Identifying Regions Favorable for Geothermal Heating and Cooling Storage

Jonathan L. Ho and Yunzhi Chen

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-90201
September 2024

Identifying Regions Favorable for Geothermal Heating and Cooling Storage

Jonathan L. Ho and Yunzhi Chen

National Renewable Energy Laboratory

Suggested Citation

Ho, Jonathan L. and Yunzhi Chen. 2024. *Identifying Regions Favorable for Geothermal Heating and Cooling Storage*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-90201. https://www.nrel.gov/docs/fy24osti/90201.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-90201
September 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by GEOTHERMICA and JPP Smart Energy Systems Joint Call by the Research Council of Norway, U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Geothermal Technologies Office, and the Austrian Research Promotion Agency.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Acknowledgments

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This project has been subsidized through the Cofund GEOTHERMICA by the DOE Office of Energy Efficiency and Renewable Energy Geothermal Technologies Office (GTO). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

We thank Whitney Trainor-Guitton for her feedback during the study and for this report. We also thank Amanda Kolker for her original conceptualization of the GEOTHERMICA FLXenabler proposal. We also thank Arlene Anderson (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Geothermal Technologies Office) for her insights and support of the project.

List of Acronyms

AEO	Annual Energy Outlook
AMY	actual meterological year
EULP	end-use load profiles
EUSS	end-use saving shapes
GHC	geothermal heating and cooling
IWG	Interagency Working Group
NREL	National Renewable Energy Laboratory
ReEDS	Regional Energy Deployment System (model)
SCC	social cost of carbon

Table of Contents

List of Figures

List of Tables

1 Introduction

Space heating and cooling represents the single largest category of in-building energy use for U.S. residential and commercial buildings. Among the existing building stock, space heating is largely met using fuel-based technologies and represents 42% of residential and 32% of commercial energy demand (EIA 2022, 2023b). The prevalence of fuel use among building heating makes it a significant contributor of greenhouse gas emissions and highlights the need for electrification of building heating to meet decarbonization goals. Though building cooling demand does not directly emit CO_2, it represents the next largest portion of building energy consumption in the United States: 19% of residential and 14% of commercial. Opportunities to improve cooling efficiency as part of building electrification will reduce electric power consumption, easing the pathway to grid decarbonization. The 2022 Infrastructure Investment and Jobs Act, commonly known as the Bipartisan Infrastructure Law, contains provisions and tax incentives that support the adoption of building electrification technologies, making the analysis of this question particularly relevant (Infrastructure Investment and Jobs Act 2021).

Geothermal heating and cooling (GHC) systems with thermal energy storage provide unique advantages that could address needs for building space heating and cooling. Relative to air source heat pumps, geothermal systems can have greater efficiencies, particularly for building space heating and across different climates. Because of the design characteristics of geothermal systems—both district and individual buildings—there is a high suitability for connecting thermal energy storage, including surface and subsurface options.

Building space heating and cooling needs are inherently seasonal, and thermal energy storage (TES) can allow a system operator to shift energy usage seasonally. The stored energy and shifting can take advantage of low-cost sources of cooling and heating to meet end-user demand. For space heating, this could be in the form of storing waste heat or producing heat during low-cost periods in the grid. For space cooling, this could leverage sufficiently low ambient temperatures to operate heat exchangers and take advantage of free cooling during the winter months. In addition, storage systems could allow building heating and cooling systems to be operated in a way that is responsive to grid conditions for both seasonal and diurnal operations.

The analysis in this report is a component of the FLXenabler analysis, which examines the flexibility of heat pumps combined with TES applied from the local to national scale. By targeting locations with the most favorable conditions, the FLXenabler project intends to optimize the deployment of geothermal and TES systems, maximizing their impact on building decarbonization and energy efficiency. This report describes the national-scale modeling approach that identifies strategic locations where TES and GHC technologies have a high potential to achieve CO_2-reducing goals. Importantly, these locations are then passed along to more detailed, local modeling efforts that will incorporate physics-based performance modeling of the GHC technologies.

2 Methods

Metrics from the U.S. electrical grid were forecast to the year 2050 under different heating and cooling scenarios and compared to a business-as-usual scenario (referred to as the reference case). Proposed implementations of GHC with storage can be designed with one of three possible goals, to provide storage for cooling only, heating only, or both. For each of these district GHC storage designs we altered hourly end-use load profiles to fully eliminate electricity and fuel demand associated with residential space heating and cooling. In addition to the reference case, this produced three separate GHC storage potential scenarios which achieve full energy savings in 2050.

Three metrics were tracked for these scenarios:

- Costs to maintain and upgrade the electrical grid
- CO_2 emissions
- Fuel-savings costs to consumers.

To accomplish this, two core National Renewable Energy Laboratory (NREL) modeling tools were used: Residential Building Stock (ResStock) for heating and cooling and Renewable Energy Deployment System (ReEDS) for capacity expansion. This section provides details on which data products were used and the metrics designed to assess the ReEDS model-based results and to compare the four scenarios.

2.1 ResStock

To identify regions with higher favorability for storage with GHC, we must quantify the amount, timing, and type of building heating and cooling that could be shifted seasonally using storage. At the time of this analysis, end-use savings shapes (EUSS) for electric power and heating fuels associated with a district GHC system were not available. ResStock is an analysis tool developed by NREL that models U.S. residential building energy use (Reyna et al. 2022). The tool incorporates detailed data sources and uses physics-based building simulation models to provide detailed insights into energy consumption patterns. ResStock releases regular updates—including aggregations by building type and state—constructed from individual representative building data.

