

Investigation of the Importance of Residential Energy Services in Normal Days and Natural Disasters

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ABSTRACT

Natural disasters (e.g., winter storms, heat waves, and hurricanes) threaten residents' energy services due to associated limited power supply or even power outages. Maintaining the desired level of residential energy services is critical. However, it is still unclear about the importance of each energy service to residents during disasters and how these services differ from normal days. In this study, we developed and distributed a large-scale survey to Texas residents to investigate the perceived importance of different energy end-uses during normal and disaster situations. The results illustrate that during disasters, residents prefer reducing energy use but keeping the continuous power supply, and the importance ratings on all energy services have significantly decreased. Based on the degree of compromise, measured as the difference in perceived importance between normal days and disasters, residential energy services are classified into two categories: critical services (i.e., HVAC, cooking, refrigerator, and freezer) and noncritical services (e.g., lighting, water heater, TV, dishwasher, and laundry). Critical services are less likely to be compromised during disasters than noncritical services. Additionally, one-way ANOVA results illustrate that race, income, education level, family size, and climate and energy beliefs influence end-use importance and compromise. Generally, these factors have larger impacts on noncritical services and vary between normal or disaster situations. In particular, higher education levels or stronger climate and energy beliefs contribute to greater compromise on energy services. The findings fill in the gaps to understand the varied importance of different energy services during disasters and inform the improved design of energy supply schemes under climate change, increasing energy service resilience.

Keywords: Residential energy services, Natural disasters, Perceived importance, Compromise

INTRODUCTION

Natural disasters (e.g., winter storms, heat waves, and hurricanes) are often accompanied with limited power supply or unexpected power outages, threatening residents' energy use.

Around 65% of power disturbances between 2001 and 2014 in the United States (US) were due to natural disasters or severe weather (Folga et al., 2016). In 2022, there are 95 electric transmission outages caused by severe weather in the US, with over 8 million households affected (US DOE, 2022). Such negative impacts on households are worse in low-income countries (Doytch & Klein, 2018). Therefore, improving energy service resilience during disasters is necessary, which requires ensuring end-use service provisions (Tiwari et al., 2022).

Maintaining energy services can be achieved from the generation side to restore the energy network and from the demand side to match the energy supply by demand response (Wang et al., 2017). Demand response aims to better balance the energy demand and supply by reducing or shifting the energy usage during peak periods or when energy system reliability is jeopardized (Paterakis et al., 2017). Residential buildings consume energy to provide various end-use services, including space heating, air conditioning, water heating, and appliances (e.g., cooking, lighting, and refrigerator) (Fell, 2017). Considering the limited energy supply in most disaster situations (Castillo, 2014), the prerequisite for resilient energy provisions is understanding what residents need and how much they can compromise for each end-use during disasters; however, this is still unclear. Therefore, this paper aims to investigate and compare the importance of residential energy services to residents during normal and disaster situations.

LITERATURE REVIEW

Existing studies acknowledge the importance of improving the resilience of residential buildings during disasters, but they mostly focus on building designs and regulations, e.g., Miller (2015), rather than residents' energy demands. It is essential to ensure the provision of residential energy services, which are vulnerable to disasters due to limited energy supply. Soares et al. (2014) asserted that the energy demand response should consider residents' needs and preferences. To design the plans for demand response, Harold et al. (2019) conducted a discrete choice experiment to investigate residents' preferences on partial end-uses, including ovens, dishwashers, and laundry. Similarly, Kadavil et al. (2018) investigated users' preferences to give up certain energy services based on surveys to achieve economic or environmental benefits. However, these studies only focus on partial energy services during normal situations and ignore disaster situations.

Multiple factors affect residential energy consumption and conservation. The review of Frederiks et al. (2015) revealed that socio-demographics (e.g., age, income, family size, housing size) influence residential energy usage and behaviors. Besides, positive attitudes towards renewable energy sources and strong beliefs on climate change issues encourage more sustainable behavior (Sapci & Considine, 2014). However, less research investigates the impacts on residents' perceived importance of energy end-uses.

Overall, there is a lack of study on the residents' perceptions of energy end-use importance, especially during disasters. The factors influencing end-use importance and compromise to residents are also not fully explored.

METHODOLOGY

Data

An online survey was developed and distributed among Fort Worth and Dallas in Texas state, with 493 responses received. 6 are excluded in that their BMIs are outliers. Also, two more are excluded due to being homeless or living motel. Therefore, there are 485 valid responses in total.

