An Improved Method to Assess the Value of Assuring Limited Local Electric Service in the Event of Major Grid Outages

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Abstract

America's dependence on reliable electric power, and our individual and collective vulnerability to power disruption, continues to grow. While it would be technically possible to make changes that could sustain many critical electricity-dependent services during widespread and long-lasting outages by implementing smart grid technologies, distributed generation resources, and other technologies, these technologies would require incremental investments where the benefits are uncertain and difficult to quantify in many cases.

For many years, distribution utilities in United States have conducted studies of the value that customers place on reliable electric services. However, these studies and associated literature suffer from several shortcomings: they have not devoted much effort to help respondents fully understand and consider the various implications of hypothetical outages that respondents may not have experienced nor previously considered; they have done little to minimize cognitive biases; they have focused almost exclusively on brief outages that last only up to a few hours; and, they have only considered the difference between full backup service and no service. Hence, their results are not adequate to assess how much individuals or society might, or should, be willing to avoid longer outages or provide full or limited backup service in the event of large outages of long duration.

To address these issues, we have developed and demonstrated a set of improved methods that help residential customers think systematically about the value they attach to reliable electric service and have used the elicited informed judgments to illustrate how the results could be used for local or regional-decision-making.

After introducing the issues in Chapter 1, Chapter 2 summarizes a new elicitation framework that has been designed to help residential electricity customers think carefully about the value they

attach to reliable electric service. The survey framework was applied to a convenience sample of residents in Allegheny County, Pennsylvania to assess their willingness-to-pay to receive backup services during a hypothetical 24-hour outage on a hot summer day. The face-to-face interview results suggest that there exists a considerable amount of consumer surplus associated with providing partial electric backup service (i.e., the respondents' willingness-to-pay per kWh is significantly higher for their first bit of electricity than the value of the last amount consumed). Further, the assessed value of sustaining demands the respondents assessed to be high priority significantly increased as they receive additional information and better understood the outage scenario and its consequences.

In Chapter 3, we estimated the cost to implement to implement the capability to provide limited emergency backup power service using isolated distribution feeders, evenly distributed the incremental investment costs across to all residential customers across outages, compared the required service payment with the measured willingness-to-pay distribution, and explored whether and when such investments can be justified. We first conducted a series of order of magnitude calculations and found that providing the low-amperage backup service can be more cost-effective than buying a small portable generator and storing diesel or gasoline for refueling even if a 24-long outage occurs once every 20 years, and the backup service appears to be more cost-effective if a region is expected to suffer more frequent and longer outages. In addition to the assessments using private willingness-to-pay, the chapter also considers two methods that might be used to recover system upgrade costs without raising a serious equity issue nor imposing an excessive burden to either residential customers or the region.

In order to explore respondents' willingness-to-pay under a variety of scenarios for different geographical regions more efficiently, the face-to-face survey framework has been modified for online use. Chapter 4 first describes the details of the generalizable web-based survey framework that a researcher or decision-maker can use to design ones' own outage scenarios. It also addresses several factors that are assumed to influence estimates from stated preference valuation studies. The framework was then used to elicit the economic and social preferences for reliable electric backup services during hypothetical 10-day widespread outages from a sample of residents of the Northeastern United States. We first demonstrated the importance of helping respondents fully consider the various aspects of the consequences of the hypothetical outages and better articulate their values, and then used the elicited preferences to explore whether and how much some of the factors that are known to affect respondents' risk perceptions influence their willingness-to-pay values for reliable electric services during the hypothetical outages. The chapter concludes with a discussion of why exploring preferences for reliable electric services under a variety of scenarios and constructing customer damage functions for electricity customers are important, and what we see as future behavioral research needs.

Finally, in Chapter 5, we discussed how the elicited preferences can be used to make more informed and collective societal decisions. Benefit-cost analysis and other forms of analysis have been widely used in policy analysis and government decision-making. However, only uncertainties about costs and physical states of the world are considered, neglecting uncertainty about the level of benefits that come from the value the public places on policy outcomes. In this chapter, we proposed such an approach that incorporates uncertainties in individual preferences. Using the public valuations of implementing smart grid technologies to mitigate impacts of large-regional outages, we showed uncertainty in individual preferences, when aggregated to form societal preference intervals, can substantially change the decision society would make.

