An Assessment of Impacts on Electric End-Use Load Profile of a Typical Residential Building from a Ground Source Heat Pump Systems Integrated with Underground Thermal Energy Storage

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Keywords

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ABSTRACT

Buildings are the primary users of electricity, and a considerable amount of electric energy consumed in residential and commercial buildings is for meeting thermal demands (e.g., space heating/cooling, water heating, etc.). Therefore, integrating thermal energy storage with a building's energy system has the potential to reshape the electric load profile of the building and mitigate the mismatch between the renewable power supply and the thermal demands of buildings. A novel ground-source heat pump system (GSHP) integrated with underground thermal energy storage (UTES) has been developed to enable flexible electric demand at buildings while meeting their thermal demands with an energy-efficient GSHP system. This paper assessed the potential impacts of the proposed system on the peak electrical demand and annual electricity consumption in a typical residential building at various climate zones in the United States. The results show that by replacing the conventional HVAC system (air conditioner and natural gas furnace) with the UTES integrated GSHP system, summer peak electric demand can be reduced by 27% to 50% depending on the weather. Although the winter peak electrical demand could be increased by up to 70% if the proposed system replaces natural

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gas furnace, the existing electricity supply system for single-family homes in most regions of the United States have adequate capacity for the replacement. While eliminating the natural gas consumption for space heating, the proposed system consumes more electricity on an annual basis in heating-dominated regions. However, it consumes less electricity in cooling dominated regions. The resulting variance in annual electricity consumption in various climate zones is within 15% compared with the baseline system.

1. Introduction

The trend of electrification in our society results in a continuous increase in the demand for electricity. The limited capacity of existing electric grids and the intermittent outputs from rapidly growing renewable power (e.g. solar or wind) generation create some challenges to balance supply and demand on the grid. When renewable sources produce more energy than can be consumed, grid operators may have to curtail renewable power, which reduces the economic and environmental benefits of renewable power. On the other hand, electricity generators need to quickly ramp up energy production when the contribution from renewable power falls, lowering efficiency, and increasing the generation cost (Liu et al., 2019).

Energy storage could address these challenges. It can be applied on either the power generation side or power demand side. Typical storage techniques (battery, pumped hydro, etc.) have limited applications in the generation side, because of economic or technical barriers, such as the high cost of the electric battery, or the special geographical conditions required for implementing pumped hydro. On the other hand, energy storage on the demand side could be a promising solution because the distributed power demand does not require large-scale storage or centralized management. The largest consumer in the demand side is buildings—75% of all U.S. electricity is consumed within buildings and building energy use drives 80% of peak electric demand (EIA, 2018). Among all end-use sectors, heating, ventilation, and air-conditioning (HVAC) systems in residential and commercial buildings contribute 34% and 27% of their total electricity consumption, respectively (Schwartz et al., 2017). Therefore, integrating thermal energy storage with the electric grids has the potential to reduce the electrical demand during peak hours and mitigate the mismatch between the renewable power supply and the thermal demands of buildings.