Measurement

End-Use Perceived Importance and Compromise. Based on US Residential Energy Consumption Survey, 13 residential energy services are selected, including space heating, air conditioner, water heating, and lighting. A 5-point scale is used to rate the importance of each end-use in normal daily life and natural disasters separately, with “1” representing the least important and “5” representing the most important. End-use compromise is measured as the differences in rated importance between normal days and disasters.

Socio-demographics. Respondents’ demographics (e.g., gender, age, race) and housing characteristics (housing size) are selected and measured. Their measurement is shown in Table 1.

Table 1. 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.)
Income	1=Less than \$25,000, 2=\$25,000 to \$49,999, 3=\$50,000 to \$99,999, 4= More than \$100,000
Family size	1-4=family size being 1-4 respectively, 5=5 or more
Housing size	1=less than 1000 ft ² , 2=1000-1500 ft ² , 3=more than 1500 ft ²

Climate and Energy Beliefs. We used two questions to measure the climate and energy beliefs separately. For climate belief, we asked if they think “the number of climate disasters (e.g., snow storms, hurricanes, wildfires, floods) has decreased (denoted as -1), stayed the same (0), or increased (1) in the past 30 years”. The higher value means stronger climate beliefs. Then, respondents were asked to choose which energy sources they favor expanding in our country, including gas, nuclear, coal, wind, and solar, among which solar and wind are clean energy. Each energy source is dummy coded, with 1 being favor this energy and 0 being not. Favoring expanding clean energy is considered a strong energy belief.

Statistical Analysis

This study compares and explores residents’ perceived importance of end-use services and influencing factors. First, a t-test examined the differences in end-use perceived importance between normal days and disasters. Then, based on their compromise, end-use services are further classified into critical and noncritical services. Finally, one-way Analysis of Variance (ANOVA) is used to analyze the impacts of socio-demographics and climate and energy beliefs on the rated importance and compromise of the two kinds of services.

RESULTS

Demographics

Among 485 valid respondents, there are 257 females and 228 males. Caucasian respondents account for around 65%. 43% of respondents lived in the community for over 15 years.

The distributions of respondents' age, education level, income, family size, and housing size are shown in Figure 1. Over 55-year-old respondents occupy 39%, twice as large as 25-34 and 35-44. 33% of respondents' education level is high school or below, followed by 29% with Bachelor. Over half of the households only have one or two persons. 30% and 33% of households' annual incomes are \$25,000-50,000 and \$50,000-100,000, respectively. Regarding housing, 31% and 59% live in apartments and single-family houses. 37% respondents' house sizes are 1000-1500 ft², while 22% are less than 1000 ft².

