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Estimating what US residential customers are willing to pay for resilience to large electricity outages of long duration

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Climate-induced extreme weather events, as well as other natural and human-caused disasters, have the potential to increase the duration and frequency of large power outages. Resilience, in the form of supplying a small amount of power to homes and communities, can mitigate outage consequences by sustaining critical electricity-dependent services. Public decisions about investing in resilience depend, in part, on how much residential customers value those critical services. Here we develop a method to estimate residential willingness-to-pay for back-up electricity services in the event of a large 10-day blackout during very cold winter weather, and then survey a sample of 483 residential customers across northeast USA using that method. Respondents were willing to pay US\$1.7–2.3 kWh^{-1} to sustain private demands and US\$19–29 day^{-1} to support their communities. Previous experience with long-duration outages and the framing of the cause of the outage (natural or human-caused) did not affect willingness-to-pay.

Electric power outages cause losses in time, material and productivity for individuals, households, businesses, governments and society. Most power outages are short and local, but large outages of long duration (LLD outages) occur more often than expected and result in considerable disruption, economic cost and social harm[1]. Although preventing blackouts altogether is infeasible, new technologies, such as islanded microgrids, make it possible to provide limited emergency back-up power to sustain critical services[2,3]. Society's willingness-to-pay (WTP) to assure that some power remains available during LLD outages should be a key input to determine how much, if any, investment in such resilient systems is socially justified.

For many years, distribution utilities in the USA have conducted studies of the value that customers place on reliable electric services[4,5]. However, the elicitation methods used in prior studies cannot address key issues relevant to estimating the cost of LLD outages to residential customers: (1) they have not ensured that respondents fully understand the implications of outages (where few people have experienced or thought much about LLD outages), (2) they focused on brief outages that last only a few hours and (3) they did not consider partial back-up service even though there exists a considerable amount of consumer surplus for small amounts of electricity (see Supplementary Discussion for more details)[6]. Hence, methods and results from these studies are not adequate to assess how much individuals or society might be willing to invest to partially mitigate LLD outages.

In this study, we developed and employed a new elicitation procedure to estimate how much residential customers are willing to pay to become more resilient to a 10-day blackout during very cold winter weather. We elicited private and social preferences for electricity back-up services from a sample of 483 residents across the northeastern USA. Using our elicitation approach, we tested three threats to quantify values for LLD outages and found that: (1) previous experience with long-duration outages was not required for people to express precise preferences, (2) individuals place significant value on promoting a resilient society (US\$19–29 day^{-1} to directly and indirectly support their communities) above and beyond their own needs (US\$1.7–2.3 kWh^{-1}) and (3) a subtle, but inconsequential, framing of the outage as human versus naturally caused did not elicit different WTP, on average, when the outage consequences were held constant. The approach provides a method to elicit preferences for LLD outages as well as specific results that can serve as a key input to resilience investment decision-making problems.

Research hypothesis and rationale

A key policy question is whether those without LLD-outage experience can express their preferences over these rare events. Individuals who have not experienced LLD outages may be unsure about the consequences of the outages and their ability to mitigate those consequences, which results in imprecisely expressed preferences. This is consistent with prior work that found WTP estimates exhibit a considerable amount of uncertainty if respondents are not familiar with the objects or situations for which they are asked to express their preferences[7]. Although most people who have not experienced LLD outages will probably have imprecise preferences[8], individuals who have experienced LLD outages may have more clarity in their desire to avoid the consequences of LLD outages[9]. Previous studies of disaster experience suggest that respondents with a higher level of disaster experience perceive greater risks[9–11], but that having more experience does not always lead to action, such as increased personal disaster preparedness levels[12–15]. Related work suggests that WTP for risk prevention increases with income, individual preparedness levels and previous experience and that the preparedness gap between households with and without previous experience is mediated by education[16,17]. Providing information to those who have not experienced LLD outages might improve their ability to understand and express their preferences for mitigating LLD-outage impacts by reducing their uncertainty[6]. However, there is mixed evidence across the social sciences about whether providing

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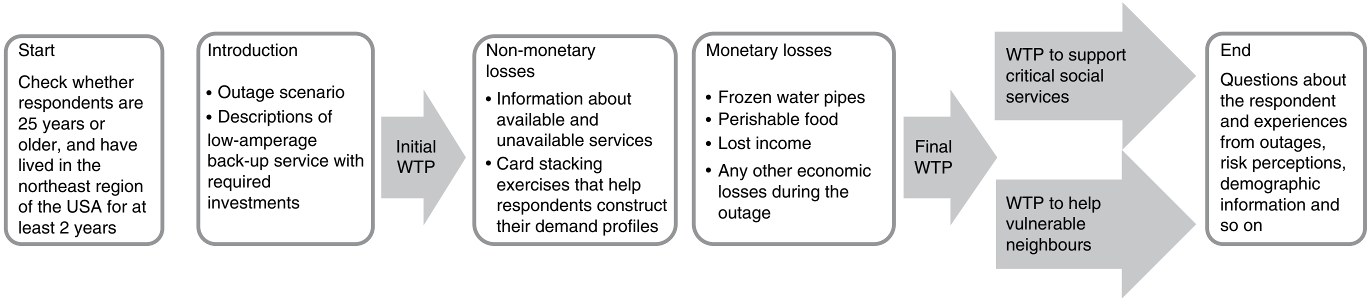

Fig. 1 | Overview of the web-based elicitation survey. The white boxes indicate information provided to the respondents. Grey arrows indicate the timing of the private and social WTP questions. The order of social WTP questions was randomized across respondents.

