Applied Energy 237 (2019) 60–69

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Future energy scenarios with distributed technology options for residential city blocks in three climate regions of the United States

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HIGHLIGHTS

- Future residential demand with heat pumps are estimated in four cities.
- Local wind and solar generation mixes are compared with and without storage.
- Cost comparisons of distributed technology options including storage are studied.

ARTICLE INFO

Keywords:
Distributed technology
Wind
Solar
Heat pump
Storage
Residential

ABSTRACT

To reduce greenhouse gas emissions, the electricity sector is going through two main transitions. First, the electric grid is integrating variable renewable generation, such as wind and solar. Second, demands are changing as heating systems are shifting from gas-based to high efficiency electric heat pumps. This paper provides a comparative analysis of future energy scenarios with distributed technology options including (1) wind and solar generation; (2) heat pumps for heating and cooling; and (3) battery and thermal storage in representative residential blocks in four cities, including New York City, New York; Minneapolis, Minnesota; Tallahassee, Florida; and Fort Collins, Colorado. These cities are located in three climate regions with different weather patterns which result in different demand profiles and different local renewable resources. Future energy demand scenarios with 100% penetration of air source or ground source heat pumps for heating and cooling are estimated for the four residential city blocks. Under a future scenario with all electric demand with air source heat pumps and high renewable energy penetration, this study finds that (1) the optimal wind and solar generation mix varies with location and amount of storage and (2) battery storage is more cost effective than thermal storage, ground source heat pumps, and overbuilt renewable generation.

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https://doi.org/10.1016/j.apenergy.2019.01.048
Received 31 May 2018; Received in revised form 12 December 2018; Accepted 4 January 2019
Available online 07 January 2019
0306-2619/

1. Introduction

The electricity sector is one of the main contributors of greenhouse gas (GHG) emissions. In recent years, the sector emits more than 25% of the GHG in the United States [1]. To reduce these emissions, the electric power grid is integrating variable renewable generation, such as wind and solar. In addition, energy demand in buildings for space heating and cooling accounts for roughly 40% of world's total annual building energy consumption and has led to increasing GHG emissions [2]. Severe environmental impacts caused by emissions related to growing building energy use have urged governments, since the approval of Montreal Protocol in 1997, to reduce energy consumption from fossil fuels and promote energy efficient technologies and renewable energy [3]. Shifting from natural gas-based heating to distributed electric heating and cooling systems in buildings, namely heat pumps, has been identified as an effective means to improve energy efficiency and reduce emissions in the residential sector [4–9].

As the electric grid transitions to more renewable based and the building heating systems transition from natural gas-based to electric heat pumps, an important question is posed as what the implications of these transitions are on the residential sector. As heat pump penetration increases, a significant rise in electricity demand is observed [10]. To ensure overall reduction in greenhouse gas emissions as the electricity demand increases, increased supply must come from renewable generation rather than carbon-intensive generation such as coal or natural gas. Renewable generation sources such as wind and solar on a distributed level are thoroughly investigated for residential use [11]. However, both renewable resources as well as demand for heating and cooling vary significantly based on geographical climate patterns. Thus, these electricity sector transitions have different implications for residential sector in cities in different climate regions.

In addition to wind and solar, other distributed technology options such as storage are also projected to be commonly implemented in residential buildings or communities. Energy autonomy in residential buildings with distributed energy systems such as battery storage, thermal storage, and solar photovoltaics is examined with a techno-economic based analysis [12]. Another study examined the joint effort of battery energy storage and solar photovoltaics in a residential community [13]. Though the residential buildings included in [12,13] represents a comprehensive load diversity at a community scale, the shift to electric heating is not considered. At high penetration levels of renewable resources, storage is needed to address the increasing uncertainty and variability on the power system [14]. Large amount of storage is needed to mitigate the variability fully, which can be high cost. However, if battery storage is used as distributed storage systems, they can provide benefits to both the residential consumers as well as the operation and planning of the distribution systems [15,16]. The distributed storage systems are multi-hour since seasonal storage is not economically justifiable when considering the overall cost of deep decarbonization [17]. In addition to distributed energy storage at a community level, demand load management and control of the residential energy systems are also desired to optimally utilize the energy storage at high levels of solar photovoltaic penetration [18,19]. Though these studies allow deeper penetration of renewable generation and subsequently greater emissions reductions while providing benefits to the consumers and power distribution systems, none explored the effect of different renewable generation mix. A recent study found that optimal renewable generation mixes for different sized areas with and without storage can vary spatially and temporally due to the varying electricity demand and availability of wind and solar resources [20]. As area of resource aggregation and demand both increase, the optimal resource mix consistently moved toward heavier wind generation. This work also showed that adding storage shifts the optimal wind and solar generation mix toward more solar generation, away from a wind dominant mix without storage. Renewable resources depend on climate. Some studies evaluated the performance of distributed technologies under different climate regions. In [21], the socio-economic performance of solar photovoltaic and heat pump are examined in three different climate regions, but wind energy and storage were not considered. Another study examined distributed energy systems with renewables for communities in different climate zones in China [22] but wind and solar energy were not included.

This paper provides a comparative analysis investigating the energy implications of the electricity sector transitions on a distributed level for representative residential blocks in cities in various climate regions. This study uses real consumption data for groups of residential buildings to represent city blocks with load diversity and a diverse portfolio of building characteristics. Distributed technologies including heat pumps, wind, solar, battery storage, and thermal storage are studied and compared for these city blocks. The cities in this study are: New York City, New York; Minneapolis, Minnesota; Tallahassee, Florida; and Fort Collins, Colorado. These four cities are located in three different climate regions. Minneapolis and For Collins are located in the "Cold/Very Cold" region; New York City is located in the "Mixed" region but near the border of the "Cold/Very Cold" region; and Tallahassee is located in the "Hot/Humid" region of the United States [23]. These cities are chosen due to data availability. The goal of this paper is to study the cross-city comparisons as cities in different climate regions have (1) different weather patterns which results in different demand profiles; and (2) different local renewable resources. This paper inspects the demand profiles, renewables resources' availabilities, and various storage capacities, and finds the optimal wind and solar generation mixes for each city. Additionally, cost comparisons of additional technology options including batteries and thermal storage are examined. In policy making, the efficiency of policy is defined as the ratio of the policy output obtained for a given level of resources [24–26]. This paper investigates for similar amount of investments the best solution that yields the most renewable energy penetration and the lowest GHG emission in future scenarios.

