

Household energy resilience in extreme weather events: An investigation of energy service importance, HVAC usage behaviors, and willingness to pay

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HIGHLIGHTS

- Household energy resilience emphasizes keeping acceptable and affordable services.
- Common energy end-uses are clustered into high, mid, and low-priority services.
- HVAC use behaviors shift towards energy-saving during disasters.
- ~60% of respondents are willing to pay more to maintain energy services in disasters.
- Household energy resilience varies across different socio-demographic groups.

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ABSTRACT

Household energy resilience, particularly maintaining essential energy services within an acceptable and affordable level, is critical during extreme weather events (e.g., winter storms, heat waves) with power shortages or outages. However, the research on the importance and acceptable compromise levels of energy services, HVAC usage behavior changes, and willingness to pay (WTP) for energy services during disasters is limited. Therefore, this study investigates the importance and compromise of household energy services, HVAC usage behaviors, and WTP, as three key dimensions of household energy resilience, in both normal days and disaster scenarios through surveys ($n = 485$). First, 12 common residential end-uses are grouped into high, mid, and low-priority services using hierarchical clustering, in which high-priority services (perceived as important and un-compromisable) include food cooking and storage (refrigerator and freezer) and thermal comfort (space heating and cooling), mid-priority services involve water heating and lighting, while low-priority services are mostly related to entertainment and housework (e.g., TV, laundry). Also, HVAC use patterns demonstrate that occupants become more energy conservative during disasters, e.g., reducing durations of running HVAC and adjusting temperature setpoints to save energy. In terms of energy cost, approximately 60% of respondents are willing to pay more to maintain energy services during disasters, although only 13% are prepared to pay over double the normal energy prices. The regression models further reveal that household energy resilience varies across different socio-demographic groups (e.g., age, income, family size) and is impacted by disaster experience and beliefs in clean energy and climate. These research findings provide important perspectives to understand household energy resilience and inform measures for disaster adaptation of households in extreme weather events.

1. Introduction

Over the years, the frequency, duration, and intensity of natural disasters or weather-related extreme events (e.g., winter storms, heat

waves) have increased with emerging climate change [1,2]. The frequency and season length of heat waves rose from 2 waves and 24 days annually during the 1960s to 6 waves and nearly 70 days per year during the 2010s and 2020s [3]. Winter blizzards have become more frequent

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as well in recent years. The severe winter storm events with billion-dollar losses have occurred 5 times since 2018, leading to around \$40 billion in losses and 380 deaths [4]. These natural disasters result in disruptions of energy infrastructure or even system failure, and subsequent interrupted power supplies or outages, which continue to be prevalent in the United States (US) [5,2]. Based on the statistics of the Department of Energy (DOE) [6], in 2022, 95 of the 390 outages were caused by severe weather, affecting over 8 million households; in 2021, the impact was even worse, with 155 of the 387 outages and >16 million households affected by severe weather or disasters. Such negative impacts on residential energy use are more serious in low-income and populous countries [7,8].

Extreme weather-related events with power shortages or outages are usually linked with poor indoor environments and result in the hazard of thermal discomfort, which threatens occupant living and health and even causes death. Since 1979, >11,000 people have died from heat-related causes in the US [9], averaging 702 heated-related deaths annually between 2004 and 2018 [10]. These negative influences on thermal comfort also exist in extreme cold disasters and are more severe. Cold-related deaths during 2006–2010 are twice as many as heat-related [11]. In a recent disaster, >60 deaths occurred during the 2022 New York blizzard [12]. Similarly, at least 246 people died during the 2021 Texas winter storms, about two-thirds attributed to thermal comfort issues, including hypothermia and frostbite [13]. These harsh statistics illustrate that the increasing natural disasters lead to disruptions of the vulnerable energy infrastructure, which further disturbs residential energy needs and exacerbates thermal discomfort, posing great risks to the health and well-being of residents.

Considering the adverse effects on residential energy needs, it is required to improve energy resilience to reduce the health risk of occupants during extreme weather events. Energy resilience, akin to resilience principles embedded in other infrastructures, underscores the capacity of energy systems to prepare for, absorb, recover from, and adapt to adverse effects to ensure reliable services [14,15], which highlights the necessity to withstand disruptions of extreme events to operate disturbed energy functioning within acceptable and affordable levels [16,17]. Besides physical infrastructure, the concept of energy resilience needs to capture energy services at the household level, as depicted in Fig. 1, since residents need desired energy services (e.g., cooking, Heating, Ventilation, and Air Conditioning [HVAC]) rather than barely energy itself or related infrastructure to survive throughout disasters [18,19]. Hence, residential energy services, which inevitably suffer degradation, must be maintained at acceptable and affordable levels in the disrupted state to achieve energy resilience.

Maintaining energy services at an acceptable level can be achieved on the demand side (e.g., reducing or shifting energy usage) to balance energy supply and demand [20,21]. Considering the diversity of residential energy service needs (e.g., HVAC, cooking, and water heater) and the limited energy supply in most disaster situations [22,23], prioritizing critical or basic energy services (the minimum requirement for residents) before full restorations of energy supplies is effective to reduce disaster impacts and improve energy resilience for households [18,24]. However, what energy services are the most critical for occupants and what services have the greatest compromise during disasters with the risk of power shortages and outages are still unclear (**gap 1**). Particularly out of all residential energy services, HVAC consumes the largest amount of residential energy [25], significantly related to occupant thermal comfort [26]. The thermal environment is heavily threatened during extreme weather events, which causes thermal discomfort and health issues. The shift in HVAC use behaviors, aiming at conserving energy while without compromising much thermal comfort, exhibits the potential to mitigate the disruptions of disasters on thermal comfort. Yet, how occupants use HVACs differently in disasters remains unclear (**gap 2**).

Additionally, maintaining energy services at an affordable level is another dimension of energy resilience from the perspective of social sustainability to ensure equitable infrastructure and services [27,28,19]. Energy resilience intertwines with the concept of sustainability and aims to provide available, accessible, and affordable energy services [29,17]. However, the energy price has a high risk of increase during disasters due to insufficient capacity of the dysfunctional energy infrastructure, as exemplified by the 2021 Texas power crisis [30]. Hence, investigating the willingness to pay (WTP) to maintain energy service during disasters is critical for optimizing energy supply plans to realize equitable infrastructure. Nevertheless, whether and how much occupants are willing to pay more for maintaining sufficient levels of energy services during extreme weather events needs further exploration (**gap 3**).

For households, higher energy resilience reflects a stronger ability to withstand the disruptions of power shortages and outages caused by disasters, involving a higher acceptable level of energy service compromise, more energy-conservative behaviors in HVAC usage, and a stronger willingness to pay for increased energy prices in disasters. Therefore, this study aims to investigate and compare energy service importance, HVAC behaviors, and WTP during normal and disaster scenarios to explore household energy resilience through survey distribution with 485 valid respondents. This study comprehensively considers common residential energy services to identify critical services for households and provide empirical evidence on energy service priorities

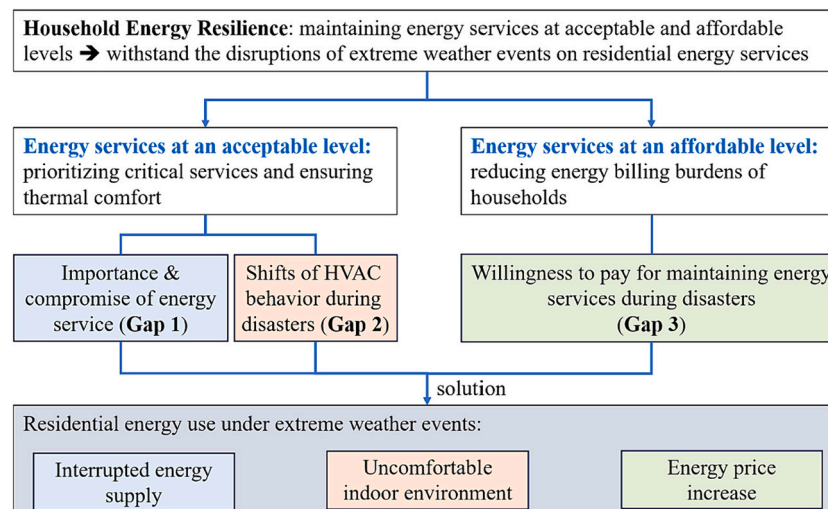


Fig. 1. Overview of household energy resilience during extreme weather events.

based on compromise and importance ratings. Also, the research delves into shifts of HVAC use behaviors and WTP by incorporating disaster impacts. Through an online survey and data analysis, this paper will answer three research questions: (1) what is the most critical energy service for households in normal and disaster scenarios, and what services are allowed to compromise during disasters? (2) whether and how HVAC use behaviors of occupants change during disasters compared to regular days? (3) whether and how much more are occupants willing to pay to maintain energy services in disasters than in normal scenarios? By comprehensively examining energy service importance and compromise during disasters, the study provides insights to inform strategies for enhancing energy resilience, designing disaster preparedness plans, and developing countermeasures to ensure reliable and affordable access to essential energy services for household members in extreme weather events.

The remainder of this paper is organized as follows: [section 2](#) reviews previous studies on household energy resilience, energy services, and willingness to pay; [Section 3](#) introduces the survey design, data collection, and socio-demographics of respondents. In [section 4](#), the methods and results of data analysis are presented. Then, [section 5](#) discusses and compares the resilience among varying socio-demographic groups. Finally, [section 6](#) draws up conclusions.

2. Literature review

2.1. Household energy resilience

Resilience is defined as “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events” [15]. This notion, aiming to minimize the adverse impacts on the system functions in extreme events [17], has been applied to numerous infrastructure fields, e.g., water, transportation, and energy, to tackle extreme events and provide essential functioning securely, reliably, and affordably [31,14,32,19]. As Jasiūnas et al. [33] pointed out, energy resilience emphasizes the ability of energy systems to bend rather than break during extreme events, i.e., operating with inevitable disruptions and reducing the extent and duration of the damages to energy functions [31].