For this analysis, we used the 2022 ResStock version 1.1 release to capture the building space conditioning end-use load profiles (EULPs) (Wilson et al. 2022). Demand for space heating and cooling is closely aligned with the conditions of the local climate. Therefore, regional patterns of energy use identified in residential buildings can function as a suitable proxy for commercial data. In this release of ResStock, EULPs modeled using 2012 actual meteorological year (AMY) data were available, which aligns with an available metrological year for wind, solar, and load used in ReEDS. A consistent metrological year between load and resource data is important in ReEDS because it ensures consistency in how weather conditions, which influence both electricity demand and renewable energy generation, are represented, improving the fidelity of the modeling results. For this reason, data from the Commercial Building Stock (ComStock), which does not include 2012 AMY, was not used. was not included in this analysis. ResStock includes information about the hourly electric, fuel oil, propane, and natural gas requirements to meet building heating and cooling needs and the number of included residential units, specific to residential building type and state.

The building space conditioning hourly EULPs serve as an upper bound for energy reduction potential if current heating and cooling systems were to be replaced by a district GHC system. This could represent a system where all heating demand might be met by storing waste heat or all cooling is addressed through free cooling (cooling using ambient air without mechanical refrigeration). It is important to note that this assumption is overly optimistic, inefficiencies and storage losses would fall short of the upper bound heating and cooling energy reductions considered in this study. These EULPs as utilized are useful for considering relative regional favorability for GHC systems considering the type of space conditioning need and interactions with the power system. The consistent methodology of ResStock provides a fair basis for comparing the scale of opportunity for regions within the United States to benefit from storage for heating and cooling.

2.2 Renewable Energy Deployment System

ReEDS is an NREL capacity expansion model that represents the regionality and topology of the U.S. power system. ReEDS uses least-cost system optimization that considers new investments and operations of grid infrastructure (e.g., generation, storage, and transmission) while satisfying all system requirements—for example, ensuring electric power demand is met by supply at all times, providing sufficient resource adequacy and regulation reserves to ensure reliable grid operations, and ensuring enforced policy requirements are met. ReEDS includes up-to-date representations of state and federal policies such as the Cross-State Air Pollution Rule, investment and production tax credits, state renewable portfolio and clean energy standards, and regional and state CO_2 emission policies (Ho et al. 2021). ReEDS is modeled with sequential solves between years through 2050.

ReEDS has two distinct levels of temporal resolution: representative days are used by operations within the optimization whereas up to 7 years of hourly data are used to inform resource adequacy requirements and curtailment. To represent maximal energy savings potentials for heating and cooling, we subtracted the hourly electric demand profiles derived from ResStock heating and cooling from the existing hourly load profiles. The selection of representative hours for the optimization step is based on k-means clustering of the full hourly data, ensuring alignment between the two distinct temporal resolutions used in the model—including any heating and cooling load changes.

2.3 Modeled Scenarios

Analysis was completed for four distinct scenarios eliminating residential space heating and cooling demand:

- **Reference:** Business-as-usual electric power demand for building space heating and cooling.

- **Cooling Demand Only:** Electric power demand required for space cooling is eliminated by 2050.[1]
- **Heating Only:** Electric power and fuel demand required for space heating is eliminated by 2050.
- **Combined Heating and Cooling:** Electric power and fuels required to meet all space heating and cooling requirements are eliminated by 2050.

For each state in the contiguous United States, we apply the three heating and cooling scenarios, eliminating residential space heating and cooling demand to model state-specific impacts. The data used from ResStock were aggregated at the state level, which made the use of a more spatially aggregated version of ReEDS appropriate. This aggregation is largely at a state level, with a limited number of states divided to better preserve features of transmission system topology. Each of the ReEDS simulations models the entire contiguous U.S. power system, with changes to demand impacting investment and operations decisions within and outside the state. Each of the state-specific runs is compared relative to a ReEDS simulation that uses default load assumptions, referred to as the reference case.

Residential hourly end-use load profiles specific to each analysis scenario are gradually applied to the hourly load profiles through a linear transition starting with no change in 2021 to full application of the state-specific hourly change in electric power consumption profile by 2050. The rate of profile adoption is intended to be prescribed purely as a modeling exercise and does not indicate any policy or learning rate. The smooth transition avoids creating significant discontinuities in the load profiles between ReEDS timesteps, which could shift investment and operations decisions unrealistically.

---

[1] Space cooling depends entirely on electric power, not associated fuel usage.