This paper is organized as follows: Section 2 summarizes the historical electricity consumption time series data used in the study. Section 3 estimates future demand scenarios with 100% penetration of air source heat pumps (ASHPs) or ground source heat pumps (GSHPs) for heating and cooling in the four cities based on the current demand and temperature data. Section 4 analyzes the energy penetration by wind and solar under high distributed local wind and solar generation for the future demand scenario with ASHP for various wind and solar generation mix with and without storage. Section 5 provides a comparative analysis among the four cities on the cost comparisons of additional technology options including overbuilt local wind and solar generation, battery storage, thermal storage, and GSHP.

2. Demand data

This study utilizes fine spatial and temporal scale real time series electricity consumption data from Fort Collins, Colorado and Tallahassee, Florida. From the Fort Collins Utilities service area, electricity consumption data was obtained from a random selection of 100 single family residential homes. This data from Fort Collins is consisted of 15-minute interval advanced metering infrastructure (AMI) electricity consumption data from these selected buildings for 2015 and 2016. From Tallahassee, Florida, 123 random residential homes with 30-minute interval electricity consumption data from 2011 to 2014 were selected. The size of the homes selected in Fort Collins ranges from 1060 to 2000 square feet (average size of 1539 square feet per home), with an average current total annual electricity demand of 8304 kW-hour (kWh) per home (average demand of 0.95 kWh per hour per home). The size of the homes in Tallahassee ranges from 572 to 2539 square feet (average size of 1091 square feet per home), with an average total annual electricity demand of 9380 kWh per home (average demand of 1.07 kWh per hour per home). These homes represent real-life load diversity as well as a diverse portfolio of building thermal characteristics. Different time periods of the historical data might generate uncertainty of the year-to-year energy consumption in the future. There are two types of year-to-year effects: (1) non-weather related which when limiting to residential loads, would arise from the number, type, efficiency and age of household energy appliances. On the time scale considered, one would not expect systemic changes here. Individual residence level variability would exist but this is addressed through premise level data for 100 or more residences. There would indeed be weather change and those changes are accounted for through the methodology presented in the paper. On a longer-term, e.g. decadal basis, changes on the demand side would occur but are not modeled in this paper.

3. Future demand scenarios

In this section, the thermal response of the homes in Tallahassee and Fort Collins are estimated by examining the relationship between demand and temperature. Using the thermal response portfolios of the homes, future demand scenarios with 100% penetration of ASHP and GSHP for heating and cooling are estimated. Comparisons against current demand are provided.

3.1. Temperature driven demand

The demand time series for the selected homes in Fort Collins and Tallahassee were aggregated and normalized by square-footage to create an hourly time series in kWh/sqft-h. Historical hourly dry-bulb temperature and dew-point temperature time series data were gathered for each city for their individually analyzed time periods from the Integrated Surface Hourly Data Base from the National Oceanic and Atmospheric Association (NOAA) [27]. The normalized demand time series data were then plotted against temperature to find the relationship between temperature and demand. Fig. 1 shows an example of such relationship in Tallahassee using peak aggregated demand in each day and the wet-bulb temperature at the time of peak demand. Because Tallahassee is located in the Hot/Humid climate region, a large portion of the thermal load is the dehumidification of moist air. Therefore, wet-bulb temperature is used in this example because it accounts for both the dry-bulb temperature and the moisture content in the air. In contrast, peak daily demand is used in this example such that behavioral effects such as occupancy at different times of the day is eliminated.

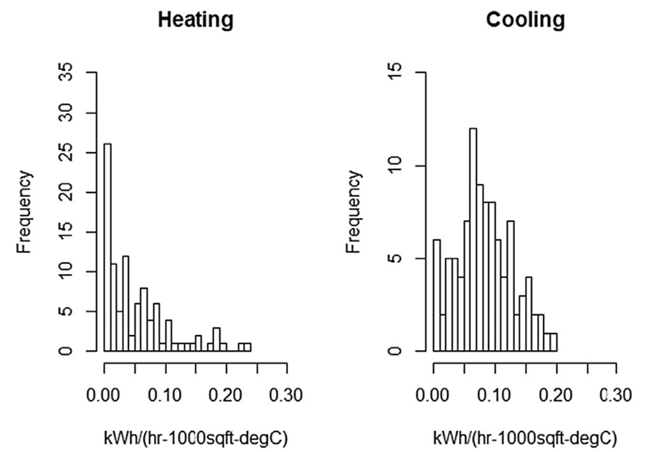

Fig. 2. Distributions of heating and cooling consumption slopes for the homes in Tallahassee in kWh/h-1000sqft-°C.

By applying break-point regression [28], the temperature driven demand can be de-coupled from the overall demand. As shown in Fig. 1, by fitting a break-point regression, the threshold temperature (break-point temperature), non-temperature driven demand (demand at the break-point), as well as the temperature driven heating and cooling demand per heating or cooling degree (slopes on the left and right side, respectively) can be estimated. Since the demand is normalized by square foot, the thermal response of the buildings, or the heating and cooling consumption slopes has the unit of kWh/sqft-h-°C, which can be directly used to estimate the heating and cooling electricity demand per floor area given the ambient temperature.

3.2. Existing heating and cooling in individual homes

For each home in Tallahassee and Fort Collins, break-point regression is applied on hourly electricity demand vs dry-bulb temperature

