Impact of Geothermal District Heating System on Flexibility of Microgrid in Tuttle, Oklahoma

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Impact of Geothermal District Heating System on Flexibility of Microgrid in Tuttle, Oklahoma

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Keywords

Grid flexibility, microgrid, geothermal district heating, heating demand, EnergyPlus, Cambium

ABSTRACT

Flexibility is the capability of the power grid to maintain a balance between electricity generation and variable demand. This study presents preliminary results evaluating the impact of geothermal district heating systems on the flexibility of a conceptual microgrid in Tuttle, Oklahoma. Heating demand profiles were modeled using EnergyPlus for the district that includes two schools and 250 single-family houses. Then, geothermal energy production was modeled using GEOPHIRES to estimate how much heating demand in the district can be supplied by five different geothermal system scenarios. The results indicated that geothermal energy production varied depending on the resource temperature at different depths, system configurations, and flow rates. For the grid flexibility analysis, electricity consumptions in the five geothermal systems were estimated for pump operations to circulate water from the wells to radiators, while electricity consumption by air-source heat pump in the base case was estimated to supply the same heating load. Electricity consumption in the geothermal systems was significantly lower than those in base cases. The electricity saved by the geothermal system was then incorporated into the microgrid electrical load profiles where variable renewable electricity generation is significantly high. The results visually showed that geothermal district heating system can improve grid flexibility as a baseload during the winter season. The results also highlighted potential opportunities to save energy costs that will be further analyzed in future study.

1. Introduction

An electrical grid is defined as an interconnected network where electricity generated from power stations is delivered to end users and varies in size from microgrid to wide area synchronous grid, or super grid that is trans-continental or interconnected throughout several countries. The microgrid represents a local grid that can be connected or disconnected from the grid, while conventional grid is a large-scale synchronous grid. The power stations connected to microgrids and/or grids in the United States consist of a wide variety of power sources including renewable energy sources particularly wind and solar energy where the resource availability may vary significantly depending on the geographical and environmental conditions. The variable renewable electricity generations increase an uncertainty of the net load met by conventional generators in the grid (i.e., non-renewable electricity generations). The grid thus needs to have a sufficient amount of flexibility to maintain a balance between power supply and variable demand and reliably supply electricity to end users especially if the grid incorporates variable renewable power generations at a high penetration. Grid flexibility describes the system capability to respond to the variability and maintain a balance between demand and supply.

The grid flexibility has been extensively studied by previous researchers, especially for the impact of variable electricity generation from wind and solar energy systems. Denholm and Hand (2011) evaluated the flexibility of an isolated region where the grid is significantly dependent on variable wind and solar power generation (up to 80% of the electric demand) and concluded that the grid requires a variety of enabling technologies including load shifting, thermal storage, or electricity storage to accommodate variable renewable electricity generation at 80% penetration and to avoid excessive curtailment. Similarly, Deetjen et al. (2017) reported growing wind and solar capacity in the electric grid shows only minor impact on the grid flexibility even though growing solar capacity improves the grid flexibility requirements at the early stages. Specifically, solar power generation of 14.5 GW increased maximum 1-h ramp rates by 135%, 3-h ramp rates by 30%, ramp factors by 140%, 1-h volatility by 100%, and 1-day volatility by 30%.

To mitigate the net load ramping and optimize the grid flexibility with variable wind energy, Fang et al. (2020) designed flexible ramping products from wind power using a probabilistic wind power ramp forecasting method. Their results demonstrated that the system operating and ramping cost can be reduced with the flexible ramping products especially when wind power provides flexible ramping products in the day-ahead market. Analogously, although geothermal electricity systems have been traditionally incorporated into a power grid for baseload, the power supply using geothermal energy can improve grid flexibility when flexibly operated. Millstein et al. (2021) reported that simple curtailment of geothermal power system operations during negative pricing episodes could increase the energy value by $1 to $2/MWh on average (up to $4/MWh depending on the amount and type of curtailment and enhancement) resulting in an increase in power production during limited peak rate hours. Moreover, the flexibility can be further optimized with in-reservoir energy storage system (Ricks et al. 2022, Ricks et al. 2024).

