Grid Resilience Analysis on Geothermal District Heating and Cooling Implementation Alongside Four Existing Oil and Gas Wells in Tuttle, Oklahoma

Preprint

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Grid Resilience Analysis on Geothermal District Heating and Cooling Implementation Alongside Four Existing Oil and Gas Wells in Tuttle, Oklahoma

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Keywords

Resilience, REopt, Ground source heat pump, Plate heat exchanger, District heating and cooling, Oil and gas well

ABSTRACT

This study builds on the existing techno-economic and environmental life cycle assessments performed for a geothermal district heating and cooling system implementation in Tuttle Oklahoma with four existing oil and gas wells. Its resilience in meeting the peak annual heating and cooling loads of the district assuming a temporary disconnection from the electrical grid is assessed both qualitatively and quantitatively. Attributes of resilience and qualitative criteria established by Kolker et al. (2022) for geothermal district heating systems are applied to the proposed case to highlight its vulnerabilities. Results indicate that increasing the redundancy and diversity in the physical configuration of the distributional piping can considerably increase the system's resilience. A quantitative assessment executed via the REopt tool predicts that the ancillary electricity required to power the geothermal system's heating and cooling can be met by an onsite emergency diesel generator during times of grid outages for over 28 days.

1. Introduction

The resilience of an energy system describes its ability to sustain normal operation and meet typical loads during and around times of disruptions induced by various forces. Disruptions are a result of system component fatigue and end of life, natural disasters, extreme weather, human error, and upstream supply chain issues. As highlighted by Kolker et al. (2022), resilience is defined differently across stakeholders such that attributes of resilience (e.g., reliability, redundancy, resourcefulness, responsiveness) are discussed to compare the resilience across energy systems that differ in primary source (e.g., natural gas, photovoltaic, wind) and physical configuration/scale (e.g., distributed energy resources, district energy system).

The potential disruptions that an energy system risks and its suitability to be resilient in a given application are geographically dependent as the environmental, political, social, and economic context changes. For example, it is not logically sensible to compare the resilience of a concentrated solar microgrid operating in Texas, United States versus southern Chile due to the stark difference in the annual distribution of incoming solar irradiance, policy around energy (resources) and security, end-use applications and social patterns of energy consumption, and the cost to deliver energy from various primary sources. The most resilient energy system for each location would look very different because their unique risks yield an optimal solution that is impactful under the local conditions of the site.

Additionally, there is no uniformly established method of quantifying the resilience of an energy system. This makes the comparison of resilience between two different energy systems a rather qualitative exercise subject to criteria established by the analyst. The existing literature on energy system resilience is sparse, conceptual, and high level. It mainly discusses concepts and definitions related to energy resilience and proposes relevant metrics that can be analyzed and/or quantified for a comparative assessment of energy resilience. Additionally, studies on energy resilience tend to be focused on grid electricity generation rather than district heating and cooling for which geothermal as an energy source is least considered.

However, the topic of energy resilience is becoming an emerging area of study in regard to meeting energy demands in a time of increasing natural disasters and extreme weather events. Namely, heating and cooling which contributes to 35% of total end use building energy consumption is a crucial service to consistently uphold. Global average surface temperatures continue to increase at an alarming rate such that natural phenomena such as droughts and hurricanes have become stronger and witnessed more frequently. Their effects have been proven to devastate energy infrastructure, including the lives and services that are dependent on such. At the same time, energy consumption has increased due to climate change and population growth such that resilient energy systems are essential to minimize the disrupting effects of energy supply shortages to society and the economy during times of critical loads. Renewable energy presents itself as a promising solution to address one key driver (e.g., carbon emissions) of warming temperatures which in turn affects energy system functionality and energy consumption patterns. Specifically, geothermal energy is a resilient alternative to heating and cooling when compared to conventional systems due to low transportation needs in its upstream supply chain, a high capacity factor, long operational lifetimes, low operational costs, and subsurface equipment which is shielded from ambient conditions.