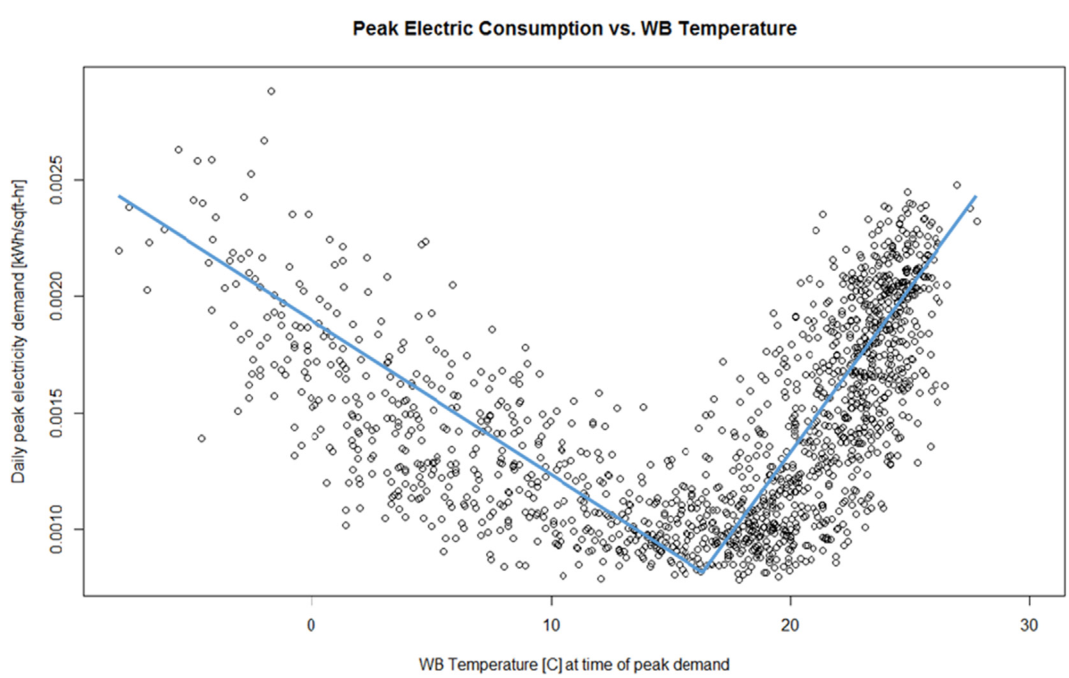

Fig. 1. Example plot showing the relationship between temperature and demand; Daily peak aggregated demand in vs wet-bulb temperature at the time during the peak demand in Tallahassee.

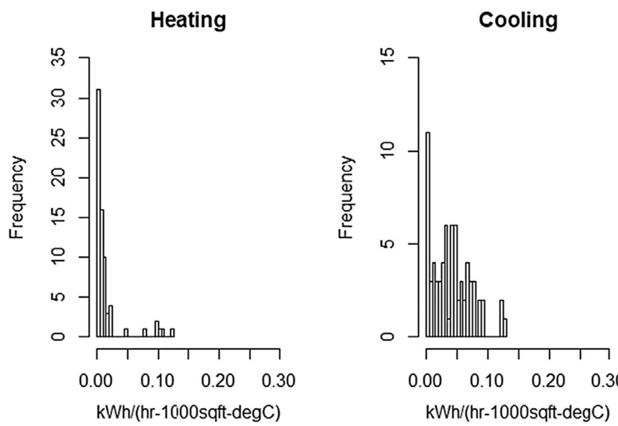

Fig. 3. Distributions of heating and cooling consumption slopes for the homes in Fort Collins in kWh/h-1000sqft-°C.

and the heating and cooling consumption slopes are collected. Figs. 2 and 3 show the distribution of the heating and cooling consumption slopes for the homes in Tallahassee and Fort Collins, respectively (after excluding outliers with negative slopes). In Tallahassee, many homes are observed to have positive non-zero cooling consumption slopes shown in Fig. 2, indicating large penetration of air conditioners. However, during periods of heating, only a small number of homes are observed consuming electricity. These electric heating loads may include resistance heating boards or electric components in the gas furnace heating systems or existing heat pumps. Alternatively, different results are observed in Fort Collins, as shown in Fig. 3. During the cooling season, although many homes are observed to have positive consumption slopes indicating that air conditioners are equipped, the magnitudes of these slopes are much smaller than those in Tallahassee due to less need for dehumidification of air. During the heating season, home property data indicate that the Fort Collins' homes included in this analysis primarily use gas furnace forced air heating systems as their heating mechanism. The positive electric heating consumptions are due to the electric components such as fans and blowers in the primary gas heating systems or secondary resistance electric heating. In both cities, slopes that are less than 0.01 kWh/h-1000sqft-°C are considered as having no primary electric equipment for heating or cooling.

3.3. Estimating future demand with ASHP and GSHP

For the homes in Tallahassee and Fort Collins that are currently equipped with air conditioners, the thermal cooling load are calculated from the electric load and a coefficient of performance (COP) curve given the ambient temperatures and the threshold temperatures of the homes. To estimate the electric heating load for when all homes are equipped with heat pumps, the thermal load per heating degree is assumed to be the same as the thermal load per cooling degree away from the threshold temperatures of the homes. Given ambient temperatures and the threshold temperatures, the electric heating load is calculated by dividing the thermal heating load by the heating COP. The cooling COP and heating COP curves as a function of ambient temperatures used in these calculations are based on typical industrial air source heat pump manufacturer's specifications [29]. For GSHP, the same COP curves are used but the COP is a function of the ground temperatures in each location rather than the ambient air temperatures [30]. For the homes in Tallahassee and Fort Collins that are not currently equipped with electric cooling, their thermal response cooling consumption slopes are assumed to be the 50th percentile of the slope distribution for the homes currently have electric cooling. Their future all electric heating and cooling demand are estimated the same way. In Fort Collins, all homes considered in this paper currently have gas furnace forced air systems, so all future electric heating are considered as demand due to new heat pump installations. In Tallahassee, primary heating mechanisms are not available in the data and it is assumed that 20% of the homes are currently equipped with natural gas-based heating according to the Residential Energy Consumption Survey (RECS) from the U.S Energy Information Administration [31].

Current natural gas consumptions are estimated using the thermal heating load in heating seasons and an assumed gas furnace efficiency of 80%. The estimated results per home agree with the annual average gas consumptions for heating published in RECS. The natural gas consumptions are then converted to have the unit of kWh.

For New York City and Minneapolis, the group of homes are assumed to have the same thermal response characteristics (current heating and cooling consumption slopes) and non-temperature driven consumption as those in Fort Collins. Their current gas consumption and future heating and cooling demands are estimated using the same methods with local temperature data.

Fig. 4 summarizes the annual total electricity demand of two future scenarios with ASHP and GSHP compared to the current annual demand in four cities, with breakdowns of the total demand by gas