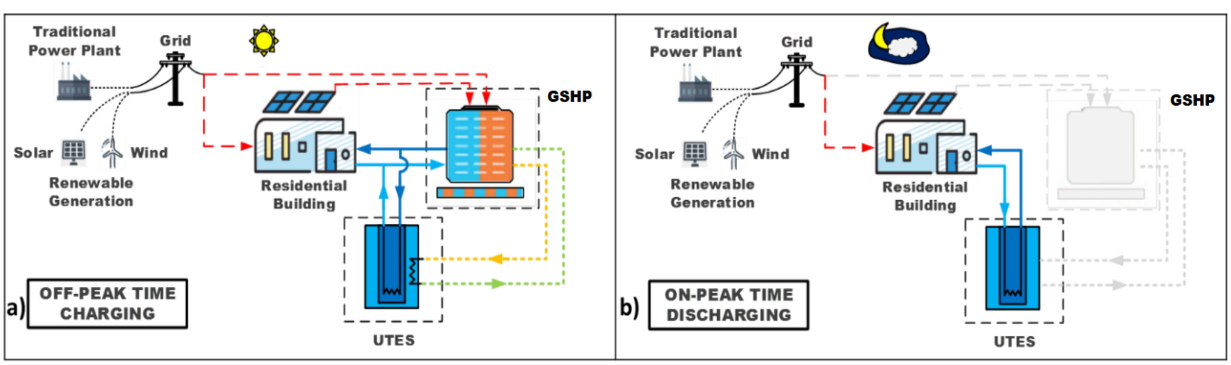


Figure 1. Schematic of the GSHP+UTES system: (a) GSHP operates to cool a building and also store cooling energy in a UTES during off-peak hours; (b) stored cooling energy in the UTES is discharged to cool the building with little electricity consumption during peak hours.

A novel underground thermal energy storage (UTES) integrated with ground source heat pumps (GSHPs) developed by Oak Ridge National Laboratory in collaboration with Purdue University is an active thermal energy storage system. It enables flexible electric demands at buildings while meeting their thermal demands with an energy efficient GSHP system. The schematic of the proposed system is shown in Figure 1. With a UTES integrated GSHP system (referred GSHP+UTES in Figure 1), the overproduced renewable power or the electricity generated at off-peak hours can be used to produce useful thermal energy to be stored in the UTES as shown in Figure 1a. The stored thermal energy is later directly utilized as shown in Figure 1b or through a GSHP to meet buildings' thermal demands during the grid's peak hours.

While the proposed UTES integrated GSHP system can be used in both residential and commercial buildings, it may be more effective in residential buildings because thermal loads of residential buildings are mostly driven by weather conditions and thus vary widely during a day, which provides more opportunities for shafting the electric demand in peak hours to off-peak hours through UTES. In addition, residential buildings usually have more balanced heating and cooling loads on an annual basis than commercial buildings. So, more energy could be saved by using the GSHP, which can provide both heating and cooling to the building. According to EIA 2015 Residential Energy Consumption Survey (RECS) (EIA, 2018), about 63% of the 118 million housing units in the US are detached single-family houses (SFHs). SFHs usually have front and back yards where the UTES can be installed underneath. Given the large amount and the generally available land for installing UTES, SFHs are a clear target market for the proposed UTES integrated GSHP systems.

A previous study indicates the proposed system could significantly reduce the summer peak electric demand of a typical residential building by shifting the electrical demand from peak to off-peak hours of a day, as shown in the following Figure 2 (Liu et al., 2019).

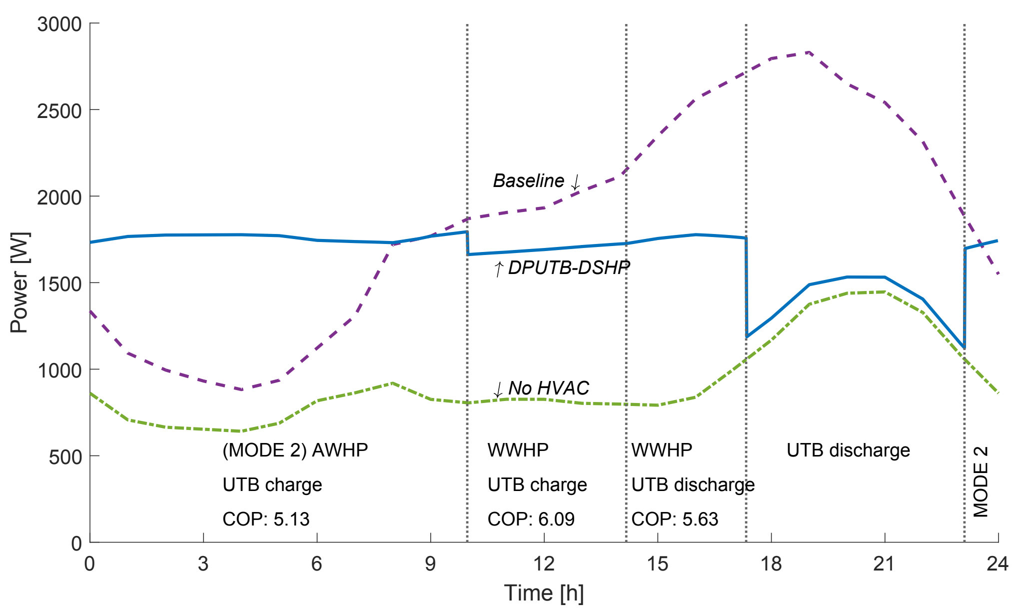


Figure 2. An example simulation result showing flattened daily electric demand of a residential building by replacing a baseline conventional HVAC system with the proposed system (referred "DPUTB-DSHP" in the figure)