To address the lack in literature assessing the system resilience of geothermal energy, we consider the use of four abandoned oil and gas wells in Tuttle Oklahoma for a direct use geothermal district heating and cooling system implementation. Its resilience is evaluated relative to the existing decentralized natural gas system of boilers and furnaces in a district of 250 homes, a primary school, and a secondary school. Details on the techno-economic feasibility and environmental life cycle impacts of such energy system transition are detailed in Oh et al. (2024) and Marroquin et al. (expected), respectively. We leverage the criteria proposed by Kolker et al (2022) as a "variety of relative resilience criteria that can be evaluated to allow more structured analysis of resilience improvements associated with a particular resilience mitigation strategy" for qualitatively measuring the resilience of geothermal district heating systems. Additionally, we configure the National Renewable Energy Laboratory's (NREL's) local-scale renewable energy dispatch model named REopt for a quantitative resilience analysis of the proposed geothermal system to answer two key questions. First, what is the maximum grid outage duration that the geothermal system can withstand while meeting 100% of the heating and cooling demand of the district at a probability of at least 50% during times of peak electricity consumption by the geothermal system (i.e., during peak heating and cooling loads)? Second, what is the probability distribution that the geothermal system will survive the outage while meeting its heat load as a function of outage duration? The model considers the existing natural gas fired heating system of the district such that results highlight the net energy resilience benefits of a geothermal energy system implementation.

2. Methods

Kolker et al. (2020) summarizes current energy use in Arctic countries and dives into the opportunities for increased geothermal energy as a renewable resource for electric and thermal energy supply, including cascaded use. In doing so, resilience attributes of integrated geothermal energy systems are highlighted to determine whether techno-economically feasible geothermal systems would be resilient relative to the current energy practices in the Arctic. The high-level resiliency attributes of geothermal energy are leveraged to formulate a list of questions which are each attributable to one of the four pillars of resiliency, including reliability, redundancy, resourcefulness, and recovery. Unique sets of resilience attributes, components, and criteria are presented for geothermal power and thermal systems, respectively. In this study, we adopt the key resilience attributes and components of thermal systems (Table 3) from Kolker et al. (2022) to qualitatively measure the resilience of the proposed geothermal district heating and cooling system for the Tuttle district.

REopt is a web-based tool that evaluates the techno-economic feasibility of integrating renewable energy resources and more energy efficient methods into the existing power grid of a residential, commercial, or small industrial stock of buildings. The model can consider resources such as photovoltaics and geothermal heat pumps including systems with combined heat and power and battery storage. User defined inputs consist of energy goals (e.g., cost savings, clean energy), energy system technologies (e.g., wind, battery), site & utility information (e.g., site location, building floor area, heating fuel cost, utility provider), and energy load profiles (e.g., annual hourly electricity consumption, heating fuel consumption, and cooling load profiles). The model optimizes the capacity sizes and dispatch strategies of the integrated electric and thermal technologies such that the electric, heating, and cooling demands of the building stock are supplied at the site's lowest life cycle cost of energy.

For the case of this study, grid electricity, central plant water-to-water ground source heat pumps, and a diesel generator were selected in REopt as source technologies to supply the energy profiles of a primary school, secondary school, and 250 single family homes located in Tuttle Oklahoma. In the previous work of Oh et al. (2024), the representative building types of the district were modelled in EnergyPlus to simulate their energy flows and heat transfers. Outputs served as input into GEOPHIRES to estimate the potential geothermal energy that can be extracted from a nearby abandoned oil and gas well site to supply heat to the district. With an economic life cycle assessment executed in parallel, the techno-economic feasibility of a direct-use geothermal district heating and cooling system integration in the aforementioned Tuttle district was established. From the previous work in EnergyPlus, the output heating fuel consumption and cooling load of the buildings (Figure 1) was inputted into REopt.