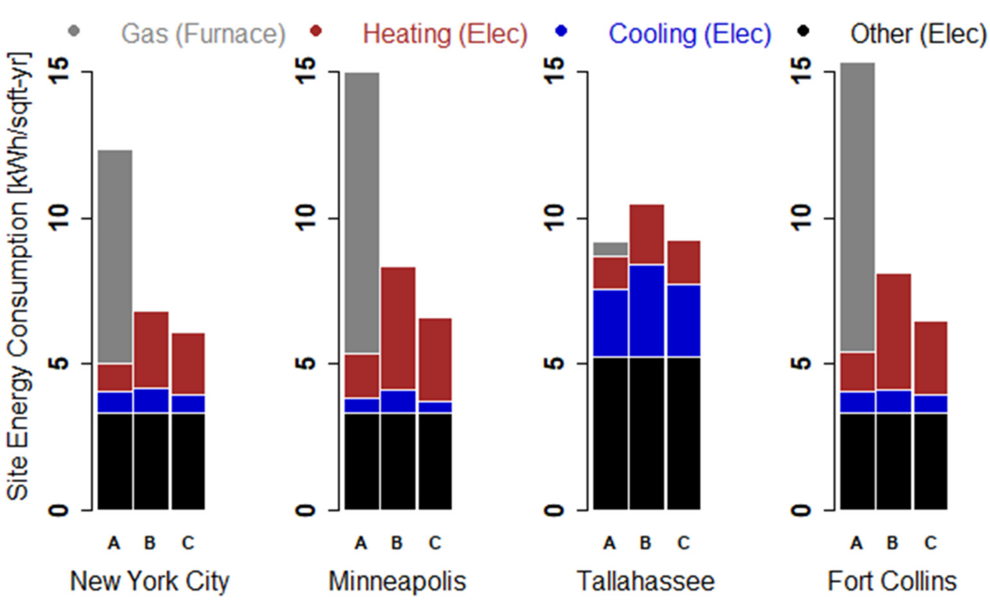

Fig. 4. Column A for each city shows the breakdown of existing demand for gas heating, electric heating, electric cooling and all other demand. Columns B and C show future annual electricity demand scenarios with 100% penetration of ASHP and GSHP respectively with breakdown by end-use. All demands are site consumption values in kWh per year normalized by square footage.

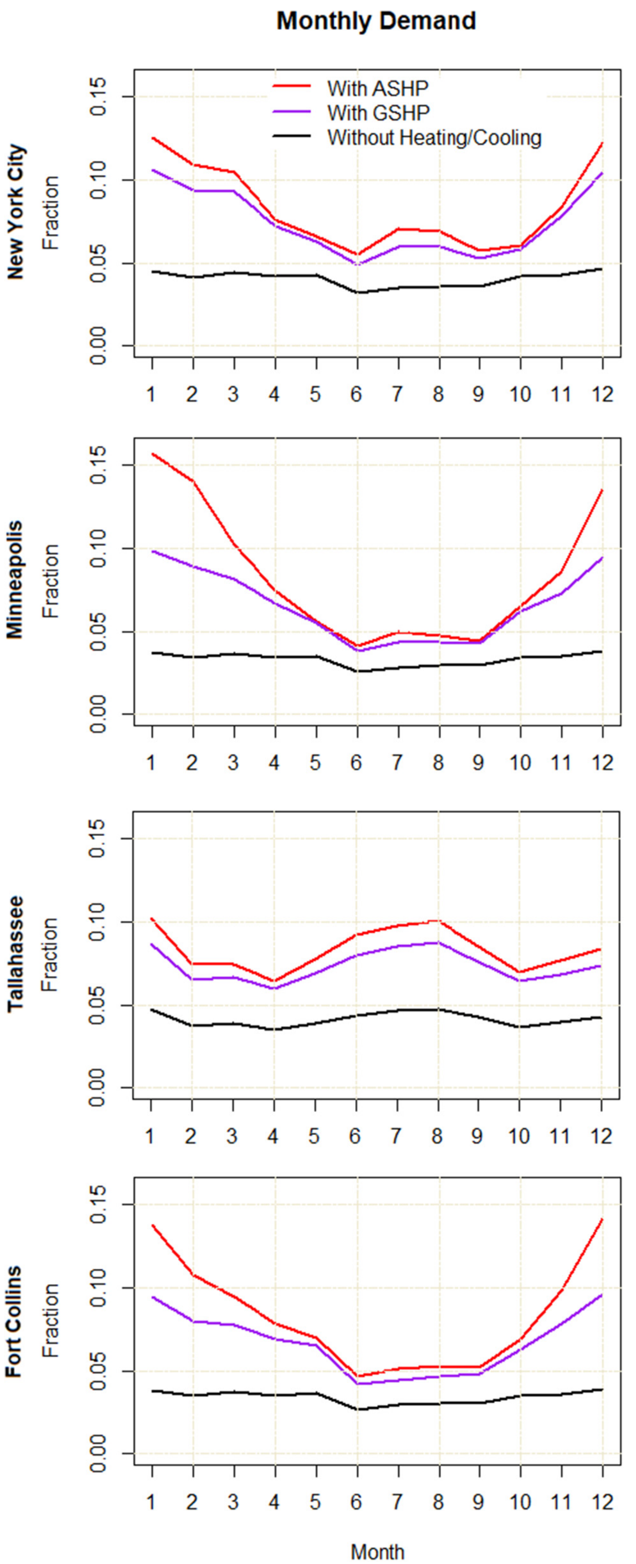

Fig. 5. Monthly demand with and without heating/cooling as a fraction of total annual demand for the future demand scenario with 100% penetration of ASHP in each city.

heating, electric heating, electric cooling, and other. In New York City, Minneapolis and Fort Collins, overall energy demand decreases due to shifting from gas to more efficient electric heating, but electricity demand in both future scenarios are higher than current demand. In Tallahassee, due to lack of gas heating causing many homes to already have electric heating and cooling, the overall demand grows in future scenarios. "Other" demand, which is the demand due to non-heating/cooling appliances, is much higher in Tallahassee, which is likely due to high constant dehumidification load due to high humidity, which is not able to be disaggregated. "Other" demand in future scenarios is considered to be identical to current "Other" demand. Therefore, factors including demand growth due to social-economic reasons and appliances' efficiency improvements are not modeled. Energy demand for domestic hot water is also not included in this model.

While Fig. 4 shows annual demand, for meeting such demand with renewables, the temporal variation of demand is just as important. In Fig. 5, the monthly demand fraction with electric cooling and heating with ASHP is shown in red for the four cities considered. Note that this demand fraction curve adds up to one for the whole year. If the ASHP is replaced with GSHP then the electric heating demand is reduced and the new lower demands are shown as fractions of the earlier demands with ASHP. Observe that the peak winter demands are now dramatically reduced, especially in the coldest climates due to increased COPs for GSHP compared to ASHP. The reduction is steep in Minneapolis but not significant in Tallahassee. For comparison, monthly demands, without the use of electricity for heating or cooling, are also shown, again as fractions of the demand with electric cooling and heating with ASHPs.

4. Future energy supply and storage scenarios

To ensure deep de-carbonization with the demand scenarios already discussed, the impact of high renewable penetration is now considered. In this section, a future grid scenario with high local distributed renewable generation is modeled. The penetration of renewables is evaluated under the demand scenario with ASHP modeled in Section 3, and shown in Fig. 5. Battery storage and thermal storage are considered as well, both within practical limits to examine their impact on meeting loads through renewable generation.