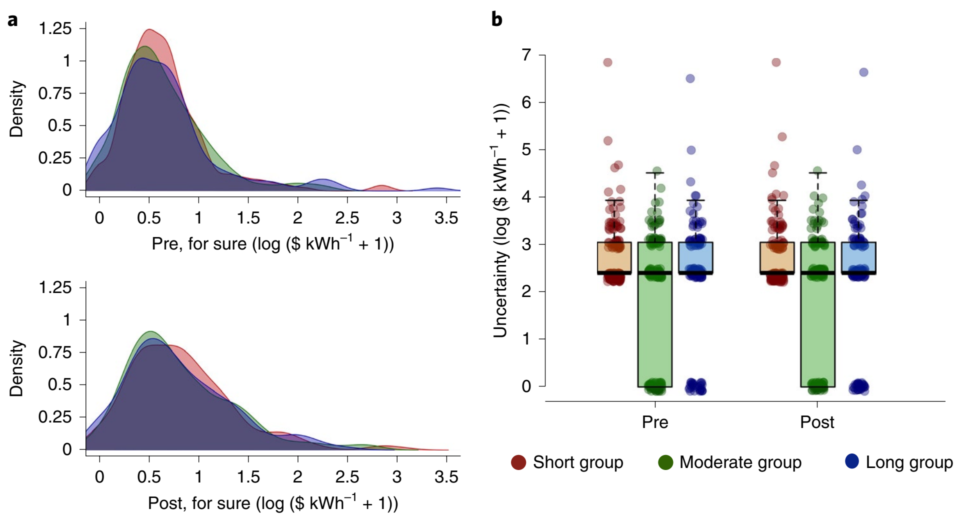

Fig. 2 | Distributions of the respondents' preferences to sustain their critical electricity-dependent demands and their preference uncertainty, separated by their previous longest outage experiences. a, Density plots showing the distributions of the three outage groups' log-transformed value per kWh to serve their own critical demands before (top) and after (bottom) the information was provided. The distributions largely overlap each other and show a similar increase after receiving more information. **b**, Distributions of the three outage groups' log-transformed preference uncertainty to serve their own critical electricity-dependent demands before (left) and after (right) the information was provided. The average preference uncertainty was not significantly different across the groups, both before and after the information was provided. Red, short group; green, moderate group; blue, long group. Boxplots show the median, interquartile range and whiskers at up to 1.5 times the interquartile range. Three respondents with very small kWh consumption were removed in the calculations. See Supplementary Data for the raw results.

information changes behaviour[18–20] and how people's stated WTP relates to their actual WTP[21,22].

As prior research found inconsistent results with respect to average WTP (and also did not measure preference uncertainty), we explored whether there is a preference gap between those who have and those who have not experienced LLD outages and, if so, whether to help respondents without prior disaster experience understand the consequences of LLD outages can close the potential gap. This leads to our first pair of hypotheses (H1a/H1b) that, compared with respondents who have not experienced LLD outages or have only experienced brief outages, respondents who have experienced long-lasting outages will have a higher WTP for a low-amperage back-up service with less uncertainty at the beginning of survey, and that neither the uncertainty nor the average WTP for those with LLD-outage experience will change as they receive additional information about LLD outages, whereas the WTP for those without experience will increase, and uncertainty will decrease, with additional information.

Understanding private WTP is important to assess the value of a back-up service to residential customers, but public decision-making also requires an understanding of how much people will support critical social services, such as water and sewage for their community, as well as services for low-income members of their community. There is good reason to expect that private and social preferences are different. People may be less familiar with making public choices compared to individual choices[7]. Public choices also reveal views on social issues, such as moral and ethical values beyond individual utility maximization[23–25]. Disaster management studies found that individuals are willing to pay more taxes to improve community preparedness and willing to invest more in improving individual-level preparedness if there are sufficient financial incentives[26]. Yet, no studies have directly assessed individuals' social preferences for avoiding LLD outages. If individuals express WTP for their community through supporting critical social services or low-income household subsidies, policy analyses that simply sum individual WTP to meet private demands will underestimate the value that society places on resilient electric services during an LLD outage. This leads to our second hypothesis (H2) that respondents will be willing to pay to support critical social services and low-income households in their communities above and beyond their WTP for their own low-amperage backup service during an LLD outage.

Our third hypothesis focuses on the framing of the cause of the outage as either a natural or human-made cause. If the

Table 1 | Respondents' values (US$ kWh^{-1}) for critical electricity-dependent demands

		For sure				With uncertainty			
		Min	M	s.d.	Max	Min	M	s.d.	Max
Short group ($n=188$)	Pre-information	US$0	US$1.2	1.8	US$17	US$0	US$2.1	3.6	US$32
	Postinformation	US$0	US$1.8	2.4	US$20	US$0	US$2.4	3.3	US$32
Moderate group ($n=156$)	Pre-information	US$0	US$1.1	1.3	US$8.9	US$0	US$1.6	1.9	US$15
	Postinformation	US$0	US$1.7	2.2	US$14	US$0	US$2.3	3.3	US$33
Long group ($n=136$)	Pre-information	US$0	US$1.4	2.9	US$29	US$0	US$2.2	3.9	US$32
	Postinformation	US$0	US$1.6	1.8	US$11	US$0	US$2.5	3.4	US$32

For-sure and with-uncertainty values to serve the respondents' critical electricity-dependent demands, separated by their previous longest outage experience. For-sure values indicate the maximum amounts that individuals would surely commit in exchange for the back-up service. With-uncertainty values indicate the minimum amounts above which they would surely not commit in exchange for the back-up service. We removed three respondents with very small kWh consumptions from the calculations (see Supplementary Data for the raw results).

consequences of two outages are the same, individuals should place the same value on avoiding them. Previous risk perception studies, however, found that many non-consequential factors can influence risk judgements[27–29]. Risk perception of human-made disasters can be explained by factors such as voluntariness and severity of consequences, whereas natural hazards also have an important novelty component[30]. Laypersons may feel more fear about terrorist attacks than about natural hazards because they are more difficult to predict, control and take precautionary measures against[31,32]. Although it is reasonable to assume that people perceive natural hazards and human-made disasters differently[31,33], no previous studies have directly compared individuals' preferences for risk reductions from natural hazards and from human-made disasters that result in identical consequences. This leads to our final hypothesis (H3) that respondents' WTP for resilient electric services during a LLD outage caused by a terrorist attack on the power system will be higher than that caused by a natural hazard.

Results

To estimate the economic and social value that residential customers place on resilient electric services during LLD outages, we developed and employed an elicitation approach based on prior work to ensure that respondents fully consider the various aspects of electricity-dependent services and consequences of the outages[6,7]. Our web-based survey framework walks respondents through a detailed description of an LLD outage and its consequences, helps them articulate their preferences and also allows a realistic expression of uncertainty, and then elicits their WTP to obtain a low-amperage resilient back-up service during the event. Figure 1 summarizes our elicitation design and more details are given in Methods and the Supplementary Method.