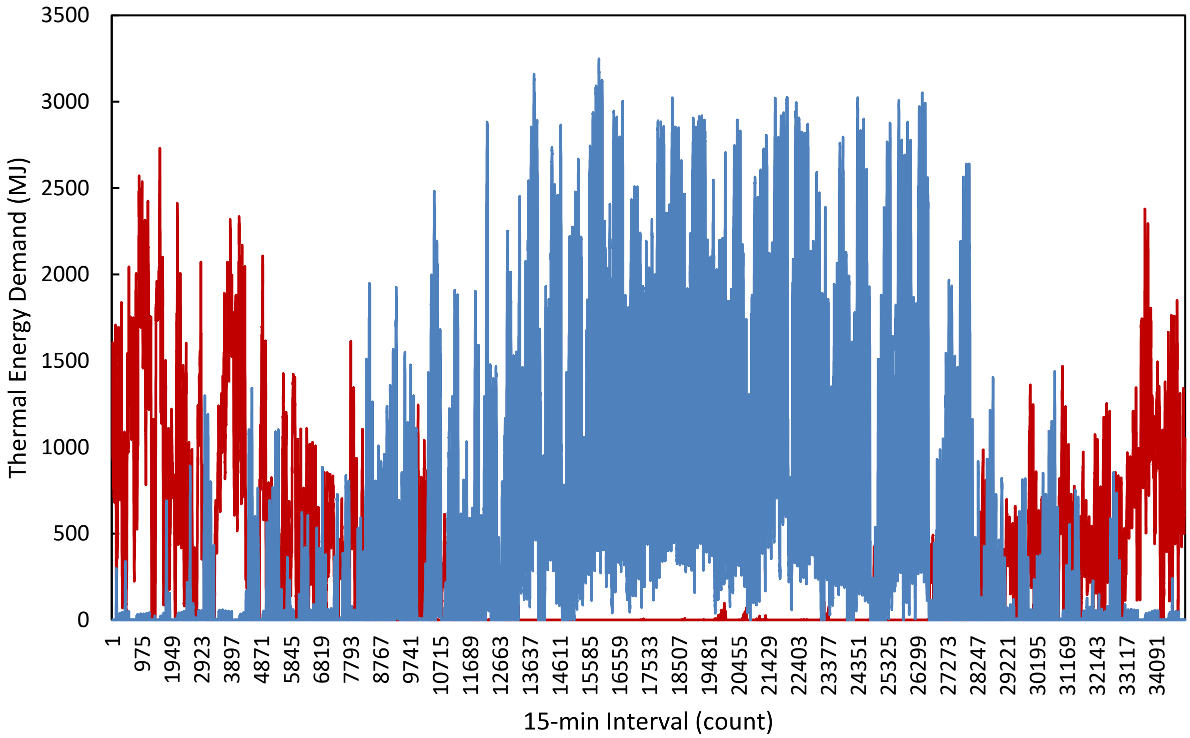

Figure 1: Heating and cooling demand of the Tuttle district as outputted by EnergyPlus based on the local weather and relevant energy performance parameters of the building stock

Although the direct-use geothermal system considers a central plate heat exchanger rather than central ground source heat pumps, a tool-based quantitative analysis of energy resilience is largely constrained to the limitations of the REopt tool. This is because no other tool with the same objective functionality exists to the knowledge of the authors at the time of this study. Geothermal capabilities within REopt are relatively new and currently have ongoing efforts to improve and expand such that the most representative energy system module within REopt to the proposed case of this study is central water-water ground source heat pumps. However, it is important to note that relevant metrics can be calculated following various approaches and equations as outlined in Das et al. (2020) whose applications are independent of the system design.

Additionally, results of Oh et al. (2024) indicated that the high electricity consumption required to power the cooling supply of the district relative to the heating supply via direct geothermal use deem the system techno-economical infeasible for cooling. This is because a direct-use geothermal system must be coupled with an absorption chiller to provide cooling in addition to heating. At the same time, a chiller requires electricity as its primary source of energy to extract heat from water while a central plate heat exchanger requires electricity as ancillary energy to extract and inject subsurface geothermal fluid. The electricity consumption of the chiller is about 80% of the cooling demand while the electricity consumption of the well pumps is orders of magnitude less than the heat demand. The annual cooling demand is also greater than heating by a factor of 1.32 and a 1:1 heat exchange is assumed at the central plate heat exchanger. As a result, significantly more electricity is consumed for cooling versus heating. More electricity consumption than a conventional air-conditioning system was concluded for the direct use geothermal system in cooling mode such that geothermal cooling is not techno-economically feasible via direct use. However, the central ground source heat pump system chosen in REopt to represent the proposed case study exhibits a higher annual average coefficient of performance (COP) for cooling relative to heating. It is determined by REopt as a function of inlet and outlet temperature. Therefore, the central plant water-to-water heat pumps within REopt are selected to serve as proxy for a geothermal system implementation that is techno-economically feasible of meeting the heating and cooling demand of the Tuttle district.

