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Abstract: Underground Thermal Energy Storage (UTES) has emerged in both specific applications and within energy policy literature as a promising technology for meeting thermal loads with locally collected and stored solar energy, as well as several other potential applications, such as time-shifting of grid-based wind and solar power to better align variable generation with loads. In Europe, UTES systems have experienced increased deployment in connection with district heating systems. But despite this academic attention and several demonstration projects, the commercial market viability of UTES systems has yet to be established in North America, and the finance world uses different conceptions of viability than engineering or academic studies. This study explores, through the conventions of finance and risk-mitigation, what capital costs North American UTES systems would need to exhibit to achieve market viability; which is to say, the up-front cost at which a UTES system represents an attractive investment when compared with natural gas-based systems for the provision of residential space heating.

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Cover Letter: Renewable Energy

Dear Referees,

Please accept this manuscript, entitled "Solar District Heating with Underground Thermal Energy Storage: Pathways to Commercial Viability in North America," for your consideration for publication in *Renewable Energy*. The research in this manuscript is funded by the United States National Science Foundation's Sustainable Energy Pathways program, grant number 1230237. The authors report no conflicts of interest.

Thank you for your consideration,

Adam L. Reed

*Highlights

Highlights

- Our model develops 10,000 scenarios for the lifetime costs of both underground thermal energy storage for solar district heating (UTES-SDH) systems and non-weatherized gas furnace (NWGF) systems, based upon historical gas prices and heating degree days in each of the 15 states, under both historical conditions and the Representative Concentration Pathway (RCP) 8.5 climate change scenario of the Climate Model Intercomparison Project.
- As the model spans a significant time-scale, it also considers the effects of inflation and discounts the future costs of both systems into today's dollars using discounted cash flow (DCF) analysis. This captures the value of the UTES-SDH system as a financial hedge against fuel price uncertainty.
- We estimate greenhouse gas emissions savings attributable to the UTES-SDH system under both the RCP8.5 and historical climates, utilizing EPA estimates for CO_2 emitted per thousand ft^2 of natural gas burned by NWGFs.
- The model's calculated discounted savings per home represents the per-unit breakeven cost of a UTES-SDH system as compared to NWGF systems under prevailing methods of financial analysis: the capital expense at which a rational investor would be indifferent between the two systems. This figure estimates a target "cost to beat" in order for the technology to compete economically with NWGF systems in the 15 states examined, presuming no additional subsidies are provided and presuming a lack of a price on greenhouse gas emissions. This target cost result ranges from ~$36,000 per home in Massachusetts, if funded through municipal bonds, and presuming low impacts to heating demand from climate change, to ~$17,500 per home in Idaho, if funded through a private residential cooperative, presuming significant effects of climate change on heating demand.
- Massachusetts, in particular, stands out as uniquely positioned to drive prospects for UTES-SDH, as the state exhibits high heating demands, above-average retail natural gas prices, and a high Mcf NG/HDD proxy suggesting an average of less thermally efficient buildings than in other states we examined. Utah, to a lesser extent, also exhibits favorable market conditions.

DRAFT

Solar District Heating with Underground Thermal Energy Storage: Pathways to Commercial Viability in North America

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Abstract

Underground Thermal Energy Storage (UTES) has emerged in both specific applications and within energy policy literature as a promising technology for meeting thermal loads with locally collected and stored solar energy, as well as several other potential applications, such as time-shifting of grid-based wind and solar power to better align variable generation with loads. In Europe, UTES systems have experienced increased deployment in connection with district heating systems. But despite this academic attention and several demonstration projects, the commercial market viability of UTES systems has yet to be established in North America, and the finance world uses different conceptions of viability than engineering or academic studies. This study explores, through the conventions of finance and risk-mitigation, what capital costs North American UTES systems would need to exhibit to achieve market viability; which is to say, the up-front cost at which a UTES system represents an attractive investment when compared with natural gas-based systems for the provision of residential space heating.

Keywords: solar thermal energy; solar district heating, underground thermal energy storage, borehole thermal energy storage, financial viability, risk mitigation.

Introduction

The intermittency of renewable energy resources is one of the primary challenges to their effective and wide scale deployment. Stated broadly, the problem involves how to make renewable energy available contemporaneously with energy demand. Experts have proposed a variety of approaches, including geographically-larger and more efficient transmission systems which reduce aggregate variability and allow a wider range of time zones for matching generation with loads (MacDonald et al. 2016), electrical energy storage and electro-chemical storage to hold charge for several hours at a time (Dunn et al. 2011, Alotto et al. 2014), and thermal storage approaches (geothermal borehole arrays, paraffin-based systems, hydrated salts) for longer-term energy storage and reduction of aggregate electrical load magnitude and variability (Jacobson et al. 2015b, Farid et al. 2004).

Underground thermal energy storage (UTES) systems used for solar district heating (SDH), as demonstrated at the 1.6 MW_{th} Drake Landing Solar Community in Okotoks, Canada, can shift peak-intensive space heating loads away from grid-based electricity or natural gas delivery systems (McClenahan et al. 2006; Sibbitt et al. 2012). If widely deployed, coupled UTES-SDH systems could thus contribute to reduced electric load variability and smaller electric power system peaks where they displace electric resistance heating. Jacobson et al. (2015b) also envision UTES systems as potentially providing storage of thermal energy collected from utility-scale wind, solar, and hydropower systems for months or even years, though this usage is theoretical at present and outside the scope of our inquiry.

The importance of the Drake Landing Solar Community project in generating attention and enthusiasm for UTES-SDH systems cannot be understated, but it is important to note that it is a publicly-funded demonstration project and not a commercial viability study. UTES-SDH systems in North America have yet to empirically demonstrate economic viability through robust real-world deployment. And while some larger UTES-SDH systems in Northern Europe have done so, they experience fundamentally different infrastructural and market conditions than those that North American UTES systems are likely to face, and so are an imperfect analogue (Reed and McCartney 2015).[1]

In this study, we examine the financial prospects for future North American UTES-SDH systems by considering the decision-processes of investors with available capital and a variety of competing options from which to choose. We have thus created a financial breakeven model that calculates the potential energy and cost savings of a residential community-scale UTES-SDH system deployed in lieu of natural gas furnaces over the entire estimated 60-year life of the system. To do so, the model integrates location-specific residential heating demand forecasts with a forward-looking retail natural gas pricing simulation for each of the top 15 heating demand states (North Dakota, Minnesota, Wyoming, Montana, Wisconsin, South Dakota, Colorado, Iowa, Michigan, Idaho, Utah, Massachusetts, Nebraska, Illinois, and New York) and performs a run-cost calculation for natural gas furnaces in each state over a 60-year period (the expected lifetime of a UTES system) including fuel, maintenance, and regular replacement costs. It then discounts those costs back to present value, which allows side-by-side comparison to the up-front investment cost of UTES-SDH systems. The result is a target break-even capital cost for UTES-SDH systems at which rational investors would consider them equivalent to conventional natural gas furnaces in each of the 15 states. Critical to this approach is the framing of the UTES-SDH system as a financial instrument: a hedge for the system owner against fluctuations in natural gas prices that would otherwise cause uncertainty in future space-heating costs.

Background

UTES-SDH systems combine solar thermal collection technologies with long-term thermal energy storage methods, often in the form of closed-loop soil borehole heat exchangers. Unlike batteries and other short-term energy storage, UTES is capable of storing thermal energy for months or years, and dispatching it on-demand to users irrespective of ambient temperatures or the present availability of sunlight (Reed and McCartney 2015, McCartney et al. 2013, Zhang et al. 2012; Nussbicker 2012, Baser et al. 2016).

The Drake Landing Solar Community in Okotoks, Canada is illustrative of the typical system design principles for UTES as envisioned in recent literature. 800 roof-mounted solar panels absorb energy from the sun to heat a water-glycol solution circulating through an insulated collector system connecting all of the panels. Heat is transferred from the glycol-water solution to water storage tanks in a central maintenance facility. These tanks provide short-term

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[1] Specifically, European SDH systems often benefit from legacy district heating infrastructures that used to be served by natural gas cogeneration, waste incineration, or other sources, and so do not require the higher capital cost outlays that are associated with brand-new SDH systems.

thermal energy storage on a diurnal basis. In the warmer months of the year, a separate closed-loop system is used to extract heat from the water-filled tanks by circulating a water glycol solution through an array of 144 37-meter-deep boreholes installed beneath a small park in the center of the neighborhood. By the end of the summer, the circulation of heated water through the borehole array leads to an increase in ground temperature to approximately 80 °C. In the wintertime, when sunlight is scarce and the panels do not collect much heat, the heat flow in the borehole array is reversed and distributed to a third district heating loop that distributes the thermal energy to the 52 homes in the community (Sibbitt et al. 2012, Sibbitt et al. 2015). The system has been providing approximately 90% of the annual space heating needs of the highly-efficient homes in the community, which normally experience 9,027 heating degree days per year. The efficiency of heat storage has been improving over several seasons (Zhang et al. 2012; Sibbitt et al. 2012; Catolico et al. 2016). The remaining heat is provided by a centralized natural gas boiler system that also serves the district heating loop.