Household energy resilience underscores maintaining critical residential energy services at acceptable and affordable levels during disasters. For households, a higher level of compromise on the disturbed energy services would increase resilience during disasters [34]. Comparably, Hasselqvist et al. [18] proposed that the key to household energy resilience is understanding the adjustments of energy activities, considering the flexibility of energy services, that can be made for households during energy-related disturbances. Similarly, the schematic model of energy resilience created by Zhou [24] emphasized withstanding the negative impacts of disruptions and restoring the critical load of energy needs for resilient energy. Additionally, affordability is another crucial goal of resilient energy to ensure secure and equitable energy [18,24]. More straightforwardly, household energy resilience necessitates that the energy services, that a household requires, should be afforded [19]. Consequently, understanding the acceptable and affordable levels of energy services is essential for developing energy resilience.

2.2. Compromise of energy service and shifts of HVAC use behavior

Previous studies have recognized the different importance and flexibility of energy services in normal days, based on which energy services have been categorized. Some studies classified energy services purely based on empirical experience without data support and evidence, e.g., Baik et al. [35], and Ren et al. [36]. Other studies are based on daily routines. Soares et al. [37] classified dishwashers, washing machines, and clothes dryers as shiftable loads based on the average daily use pattern. Stelmach et al. [38] clustered energy services into high-likely

performing (e.g., cooking and entertainment), medium-likely (e.g., laundry), and improvisational activities (e.g., house cleaning) during peak demand periods. Besides energy use patterns, several studies investigated the subjective preferences of occupants directly. For example, Harold et al. [39] and Kadavil et al. [40] collected the willingness of residents to give up certain energy services. However, these categories are mostly from the perspective of building-energy efficiency (e.g., demand response), and the impacts of disasters on the importance and flexibility of energy services to occupants are seldom involved.

Similarly, the shifts in HVAC behaviors during disasters have been incompletely identified. Prior studies have proved that occupants can adapt and reestablish thermal comfort in uncomfortable situations, including behavioral adaption [41,42]. Occupants can adapt to a relatively poor thermal environment and alter their comfort zone, through which energy use is reduced [43]. Hu and Xiao [44] emphasized the potential of HVAC in energy-flexibility control strategies. Specific to the behaviors related to HVAC, setpoints and operation durations are the main factors focused by existing studies. For example, Afzalan and Jazizadeh [45] quantified the deferrable loads of air conditioners using the temperature setpoints. Papadopoulos et al. [26] verified that adjusting HVAC setpoints can reduce energy usage and not induce much thermal discomfort. Likewise, Sun and Hong [46] proposed that HVAC electricity use could save by 30% ~ 50% through reducing the usage and not affecting thermal comfort. Nie et al. [47,48] investigated occupants' preferences on some behavioral energy-saving measures, including reducing HVAC thermostat setpoint and duration of HVAC use during the night. These studies were conducted in normal conditions with enough resources to adjust the thermal environment. However, resource constraints will affect residential energy consumption behaviors, including space heating and cooling [49]. Little is known about the shifts of HVAC behaviors in extreme weather events with the risk of power shortage or outage.

There is limited research on the factors influencing energy service flexibility. Different demographic groups, e.g., gender, education level, and family size, demonstrate varying compromises or flexibility on energy services. Tomat et al. [50] proposed that females are more likely to participate in energy flexibility schemes due to higher environmental awareness. Similarly, females and elder occupants tend to be more energy-saving [51]. Stelmach et al. [38] found that smaller houses or larger families are more willing to shift energy activity during peak. Elder groups show lower flexibility in energy demand response schemes [52,53], while higher education level contributes to a stronger willingness to offer flexible energy demand [54,55]. Also, occupants with stronger environmental beliefs, e.g., valuing decarbonization, are more likely to accept demand flexibility [54]. On the other hand, individuals with fewer environmental concerns are less likely to engage in energy-saving behaviors [56]. These studies are related to the flexibility of energy services in normal scenarios; instead, research gaps remain in the influencing factors of energy service compromise under disasters.

Individual differences can be found in HVAC use behavior as well. Different genders demonstrate varying behaviors on HVAC use patterns [57]. Females are more energy-saving due to more positive attitudes towards energy-saving [58], consistent with males behaving more frequently to turn on AC [59]. Elderly occupants have a greater tolerance for thermal discomfort and hence reduce the frequency of using HVAC [59]. Different races demonstrate different HVAC energy-saving behaviors [51,60]. Family size is another critical factor influencing HVAC energy use behaviors [61]. Economic status also determines occupant behaviors. Higher-income groups are more active in using HVAC to achieve an acceptable thermal environment [62]. HVAC setpoints in different housing sizes are significantly different, as proved by Wright et al. [60]. Occupant beliefs and attitudes towards the environment influence individual behaviors as well [49]. Stronger environmental concerns and beliefs contribute to more likely adopting energy-saving measures [47]. Besides the impacts of socio-demographics, past experience and contextual factors also contribute to diverse HVAC use

behavior and adaption to uncomfortable environments [43,63,64]. Extreme weather events change the thermal environment greatly and pose the risk of energy restrictions. However, the comparisons in HVAC use behavior between normal and disaster scenarios are almost absent.

2.3. Willingness to pay for energy services

The affordability of energy services is another dimension of energy resilience [17], which ensures equitable infrastructure. The willingness to pay of occupants is a critical topic concerning affordability and energy-related social equality issues [65]. Numerous studies have been conducted on WTP for energy, e.g., renewable or green energy sources [66,67]. Residents demonstrate a positive willingness to pay more for reliable and high-quality energy supply to reduce the chances of power outages, including emergent or planned [68].

Although former studies have involved power outages in investigating the willingness of occupants to pay for reliable energy, limited research has considered disaster-induced power outages. Vallejo et al. [69] analyzed the WTP of residents for electricity during the 2021 winter storm in Texas. Baik et al., [70,71] investigated residents' WTP for backup electricity services during long-duration power outages (10 days) during cold winter, among which the WTP was measured by the total energy bill per day during disasters. However, there are inherent energy bill differences among households during regular scenarios [25].

Additionally, existing studies have shown that WTP varies with socio-demographics, e.g., gender, income, age, and family size [65,72]. Those differences among varying socio-demographic groups can be explained by the demand for energy services or the ability to pay energy bills [69]. For example, households with larger family sizes rely more on energy services; therefore, they are more willing to pay high energy bills than sacrifice energy use [67]. Higher-income groups have a stronger ability to pay energy bills and thus have higher WTP [65]. Occupants' environmental beliefs are also critical. For example, occupants with higher green values have a higher willingness to pay for energy services [73]. Besides, the experience of power outages (e.g., frequency and duration) contributes to the willingness to pay higher for energy services [68,72]. Particularly, experiencing severe power outages leads to stronger WTP for energy services [74]. However, the variations of WTP among different socio-demographical groups need to be further examined under disaster scenarios.

2.4. Summary

Household energy resilience emphasizes maintaining energy services at acceptable and affordable levels during extreme events. The key to maintaining energy services at acceptable levels during disasters lies in identifying essential energy services, determining the compromisable levels of energy services, and exploring potential shifts in the utilization of HVAC, as the largest sector of household energy end-use. Also, the affordability of energy services aims to ensure secure and equitable access to energy for households, among which willingness to pay is a critical topic.

Prior studies have recognized the differences of importance and flexibility of household energy services on normal days, based on which the energy services are categorized. Likewise, occupant HVAC behaviors, mainly the setpoint and operation duration, have demonstrated adaptation in several studies, i.e., the potential to save energy while not inducing much thermal discomfort. However, these studies on the flexibility of energy services and HVAC behaviors were only conducted on normal days with sufficient resources, which is not applicable to extreme weather events characterized by interrupted energy supply and severe outdoor conditions. Similarly, the willingness of occupants to pay for a reliable energy supply has also been examined in existing studies, but there has been limited research related to disaster-induced power outages. Therefore, there is a lack of research on what energy services are most important or have the largest compromise for households

during disasters, how HVAC behaviors shift in extreme weather events with the risk of power shortage or outage, as well as how much more occupants are willing to pay to maintain energy services in disasters. To address these gaps, this study, considering the impacts of extreme events, aims to investigate the importance and compromisable level of energy services, analyze the shifts of HVAC behaviors, and assess the willingness to pay for energy services during extreme weather events.

3. Data

3.1. Participants and data screening

Based on the literature review, an online survey was designed to investigate energy resilience at the household level. This survey was distributed in Fort Worth and Dallas, TX between September 2022 and December 2022 by Qualtrics. Dallas/Fort Worth is in a humid subtropical area with hot summers and mild winters [75]. The average temperatures are around 85 degrees Fahrenheit (°F) (29.4 degrees Celsius [°C]) from June to August and 45 °F (7.2 °C) from December to February [76]. This area is vulnerable to weather-related disasters, from heat waves to winter storms. The duration of temperature over 100 °F (37.8 °C) in both 2022 and 2023 has exceeded 45 days [77], and the most recent severe winter storm occurred in 2021, leading to the 2021 Texas power crisis [30]. To reduce the potential regional and climate differences [25], we strictly restrict the locations of participants by verifying their postal codes. Before formal distribution, we conducted a soft launch and collected 50 samples to check the quality and reliability of the survey design. Then, the survey was further improved based on soft launch results.

There are 549 responses received in this survey. We have applied two more criteria to check entries besides scrubbing the same IP addresses, duplicate responses, and non-insightful inputs in open-ended questions by Qualtrics. First, we set a threshold (350 s, based on the soft launch) for the duration of the survey completion to filter unthoughtful answers. Any response completed within 350 s would be excluded ($n = 13$, 2.4%). Then, we added a logic check to ensure the answer consistency of HVAC behaviors. For the HVAC setpoints, we asked their setpoints in normal scenarios, followed by a question checking their willingness to decrease/increase the setpoints of space heating/cooling during disasters to conserve energy. If they are willing to decrease (increase) the setpoint of space heating (cooling) during disasters but report a higher (lower) setpoint during disasters than normal days, the responses ($n = 43$, 7.8%) would be excluded as well.

Following the strict data quality checking, we have received 493 responses, of which 6 are excluded as their BMIs are outliers. Also, two more responses are excluded due to being homeless or living in a motel. Therefore, there are 485 valid responses in total, and the effective response rate is 88.3%.