Furthermore, existing energy resilience analyses optimize electricity supply rather than heating and cooling. As an example, critical load within REopt is defined as the electricity demand that must be met during an outage (i.e., temporary disconnection from the electric grid) such that the probability of an off-grid energy system to meet the electric loads of a community is the metric to quantify the resilience of the system. However, a geothermal heating and cooling system is inherently tied to the electric grid. This is because delivering geothermal energy requires an ancillary electrical input to circulate fluid and upgrade the exergy of extracted geothermal energy as needed to meet a given demand. This means that during times of a grid outage, a geothermal heating and cooling system will lose functionality in addition to all other electrical appliances in a building. This also indicates that by specifying the electrical load of the district to be the total consumption at the meter as outputted by EnergyPlus (Figure 2), results of energy resilience from REopt would be optimized to meet the loads of existing electronic appliances rather than heating and cooling from geothermal energy.

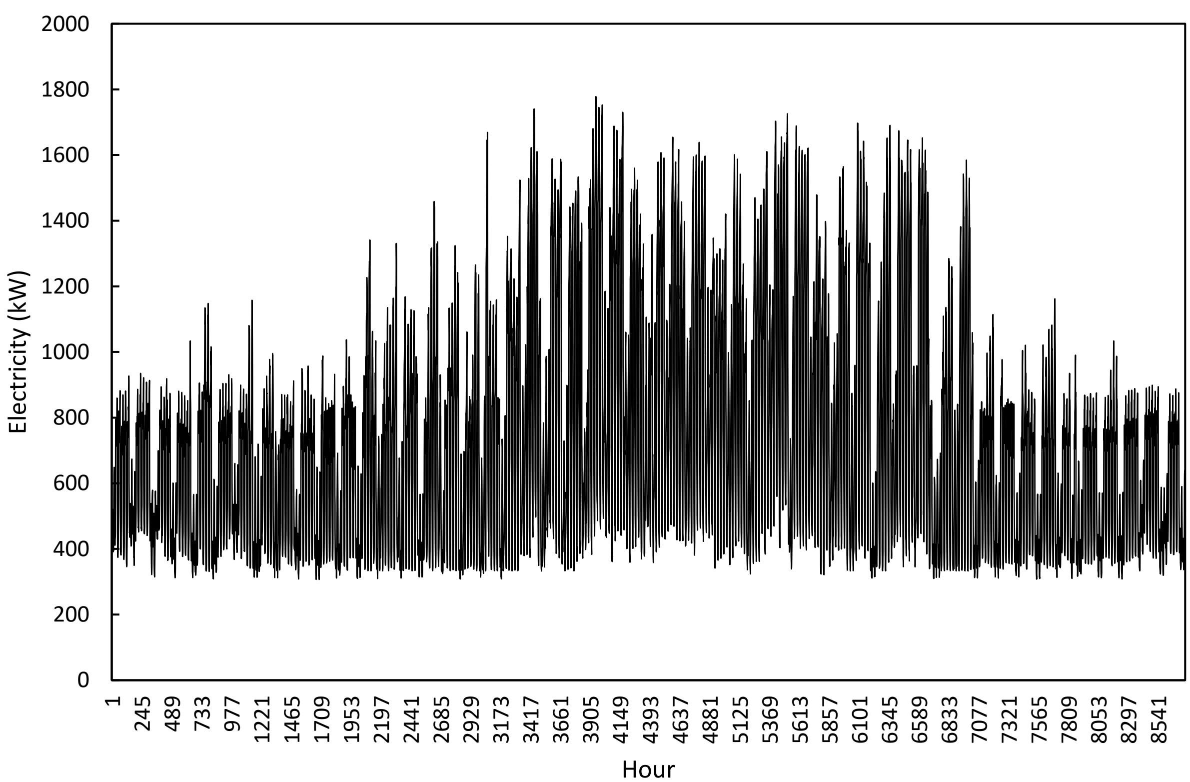

Figure 2: Electricity consumed by the district as outputted by EnergyPlus based on the local weather and relevant energy performance parameters of the building stock

Given that the objective of this study is to evaluate the resilience of a geothermal district heating and cooling system, the application of the REopt tool to assess energy resilience was strategically modified from current practice. To overcome its limitation of considering only the effect of an outage on electricity supply, REopt was executed in two sequentially dependent runs. The initial execution of REopt involved selecting only cost savings as the energy goal in order to generate and leverage cost optimal system performance dispatch information (i.e., the main functionality in REopt). The energy system dispatch represents a single-year of data at the hourly level of electricity generation and/or consumption by the technologies considered in the model's optimization. Non-zero electric loads are outputted for the relevant technologies if they are deemed cost effective for installation and operation against the continuing operation of the existing grid and heating and cooling system to meet building loads. However, new technologies can be forced into the solution of the objection function which is set to minimize the life cycle cost of energy even if operating the existing system is the cost optimal solution.

