Energy burden aware and thermal resilience informed thermal energy storage system planning for disadvantaged communities

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ABSTRACT

Disadvantaged communities often face a disproportionate energy burden because they need to allocate a higher percentage of their income to energy costs. More importantly, climate change-induced extreme weather events, such as heat waves and severe cold snaps, exacerbate these communities' energy burdens. As a result, low- and medium-income communities are more likely to experience energy supply disruptions, increased health risks, and elevated energy bills because of inadequate thermal insulation and airtightness in their houses.

Thermal energy storage (TES) systems, such as large-scale (community-level) geothermal energy storage and small-scale (building-level) phase change material (PCM)–based storage, have a great potential to improve building energy efficiency and to enhance thermal comfort, load shifting, and integration with renewable energy. The objective of this study is to optimally allocate building level PCM-based TES systems at the community level by considering energy equity and extreme weather effects. To this end, we developed an energy burden and thermal resilience–informed TES system planning framework, which includes three modules: (1) a community-level energy burden and thermal resilience assessment module, (2) building-level a TES system integration and assessment module, and (3) a community-level optimal planning module. Case studies were conducted on four disadvantaged communities in Montgomery and Shelby Counties in Tennessee with energy burdens >10% and with high percentages of people of color. The results indicate that this comprehensive planning framework can assist disadvantaged communities in reducing their energy burden and in bolstering their resilience against the adverse effects of climate change.

Introduction

Disadvantaged communities is the term for areas that suffer most from a combination of economic, health, and environmental burdens (Buckley et al. 2021). Among the economic burdens, energy burden (EB) is highlighted because it serves as a critical indicator of the challenges faced by disadvantaged communities in access to reliable and affordable energy supply. EB is defined as the percentage of gross household income spent on energy costs (US Department of Energy 2020). It not only reflects the financial stress associated with meeting basic energy needs but also emphasizes the complex interplay among socioeconomic factors, utility affordability, and adverse mental and physical health outcomes (Boateng et al. 2020;

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Fefferman et al. 2021; Reames et al. 2021). Bohr and McCreery (2020) emphasized the connection between higher EB and an elevated risk of falling into poverty. In the United States, disadvantaged communities—which include individuals with low income, people of color (Black, Hispanic/Latino), multifamily households, and renters—tend to consume less energy on average. Despite this reduced energy use, they face a higher EB than that of their counterparts in other communities (Chen et al. 2022; Drehobl et al. 2020; Shen et al. 2022).

Meanwhile, climate change–induced extreme weather events, such as heat waves and cold snaps, bring unprecedented challenges to disadvantaged communities. These events not only disrupt the normal operation of existing infrastructures, compromise indoor thermal comfort, and jeopardize residents' health but also lead to significant power outages. According to a recent study by Do et al. (2023), 62.1% of power outages lasting over 8 hours were caused by extreme weather events, especially heavy precipitation, hurricanes, cold snaps, and anomalous heat. Beyond physical disruptions, escalated energy demand during peak hours strains the grid and increases the likelihood of blackouts. Shield et al. found that the overlap of storm activity and heightened electricity demand nearly quadrupled the likelihood of blackouts during late afternoons(Shield et al. 2021). Extended periods of extreme heat increase the risks of heat-related illnesses, particularly among vulnerable groups such as the elderly and outdoor workers. Extreme cold also poses a significant threat, as evidenced by Winter Storm Uri, which caused 246 winter storm–related injuries, including 161 attributed to extreme cold exposure (Texas Department of State Health Services 2021). Hence, evaluating the thermal resilience of existing buildings and exploring mitigation strategies coincident with potential power outages is imperative. Building thermal resilience goes beyond insulation and ventilation, involving a comprehensive approach that integrates sustainable materials, energy-efficient systems, and passive and active design elements to minimize energy consumption and enhance buildings' resistance to extreme weather events (Hong et al. 2023).

In addition, interest is growing in integrating thermal energy storage (TES) systems into buildings, especially those using phase change material (PCM), because their high potential in demand-side management offers effective solutions for reducing and shifting peak electricity demand. TES can be integrated into building equipment such as air-conditioning systems (Allouche et al. 2017; Pop et al. 2018), heat pumps (Arteconi et al. 2013; Patteeuw et al. 2015), and chiller plants (Kamal et al. 2019; Powell et al. 2013). Arteconi et al. examined the viability of integrating TES with a heat pump for residential buildings in Northern Ireland and demonstrated that cost savings of 20%–30% was achievable (Arteconi et al. 2013). TES has also been integrated into building envelopes; researchers such as Shen et al. have integrated TES with thermally anisotropic building envelope (TABE), or TABE+TES, for demand-side management and found that 70% peak load was reduced in Los Angeles, California, and Denver, Colorado, and 20% peak load was reduced in Birmingham, Alabama, and Oak Ridge, Tennessee (Shen et al. 2024).