4.1. Wind generation model

Hourly mean wind speed time series data for each city for their individually analyzed time periods were collected from the Integrated Surface Hourly Data Base from NOAA [27]. The sites selected are located at the nearest airport in each city. The hub height of the data measurements is at 10 m. To account for the hub height of a typical industrial wind turbine, a power law wind speed correction is applied using Eq. (1).

$$u_{hub} = u_{ref} \cdot (z_{hub}/z_{ref})^{\alpha} \quad (1)$$

where u_{hub} is the wind speed at z_{hub}, the hub height of the turbine (assumed to be 100 m) and u_{ref} is the measured wind speed at z_{ref}, the measurement height for NOAA data, which is 10 m. Here α is assumed to be 0.11 for hub height corrections [32]. Using the corrected wind speed at turbine hub height, the hourly wind power potential output time series is estimated using the manufacturer's power curve for a typical industrial wind turbine with a cut-in wind speed of 3 m/s and a cut-out wind speed of 25 m/s [33]. The time series is then divided by the capacity of the turbine to obtain a normalized wind power generation time series in MWh-per-h/MW-nameplate-capacity.

4.2. Solar generation model

Hourly solar irradiation data for each city for their individually analyzed time periods were collected from National Solar Radiation Data Base from the National Renewable Energy Laboratory [34]. Using the manufacturer's specification sheet for a typical industrial solar photovoltaic panel [35], the hourly solar power potential output time series is estimated using Eqs. (2) and (3).

$$T_{cell} = T_a + (NOCT - 20)\cdot GHI/800 \quad (2)$$

$$P/P_{peak} = (1 - C_{power}\cdot(T_{cell} - 25))\cdot GHI/1000 \quad (3)$$

where T_{cell} is the photovoltaic cell temperature, T_a is the ambient temperature, $NOCT$ is the normal operating cell temperature of the panel, GHI is the global horizontal irradiance, P is the actual output of the solar panel, P_{peak} is the rated capacity of the solar panel, and C_{power} is the temperature coefficient of rated power. $NOCT = 44\,^{\circ}\mathrm{C}$ and $C_{power} = -0.39\%/^{\circ}\mathrm{C}$ are used to estimate the normalized solar power generation time series in MWh-per-h/MW-nameplate-capacity.

4.3. Battery and thermal storage model

A simple linear model for battery storage is used in this study. The battery is modeled with a round trip efficiency of 90% and a minimum charge/discharge rate of C/5, corresponding to the ability to fully charge or discharge in 5 h. The battery depth of discharge is assumed to be 100% and chemical degradation as a function of age and operating patterns is not modeled. In this linear model, the battery is allowed to charge only using excess renewable generation and discharge during the hours when renewable generation is insufficient to meet the demand. Note that battery is allowed to meet all end-uses.

A similar linear model for thermal storage is used in this study. The thermal storage is modeled with a round trip efficiency of 90% and a charge/discharge rate limit of 5 h. However, thermal storage is modeled such that it is only able to meet the heating demand. In this linear model, thermal storage is modeled to be charging using excess renewable generation and discharging during the hours when there is unmet heating demand. During charging, the thermal storage is modeled to have a maximum COP of 3 and it declines to one by the time the ambient temperature reaches 7.2 °C [29]. If both battery and thermal storage are present, the system is modeled such that the battery gets utilized first and thermal storage serves as a secondary storage if there is additional excess renewable generation or additional unmet heating demand.

4.4. High local renewable generation scenario with and without storage

As in [20], renewable supply either from all solar, all wind, or an optimal (highest utilization) mix of sources are considered in the scenario where the total generation is sized such that annual energy from generation equals annual demand (1X Gen). Unlike [20], the demand profile considered in this paper is purely residential and with a complete shift from any form of existing space heating to purely electric heating using ASHPs. Adding battery storage is considered next, where the amount of battery capacity is measured in the form of “Hours of Storage” where each hour of storage represents one hour of electric demand (including heating, cooling and all other demands) averaged over the entire year. Thermal storage (without battery) is also evaluated, again measured in the form of “Hours of Storage” where each hour of storage is equal to the average heating demand, where the averaging is carried out only over the hours when there is heating demand. In all of the above cases, the performance metric is the percentage of demand met. The results of these computations are shown in Fig. 6, using a group of heat maps, with percentage demand met with no battery storage, 12 h and 36 h battery storage at the optimal generation mix also shown.

4.4.1. Without storage

The results without storage for the case of all solar, all wind and an optimal mix, for each of the four cities in 1X Gen scenario are summarized in Table 1. If only solar generation is present, Tallahassee shows the highest percentage of demand met at 41%. If only wind generation is present, New York City shows the highest percentage of demand met at 57%. In all four cities, the joint capacity factor of wind and solar at the optimal mix is approximately identical at 25%. Although in each of the four cities the total annual generation of wind and solar is equal to the total annual demand, large amounts of renewable generation is curtailed without storage due to real time misalignment of generation and demand shown later in Fig. 7. Without storage, New York City and Minneapolis demonstrate wind dominant optimal mixes, whereas Tallahassee and Fort Collins demonstrate even mixes in wind and solar.

4.4.2. With storage vs. without storage

When interpreting the battery or thermal storage capacity, it is important to recognize the physical kWh of battery storage or the physical thermal kWh of storage will be different in each city. For cost comparison purposes in Section 5, 12 h of battery and 36 h of thermal storage at a community level are evaluated. Their sizes in kWh in each city are summarized in Table 2. For reference, 10 kWh of thermal storage corresponds to approximately a 200-gallon hot water tank at 140 °F.

With battery implemented, significant additional renewable energy penetration is observed, as shown in Fig. 6. 12 h of battery raises the renewable penetration from: 62% to 80% in New York City; 54% to 70% in Minneapolis; 54% to 83% in Tallahassee; and 49% to 69% in Fort Collins. The optimal wind and solar generation mix with 12 h of storage shifts towards more even in New York City but towards more solar in Tallahassee and Fort Collins. With three days of battery storage (36 h), the renewable energy penetration in all four cities reaches at least 74% (87% in New York City and 88% in Tallahassee). However, implementing thermal storage has less impact on additional renewable penetration even at large capacity.