In addition to the flexible operations of geothermal power systems, geothermal resources have great potential to improve grid flexibility particularly using geothermal district heating system where thermal energy is supplied from the subsurface to a group of buildings through a distribution network (i.e., large-scale heating system). For example, pumps may be the only component where electricity is consumed in the geothermal system to circulate water from wells to heat exchangers or radiators for heating, while electric boilers and furnace in non-geothermal heating system may consume more electricity for the same heating load. However, there are very limited studies to analyze how much electricity could be saved with the geothermal district heating and how the geothermal district heating can contribute to grid flexibility. This study evaluated the impact of geothermal district heating system that has five different production scenarios on the flexibility of a conceptual microgrid in Tuttle, Oklahoma. Electricity consumed for circulating pumps in the geothermal system was estimated for the five production scenarios and then incorporated into Cambium data sets, which contain modeled hourly emissions, costs, and operational metrics in

Southwest Power Pool (SPP) south region where the study area is located (p50). The results were also compared with a base case where the same heating load is supplied by air-source heat pump (ASHP).

2. Geothermal District Heating System in Tuttle, Oklahoma

The study area includes one primary school, one secondary school, 250 single-family homes, and four inactive oil and gas wells, approximately 1.5 km away from the district (Figure 1). As demonstrated by Oh et al. (2024), this study assumed that geothermal energy is reliably and continuously produced from the four oil and gas wells for space heating using radiators.

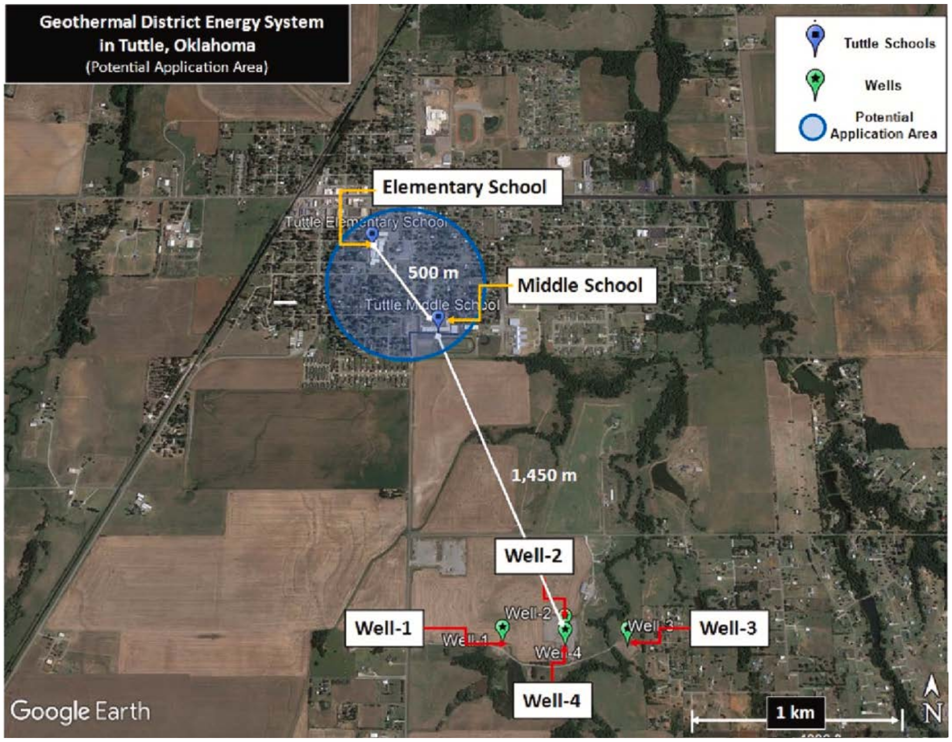


Figure 1. Geothermal district heating system in Tuttle, Oklahoma (Oh et al. 2024).

This study leveraged the reservoir and building energy modeling results in Oh et al. (2024). For geothermal energy production, there were five scenarios that have different well configurations, depths, and flow rates (Table 1). Regional geothermal gradient in the study area was estimated as 25.3 °C/km, and the production temperature, power ($MW_{thermal}$), and energy ($MWh_{thermal}$) varied depending on the configurations and flow rates. Figure 2 shows the variable geothermal energy production with five scenarios. As discussed in Oh et al. (2024), none of the five scenarios fully supply the district heating demand when the system size underwent techno-economically optimization. Peak loads required supply of natural gas to fire boilers during peaking periods (see red bars in Figure 2). The analysis in this study did not consider heating demand supplied by the natural gas boiler but compared power consumptions for each of the same load profiles in the five scenarios by ASHP (i.e., base case) and by circulating pumps, following the logic: 1) how much geothermal energy can be produced in each scenario, 2) how much electricity is consumed by circulating pumps to produce the energy in each scenario, and 3) how much electricity is consumed by ASHP to supply the same loads.