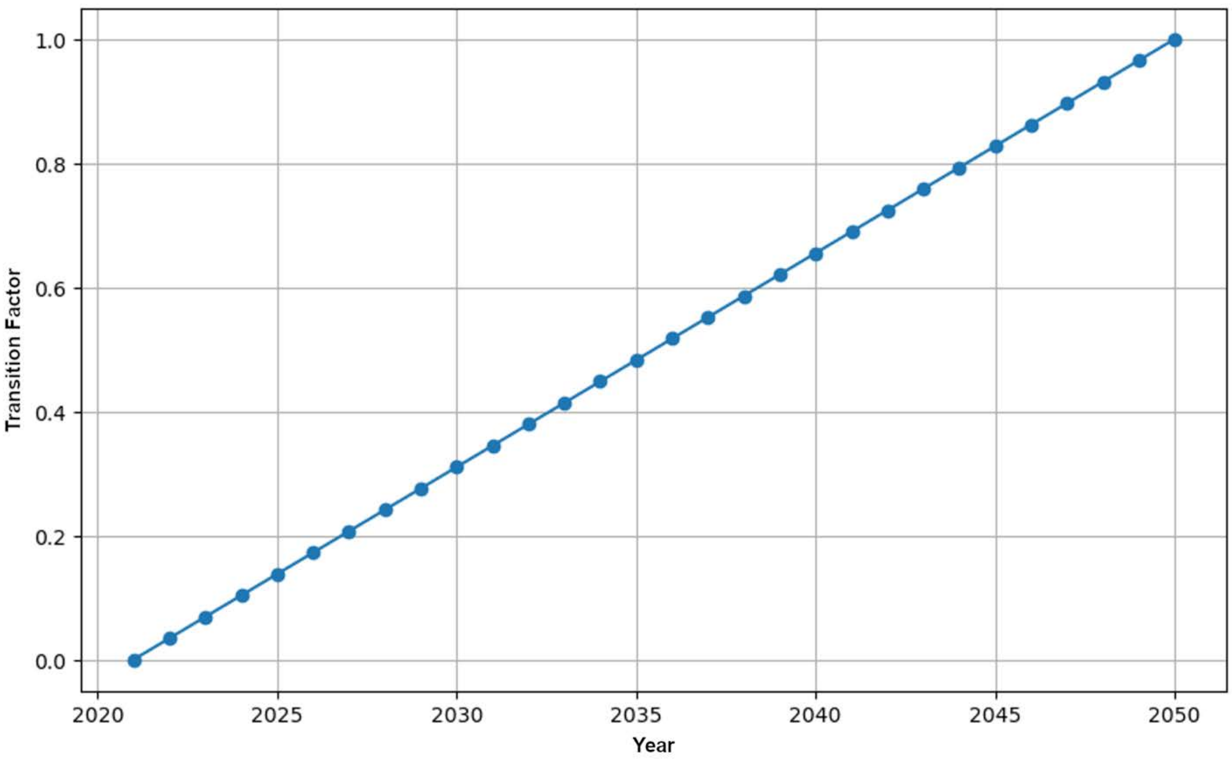

Figure 1 Factor indicating the portion of heating and cooling EULP modeled as offset through storage.

In addition to the residential heating and cooling reduction, each scenario also included a power-sector-specific decarbonization policy, with 95% reductions in emissions relative to 2005 by 2050. The modeled policy and cost assumptions are closely aligned with Mid-Case 95% Decarbonization from Standard Scenarios 2023 (Gagnon et al., 2024).

2.4 Metric for Geothermal Heating and Cooling Favorability

Though a central focus of this analysis is quantifying the impact to the grid from reduced electric power demand, it is not the sole value to be considered. The ability to impact building fuel consumption and associated emissions (social cost of carbon [SCC]) is an important consideration when identifying priority regions for GHC technologies. To make these three impact areas (grid costs, in building fuel costs, and emissions damages) comparable, we calculated the change in present value for each category relative to the reference case and normalized by the total number of residential units in 2050. Costs within the metric are calculated for 2023 present value and dollar year, assuming a 2% discount rate.

$$GHC\ Favorability\ Metric =$$

$$\frac{\Delta\ Electric\ Power\ System\ Cost + \Delta\ Fuel\ Costs +\ \Delta\ SCC\ Emissions}{Total\ Units\ in\ 2050}$$

Electric power system costs are based on the total system cost in ReEDS and include the financed cost of investments and operations for the model time horizon (e.g., 2023–2050). ReEDS usually includes, as part of the optimization, the value of investment and production tax credits to inform investment and operation decisions. However, for this metric we excluded these components to more holistically measure the impact to grid costs.

The fuel costs were calculated using the annual consumption of fuel oil, natural gas, and propane and multiplying by Annual Energy Outlook (AEO) 2023 regional residential fuel cost projections (EIA 2023a). A linear transition between 2021 and 2050 was applied to the fuels to determine consumption for a specific year. This aligned methodologically with the treatment for electric power demand and ensured a fair basis for comparison. No changes in fuel consumption occur in the No Cooling scenario because the impacts are isolated entirely to electric power demand.

To include CO_2 emissions as a component of the metric, we needed to consider it in terms of a monetary value. Though the emission of CO_2 has no direct costs in the United States, we assigned a value based on the externalities that account for the indirect costs and negative consequences of emissions (Cole et al. 2023). There exists a range of estimates for the externality cost of CO_2, depending on discount rates and what affects are included in analysis. We used the Interagency Working Group (IWG) value of $51 per ton SCC (IWG 2021).

The resulting metric quantifies the relative benefit on a per-residential-unit basis, allowing comparison between states. It is important to note changes in assumption in any of the three categories (different ReEDS simulation assumptions, altered fuel costs, or a higher SCC) would change the value of the metric and the proposed metric should serve as an effective starting point for further regional analysis.

3 Results

3.1 Combined Heating and Cooling Favorability

The combination of building heating and cooling identifies states where there exists the greatest opportunity to address the combination of building heating and cooling demands. The results demonstrate regional patterns in GHC favorability, driven by climate and state-specific heating and cooling technologies. The states of New England have significant heating loads because of their cold climates, and a high proportion of their units relies on heating oil. These high energy costs give them higher rank in GHC favorability (shown in Figure 1), with their patterns of demand dominated by heating requirements. Outside of New England, the GHC favorability metric is composed of a higher fraction of the grid costs (electricity) compared to in-building fuels. This reflects a shift toward greater cooling loads and milder climates, which enjoy a greater installation base of air-source heat pumps.