3.2. Measurement and survey design

This survey includes socio-demographics, clean energy beliefs, disaster experiences, perceptions of energy services, and HVAC behaviors.

3.2.1. Independent variables

The selection of independent factors is based on the literature review encompassing general energy services, HVAC use, and WTP. The main references of these factors are summarized in Table 1.

3.2.1.1. Socio-demographics. Socio-demographics reflect demographic characteristics, social roles, and economic status. Demographics (e.g., gender, age, race) and housing characteristics (home size) are collected, as shown in Table 2. Two dummy variables are used to record the gender and race of respondents. The remaining predictors, e.g., age, income,

Table 1
Main references of independent variable selection.

	Variable	General Energy use	HVAC Use	WTP
Socio-demographics	Gender	[[78]; [50]]	[[58]; [59]]	[[65]; [72]]
	Age	[[78]; [50]]	[59]	[[65]; [72]]
	Race	[38]	[60]	[79]
	Education	[[54]; [38]]	[62]	[[65]; [72]]
	Household Income	[[78]; [38]]	[62]	[[65]; [72]]
	Family Size	[[78]; [38]]	[61]	[72]
Disaster Experience	Home Size	[38]	[60]	[79]
	Experience with power outages & disaster	[80]	[[63]; [64]]	[[68]; [72]]
Climate and Energy Beliefs	Climate & energy belief	[[54]; [81]]	[47]	[73]

Table 2
Measurement of socio-demographics.

Variable	Descriptions
Gender	0 = Females, 1 = Males
Age	1 = 19–24, 2 = 25–34, 3 = 35–44, 4 = 45–54, 5 = 55+
Race	1 = Caucasian, 0 = Other
Education	1 = High school or below, 2 = Associate degree, 3 = Bachelor's degree, 4 = Degrees beyond Bachelor's (e.g., MS, MD, Ph.D.)
Household income	1 = < \$25,000, 2 = \$25,000–\$49,999, 3 = \$50,000–\$99,999, 4 = > \$100,000
Family size	1–4 = family size being 1–4 respectively, 5 = 5 or more
Home size	1 = <1000 ft ² , 2 = 1000–1500 ft ² , 3 = 1500–2500 ft ² , 4 = >2500 ft ²

and home size, are ordinal variables.

3.2.1.2. Disaster experience. This survey investigates whether respondents have experienced extreme weather events and associated power outages in the past five years [80,68]. First, the experience of extremely cold and hot weather (e.g., winter storms and heat waves) and associated power outages in the past 5 years are collected and labeled as “Extremecold”, “Extremehot”, and “Exp_po” respectively. These factors are dummy-coded. Then, the frequency and duration of coincided power outages are also collected to measure the intensity of experienced power outages [68]. Power outage frequency is named “Pofrequency”, with 0–6 representing experiencing power outages from none to over 5 times. The average power outage duration (“Poduration”) is used 0–5 to indicate not applicable, <1 day, 1–3 days, 4–7 days, 1–2 weeks, and >2 weeks.

3.2.1.3. Climate and energy beliefs. We use two questions to measure clean energy and climate beliefs separately. The acceptability of renewable energy is adopted to quantify clean energy belief [82,83]. Respondents are surveyed to determine their preferences for expanding energy sources, including gas, nuclear, coal, wind, and solar, among which solar and wind are identified as clean energy alternatives. Favoring expanding clean energy is considered as a strong energy belief. Each energy source is dummy coded, with 1 favoring this energy and 0 not. “Cleanenergy” is represented as the sum of solar and wind, ranging from 0 to 2. For climate belief, we asked if they agree that climate change has introduced extreme weather-related events (1 = not at all and 5 = a great deal).

3.2.2. Dependent variables

We apply identical questions to investigate the perceptions of energy service importance and HVAC behaviors in normal and disaster

scenarios separately. The number of observations for the ratings of energy service importance and HVAC behavior is $485 \times 2 = 970$. The disaster scenario is denoted using a dummy variable, namely “In_disaster”. To reduce the inconsistency and uncertainty in understanding the disaster scenarios [70], this study provides a background before each disaster-related question to define the disaster scenarios: if you were in an extreme weather event (e.g., heat waves and winter storms) that energy supply is limited with power outage/shortage and high energy price risks.

3.2.2.1. Perceived importance of energy services. The perceptions and behaviors of occupants during disasters play a critical role in making an acceptable indoor environment [1]. Based on the US Residential Energy Consumption Survey [84], 12 residential energy services are selected, including space heating, air conditioner, water heating, and lighting. Then, a 5-point scale is used to gather respondents' subjective perceptions on the importance of each service on regular days and weather-related disasters separately (1 = least important; 5 = most important). The compromise of each service is measured as the differences in rated importance between normal days and disasters, i.e., *normal - disaster*.

3.2.2.2. HVAC behaviors. HVAC setpoints [45], duration of running the main space heating/cooling per day [85], and common behaviors [84] are investigated. Setpoints and common behaviors in disasters and normal days are measured separately. The variable “In_disaster” is used to differentiate the disaster from the normal scenario. For those households without space heating or space cooling, we instructed them to assume that they have corresponding equipment to investigate their HVAC behaviors.

3.2.2.3. Willingness to pay. The multiples of the normal energy price are adopted to investigate the willingness to pay for maintaining energy services during disasters [69]. We use a question to inquire about the extent to which occupants would be willing to increase their payment to sustain regular daily energy use during disaster scenarios compared to normal days. This dependent variable is ordinal, with 0 to 5 demonstrating not interested in paying more, 1.5 times, 2 times, 5 times, 10 times, and 100 times of the normal average.

3.3. Demographics

Among 485 valid respondents, there are 257 females (53%) and 228 males. Caucasian respondents account for around 65%. 43% of respondents reported living in the community for over 15 years; only 14% had resided for <2 years. The distributions of respondent demographics are depicted in Fig. 2. Respondents aged over 55 represent 39% of the sample, which is roughly twice the proportion of those in the 25–34 and 35–44 age groups. 33% of respondents' education level is high school or below, followed by 29% holding a Bachelor's degree. More than half of the households consist of one or two people. 30% and 33% of households earn \$25,000–50,000 and \$50,000–100,000 annually, respectively. Regarding housing, 31% and 60% live in apartments and single-family houses. 37% of respondents' house sizes are 1000–1500 ft² (93–139 m²), while 22% are <1000 ft² (93 m²).

The sample data, based on 2022 American Survey Data [86,87], is representative of the general population in terms of gender, age, and race. For instance, in terms of gender, females account for 51% of the population, while males make up 49%. Among the age groups within the 20 and above category, the proportions are as follows: 10.2% aged 20–24, 22.8% aged 25–34, 19% aged 35–44, 16.6% aged 45–54, and 31.4% aged 55 and above. Additionally, 53.8% of the population consists of white people. These distributions align with our sample data.

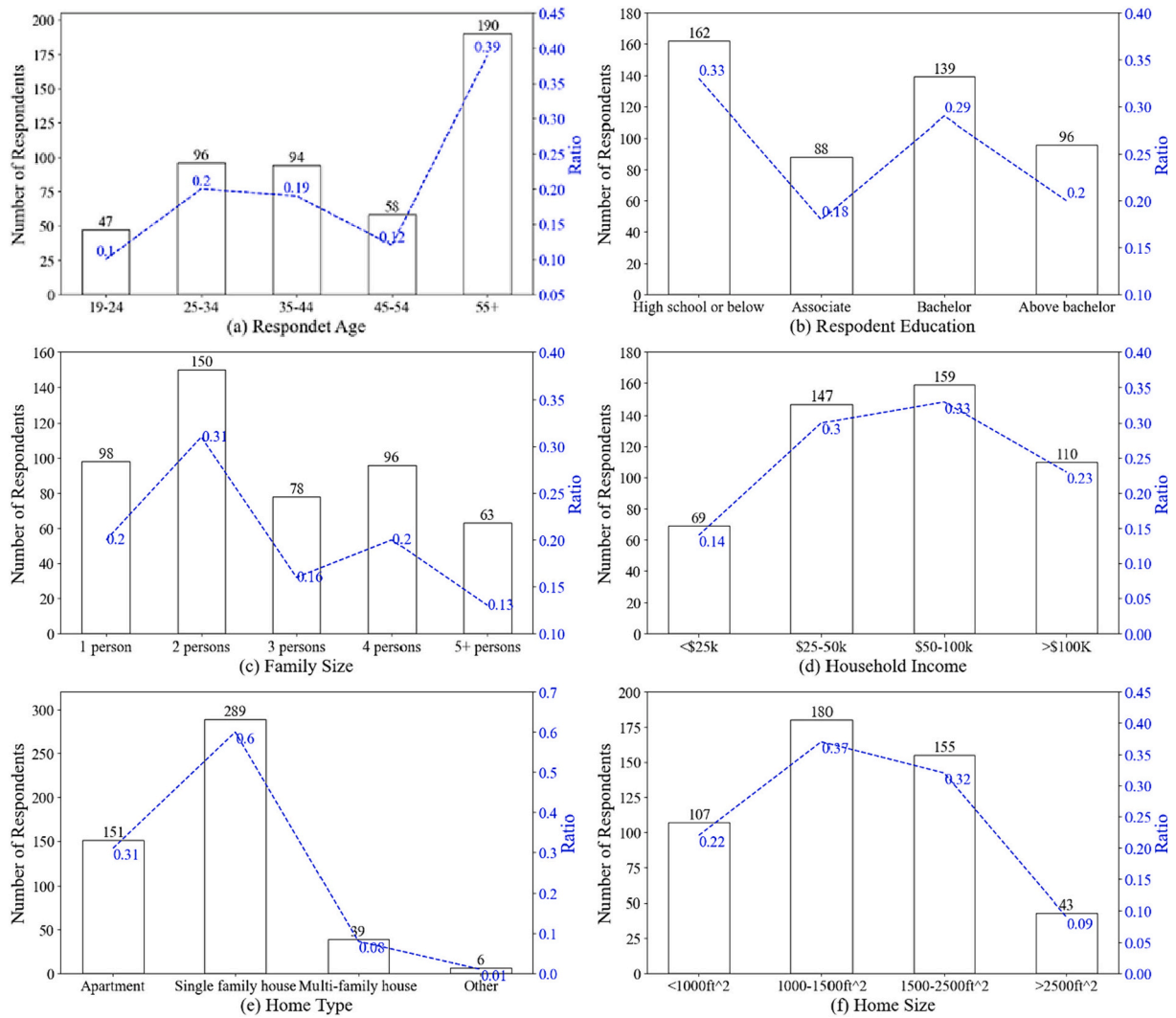


Fig. 2. Socio-demographics of respondents.