Though SDH systems are rare in North America, they have expanded rapidly in Northern Europe in the last decade. A number of these systems have coupled SDH systems with UTES systems, including a 13 MW_{th} system in Braedstrup, Denmark; a 5.1 MW_{th} system in Crailsheim, Germany; a 4 MW_{th} system in Neckarsulm, Germany; a 1.7 MW_{th} system in Groningen, The Netherlands; a 1.7 MW_{th} system in Anneberg, Sweden; and a 0.8 MW_{th} system in Kerava, Finland (Solar District Heating 2016). The rapid expansion is due in part to high fossil fuel prices, preexisting district heating infrastructures, clean energy subsidies, and related energy policies and market conditions (Chittum and Østergaard 2014, Reed and McCartney 2015). These conditions are notably different from North America, where subsidies are lower (Wüstenhagen and Menichetti 2012), natural gas is inexpensive (Wang et al. 2014), and there is a general absence of pre-existing district heating infrastructure other than the remnants of century-old downtown steam systems (Ulloa 2007).

Capital costs for installed SDH systems in Northern Europe range from 400 to 800 USD/m^2 of installed solar collectors (Dalenbäck and Werner 2012). But these figures are not sufficient for estimating UTES-SDH system capital costs in the US because of pre-existing district heating infrastructures in Northern Europe that were initially run using natural-gas-fired combined-heat-and-power plants. SDH systems in Europe thus rarely need to build distribution or storage capacity from scratch, and can connect solar thermal collectors directly to the existing heat distribution system. The Drake Landing system, which had to construct both storage and distribution infrastructure from scratch, achieved capital costs of approximately 1,100 USD/m^2 of installed solar collectors (Sibbitt et al. 2012, Sibbitt et al. 2015).

The relatively high initial cost of UTES-SDH systems may be balanced by their longevity and minimal operational costs when compared to conventional natural gas furnaces, which require fuel to operate and must be replaced approximately every 20 years (Petro 2016). Manufacturers claim that UTES ground loop components typically last well over 50 years (Geothermal Genius 2014) and solar thermal panels last approximately 30 years (YouGen 2011). Critical to the successful deployment at scale of UTES-SDH systems is confidence among investors that they will provide substantial fuel, maintenance, and replacement cost savings over the life of the system under a variety of potential scenarios for heating demand and natural gas prices. We have thus attempted in this study to quantify cost savings in terms of net present value for potential UTES-SDH systems in each of the 15 U.S. states with the highest number of annual heating degree days.

Methodology

UTES-SDH and non-weatherized gas furnace (NWGF) systems realize their respective costs over different time-horizons: UTES-SDH systems require significant upfront costs, but have minimal operating expenses and long lifespans – approximately 60 years[2]; gas furnaces have lower upfront costs, but shorter lifespans and higher operating expenses due to maintenance and fuel costs (DOE 2015). Moreover, the highly predictable costs of the UTES-SDH system have their own financial value as a hedge against uncertainty compared to historically volatile fuel costs. In order to compare the two investment options on the basis of net present value (NPV), we have constructed an uncertainty-driven system lifetime-cost model[3] that compares capital and operating costs between UTES-SDH and NWGF systems for a 50 home development, over a 60-year time horizon, on a state-by-state basis, discounted to present value. The central feature of the model is its forecasting of annual prices for residentially-delivered natural gas through a probabilistic simulation that performs 10,000 independent iterations based on historical price inflation and volatility.[4] In the language of finance, this approach conceptualizes the UTES-SDH system as a long-term investment wherein returns are realized through hedging against difficult-to-predict fluctuations in fossil fuel prices. Thus the model aims to capture not only the value of potential savings under 10,000 separate fossil-fuel price scenarios in the future, but the value today of being insulated from price uncertainty over the given time period.

The practical goal of the model is to quantify the maximum up-front expenditure for a UTES-SDH system that would satisfy a breakeven NPV against an alternative investment in NWGFs. In other words, the model calculates the initial capital expenditure equivalent to the value of the system's hedge against uncertainty—a point where the life-time cost for the UTES-SDH and the comparable costs associated with NWGF systems for the same period are equivalent. This value may then serve as a target capital cost for future efforts at commercializing UTES-SDH systems in North America. Our model considers unique environmental and market conditions for 15 states: Colorado, Idaho, Illinois, Iowa, Massachusetts, Michigan, Minnesota, Montana, Nebraska, New York, North Dakota, South Dakota, Utah, Wisconsin, and Wyoming. These

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[2] Empirical data on the lifespan of a modern, commercially-installed UTES loop system is not yet solidified. We have decided on 60 years as a reasonable estimate, but this may require revisiting in subsequent studies as more data is available.

[3] Our model utilizes Analytic Solver Platform for Education (ASPE), a commercially-available platform that facilitates the construction of uncertainty-driven models.

[4] We have elected to model future natural gas prices in this mechanics-agnostic fashion so as to match the practices of the business/finance community, as opposed to the energy forecasting community. As such, the model reflects a desire to hedge risk broadly rather than an attempt to forecast prices or theorize about the drivers of natural gas price movements.

states were chosen due to their cold climates[5] (NOAA 2016), as well as their primary utilization of natural gas for residential space heating (US Census Bureau 2016).

The model develops 10,000 scenarios for the lifetime costs of both UTES-SDH and NWGF systems, based upon historical gas prices and heating degree days in each of the 15 states, under both historical conditions and the Representative Concentration Pathway (RCP) 8.5 climate change scenario of the Climate Model Intercomparison Project (Petri and Caldeira 2015). Historical and projected heating degree days for all 15 states are listed in Table 1 (all tables are located in the appendix). The NWGF system's costs include the initial purchase and installation of the gas furnaces for each of the 50 homes, as well as annual maintenance and replacement after their useful lives are complete (DOE 2015).[6] DOE estimates the average annual maintenance cost for NWGFs at $62.30 and expected lifespan at 21.5 years, with significant volatility in useful life estimates.[7] We assume that our homes incur the average cost of purchase and installation of NWGFs at $3,894 (Home Advisor 2016).[8] The time of replacement for the NWGFs is simulated using the above distribution of useful lives. The cost model for the UTES-SDH incorporates system-wide operating and maintenance costs, along with the expected lifespan of the system's back-up heat-generation system.[9]

The model constructs residentially-delivered natural gas prices over the next 60 years as a product of average annual price inflation μ and standard deviation of annual price inflation σ over the past 30 years for each state (EIA, 2016a), displayed in Table 2. The annualized continuously compounding inflation rate for natural gas was derived from EIA data for each of the 15 states through the equation

$$Annual\ Inflation = \ln\left(\frac{RP_t}{RP_{t+1}}\right)$$

where RP_t is the real price of gas in the base year and RP_{t+1} is the real price of gas in the following year for the state. Averages and standard deviations of historical price inflation were calculated from these thirty data points, and assigned unique values of μ and σ, respectively, for each state.

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[5] As measured by annual heating degree days (HDDs)

[6] Electricity costs are assumed to be negligible in this iteration of the model (NYSERDA 2013).

[7] Here, assumed to be normally distributed with standard deviation 3 years.

[8] We break with DOE estimates of these costs, as they differ with the Air-Conditioning, Heating, and Refrigeration Institute (AHRI 2015).

[9] While robust data sets exist for the expected lifespans and maintenance costs for single-home gas furnaces, data for the costs and lifespans of both industrial boilers and solar thermal collectors (STCs) are more difficult to access. Currently, we do not take into account the 30-year lifespan of STCs (NREL 2016), and assume that the UTES-SDH system would require a $10,000 industrial boiler that faces the same expected lifespan as single-home furnaces. We have arbitrarily assumed $500 per year in other maintenance costs for the UTES-SDH system.

Using this data, the model runs 10,000 possible future scenarios for the price of residentially-delivered natural gas for all 15 states. Simulated, state-specific price increases were modelled for 60 years and were calculated through the equation

$$MP_{t+1} = MP_t * e^x$$

where MP_t is the modeled price of gas in year t, x is a normally-distributed random variable with mean μ and standard deviation σ, and MP_0 is equal to the cost of the state's residentially delivered natural gas as of February, 2016 (EIA 2016b). Representative data from the Wisconsin and Massachusetts simulations are displayed in Table 3.