Although recent studies have explored various facets of TES, its potential to mitigate community energy burden and enhance thermal resilience has not yet been investigated. This study aims to fill this research gap by optimally allocating PCM-based TES systems at the community level by considering energy equity and extreme weather effects. To achieve this objective, we developed an energy burden–aware and thermal resilience–informed TES system planning framework. Case studies were conducted on four disadvantaged communities in Montgomery and Shelby Counties of Tennessee, characterized by energy burdens >10% and with high percentages of people of color, using the TABE+TES system. This research contributes valuable insights into community energy justice, thermal resilience, and TES applications, providing policymakers and household owners with crucial information to inform decision-making.

Methodology

The overall methodology of energy burden–aware and thermal resilience–informed TES system planning for disadvantaged communities is shown in Figure 1. It includes three key modules: community-level energy burden and thermal resilience assessment (Module 1); building-level TES system integration and assessment (Module 2); and community-level optimal planning (Module 3). In Module 1, the regional energy burden and historical weather data are used to identify potential disadvantaged communities. Within each identified disadvantaged community, the energy burden and thermal resilience of each household are calculated or estimated. Module 2 evaluates the effect of integrating TES systems into the building level (TABE+TES for this study), with respect to energy burden reduction and thermal resilience enhancement. Module 3 focuses on minimizing community energy burden and maximizing thermal resilience through community planning; it entails strategic decision-making to achieve an optimal balance within the community context.

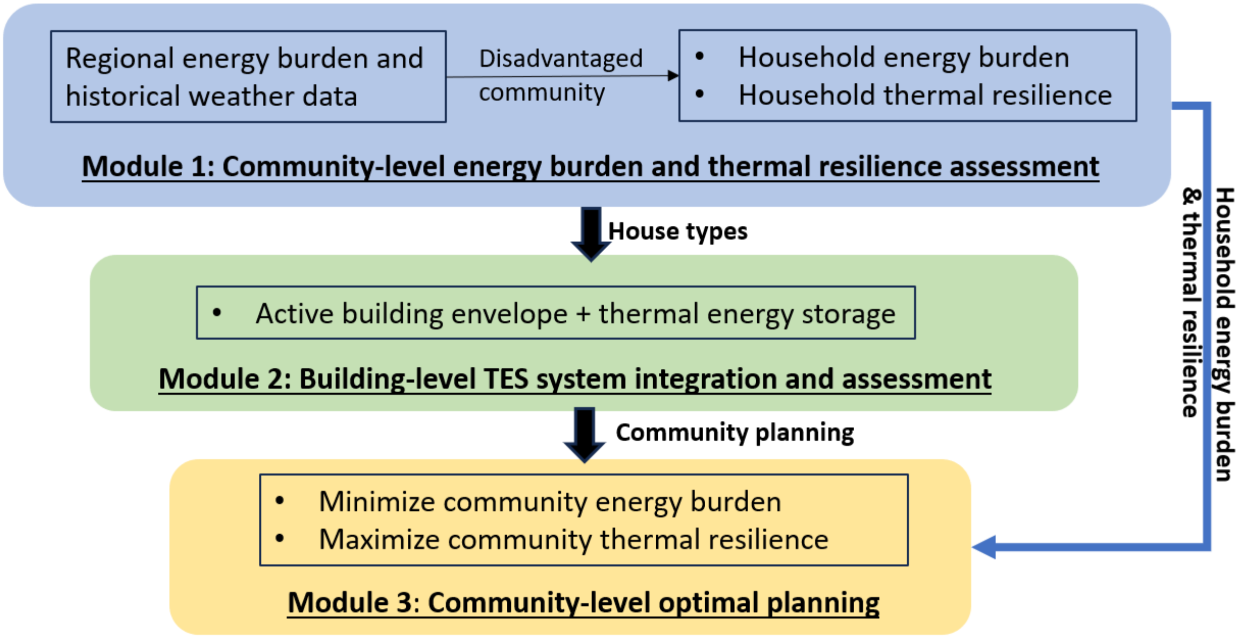

Figure 1. Overview of energy burden–aware and thermal resilience–informed thermal energy storage system planning for disadvantaged communities.