The adoption of a geothermal district heating and cooling system to displace the existing natural gas boilers and electric chillers of the Tuttle district results in a negative net present value such that by default, REopt outputs zero dispatch of the geothermal system. It also indicates that loads are met entirely by the grid and existing heating and cooling systems. This is due to the high upfront cost of manufacturing and installing the various geothermal energy system components which would not be required for the existing system. The integration of the diesel generator is also neglected due to the cost of delivering diesel as a fuel for on-site electricity generation rather than purchasing from the grid. Therefore, the geothermal heat pump was manually forced to be integrated into the solution by specifying in the inputs that its purchase and installation to displace the existing heating and cooling system is a constraint that must be met. The model now considers the input heating and cooling loads to be entirely met by the new geothermal technology. As a result, dispatch results contain the required annual electrical consumption profile of the ground source heat and circulation pumps to meet the specified heating and cooling demand of the district (Figure 1).

The hourly system performance dispatch results of the pumps for heating and cooling as outputted by REopt served as the input electrical load for the second simulation. GSHP as an energy source was unselected such that the electric grid and emergency diesel generator are the two options the model must now choose from to meet the electrical demand of the district. In this run, electrical demand represents the electricity required to deliver the heating and cooling demand of the district via a central plant geothermal heat pump system. At the same time, electricity is the constraining factor to a continuous supply of heating and cooling by the geothermal system during times of grid outages such that the resilience outputs of the new REopt run can be used to infer the resiliency of the geothermal system in supplying heating and cooling. In fact, one can expect the ancillary electrical energy needed by the geothermal system to be supplied by the off-grid emergency generator during times of grid outages.

The last input parameters to be specified in REopt before initiating the second run were specific to the assessment of resilience. The "multiple outage" model was selected to consider four 2-hour outages over the course of a year whose outage periods (i.e., start date and time) are by default determined by the model to occur at seasonal energy demand peaks based on the input electricity load profile and its seasonal maximum values. Mixed integer linear programming optimizes the objective function with respect to life cycle cost of energy such that demand is supplied at the lowest cost from various sources. This applies to times of critical and non-critical load. The sizing and dispatching of energy is constrained to the technologies specified by the analyst and their limitations (e.g., operational and maintenance cost). Therefore, loads met during times of grid outages by technologies with ancillary input electricity requirements (e.g., geothermal) must rely on a generator.

3. Results

Kolker et al. (2022) expands on the four qualitative attributes of energy system resilience by developing a list of criteria to assess large scale grid connected geothermal power systems, geothermal microgrids, and geothermal district heating systems (section 6). The criteria are presented as generic then further applied to a set of case studies representing existing systems in Artic countries. In this study, we adopt the established qualitative criteria to assess the resilience of the proposed geothermal district heating and cooling system of the Tuttle district in meeting the peak thermal loads of the district at times of electric grid disruptions. As formatted in Table 9 and 10 of Kolker et al. (2022), we present the results below.

Table 1. Qualitative criteria of resilience for a geothermal district energy system as established by Kolker et al. (2022) and applied to the proposed case of Tuttle Oklahoma

Attribute	**District Energy Components**
Reliability **(How does the system perform under typical conditions?)**	**Maintenance plans** Monitor heat carrier working fluid and refrigerant levels in the heat pump-based system and water in the distributional side of the direct use geothermal system. Replenish fluids to levels required for typical operating conditions as needed. Ensure geothermal heat extraction does not exceed regulation and reinjection of fluid follows protocol.
	Performance monitoring Continuously record the production and injection temperatures of the wells including production flow and geothermal exchange rates. Monitor inputs and outputs of system components during peak thermal loads.
	Age of system/components As part of the maintenance, track the length of service each system component has acquired since the commencement of its operation. Different units have varying design lifetimes.
	Maintain outage stats Document the energy flows of the system during times of grid outages. Statistically analyze historical data to predict the