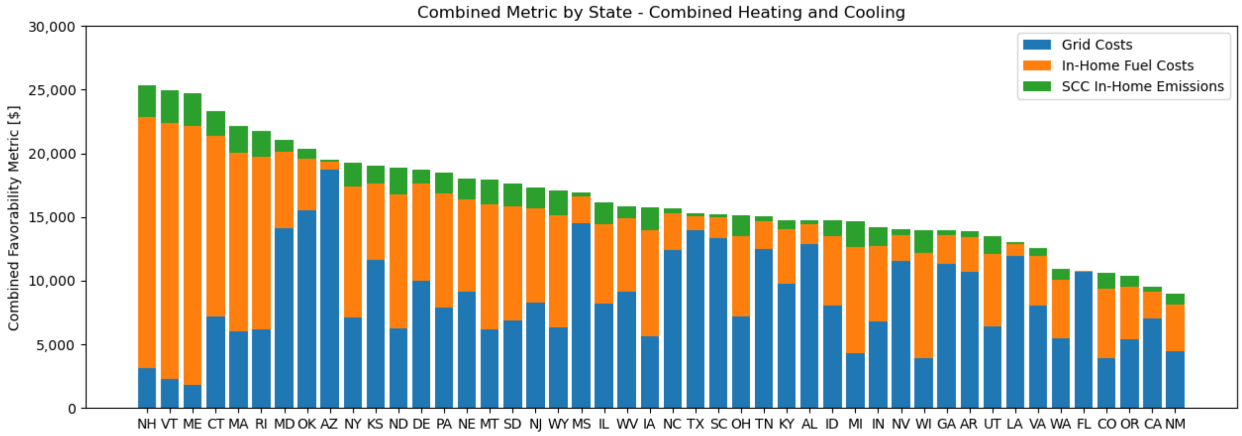

Figure 2. Favorability for fulfilment of residential space heating and cooling through GHC with storage

Table 1 outlines the top 10 states for the combined metric, breaking down the three contributions for the GHC favorability metric. For the combined metric, the top 10 most favorable states are dominated by cold climate regions. Regions with mixed humid climates make up a significant portion of the latter portion of the top 10. The only hot climate region listed in the combined table is Arizona, with substantial per building cooling requirements.

Table 1. Ten Most Favorable States for Addressing Heating and Cooling Using GHC With Storage

Rank	**State**	**Combined Favorability [$/Unit]**	**Most Populous Metro Area**		**Second Most Populous Metro Area**	
			Name	**BA Climate Zone**	**Name**	**BA Climate Zone**
1	NH	25,400	Manchester	Cold	Nashua	Cold
2	VT	24,900	Burlington	Cold	South Burlington	Cold
3	ME	24,700	Portland	Cold	Bangor	Cold
4	CT	23,300	Bridgeport	Cold	Hartford	Cold
5	MA	22,200	Boston	Cold	Worcester	Cold
6	RI	21,700	Providence	Cold	Warwick	Cold
7	MD	21,100	Baltimore	Mixed-Humid	Washington, D.C.	Mixed-Humid
8	OK	20,400	Oklahoma City	Mixed-Humid	Tulsa	Mixed-Humid
9	AZ	19,500	Phoenix	Hot-Dry	Tucson	Hot-Dry
10	NY	19,300	New York City	Cold	Buffalo	Cold

3.1.1 Building Cooling Only

In contrast to the earlier combined metric, the building cooling load removal scenario only impacts electric power consumption within the GHC favorability metric, as air conditioners and heat pumps are all electrically powered. The southeastern U.S. region has the largest representation of favorable sites for this cooling reduction only scenario. Hot-dry states in the Southwest—including Arizona and Nevada—are also highly favorable among the opportunities for building cooling.

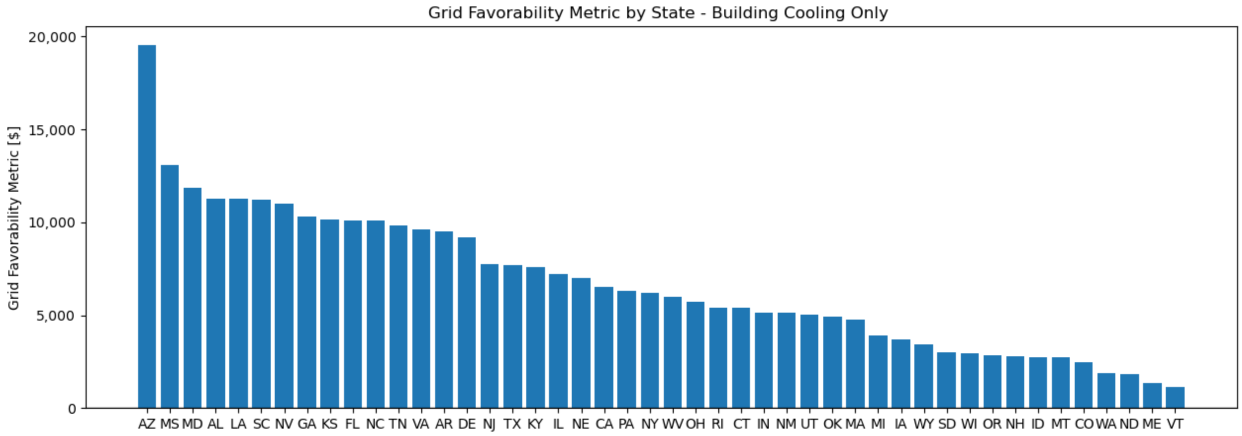

Figure 2. Electric power only favorability for fulfilment of residential space cooling through GHC with storage

Among the 10 best performing states based on favorability, there exists an intermix between states' population centers with hot climates and mixed climates (see Table 2). The regions with mixed-humid climate may present a better opportunity because they would be more likely to have conditions to support free cooling, which may be more challenging in hot-dry and hot-humid locations.