Community-level energy burden and thermal resilience assessment

The regional energy burden and historical weather data were obtained from the Low-Income Energy Affordability Data (LEAD) tool (US Department of Energy 2021) and the National Solar Radiation Database (Sengupta et al. 2018), respectively. The LEAD raw data include the category of tenure (TEN) and various building characteristics such as year of building first construction (YBL6), number of units in the building/type of dwelling (BLD), and primary heating fuel type (HFL). Additionally, it uses the area median income (AMI), federal poverty level (FPL), and state median income (SMI) to account for different income levels to estimate the energy burden for a particular demographic. Table 1 presents a summary of the chosen criteria to create data for low-to-medium income households, with a focus on the 0%–200% FPL income range for this study. Furthermore, our analysis concentrates on a single-unit detached house with ownership and uses utility gas as heating fuel.

Table 1. Selected criteria for low-to-medium income households

Category	Selected criteria
TEN	Owner
YBL6	Building constructed before 1940, 1940 to 1959, 1960 to 1979, 1980 to 1999, 2000 to 2009, 2010 and later
BLD	1 unit detached
HFL	Utility gas
FPL	0%–100%, 100%–150%, and 150%–200%

The community energy burden (EB^c) can be calculated by averaging the EB of each household (EB^h) in a community as:

$$EB^c = \sum_{i=1}^{n} EB_i^h \Big/ n \qquad (1)$$

where superscripts c and h represent community level and building level (household), respectively; and i is the i^{th} household in a community. The EB of a household is calculated as the household energy expenditures divided by the household's corresponding income.

To assess the community thermal resilience (TR^c), the research team first characterizes the thermal resilience of each building (TR^h). Then, the building level thermal resilience is aggregated into the community level by considering the number of occupied housing units (*units*) in each building as the weights. It can be calculated as:

$$TR^c = \sum_{i=1}^{n} units_i TR_i^h \Big/ \sum_{i=1}^{n} units_i \qquad (2)$$

Building-level TES system integration and assessment

Module 2 focuses on the integration and evaluation of the TES system at the building level. This involves selecting the prototype building based on community house types, integrating TES into the chosen prototype building, and assessing both energy performance and thermal resilience (Figure 2).

Prototype building. The US Department of Energy (DOE) prototype single-family detached house (U.S. Department of Energy 2018) is used as the prototype building to calculate the HVAC energy consumption before and after adopting TES. The prototype is a two-story, south-facing building with a total floor area of 223 m^2 (2,400 ft^2; see Figure 2). It uses an electric variable air volume reheat system with electricity for cooling and natural gas for heating. The set points for heating and cooling are 22.2°C and 23.9°C, respectively. The occupancy, lighting, equipment, and ventilation settings and schedules have been derived from the prototype building and meet the International Energy Conservation Code (IECC)-2006 requirements. The HVAC system's efficiency and the envelope's physical thermal properties are summarized in Table 2.

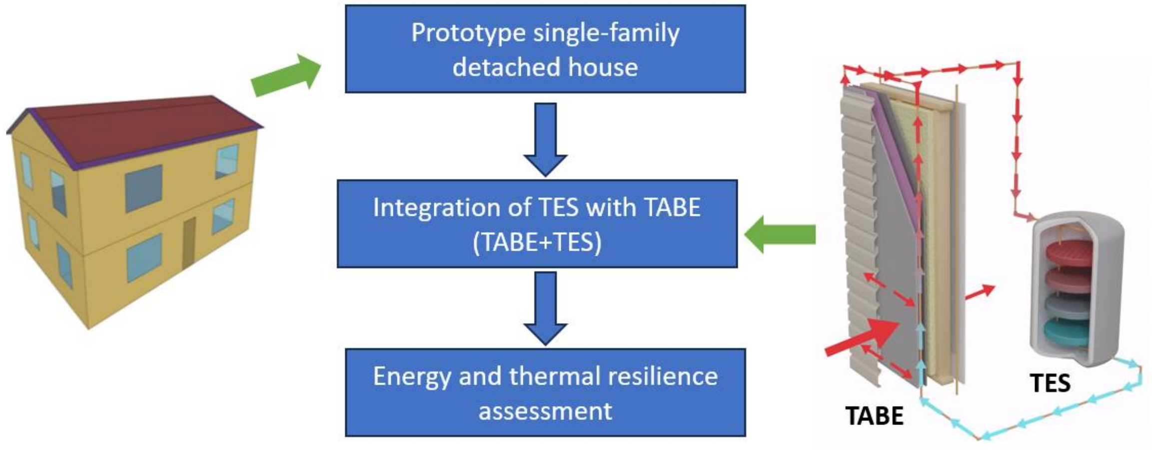

Figure 2. Schematic of integrating TABE+TES into the prototype building for an energy and thermal resilience assessment.