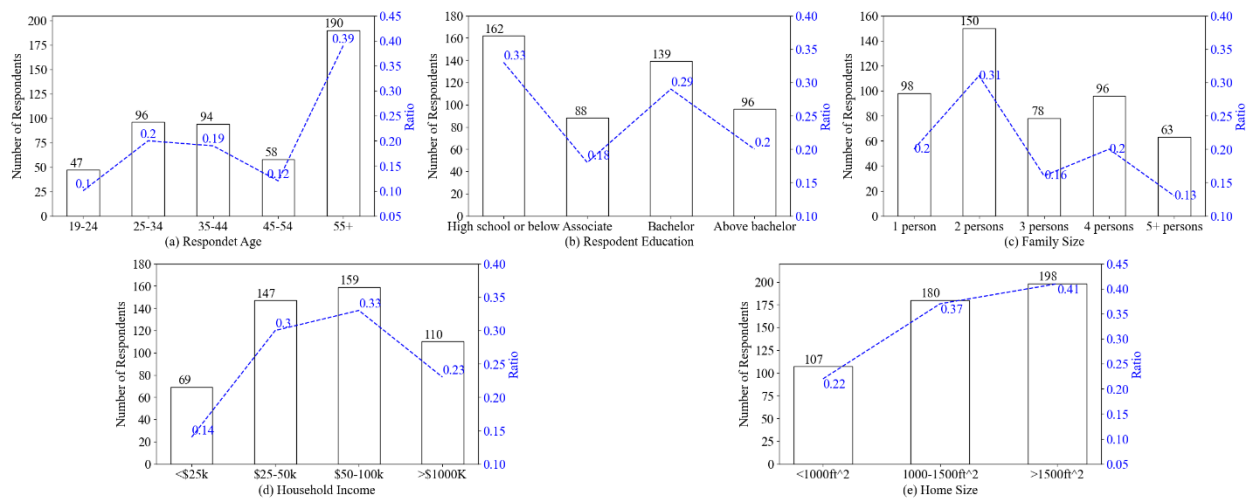


Figure 1. Distribution of Socio-Demographic Indicators

Differences in End-Use Rated Importance

Table 2 and Figure 2 show the t-test results and comparisons of end-use perceived importance between disasters and normal days. Air conditioner and refrigerator are the two most important services during normal days and disasters, with ratings over 4 out of 5. Water heaters, 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 in disaster. In addition, electric vehicles (EVs) have the lowest average importance due to only 61 respondents with Evs. If we only considered the 61 respondents with EV, the rated importance of Evs in normal days and disasters are 3.79 (standard deviation [SD] =1.20) and 3.52 (SD=1.49) on average, respectively. The mean difference is 0.28 and not statistically significant (p-value = 0.26).

Generally, all residential services show the potential to compromise during disasters. The descriptive analysis demonstrates that for energy supply during disaster situations, 395 respondents (81%) prefer to reduce energy use but keep the continuous power supply, while only 90 are willing to follow rotational power outages. The t-test results illustrate significant differences in the rated importance of all end-use between normal days and disasters (p-value<0.05). The mean differences and change percentages related to normal days are calculated to measure the compromise of each energy service. The importance of laundry (i.e., clothes washer and dryer) has the largest decline during disasters by over 1 (out of 5), with relative compromises of around 30%, followed by TV and dishwasher. The decreases in residents' rated

importance of water heating, lighting, and fan are over 0.7 (relative changes over 15%). On the contrary, the compromises of other end-uses are less than 0.5, with space heating being the least.

Table 2. T-test Results of End-Use Perceived Importance and Compromise

End-use	Normal		Disaster		T-test		Compromise	
	Mean	SD	Mean	SD	T	p-value	Dif. Mean ¹	Relative change ²
Space Heating	3.68	1.28	3.51	1.27	2.07	0.039	0.17	4.6%
Electric Vehicle	1.96	1.32	1.78	1.32	2.16	0.031	0.18	9.3%
Freezer	3.82	1.20	3.53	1.34	3.58	<0.001	0.29	7.7%
Refrigerator	4.40	0.86	4.01	1.02	6.48	<0.001	0.39	8.9%
Air conditioner	4.51	0.83	4.07	1.14	6.86	<0.001	0.44	9.8%
Cooking	4.14	0.98	3.66	1.15	7.07	<0.001	0.48	11.7%
Water Heating	4.17	0.88	3.46	1.18	10.62	<0.001	0.71	17.0%
Fan	3.19	1.30	2.48	1.41	8.18	<0.001	0.71	22.3%
Lighting	4.10	0.99	3.32	1.27	10.66	<0.001	0.78	19.0%
Dishwasher	2.89	1.37	2.06	1.30	9.73	<0.001	0.83	28.8%
TV	3.50	1.19	2.56	1.36	11.40	<0.001	0.94	26.8%
Cloth dryer	3.54	1.14	2.45	1.34	13.66	<0.001	1.09	30.8%
Cloth wash	3.83	1.09	2.70	1.34	14.40	<0.001	1.13	29.5%

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

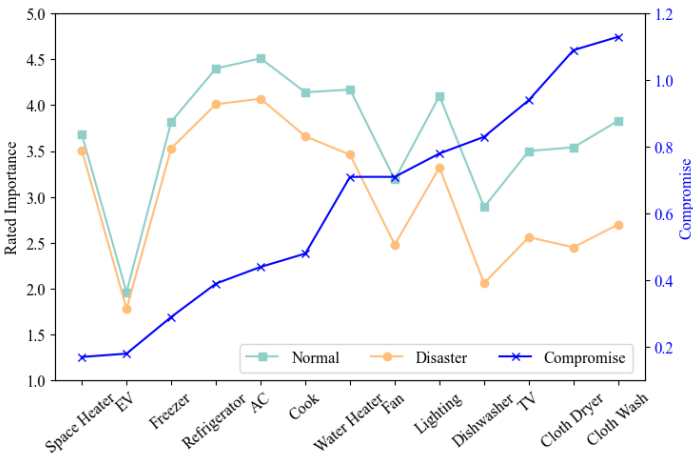


Figure 2. Difference in End-Use Perceived Importance Between Disasters and Normal Days