Attribute	District Energy Components
	probability distribution of future outages. Leverage results to reinforce the system to better withstand such events.
	Leakage detection system As part of the maintenance, periodic checking of pipes for deterioration and signs of potential failure. Installation of continuous pressure monitoring system to detect fluctuations that occur at pipe failure.
Redundancy **(What single points of failure does the system exhibit?)**	**Multiple heat plants** Multiple water-to-water ground source heat pumps at central plant in the geothermal heat pump-based system. A heat exchanger of multiple brazed steel plates at the central plant and a natural gas boiler in the direct use geothermal system.
	Multiple heat sources Four inactive oil and gas wells 2 km south of the district with a borehole depth of 2.1 to 3.3 km and geothermal resource temperatures of 65 to 90 deg C. Geometry of wells offer a doublet or quartet configuration with variable flow rate and heat extraction.
	Redundant workforce Electric utility would ensure a secure grid connection of the geothermal system during normal operating conditions. An on-site team dedicated to maintaining the physical components of the district heating system would involve geothermal heat pump or plate heat exchange and water pump design experts.
	Redundant pumps Submersible water pumps sit inside the boreholes, circulation pumps between the wells and the central plant, and circulation pumps between the central plant and district. To prevent system malfunction due to pump failure, auxiliary backup pumps should be installed.
Resourcefulness **(Are there diverse and flexible options to bounce back from disruption?)**	**Building level thermal resilience** Thermal performance of buildings affects the loads imposed on energy systems and therefore indirectly influences the planning strategies for system resilience. Assuming thermal loads predicted by REopt will be consistent during anticipated grid outages, the thermal performance of buildings is not further considered as a

Attribute	District Energy Components
	factor affecting the resilience of the proposed geothermal district heating system in this study.
	Meshed distribution systems One production and one injection pipe form a closed geothermal loop at the wellfield side of the system. The distributional side consists of a central, bi-directional, hot/cold supply/return loop that connects to the piping networks of the individual buildings. Further efforts to design a more resilient pipe network is required to ensure the delivery of thermal energy in the case of a main line failure.
	Ability to exceed design capacity in extreme hot or cold events Thermal energy equipment sizing such as central heat pumps or absorption chiller are based on the annual peak heating and cooling demands of the district. A factor of safety in the design of each system component would be required to accommodate for extreme hot or cold events that exceed the current design capacity of the proposed geothermal system.
	Thermal storage capacity The central heat pump-based system can fully meet thermal requirements without any thermal storage, given sufficient electricity to fill the exergy gap between geothermal supply and thermal demand. The central plate-based system can also fully meet thermal requirements given sufficient natural gas for peak heat and an absorption chiller for cooling. In any case, thermal storage can be utilized to store energy when geothermal supply is greater than demand and used during peak thermal loads. This would decrease the dependency on imported electricity and natural gas.
	Ability to meet multiple temperature delivery needs Delivery of thermal energy is in the form of water. Existing buildings have temperature mixing valves such that they are repurposed for the proposed geothermal system to deliver water at desired and variable end use temperatures.
	Time to recover – thermal resilience of buildings Thermal performance of buildings affects the loads imposed on energy systems and therefore indirectly influences the planning strategies for system resilience. Assuming thermal loads predicted by REopt will be consistent during anticipated grid outages, the thermal performance of buildings is not further considered as a

Attribute	District Energy Components
	factor affecting the resilience of the proposed geothermal district heating system in this study.
	Ease of recovery – supply chain flexibility Supply chain issues during critical loads are not expected as the primary source of geothermal energy is undisrupted and diesel for electricity is stored on-site.
Recovery **(Will the system return to normal operation after undergoing a disruption?)**	**Standardized parts and supplies** For all major and minor physical system components, an up-to-date list of the most readily available vendors and manufactures must be maintained. Contact information and relevant products must be documented in the database.
	Plan for recovery Replace damaged components (if any) and redirect electrical input to geothermal system from grid to emergency generator. Monitor on-site supply of diesel. Ensure diesel shortages do not occur via communication with the electric utility regarding their recovery and informing the district of excessive thermal loads.
	Spare parts inventory Each main physical system component (e.g., heat pump) with an expected lifetime of less than 30 years must have a spare stored on-site. Ancillary components such as wirings and insulation can be ordered accordingly after unforeseen events occur.
	Workforce for recovery A specialized force would be kept on standby and deployed by the central, on-site maintenance team during grid outages to ensure expected functionality of the emergency generator in replacing the grid's service at critical loads.