Table 2. Ten Most Favorable States for Fulfilling Residential Cooling Using GHC With Storage

Rank	State	Grid Favorability [$/Unit]	Most Populous Metro Area		Second Most Populous Metro Area	
			Name	BA Climate Zone	Name	BA Climate Zone
1	AZ	19,600	Phoenix	Hot-Dry	Tucson	Hot-Dry
2	MS	13,100	Jackson	Hot-Humid	Gulfport	Hot-Humid
3	MD	11,900	Baltimore	Mixed-Humid	Washington, D.C.	Mixed-Humid
4	AL	11,300	Birmingham	Mixed-Humid	Mobile	Hot-Humid
5	LA	11,200	New Orleans	Hot-Humid	Baton Rouge	Hot-Humid
6	SC	11,200	Columbia	Mixed-Humid	Charleston	Hot-Humid
7	NV	11,000	Las Vegas	Hot-Dry	Reno	Cold
8	GA	10,300	Atlanta	Mixed-Humid	Augusta	Mixed-Humid
9	KS	10,100	Kansas City	Mixed-Humid	Wichita	Mixed-Humid
10	FL	10,100	Miami	Hot-Humid	Tampa	Hot-Humid

3.1.2 Building Heating Only

Building heating in this scenario is dominated by northern states with colder climates (Figure 3). Similar to the combined heating and cooling favorability result, New England states show high favorability, driven in part by high regional fuel costs. In comparison, states such as North Dakota and Montana also rank highly but benefit from lower comparable fuel costs.

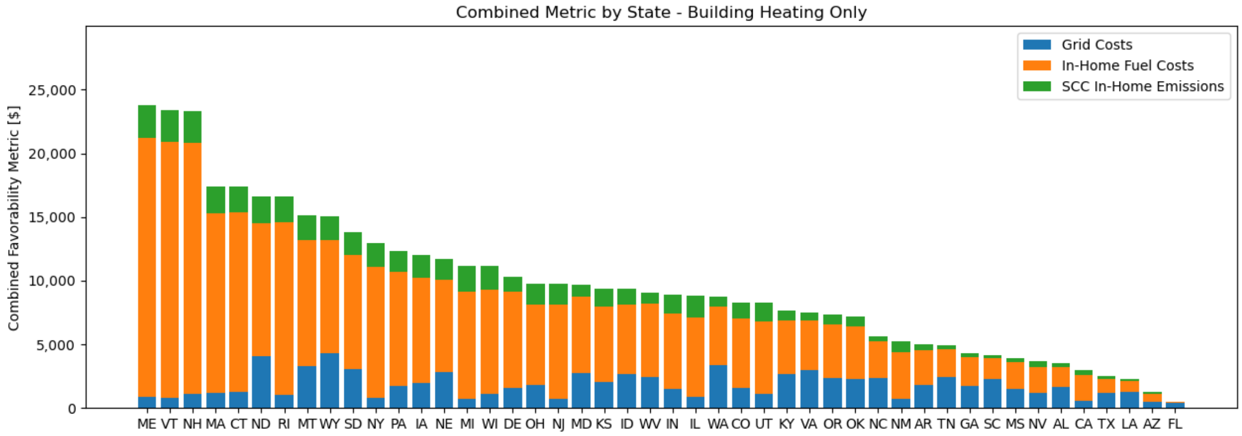

Figure 3. Favorability for fulfilment of residential space heating through GHC with storage

The states with the highest favorability for addressing heating alone are within cold or very cold climate zones. This contrasts with the greater intermixing of climate zones shown in the combined metric. Suitability for addressing space heating through GHC with storage is a function exclusively of demand; climate is not a significant consideration in the ability to supply heat. In contrast to cooling where low ambient temperatures to supply free cooling might be required, opportunities to apply space heating could benefit from heat pumps or waste heat and could be available in these regions (Table 3).

Table 3. Ten Most Favorable States for Fulfilling Residential Heating Using GHC With Storage

Rank	**State**	**Combined Favorability [$/Unit]**	**Most Populous Metro Area**		**Second Most Populous Metro Area**	
			Name	**BA Climate Zone**	**Name**	**BA Climate Zone**
1	ME	23,800	Portland	Cold	Bangor	Cold
2	VT	23,400	Burlington	Cold	South Burlington	Cold
3	NH	23,300	Manchester	Cold	Nashua	Cold
4	MA	17,400	Boston	Cold	Worcester	Cold
5	CT	17,400	Bridgeport	Cold	Hartford	Cold
6	ND	16,600	Fargo	Very Cold	Bismarck	Cold
7	RI	16,600	Providence	Cold	Warwick	Cold
8	MT	15,100	Billings	Cold	Missoula	Cold
9	WY	15,100	Cheyenne	Cold	Casper	Cold
10	SD	13,800	Sioux Falls	Cold	Rapid City	Cold

4 Summary

Past quantifications of energy saving benefits from building simulation typically focus on the quantify of energy saved and costs built upon fixed energy price profiles (Present et al., 2024). Incorporating region specific electric power savings, in ReEDS captures how grid investments and operations would shift to a new equilibrium. Using the combined present value of electric power grid system costs, fuel savings, and carbon savings, all states were ranked by their relative favorability. The approach utilized in this study provides a holistic measure for identifying where GHC with storage characteristics would have the greatest benefit.