A bottom-up approach was taken to assess the potential impacts of the proposed UTES integrated GSHP systems on the existing electric grids in the United States. The impacts are assessed based on three inputs. The first input is the change of electric demand profile of a typical SFH resulting from retrofitting conventional HAVC systems with the proposed system. The second input is the maximum number of the existing SFHs that can be retrofitted with the proposed systems without demanding more electricity than the existing electric grids can provide. The third is the annual demand profiles of various electricity markets. The assessment of the impacts in seven major electricity wholesale markets is detailed in a technical report (Shi et al., 2020). This paper presents the methodology and a preliminary analysis of the impacts of retrofitting conventional HAVC systems with the proposed system on the electric demand of a typical SFH in various climate zones in the US.

2. Methodology

Changes of Electric End-Use Load Profile (EULP) in a typical residential building resulting from retrofitting the conventional HVAC systems with the proposed system is determined through a series of computer simulations using DOE's prototype building model for the single-family house (DOE, 2014). Eighteen cities have been selected to represent the service areas of seven electricity wholesale markets in the US, as listed in Table 1. Multiple reprehensive locations are selected to account for the different climates within a service area.

Table 1. List of selected locations representing climate zones in service areas of electricity wholesale markets

Electricity Market	City	State	ASHRAE CZ	Weather type	Census Region
CAISO	Los Angeles	CA	3B	hot-dry/mixed-dry	West
MISO	Baton Rouge	LA	2A	hot-humid	South
	Jackson	MS	3A	hot-humid	South
	Indianapolis	IN	5A	cold/very cold	Midwest
	Duluth	MN	7	cold/very cold	Midwest
ISO-NE	Boston	MA	5A	cold/very cold	Northeast
NYISO	New York	NY	4A	cold/very cold	Northeast
Northwest	Helena	MT	6B	cold/very cold	West
	Seattle	WA	4C	marine	West
	Salt Lake City	UT	5B	cold/very cold	West
PJM	Baltimore	MD	4A	mixed-humid	South
Southeast	Atlanta	GA	3A	mixed-humid	South
	Tampa	FL	2A	hot-humid	South
Southwest	Phoenix	AZ	2B	hot-dry/mixed-dry	West
	Albuquerque	NM	4B	hot-dry/mixed-dry	West
SPP	Oklahoma City	OK	3A	mixed-humid	South
	Omaha	NE	5A	cold/very cold	Midwest
ERCOT	San Antonio	TX	2A	hot-humid	South

The prototype single-family house (SFH) has two floors above the ground and an attic. The entire house is divided into two thermal zones: the attic zone, which is not air-conditioned, and the living zone (223 m^2). The conventional HVAC system commonly used in the SFHs in the US uses a gas furnace (GF) for space heating and uses an air conditioner (AC) for space cooling. The rated efficiency of the AC unit, expressed with the coefficient of performance (COP) for cooling, is 3.97. The heating efficiency of the GF is 0.8, and the electricity consumption for running the GF is ignorable.

To evaluate the impacts of the proposed UTES integrated GSHP system on the electricity use of the prototype building, the electricity consumption of the proposed system, and three conventional HVAC systems for meeting the same thermal loads are calculated. The first conventional HVAC system uses a gas furnace (GF) for space heating and uses an air conditioner (AC) for space cooling, as described above. The second system uses a conventional air-source heat pump (ASHP) supplemented with an electric resistance heater. The rated cooling COP of the ASHP is 3.97, and the heating COP is 3.63 at rating condition (i.e., at 8.3ºC ambient air temperature). The third system uses a GSHP for both space heating and space cooling. Because the ground temperature does not change widely as the ambient air temperature, the GSHP system has higher efficiencies than the ASHP—5.5 cooling COP and 4.0 heating COP. The GSHP system can meet the peak space heating demand without using any supplemental heating. For the proposed UTES integrated GSHP system, it is assumed that the UTES has enough capacity, and the GSHP can operate at the efficiency mentioned above of the conventional GSHP system. Energy consumption related to the domestic hot water (DHW) was not included in this study because DHW demand is highly dependent on occupant behaviors instead of the time of a day, and the energy consumption for supplying DHW is usually much smaller than that for space cooling and space heating.