These annual prices are then translated into the model housing development's estimated annual space heating costs using a proxy variable for the amount of natural gas used as a function on the cold experienced by the home. This proxy variable translates the HDDs experienced by the home over the course of a year into the amount of natural gas used by the average NWGF-heated home. The proxy variable was constructed on a state-by-state basis by cross-referencing the average consumption of natural gas in homes heated by natural-gas furnaces in 2009 (EIA 2013) with the actual HDDs those homes experienced in 2009.[10] The state-specific proxy variables were calculated using the equation

$$P = \frac{\mathrm{N\mu}}{\mathrm{H}}$$

where P is the proxy variable for each state, N_μ is the average amount of natural gas used by homes with natural gas furnaces in the state in 2009, and H is the amount of heating degree days experienced by the state during 2009.[11] These proxy variables, listed for each state in Table 4, provide an approximation of the amount of natural gas used by the average home in each state as a function of the cold weather the home experienced. The proxy variable is then multiplied by NOAA's normalized HDDs for each state (NOAA 2016) and the modelled residentially-delivered natural gas prices in order to forecast space heating costs per unit for the NWGF system over the entire 60-year period, displayed in Tables 5 and 6. As demonstrated by the Drake Landing Solar Community, a UTES-SDH system can reduce district-wide natural gas consumption by 94% (McClenahan et al. 2006, Sibbitt et al. 2015), which allows for a projection of life-time savings in natural gas costs of the UTES-SDH system as compared to NWGFs.

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[10] At present, the non-RCP 8.5 scenario assumes that the development will experience the NOAA's normalized HDDs for each state over the entirety of the 60 year study period, but we intend for future iterations of this study to better incorporate the effects of climate change and weather uncertainty under a variety of scenarios.

[11] Our present model only uses data from 2009 to construct the proxy variable, as previous EIA residential gas usage surveys only offer regional data, while the 2009 survey gives state-by-state information. In the future, we will refine our data as further insights are furnished by the EIA.

The natural gas consumed by both systems is modelled as a linear product of the amount of cold experienced by the home, so the model estimates space heating costs using both the normalized historical HDDs experienced by each state (Table 4), and the expected HDDs under the Representative Concentration Pathway (RCP) 8.5[12] climate change scenario of the Climate Model Intercomparison Project (CMIP5) (Petri and Caldeira 2015) (Table 5). A graphical comparison of the 15-State average of simulated space heating costs under no-climate-change and RCP 8.5 scenarios is displayed in Figure 1. Under the RCP 8.5 scenario, we linearly model the decrease in HDDs in each state across the 60-year evaluation period. Using the equation

$$HDD_t = HDD_0 * \frac{t}{60} * \Delta_{HDD}$$

Where HDD_t is the modeled heating degree days experienced by the specific state in year t, the number of years after the system's installation in 2016, HDD_0 is the state's normalized heating degree days, and Δ_{HDD} is the expected change in HDDs experienced by each state, as modelled by the RCP8.5 scenario.

As the model spans a significant time-scale, it also considers the effects of inflation and discounts the future costs of both systems into today's dollars using discounted cash flow[13] (DCF) analysis. We assume that the future prices incurred for repairs, maintenance, and replacement of system components can be calculated by applying the annualized inflation rate for the last 30 years, 2.74% (BLS 2016). We have run the model with two different discount rates to reflect two possible financing schema for a project of this scale. The first scheme considers municipal funding for the initial capital expenditure and an issuance of a 20 year, AAA municipal bond. These results are displayed in Tables 7 and 9. We used current AAA municipal bond yields (Yahoo Finance 2016) and the 30-year interest rate swap rate (Board of Governors of the Federal Reserve System 2016),[14] to develop a low-risk discount rate of 4.78%. The

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[12] The RCP8.5 scenario represents the CMIP5's unmitigated high emission scenario, which presumes that no significant action is undertaken to curb greenhouse gas emissions over the course of the 21st Century. As the UTES-SDH systems conceptualized here are heating systems, the RCP8.5 scenario presents the most unfavorable investment case with respect to heating demand, as projected heating degree days under the scenario decline in all 15 states.

[13] DCF is the standard financial modeling tool to find the present value of cash flows in the future. The discounted value of the cash flows (DCF) of this project is calculated by taking the annual cash flows CF_1,$CF_{2,\ldots}CF_{60}$, which represent the raw costs of energy heating, and discounting them by the discount rate (r)

$$DCF = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_{60}}{(1+r)^{60}}$$

[14] Interest rate swaps allow interest-bearing debtors to exchange floating-rate interest payments for a fixed rate. Functionally, this allows us to model the future yields of AAA municipal bonds with zero uncertainty. A 30-year swap over-estimates the cost of utilizing this financial instrument as the proposed bond matures in 20 years, but data on the market rates for 20-year swaps is not readily available.

second scheme considers a higher-risk debtor undertaking, such as a private residential co-operative, with a discount rate set arbitrarily at 6%.[15] These results are displayed in Tables 8 and 10.

Finally, we estimate greenhouse gas emissions savings attributable to the UTES-SDH system under both the RCP8.5 and historical climates, utilizing EPA estimates for CO_2 emitted per thousand ft^2 of natural gas burned by NWGFs (EPA 1998). This calculation is a conservative estimate of the emissions savings of the UTES-SDH system, as most NWGFs burn less than 95% of all natural gas drawn and there are significant inefficiencies and leakages in natural gas production and distribution that lead to emissions of methane, which has roughly 20 times the global warming potential of CO_2 (Howarth et al. 2011, Cathles 2012a, Cathles 2012b).[16] These results are displayed in the final column of Tables 7-10.

Results and Discussion

The model's calculated discounted savings per home represents the per-unit breakeven cost of a UTES-SDH system as compared to NWGF systems under prevailing methods of financial analysis: the capital expense at which a rational investor would be indifferent between the two systems. This figure estimates a target "cost to beat" in order for the technology to compete economically with NWGF systems in the 15 states examined, presuming no additional subsidies are provided and presuming a lack of a price on greenhouse gas emissions. This target cost result ranges from ~$36,000 per home in Massachusetts, if funded through municipal bonds, and presuming low impacts to heating demand from climate change, to ~$17,500 per home in Idaho, if funded through a private residential cooperative, presuming significant effects of climate change on heating demand.

The discounted savings per home figure is sensitive to several factors: climatic conditions in the state, differences in retail gas prices between states, differences in the energy efficiency of the built environment (as represented by our Mcf NG/HDD proxy), the type of funding utilized (and thus the presumed discount rate applied), and the extent of future climate change and its effects on future heating demand.

Conclusions and Policy Implications

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[15] We use an arbitrary discount rate here because there are scant examples of district-level infrastructure not funded through municipal bonds. This number is a 33% premium on current average interest rates offered to homeowners for NWGF upgrades (DOE 2015).

[16] Both the global warming potential of methane and the leakage rates from the gas sector are debated. Howarth et al. (2011) and Cathles et al. (2012a, 2012b), among others, spar over the appropriate time horizon for considering global warming impacts of methane in the atmosphere. Leakage rates for the natural gas supply system span a large range of uncertainty, from 1% to 10% (Allen 2014).

By utilizing concepts from financial analysis and fuel-price risk hedging in the assessment of commercial viability for UTES-SDH systems, we have attempted to explore macro-economic prospects for wide-scale deployment through micro-economic, investor-specific considerations. The range of target system costs represented by the discounted savings per home figures may provide useful guidance to developers and policymakers interested in the prospects of UTES-SDH systems. The government-funded Drake Landing demonstration project, for example, developed a UTES-SDH system for 52 homes at a subsidized capital cost of approximately 2.6 million USD (Sibbitt et al. 2012, 2015). This per-home cost of $50,000 is above the highest target costs produced by our model, and suggests that capital costs for Drake Landing-like projects must come down by ~28% to compete in the most attractive market conditions we modeled, and ~65% to compete in the most challenging market conditions we modeled.

These cost reductions are not insubstantial, but neither are they insurmountable, given that Drake Landing was the first project of its kind in North America, and that we can expect capital costs to decline as deployment rates increase, as has been observed in countless other markets for clean energy. A 28% reduction in Drake Landing's \$1100/m^2 of collector area capital cost figure would bring the capital cost to \$792/m^2, comparable to the high range of European SDH systems in Austria. Getting to 65% reductions, on the other hand, is more daunting, as this would bring capital costs below those enjoyed by the low end (\$400/m^2) of Danish systems, which have the tremendous advantage of using pre-existing district heating infrastructure coupled with dense Scandinavian community designs.

Massachusetts, in particular, stands out as uniquely positioned to drive prospects for UTES-SDH, as the state exhibits high heating demands, above-average retail natural gas prices, and a high Mcf NG/HDD proxy suggesting an average of less thermally efficient buildings than in other states we examined. Utah, to a lesser extent, also exhibits favorable market conditions. Previous work by Reed and McCartney (2015) identified states (among the top 10 states for solar energy installations) with favorable utility regulatory schemas for UTES-SDH system deployments, where the systems would likely not face charges of illegal competition with existing electric or gas utilities. Notably, Massachusetts, New York, and Colorado all exhibited such open regulatory environments, allowing heat provision to the public through UTES systems without subjecting them to cost-of-service rate regulation. Reed and McCartney 2015 did not examine regulatory environments in Idaho, Illinois, Iowa, Michigan, Minnesota, Montana, Nebraska, North Dakota, South Dakota, Utah, Wisconsin, and Wyoming, and future legal and regulatory research should examine those states.