Table 1. Geothermal district heating system with five production scenarios

Models	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Number of Production Wells	1	3	1	3	1
Number of Injection Wells	1				
Well Depth (m)	2,100				3,300
Geothermal Gradient (°C/km)	25.3				
Flow Rate per Production Well (kg/s)	9.3	3.1	6.2	6.2	9.3
Initial Reservoir Temp. (°C)	68.1	68.1	68.1	68.1	98.5
Max. Production Temp. (°C)	63.7	55.1	61.8	59.9	87.9
Avg. Production Temp. (°C)	61.3	53	61.3	45.8	87.1
Avg. Heat Production (MW_{th})	0.71	0.39	0.43	0.35	1.42
Avg. Annual Heat Production (GWh_{th}/yr)	1.92	1.33	1.43	1.12	2.49

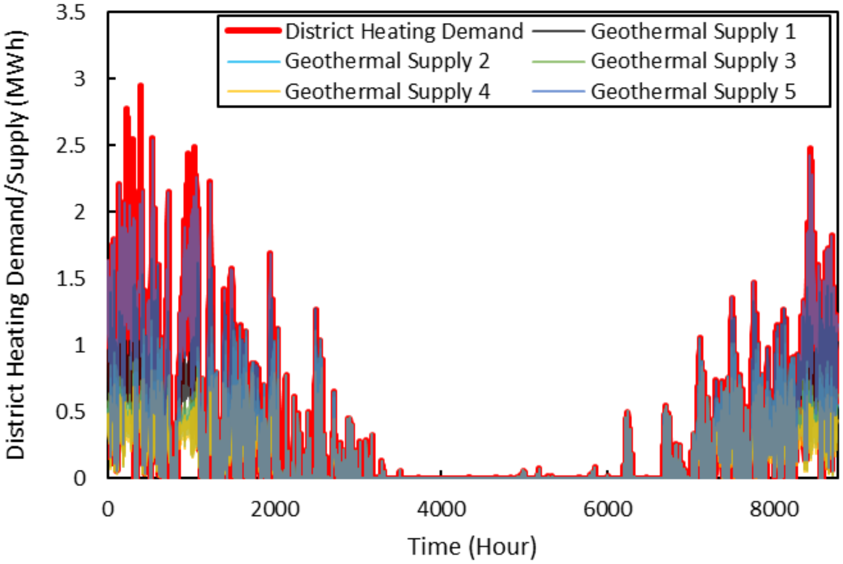


Figure 2. District heating demand and thermal energy supplied by the geothermal system using five production scenarios.

3. Estimating Electricity Consumption in a Base Case and the Five Geothermal Systems

As mentioned, the ASHP was assumed in the base case (i.e., non-geothermal heating system) as a heating equipment to supply the district heating demand and assumed to have a constant coefficient of performance (COP) of 2 (i.e., the ratio of thermal energy generated from the ASHP to electricity consumed in the ASHP is always 2 throughout the year). Solid lines in Figure 3 represent the district heating demand in example days ($\mathrm{MWh_{thermal}}$), and the dashed lines demonstrate electricity consumption by the ASHP to supply the demand ($\mathrm{MWh_{electric}}$).