4. Methods and results

4.1. Energy service importance and compromise

4.1.1. Descriptive analysis and energy service clustering

Table 3 and Fig. 3 demonstrate the comparisons and distributions of

perceived end-use importance between disasters and normal days. Air conditioners and refrigerators are the two most important end-uses, with ratings over 4 out of 5, during normal days and disasters. Water heater, cooking, and lighting are also important residential energy services on normal days, with average rates larger than 4, while these end-use importance scores drop to around 3.5 during disasters. In contrast, the

Table 3

Descriptive statistics of perceived importance and compromise.

Energy Service	Normal Importance			Disaster Importance			Compromise	
	Rank	Mean	SD	Rank	Mean	SD	Dif. mean ¹	Relative change ²
Space Heating (SH)	8	3.68	1.28	5	3.51	1.27	0.17	4.6%
Freezer	7	3.82	1.20	4	3.53	1.34	0.29	7.7%
Refrigerator (Refri)	2	4.40	0.86	2	4.01	1.02	0.39	8.9%
Air conditioner (AC)	1	4.51	0.83	1	4.07	1.14	0.44	9.8%
Cooking	4	4.14	0.98	3	3.66	1.15	0.48	11.7%
Water Heating (WH)	3	4.17	0.88	6	3.46	1.18	0.71	17.0%
Fan	11	3.19	1.30	10	2.48	1.41	0.71	22.3%
Lighting	5	4.10	0.99	7	3.32	1.27	0.78	19.0%
Dishwasher (Dwash)	12	2.89	1.37	12	2.06	1.30	0.83	28.8%
Television (TV)	10	3.50	1.19	9	2.56	1.36	0.94	26.8%
Cloth dryer (Cdryer)	9	3.54	1.14	11	2.45	1.34	1.09	30.8%
Cloth wash (Cwash)	6	3.83	1.09	8	2.70	1.34	1.13	29.5%

Notes: 1. Dif. Mean: difference of mean = mean of normal-mean of disaster, measuring the absolute compromise. 2. relative change = difference of mean/mean of normal, measuring the relative compromise to normal days.

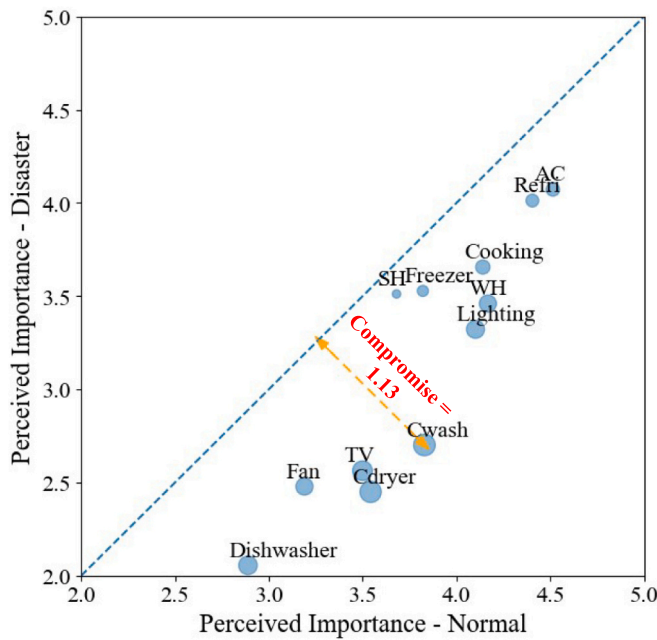


Fig. 3. Distribution of perceived importance of energy services. Note: The size of each bubble or distance to the blue diagonal symbolizes the compromise of each service during disasters. Abbreviations: SH: space heating, AC: air conditioner, WH: water heating, TV: television, Cwash: cloth washer, Cdryer: cloth dryer, Refri: refrigerator (the same below).

ratings of fans, dishwashers, TVs, and laundry (i.e., clothes washer and dryer) are <3 during disasters.

Generally, all residential energy services show the potential to compromise during disasters. In Fig. 3, the distance of each service away from the blue diagonal (i.e., Disaster = Normal) is the absolute compromise during disasters, measured as the difference in perceived importance rating between normal days and disasters. Of these energy services, the importance of laundry has the largest decline during disasters by over 1, with relative compromises of around 30%, followed by TV and dishwasher. The decreases of water heater, lighting, and fan are over 0.7 (relative changes over 15%). Instead, the compromises of other energy services during disasters are <0.5, with space heating being the least.

Then, based on the importance and compromise of services during disasters, this study adopts hierarchical clustering to classify energy services into three categories, as shown in Fig. 4. Hierarchical clustering uses standardized Euclidean distance to measure point distances and Ward as the linkage method. Cluster I is critical energy services, which

are related to thermal comfort, food cooking and storage, including space heating, air conditioning, cooking, refrigerators, and freezer. These services have the least compromise but the highest importance during disasters (see Table 4), averaging importance and compromise of 3.76 and 0.35, respectively. Therefore, cluster I has a high priority to satisfy during disasters. Cluster II includes water heating and lighting. These energy services are also deemed important (averaging 3.39) but can be subject to compromise if necessary during disasters, as reflected by an average compromise score of 0.74. Conversely, cluster III is low-priority, including TV, fan, cloth washer, and cloth dryer, which exhibit the largest compromise, around 0.94, and the lowest importance rating during disasters, falling below 2.5. Hence, the services in cluster III have the greatest potential to sacrifice in disaster scenarios.

4.1.2. Influencing factors of perceived importance of energy services

Three end-use clusters are further analyzed to explore influencing factors. The importance rating of each cluster is the average importance of the energy services in the corresponding group, which is considered as continuous variable. Step-wise regression is adopted to analyze the influencing factors of the importance ratings of three energy service clusters (the same below), as shown in Table 5. There is no multicollinearity ($VIF < 5$) between the independent variables of each regression model.

The regression models between the importance rating of energy services and potential influencing factors reveal that all services have the potential to be compromised during disasters, i.e., the importance ratings are significantly decreased. Among these potential factors, “In_disaster” is the most determinant variable driving importance ratings of services, with the largest standardized estimate (β) in regression models. The impact of disaster scenarios on low-priority services is the largest. Also, previous disaster experiences (mainly extreme heat) or disaster-induced power outages contribute to reporting higher importance ratings on energy services.

Regarding demographics impact, race difference is a notable

Table 4

Descriptive statistics of perceived importance and compromise for service clusters.

Cluster	Number of Services	Normal Importance		Disaster Importance		Compromise	
		Mean	SD	Mean	SD	Mean	SD
High-priority	5	4.11	0.64	3.76	0.75	0.36	0.60
Mid-priority	2	4.13	0.81	3.39	1.05	0.74	0.94
Low-priority	5	3.39	0.87	2.45	1.10	0.94	0.90

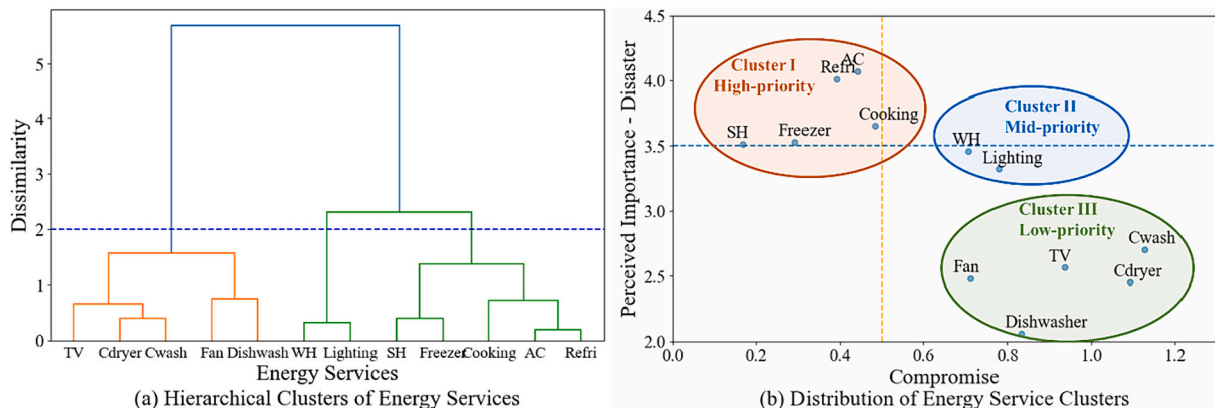


Fig. 4. Clusters of energy services based on perceived importance and compromise.

Table 5Multiple linear regression models for perceived importance of energy services ($n = 970$).