State policies providing subsidized support to UTES-SDH system deployment, particularly those aimed at retrofits for older, less efficient housing, may both provide a scaffolding for system costs to decline to competitive levels in these low-hanging-fruit markets, while also addressing high heating costs and uncertainties that may disproportionately affect low-income populations. State policies that support or enable municipally-funded UTES-SDH projects are also recommended at this early stage, as the lower interest rates associated with municipal bonds provide greater headroom for systems to realize savings for residents than higher-interest private debt, and municipal governments are well-suited to the management of longlived infrastructures that last for over half a century. Numerous exogenous factors complicate these decisions, however. We have not, for example, modeled the availability of UTES components and transport costs on a state-by-state basis. States with thriving geothermal heat pump markets, for example, might exhibit cheaper materials costs for UTES loop fields. Nor have we taken into consideration differences in soil composition and hydrogeology, which can impact both construction costs (if the soil is particularly rocky, for example) and borehole field design (if, for example, an underground water flow causes heat leakage from the field and necessitates the addition of a thermal barrier). Nevertheless, this analysis aims to provide useful markers for the contours of a future potential UTES-SDH industry with respect to target system costs and likely regions for favorable deployment.

Declaration of Interest

Conflicts of interest: none.

SOURCES

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APPENDIX: Data Tables and Charts

Table 1: Heating Degree Days by State: Historical and Projected

State	**Historical Average (1981-2010)**	**RCP8.5 Climate Change Scenario (2080)**
Colorado	6947	4797
Idaho	6787	3987
Illinois	6168	4059
Iowa	6815	5065
Massachusetts	6369	4369
Michigan	6792	4992
Minnesota	8471	5471
Montana	7853	5753
Nebraska	6314	4414
New York	6147	3897
North Dakota	9103	6103
South Dakota	7466	5466
Utah	6442	4492
Wisconsin	7504	5504
Wyoming	7911	5711

Table 2: Price of Natural Gas Delivered to Residential Consumers by State ($/Mcf)

	CO	ID	IL	IA	MA	MI	MN	MT	NE	NY	ND	SD	UT	WI	WY
1986	5.01	6.02	5.07	5.12	7.41	5.74	5.28	4.45	4.59	7.46	5.29	5.26	4.64	6.2	4.93
1987	4.74	5.5	4.81	4.75	6.64	5.46	4.58	4.41	4.36	6.88	5.47	4.87	4.97	5.99	4.7
1988	4.42	5.49	4.6	4.79	6.47	5.34	4.64	4.3	4.46	6.5	5.15	4.91	5.11	5.89	4.48
1989	4.63	5.05	4.92	4.7	7.16	5.19	4.57	4.37	4.48	7.22	4.68	4.85	5.14	5.64	4.71
1990	4.57	5.05	5.06	4.99	7.82	5.02	4.63	4.59	4.6	7.4	4.7	5.14	5.28	5.74	4.84
1991	4.59	5.19	4.95	4.81	8.11	5.07	4.52	4.52	4.64	7.35	4.82	4.94	5.44	5.61	4.74
1992	4.56	5.23	5.09	5.23	7.92	5.06	4.86	4.8	4.82	7.58	5	5.15	5.44	5.87	4.72
1993	4.52	5.38	5.52	5.48	8.33	5.04	5.31	4.92	4.96	8.15	5.23	5.3	5.13	6.34	4.77
1994	4.92	5.29	5.5	5.4	8.94	4.98	5.18	5.23	5.01	8.75	5.19	5.27	4.96	6.28	5.1
1995	4.8	5.59	4.66	5.09	9.04	4.72	4.8	5.15	4.83	8.42	4.66	5.05	4.74	5.82	4.83
1996	4.39	5.2	5.28	5.49	8.88	4.96	5.46	4.86	4.88	8.9	4.54	5.25	4.47	6.04	4.26
1997	4.81	5.12	5.95	6.17	9.43	5.2	5.76	5.05	5.69	9.73	4.99	5.75	5.13	6.43	4.58
1998	5.22	5.33	5.47	5.96	9.42	5.17	5.48	5.25	5.13	9.59	5.16	5.59	5.57	6.15	5.19
1999	5.38	5.42	5.5	6.1	9.25	5.13	5.56	5.16	5.06	9.12	5.32	5.83	5.37	6.17	5.11
2000	6.14	6.28	7.33	7.81	9.91	5.11	7.13	6.03	6.43	9.86	6.37	7.34	6.2	7.55	6.11
2001	8.37	8.48	9.04	8.9	12.8	5.77	8.74	7.26	8.71	11.75	7.68	8.57	8.09	8.76	8.45
2002	5.62	8.41	6.41	7.08	10.05	6.32	6.61	5.3	6.18	9.85	5.14	6.93	6.39	7.35	6.08
2003	6.61	7.59	8.65	9.14	12.52	7.31	8.58	7.08	7.83	11.59	7.25	8.49	7.33	9.27	7.14
2004	8.47	9.04	9.41	10.14	14.41	8.52	9.5	9.19	9.06	12.5	9.03	9.52	8.12	10.16	8.65
2005	10.29	10.59	11.62	12.3	15.43	10.55	11.21	10.7	10.68	14.89	11.4	11.68	9.71	11.93	10.53
2006	10.45	12.25	11.18	12.42	17.66	11.97	11.67	11.26	11.3	15.35	10.8	11.11	11.02	12.17	11.6
2007	8.84	11.47	10.76	11.76	16.99	11.06	11.14	9.91	11.15	15.73	9.13	10.49	9.44	12.02	8.84
2008	9.77	11.07	12.07	11.91	17.18	11.93	11.29	11.45	11.11	16.78	10.34	11.32	9	12.81	10.16
2009	8.8	10.54	8.97	9.83	14.85	11.27	8.99	9.5	9.34	15.05	8.46	9.14	8.95	10.76	9.39
2010	8.13	8.95	9.39	9.57	14.53	11.32	8.76	8.64	8.95	14.04	8.08	8.77	8.22	10.34	8.58
2011	8.25	8.8	8.78	9.54	13.81	10.47	8.85	8.8	8.84	13.71	8.1	8.59	8.44	9.77	8.72
2012	8.28	8.26	8.26	9.46	13.22	9.95	7.99	8.05	8.68	12.97	7.43	8.39	8.7	9.27	8.42
2013	7.85	8.12	8.2	8.99	13.49	9.09	8.19	8.19	8.39	12.49	7.43	8.23	8.55	8.65	8.27
2014	8.89	8.54	9.59	10.02	14.5	9.33	9.89	9.11	8.77	12.54	8.86	9.27	9.48	10.52	9.34
2015	9.56*	8.62	7.95	8.49	12.91*	8.78	8.84	8.21	8.94	11.2	10.15*	8.21	9.72	10.09*	9.19
Average Inflation	2.23%	1.24%	1.55%	1.74%	1.92%	1.47%	1.78%	2.11%	2.30%	1.40%	2.25%	1.54%	2.55%	1.68%	2.15%

Inflation Std. Dev.	13.43%	9.71%	15.07%	11.38%	10.36%	7.85%	12.77%	12.71%	12.51%	8.73%	14.91%	10.83%	10.29%	10.11%	13.63%

*Data for Full Year 2015 unavailable at last running of simulation for CO, MA, ND, & WI. 2015 numbers for these states are average prices for residentially delivered natural gas for each state for the year of 2015 through 6/30/2015

Table 3: Simulated NG Prices over UTES-SDH Lifetime for Wisconsin and Massachusetts[23] ($/Mcf)

	Wisconsin			**Massachusetts**		
Year	***Simulation Min***	**Simulation Max**	**Expected**	**Simulation Min**	**Simulation Max**	**Expected**
0	7.24	7.24	7.24	12.02	12.02	12.02
1	4.96	11.43	7.36	7.99	18.06	12.25
2	4.56	12.38	7.49	7.09	22.81	12.48
3	3.73	14.49	7.61	6.91	26.01	12.72
4	3.72	18.23	7.74	6.19	29.42	12.97
5	3.52	18.04	7.87	5.60	32.71	13.22
6	3.19	19.26	8.00	5.41	35.81	13.47
7	2.91	21.55	8.14	4.95	41.42	13.73
8	2.83	24.32	8.27	4.87	45.48	13.99
9	2.95	25.37	8.41	4.90	47.86	14.26
10	3.03	25.83	8.55	4.29	51.84	14.53
11	2.71	30.81	8.70	4.38	59.53	14.81
12	2.53	33.25	8.84	3.84	62.11	15.09
13	2.39	31.46	8.99	3.98	62.77	15.38
14	2.15	41.39	9.14	3.79	70.98	15.68
15	2.18	44.96	9.30	3.56	61.28	15.98
16	2.14	53.48	9.45	3.50	67.61	16.28
17	2.07	54.65	9.61	3.16	75.09	16.60
18	1.96	50.29	9.77	3.31	77.16	16.91
19	1.85	60.84	9.94	3.20	81.81	17.24
20	1.77	63.46	10.10	3.00	87.71	17.57
21	1.80	73.02	10.27	3.25	109.00	17.90
22	1.46	74.09	10.45	3.01	105.80	18.25
23	1.24	94.71	10.62	2.83	108.13	18.60
24	1.46	94.23	10.80	2.94	117.07	18.95
25	1.46	88.11	10.98	3.27	116.31	19.32
26	1.31	109.51	11.17	3.01	131.67	19.68
27	1.49	112.30	11.35	2.98	126.45	20.06
28	1.58	111.09	11.54	2.96	132.30	20.45
29	1.63	113.83	11.74	3.03	139.47	20.84
30	1.68	109.99	11.94	2.75	147.91	21.24
31	1.44	120.58	12.14	2.52	163.79	21.64
32	1.35	124.49	12.34	2.41	184.01	22.06
33	1.25	136.48	12.55	2.39	229.95	22.48
34	1.25	138.23	12.76	2.50	219.27	22.91

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[23] These are provided for illustrative purposes. Simulated NG price data for other states is available upon request.