Furthermore, based on the differences in perceived importance, we classify the end-uses into two categories, which are consistent with the results obtained by the hierarchical clustering: (1) noncritical services, i.e., water heating, fan, lighting, dishwasher, TV, cloth dryer, and cloth washer; (2) critical services: space heating, air conditioner, cooking, freezer, and refrigerator. As the electric vehicle does not apply to all respondents, it is excluded from future analysis. The critical services reflect the demands regarding thermal comfort and sustenance, with averaging compromise of 0.36. In contrast, noncritical energy services include entertainment appliances

(e.g., TV) and some appliances that can replace or assist people's housework (e.g., laundry and dishwasher) and have a higher average compromise, around 0.88.

Influencing Factors of End-Use Importance and Compromise

One-way ANOVA was employed to examine the impact of socio-demographics and climate and energy beliefs on end-use perceived importance and compromise. The results are shown in Table 3, and the corresponding results of the post-hoc tests for significant factors are shown in Table 4.

Table 3. ANOVA Test for End-Use Importance and Compromise

Dependent	Factors	Normal		Disaster		Compromise	
		F	p-value	F	p-value	F	p-value
Critical	Age	1.587	0.177	0.338	0.853	1.174	0.321
	Race	9.584	0.002**	5.599	0.018*	0.120	0.729
	Gender	3.035	0.082	3.961	0.047*	0.379	0.538
	Income	4.595	0.003**	1.649	0.177	0.820	0.483
	Education	1.628	0.182	3.286	0.021*	0.871	0.456
	FamilySize	0.691	0.598	2.243	0.063	1.814	0.125
	HomeSize	1.485	0.228	0.298	0.742	4.000	0.019*
	Climate	2.191	0.113	0.266	0.767	1.679	0.188
	Gas	1.732	0.189	4.487	0.035*	1.510	0.220
	Solar	0.967	0.326	2.508	0.114	9.342	0.002**
	Wind	2.467	0.117	0.107	0.743	4.404	0.036*
Noncritical	Age	0.515	0.725	0.793	0.530	0.220	0.927
	Race	5.408	0.020*	7.601	0.006**	1.461	0.227
	Gender	1.329	0.249	0.035	0.851	1.632	0.202
	Income	2.715	0.044*	1.350	0.257	0.910	0.436
	Education	0.074	0.974	3.796	0.010*	4.981	0.002**
	FamilySize	2.099	0.080	4.840	0.001**	2.215	0.066
	HomeSize	0.493	0.611	0.327	0.721	0.372	0.690
	Climate	0.344	0.709	3.551	0.029*	7.872	<0.001**
	Gas	8.479	0.004**	3.879	0.049*	0.064	0.801
	Solar	1.217	0.271	28.638	<0.001**	29.725	<0.001**
	Wind	2.389	0.123	40.368	<0.001**	38.697	<0.001**

Notes: *statistically significant result at the 0.05 level;

** statistically significant result at the 0.01 level

Significant differences exist in the rated importance of critical and noncritical services between different races. The post-hoc tests illustrate that Caucasian rate end-use importance lower than other races ($p < 0.05$) during disasters and normal days. Income has significant impacts on the end-use importance only on normal days. Respondents with higher household income rate lower for critical services but higher for noncritical services. Also, education and family size contribute to the rated importance only in disasters. Households with larger family sizes report higher importance to noncritical services, while residents with higher education levels perceive lower importance of end-use. In addition, respondents with stronger climate and energy beliefs (preferring clean energy, i.e., solar and wind) rate lower importance on energy services. The impacts of energy beliefs are more obvious for noncritical services during disasters, with the

group differences around 0.5. Contradictorily, we did not find the influences of age and housing size on the rated importance of energy services.

In terms of the end-use compromise during disasters, households with larger housing sizes are less likely to compromise in critical services, while the difference in noncritical services is not significant. Respondents with higher education have a larger potential to sacrifice noncritical services during disasters. The influences of other socio-demographics (e.g., race, household income, gender) are not found. Furthermore, those occupants who prefer clean energy or have stronger climate beliefs are more willing to compromise for critical and noncritical services, but the decrease of importance in noncritical services is larger than the critical, with over 0.4 for noncritical and around 0.15 for critical services.