Our analysis identified the regional distribution of favorability for district GHC with storage to provide seasonal storage for heating, cooling, or both. Location specific analysis is planned as part of the FLXenabler effort, using tools like SUTRA modeling of subsurface storage and URBANopt district energy analysis (Provost, Alden & Voss, Clifford, 2019). The metrics calculated in this study will prioritize which locations should be considered for more granular modeling and whether prioritizing heating or cooling is more favorable.

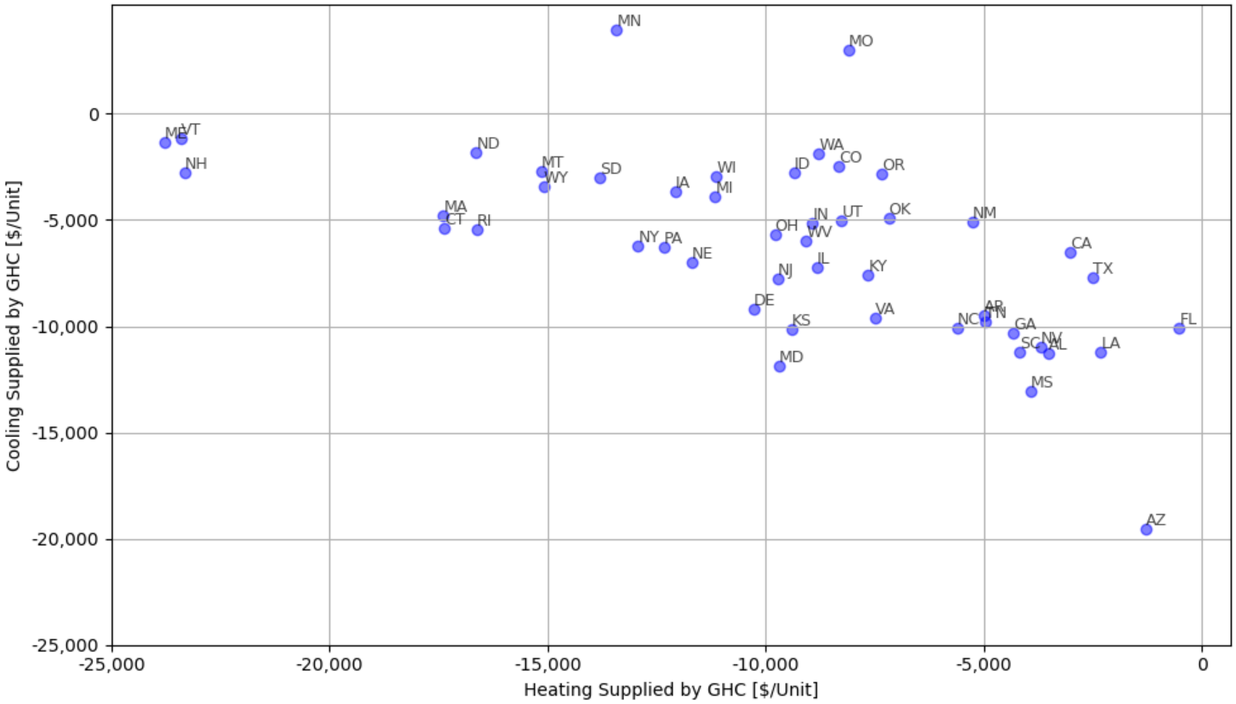

Figure 4. Distribution of states based on exclusive heating vs. exclusive cooling favorability metrics. Heating favorability increases for states further to the left of the plot, while cooling favorability increases for states lower on the plot.

The most favorable states are largely concentrated in cold climate zones with significant portions of existing building heating demand met using fuels. The distribution of states based on building heating and cooling are shown in Figure 4; states with greater cooling benefits are toward the bottom right corner of the plot. States with greater heating benefit are distributed toward the top right corner of the plot[2].

The ResStock data are represented at a state level, which limits insights into the potentially significant intrastate differences within climate and population density—factors that would influence the favorability of a district GHC system. With district heating and cooling systems benefiting from density we provided the two largest metropolitan areas in each state along with their associated climate zones to provide further relevant location information for analysis. In subsequent analysis it will be important to consider the locational suitability for developing storage systems. Examples of these considerations include whether a location has the necessary subsurface geology for storage or for free cooling if temperatures are sufficiently low to operate heat exchangers with the ambient air.

Our analysis finds that there are substantial operational savings potential in leveraging storage to meeting building heating and cooling needs. Offsetting building cooling over heating has a greater potential to reduce electric power system costs given the current mix of end-use technologies to provide building space conditioning. For heating the existing building stock benefits are oriented heavily towards reduced fuel consumption and in building emissions. While not considered as part of this study, electrification using air source heat pumps would shift the heating energy consumption from fuels (e.g. natural gas) to electricity increasing the potential scope of benefit for interactions between the grid and district GHC storage.