35	1.33	136.27	12.97		2.23	210.04	23.35
36	1.27	141.84	13.19		1.82	226.57	23.80
37	1.35	149.71	13.41		1.76	241.27	24.25
38	1.43	166.53	13.64		1.62	246.80	24.72
39	1.39	187.98	13.87		1.67	278.67	25.19
40	1.23	192.68	14.10		2.01	263.10	25.67
41	1.08	206.25	14.34		1.80	273.00	26.17
42	1.11	226.32	14.58		1.87	267.96	26.67
43	1.02	208.33	14.82		1.91	295.40	27.18
44	1.04	225.73	15.07		1.73	344.61	27.70
45	1.02	208.75	15.32		1.94	416.12	28.23
46	1.10	209.27	15.58		1.87	443.24	28.77
47	1.17	220.04	15.84		1.76	434.37	29.32
48	1.16	233.84	16.11		2.06	417.25	29.88
49	0.92	243.69	16.38		2.02	503.47	30.45
50	0.97	235.12	16.66		1.82	524.12	31.04
51	1.05	263.99	16.94		2.16	508.17	31.63
52	1.12	352.48	17.22		1.83	510.25	32.24
53	1.00	366.31	17.51		2.08	520.67	32.86
54	0.94	428.29	17.80		2.22	531.89	33.48
55	0.77	475.81	18.10		2.20	567.93	34.13
56	0.70	433.26	18.41		2.12	724.35	34.78
57	0.77	464.94	18.72		1.97	614.85	35.45
58	0.75	456.31	19.03		1.90	630.95	36.12
59	0.83	493.82	19.35		1.85	677.75	36.82
60	0.94	684.68	19.68		1.84	818.50	37.52

Table 4: State-Specific Natural Gas Consumption Proxy Variables

State	**State-wide HDDs in 2009**	**Average thousand cubic feet (Mcf) of NG used for space heat by residential homes with NWGFs in 2009**	**Proxy Variable (Mcf NG used per HDD)**
Colorado	6953	60.07	0.0086
Idaho*	7145	55.99	0.0078
Illinois	6319	70.70	0.0112
Iowa*	7104	65.62	0.0092
Massachusetts	6472	64.84	0.0100
Michigan	7005	70.70	0.0101
Minnesota*	8909	65.62	0.0074
Montana*	8143	55.99	0.0069
Nebraska*	6712	54.80	0.0082
New York*	6368	59.18	0.0093
North Dakota*	9674	65.62	0.0068
South Dakota*	7985	65.62	0.0082
Utah*	6607	55.99	0.0085
Wisconsin	7747	70.670	0.0091
Wyoming*	8078	55.99	0.0069

Table 5: Average Simulated Space Heating costs per unit with NWGFs without Climate Change ($s)

Year	CO	ID	IL	IA	MA	MI	MN	MT	NE	NY	ND	SD	UT	WI	WY
0	386.52	436.08	434.05	409.17	767.02	519.58	432.38	372.01	338.12	539.80	347.01	403.10	479.83	495.78	392.57
1	398.81	443.61	445.87	419.07	786.06	528.88	443.74	383.03	348.70	549.50	358.86	411.74	494.84	506.77	404.83
2	411.56	451.23	458.11	429.14	805.65	538.30	455.26	394.29	359.67	559.30	371.18	420.55	510.25	518.03	417.58
3	424.76	458.96	470.29	439.46	825.59	547.93	467.38	405.91	370.99	569.45	383.89	429.58	526.17	529.38	430.81
4	438.31	466.96	483.08	450.01	846.18	557.75	479.55	417.87	382.66	579.74	396.92	438.85	542.47	541.33	444.36
5	452.17	474.95	496.51	460.82	867.38	567.85	492.06	430.29	394.66	590.15	410.69	448.29	559.33	553.36	458.18
6	466.48	483.16	510.10	471.82	889.15	578.02	505.24	442.99	406.93	600.82	424.36	457.91	577.03	565.59	472.62
7	481.25	491.50	524.03	483.05	911.00	588.32	518.41	456.04	419.46	611.52	438.86	467.66	595.08	578.33	487.52
8	496.34	500.01	537.87	494.72	933.65	598.76	532.48	469.42	432.89	622.53	453.80	477.78	613.91	590.83	502.53
9	512.29	508.67	552.43	506.72	957.11	609.57	546.07	483.29	446.44	633.66	469.18	487.83	633.19	603.73	518.11
10	527.93	517.43	567.20	519.30	980.40	620.63	560.09	497.60	460.28	645.24	485.63	498.69	653.50	617.04	534.10
11	544.73	526.43	582.53	531.67	1004.82	631.85	574.97	512.09	474.55	656.82	502.30	509.50	674.00	630.45	550.46
12	561.69	535.79	598.66	544.37	1029.24	643.05	590.31	526.95	488.91	668.74	519.55	520.36	695.21	644.30	567.72
13	579.62	544.94	615.50	557.25	1054.42	654.37	605.81	542.42	504.19	680.48	537.30	531.89	717.43	658.47	585.90
14	597.62	554.52	632.34	570.83	1079.90	665.99	621.80	558.97	520.55	692.34	556.39	543.48	739.80	673.15	604.21
15	617.21	563.84	649.13	584.74	1106.69	677.96	637.83	575.44	536.78	704.71	575.73	555.07	762.83	687.89	623.07
16	637.51	573.72	666.58	599.00	1133.91	690.39	655.02	592.42	552.90	717.37	596.07	567.53	786.33	703.11	642.85
17	657.41	583.46	685.30	613.31	1160.97	702.77	672.58	609.85	569.86	730.69	616.43	580.22	810.80	718.70	663.99
18	678.31	593.73	704.16	628.02	1190.25	715.56	690.49	627.90	587.06	743.62	637.98	592.40	836.28	734.56	683.96
19	698.86	603.80	723.73	642.60	1219.28	728.43	707.41	647.25	605.21	756.63	659.37	605.09	863.27	751.09	705.75
20	720.60	613.82	743.28	658.23	1249.43	741.42	725.67	667.11	623.90	770.38	680.92	618.06	890.15	768.31	728.50
21	743.16	624.34	764.59	673.76	1280.66	755.02	743.95	686.62	643.16	784.44	705.21	631.23	918.13	784.85	750.76
22	767.78	635.21	783.71	689.89	1313.03	768.45	763.80	706.30	663.63	798.91	729.70	644.94	946.92	802.42	775.31
23	792.59	646.09	803.74	705.88	1345.78	782.26	783.44	726.64	684.34	813.01	756.77	658.71	976.31	820.15	798.93
24	817.89	657.30	825.33	723.02	1379.80	795.77	804.42	748.82	705.83	827.57	783.78	671.86	1006.24	838.21	823.50
25	845.11	668.83	845.89	739.54	1414.24	809.74	825.76	770.18	728.66	842.75	810.78	686.80	1037.29	857.03	850.76
26	871.92	680.15	868.37	757.87	1449.39	823.65	847.68	793.42	750.40	858.00	838.75	700.88	1070.20	876.18	877.65
27	899.59	692.40	890.46	776.68	1486.74	838.23	868.90	815.84	773.45	873.16	867.42	716.19	1103.57	895.54	902.80
28	927.92	704.30	913.83	796.10	1522.93	853.41	891.68	841.09	798.37	888.49	898.48	731.51	1138.60	915.55	930.64
29	956.89	716.26	939.96	815.21	1561.79	868.93	915.48	865.14	823.16	904.26	928.49	747.29	1174.90	937.04	959.05
30	985.94	727.96	965.17	834.52	1601.02	884.49	939.26	889.51	848.73	920.48	961.57	762.56	1213.10	957.99	987.59