3. Simulation Results and Discussions

Thermal load profiles for space heating and space cooling of the prototype building are predicted with computer simulations, and they are independent of the HVAC system used for the building. As an example, Figure 3 shows the simulation-predicted thermal load profiles of an SFH located in Indianapolis, IN, on the extremely cold day in winter and the extremely hot day in summer, respectively.

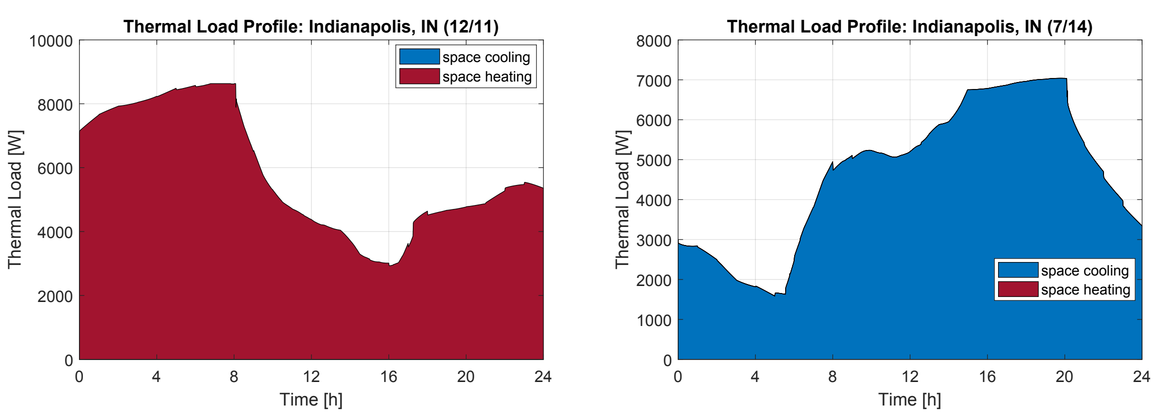
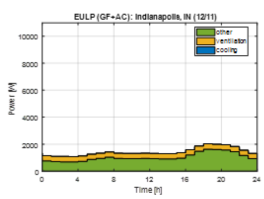
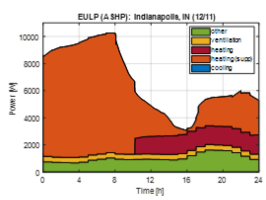
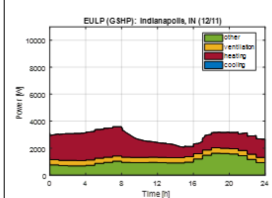
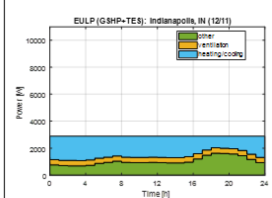
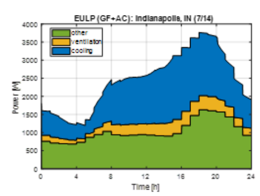
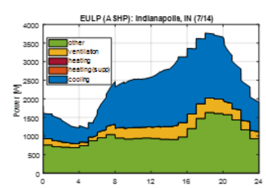
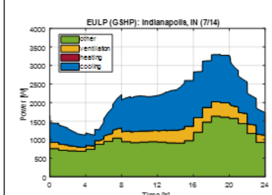
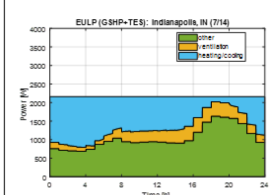


Figure 3. Thermal load profiles of prototype residential building in Indianapolis, ID on a typical day in winter (left) and in summer (right)