Fig. 7 shows monthly generated and utilized wind and solar energy as a fraction of total annual demand with ASHP with and without 12 h of battery under: (1) 100S; (2) optimal mix; and (3) 100 W generation mix in four cities. In New York City and Minneapolis, wind is shown to have much better alignment on a monthly scale with the demand than solar. Thus the optimal mixes with and without storage are wind dominant. Solar, on the other hand, only shows alignment on a monthly scale in Tallahassee. Installing 12 h of battery achieves the most percentage of demand met at 83% as well as the most percentage increase of 29% (54–83%) in Tallahassee. The second highest percentage increase is 20% (49–69%) in Fort Collins. Both Tallahassee and Fort Collins have solar dominant generation portfolios with battery indicating that 12 h of battery greatly mitigates the diurnal variability of solar generation, resulting in high percentage increase. At the optimal generation mix, the percentage of demand met in New York City and Tallahassee is able to reach over 80% because the monthly alignment of renewable generation and demand shown in Fig. 7. In Minneapolis and Fort Collins, however, the percentage of demand met at the optimal mix is around 70% due to the poor monthly alignment of renewable generation and demand shown in Fig. 7.

5. Cost comparisons for distributed technology options

5.1. Cost assumptions for distributed technology options

In addition to battery or thermal storage, other options may also be viable to achieve higher renewable penetration, such as overbuilt local wind and solar generation capacity or installing GSHPs at a higher cost but more efficient than ASHPs. However, each of these options incurs a different unit cost. Thus, this section aims to provide a comparison of these technology options at approximately the same annual costs.

Installed capital costs are taken to be $2346/kW-capacity for wind turbines and a fixed O&M cost of $33/kW-year with a life span of 20 years; similar figures for solar photovoltaic panels are taken to be $2025/kW-capacity and a fixed O&M cost of $16/kW-year with a life span of 33 years [36]. The installation costs are those at 1 to 10 MW size at the distributed level.

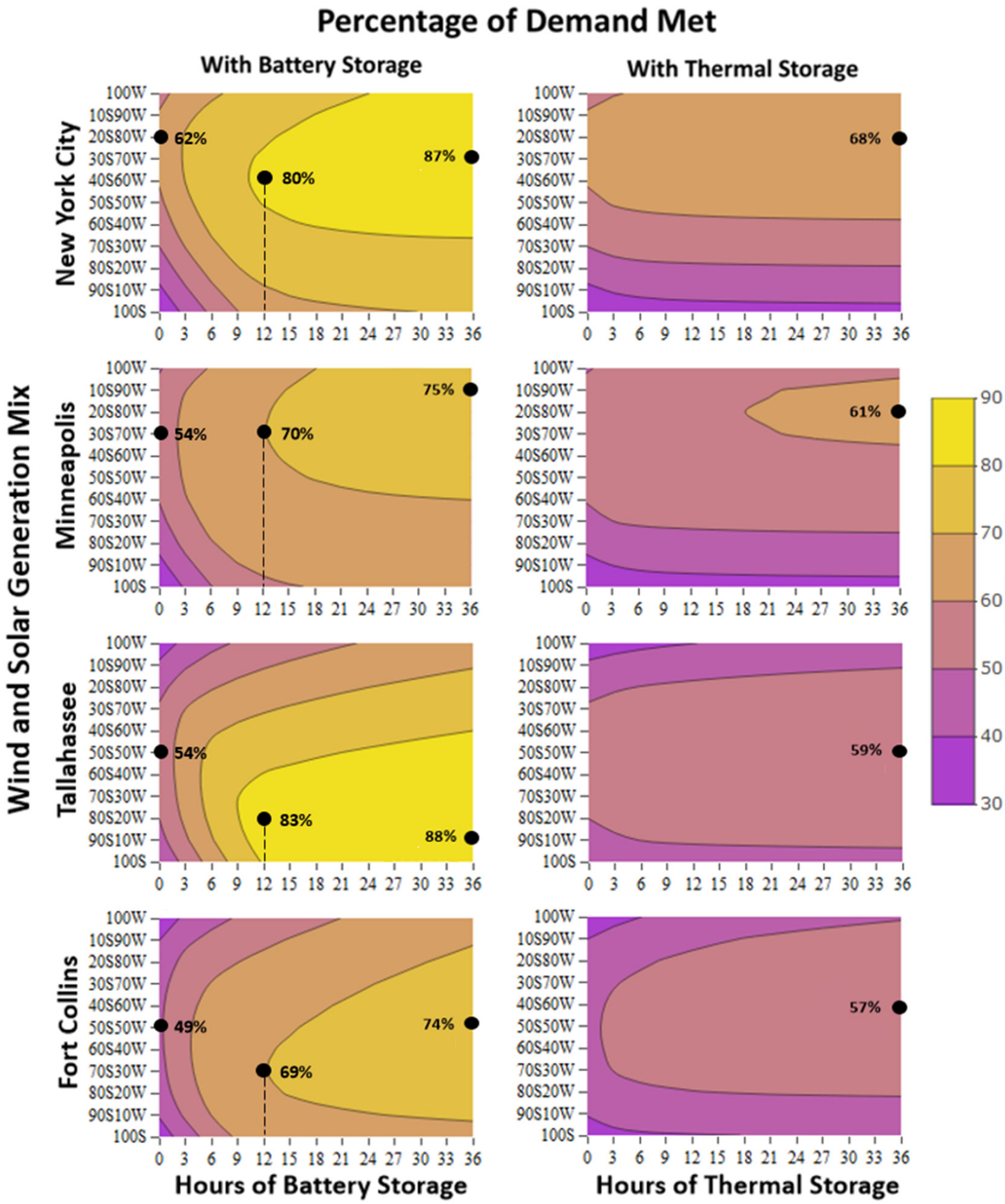

Fig. 6. Percentage of demand met by wind and solar for different combinations of wind and solar generation for increasing battery or thermal storage in four cities. Total generation is sized such that annual energy from generation equals annual future demand with ASHP (1X Gen).

Table 1
Percentage of demand met at wind and solar generation mix: (1) 100S; (2) Optimal mix; and (3) 100 W; for each city without storage. The generation is 1X in all columns.

City	100S	At Optimal Mix	100 W
New York City	32%	62%(20S80W)	57%
Minneapolis	31%	54%(30S70W)	49%
Tallahassee	41%	54%(50S50W)	35%
Fort Collins	34%	49%(50S50W)	34%

Electric battery storage is considered here with a cost of $250/kWh with a life span of 10 years [37] and the cost of thermal storage is considered to be $40/kWh-capacity with a life span of 15 years [38]. Investment costs for ASHP are assumed to be $4050–$5625 per unit [39], including installation, equipment, labor, overhead and profit. GSHP is assumed to be $12,878–$13,978 per unit [40]. Both ASHP and GSHP are considered to have a life span of 15 years.