31	1014.87	740.54	994.69	855.29	1639.27	900.39	963.61	917.52	875.83	937.88	993.69	779.40	1251.77	979.61	1019.06
32	1045.92	753.21	1019.53	874.90	1681.33	916.51	987.37	944.92	902.73	954.69	1030.91	796.60	1289.57	1001.69	1050.48
33	1078.27	765.71	1044.14	895.49	1722.02	932.81	1014.21	973.95	930.75	971.77	1068.15	814.74	1328.28	1023.14	1082.27
34	1112.37	778.85	1070.19	917.83	1762.41	948.82	1041.41	1002.79	960.89	989.18	1106.05	833.26	1370.63	1046.65	1114.26
35	1147.44	792.32	1098.36	940.47	1805.85	965.66	1069.81	1030.94	991.59	1007.08	1149.90	851.20	1413.91	1069.37	1148.05
36	1184.27	806.08	1127.15	964.01	1850.49	982.98	1097.78	1062.74	1021.96	1025.84	1190.22	868.42	1458.80	1094.32	1186.63
37	1221.07	818.75	1156.28	986.51	1894.65	1000.99	1124.14	1093.56	1054.16	1043.23	1236.61	886.80	1504.83	1119.99	1224.30
38	1259.37	832.68	1187.14	1009.96	1942.39	1018.68	1154.34	1124.69	1088.01	1061.94	1281.79	904.02	1551.75	1145.30	1261.43
39	1298.14	847.22	1219.97	1033.77	1991.45	1036.59	1184.02	1157.17	1121.97	1081.57	1323.36	922.90	1600.54	1171.18	1299.89
40	1337.61	861.67	1255.28	1059.46	2043.02	1055.47	1215.45	1191.31	1157.26	1101.37	1361.40	944.55	1647.87	1196.70	1337.89
41	1380.93	876.43	1286.54	1085.79	2094.47	1073.98	1246.12	1227.71	1192.87	1121.92	1406.47	964.79	1697.93	1223.04	1380.79
42	1426.82	892.02	1320.70	1114.14	2146.55	1093.83	1281.86	1264.94	1227.78	1141.83	1450.93	985.72	1751.93	1251.04	1421.39
43	1475.96	908.02	1358.40	1140.56	2200.50	1114.31	1314.27	1305.14	1268.51	1162.39	1505.45	1006.18	1803.23	1279.53	1464.39
44	1524.81	923.94	1388.78	1167.24	2253.14	1134.30	1349.08	1340.63	1309.20	1183.71	1555.15	1027.00	1859.84	1308.95	1509.12
45	1573.65	939.93	1429.81	1195.45	2312.06	1155.57	1381.99	1381.64	1350.85	1205.38	1607.96	1047.26	1917.93	1337.71	1555.83
46	1622.18	955.77	1473.85	1225.85	2366.79	1176.63	1418.65	1422.71	1393.54	1226.88	1671.15	1070.22	1973.45	1366.71	1603.36
47	1673.58	972.44	1513.07	1255.19	2424.54	1197.90	1455.79	1465.69	1437.60	1249.15	1732.99	1092.15	2034.95	1397.72	1653.27
48	1729.45	987.61	1557.36	1284.62	2480.98	1219.85	1489.87	1511.88	1481.08	1272.94	1788.19	1118.03	2100.42	1426.72	1707.41
49	1782.91	1004.12	1600.79	1313.97	2543.91	1242.03	1529.11	1556.95	1528.15	1296.27	1855.21	1140.53	2164.37	1458.32	1758.07
50	1842.67	1021.88	1639.25	1343.57	2607.69	1264.21	1569.99	1602.63	1576.21	1320.50	1925.08	1163.53	2232.86	1490.33	1819.36
51	1903.13	1040.53	1689.70	1374.18	2668.41	1286.78	1613.39	1646.68	1620.59	1343.89	1984.27	1189.47	2301.95	1524.21	1870.13
52	1961.32	1058.41	1738.70	1406.74	2736.72	1310.12	1657.42	1695.15	1672.53	1368.41	2050.39	1214.20	2374.99	1558.91	1930.23
53	2025.69	1077.53	1785.59	1442.70	2801.26	1332.89	1701.13	1741.06	1723.95	1392.68	2130.48	1238.86	2453.92	1595.06	1989.44
54	2091.61	1097.30	1828.64	1478.44	2866.64	1356.61	1747.32	1791.23	1774.23	1417.10	2206.74	1266.66	2527.33	1629.87	2053.98
55	2162.51	1115.87	1879.75	1513.10	2934.85	1380.33	1796.80	1849.14	1836.11	1442.92	2282.96	1294.57	2607.89	1666.19	2117.99
56	2229.14	1135.57	1933.58	1549.25	3009.29	1406.43	1848.18	1906.67	1895.75	1468.50	2371.33	1320.28	2695.68	1699.43	2180.99
57	2291.68	1154.27	1991.72	1589.25	3082.71	1431.30	1897.42	1965.46	1949.30	1494.23	2458.79	1347.42	2781.21	1735.93	2247.24
58	2370.90	1175.12	2046.95	1631.22	3157.70	1456.19	1943.77	2019.58	2009.98	1521.09	2535.43	1375.00	2870.04	1777.18	2323.74
59	2440.07	1197.40	2103.03	1671.31	3238.85	1482.17	1993.80	2077.66	2068.10	1547.44	2618.13	1401.89	2959.67	1814.34	2392.13
60	2518.75	1217.03	2157.43	1712.04	3320.45	1510.80	2045.00	2131.96	2128.27	1575.90	2704.15	1432.05	3051.16	1854.34	2468.30

Table 6: Average Simulated Space Heating costs per unit with NWGFs with Climate Change ($s)

Year	CO	ID	IL	IA	MA	MI	MN	MT	NE	NY	ND	SD	UT	WI	WY
0	386.52	436.08	434.05	409.17	767.02	519.58	432.38	372.01	338.12	539.80	347.01	403.10	479.83	495.78	392.57
1	396.75	440.55	443.33	417.28	781.95	526.54	441.12	381.32	346.95	546.15	356.90	409.90	492.33	504.51	402.96
2	407.16	444.93	452.70	425.59	797.13	533.57	450.09	390.82	355.90	552.58	367.09	416.78	505.22	513.34	413.62
3	418.04	449.38	462.34	434.06	812.96	540.60	459.24	400.44	365.23	559.15	377.43	423.93	518.41	522.39	424.39
4	429.14	453.95	472.19	442.81	828.50	547.78	468.58	410.53	374.72	565.69	388.02	431.12	531.77	531.63	435.57
5	440.24	458.59	482.52	451.74	844.33	554.99	477.80	420.72	384.20	572.14	398.92	438.18	545.65	541.15	447.35
6	451.67	463.21	492.73	460.63	860.32	562.40	487.52	431.23	394.20	578.73	410.07	445.52	559.95	550.52	459.22
7	463.56	467.95	502.81	469.52	877.09	569.84	497.45	441.99	404.49	585.52	421.80	453.06	574.50	560.00	471.24
8	475.95	472.49	513.75	478.60	893.87	577.38	507.16	452.55	414.70	592.16	433.53	460.53	589.45	569.82	484.01
9	488.92	476.96	524.62	488.35	911.35	584.95	517.38	463.68	425.41	598.97	445.94	468.20	604.25	579.59	496.74
10	501.61	481.83	535.01	497.97	928.82	592.35	527.76	475.48	436.45	605.80	458.19	476.07	619.68	589.72	509.74
11	515.07	486.15	546.30	507.55	946.81	600.07	538.35	487.16	447.93	612.84	470.69	484.07	635.66	600.27	522.98
12	528.01	490.69	557.64	517.85	965.34	607.96	549.12	499.87	459.81	619.63	483.85	491.78	652.36	610.76	536.89
13	541.92	495.26	569.56	528.21	983.44	615.96	560.61	512.48	471.72	626.62	497.77	499.83	668.43	621.62	550.44
14	555.78	499.78	581.22	538.72	1002.13	623.95	571.28	525.38	484.11	633.58	511.06	508.10	685.70	631.93	564.68
15	570.63	504.71	593.13	549.43	1021.13	632.10	582.40	538.23	496.51	640.76	525.38	516.49	703.36	643.21	580.05
16	585.09	509.43	605.79	560.22	1040.06	640.19	594.27	551.45	509.28	647.80	539.93	525.00	721.25	654.26	595.13
17	600.08	514.50	619.00	571.44	1059.40	648.63	606.50	565.00	522.43	655.19	554.86	533.92	739.23	665.50	611.76
18	614.95	519.35	632.56	582.74	1079.54	656.85	617.17	579.57	535.56	662.33	570.38	542.85	758.10	676.69	626.65
19	631.19	524.08	645.71	593.51	1099.33	665.52	628.83	594.15	549.22	669.76	586.77	551.43	777.61	687.73	642.38
20	648.27	528.91	659.83	605.11	1120.18	674.30	640.88	608.20	563.68	676.97	604.02	559.85	797.05	699.59	659.60
21	665.33	533.79	674.31	616.50	1142.51	682.86	652.95	622.96	577.30	684.32	620.64	569.87	817.63	711.53	676.02
22	682.33	538.40	687.93	627.89	1165.16	691.45	665.61	637.54	591.97	692.05	636.65	578.76	838.21	723.76	692.43
23	700.47	543.26	703.12	640.12	1186.51	700.33	678.10	653.58	607.08	699.47	653.69	588.14	859.16	736.09	709.66
24	718.75	548.22	716.70	652.06	1208.50	709.31	690.77	669.65	623.08	706.73	672.21	597.80	880.72	748.42	726.67
25	738.38	553.11	729.79	664.09	1230.60	718.46	704.19	686.66	638.64	714.80	691.04	607.82	903.00	761.85	744.32
26	756.96	558.43	743.90	676.86	1253.31	727.69	717.79	702.56	654.67	722.25	710.36	618.25	926.43	774.48	765.00
27	777.24	563.48	758.43	689.97	1276.42	737.09	732.18	720.41	670.43	729.88	730.44	628.32	950.32	788.14	784.73
28	795.85	568.23	773.01	703.68	1301.40	746.70	745.65	737.57	686.85	738.00	751.13	638.13	974.03	801.90	805.66
29	816.78	573.03	789.03	718.34	1325.25	755.80	759.87	756.25	704.80	746.05	771.91	648.75	998.59	816.75	827.99
30	836.69	577.80	805.38	731.85	1349.87	765.55	775.23	773.68	723.72	753.81	792.28	659.73	1024.02	829.97	850.23