Table 2 presents a small sample of simulation results of a typical SFH at Indianapolis, IN. As can be seen in Table 2, the electric demand increases dramatically by 384% in winter by replacing the GF + AC system with the ASHP system. This is because the heating capacity of the conventional ASHP drops significantly when the ambient air temperature is below freezing point, so the electric resistance heater, which has a COP of 1, has to be turned on to supplement the ASHP. When the ambient temperature is below -17.8ºC, the heat pump shuts down, and only the electric resistance heater is used to meet the heating demand of the building. The conventional GSHP system, which can more efficiently heat the building than the ASHP system without using any supplemental heating, results in a moderate increase (69%) in the winter peak electric demand compared with the GF + AC system, and it results in a small downward shift of the electric demand in summer due to its higher cooling efficiency than the AC and ASHP. By shifting the electric load from peak to off-peak hours, the UTES integrated GSHP system reduces the summer peak demand by 43% compared with the AC and ASHP and it results in a moderate increase (36%) in the winter peak compared with GF. By replacing the GF + AC system with the UTES integrated GSHP, the annual peak electric demand of the building is reduced by 23% from 3,766 kW to 2,888 kW. Results at other locations are presented in a technical report by the authors (Shi et al. 2020).

Table 2. Prototype building simulation results for Indianapolis

	GF + AC	ASHP	GSHP	UTES integrated GSHP
Winter				
Peak [W]	2,120	10,257	3,584	2,888
Summer				
Peak [W]	3,766	3,766	3,295	2,155

The summer peak electric demands of the prototype buildings resulting from various HVAC systems in the 18 selected locations are listed in Table 3, along with the summer peak reduction rate resulting from replacing the commonly used GF + AC system with the proposed UTES integrated GSHP system. The summer peak reduction rate is calculated with Equation (1):

$$Summer\ Peak\ Reduction\ Rate = \frac{Summer\ Peak\ (GF + AC) - Summer\ Peak\ (UTES + GSHP)}{Summer\ Peak\ (GF + AC)} \times 100\% \quad (1)$$

Table 3. Summer peak electric demands at 18 locations resulting from various HVAC systems

Market	City	Summer peak [W]				Summer peak reduction rate
		GF+AC	ASHP	GSHP	UTES integrated GSHP	
CAISO	Los Angeles, CA	2553	2553	2457	1871	27%
MISO	Baton Rouge, LA	4028	4028	3476	2255	44%
	Jackson, MS	3589	3589	3105	2015	44%
	Indianapolis, IN	3766	3766	3295	2155	43%
	Duluth, MN	3207	3207	2931	1982	38%
ISO-NE	Boston, MA	3655	3655	3174	2032	44%
NYISO	New York, NY	3492	3492	3104	1983	43%
Northwest	Helena, MT	3401	3401	2986	2015	41%
	Seattle, WA	3159	3159	2876	1960	38%
	Salt Lake City, UT	3913	3913	3285	2106	46%
PJM	Baltimore, MD	3789	3789	3346	2148	43%
Southeast	Atlanta, GA	3611	3611	3158	2007	44%
	Tampa, FL	3876	3876	3438	2199	43%
Southwest	Phoenix, AZ	4985	4985	3847	2623	47%
	Albuquerque, NM	3828	3828	3226	2099	45%
SPP	Oklahoma City, OK	3928	3928	3315	2124	46%
	Omaha, NE	3999	3999	3382	2093	48%
ERCOT	San Antonio, TX	4272	4272	3572	2143	50%

The above results show that by replacing the conventional HVAC system with the proposed system, the summer peak electric demand can be reduced by 27% to 50% depending on whether—higher peak demand reduction at locations with warmer weather and larger cooling loads.