Table of Contents

List of Tables

List of Figures

1. Introduction

Because residents in developed economies depend heavily on services provided by electricity, power outages have substantial economic and social impacts. While society should take reasonable measures to *avoid* outages (i.e. to assure *reliability*), widespread and long-duration outages (WLD-outages) cannot be completely avoided. Given the proliferation of modern "smart" technology and distributed generation (DG), with some modest additional capability, it would be possible to provide at least limited service to some customers and sustain critical services when WLD-outages occur [1]. However, because WLD-outages are very rare and many possible precipitating events have not happened, it is hard to use statistical measures when determining how much society should invest in risk mitigation and preparation strategies that make our power system less vulnerable. Instead, an informed estimate of willingness-to-pay (WTP) can be used as an input to such decisions.

1.1 Previous Studies on Value of Electric Service Reliability

Since the mid 1980s, electric utilities have conducted a number of studies to assess customer costs for power outages lasting a few hours. Utilities and public utility commissions (PUCs) have used these results to justify investments to achieve a desired level of reliability. While it is relatively straightforward to estimate the economic costs of blackouts experienced by industrial and commercial customers (although assessing subsequent business rebound after an outage can be more challenging), the *soft costs* experienced by residential households (e.g., not being able to use air conditioners on a very hot day) are more difficult to quantify.

To estimate residential customer outage costs, most studies use one of four methods. The first uses revealed preferences in which respondents are asked how much they have paid for backup equipment or other mitigating services to avoid power outages. For example, Caves, Herriges, and Windle infer industrial customers' interruption costs from what is known as Interruption and Curtailment (I/C) programs, which provide special discounted electricity rates for commercial and industrial customers in return for curtailing usage on request or allowing a utility to occasionally interrupt electrical service [2]. This approach only reveals meaningful preferences if customers have accurate expectations about the probabilities and costs of outages, two key parameters that are difficult for researchers to estimate, making it unlikely that they are common knowledge [3]. In addition, most residential and commercial customers do not use backup generation or interruptible contracts even though they experience interruption costs. In a recent study conducted by Burlingame and Walton, the monetary losses experienced by each customer group were added up on a daily-basis and then extrapolated for periods up to a week [4]. While the method could be useful to obtain something like a monetary upper bound, not all monetary losses recur in an outage (for instance, in some regions' firms may have backup power for their water and sewer system, and some people who are not employed or can get paid during outages do not need to worry about their lost income). Perhaps more importantly, this method does not include non-monetary losses, such as inconvenience, that for residential customers may dominate.

Second are stated preference methods that ask respondents to state their maximum WTP to avoid a given interruption [5, 6]. An example method uses yes-no questions to given bids and assesses the dollar value at which respondents switch from “yes” to “no” [7] or asks respondents to choose between scenarios with varying levels of reliability and associated prices (i.e., choice modeling, discrete choice experiments, or conjoint analysis). For example, Baarsma and Hop use conjoint analysis to assess the trade-off between changes in outage frequency, duration, day of the week, part of the day, season, warning in advance, and changes in electricity bill [8]. London Economics uses choice experiments to assess the trade-off between outage duration, season, time of day, day of week, and one-time WTP or willingness-to-accept (from £1 to £15) [9]. This method is a bottom-up approach and generates results without relying on other data, such as historical data on backup power installation cost. However, interruption costs from hypothetical outages are highly subjective, and individuals may not fully understand the consequences of an outage.

The third approach, called the production function method, produces estimates based on macroeconomic data (for example, gross domestic product or the average annual income per household), which is useful when there are limitations in the availability of data (such as data on customer tradeoffs between reliability and price [10]) and resources (such as time and money because the analysis only requires a small quantity of easily obtainable data [11]). For example, Munasinghe calculates the value of foregone leisure, which is estimated as the product of after-tax earning rate (per hour) and outage duration, to estimate residential customers' outage costs [12]. Similarly, de Nooij, Koopmans and Bijvoet calculate the value of leisure time by multiplying the average gross hourly wage rate after tax, outage duration, and the percentage of households that are expected to lose their leisure time [13]. Stevie *et al.* develop econometric load forecasting models for three electric customer groups (for instance, residential customers' demands are roughly estimated by their electricity price, income, weather and other variables) to calculate the value of electric service to the customer [14]. But such macroeconomic estimates are of limited usefulness because they: 1) simply divide direct costs of production (for example, annual GDP per capita or average annual income after tax) by annual electricity consumption, 2) do not consider interruption attributes such as timing of outages, 3) only consider a subset of all relevant costs (i.e., they do not include other monetary losses such as repairing damaged equipment, lost income, and other non-monetary losses such as lost free time and inconveniences), and 4) do not consider the consumer surplus associated with leisure or other forgone activity.