The subsequent planned analysis will provide detailed insights into how district GHC with storage would operate and what changes to energy and costs could be expected. Deployed at scale these demand side technologies have a potential to address building decarbonization goals and operate responsive to grid conditions. Following further developments in ResStock and ComStock along with work planned as part FLXenabler study, further analysis GHC storage linked to power system modeling tools would provide important insights into opportunities for addressing energy system decarbonization goals.

---

[2] Missouri and Minnesota showed a small increase in costs associated with reducing cooling demand, which is likely an effect of the sequential solve used in ReEDS and should not be considered a robust result.

References

Cole, W., Antonysamy, A., Brown, P., Sergi, B., Mai, T., & Denholm, P. (2023). How much might it cost to decarbonize the power sector? It depends on the metric. *Energy*, *276*, 127608. https://doi.org/10.1016/j.energy.2023.127608

EIA. (2022). *Commercial Buildings Energy Consumption Survey (CBECS)*. Energy Information Agency. https://www.eia.gov/consumption/commercial/data/2018/pdf/CBECS%202018%20CE%20Release%202%20Flipbook.pdf

EIA. (2023a). *Annual Energy Outlook 2023*. U.S. Energy Information Administration. https://www.eia.gov/outlooks/aeo/pdf/AEO2023_Narrative.pdf

EIA. (2023b). *Residential Energy Consumption Survey (RECS)* [Dataset]. https://www.eia.gov/consumption/residential/data/2020/

Gagnon, P., Pham, A., Cole, W., Awara, S., Barlas, A., Brown, M., Brown, P., Carag, V., Cohen, S., Hamilton, A., Ho, J., Inskeep, S., Karmakar, A., Lavin, L., Lopez, A., Mai, T., Mowers, J., Mowers, M., Murphy, C., … Williams, T. (2024). *2023 Standard Scenarios Report: A U.S. Electricity Sector Outlook* (NREL/TP-6A40-87724). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy24osti/87724.pdf

Ho, J., Becker, J., Brown, M., Brown, P., Chernyakhovskiy, I., Cohen, S., Cole, W., Corcoran, S., Eurek, K., Frazier, W., Gagnon, P., Gates, N., Greer, D., Jadun, P., Khanal, S., Machen, S., Macmillan, M., Mai, T., Mowers, M., … Zhou, E. (2021). *Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/78195.pdf

Infrastructure Investment and Jobs Act, Pub. L. No. 117–58 (2021). https://www.govinfo.gov/content/pkg/PLAW-117publ58/pdf/PLAW-117publ58.pdf

IWG. (2021). *Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide*. Interagency Working Group on Social Cost of Greenhouse Gases, United States Government. https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

Present, E., White, P., Harris, C., Adhikari, R., Lou, Y., Liu, L., Fontanini, A., Moreno, C., Robertson, J., & Maguire, J. (2024). *ResStock Dataset 2024.1 Documentation* (NREL/TP--5500-88109, 2319195, MainId:88884; p. NREL/TP--5500-88109, 2319195, MainId:88884). https://doi.org/10.2172/2319195

Provost, Alden & Voss, Clifford. (2019). *SUTRA, a Model for Saturated-Unsaturated, Variable-Density Groundwater Flow with Solute or Energy Transport—Documentation of Generalized Boundary Conditions, a Modified Implementation of Specified Pressures and Concentrations or Temperatures, and the Lake Capability* (Techniques and Methods) [Techniques and Methods]. U.S. Geological Survey. https://pubs.usgs.gov/tm/06/a52/tm6a52.pdf

Reyna, J., & et al. (2022). *U.S. Building Stock Characterization Study: A National Typology for Decarbonizing U.S. Buildings* (NREL/TP-5500-83063). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy22osti/83063.pdf

Wilson, E. J. H., Parker, A., Fontanini, A., Present, E., Reyna, J. L., Adhikari, R., Bianchi, C., CaraDonna, C., Dahlhausen, M., Kim, J., LeBar, A., Liu, L., Praprost, M., Zhang, L., DeWitt, P., Merket, N., Speake, A., Hong, T., Li, H., … Li, Q. (2022). *End-Use Load Profiles for the U.S. Building Stock: Methodology and Results of Model Calibration,* *Validation, and Uncertainty Quantification* (NREL/TP-5500-80889). National Renewable Energy Laboratory. https://doi.org/10.2172/1854582

Appendix A Scenario Value Metrics

Table A-1. Value Metric for Eliminating Residential Heating and Cooling Energy Consumption

Rank	State	Grid Costs [$/Unit]	Fuel Costs [$/Unit]	Emissions [$/Unit]	Combined [$/Unit]
1	NH	3,160	19,700	2,510	25,400
2	VT	2,310	20,100	2,520	24,900
3	ME	1,840	20,300	2,580	24,700
4	CT	7,180	14,200	1,990	23,300
5	MA	6,000	14,100	2,110	22,200
6	RI	6,200	13,500	2,020	21,700
7	MD	14,100	6,020	921	21,100
8	OK	15,500	4,090	766	20,400
9	AZ	18,700	657	140	19,500
10	NY	7,150	10,300	1,880	19,300
11	KS	11,700	5,930	1,410	19,000
12	ND	6,260	10,500	2,100	18,800
13	DE	10,000	7,610	1,100	18,700
14	PA	7,880	9,000	1,630	18,500
15	NE	9,170	7,200	1,660	18,000
16	MT	6,140	9,860	1,970	18,000
17	SD	6,860	8,950	1,800	17,600
18	NJ	8,250	7,410	1,630	17,300
19	WY	6,320	8,830	1,920	17,100
20	MS	14,500	2,100	336	16,900
21	IL	8,200	6,240	1,690	16,100
22	WV	9,160	5,760	890	15,800
23	IA	5,650	8,300	1,800	15,800
24	NC	12,400	2,870	397	15,700
25	TX	13,900	1,110	216	15,300
26	SC	13,300	1,620	240	15,200
27	OH	7,180	6,340	1,640	15,200
28	TN	12,500	2,140	389	15,000
29	KY	9,770	4,250	750	14,800
30	AL	12,900	1,590	271	14,700
32	MI	4,300	8,350	2,060	14,700