Table 2. Summary of the HVAC system and envelope

Category	Summary
HVAC	• Heating: burner efficiency 0.80 • Cooling: coefficient of performance 4.07 • Set points: heating 22.2°C, cooling 23.9°C
Envelope	• Walls: area 179.6 m^2, R-value 3.17 m^2K/W, solar reflectance 0.50, thermal absorptance 0.88 • Window: window to wall ratio 0.184, U-value 3.69 W/m^2K, solar heat gain coefficient 0.334 • Roof: area 116.4 m^2, R-value 4.61 m^2K/W, solar reflectance 0.25, thermal absorptance 0.90

Integrating TABE+TES system into the residential building. As mentioned earlier, we considered the integration of a TABE+TES system into the residential building (Figure 2). TABE is a water-based active building envelope equipped with embedded pipes that uses fluid to enhance the thermal management of a building envelope (Biswas et al. 2019a; b; Shrestha et al. 2020). Highly thermally conductive metal sheets, like aluminum, were used to facilitate directional heat dissipation through hydronic loops. TABE can effectively capture natural thermal energy from diurnal weather variations. Laboratory and field evaluations (Biswas et al. 2019a; Howard et al. 2023) have demonstrated a significant reduction of over 80% cooling loads and 60% heating loads compared with a baseline wall with identical construction. A finite element model of TABE has been calibrated using field evaluation data (Howard et al. 2023) and has been applied into various studies, including using machine learning for a TABE wall heat flux prediction (Shen et al. 2023) and demand-side management (peak load shaving) of the building using TABE+TES (Shen et al. 2024).

In this study, the same TABE+TES configurations were adopted from our previous work (Shen et al. 2024). The TABE roof and south wall are used to collect heat or coolness energy, which is stored in the TES system and subsequently released by the TABE floor to the indoor environment when the building has a need. Notably, the TES system includes two TES units that use PCM to store the cooling and heating energy. The TES unit for cooling has a phase change temperature of 21°C, whereas the one for heating has a phase change temperature of 26°C; each has a storage capacity of 80 kWh.

Building thermal resilience analysis. The assessment of building-level thermal resilience focused on its ability to resist a cold snap coincidence with a power outage. The cold snap was identified using Ouzeau et al.'s extended method originally developed for heat waves (Ouzeau et al. 2016). It analyzes the mean daily temperature and employs three temperature thresholds (T_{pic}, T_{deb}, and T_{int}) representing the 99.5th, 97.5th, and 95th percentiles over a 30-year period. These thresholds determine the occurrence, start, and end of the extreme temperature event.

The standard effective temperature (SET) was used as the thermal resilience metric, which is based on heat-balance equations. It considers factors like relative humidity, mean radiant temperature, air velocity, anticipated activity rate, and clothing levels. SET values between 12.2°C (54°F) and 30°C (86°F) are defined as "livable functions," according to the LEED v4.1 Credit for Passive Survivability and Backup Power During Disruptions, as described in ASHRAE 55-2010 (ASHRAE 55 2012). Building thermal resilience was analyzed in EnergyPlus by using a selected cold snap with a 1-day power outage. EnergyPlus provides direct SET output when selecting the Pierce model as the thermal comfort model.

Considering building age in building energy and thermal resilience analysis. Several studies indicate a positive correlation between building age and building energy consumption (Levinson 2016; U.S. Energy Information Administration 2015). This could be attributed to newer residential buildings complying with the latest building energy codes, such as better insulation and glazing, advanced HVAC systems, and energy-saving appliances. Consequently, these newer buildings usually demonstrate lower energy consumption compared with their older counterparts. In this light, we posit that buildings' ages are associated with different IECCs. Specifically, we assume that buildings constructed before 2000 adhered to IECC 2000, buildings constructed from 2000 to 2009 followed IECC 2006, and buildings constructed in or after 2010 conformed to IECC 2012. The detailed requirements for windows and walls are listed in Table 3.

Table 3. Building energy code requirements of walls and windows

Building code	Wall	Window	
	R-value (m^2K/W)	U-value (W/m^2K)	SHGC*
IECC 2000	2.82	4.31	0.39
IECC 2006	3.17	3.69	0.33
IECC 2012	4.58	1.99	0.21

*SHGC = solar heat gain coefficient.

TES community-level optimal planning

The TES community-level planning involves careful consideration of various factors to ensure effectiveness, efficiency, and community engagement. Among those factors, initial cost and benefits such as energy burden reduction and thermal resilience improvement are critical for ensuring long-term sustainability and overall well-being. Balancing these factors effectively will contribute to the successful integration of TES and ensure it has lasting positive effects on the community.

For the initial cost, we consider the total TES capacity for a community (Cap_{TES}^{c}) as a constraint for optimal planning. We assume maximum funding for installing a 480 kWh TES for heating and cooling purposes (i.e., Cap_{TES}^{c} = 480 kWh). A TES system with a capacity of 80 kWh for each household can be allocated for heating and cooling.