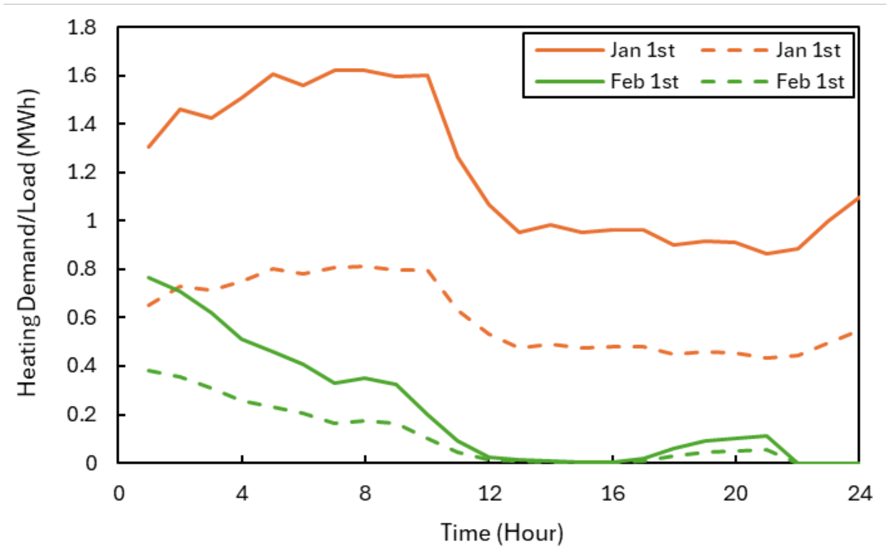


Figure 3. Heating and electrical load profiles in example days. Note that heating demand profiles ($\mathrm{MWh_{thermal}}$) are represented as solid lines and dashed lines represent electrical loads by air-source heat pumps for the district heating demand ($\mathrm{MWh_{electric}}$).

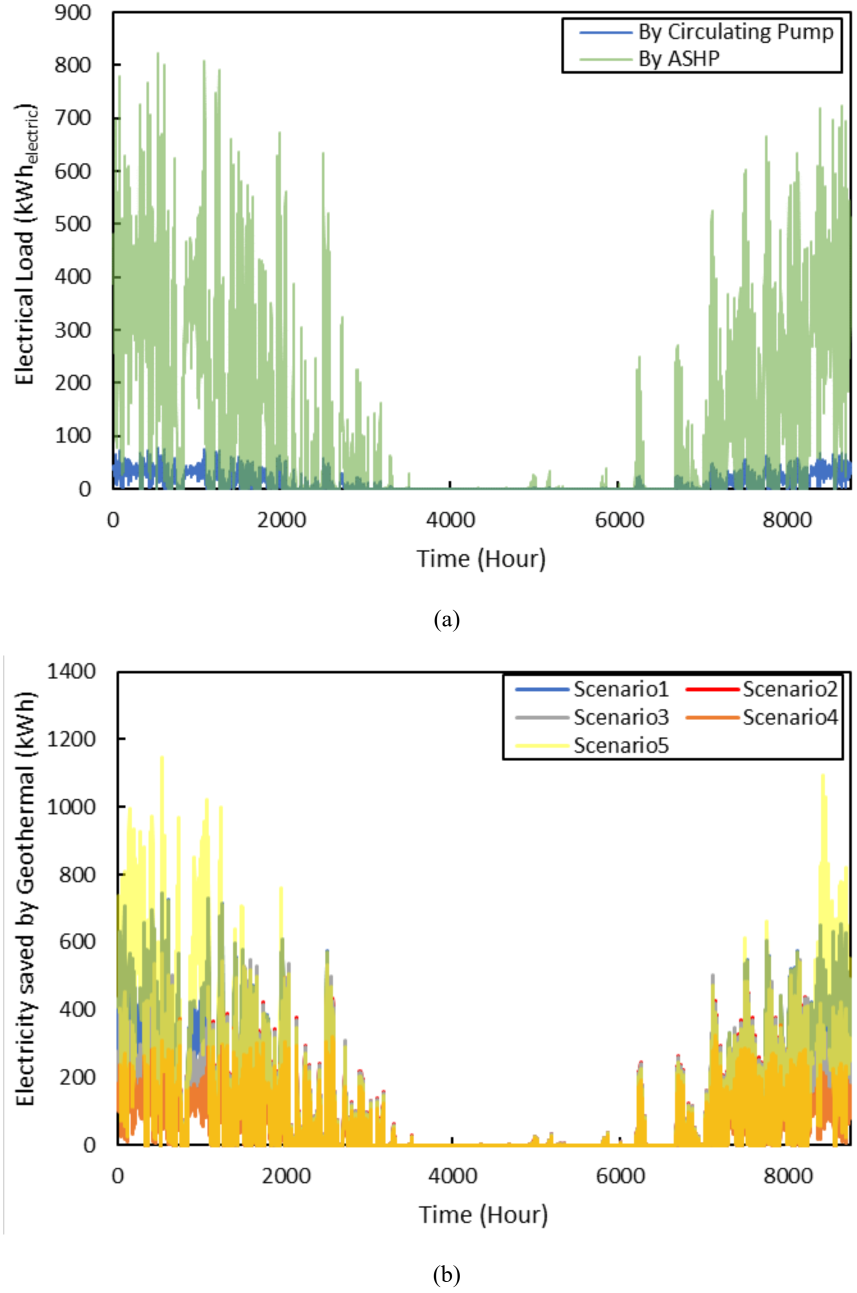
While electricity consumption in the base case was calculated with the demand profile and COP assuming the ASHP is the only component where electricity is consumed to generate thermal energy for space heating, this study assumed that the geothermal district heating system supplies the heating demand by circulating water throughout the geothermal wells using circulation pumps implying that there is no other energy consumption for generating thermal energy. The pumping power was estimated using Eqn. (1).