31	858.90	582.43	823.74	746.18	1375.07	775.10	789.43	791.64	740.06	762.11	815.63	669.46	1049.56	843.80	870.92
32	881.81	587.43	841.25	760.89	1399.30	784.29	803.58	812.93	758.22	769.62	838.30	679.43	1075.44	857.57	891.74
33	902.85	592.66	858.02	775.17	1423.87	794.27	819.65	832.58	776.64	777.71	863.34	690.38	1103.07	871.23	914.00
34	926.33	597.42	874.14	790.01	1450.32	804.33	834.01	854.95	797.32	785.19	885.36	700.73	1131.19	886.18	934.37
35	949.50	602.10	893.39	804.89	1476.00	814.44	850.32	876.30	817.48	792.33	910.31	711.56	1160.07	899.70	958.11
36	971.20	606.76	911.00	819.78	1503.96	824.52	867.74	898.04	837.81	800.91	934.34	722.93	1188.61	915.19	982.68
37	998.49	612.40	929.56	835.24	1532.11	834.68	883.81	919.80	859.48	808.21	959.31	735.12	1218.83	930.31	1007.19
38	1022.59	617.52	946.41	853.67	1561.31	845.28	900.74	940.86	881.33	815.83	986.71	747.37	1250.03	946.20	1030.42
39	1050.44	622.31	962.64	868.45	1588.41	855.22	917.97	963.65	903.13	823.50	1016.02	759.82	1280.86	962.21	1055.93
40	1075.54	626.57	979.78	886.73	1616.23	865.73	932.84	986.01	925.91	831.84	1044.02	772.27	1312.14	977.67	1082.24
41	1103.64	631.19	997.14	903.64	1644.88	876.39	948.65	1006.64	950.24	840.38	1075.07	783.72	1345.29	994.72	1110.42
42	1129.71	636.87	1016.64	920.36	1675.15	887.13	966.72	1030.14	973.27	848.49	1104.40	796.34	1379.18	1010.85	1136.62
43	1159.96	641.37	1037.57	937.92	1703.73	898.25	984.57	1052.66	997.76	857.06	1130.71	807.88	1412.99	1027.34	1165.34
44	1186.55	645.59	1057.02	955.37	1733.76	909.30	1003.20	1077.63	1021.63	865.41	1163.75	821.22	1448.19	1044.79	1196.72
45	1216.63	649.97	1076.19	972.43	1765.39	920.60	1021.26	1101.83	1047.27	874.12	1196.63	833.61	1482.72	1061.92	1227.59
46	1245.82	654.21	1095.38	990.16	1797.64	931.99	1036.68	1128.56	1074.48	881.69	1229.77	847.75	1518.88	1079.31	1263.17
47	1276.63	658.82	1117.48	1009.12	1831.15	943.65	1054.52	1155.21	1100.68	889.45	1259.81	860.87	1556.14	1097.33	1296.14
48	1311.95	663.51	1141.09	1026.56	1863.70	954.97	1071.48	1182.07	1128.92	897.84	1294.16	875.09	1594.10	1114.88	1327.41
49	1345.90	667.46	1165.30	1045.04	1898.91	967.12	1091.83	1210.16	1155.40	905.71	1329.76	889.20	1631.94	1132.79	1357.87
50	1378.69	671.93	1187.51	1063.49	1932.03	978.74	1110.80	1238.21	1183.96	914.66	1361.60	903.54	1671.24	1150.46	1390.55
51	1414.00	676.17	1210.48	1083.35	1965.81	990.21	1130.33	1268.19	1213.64	923.56	1395.12	919.36	1714.50	1169.30	1426.61
52	1450.30	680.98	1230.20	1105.51	1998.26	1002.99	1150.55	1298.02	1246.51	930.96	1432.16	933.99	1759.19	1187.14	1463.71
53	1483.55	685.04	1252.51	1126.34	2032.46	1015.00	1170.44	1327.01	1280.37	939.04	1474.68	949.07	1800.20	1205.59	1501.22
54	1522.67	689.80	1273.05	1148.94	2068.49	1026.93	1190.06	1357.59	1309.71	946.34	1513.41	964.72	1844.13	1224.80	1538.04
55	1560.17	693.75	1298.21	1169.44	2103.20	1038.96	1211.75	1389.45	1338.97	954.50	1547.42	979.48	1887.05	1244.33	1577.08
56	1598.96	697.63	1322.82	1191.83	2138.83	1051.48	1232.24	1420.48	1370.53	962.87	1586.45	994.21	1931.56	1263.84	1617.04
57	1633.46	701.43	1352.03	1212.85	2173.24	1064.08	1253.44	1451.41	1403.82	970.69	1628.32	1009.37	1980.26	1285.10	1655.52
58	1669.14	705.11	1374.65	1235.63	2212.34	1076.04	1275.54	1486.76	1435.44	978.39	1676.50	1025.54	2030.41	1306.61	1698.85
59	1708.16	709.63	1396.77	1259.82	2246.63	1088.62	1300.85	1522.80	1470.27	987.03	1722.93	1041.29	2076.69	1326.86	1738.77
60	1753.29	713.21	1422.97	1281.88	2283.48	1100.57	1320.98	1559.70	1508.47	995.40	1768.50	1056.82	2124.13	1349.67	1780.73

Figure 1: Per NWGF-Heated Unit Simulated Space Heating Costs Per Annum, 15 State Average