The objective is to allocate the total TES capacity to six households to (1) minimize the community energy burden and (2) maximize the community thermal resilience. These can be expressed as the following function forms:

$$\min\left(EB_{TES}^{c}\right) = \min\left(\sum_{i=1}^{k} EB_{i,TES}^{h} + \sum_{j=k+1}^{n} EB_{j}^{h}\right) \bigg/ n \tag{3}$$

$$\max\left(TR_{TES}^{c}\right) = \max\left(\sum_{i=1}^{k} TR_{i,TES}^{h} units_{i,TES} + \sum_{j=k+1}^{n} TR_{j}^{h} units_{j}\right) \bigg/ \sum_{m=1}^{n} units_{m} \tag{4}$$

where EB_{TES}^{c} and $EB_{i,TES}^{h}$ are the community and household energy burdens, respectively, after adopting the TABE+TES system; TR_{TES}^{c} and $TR_{i,TES}^{h}$ are the community and household thermal resilience, respectively, after adopting the TABE+TES system; and *k* is the total number of households that adopted the TABE+TES system.

The TES optimal planning problem is a multi-objective integer linear optimization problem, where the two objectives are linear functions of the assigned TABE+TES system to different households with various EB and thermal resilience. This problem can be solved by the scalarizing method, which transfers the multi-objective optimization problem into a single-objective optimization problem, so that it becomes the Pareto optimal solution of the multi-objective optimization problem. Specifically, the ε-constraint method (Miettinen 1999) was used to obtain optimal planning of the TABE+TES system to different households.

Case study

Community-level EB

Four disadvantaged communities were chosen based on their EB and community composition. Figure 3 presents the distribution of EB in Tennessee and in Shelby and Montgomery Counties. The distribution of EB exhibits unevenly, with lower EB regions interspersed among higher EB regions (Figure 3[a]). In both Shelby and Montgomery Counties, we identified two communities each, considering variations in community EB, total household count, number of occupied housing units, and average household annual income. The details for each community are outlined in Table 4.

It is important to note that EB varies significantly within a community. For example, Community C2 has a minimum EB of 4.1% and a maximum of 39.6%, attributed to the disparities in household income and energy cost. Such a nonuniform distribution of EB provides an opportunity for the optimal distribution of TES to households.

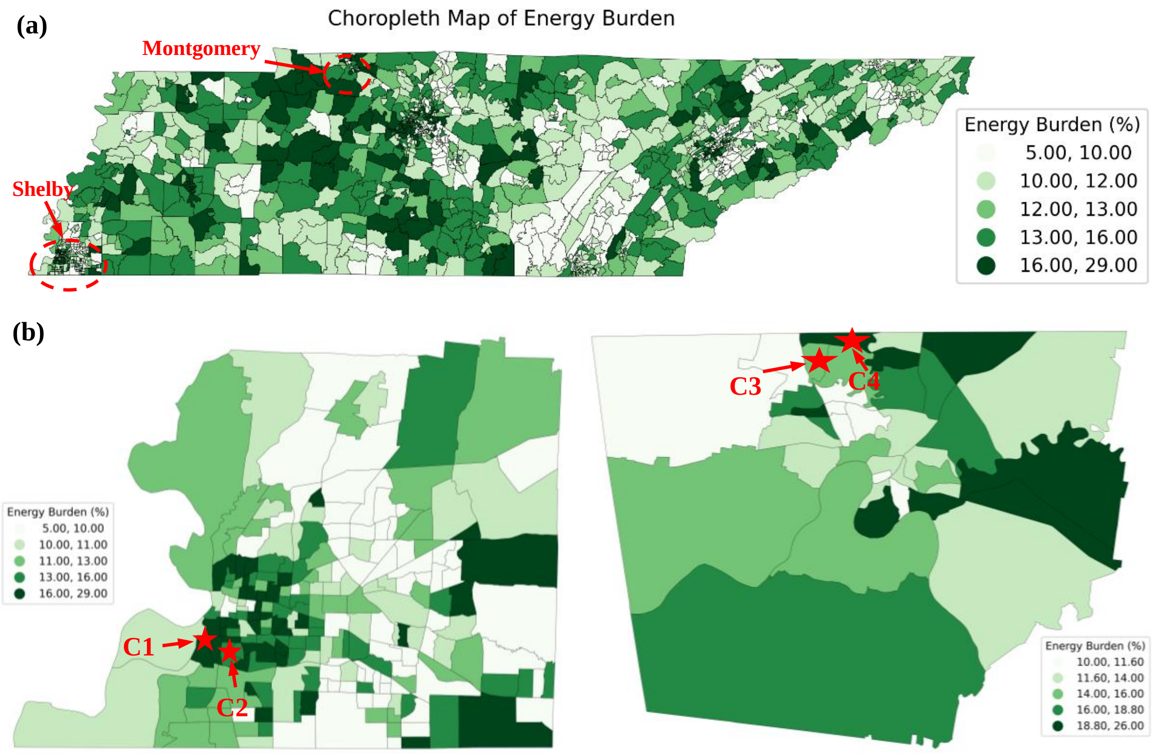

Figure 3. EB in: (a) Tennessee, (b) Shelby County, and (c) Montgomery County.