Prior experience with long outages is unrelated to WTP

To determine whether the preferences of respondents who have had prior experience with LLD outages are affected by providing more information about the blackout and its consequences, we divided respondents into three groups: the short group who had lost power for periods of less than one day or had never experienced any power outages, the moderate group who had experienced outages of 'several days' and the long group who had lost power for 'more than several days'. The mean value per kilowatt hour to sustain the critical electricity-dependent demands for the three groups after excluding three respondents who reported very small kilowatt hour consumption (which lead to an extraordinarily large value per kilowatt hour) were statistically similar at the beginning of the survey (two-sample Kolmogorov–Smirnov (KS) tests, all $P>0.05$ (Fig. 2a (top), Table 1, Supplementary Table 1 and Supplementary Data)), and all three groups significantly increased their value to sustain critical electricity-dependent demands as the survey progressed (paired Wilcoxon signed rank (WSR) tests, all $P<0.05$ (Fig. 2a (bottom), Table 1, Supplementary Table 2 and Supplementary Data)). The interaction effect between experience and pre-/postinformation with respect to the respondents' value per kilowatt hour was not statistically significant (linear regression, $F(2,477)=2.2$, $P=0.12$). The results are generally inconsistent with H1a and H1b, as respondents had similar WTP distributions regardless of the extent of their prior experience, and shifted their WTP distributions upward to the same degree as they went through the study.

Preference uncertainty after excluding the 30 respondents who reported a very high WTP (see above) also showed similar patterns. The three groups had statistically similar levels of preference uncertainty both at the beginning and at the end of the survey (two-sample KS tests all $P>0.05$ (Fig. 2b (left), Supplementary Table 3 and Supplementary Data)). Providing more information significantly decreased the preference uncertainty for the short group (from US$20 to US$14 day^{-1} on average, paired WSR test, $P<0.05$), whereas the other two groups had a slightly increased uncertainty (paired WSR tests both $P>0.05$ (Fig. 2b (right), Supplementary Table 4 and Supplementary Data)). The interaction effect between prior experience and pre-/postinformation with respect to the respondents' preference uncertainty was not statistically significant (linear regression, $F(2,426)=1.4$, $P=0.24$). Thus, the preference uncertainty results were mostly inconsistent with H1a and H1b.

Substantial WTP to support community resilience

To explore respondents' social preferences for resilience, and the relationship between their WTP for private and social demands, we first compared daily WTP results and found that respondents placed a significant value on supporting critical social services and helping low-income households above and beyond the WTP for their own back-up service (one-sample KS tests to check whether the WTP is significantly higher than US$0, both $P<0.05$ (Table 2)). Respondents' WTP to sustain their own demands barely correlated with the social preferences (Fig. 3a,b, Supplementary Table 5 and Supplementary Data), but their WTP values for indirectly and directly helping others in their communities were highly correlated with each other (Fig. 3c, Supplementary Table 5 and Supplementary Data). The results suggest that respondents were willing to pay for community resilience, and that social decisions stemmed from different concerns other than private decisions.

As respondents' preferences are related to income (see Supplementary Table 6 for a summary of the multiple linear regression analyses and Supplementary Data for the raw results), we further examined the relationship between their preferences and ability to pay. The lowest income group's WTP per day to sustain their own private demands was substantially lower than that of other income groups, but the WTP-per-day values for the other income groups

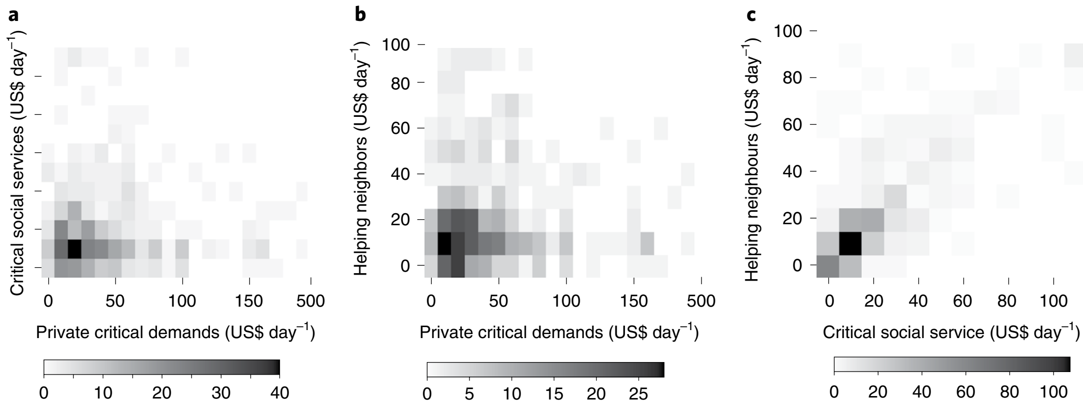

Fig. 3 | Heat-map representation of the respondents' WTP-per-day preferences for enhanced grid resilience. a, Heat map depicting the respondents' for-sure WTP per day to sustain their private critical demands after receiving additional information (*x* axis) across their for-sure WTP per day to sustain critical community social services (*y* axis). **b**, Heat map depicting the respondents' for-sure WTP per day to sustain their private critical demands after receiving additional information (*x* axis) across their for-sure WTP per day to support vulnerable neighbours in their communities (*y* axis). **c**, Heatmap depicting the respondents' for-sure WTP per day to sustain critical community social services (*x* axis) across their for-sure WTP per day to support vulnerable neighbours in their communities (*y* axis). Private and social WTP were nearly uncorrelated, but WTP for directly and indirectly helping other members of the community were highly correlated (see Supplementary Data for the raw results).