Model	Variable	B	S.E.	β	t	Sig.	VIF	R ²	Adjusted R ²	ANOVA
(1) High-priority importance	const	4.29	0.06							
	In_disaster	-0.36	0.04	-0.25	-8.15	<0.001	1.000			
	Gender	-0.12	0.04	-0.08	-2.74	0.006	1.039			
	Race	-0.19	0.05	-0.13	-4.08	<0.001	1.058	0.114	0.108	F = 20.64, p < 0.001
	Edu	-0.06	0.02	-0.10	-3.04	0.002	1.065			
	Gas	0.17	0.05	0.11	3.53	<0.001	1.039			
	Pofrequency	0.05	0.01	0.12	3.82	<0.001	1.014			
(2) Mid-priority importance	const	4.02	0.14							
	In_disaster	-0.74	0.06	-0.37	-12.66	<0.001	1.000			
	Gender	-0.14	0.06	-0.07	-2.42	0.016	1.025			
	Age	0.07	0.02	0.10	2.87	0.004	1.352			
	Race	-0.33	0.07	-0.16	-5.01	<0.001	1.164	0.186	0.179	F = 27.37, p < 0.001
	Familysize	0.05	0.02	0.07	2.07	0.039	1.208			
	Gas	0.16	0.07	0.08	2.41	0.016	1.180			
(3) Low-priority importance	Cleanenergy	-0.07	0.04	-0.06	-1.97	0.049	1.143			
	Extremehot	0.23	0.08	0.09	2.97	0.003	1.022			
	const	3.39	0.11							
	In_disaster	-0.94	0.06	-0.43	-15.30	<0.001	1.000			
	Race	-0.13	0.07	-0.06	-1.99	0.047	1.105			
	Familysize	0.08	0.02	0.10	3.49	0.001	1.093	0.247	0.242	F = 52.59, p < 0.001
	Gas	0.14	0.07	0.06	2.02	0.043	1.106			
	Cleanenergy	-0.21	0.04	-0.16	-5.42	<0.001	1.121			
	Extremehot	0.30	0.08	0.10	3.71	<0.001	1.014			

Note: B = unstandardized estimates; S.E. = standard error; β = standardized estimates; Sig. = significance; VIF = variance inflation factor. The same below.

disparity in end-use importance ratings. Caucasians rate relatively lower scores on high, mid, and low-priority services (0.12, 0.33, and 0.13 of difference, respectively) than other racial groups. Family size positively affects the importance ratings of mid and low-energy services, i.e., households with larger family sizes are more reliant on these energy services. Males perceive less importance on high and mid-priority services than females. Additionally, respondents with stronger clean energy beliefs, i.e., supporting clean energy or not supporting expanding gas, are less reliant on energy services, with lower importance scores for all energy end-uses, where the impact of energy beliefs on low-priority services is the most ($B = -0.21$ for clean energy).

4.1.3. Influencing factors of compromise of energy service during disasters

Linear regression models between the compromise of each service cluster (i.e., the average compromise of the energy services in each cluster) and potential influencing factors are summarized in Table 6. The compromise of high-priority services is negatively correlated with age, education levels, family size, and housing size. The older occupants or households with larger family sizes or housing sizes result in lower compromises on high-priority services ($B < 0$). On the contrary, respondents with higher education levels or stronger energy beliefs are more willing to sacrifice these high-priority services. Similarly, stronger clean energy beliefs contribute to higher compromise on mid and low-priority services as well. Furthermore, respondents with disaster experience have lower compromise on high-priority services (-0.16) but higher compromise (0.17) on low-priority services.

Table 6Multiple linear regression models for compromise of energy services ($n = 485$).

Model	Variable	B	S.E.	β	t	Sig.	VIF	R ²	Adjusted R ²	ANOVA
(1) High-priority compromise	const	0.66	0.13							
	Age	-0.05	0.02	-0.13	-2.52	0.012	1.277			
	Edu	0.05	0.02	0.09	1.97	0.050	1.046			
	Homesize	-0.07	0.04	-0.10	-2.04	0.042	1.113	0.07	0.059	F = 6.02, p < 0.001
	Familysize	-0.06	0.02	-0.12	-2.04	0.013	1.240			
	Cleanenergy	0.09	0.03	0.13	2.89	0.004	1.043			
	Extremehot	-0.16	0.07	0.13	2.89	0.004	1.019			
(2) Mid-priority	constant	0.45	0.07							
	Cleanenergy	0.25	0.05	0.22	5.04	<0.001		0.050	0.048	F = 25.39, p < 0.001
(3) Low-priority	const	0.48	0.08							
	Cleanenergy	0.29	0.05	0.27	6.21	<0.001	1.033	0.092	0.088	F = 24.28, p < 0.001
	Extremecold	0.17	0.08	0.09	2.00	0.046	1.033			

4.2. Shift of HVAC use behavior

4.2.1. Descriptive analysis

The distributions of duration and behaviors of using HVAC are shown in Fig. 5 and Fig. 6. Generally, in the investigated area, occupants rely more on space cooling than on space heating. Specifically, there are higher penetrations of space cooling than heating, with 95% and 85%, respectively. Besides, more occupants keep running space cooling throughout the day (25% with 22–24 h of use) than space heating (13%). Additionally, Fig. 6 demonstrates that those respondents who keep running HVAC are willing to shift HVAC behaviors during disasters, decreasing around 7% in the winter and 13% in the summer. More respondents prefer turning on HVAC only during sleep or based on indoor/outdoor temperature in disaster scenarios, increasing around 5% in the winter and 10% in the summer.

Fig. 7 and Fig. 8 illustrate the distributions of HVAC setpoints and compromise during disasters. In the winter, 33% more respondents set the temperature of space heating to 67 °F (19.4 °C) or less during disasters to reduce energy consumption, compared with normal days. The mean setpoints of space heating during normal days and disasters are 70.37 °F (21.32 °C, SD = 5.23 °F) and 66.73 °F (19.29 °C, SD = 5.65 °F), with medians of 70 °F (21.1 °C) and 66 °F (18.9 °C), respectively. In the summer, compared with normal scenarios, 21% more respondents during disasters increase the setpoints of space cooling to 76 °F (24.4 °C) or above to save energy usage. The temperature setpoint of space cooling increases from 72.63 °F (SD = 6.00 °F, median = 73 °F [22.8 °C]) during

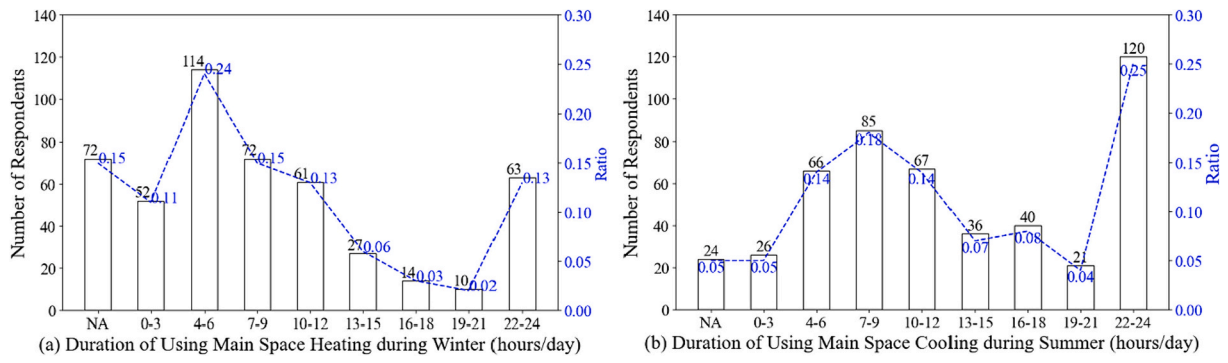


Fig. 5. Duration of using HVAC during normal days.

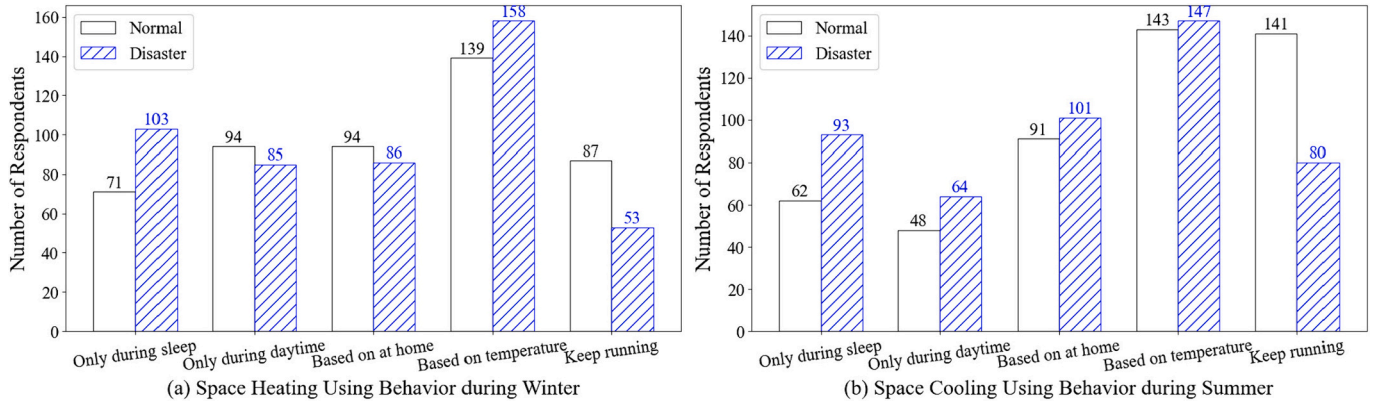


Fig. 6. HVAC behavior during normal days and disasters.

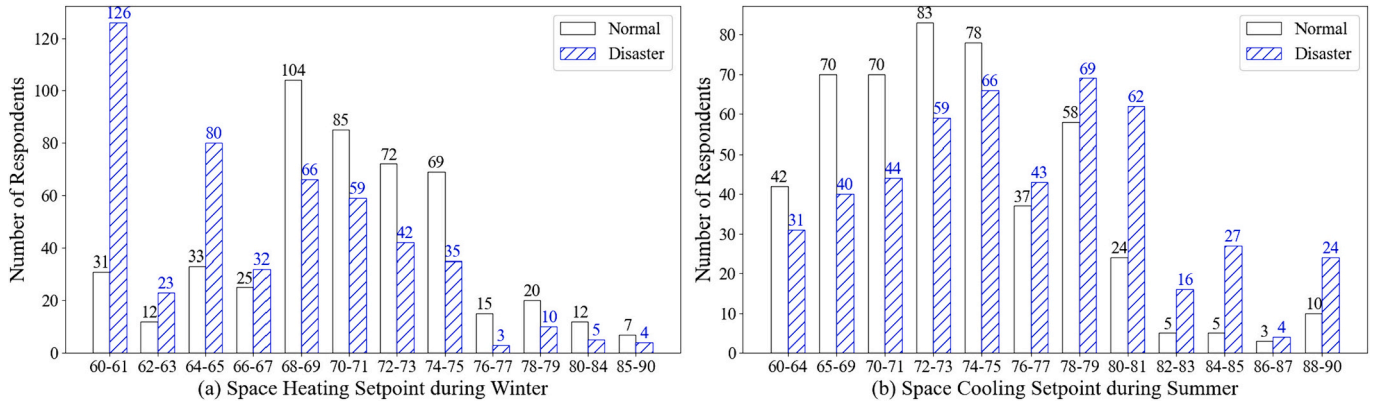


Fig. 7. HVAC setpoints during normal days and disasters.

normal days to 75.42 °F (SD = 6.71 °F, median = 76 °F [24.4 °C]) during disasters on average.