Table 4. Summary of EB datasets for selected communities in Shelby and Montgomery Counties

Community	C1	C2	C3	C4
GEOID	47157000100	47157000200	47125101101	47125101303
Number of households	9	15	13	15
YBL6	1940–59, 1980–99, 2000–09	Before 1940, 1940–59, 1960–69, 1980–99, 2000–09	Before 1940, 1940–59, 1960–79, 1980–99, 2000–09	Before 1940, 1960–79, 1980–99, 2000–09, 2010+
Units	0.001–12.54	0.09–2.61	0.11–4.13	0.33–23.52
HINCP	2,817–64,051	9,491–48,603	2,517–45,758	3,952–73,260
ELEP	946–2,319	1,149–3,135	842–2,123	871–2,817
GASP	169 –1,578	256–1,517	273–779	352–2,202
FULP	0–606	0–484	0–107	0–663
ENEP	1,417–3,562	1,404–3,940	1,483–2,710	1,676–5,019
EB	3.6%–50.9% (avg. = 22.7%)	4.1%–39.6% (avg. = 16.0%)	4.6%–78.1% (avg. = 17.3%)	2.6%–69.7% (avg. = 22.9%)

GEOID = geographic identifier; Units = number of occupied housing units; HINCP = average annual household income ($/year); ELEP = average household annual electricity expenditure ($/year); GASP = average household annual gas expenditure ($/year); FULP = average household annual fuel expenditure ($/year); ENEP = average household annual energy expenditure ($/year).

Building-level annual energy consumption, cost, and thermal resilience before and after adopting TABE+TES system

The building-level annual energy consumption is listed in Table 5. It consists of natural gas for heating and electricity for cooling, fan, and pump. The pump enables the heat exchange between TABE panels and TES units. Clearly, the building envelope has a significant effect on building energy consumption; of particular note is the effect of insulation level on heating energy consumption. The buildings in compliance with IECC-2000 and IECC-2012 consumed 17,104 kWh and 13,887 kWh of natural gas, respectively, a difference of 1,974 kWh (12% saving). For cooling electricity, they consumed 2,908 kWh and 2,317 kWh, respectively, a difference of 591 kWh (20% saving). This demonstrates the importance of adopting strict building energy codes to combat climate change.

The building that adopted the TABE+TES system achieved more significant savings. Compared with the IECC-2000 building, it saved 3,217 kWh (19% savings) of natural gas and 1,444 kWh of electricity (37% savings). This savings occurred primarily because the TABE collected heating and coolness energy from the diurnal outdoor conditions, solar irradiance, and night sky radiation. This process consumes only a small amount of pump electricity, 33 W for each TABE panel with a water flow rate of 0.1 gallon/min (Shen et al. 2024).

The corresponding energy costs for buildings complying with different IECC codes and after adopting the TABE+TES system are shown in Figure 4. The costs were calculated by using energy consumption multiplied by the unit price—16.52 $/ft^3 for natural gas and 0.123 $/kWh for electricity (U.S. Energy Information Administration (EIA) 2021). As expected, the building integrated with TABE+TES generates the highest cost savings, 25%, compared with the IECC-2000 building. Interestingly, the savings from natural gas and electricity are almost the same, about $180 for each. The total annual cost savings are $359.

Table 5. Annual energy consumption for buildings complying with different IECC codes and after adopting the TABE+TES system

	Natural gas	Fan electricity	Cooling electricity	Pump electricity	Total electricity
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
IECC-2000	17,104	1,048	2,908	0	3,956
IECC-2006	17,004	947	2,591	0	3,538
IECC-2012	15,130	806	2,317	0	3,123
TABE+TES	13,887	644	1,549	318	2,512