Table 2 | Summary of the respondents' WTP per day for private and social demands and correlation coefficients

	For sure				With uncertainty				Correlations		
	Min	M	s.d.	Max	Min	M	s.d.	Max	Private–social	Private–neighbour	Social–neighbour
Private demands, post (US$ day^{-1})	0	43	51	500	0	60	80	1,000	$\tau_{sure}=0.030$, $\tau_{uncertain}=0.033$	$\tau_{sure}=0.0033$, $\tau_{uncertain}=0.027$	$\tau_{sure}=0.64$, $\tau_{uncertain}=0.69$
Critical social services (US$ day^{-1})	0	19	20	100	0	28	25	100			
Helping neighbours (US$ day^{-1})	0	20	21	100	0	29	26	100			

Kendall rank correlation coefficients between the preferences. Respondents placed significant values on helping others (both directly and indirectly) above and beyond their own WTP to sustain their private electricity needs (see Supplementary Data for the raw results). Max, maximum; M, median; min, minimum.

were not significantly different in most cases (sixth row of Table 3). In the case of the WTP-per-day values to support respondents' communities, their preferences were similar across all income levels. However, dividing WTP-per-day values by the median annual household income bracket, which reflects the respondents' ability-to-pay, yielded quite different results. The fraction was inversely proportional to the respondents' income levels, which suggests that the lower-income groups were willing to pay significantly more as a fraction of their income than the higher-income groups (seventh row of Table 3). This result implies that the lower WTP-per-day values from the lowest income group were mainly due to income effects that mask a higher valuation of the services.

No relationship between outage cause and WTP

To test whether respondent preferences vary depending on the cause of the outage, we used a between-subjects design, in which the consequences of the blackout were held constant, but the cause of the outage was varied (terrorist attack versus solar storm). As shown in Fig. 4 and Supplementary Table 7, all but three respondents out of a total of 238 reported very similar WTP to sustain their own critical electricity-dependent demands in the earlier parts of the survey (US$1.2–1.3 kWh^{-1} for sure and US$1.9–2.0 kWh^{-1} with uncertainty on average) and the responses became more similar as the survey progressed (US$1.7 kWh^{-1} for sure and US$2.3–2.4 kWh^{-1} with uncertainty on average) except two respondents with a very high WTP (see Supplementary Data for the raw results). The two groups' preferences for supporting their communities were almost identical. To conclude, the results do not support H3 as preferences were not statistically different between the two identical outages caused by different events.

Discussion

Since the mid-1980s, electric utilities have conducted a number of studies to assess the customer costs of power outages that last a few hours and used these results to justify investments to achieve a desired level of reliability. Yet, as most respondents have limited familiarity with resilient electric services during LLD outages and studies have not included durations of more than 24 hours, these prior results have limited usefulness as inputs to policy decision-making for resilience to LLD outages. To elicit informed judgements about the economic and social value of mitigating LLD outages, we provided respondents with detailed information about 10-day LLD outages and then elicited their WTP to sustain critical private and social demands during the events.

Our results have three major implications. First, those with and without previous outage experiences were not different in their average WTP or preference uncertainty, and both groups seemed to learn about their preferences as they progressed through the task. A common criticism of value-elicitation studies holds that only those who have prior experience with rare events can express

Table 3 | Summary of respondents' private and social daily WTP (in dollars and as a proportion of annual household income)

		Income 1 (<US$17 K)	Income 2 (US$17–30 K)	Income 3 (US$30–46 K)	Income 4 (US$46–75 K)	Income 5 (US$75–148 K)	Income 6 (>US$148 K)
Number of respondents		29	51	63	138	147	55
Private (WTP per day, proportion of annual household income) (US$ day^{-1}, % day^{-1})		22, 0.26	37, 0.16	40, 0.10	37, 0.061	48, 0.043	69, 0.046
Social (WTP per day, proportion of annual household income) (US$ day^{-1}, % day^{-1})		14, 0.17	16, 0.067	17, 0.045	20, 0.033	21, 0.019	16, 0.011
Neighbour (WTP per day, proportion of annual household income) (US$ day^{-1}, % day^{-1})		17, 0.20	18, 0.078	17, 0.046	21, 0.035	22, 0.019	15, 0.010
Significantly different among the types of demands within the income level			Private–social, private–neighbour	Private–social, private–neighbour	Private–social, private–neighbour	Private–social, private–neighbour	Private–social, private–neighbour
Significantly different from higher income level group(s) without adjustment	Private	Incomes 3, 5, 6			Income 6		–
	Social						–
	Neighbour						–
Significantly different from higher income level group(s) after adjustment for income	Private	Incomes 2, 3, 4, 5, 6	Incomes 3, 4, 5, 6	Incomes 4, 5, 6	Incomes 5, 6		–
	Social	Incomes 2, 3, 4, 5, 6	Incomes 3, 4, 5, 6	Incomes 4, 5, 6	Incomes 5, 6	Income 6	–
	Neighbour	Incomes 2, 3, 4, 5, 6	Incomes 3, 4, 5, 6	Incomes 4, 5, 6	Incomes 5, 6	Income 6	–

Although the maximum for-sure WTP per day values to sustain their private critical electricity-dependent demands (after receiving additional information) increased slightly as household income increased, the proportions of the maximum for-sure WTP per day to the annual household income suggest that lower-income groups actually had stronger preferences for resilient electric services (see Supplementary Data for the raw results).

valid preferences over those events. In contrast, we found little to no difference in the distributions of WTP (and uncertainty in WTP) between those who had experienced severe multiday blackouts with others who had not.

Second, respondents were willing to pay to support their communities and low-income neighbours beyond what they would be willing to pay to sustain their private critical electricity-dependent demands, which indicates that the economic and societal value of a back-up service is substantially greater than the sum of the individual private values. Interestingly, respondents with lower household income levels indicated stronger preferences for both private and social back-up services in proportion to their income. Without further study, it is not possible to say how general this finding might be, but it suggests that to address equity issues, for example, by covering part of the system upgrade costs with progressive tax revenues or providing some form of subsidy proportional to individual wealth levels, may bring high value to society, especially for those in vulnerable segments of the population[3].

Third, respondents did not respond differently based on the cause of outages (human-made versus natural), reporting similar WTP at the beginning of the study, values that became more similar by the end. For the value of lost-load studies that construct customer-damage functions based on specific scenarios, this finding implies that researchers can focus more on consequential factors, such as the weather conditions during an outage, how long it takes to restore the power and levels of preparedness, rather than on inconsequential framing effects.

In this study, we focused on several key variables to define the outage scenario (outages fixed at 10-day duration, back-up coverage at 20 A and weather conditions below freezing). These estimates could be used in regional investment decision-making problems under these specified conditions (Baik et al.[3,34] are examples), but should not be generalized to investment decision-making that involves significantly different conditions. However, using the methods developed in this study, it is possible to construct context-specific customer-damage functions by conducting a series of studies across different scenarios. Results from such studies could help support decision-makers in high-risk regions who must decide between many possible upgrades to advanced distribution systems.