Rank	State	Grid Costs [$/Unit]	Fuel Costs [$/Unit]	Emissions [$/Unit]	Combined [$/Unit]
33	IN	6,770	5,960	1,470	14,200
34	NV	11,500	2,050	464	14,000
35	WI	3,950	8,200	1,840	14,000
36	GA	11,300	2,250	350	13,900
37	AR	10,700	2,740	486	13,900
38	UT	6,420	5,690	1,430	13,500
39	LA	12,000	860	169	13,000
40	VA	8,020	3,950	587	12,600
41	WA	5,500	4,560	836	10,900
42	FL	10,700	67	10	10,800
43	CO	3,890	5,450	1,270	10,600
44	OR	5,400	4,160	794	10,400
45	CA	7,050	2,100	390	9,530
46	NM	4,440	3,710	846	9,000

Table A-2. Value Metric for Offsetting Residential Space Cooling Energy Consumption

Rank	State	Grid Costs [$/Unit]
1	AZ	19,600
2	MS	13,100
3	MD	11,900
4	AL	11,300
5	LA	11,200
6	SC	11,200
7	NV	11,000
8	GA	10,300
9	KS	10,100
10	FL	10,100
11	NC	10,100
12	TN	9,800
13	VA	9,590
14	AR	9,510
15	DE	9,180
16	NJ	7,760

Rank	**State**	**Grid Costs [$/Unit]**
17	TX	7,700
18	KY	7,560
19	IL	7,230
20	NE	7,010
21	CA	6,550
22	PA	6,280
23	NY	6,220
24	WV	5,980
25	OH	5,720
26	RI	5,430
27	CT	5,400
28	IN	5,130
29	NM	5,110
30	UT	5,040
31	OK	4,920
32	MA	4,780
33	MI	3,880
34	IA	3,690
35	WY	3,420
36	SD	3,010
37	WI	2,930
38	OR	2,820
39	NH	2,770
40	ID	2,750
41	MT	2,710
42	CO	2,480
43	WA	1,870
44	ND	1,800
45	ME	1,360
46	VT	1,150

Table A-3. Value Metric for Offsetting Residential Space Heating Energy Consumption

Rank	State	Grid Costs [$/Unit]	Fuel Costs [$/Unit]	Emissions [$/Unit]	Combined [$/Unit]
1	ME	914	20,300	2,580	23,800
2	VT	791	20,100	2,520	23,400
3	NH	1,100	19,700	2,510	23,300
4	MA	1,220	14,100	2,110	17,400
5	CT	1,240	14,200	1,990	17,400
6	ND	4,050	10,500	2,100	16,600
7	RI	1,070	13,500	2,020	16,600
8	MT	3,310	9,860	1,970	15,100
9	WY	4,340	8,830	1,920	15,100
10	SD	3,070	8,950	1,800	13,800
11	NY	785	10,300	1,880	12,900
12	PA	1,700	9,000	1,630	12,300
14	NE	2,850	7,200	1,660	11,700
15	MI	755	8,350	2,060	11,200
16	WI	1,100	8,200	1,840	11,100
17	DE	1,570	7,610	1,100	10,300
18	OH	1,810	6,340	1,640	9,790
19	NJ	692	7,410	1,630	9,730
20	MD	2,750	6,020	921	9,690
21	KS	2,050	5,930	1,410	9,390
22	ID	2,670	5,480	1,200	9,350
23	WV	2,420	5,760	890	9,070
24	IN	1,500	5,960	1,470	8,920
25	IL	897	6,240	1,690	8,830
26	WA	3,390	4,560	836	8,780
27	CO	1,600	5,450	1,270	8,320
28	UT	1,140	5,690	1,430	8,250
29	KY	2,650	4,250	750	7,650
30	VA	2,960	3,950	587	7,500
31	OR	2,380	4,160	794	7,340
32	OK	2,310	4,090	766	7,170
33	NC	2,340	2,870	397	5,600

Rank	**State**	**Grid Costs [$/Unit]**	**Fuel Costs [$/Unit]**	**Emissions [$/Unit]**	**Combined [$/Unit]**
34	NM	694	3,710	846	5,250
35	AR	1,780	2,740	486	5,000
36	TN	2,440	2,140	389	4,970
37	GA	1,710	2,250	350	4,310
38	SC	2,310	1,620	240	4,170
39	MS	1,480	2,100	336	3,920
40	NV	1,190	2,050	464	3,700
41	AL	1,650	1,590	271	3,520
42	CA	535	2,100	390	3,020
43	TX	1,160	1,110	216	2,490
44	LA	1,290	860	169	2,310
45	AZ	481	657	140	1,280
46	FL	434	67	10	511