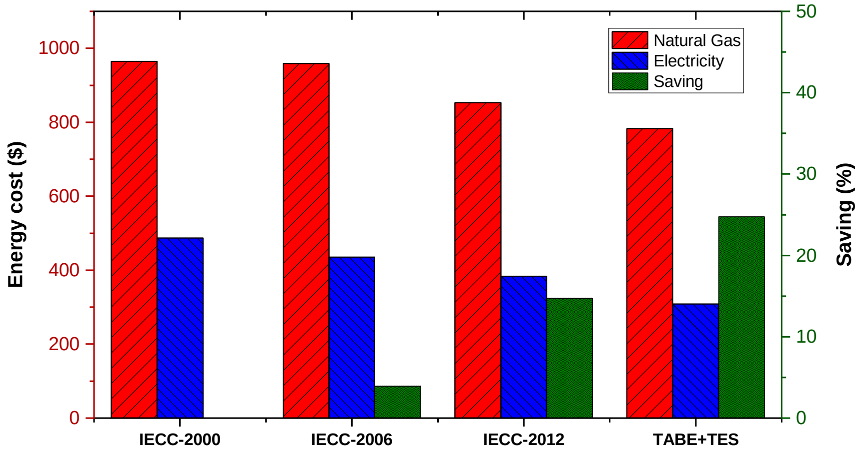

Figure 4. Annual energy costs and savings for buildings complying with different IECC codes and after adopting the TABE+TES system (the IECC-2000 building was used as the baseline).

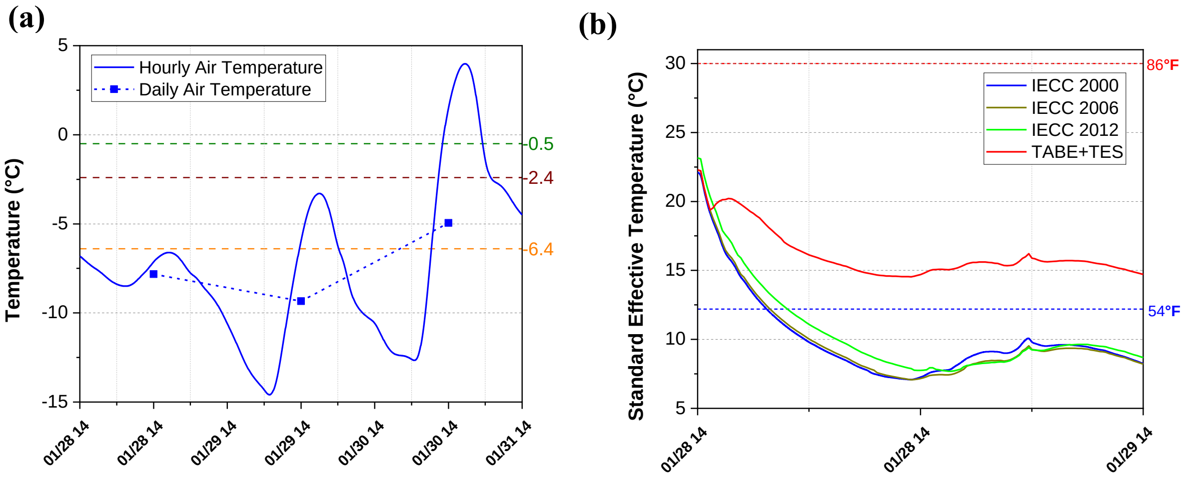

Figure 5. Selected cold snap and the obtained SET for different buildings: (a) a 3-day cold snap between 1/28/2014 and 1/30/2014; and (b) SET for building complies with IECC-2000, IECC-2006, and IECC-2012, and the building integrated with TABE+TES. The dashed horizontal lines in Figure 5(a) represent the temperature thresholds that the daily air temperature needs to meet to be identified as cold snap, orange: peak (occurrence) temperature, wine: debut temperature, green: start temperature.

The thermal resilience was assessed using an identified 3-day cold snap (1/28/2014–1/30/2014) with a 1-day power outage (1/28/2014). Figure 5(a) shows the identified cold snap, with the lowest air temperature reaching −14.8°C on 1/29/2014. On 1/28/2014, the air temperature was constantly below −5°C; a temperature that low poses a potential health hazard when a power outage occurs. Figure 5(b) shows the SET on the day of the power outage. It is evident that all the buildings, except the one equipped with TABE+TES, present an unsafe indoor environment. Remarkably, the TABE+TES system maintains the indoor air temperature close to 15°C, exceeding the required 12.2°C (54°F). Moreover, our findings indicate that buildings meeting high energy efficiency codes exhibit limited effectiveness in resisting cold snaps when a power outage occurs, compared with less energy-efficient buildings. The accumulated time for the buildings in compliance with IECC-2000, IECC-2006, and IECC-2012 to have a safe indoor air temperature are 3.67 h, 3.83 h, and 4.83 h, respectively. When assessing the buildings' thermal resilience during a 1-day power outage, these translate to values of 0.15, 0.16, and 0.2, respectively. In contrast, the building integrated with TABE+TES demonstrates a thermal resilience value of 1, indicating its superior ability to maintain safe indoor temperatures throughout the entire outage period.