As expected, the electricity required to supply the heating and cooling demand of the district during grid outages (i.e., critical load) is met entirely by the emergency diesel generator. It is expected to meet 100% of the critical loads at an average probability of 98.4% for an outage duration of two hours. This corresponds to an annual total of 5,162 kWh of electricity generated on site for which 1,206 kWh (23.4%) is attributable to the winter outage, 1,311 kWh (25.4%) to spring, 1,376 kWh (26.7%) to summer, and 1,269 kWh (24.6%) to autumn. Their corresponding times of occurrences which are consistent with the seasonal thermal demand peaks are February 17 at 3pm, May 24 at 2pm, June 14 at 2pm, and September 11 at 2pm.With an assumed fuel higher heating value (HHV) of 40.7 kWh/gallon and a thermal-to-electric conversion efficiency (% HHV-basis) of 32.2%, at least 394 gallons of diesel are expected to be stored on site per year to drive the critical heating and cooling load supply. Additionally, the maximum grid outage duration that REopt's Energy Resilience Performance (ERP) post-processing tool can consider is 672 hours (i.e., 28 days). For 28 days of dysconnectivity from the grid, the geothermal system has a 53.5% chance of meeting 100% of the heating and cooling demand during those times.

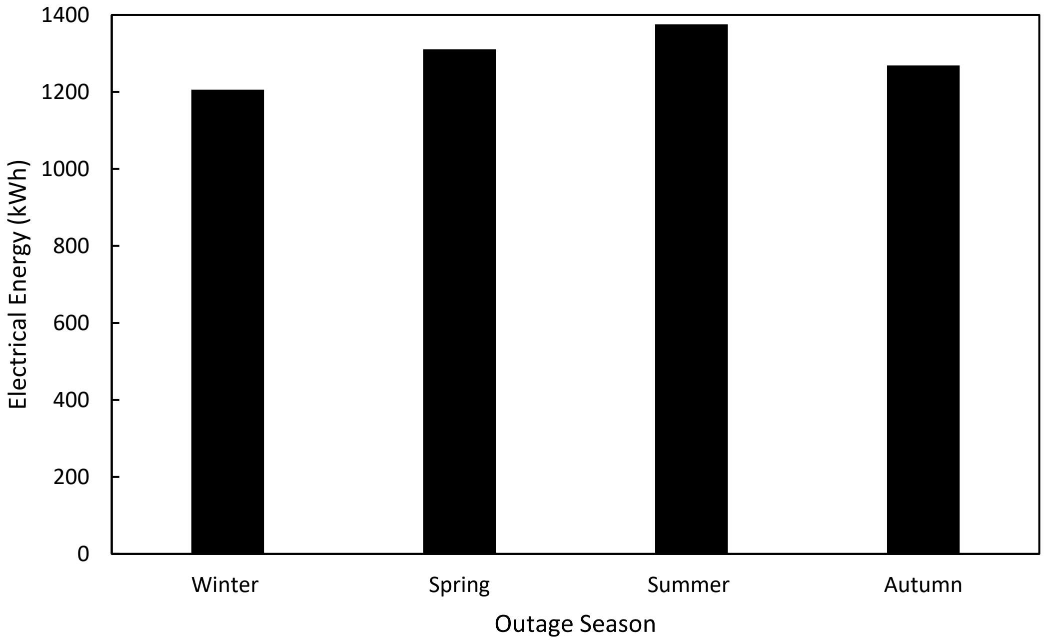

Figure 3: Electrical power supply of emergency diesel generator to geothermal heat pump system for heating and cooling during the Winter, Spring, Summer, and Autumn 2-hour grid outages occurring on February 17 at 3pm,May 24 at 2 pm (bottom), June 14 at 2pm, and September 11 at 2 pm, respectively

As the modelled outage duration increases from 1 to 672 hours, the average probability of surviving an outage starting at any time during the year steadily decreases (Figure 4). Although difficult to infer from the graph, the rate of change in probability decreases with respect to increasing outage duration. In other words, the difference in probability between surviving a 24- (96.4%) versus 48-hour (94.4%) outage is greater than the difference in probability between surviving a 624-hour (55.9%) versus 648-hour (54.7%) outage. This equates to a difference in probability of 2.08% versus 1.21%, respectively. The greatest rate of decrease in survival probability (1.52%) is observed between a 0-hour (100%) and a 1-hour (98.5%) outage.