The winter peak electric demands under various conditions are summarized in Table 4, along with the winter peak increase rate resulting from replacing the commonly used GF + AC system with the proposed UTES integrated GSHP system. The winter peak increase rate is calculated with Equation (2):

$$Winter\ Peak\ Increase\ Rate = \frac{Winter\ Peak\ (UTES + GSHP)\ -\ Winter\ Peak\ (GF + AC)}{Winter\ Peak\ (GF + AC)} \times 100\% \qquad (2)$$

Table 4. Winter peak electric demands at 18 locations resulting from various HVAC systems

Market	City	Winter peak [W]				Winter peak increase rate
		GF+AC	ASHP	GSHP	UTES integrated GSHP	
CAISO	Los Angeles, CA	1690	2127	1922	1690	0%
MISO	Baton Rouge, LA	1826	5905	3014	2136	17%
	Jackson, MS	1896	5786	2811	2263	19%
	Indianapolis, IN	2020	10257	3584	2888	43%
	Duluth, MN	1950	11004	3718	3324	70%
ISO-NE	Boston, MA	1999	10515	3765	3057	53%
NYISO	New York, NY	1999	8018	3375	2920	46%
Northwest	Helena, MT	2025	9755	3463	2892	43%
	Seattle, WA	1940	4906	2609	2074	7%
	Salt Lake City, UT	2106	6190	3020	2345	11%
PJM	Baltimore, MD	2029	7487	3174	2682	32%
Southeast	Atlanta, GA	1869	7671	3261	2409	29%
	Tampa, FL	1661	3854	2617	1747	5%
Southwest	Phoenix, AZ	1631	3621	2340	1631	0%
	Albuquerque, NM	1807	4391	2581	1807	0%
SPP	Oklahoma City, OK	2048	10008	3783	3264	59%
	Omaha, NE	2049	10743	3727	3140	53%
ERCOT	San Antonio, TX	1722	5768	2991	2211	28%

The above results show that by replacing the conventional GF with the proposed system, the winter peak electric demand will increase between 0 to 70%, varying by location. This increase is much smaller compared with that resulting from using the conventional ASHP system, especially at locations with cold climates. For locations with a hot climate, the winter peak increase is smaller and even negligible.

By comparing the summer and winter peaks, the annual peaks (the larger one of the summer/winter peaks) for various systems in different locations are determined. The annual peaks are listed in Table 5, along with the annual peak reduction rate resulting from replacing the commonly used GF + AC system with the proposed UTES integrated GSHP system. The annual peak reduction rate is calculated with Equation (3):

$$Annual\ Peak\ Reduction\ Rate = \frac{Annual\ Peak\ (GF + AC) - Annual\ Peak\ (UTES + GSHP)}{Annual\ Peak\ (GF + AC)} \times 100\% \quad (3)$$

The results in Table 5 show that except for Duluth, MN, the annual peak for all other locations can be reduced by replacing the conventional HVAC system with the proposed system. The annual peak electric demand can be reduced by 15% to 47%, which means the existing electricity supply system of the SFHs in these regions has enough capacity for running the proposed system. Cooling-dominated areas have a greater reduction rate than cold places.

Table 5. Annual peak electric demands at 18 locations resulting from various HVAC systems

Market	City	Annual peak [W]				Annual peak reduction rate
		GF+AC	ASHP	GSHP	UTES integrated GSHP	
CAISO	Los Angeles, CA	2553	2553	2457	1871	27%
MISO	Baton Rouge, LA	4028	5905	3476	2255	44%
	Jackson, MS	3589	5786	3105	2263	37%
	Indianapolis, IN	3766	10257	3584	2888	23%
	Duluth, MN	3207	11004	3718	3324	-4%
ISO-NE	Boston, MA	3655	10515	3765	3057	16%
NYISO	New York, NY	3492	8018	3375	2920	16%
Northwest	Helena, MT	3401	9755	3463	2892	15%
	Seattle, WA	3159	4906	2876	2074	34%
	Salt Lake City, UT	3913	6190	3285	2345	40%
PJM	Baltimore, MD	3789	7487	3346	2682	29%
Southeast	Atlanta, GA	3611	7671	3261	2409	33%
	Tampa, FL	3876	3876	3438	2199	43%
Southwest	Phoenix, AZ	4985	4985	3847	2623	47%
	Albuquerque, NM	3828	4391	3226	2099	45%
SPP	Oklahoma City, OK	3928	10008	3783	3264	17%
	Omaha, NE	3999	10743	3727	3140	21%
ERCOT	San Antonio, TX	4272	5768	3572	2211	48%