$$P = Q \cdot \Delta P / \eta \tag{1}$$

where P = pump power (W), Q = volumetric flow rate ($\mathrm{m^3/s}$), ΔP = pressure drop (Pa), η = pump efficiency, which was assumed as 80% in this study. ΔP was calculated using Darcy-Weisbach equation (i.e., pressure drop caused by friction):

$$\Delta P = \frac{f\, L\, V^2\, \rho}{2\, D} \tag{2}$$

where f = Darcy's friction factor, L = length (m), V = flow velocity (m/s), ρ = fluid density ($\mathrm{kg/m^3}$), D = diameter (m), which was 2.5 in. The calculated pumping powers in the five scenarios were 84.91 kW, 14.29 kW, 26.71 kW, 102.08 kW, and 130.45 kW, respectively. The calculated pumping powers were considered as maximum (i.e., the highest flow rate, such as 9.3 kg/s for Scenario 1 in Table 1) and then reallocated in hourly electrical load profiles in terms of percentage of geothermal system operations (from zero to peak). Figure 4(a) compares electrical load profiles of the base and geothermal cases in Scenario 1. As the geothermal system does not require power consumption for thermal energy, electrical load in the geothermal system was significantly lower than that in the base case (about 10 times), particularly in Scenario 5 where the heating load supplied by geothermal system was the highest among the five scenarios (Figure 4(b)).



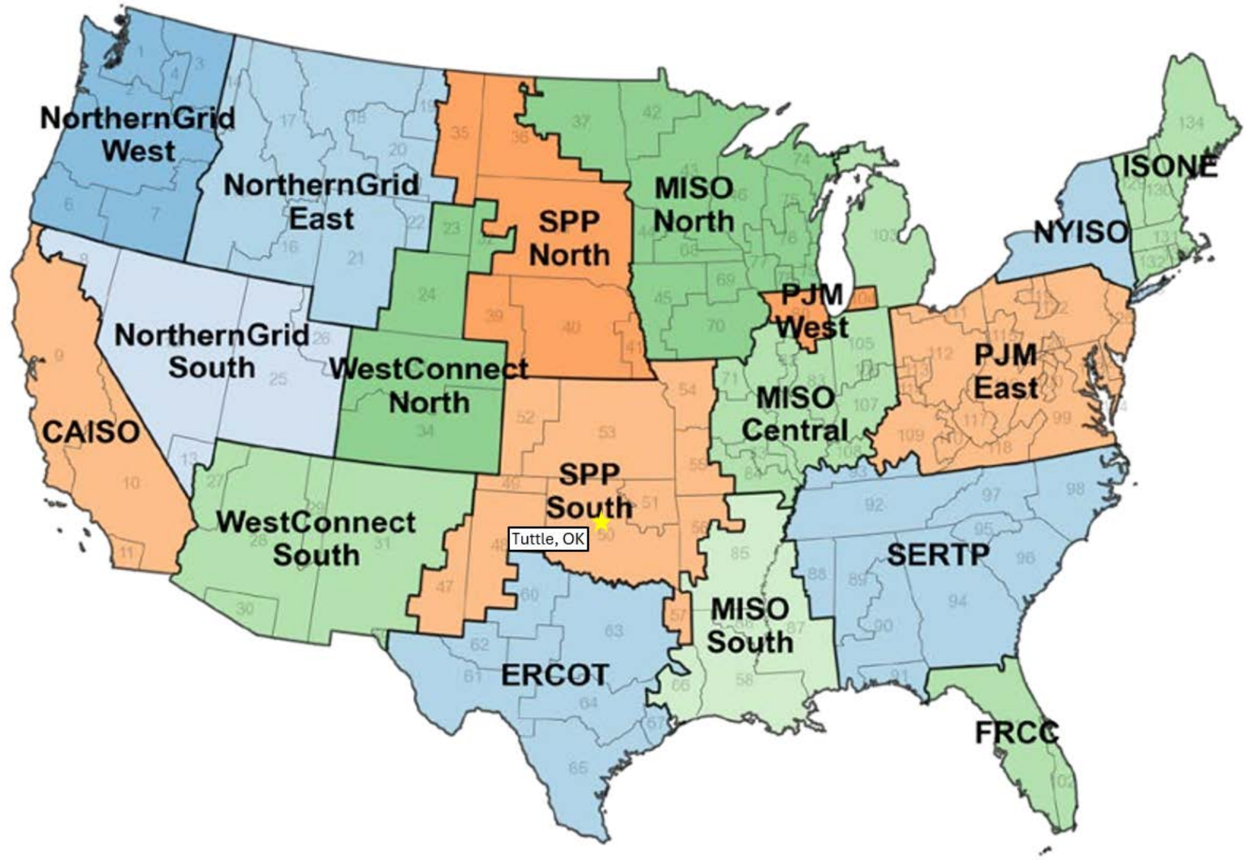
(a)