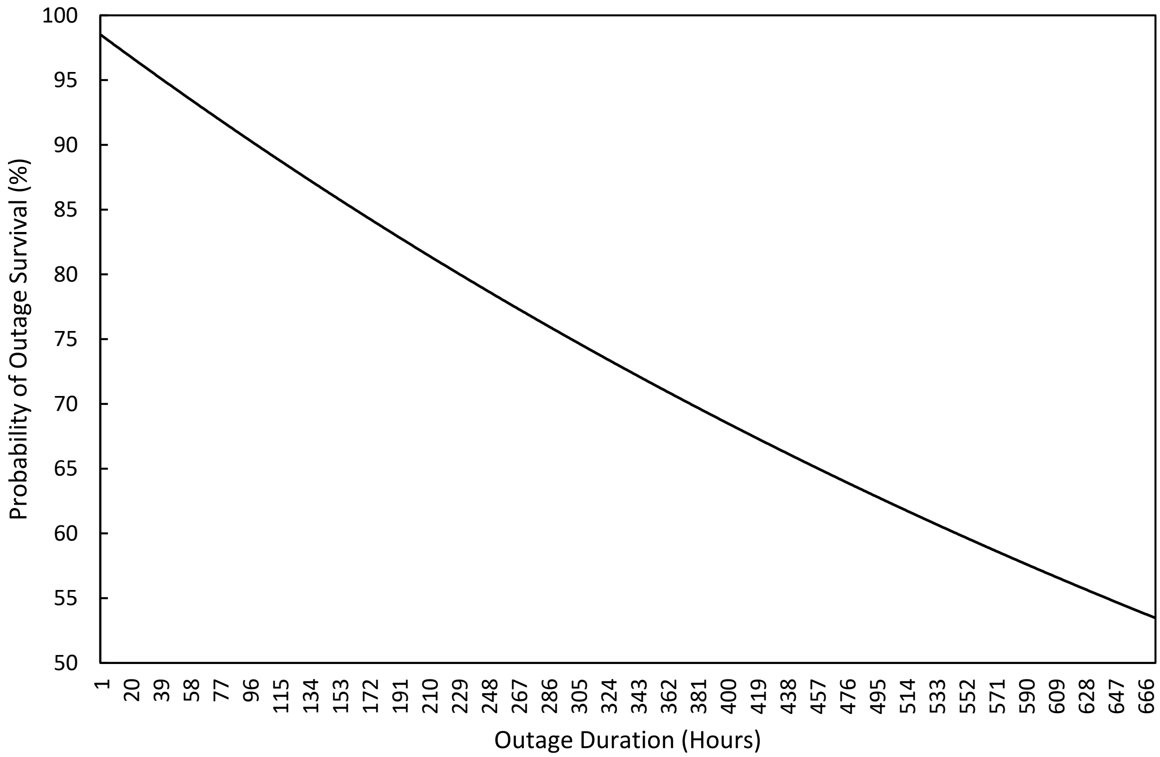

Figure 4: Probability distribution as a function of outage duration of outage survival for the emergency diesel generator in meeting the electrical load of the geothermal district heating and cooling system for a 2-hour outage

Conclusions

Literature and tools that assess the energy resilience of a geothermal district heating and cooling system are sparse in the existing domain. Additionally, the repurposing of inactive oil and gas wells for direct geothermal use is a renewable energy option that can meet the thermal loads of communities. This study adopts the qualitative framework from Kolker et al. (2022) and the quantitative assessment tool, REopt, from the National Renewable Energy Laboratory to establish the resilience of a direct-use geothermal district energy system in meeting the thermal loads of an existing community in Tuttle Oklahoma. The previous works of Oh et al. (2024) determined the techno-economic feasibility of such an energy system implementation via life cycle cost estimations, geologic modelling, and building energy simulations for which the results served as input to this study.

The qualitative assessment performed highlights critical properties of the proposed geothermal energy system which influence its reliability, redundancy, resourcefulness, and recoverability. While it also serves as a blueprint of best practices to maximize the system's resilience in meeting the typical thermal loads of the community, the quantitative assessment estimates the system's capability in meeting the four seasonal peak thermal loads with an assumed grid outage. Although the results of this study are high level, the methods described can serve as a foundational building block to increase the available literature on the intersection of energy resilience and geothermal district systems. Additionally, results can support others' analyses.

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