Specific to the compromise of HVAC setpoints (Fig. 8), occupants are more willing to compromise in space heating than in space cooling. First, more occupants are willing to decrease the setpoints of space heating during extreme cold weather (61%) than increase the setpoints of space cooling during extreme hot summer (56%) to reduce energy consumption. Also, more respondents can tolerate the changes of 5 °F (2.78 °C) or more of the setpoints of space heating than space cooling, around 26% and 19%, respectively. The averaging setpoint compromises of HVAC during winter and summer are 3.65 °F (2.03 °C) and 2.80 °F (1.56 °C), respectively.

4.2.2. Influencing factors of HVAC Setpoints

Regression models for HVAC temperature setpoints in the winter and summer are summarized in Table 7. The independent variables in each regression model have no multicollinearity, as indicated by VIF values below 5. HVAC setpoints are significantly impacted by disaster scenarios, during which occupants prefer to adjust the heating and cooling temperature setpoint to conserve energy, i.e., reducing 3.65 °F in the winter and increasing 2.8 °F in the summer.

Temperature setpoints vary among distinct socio-demographic groups, including age, race, and education. Elderly residents are more energy-conservative, using lower temperature setpoints in the winter ($B = -0.45$) and higher in the summer ($B = 0.86$). On average, the space heating setpoints of Caucasians are 2.3 °F (1.28 °C) lower than other races. Occupants with higher education levels set lower temperatures

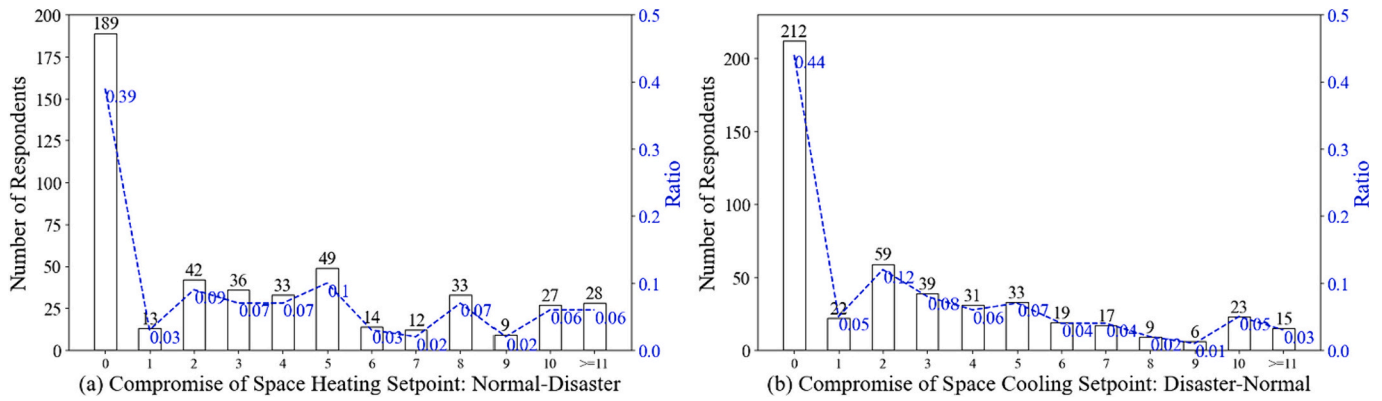


Fig. 8. Compromise of HVAC setpoints during disasters.

Table 7

Multiple linear regression models for HVAC temperature setpoints ($n = 970$).

Model	Variable	B	S.E.	β	t	Sig.	VIF	R ²	Adjusted R ²	ANOVA
(1) Winter setpoints	const	73.68	0.67							
	In_disaster	-3.65	0.34	-0.32	-10.88	<0.001	1.000			
	Age	-0.45	0.13	-0.11	-3.49	<0.001	1.167			
	Race	-2.27	0.38	-0.19	-6.02	<0.001	1.157	0.179	0.174	F = 35.03, p < 0.001
	Edu	-0.33	0.15	-0.07	-2.18	0.03	1.066			
	Homesize	0.45	0.19	0.07	2.33	0.02	1.070			
	Cleanenergy	-0.43	0.20	-0.06	-2.12	0.034	1.031			
(2) Summer setpoints	const	66.78	0.89							
	In_disaster	2.80	0.37	0.22	7.55	<0.001	1.000			
	Gender	0.86	0.38	0.07	2.30	0.022	1.018			
	Age	0.86	0.15	0.19	5.84	<0.001	1.264	0.219	0.214	F = 45.02, p < 0.001
	Homesize	1.33	0.21	0.18	6.20	<0.001	1.093			
	Familysize	-0.78	0.16	-0.16	-5.04	<0.001	1.248			
	Cleanenergy	1.33	0.23	0.17	5.89	<0.001	1.039			

during winter. Males prefer higher temperature points during summer. Moreover, stronger clean energy beliefs contribute to energy-saving HVAC setpoints as well. Occupants with stronger energy beliefs prefer higher temperatures in the summer and lower setpoints in the winter. However, housing size does not always contribute to more energy-saving setpoints. As home size increases, the temperature setpoints go up in the summer (reducing energy usage) but also in the winter (consuming more energy). Also, space cooling setpoints in households with larger family sizes are usually lower.

4.2.3. Influencing factors of compromise of HVAC Setpoints

Table 8 illustrates the influencing factors of shifts in HVAC setpoints. Clean energy or climate belief and disaster experience are two determinant factors for the compromise. Occupants supporting clean energy or with stronger climate beliefs have greater inclinations to compromise in thermal comfort to shift HVAC setpoints to save energy usage. Similarly, respondents experiencing disaster-induced power outages are

more willing to reduce setpoints of space heating and increase setpoints of space cooling. These influencing factors have larger impacts on the setpoint compromise in winter than in summer. Additionally, occupants living in larger homes have a larger potential to reduce setpoints of space heating. Caucasians are more resilient in increasing setpoints of space cooling during disasters.

4.3. Willingness to pay and energy supply scheme preference

4.3.1. Descriptive analysis

For energy supply schemes during disasters, 395 respondents (81%) prefer to reduce energy use but keep the continuous power supply, while only 90 (19%) are willing to follow rotational power outages. The distribution of WTP (Fig. 9) shows that around 41% of respondents are unwilling to pay more for energy services during disasters, followed by 1.5 times of the normal daily average (26%). In contrast, only 3% of respondents are willing to pay 10 times or more than the normal daily

Table 8

Multiple linear regression models for compromise of HVAC temperature setpoints ($n = 485$).

Model	Variable	B	S.E.	β	t	Sig.	VIF	R ²	Adjusted R ²	ANOVA
Winter compromise	const	-0.94	0.79							
	Homesize	0.44	0.20	0.09	2.18	0.030	1.018			
	Influence	0.36	0.15	0.11	2.46	0.014	1.164	0.106	0.097	F = 11.36, p < 0.001
	Cleanenergy	0.87	0.23	0.17	3.74	<0.001	1.153			
	Extremehot	-0.99	0.49	-0.09	-2.00	0.046	1.088			
	Exp_po	1.97	0.44	0.20	4.44	<0.001	1.099			
	const	0.28	0.54							
Summer compromise	Race	0.68	0.34	0.09	1.99	0.047	1.029			
	Influence	0.27	0.13	0.10	2.06	0.040	1.165	0.057	0.049	F = 7.30, p < 0.001
	Cleanenergy	0.53	0.21	0.12	2.54	0.011	1.167			
	Poduration	0.35	0.14	0.11	2.44	0.015	1.008			

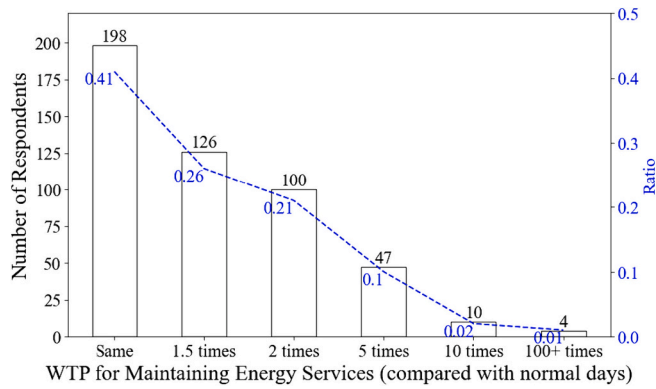


Fig. 9. Distribution of WTP for maintaining energy services.

average.

4.3.2. Influencing factors of willingness to pay

Ordered logit regression is adopted to analyze the influencing factors of willingness to pay of occupants for maintaining energy services during disasters, as demonstrated in Table 9. The p -value for the test of parallel lines assumption is 0.993 (indicating the appropriateness of using ordered logit regression), and the model fitting is significant ($p < 0.001$).

Age, home size, and clean energy beliefs negatively affect WTP for energy services during disasters. Older occupants or occupants living in larger houses or with stronger clean energy beliefs are less willing to pay higher energy prices during disasters. In contrast, higher household income or education levels contribute to higher WTP. Occupants with larger family sizes have a stronger willingness to pay higher energy prices. Males are more willing to pay higher for energy services during disasters than females. Also, the power outage experience increases WTP. Respondents having experienced relatively longer power durations are inclined to pay more for energy services during disasters. However, occupants with extreme cold experiences have lower WTP.

4.3.3. Relationships between willingness to pay and energy service compromise

We further adopt the Spearman correlation to analyze the relationships between willingness to pay, compromise of three end-use clusters (high, mid, and low-priority), and shifts of HVAC setpoints during winter and summer. The results are shown in Fig. 10 and illustrate that the compromises of three end-use clusters are positively correlated, with correlation coefficients (r) of over 0.4. Therefore, households have similar compromises in different energy services, indicating that those who demonstrate a preference for compromising on certain services are

likely to extend the compromise to other services as well. Similarly, the shifts of the HVAC setpoints in the winter and summer are strongly correlated, with $r = 0.5$. This finding highlights that if the households are willing to adjust HVAC setpoints to conserve energy during winter storms, it is highly probable that they will exhibit the same energy-saving behaviors during heat waves.