(b)

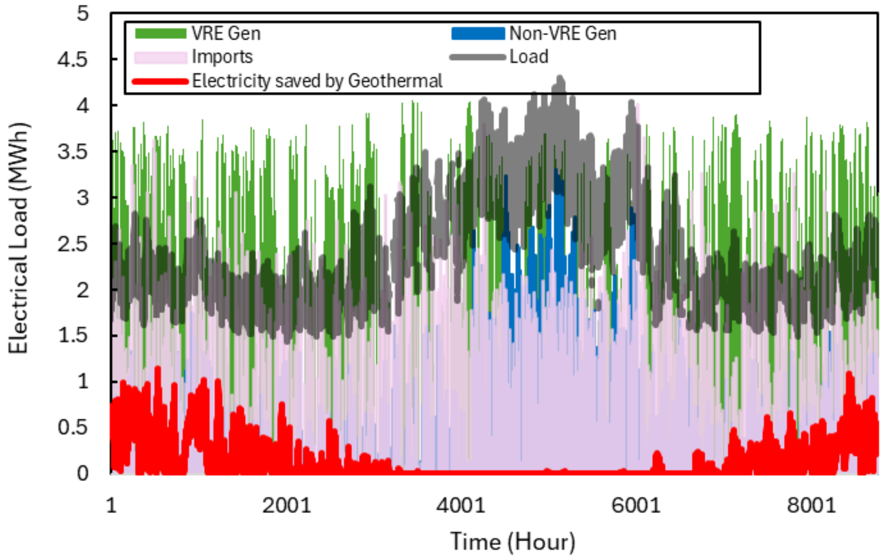
Figure 4. (a) Electrical load profiles in Scenario 1. Blue bars represent electricity consumed by circulating pump in the geothermal system and green bars represent electricity consumed by ASHP in the base case to supply the same district heating demand. (b) electricity saved by the geothermal district heating system in the five scenarios.