5.2. Cost comparisons

The above options are compared at a similar annualized investment level assuming the 1X Gen scenario and a 100% penetration of ASHP are already in place. The annualized investment is the sum of fixed O% M cost per year and the annualized installation cost. A discount rate of 5% is used in this analysis.

“1.5X Gen” is analyzed in this section in order have a common cost comparison with other technology options. Using the definition described in Section 4.3, “1.5X Gen” means the local wind and solar uncurtailed total annual generation is equal to 150% of the total annual electricity demand in each of the four cities. The annualized investments per home for overbuilt wind and solar generation (1.5X Gen),

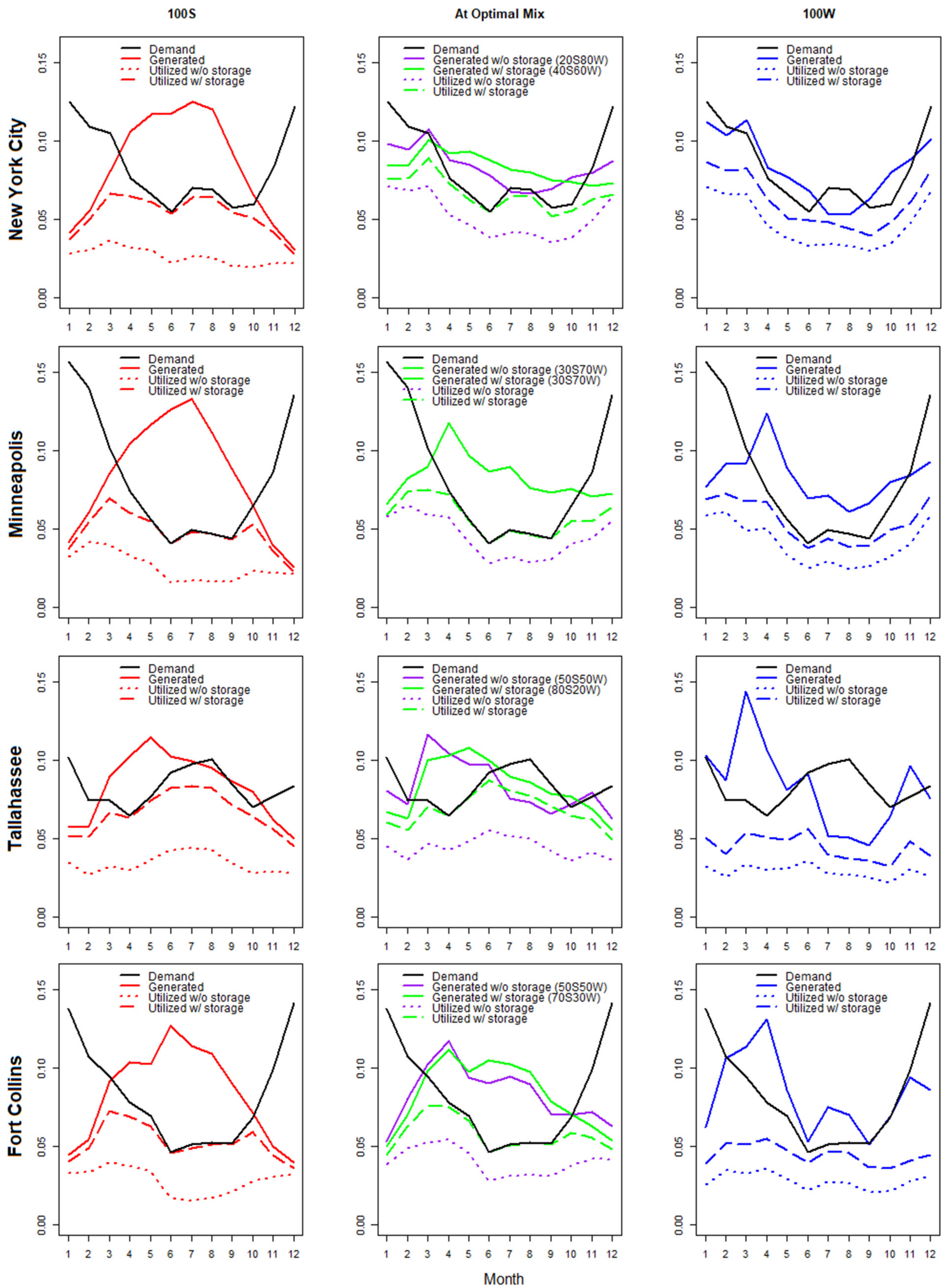

Fig. 7. Monthly generated and utilized wind and solar energy as a fraction of total annual demand with ASHP with and without 12 h of battery under: (1) 100S; (2) optimal mix; and (3) 100 W generation mix. The generation is 1X in all columns.

Table 2
Storage sizes in kWh for 12 h of battery and 36 h of thermal storage in each city.

City	12 hours of battery in kWh (electric)	36 hours of thermal storage in kWh (thermal)
New York City	14.3	114.6
Minneapolis	17.6	121.2
Tallahassee	15.7	115.0
Fort Collins	17.0	138.4

12 h of battery, 36 h of thermal storage, and GSHP rather ASHP are summarized in Table 3. Notice that these four options have very similar additional annualized investment per home. The additional annualized investments are also shown for selected combinations of technology options: (1) 12 h of battery combined with 36 h of thermal storage and (2) GSHP combined with 12 h of battery. When GSHP is installed rather than ASHP, the annual total electricity demand as well as peak weather driven demand are both less due to high efficiency. Thus the investments involving GSHPs are adjusted for less wind and solar generation capacity requirements.

As shown in Table 4, for similar annualized investment per home, implementing 12 h of battery stands out as the most cost effective in terms of increasing the percentage of demand met from the base case. Approximately doubling the investment brings an additional 2–4% increase in percentage of demand met by renewables. However, the additional renewable energy penetration of doubling the investment is much smaller compared to installing battery alone from the base case.

6. Discussions

Under a future scenario with all electric demand with air source heat pumps and high renewable energy penetration (1 X Gen), this study shows that the optimal wind and solar generation mix varies with location and amount of battery storage. For New York City, located in the “Mixed” region, the optimal generation mix shifts from 20S80W without battery to 40S60W with 12 h of battery. For Minneapolis, located in the “Cold” region, the optimal mix remains at 30S70W with no battery and 12 h of battery. For both New York City and Minneapolis, the optimal generation mixes with or without battery storage are wind dominant. For Tallahassee and Fort Collins, even though they are located in different climate regions with Tallahassee being in the “Hot-Humid” region and Fort Collins being in the “Cold” region, they both display even generation mix of 50S50W with no battery storage. With 12 h of battery, however, the optimal generation mixes for both Tallahassee and For Collins shift toward solar dominant (80S20W in Tallahassee and 70S30W in Fort Collins), as opposed to wind dominant mixes in New York City and Minneapolis.