The annual electricity consumption of the prototype building under various conditions is listed in Table 6, along with the annual electricity consumption reduction rate resulting from replacing the commonly used GF + AC system with the proposed UTES integrated GSHP system. The annual electricity consumption reduction rate is calculated with Equation (4):

$$Annual\ Electricity\ Consumption\ Reduction\ Rate = \frac{Annual\ Electricity\ Consumption\ (GF + AC) - Annual\ Electricity\ Consumption\ (UTES + GSHP)}{Annual\ Electricity\ Consumption\ (GF + AC)} \times 100\% \quad (4)$$

Table 6. Annual electricity consumption at 18 locations resulting from various HVAC systems

Market	City	Annual Electricity Consumption [kWh]				Consumption reduction rate
		GF+AC	ASHP	GSHP	UTES integrated GSHP	
CAISO	Los Angeles, CA	13922	14477	12548	12548	10%
MISO	Baton Rouge, LA	16533	18750	15572	15572	6%
	Jackson, MS	15974	18270	14964	14964	6%
	Indianapolis, IN	16348	23855	17051	17051	-4%
	Duluth, MN	16237	28840	17951	17951	-11%
ISO-NE	Boston, MA	15675	21877	16440	16440	-5%
NYISO	New York, NY	15807	20778	16151	16151	-2%
Northwest	Helena, MT	16082	24011	16875	16875	-5%
	Seattle, WA	14721	18446	14717	14717	0%
	Salt Lake City, UT	16184	20995	16022	16022	1%
PJM	Baltimore, MD	15931	20382	15920	15920	0%
Southeast	Atlanta, GA	15702	18312	14979	14979	5%
	Tampa, FL	17192	17857	15372	15372	11%
Southwest	Phoenix, AZ	18865	19829	16403	16403	13%
	Albuquerque, NM	15987	19035	15180	15180	5%
SPP	Oklahoma City, OK	16322	20519	16017	16017	2%
	Omaha, NE	16646	24158	17322	17322	-4%
ERCOT	San Antonio, TX	17218	19082	15948	15948	7%

Results in Table 6 show that by replacing the commonly used GF + AC system with the proposed system, the annual electricity consumption of the building will increase in heating-dominated regions and decrease in cooling dominated regions, and the variance is within 15%. While the proposed system reduces electricity consumption for space cooling due to its higher cooling efficiency than the conventional AC and ASHP, it consumes more electricity in winter than the GF + AC system for space heating. In heating-dominated regions, the increase in electricity consumption for space heating is more than the reduction of electricity consumption for space cooling, so that the annual electricity consumption increases. On the other hand, in cooling dominated regions, the increase in electricity consumption for space heating is less than the reduction of electricity consumption for space cooling, so that the annual electricity consumption decreases.

5. Conclusions

This study preliminarily investigated the potential impacts of applying the proposed UTES integrated GSHP system on the peak electric demand and annual electricity consumption of a typical residential building at various climate zones in the United States. The UTES integrated GSHP system can flatten the electric demand profile of the building by shifting electric demands from peak to non-peak hours. Simulation results indicated that replacing the conventional HVAC system with the proposed system could:

- reduce summer peak electric demand by 27% to 50% depending on whether—higher peak demand reduction at locations with warmer weather and larger cooling loads;
- increase the winter peak electric demand by 0 to 70%, varying by locations. This increase is much smaller compared with that resulting from using the conventional ASHP system, especially at locations with cold climates. For locations with a hot climate, the winter peak increase is smaller and even negligible;
- shed the annual peak electric demand for all locations by 15% to 47%, except at Duluth, MN. It means the existing electricity supply system of the SFHs in most regions has enough capacity for running the proposed system; and
- consume more electricity on an annual basis in heating-dominated regions and consume less electricity in cooling dominated regions, and the variance in annual electricity consumption in various climate zones is within 15%.

Simulations of the UTES integrated GSHP system in this study are based on a few assumptions (e.g. constant heating/cooling COP of the GSHP, enough capacity of the UTES, and ideal control of the UTES and the GSHP) because the UTES system is still under development at the time of this study. Detailed simulations of the UTES integrated GSHP system will be developed to provide more accurate results, and the market assessment will be updated with the more accurate simulation results then.

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