Community-level TES optimum planning

Figure 6 shows the Pareto front for community-level TES optimum planning. As mentioned earlier, our planning involved the implementation of six TABE+TES systems with a total capacity of 480 kWh for disadvantaged communities in Shelby and Montgomery Counties, Tennessee. The results underscore the effectiveness of adopting the TABE+TES system at the building level to reduce energy burden and enhance thermal resilience at the community level. Notably, the impact is most significant in community C1, where the EB_c has been reduced from approximately 23% to about 19% and the TR_c has increased to 1, suggesting the community is nearly immune to a cold snap coinciding with a 1-day power outage. This large improvement is primarily attributed to the small size of community C1 compared with the others in the study. Communities C2, C3, and C4 exhibit similar TR_c improvement (to around 0.8), whereas community C2 has a slightly lower EB_c reduction. This discrepancy arises from the presence of households in community C2 with a lower energy burden but higher energy costs.

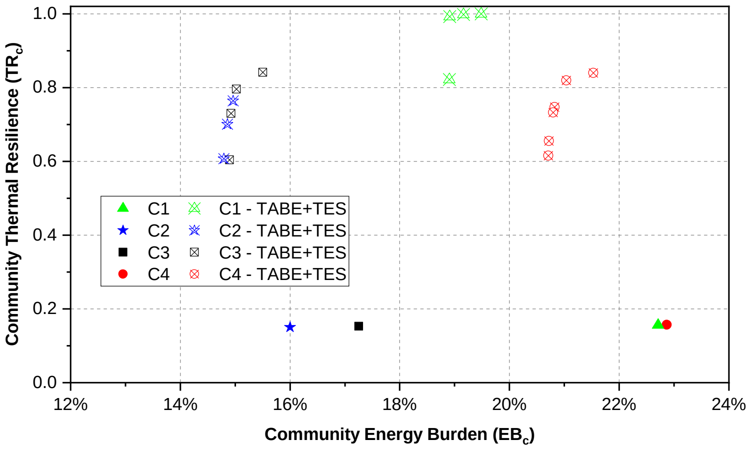

Figure 6. Community energy burden and thermal resilience before and after adopting the TABE+TES system at the building level. The solid markers represent the community energy burden and thermal resilience before adopting TABE+TES system, whereas the hollow marks are the optimal planning results.

Discussion

This research contributes valuable insights to policies related to community energy justice, thermal resilience, and TES application.

1. Energy efficiency and renewable energy use are critical to achieving community energy justice. Stringent building energy codes and policies advocating renewable energy use play a critical role in shaping a sustainable future as they establish clear guidelines and standards to promote efficient use of energy resources and reduce carbon emissions. In

the process of implementing and enforcing building energy codes and encouraging adoption of renewable energies, the policy implications on energy justice must also be considered. Ensuring that the codes and policies do not disproportionately burden disadvantaged communities is important.

2. Building thermal resilience is a key aspect of reducing the effects of climate change. Local policies should advocate for resilient design to consider the devastating effects of extreme weather events. In addition, because disadvantaged communities are often the most significantly affected by climate-related impacts, policymakers should prioritize resilience needs in areas with higher socioeconomic vulnerability.
3. TES technology deployment and advancement are crucial for achieving building energy efficiency, enhancing thermal resilience, and promoting community energy justice. Policymakers need to realize the importance of TES to reduce building energy consumption and associated greenhouse gas emissions. Moreover, TES's affordability and accessibility to disadvantaged communities are keys to achieving an equitable future.

Conclusion

In this study, we developed a methodology to optimally plan a TES system at the building level to reduce the energy burden and enhance thermal resilience at the community level (i.e., energy burden–aware and thermal resilience–informed thermal energy storage system planning for disadvantaged communities. Case studies were conducted on four disadvantaged communities having high EB in Shelby and Montgomery Counties, Tennessee. Based on the presented results, the following conclusion can be drawn:

- Buildings complying with stringent building energy codes can effectively reduce building energy consumption and associate costs. However, such building codes have a very small effect on improving a building's thermal resilience when extreme weather occurs in coincidence with a power outage.
- Integration of the TABE+TES system into buildings not only substantially lowers energy costs but also strengthens the buildings' thermal resilience, making the system a valuable solution for mitigating the effects of extreme weather and power interruptions.
- Optimally planning TES systems at the building level for disadvantaged communities is a crucial step toward achieving greater energy efficiency, reducing economic burdens, and fortifying thermal resilience. This approach helps communities with socioeconomic challenges manage energy more effectively, thereby fostering sustainability and resilience in their built environments.

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