Finally, it is hard to directly compare the results of this study to estimates reported in other studies because each study has used different, and in many cases much shorter, outage scenarios, study designs, elicitation techniques and underlying assumptions. We note, however, that the estimated values per kilowatt hour from our study (median US$1.8 kWh^{-1} for sure and US$2.2 kWh^{-1} with uncertainty after providing additional information) are closer to the lower bound of the range reported in previous studies' estimates (from US$1.3 per unserved kilowatt hour[35] to US$12 per unserved kilowatt hour[36,37] for outages that last longer than 16 hours). The main differences between our estimates and those of prior work are that we included residential customers only, accounted for their direct costs, made systematic efforts to help respondents fully understand the outages and their consequences, added checks for bias and consistency and allowed more realistic expressions of preference uncertainty. It is also important to note that the stated WTP estimated here is likely to overstate actual the WTP, which is consistent with prior study findings[21,22]. Although

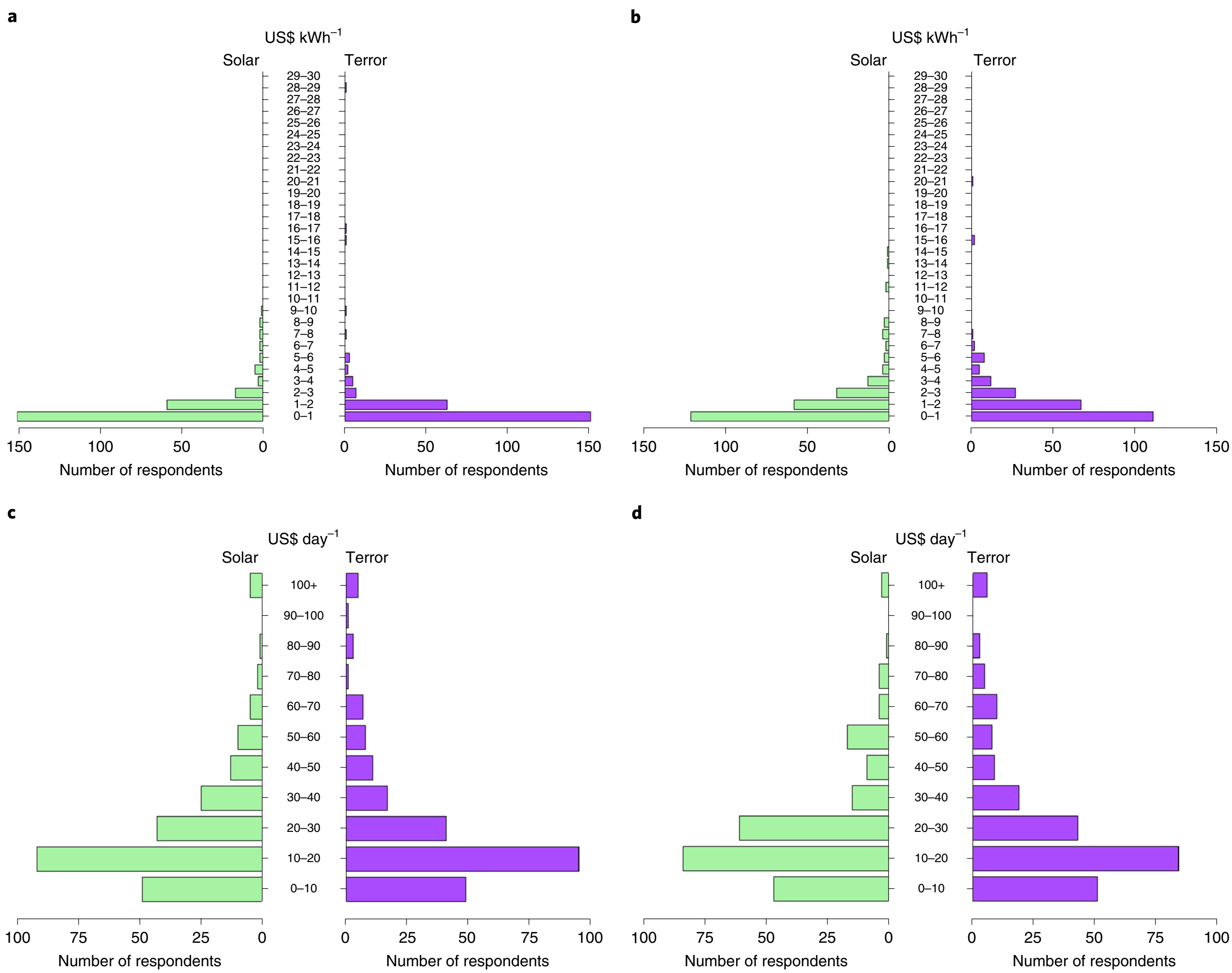

Fig. 4 | Pyramid diagram showing the respondents' preferences against LLD outages that occurred through two different causes. a–d, The value per kWh and WTP-per-day distributions before (**a**) and after (**b**) providing more information, and the maximum for-sure WTP per day to sustain critical social services (**c**) and help their vulnerable neighbours (**d**) were almost identical even though the hypothetical outages were caused by two different events, a large solar storm and distant terrorist attacks on the power system. In **a** and **b**, we removed three respondents whose electricity consumptions were very low and thus had exceptionally high value-per-kWh results (see Supplementary Data for the raw results).

the stated WTP is frequently higher than the actual WTP, the direct estimates of WTP will probably yield better estimates than those of indirect methods[22].

Conclusion

As residents in developed economies depend heavily on services provided by electricity, power outages have substantial economic and social impacts. Although society should increase the power-system resiliency at a reasonable cost, LLD outages cannot be avoided. To properly address the question "how much are individuals and society prepared to pay to improve resilience in the face of LLD outages?", we developed a generalizable web-based survey framework that helps decision-makers explore the value of resilient electric services under a variety of scenarios. Using the framework, we assessed residential customers' WTP to pay for resilient electric services during hypothetical 10-day LLD outages and obtained values of US\$1.7–2.3 kWh^{-1} to sustain their private demands and US\$19–29 day^{-1} to support their communities. Also, we analysed three threats to the validity of the elicited preferences and found that individuals are able to express their preferences even if they have not experienced long-duration outages, that they care about societal outcomes and that they are able to look past surface aspects of the outage to focus on the consequences that matter. The approach can help service providers, utilities, regulators and other relevant stakeholders improve the resilience of electric power systems in an equitable manner.