Also, the compromises of mid and low-priority energy services are moderately correlated with the shifts of HVAC setpoints ($r \approx 0.2$), which means that the households with larger compromises on general energy services are more likely to adjust the setpoints to save energy consumption during disasters. However, the correlations between the compromise of low/mid-priority energy services and WTP are weak and negative ($r \approx -0.2$), indicating that households with a higher willingness to pay for energy services during disasters tend to have lower compromises on nonessential energy services.

5. Discussions

This survey-based study investigates household energy resilience by comparing occupants' subjective perceptions of the energy service importance and compromise, HVAC behaviors, and willingness to pay for maintaining energy services in normal and disaster scenarios.

5.1. Resilience of energy services and HVAC use behavior

First, this study provides empirical evidence on the compromise of disrupted energy services during disasters. Major respondents (over 80%) prefer to sacrifice partial energy use while ensuring continuous energy supply during disasters in the absence of full power supplies. The importance scores of all energy services are significantly decreased in disaster scenarios, albeit to varying compromise levels. Then, based on the compromise and importance ratings during disasters, 12 investigated residential energy services have been clustered into three categories: high, mid, and low-priority services. Specifically, high-priority services, encompassing food cooking and storage (i.e., refrigerator and freezer) and thermal comfort (i.e., space heating and cooling), emerge as exceptionally crucial with minimum compromise. Diet and thermal comfort are basic demands that need to be fulfilled as a matter of priority both on regular days and disasters. Based on open-ended comments from respondents concerning the critical issues during disasters with power outages, 97 respondents raised their concerns on food cooking and storage, such as "The most critical issue for me is making sure I have power to cook meals", "Keep food from spoiling", and "The refrigerator is the most important appliance to get back running", and over 140 respondents valued the issues regarding thermal comfort and commented "Keeping physically warm or cool depending on the situation", "[Keeping] heat when disaster is caused by extreme cold." and "Staying cool in extreme heat". Mid-priority services include water heating and lighting. While they

Table 9
Ordered logit regression models for WTP ($n = 485$).

Model	Variable	coef	S.E.	Z-value	Sig.	95% Confidence Interval		Summary of Statistics
WTP	Gender	0.495	0.180	2.747	0.006	0.142	0.847	Log Likelihood = -601.87,
	Age	-0.305	0.069	-4.41	0.000	-0.441	-0.170	
	Income	0.260	0.091	2.843	0.004	0.081	0.439	
	Edu	0.332	0.077	4.305	0.000	0.181	0.483	
	Homesize	-0.299	0.11	-2.724	0.006	-0.513	-0.084	
	Familysize	0.183	0.068	2.693	0.007	0.050	0.316	P < 0.001,
	Influence	0.198	0.072	2.769	0.006	0.058	0.338	
	Cleanenergy	-0.397	0.113	-3.499	<0.001	-0.618	-0.174	McFadden's R-Square = 0.105,
	Extremecold	-0.812	0.243	-3.338	0.001	-1.288	-0.335	
	Poduration	0.433	0.099	4.385	<0.001	0.239	0.626	Cox and Snell R-Square = 0.254, AIC = 1234
	[WTP = 0]	0.310	0.501	0.619	0.536	-0.672	1.292	
	[WTP = 1]	0.283	0.081	3.481	<0.001	0.124	0.442	
	[WTP = 2]	0.439	0.094	4.683	<0.001	0.255	0.622	
	[WTP = 3]	0.572	0.146	3.907	<0.001	0.285	0.859	
	[WTP = 4]	0.282	0.329	0.857	0.391	-0.362	0.926	

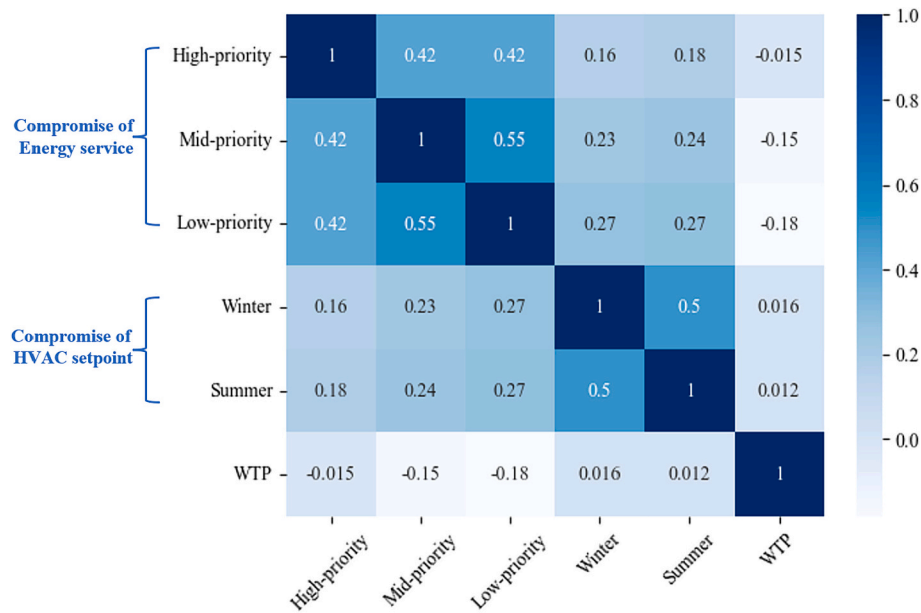


Fig. 10. Correlations between energy service compromise and WTP.

retain importance during disasters, as indicated by their average importance ratings exceeding 3.3, they can compromise when required, exhibiting relatively higher compromise scores than high-priority services. By contrast, low-priority services are less important during disasters and possess the largest compromises, including entertainment (e.g., TV) and appliances that can substitute or assist individuals with housework (e.g., laundry and dishwasher). Therefore, these low-priority services hold the greatest potential for postponement without inflicting much discomfort during limited power-supply periods. The priority of energy end-uses can be references to devising energy supply schemes that guarantee essential energy services at acceptable levels during disasters, thereby augmenting household energy resilience.

Compared with former studies, although former research has categorized energy services in some scenarios (e.g., peak hours), the definitions and supporting evidence for classifications are insufficient, e.g., Baik et al. [35], and the impact of disasters is seldom involved. The classification in our study, centered on importance and compromise during disasters, concurs with Soares et al. [37], which considered laundry, dishwasher, and water heater as shiftable loads since they can be shifted during peak hours. However, our categorization moderately differs from some existing studies. Candan et al. [22] viewed lighting as more important than cooking and heater but did not provide clear evidence. As confirmed by Tanabe et al. [88], occupants are more receptive towards decreased illumination, compared with the compromise on thermal comfort, after disasters. Also, Stelmach et al. [38] clustered cooking and entertainment together during peaks based on the energy use patterns, which contrasts with our findings. The disagreement may partially stem from the impact of disasters, which emphasizes resource constraints [23]. While TV holds importance during normal days, with an average rating of approximately 3.50, the importance of entertainment appliances has decreased to 2.56 due to the limitations imposed by disasters.

Secondly, we found shifts in HVAC use behavior to reduce energy use during disasters. Compared with regular days, more occupants prefer energy-saving behaviors during disasters, e.g., less running HVAC continuously, more based on temperature or only during sleep. Also, occupants, particularly those in households that exhibit a greater willingness to compromise on general energy services, are willing to adjust HVAC setpoints to conserve energy during disasters with limited energy supply. Occupants have similar energy-saving patterns in compromising the HVAC setpoints during extremely cold and hot days (with strong

correlations). However, occupants have larger flexibility in using space heating during disasters in the investigated areas (a relatively hot climate), i.e., more likely to adjust the space heating equipment. Specifically, occupants are less reliant on space heating than on space cooling, with lower penetration of space heating equipment than space cooling (space heating vs. cooling: 85% vs. 95%), which is different from the national average (97% vs. 88%) [89], and fewer occupants keeping running space heating continuously (13% vs. 25%). Furthermore, the space heating setpoints show larger adaptations than space cooling, as indicated by more respondents willing to shift the setpoints of space heating (61% vs. 56%) and larger changes in space heating setpoints (3.65 °F vs. 2.80 °F, i.e., 2.03 °C vs. 1.56 °C). One of the reasons for the difference is likely due to the climate of Fort Worth/Dallas, TX, which is hot in the summer and mild in the winter [75]. The hot climate intensifies the dependence on space cooling in the summers, further affecting HVAC behaviors. Therefore, regional and climate variations in the resilience of HVAC behavior should be considered in future nationwide studies.

In addition, approximately 60% of respondents are willing to pay higher energy prices than regular days to maintain energy services during disasters with a high risk of power shortages or even outages. Nevertheless, the magnitude of acceptable levels of increasing prices is modest, as only 13% express a willingness to pay over twice the normal prices. The conservative willingness to pay more can also be observed in the investigation of the 2021 Texas winter storm, with only 35.73% of respondents accepting a 70% or above increase per kWh [69]. We also found that households with higher WTP for maintaining energy services are less likely to compromise more on nonessential energy services. Additionally, compared with investigating the willingness according to energy bill [70], that overlooks the intrinsic difference in household daily total energy expenditures on normal days, the surveyed multiplication of normal price per kWh provides a clearer perspective on determining acceptable energy prices during disasters. It is noted that affordability is critical for energy resilience and equitable infrastructure [28,17]. Therefore, given the cautious willingness observed, the cost of energy supply is still a concern to residents.

5.2. Varying resilience profile among different socio-demographic groups

Distinct socio-demographic groups (e.g., gender, age, and family size) display varying energy use resilience and willingness to pay. The

socio-demographic influences are summarized in Fig. 11.