Table 4. Post-hoc Results of Impacts on End-use Importance and Compromise*

Service		Factors	G1	G2	Dif.	p	Service		Factor	G1	G2	Dif.	p
Normal	Critical	Race	0	1	-0.19	<0.01	Disaster	Noncritical	FamilySize	2	4	0.48	<0.01
		Income	2	4	-0.29	<0.01			Climate	-1	1	-0.49	0.03
			3	4	-0.2	0.05			Gas	0	1	0.19	0.05
	Noncritical	Race	0	1	-0.16	0.02			Solar	0	1	-0.49	<0.01
		Income	1	2	0.31	0.02			Wind	0	1	-0.56	<0.01
		Gas	0	1	0.21	<0.01							
Disaster	Critical	Race	0	1	-0.17	0.02	Compromise	Critical	Homesize	1	3	-0.2	0.01
		Gender	0	1	-0.14	0.05			Solar	0	1	0.17	<0.01
		Education	1	4	-0.25	0.04			Wind	0	1	0.11	0.04
		Gas	0	1	0.15	0.03							
	Noncritical	Race	0	1	-0.26	0.01		Noncritical	Education	1	2	0.32	0.01
		Education	1	2	-0.35	0.04			Solar	0	1	0.41	<0.01
		FamilySize	1	3	-0.32	0.03			Wind	0	1	0.45	<0.01
									Climate	-1	0	0.41	0.04
										-1	1	0.58	<0.01

Notes: * only significant results ($p < 0.05$) are reported.

Abbreviations: G1: group 1, G2: group 2, Dif: Mean difference = mean of G2 - mean of G1

DISCUSSIONS

Our study found that more residents prefer reducing energy use but keeping a continuous power supply than rotational power outages during disasters with limited energy supply. 12 surveyed household energy services (EV is excluded) show different degrees of potential to be compromised during disasters and are classified into critical and noncritical services. This classification is similar to Soares et al. (2014), which considers laundry, dishwasher, and water heaters as shiftable loads (i.e., noncritical services in this study) since they can be postponed but not bring discomfort. In contrast, critical services, related to food cooking and storage (refrigerator and freezer) and thermal comfort (space heating and cooling), should be given priority during disasters. Compared with Harold et al. (2019) and Kadavil et al. (2018), disaster scenarios and more energy services are included and examined in our study.

We also concluded that different resident groups have varying perceptions of importance and compromise on end-uses during disasters. The variations in critical services between different resident groups are smaller than in noncritical services. Households with larger family sizes have stronger demands on noncritical services. Similarly, larger home size shows less compromise on critical services. Besides, residents with higher education levels are more willing to sacrifice

energy services during disasters. These impacts and differences among resident groups should be incorporated into the design of demand response schemes for energy supply.

Additionally, this study confirms the impact of environmental attitudes on energy usage (Sapei & Considine, 2014), from the perspective of residents' perceived importance. Stronger climate and energy beliefs contribute to greater compromise on end-uses and lower ratings on end-use importance. Therefore, increasing the advocacy of climate change and clean energy is conducive to reducing energy consumption and dependency, further increasing energy service resilience.

CONCLUSIONS

This study investigates how residential energy services vary in perceived importance between normal and disaster situations and what factors contribute to the differences. First, occupants are willing to reduce energy use but keep a continuous power supply during disasters, and their importance perceptions on energy services are significantly decreased. Based on the compromise, these services were classified into two classes: critical services (i.e., HVAC, cooking, refrigerator, and freezer) and noncritical services (e.g., lighting, water heater, TV, dishwasher, and laundry). Critical services have less potential to be compromised during disasters than noncritical services. In addition, one-way ANOVA identified some influencing factors on end-use perceived importance, including race, income, education level, family size, and climate and energy beliefs. The influencing factors on the importance of critical and noncritical services vary in normal or disaster situations. Households with larger family sizes have stronger demands on energy services, especially during disasters. Furthermore, residents having higher education levels or stronger climate and energy beliefs are more likely to sacrifice energy services during disasters, reporting lower importance ratings and greater compromise.

However, there are limitations. The survey was only distributed among two cities. A nationwide study is needed to explore other impacts, e.g., regional differences. Secondly, although some influencing factors have been identified, how these factors affect end-use importance and compromise is unclear. Further quantitative models are needed to explore these impacts. Nevertheless, this study still contributes to theory and practices in residential energy end-uses. The paper fills in the gaps to understand the varied importance of different categories of energy services. The findings contribute to the enlightenment for the improved design of resilient buildings and energy demand response schemes under climate change, further increasing energy service resilience.

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