Methods

Elicitation format to assess the value of grid resilience. Many previous studies that elicited residential customers' stated preferences used contingent valuation or discrete-choice experiments. Contingent valuation asks respondents directly how much they are willing to pay to avoid hypothetical outages. For instance, studies that adopt the survey framework proposed by Sullivan and Keane[5] present several hypothetical outage scenarios that specify the duration, season and other attributes of the outage, and then ask respondents to state their WTP to avoid the outages. Although the method is direct and easy to understand, it is difficult to estimate marginal WTP for outage attributes (such as duration) and is susceptible to well-known biases (such as anchoring effects[38], scope sensitivity[39] and hypothetical bias[40]). In contrast, discrete-choice experiment studies estimate WTP for changes in attribute levels using a series of multi-alternative, multi-attribute choices. For instance, Morrissey et al.[41] used the choice experiment approach to estimate the value of continuous electricity supply among residential customers in northwest England, using a mixed logit model with duration, time of day, day of week, season and sociodemographic and household variables.

Although the discrete-choice approach is appealing because it can be used to estimate a multi-attribute utility function that can make predictions over new scenarios, we chose the contingent-valuation approach for the following six reasons: (1) discrete-choice methods assume individuals are certain about their preferences but make unsystematic errors in choice, an inappropriate representation for decision-makers who express substantial uncertainty for complex and unfamiliar alternatives (such as LLD outages)[6], (2) our prior work in eliciting WTP for LLD outages found that anchoring effects were not present using our elicitation method, whereas discrete-choice methods have known issues with context effects[42] and induce heuristic decision-making strategies to get through complex repetitive tasks[43,44], (3) testing the axioms of probabilistic discrete-choice models, such as a weak stochastic transitivity and the quadruple condition[45,46], requires prohibitive data collection efforts (many repeated pairwise comparisons), (4) discrete-choice methods require many repeated choices from respondents, which take time away from helping the respondents understand the time dynamics of the lost electricity-dependent services (outages with varying durations have very different consequences), (5) discrete-choice experiments often require unrealistic stimuli (for example, situations in which there are frozen water pipes but no water service because the two attributes must vary independently for the parameter estimation to work in choice models) and (6) when there exists a large heterogeneity across people in their WTP for resilient electric services due to different electricity use profiles, demographics and needs, heterogeneity is often poorly captured by traditional discrete-choice models, because heterogeneity is assumed to come from a set of known functions in the same parametric family (de la Maza et al.[47]). Instead of asking respondents to make many choices between hypothetical alternatives that systematically vary on a set of attributes, we chose the contingent valuation approach to help respondents understand the problem and think carefully about a single scenario.

It is important to note that both discrete-choice experiments and contingent-valuation methods suffer from a potential hypothetical bias; prior work finds that respondents, on average, overstate their WTP by about 20% (ref. [22]). However, there is little evidence that hypothetical bias is lower for discrete-choice experiments than for contingent-valuation methods. Previous studies that compared estimates from contingent-valuation methods and discrete-choice experiments found mixed results (for instance, Boxall et al.[48] report that values elicited by choice experiments are larger than those elicited by contingent valuation, whereas Mogas et al.[49] report the opposite result and Foster and Mourato[50] and Jin et al.[51] suggest that the confidence intervals from choice experiments overlap with those of contingent-valuation studies). In addition, a recent review by Schmidt and Bijmolt[22] suggests that values elicited using indirect methods (discrete-choice methods) overestimate more than direct methods (contingent valuation). One consistent result is that more carefully designed studies provide more valid and reliable results[52]. In addition, study estimates may also be adjusted ex-post by using the ratios of hypothetical to actual stated values from meta-analysis studies (for instance, Schmidt and Bijmolt[22], List and Gallet[53] and Murphy et al.[21]).

In this study, we used a multiple bounded discrete choice (MBDC) elicitation format. This approach asks respondents whether they would definitely, maybe or definitely not pay for back-up service at an increasing sequence of prices (Supplementary Fig. 1)[54,55,56]. If respondents hit the upper bound of the prices, they were then asked an open-ended question about their WTP. Our prior work found that the approach adheres to a number of important consistency criteria (a higher WTP for more service, a WTP greater than the market price of electricity) and is not susceptible to anchoring effects (see Baik et al.[6] for more discussions about traditional contingent-valuation techniques and the benefits and limitations of MBDC). We denoted the for-sure amount as the amount at which respondents switch from definitely willing to pay to maybe willing to pay (US\$19.99 day^{-1} in Supplementary Fig. 1). We denoted 'with uncertainty' as the amount at which respondents switch from maybe willing to pay to definitely not (US\$49.99 day^{-1} in Supplementary Fig. 1). Once respondents indicate their for-sure and with-uncertainty WTP, the blue box in Supplementary Fig 1 comes up to make sure that they understand the concept of total payment (in this case, the respondent needs to pay up to US\$200 for sure but no more than US\$500 for the 10-day limited emergency back-up service).

Experimental design and web-based survey design. To address the shortcomings of the previous value of lost-load studies and obtain the judgements of individuals about their economic and social preferences for a low-amperage back-up service for enhanced grid resilience in the event of LLD outages, we developed a web-based preference-elicitation platform. We modified our earlier design that was used in face-to-face interviews[4] and completed multiple rounds of pilot testing[57]. The elicitation framework is designed to help individuals think systematically about the value they attach to resilient electric services by employing detailed and realistic blackout scenarios, questions about private and social WTP using MBDC questions with follow-up checks, information regarding inconvenience and economic losses, and a check for consistency. A more detailed summary of the sequence of the web-based survey is provided in Supplementary Fig. 2.

In the survey, half of the respondents were randomly assigned to an outage scenario that had been caused by a terrorist attack, and the other half to the outage scenario that had been caused by a solar storm. These two initiating events were selected because: (1) they could cause essentially identical major disruptions to the bulk power system without damaging distribution circuits, and thus allow utilities to provide a low-amperage back-up service with modest system upgrades and (2) although there have been some efforts to mitigate the risks posed by these emerging threats, none have explored individuals' WTP to avoid such events. In both cases, respondents were told that this event had damaged a number of critical high-voltage transformers and caused a 10-day LLD outage across the northeastern USA, midwestern USA and southeastern Canada during a period of very cold winter weather. Respondents were then told that federal and state governments had declared a state of emergency so that severely ill or injured patients or residents with disabilities could be immediately evacuated and that essential commodities would be distributed within few days (that is, there is no serious risk of death).

