the CHP system because more fluid circuits have to be implemented. First estimations put the pump power to run the pumps of the CHP system to around 20.0 GWh and to run the pumps of the geothermal system to around 45.0 GWh. For both systems simplifying assumptions have been made for the simulation. The main assumptions are that the CHP plant has a constant efficiency and that one simulated heat pump and borehole system can be up scaled linearly. In reality, a large array of heat pumps and boreholes would be needed to cover such a high demand, which would provide additional opportunities for optimization. The results are strongly dependent on the chosen electrical efficiency of the CHP plant and the COP of the heat pump. By operating a large set of boreholes extraction temperatures can be optimized to increase the overall COP, while the pumping costs would be more distributed. Even though the geothermal system needs a slightly higher amount of energy to produce the same output, when the pump energy demand estimation is taken into account, roughly one third of its input is geothermal heat which is a renewable, low exergy heat source, making it a better choice from a sustainable and exergy point of view. Changing the supply and return temperatures affects not only the energy balance, but a reduction of supply temperatures would presumably also require additional measures on the buildings itself regarding heat transfer stations and radiators.

## 5 CONCLUSION

Two alternatives to the Princeton University campus heating system are modelled to provide the needed heat. A low temperature heating hot water CHP system consisting of a CHP plant and an auxiliary boiler is compared to a geothermal system consisting of a borehole field and a heat pump. The results show that the geothermal system has a higher share of renewable energy and has better exergetic performance for the input parameters, and energy conditioned determined from historical operation. This is in part due to one third of its energy input being renewable energy and its exergy efficiency is 30.7 %, whereas the CHP system has an exergy efficiency of only 19.9 %. A compensated grid electricity use for the geothermal system is calculated to make the geothermal system comparable to the CHP that produces electricity and the energy efficiency for both systems is around 60 %. These results provide valuable input into the planning process of the future Princeton campus system considering the effect of exergy that is often overlooked. The variation of the supply and return temperatures shows that the total energy input into both systems decreases with decreasing system temperatures, because of decreasing pipe losses. Heat pumps benefit even more from decreasing system temperatures, because the temperature spread that they have to overcome to provide heat at the desired temperature decreases, which leads to a higher COP. Overall, the geothermal system seems to have a superior performance, but the results are strongly dependent on the CHP plant efficiency and the heat pump COP. Both values should be increased. In general it is demonstrated that exergy analysis helps finding the more suitable of the two investigated heat supply alternatives. In further studies the energy needed to run the system pumps should be included in the analysis. To which degree a reduction of supply and return temperatures is realizable for the Princeton University campus heating system has to be determined in further studies.

## 6 ACKNOWLEDGMENTS

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