Elderly and low-income residents are vulnerable to disasters and demonstrate weak resilience in energy services and HVAC behavior. The older population is reluctant to compromise on daily basic needs, which aligns with the finding that older individuals have less flexibility in energy services [53]. Nonetheless, the HVAC behaviors of older residents are more frugal than the young, reflecting energy-saving setpoints. Also, they are less willing to pay more for energy services. This finding concurs with a study in Australia, which found that older occupants care more about energy cost and prefer some adaptive behavior to achieve thermal comfort, rather than relying on HVAC, even during extreme weather conditions [90]. Likewise, we reveal that lower household income decreases the willingness to pay more for energy services when encountering the risk of rising energy prices during weather-related extreme events. However, we do not find significant differences in HVAC behaviors and energy services compromise between income groups. This conclusion is testified by Belaïd and Garcia [51], which found no significant impact of income on energy-saving behaviors. In similar studies, older and low-income groups demonstrate a decreased willingness to pay for reliable energy services to minimize the occurrence and duration of power outages [72]. Also, bill consciousness is a significant issue contributing to energy-related behaviors of vulnerable groups [91]. Therefore, reducing the burdens of energy bills for vulnerable groups during disasters is imperative to achieve resilient and equitable energy services.

We further explore the impact of race and gender on energy resilience, i.e., the ability to compromise the disturbed energy services (including HVAC behavior) during disasters. Non-white groups tend to have greater dependence on energy services, as illustrated by rating energy services higher than the Caucasian group. Such differences in varying racial groups can be explained by a nationwide study in the US, which concluded that African-American households consume more energy in end-uses than white households, including HVAC, water heating, and lighting [92]. Additionally, white groups show a larger potential to sacrifice by increasing the setpoints in the summer to save energy usage. However, we didn't observe corresponding influences of race on WTP and the compromise on energy services. We also identified the gender disparities. Females have high demands on high and mid-priority services. Males prefer higher setpoints during summer and are willing to pay more for energy services. The finding aligns with Yilmaz et al. [55],

which found that females are relatively conservative in flexible energy responses.

Larger family sizes increase the dependence on energy services, whereas higher education levels tend to diminish the reliance on energy. Households with larger family sizes report higher importance ratings on mid and low-priority services and less compromise on high-priority services. Also, the setpoints of AC during summer in larger family sizes are lower, which consumes more energy. Due to the higher energy demands, larger family sizes are more willing to pay for increasing energy prices. Similar conclusions can be found in Abdullah and Mariel [79]. Considering the higher energy demand, the emergency energy supply needs to prioritize energy allocations to larger family sizes. In contrast, individuals with higher education levels rely less on energy services and have larger compromises. They express a greater willingness to pay for sustaining energy services during disasters. This finding agrees with Taale and Kyeremeh [93] and Sridhar [52], which prove that occupants with higher education have a stronger awareness of climate change and are more willing to pay higher for energy services.

The size of housing is also important. The setpoints in larger homes are relatively higher in winter and summer to achieve thermal comfort. Regarding energy resilience (including the compromise on disturbed energy services, shift in HVAC behaviors, and WTP), larger home sizes have less compromise on high-priority energy services (including HVAC) and have less willingness to pay for energy services during disasters. In previous studies, larger houses have been considered to have greater heat transfer areas, which require higher heat demands [94]. Also, our recent study identified housing size as a key determinant of HVAC energy usage [25], increasing reliance on energy and leading to lower resilience on high-priority services. Moreover, due to greater energy consumption in larger home sizes [25], the inherent higher energy bills on regular days may impede their inclination to pay for increasing energy prices during disasters.

5.3. Influencing factor of energy service resilience

Besides the influences of socio-demographics, disasters and occupants' beliefs contribute to energy service resilience. "In_disaster" (i.e., occupants in the disaster environment) is the most critical variable in determining the perception of energy service importance and HVAC setpoints, according to the standard estimate in regression models (refer

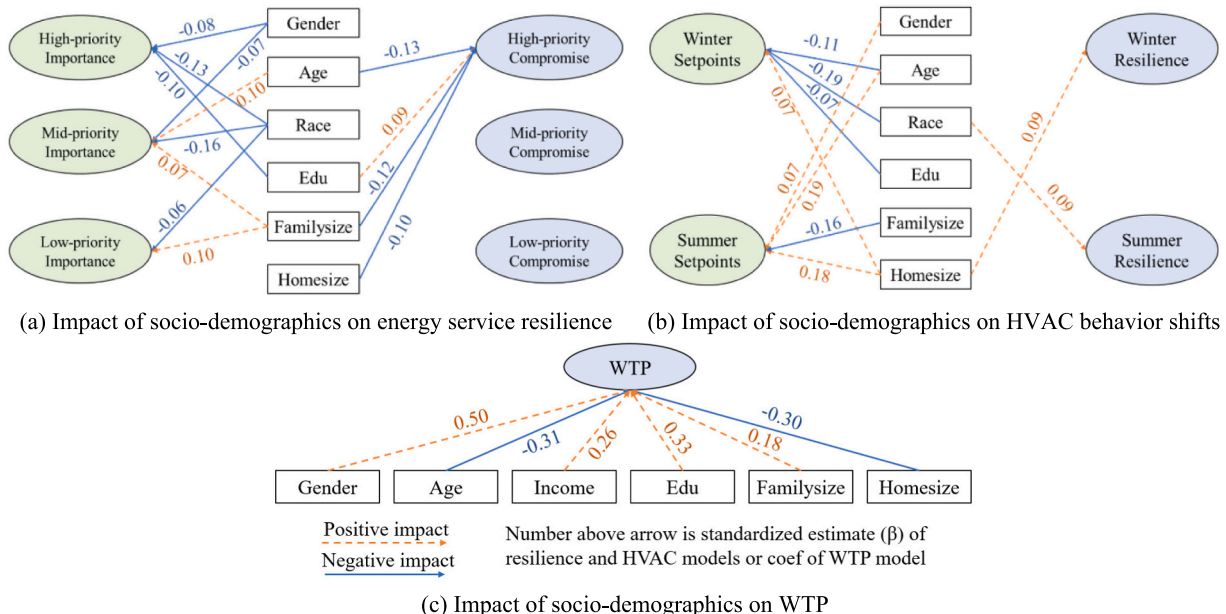


Fig. 11. The impacts of socio-demographics on the resilience of residential energy use.

to Table 5 and Table 7). The more pronounced influence of environmental factors has been substantiated by the findings of Ming et al. [95], which found that the impact of environment on thermal sensations and energy use is over psychological and behavioral factors. Also, previous disaster experiences, including extreme weather events and power outages, are critical factors. Previous disaster experience increases the reliance on energy services and the energy resilience of households, i.e., the potential to compromise distributed services, as well as the willingness to pay for increasing energy prices. Former studies have proved that occupants with disaster experience display more psychological preparedness to tolerate thermal discomfort [59,96]. The longer power outages increase the willingness to pay more for energy services [93].

Another critical influencing factor is clean energy and climate beliefs. Occupants with stronger climate beliefs or favoring clean energy rely less on energy services and have larger compromises during disasters. It can be explained by more energy-saving behaviors of those occupants [97,98]. Therefore, increasing the advocacy of climate change and clean energy is conducive to reducing energy consumption and dependency, further increasing household energy resilience.

6. Conclusions

This study analyzes household energy resilience during disasters, including compromise on general energy services, shift of HVAC behaviors, and willingness to pay for increasing energy prices. In disaster scenarios, importance ratings of energy services significantly decrease, albeit with diverse compromise levels. Based on the importance rating and compromise of services during disasters, 12 energy end-uses are investigated and classified into three categories: high, mid, and low-priority services. High-priority cluster, characterized by the largest importance and minimum compromise during disasters, includes daily diet (food cooking and storage) and thermal comfort (space cooling and heating). Mid-priority services are water heating and lighting. In contrast, low-priority services, with the least importance and maximum compromise, involve entertainment and housework appliances, e.g., TV, laundry, and dishwasher, which can be postponed without causing substantial discomfort. Moreover, occupants show the willingness to shift HVAC use patterns to conserve energy in extreme weather events, i.e., adjusting HVAC setpoints and reducing running HVAC continuously. On average, HVAC setpoint decreases by 3.65 °F (2.03 °C) in winter and increases by 2.80 °F (1.56 °C) in summer. Additionally, roughly 60% of respondents are willing to pay for increasing energy prices, while only 13% are prepared to pay over double normal prices.

Then, we conclude the influencing factors of household energy resilience, i.e., the ability to withstand the disturbances of disasters, including socio-demographics, energy beliefs, and disaster experience. Disadvantaged populations (e.g., elderly and low-income groups) are vulnerable to disasters and have lower energy resilience. Elderly residents display a lower level of compromise on energy services and express limited willingness to pay for increasing energy prices during disaster scenarios. Similarly, low-income groups exhibit reluctance to pay higher energy prices than regular days. Non-white groups rely more on energy services and have less compromise on shifting space cooling setpoints, but we did not find gaps between races about WTP. Furthermore, occupants residing in larger houses are less compromised on high-priority services with weaker WTP for energy services, while larger family sizes are more dependent on adequate energy services with stronger WTP. Females are more reliant on high and low-priority energy services and are less willing to pay higher prices to maintain energy services. Additionally, higher education levels and stronger clean energy and climate beliefs reduce the importance ratings on energy services but increase the compromise on energy services. By contrast, disaster experiences (e.g., extreme hot/ cold and coincided power outages) increase the reliance on energy services.

However, there are limitations in this paper. The survey was only distributed among two areas in Texas. A nationwide study is needed to

further confirm the findings of regional and climate differences. Secondly, due to the difficulty in obtaining longitudinal field disaster data on energy use and HVAC behavior, this study adopts a survey as a subjective approach to collect occupants' perceptions of energy services and HVAC behaviors. Objective energy use data, such as HVAC setpoints and appliance use behaviors, are expected to explore household energy resilience. Nevertheless, this study still contributes to understanding household energy resilience (e.g., energy service compromise and HVAC behavior shift) during disasters with a high risk of power shortage or outages and related influencing factors. The findings facilitate the enlightenment for designing disaster preparedness plans and countermeasures to address weather-related threats and ensure reliable access to essential energy services, increasing household energy resilience.

CRedit authorship contribution statement

Biao Kuang: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Yangming Shi:** Writing – review & editing, Investigation. **Yuqing Hu:** Writing – review & editing. **Zhaoyun Zeng:** Writing – review & editing. **Jianli Chen:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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