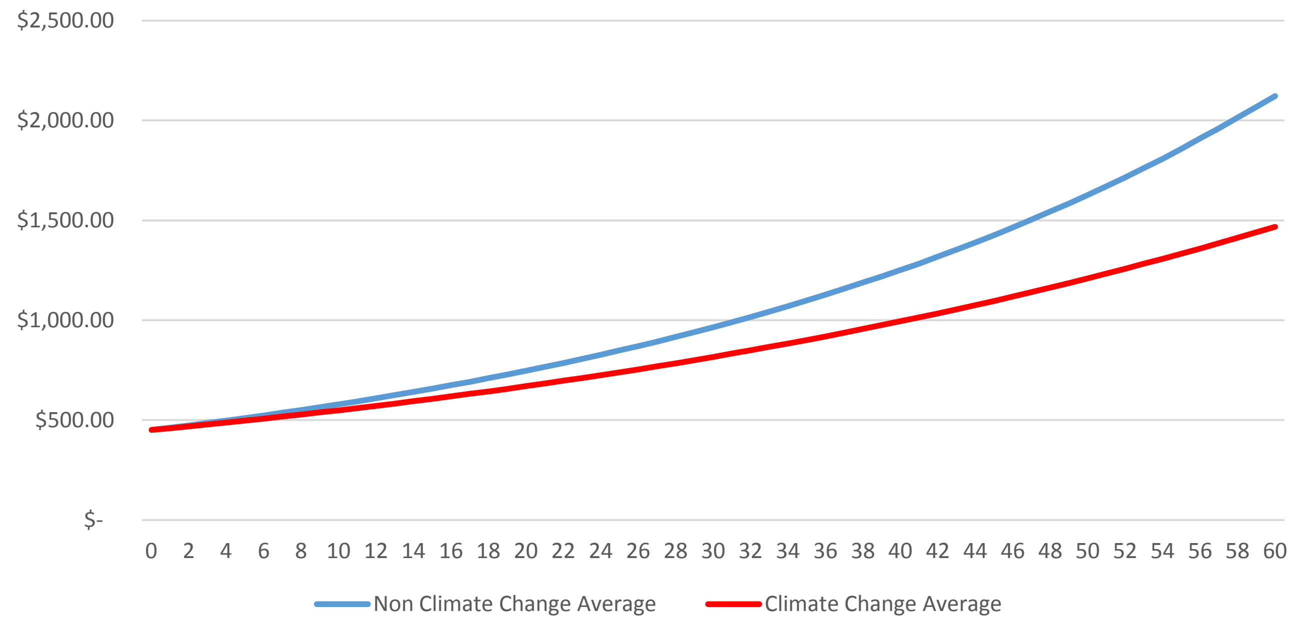

Table 7: Funding: Municipal Bonds, No Climate Change

State	**Total Average Savings of UTES**	Total Average Savings per Home	**Discounted Average Savings**	Discounted Savings per Home	**Metric Tons CO_2 Saved**	Metric Tons CO_2 Saved per Home
Colorado	**$ 6,015,267**	$ 120,305	**$ 1,302,426**	$ 26,049	**9.37**	0.19
Idaho	**$ 4,904,416**	$ 98,088	**$ 1,163,871**	$ 23,277	**8.30**	0.17
Illinois	**$ 5,825,176**	$ 116,504	**$ 1,305,053**	$ 26,101	**10.77**	0.22
Iowa	**$ 5,336,291**	$ 106,726	**$ 1,217,034**	$ 24,341	**9.82**	0.20
Massachusetts	**$ 7,720,625**	$ 154,412	**$ 1,791,244**	$ 35,825	**9.96**	0.20
Michigan	**$ 5,376,963**	$ 107,539	**$ 1,285,059**	$ 25,701	**10.70**	0.21
Minnesota	**$ 5,729,043**	$ 114,581	**$ 1,289,871**	$ 25,797	**9.74**	0.19
Montana	**$ 5,637,627**	$ 112,753	**$ 1,238,656**	$ 24,773	**8.43**	0.17
Nebraska	**$ 5,529,871**	$ 110,597	**$ 1,200,315**	$ 24,006	**8.04**	0.16
New York	**$ 5,491,818**	$ 109,836	**$ 1,314,404**	$ 26,288	**8.91**	0.18
North Dakota	**$ 5,928,003**	$ 118,560	**$ 1,263,024**	$ 25,260	**9.64**	0.19
South Dakota	**$ 5,052,026**	$ 101,041	**$ 1,169,045**	$ 23,381	**9.57**	0.19
Utah	**$ 6,719,967**	$ 134,399	**$ 1,464,502**	$ 29,290	**8.52**	0.17
Wisconsin	**$ 5,678,315**	$ 113,566	**$ 1,319,001**	$ 26,380	**10.69**	0.21
Wyoming	**$ 6,001,354**	$ 120,027	**$ 1,304,019**	$ 26,080	**8.56**	0.17

Table 8: Funding: Residential COOP, No Climate Change

State	**Total Average Savings of UTES**	Total Average Savings per Home	**Discounted Average Savings**	Discounted Savings per Home	**Metric Tons CO_2 Saved**	Metric Tons CO_2 Saved per Home
Colorado	**$ 6,010,143**	$ 120,203	**$ 1,011,814**	$ 20,236	**9.37**	0.19
Idaho	**$ 4,897,841**	$ 97,957	**$ 927,407**	$ 18,548	**8.30**	0.17
Illinois	**$ 5,823,194**	$ 116,464	**$ 1,022,979**	$ 20,460	**10.77**	0.22
Iowa	**$ 5,348,632**	$ 106,973	**$ 961,028**	$ 19,221	**9.82**	0.20
Massachusetts	**$ 7,732,262**	$ 154,645	**$ 1,407,415**	$ 28,148	**9.96**	0.20
Michigan	**$ 5,376,833**	$ 107,537	**$ 1,023,758**	$ 20,475	**10.70**	0.21
Minnesota	**$ 5,719,982**	$ 114,400	**$ 1,012,150**	$ 20,243	**9.74**	0.19
Montana	**$ 5,621,637**	$ 112,433	**$ 966,097**	$ 19,322	**8.43**	0.17
Nebraska	**$ 5,513,118**	$ 110,262	**$ 936,635**	$ 18,733	**8.04**	0.16
New York	**$ 5,490,209**	$ 109,804	**$ 1,046,776**	$ 20,936	**8.91**	0.18
North Dakota	**$ 5,946,414**	$ 118,928	**$ 981,103**	$ 19,622	**9.64**	0.19
South Dakota	**$ 5,056,415**	$ 101,128	**$ 928,057**	$ 18,561	**9.57**	0.19
Utah	**$ 6,718,120**	$ 134,362	**$ 1,138,177**	$ 22,764	**8.52**	0.17
Wisconsin	**$ 5,673,152**	$ 113,463	**$ 1,043,017**	$ 20,860	**10.69**	0.21
Wyoming	**$ 6,004,617**	$ 120,092	**$ 1,015,371**	$ 20,307	**8.56**	0.17

Table 9: Funding: Municipal Bonds, Climate Change

State	**Total Average Savings of UTES**	Total Average Savings per Home	**Discounted Average Savings**	Discounted Savings per Home	**Metric Tons CO_2 Saved**	Metric Tons CO_2 Saved per Home
Colorado	**$ 5,320,325**	$ 106,407	**$ 1,203,927**	$ 24,079	**7.92**	0.16
Idaho	**$ 4,368,606**	$ 87,372	**$ 1,076,958**	$ 21,539	**6.59**	0.13
Illinois	**$ 5,143,519**	$ 102,870	**$ 1,204,186**	$ 24,084	**8.93**	0.18
Iowa	**$ 4,925,854**	$ 98,517	**$ 1,154,417**	$ 23,088	**8.56**	0.17
Massachusetts	**$ 6,760,273**	$ 135,205	**$ 1,645,329**	$ 32,907	**8.39**	0.17
Michigan	**$ 4,960,343**	$ 99,207	**$ 1,217,973**	$ 24,359	**9.28**	0.19
Minnesota	**$ 5,066,382**	$ 101,328	**$ 1,190,126**	$ 23,803	**8.01**	0.16
Montana	**$ 5,132,233**	$ 102,645	**$ 1,164,589**	$ 23,292	**7.30**	0.15
Nebraska	**$ 4,993,161**	$ 99,863	**$ 1,124,167**	$ 22,483	**6.83**	0.14
New York	**$ 4,891,601**	$ 97,832	**$ 1,217,504**	$ 24,350	**7.28**	0.15
North Dakota	**$ 5,235,588**	$ 104,712	**$ 1,166,433**	$ 23,329	**8.05**	0.16
South Dakota	**$ 4,680,289**	$ 93,606	**$ 1,111,330**	$ 22,227	**8.29**	0.17
Utah	**$ 5,937,544**	$ 118,751	**$ 1,352,602**	$ 27,052	**7.23**	0.14
Wisconsin	**$ 5,179,301**	$ 103,586	**$ 1,242,824**	$ 24,856	**9.26**	0.19
Wyoming	**$ 5,377,907**	$ 107,558	**$ 1,216,103**	$ 24,322	**7.37**	0.15

Table 10: Funding: Residential COOP, Climate Change

State	**Total Average Savings of UTES**	Total Average Savings per Home	**Discounted Average Savings**	Discounted Savings per Home	**Metric Tons CO_2 Saved**	Metric Tons CO_2 Saved per Home
Colorado	**$ 5,339,586**	$ 106,792	**$ 949,631**	$ 18,993	**7.92**	0.16
Idaho	**$ 4,370,799**	$ 87,416	**$ 868,523**	$ 17,370	**6.59**	0.13
Illinois	**$ 5,160,415**	$ 103,208	**$ 955,839**	$ 19,117	**8.93**	0.18
Iowa	**$ 4,908,211**	$ 98,164	**$ 915,985**	$ 18,320	**8.56**	0.17
Massachusetts	**$ 6,756,487**	$ 135,130	**$ 1,307,848**	$ 26,157	**8.39**	0.17
Michigan	**$ 4,963,019**	$ 99,260	**$ 977,595**	$ 19,552	**9.28**	0.19
Minnesota	**$ 5,034,578**	$ 100,692	**$ 943,275**	$ 18,866	**8.01**	0.16
Montana	**$ 5,138,821**	$ 102,776	**$ 920,185**	$ 18,404	**7.30**	0.15
Nebraska	**$ 4,983,265**	$ 99,665	**$ 884,929**	$ 17,699	**6.83**	0.14
New York	**$ 4,883,334**	$ 97,667	**$ 979,319**	$ 19,586	**7.28**	0.15
North Dakota	**$ 5,218,077**	$ 104,362	**$ 914,614**	$ 18,292	**8.05**	0.16
South Dakota	**$ 4,668,370**	$ 93,367	**$ 886,055**	$ 17,721	**8.29**	0.17
Utah	**$ 5,935,454**	$ 118,709	**$ 1,063,389**	$ 21,268	**7.23**	0.14
Wisconsin	**$ 5,196,317**	$ 103,926	**$ 992,653**	$ 19,853	**9.26**	0.19
Wyoming	**$ 5,382,144**	$ 107,643	**$ 956,854**	$ 19,137	**7.37**	0.15