During the survey, we used MBDC with follow-up checks and open-ended questions to elicit respondents' preferences for private and social back-up services three times: (1) right after introducing the scenarios and private back-up service (first grey arrow in Fig. 1), (2) after providing more information about non-monetary and monetary losses that respondents may suffer during the LLD outages (second grey arrow in Fig. 1) and (3) after introducing two different methods that directly and indirectly support their communities (and grey arrows in Fig. 1). For the private back-up service, we offered 20 A for individual houses, which could support the use of a refrigerator, a freezer, a few lights and a furnace pump or blower at the same time. For the social back-up service, we offered a full back-up service for a predetermined set of critical social services that do not have their own emergency back-up generators and do not store enough fuel to cover a 10-day outage (police and fire departments, water and sewage treatment service, and traffic lights at important intersections).

After the final value elicitations, the survey finished with questions that asked respondents about their experiences from previous outages as well as demographic information, such as household income brackets, levels of risk mitigation and the durations of the longest power outages they have ever experienced. More details about the survey elicitation design, hypothetical outage scenarios, information and exercises we provided, as well as technical details, can be found in Supplementary Methods and Baik et al.[58], and actual survey framework and scripts can be found at Supplementary Notes 1.

Data. Using our web-based elicitation framework, we conducted three rounds of surveys with residents from the northeastern USA, with each round of respondents recruited in three different ways. The first round of surveys included respondents recruited through Amazon Mechanical Turk in early January 2018 (204 respondents), the second round of surveys with randomly selected northeastern residents through address-based sampling was conducted between February and March 2018 (74 respondents among 1,872 selected residents; response rate 4.0%)[59] and the third round of surveys with Turkprime research panels was conducted in early December 2018 (205 respondents). The respondents were required to be 25 years old or older, have lived in the northeast USA region (which includes Connecticut, New Hampshire, New Jersey, New York, Maine, Massachusetts, Pennsylvania, Rhode Island and/or Vermont) for at least two years and be aware of their electricity bills. In the case of Hurricane Sandy samples, we also added zip-code eligibility constraints (they must have lived in one of the 16 zip-code regions that were heavily affected by Hurricane Sandy). Supplementary Notes 2 contain more details about the recruitment strategies and a summary of the demographic information.

Statistical information. *WTP-per-day calculation.* We used MBDC to elicit respondents' WTP per day for the limited back-up service using the MBDC method. For each question, respondents were asked to indicate their maximum for-sure WTP (the upper limit from the 'yes' column) and maximum with-uncertainty WTP (the upper limit from the not-sure column). For some respondents whose WTP was very high and marked the entire yes column, we elicited their maximum for-sure WTP using follow-up open-ended questions. Supplementary Note 1 gives the actual WTP questions we used in this study.

Value-per-kWh calculation. During the survey, we asked respondents to select the critical electricity-dependent appliances they wanted to use during morning, mid-day, evening and late night. Using the data, we roughly calculated their power consumption within the 20 A limit and divided the maximum for-sure and with-uncertainty WTP for the back-up service by the amount of power consumed. In value-per-kWh statistical comparisons, we excluded three respondents who only wanted to use appliances operated by gas and thus had an electricity consumption per day of less than 1 kWh (the average electricity consumption in our sample was 30 kWh day^{-1}). However, we added a summary of the respondents' value per kWh without excluding anyone in the Supplementary information (Supplementary Table 8 for the comparisons between the outage experience groups and Supplementary Table 9 for the comparisons between the different outage causes).

Preference uncertainty calculation. To calculate the respondents' range of uncertainty, we assessed the difference between the upper limit of the not-sure column and the yes column, and then compared the results before and after providing more information and exercises (a graphical representation is given in Baik et al.[3]). In this analysis, we excluded 30 respondents whose WTP per day for the back-up service was very high (marking the entire yes column) and specified their maximum WTP per day because we were not able to obtain their ranges of uncertainty in at least one of the stages (as we were only able to assess their maximum sure WTP per day, but not their maximum not-sure WTP per day). Of the respondents, 8 had very high preferences throughout the study, 2 had a very high preference in the beginning but decreased their WTP as the survey progressed and 20 became very interested in the back-up service as they received information and exercises.

Hypotheses testing. Before we compared the elicited preferences, we first conducted Box–Cox analyses. The results suggest a log transformation for both WTP-per-day and value-per-kWh results after adding 1.

For comparisons between respondents with different outage experiences (that is, to test H1a and H1b), we used two-sample KS tests to compare pairs of independent empirical cumulative distribution functions, and report the largest differences between the two empirical cumulative distribution functions (KS D statistics; Supplementary Tables 1 and 3)[60]. We also compared the respondents' preferences for the value of resilient electric services and their preference uncertainty within each group using paired WSR tests, and reported the statistic V which describes the smaller of the sum of positive signed ranks and the sum of the negative signed ranks, and Cohen's D, which calculates the effect size based on standardized mean differences between the two populations (Supplementary Tables 2 and 4)[60].

For the explorations of respondents' social preferences for resilience (that is, to test H2), we compared the respondents' WTP-per-day results with a sample of zeros using one-sample KS tests and reported KS D statistics. In the case of comparing respondents' private and social WTP-per-day results between different income groups, we used two-sample KS tests[60]. To adjust the respondents' WTP per day for their annual household incomes, we divided the total WTP per day for the back-up services by the median of each tax bracket and compared the proportion of WTP per day to the median of the annual household income bracket.

Finally, for the comparisons between the respondents' value per kWh to sustain their critical electricity-dependent demands and WTP per day to support their communities (that is, to test H3), we used two-sample KS tests and reported the KS D results (Supplementary Table 8).

Ethics statement. The Carnegie Mellon Institutional Review Board approved the survey experiment described in this article. Informed consent was obtained from all the survey respondents before they started the survey.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability
The data that is directly used for the statistical tests in the results section and for generating Figs. 2–4 and Tables 1–3 can be found in Supplementary Data. The complete datasets that support the plots and other findings of this study are available in the Open Science Framework project page, https://osf.io/ugvqh/.