4. Impact of the Geothermal District Heating System on the Microgrid Electrical Load

In addition to the comparison of electricity consumption by circulating pump in the geothermal system and by ASHP in the base case to supply the same heating load, the benefit of geothermal district heating system on the microgrid was evaluated with Cambium, which is a dataset annually released by the National Renewable Energy Laboratory for simulated hourly emissions, cost and operational data of the U.S. electric sector (Gagnon et al. 2024). Balancing area is the smallest geographic resolution for which Cambium data are reported (i.e., model nodes, not perfectly aligned with balancing authority defined by the North American Electric Reliability Corporation). Figure 5(a) shows that the study area is in p50 in Southwest Power Pool (SPP) south region. For the analysis in this study, the Cambium data for p50 was further scaled down to the study area in terms of the populations. Figure 5(b) represents electrical load, imports (into the microgrid through interregional transmission lines), and variable renewable electricity (VRE) and non-variable electricity generations in the microgrid. As an example, electricity saved by the geothermal system scenario 5 was also added in the graph to visualize how the geothermal district heating system may improve the grid flexibility. For example, electrical load in the microgrid was significantly supplied by VRE sources (represented as green bars), particularly including wind and solar energy that may not be always available, while the graph shows that certain amount of electricity can be saved with the geothermal district heating system. In future study, this ongoing effort will be extended more quantitatively.



(a)



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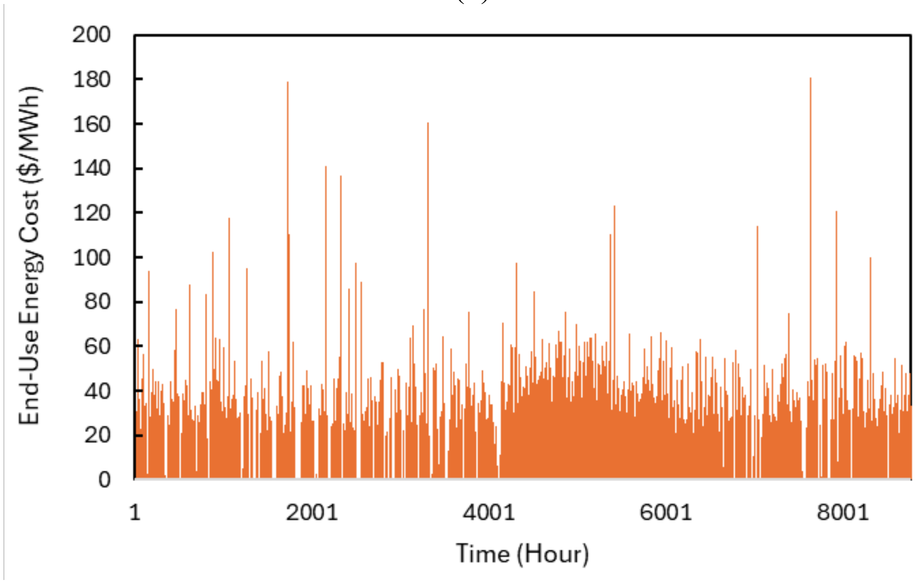

(c)

Figure 5. Cambium dataset used for grid flexibility analysis: (a) the U.S. map for generation and emissions assessment regions. The study area is represented with yellow star sign in p50 in SPP South (Gagnon et al. 2024). (b) electrical load profiles in the microgrid. (c) marginal costs induced by an increase in demand, or costs avoided from a decreased demand, for energy and capacity end uses in p50.

Figure 5(c) shows end-use marginal costs induced by increased demand or costs avoided from a decreased demand in p50. The end-use energy cost represents short-term marginal costs to provide the energy for a marginal increase in load including short-run costs that vary as a function of load, inter-balancing area transmission losses, and inter-balancing area transmission congestion, while other operational costs are not reflected in the energy cost (Gagnon et al. 2024). This is another ongoing effort of this study to quantitatively evaluate the impact of geothermal district heating system on energy cost in the microgrid.

5. Summary and Conclusion

The impact of geothermal district heating system on flexibility of microgrid in Tuttle, Oklahoma was discussed in this study. The annual heating demand profile in the microgrid was modeled using EnergyPlus and geothermal energy production was modeled with five different scenarios to estimate how much the heating load can be supplied by the geothermal systems. Then, electricity consumption by pumps to circulate water from the wells to radiators was estimated for the five scenarios, while electricity consumption by ASHP in base case was estimated to supply the same heating load. Electricity consumptions in the geothermal systems were significantly lower than those in base cases (about 10 times), and electricity saved by the geothermal systems was then calculated. Scenario 5, where the production depth was 3.3 km, showed the greatest geothermal energy production and electricity saving. The electricity saving from the geothermal scenario 5 was incorporated into the electrical load profiles in the microgrid showing potential improvements in grid flexibility especially during the winter season. The analysis will be further extended in future study to quantify the flexibility improvements and energy cost savings.

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