Using demand with ASHP under 1X Gen supply scenario as a base case, it is shown that installing 12 h of battery system is the most cost-beneficial option compared to other technology options including thermal storage, GSHP, and overbuilt local wind and solar generation. There are three main reasons that battery is the most cost-beneficial choice. First, the misalignment of local renewable generation and demand can be largely absorbed and utilized by 12 h of battery shown in Fig. 7. This can also be explained by comparing the base case (1X Gen) to 1.5X Gen case: by increasing 50% of generation across all four cities, the renewable energy penetration only increases 6–9%, translating to 82–88% of the extra generation being curtailed. Second, battery can be used to meet all types of demand including heating, cooling, and other demand since all demands would have been shifted to electric. Third, the costs of battery is already low enough that the cost-effectiveness exceeds overbuilt wind and solar generation as well as high efficiency equipment such as GSHPs. As the costs of battery keep decreasing as technology evolves, the choice of installing battery would become even more intuitive.

ASHP implementation scenarios display very low efficiencies in cities in colder climate regions during the winter such as in Minneapolis and Fort Collins. When ambient temperature is very low, ASHP performs much like resistance heater with COP nearly goes to one, resulting in peaky demand in the winter as shown in Fig. 5. In Minneapolis and Fort Collins, wind and solar generation are not aligned with the demand in the winter as shown in Fig. 7. Thus, dispatchable fossil generators will be needed to meet demand, resulting in higher emissions. Even though GSHP is not the most cost competitive of the technology options investigated in this study, it is much more efficient during the winter, reducing the use of high-emitting generation requirements during the winter peaks. As many local governments provide incentives for purchasing such energy efficient appliance, the policies should be better customized regarding on local climate characteristics. For home owners who reside in colder regions that wish to decarbonize their energy consumption, installing heat pumps should be prioritized since it directly avoids burning fuel on site for heating. Though according to Database of State Incentives for Renewables & Efficiency several federal or local financial incentives for installing ASHP and GSHP are already in place in New York, Minneapolis, and Fort Collins, these policies currently do not provide enough incentives for home to shift to electric heating since the natural gas retail price is low in cold regions. For cities such as New York in which the current grid already has large amount of renewable generation, more aggressive incentives should be prioritized for home heat pump installations. On the other hand, expansion in renewable generation should be emphasized and prioritized by policy makers in other cities since the increased electricity consumption from installing heat pumps is still served by generation with high emissions. Though GSHP is not as cost competitive as ASHPs, they have much higher efficiency which will result in both energy savings and emissions reduction. Policy makers should put more emphasis on incentives that is related to energy efficiency of the heat pump.

This study implies that the trending renewable energy is not an ultimate solution by itself. In recent years, “Net-Zero Carbon Building by 2030” has been a buzzing concept for city administrators. The idea is that either that a building does not create carbon emission, or the additional renewable energy generated will offset the non-renewable energy consumed by this building. This study shows that it is neither cost-effective nor realistic to purely rely on renewable energy to generate electricity. Although fossil fuel will not be heavily replied upon, it will still play an important role in energy supply. Ambitious administrators should understand that using fossil fuel is inevitable, the point is not to absolutely get rid of fossil fuel, but to find a balance between fossil fuel and renewable energy. As shown in Section 5, even at high levels of uncurtailed renewable generation, energy demand cannot be met 100% with either solar or wind due to the dynamics of consumption and natural resource availability. Although battery or thermal storage partially meet the deficit, they would not be the final solution to cover all

Table 3
Additional annualized investment [average $/year per home] compared to the base case (1X Gen with 100% penetration of ASHP). Except for the second column, where generation is 1.5X, the generation is 1X in all other columns.

ASHP + no storage	Overbuilt wind and solar generation; 1.5X	12 hours of battery	36 hours of thermal storage	GSHP	12 hours of battery + 36 hours of thermal storage	GSHP + 12 hours of battery
0 (Base case)	431	463	468	448	931	911

Table 4
Energy penetration by wind and solar (percentage of demand met) with the optimal wind and solar mix for various technology options. Except for the second column, where generation is 1.5X, the generation is 1X in all other columns.

City	ASHP + no storage	Overbuilt wind and solar generation; 1.5X	12 hours of battery	36 hours of thermal storage	GSHP	12 hours of battery + 36 hours of thermal storage	GSHP + 12 hours of battery
	Base case	Similar additional annualized investments: ~$450/year per home				Approximately doubling investment to $900/home	
New York City	62%(20S80W)	71%(20S80W)	80%(40S60W)	68%(20S80W)	62%(20S80W)	81%(30S70W)	82%(40S60W)
Minneapolis	54%(30S70W)	63%(30S70W)	70%(30S70W)	61%(20S80W)	57%(30S70W)	71%(20S80W)	75%(40S60W)
Tallahassee	54%(50S50W)	60%(50S50W)	83%(80S20W)	59%(50S50W)	54%(50S50W)	84%(80S20W)	85%(80S20W)
Fort Collins	49%(50S50W)	55%(50S50W)	69%(70S30W)	57%(40S60W)	50%(50S50W)	71%(60S40W)	74%(70S30W)

residential electricity need. This indicates that distributed generation infrastructure is highly unlikely to operate by itself, without connecting to a centralized power grid. When cities continue to sprawl, adopting renewable energy in new development will not replace the need for electricity infrastructures.

7. Conclusions

In this paper, fine spatial and temporal scale electricity consumption time series data coupled with temperature data are used to develop an estimation for future demand scenarios in four cities in three climate regions for residential blocks where heating and cooling demands are met by using air source or ground source heat pumps. A high renewable based supply scenario is constructed for all four cities. Local wind and solar resources and demands are compared across the four cities. Additional technology options including battery and thermal storage are examined based on their costs and abilities to further increase renewable penetration. Among the various technology options analyzed in this paper, installing 12 h of battery storage is the most cost competitive option under the future energy scenarios.

Declaration of interest

None.

Acknowledgement

This research was supported by funding from NSF Sustainability Research Networks (award 1444745): “Integrated Urban Infrastructure Solutions for Environmentally Sustainable, Healthy, and Livable Cities.” The authors would also like to thank Colorado State University, Florida State University, the City of Fort Collins Utilities, and the City of Tallahassee Utilities for providing the data for this research.

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