Code availability
The R code file written for the data analysis is available in the Open Science Framework project page, https://osf.io/ugvqh/.

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Author contributions

M.G.M. and A.L.D. secured project funding; S.B., A.L.D. and M.G.M. designed the study; J.P. and S.S. developed and demonstrated the online survey framework; S.B., J.P. and S.S. conducted pilot tests; S.B. and J.P. conducted online surveys; S.B. analysed the data and created the figures and tables with iterative feedback from A.L.D. and M.G.M.; S.B., A.L.D. and M.G.M. drafted and edited the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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Software and code

Policy information about availability of computer code

Data collection	To obtain the judgments of individuals about their economic and social preferences for a low-amperage backup service for enhanced grid resilience in the event of large outages of long duration, we developed our own web-based preference elicitation framework. The survey was implemented as a web application mainly built with HTML, CSS, and JavaScript for the frontend (i.e., respondent interface), Node.JS backend framework for the server (i.e., the backend processor), and a NoSQL database (integrated with Amazon AWS environment) to store the information about respondents and their survey responses. The code is not publicly available at this point, but the more details on survey framework design and technical aspects of the framework is provided in Baik et al. (2019), a workshop proceeding paper.
Data analysis	All the codes that we have used for the statistical analyses are provided in the Open Science Framework project page, https://osf.io/ugvqh/.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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Behavioural & social sciences study design

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Study description	To obtain the judgments of individuals about their economic and social preferences for a low-amperage backup service for enhanced grid resilience in the event of large outages of long duration, we used our own web-based preference elicitation platform. We asked the respondents to imagine a hypothetical 10-day outage that affect the entire Northeastern United States and indicate their willingness-to-pay for reliable electric services for themselves and for their community. The elicitation framework is designed to help individuals think systematically about the value they attach to resilient electric services by employing detailed and realistic blackout scenarios, questions about private and social willingness-to-pay using multiple bounded discrete choice questions with follow-up checks, information regarding inconveniences and economic losses, and a check for consistency.
Research sample	To participate in the study, respondents must be: 1) 25 years old or older, 2) have lived in Northeast region (one of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey and Pennsylvania) for at least two years, and 3) be aware of, or responsible for their homes' electricity bills. In case of Hurricane Sandy participant, we added an additional constraint which is: having lived in 16 zip codes regions that are hardly hit by Hurricane Sandy (10 from New Jersey and 6 from New York). The criteria for eligibility were tested in the pilot tests (for both face-to-face and online settings) and face-to-face surveys (Baik, Davis and Morgan (2018)), and then slightly modified before the actual implementation.
Sampling strategy	To recruit a representative sample of Northeastern United States residents, we used three methods. First, we recruited Amazon Mechanical Turk (MTurk) panels from nine Northeastern United States, proportional to the population of the states. Second, we used address-based sampling to randomly recruit individual residential electricity customers. Third, we recruited residential electricity customers who have lived in the neighborhoods that were hardly hit by Hurricane Sandy.
Data collection	All the participants accessed to our survey website and completed the survey (more details are provided in "Recruitment" question below). Once eligible participant completed the survey, we compensated individual respondents $10 for their time. Prime Panels were compensated through Turkprime.
Timing	The time required to complete the online surveys averaged 45 minutes.
Data exclusions	In value-per-kWh calculations and comparisons, we excluded three respondents who only wanted to use appliances operated by gas thus had the electricity consumptions per day less than 1kWh (average electricity consumption was 30kWh/day). In case of preference uncertainty calculations and comparisons, we excluded 30 respondents whose WTP-per-day for the backup service was very high thus marked the entire "yes" column and specified their maximum WTP-per-day because we were not able to obtain their ranges of uncertainty in at least one of the stages (as we were only able to assess their maximum "sure" WTP-per-day but not maximum "not sure" WTP-per-day). 8 respondents had very high preferences throughout the study, 2 respondents had very high preference in the beginning but decreased their WTP as the survey progressed, and 20 respondents became very interested in the backup service as they received information and exercises.
Non-participation	In case of MTurk respondents, 205 out of 286 respondents were eligible and completed the survey (~72%). In case of address-based sampling, we randomly contacted 2000 residential addresses. 128 were returned as undeliverable, and 74 eligible residents completed the survey (response rate: 4.0%). Third, we recruited 216 residential electricity customers who have lived in the neighborhoods that are hardly hit by Hurricane Sandy. The response rate was 58% (216 eligible and complete answer out of 372).
Randomization	The server internally conducts two coin flips to determine which of the two outage scenarios (terrorist attack vs solar storm) to use and the order of social WTP questions (critical social service question first and then vulnerable neighbor question vs vulnerable neighbor question first and then critical social service question), and stores the result of flips in the database.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☐	☒ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	In this study, we surveyed 483 individuals to understand how people use and value electricity when a large outage of long duration occurs. More detailed demographic information of the study participant (age, race, state, years respondents had lived in the states, years respondents had lived in their current houses or apartments, income, house type, having life-critical medical devices, and hurricane Sandy outage experience) is summarized in Supplementary Information, Appendix A. Yet, we found that our MTurk respondents were younger, earned less, and had lived in their current residency for shorter periods of time than those who were recruited via address-based sampling and Turkprime.
Recruitment	The first round of surveys with respondents recruited through Amazon Mechanical Turk (MTurk) was conducted in early January 2018 (204 respondents). In this case, we uploaded our study information via MTurk request page and MTurk panels who were interested in the study accessed the website. The second round of surveys with randomly selected Northeastern residents was conducted between February and March 2018 (74 respondents). In this case, we randomly drew 2000 residential addresses and sent a recruitment letter with a $2 prepaid cash incentive. After one week, we sent a follow-up postcard as a reminder. Once eligible respondents completed the survey, we compensated $8 as their bonus. The third round of surveys with Turkprime research panels was conducted in early December 2018 (205 respondents). In this case, we provided the three eligibility conditions and the 16 zip code areas that were hardly hit by Hurricane Sandy to Turkprime to recruit eligible respondents.
Ethics oversight	Carnegie Mellon Institutional Review Board (IRB) approved the survey experiment. Informed consent was provided to all survey respondents before they started the survey.

Note that full information on the approval of the study protocol must also be provided in the manuscript.