Finally, the fourth method involves case studies of historical blackouts and outages. For example, Corwin and Miles estimate economic and social impacts of the 1977 New York City blackout [15]. While such an approach can provide important qualitative results, quantitative analysis is difficult because of the limited data available from rare outages. Moreover, because future large outages may not be the same as past ones, historical data may not reflect future outcomes.

Many previous studies have used contingent valuation method. These studies typically deal with outages for particular regions (for example, only surveying customers in the Midwest United States who are served by the MidAmerican Energy company [6]) and examine specific customer mixes (for example, only residential customers [16-18]). Also, they focus on specific outage scenarios, mostly brief outages. For instance, Carlsoon, Martinsson and Akay consider planned outages lasting for 1, 4, 8, and 24 hours and unplanned outages lasting for 2-6 hours [16].

To generalize these results, researchers working for the Lawrence Berkeley National Laboratory have conducted meta-analyses of previous studies every 5 years, extending the effort over time to include more participating companies, and deriving additional customer outage models, using a two-part regression model [19-21]. The resulting estimates of customer damage functions can be applied to estimate interruption costs for a given season, day of week, timing of interruption, duration, geographical region, and customer type.[1] The more detailed data on which these results are based are not publicly available [20].

1.2 Characteristics of Backup Services during Widespread and Long-duration Outages

If one wants to elicit *informed* estimates of WTP from individuals, three important elements should to be carefully considered: 1) the degree to which respondents understand the good or service (being interrupted), 2) the degree to which respondents understand their preferences for that good or service, and 3) the most appropriate elicitation format. In preference elicitation, respondents should be helped to understand the consequences of their choices before they are asked to choose, and elicitation mechanisms should not assume more than is required or verifiable for that task. For significant and unfamiliar choices, respondents should be allowed to express uncertainty in their preferences. Fischhoff presents a continuum of philosophies to explain these concepts: at one extreme, people are assumed to have fully articulated values ('philosophy of articulated values') whereas at the other extreme, people are assumed to lack articulated preferences and to only have basic values from which, with help, they can construct their preferences ('philosophy of basic values') [22]. In the middle of these two extremes, people are assumed to have stable values of moderate complexity, thus the elicited values may be rendered uncertain and incomplete.

[1] Freeman, Sullivan & Co. and Lawrence Berkeley National Laboratory recently update the Interruption Cost Estimate calculator for reliability planning (available at http://icecalculator.com). Using the tool, electric reliability planners, government organizations, or other relevant authorities can roughly estimate their interruption costs by entering reliability inputs (e.g., SAIFI and SAIDI/CAIDI), numbers of residential and non-residential customers, and state.

The value of a low-amperage backup service during WLD-outages is a good example of eliciting individuals' preferences when they are likely in the intermediate position. Most people are familiar with the services provided by electricity, but few have experienced WLD-outages or have previously considered their WTP to avoid such outages. For instance, respondents may know that their batteries last a few hours or days, but they may not know that their water and sewage service may be unavailable after a few days. Similarly, consequences in communities likely also vary over outage durations; for instance, many people may not know that many banks, ATMs, and many stores and other businesses will not work immediately, and that some critical social services such as police and fire station and TV and radio stations may run out of fuel for backup power in a few days. Finally, a low-amperage backup service that allows people to only run a few critical appliances is novel and is unlikely to have been previously considered.

Thus, in this case, based on their prior knowledge, respondents can be assumed to have rough but not well-defined preferences for their reliable electric services, and they should be able to better articulate their values and preferences as they receive more information about a given outage scenario and its consequences. However, because most respondents have limited (if any) familiarity with the backup services and additional interpretation of the scenario beyond the description provided in the survey, they may still need an opportunity to express uncertainty in their preferences even after researchers providing information and exercises.

1.3 Assessing the Value of Reliable Electric Services for Residential Customers in the Event of Widespread and Long-duration Outages

Previous studies which adapt the survey frameworks proposed by Sullivan and Keane [5], especially the framework that is designed for residential customers, suffer from several shortcomings. First, previous studies have not involved any systematic effort to help respondents fully understand and consider the various implications of the hypothetical outages –impacts and outages that they may not have experienced or previously considered. While various surveys have asked people about their WTP to avoid a hypothetical outage after providing a brief description of an outage and its duration, these studies often leave respondents guessing about many of the details of what such a hypothetical outage would entail, providing little detail about the blackout, its geographical extent, the services that would be available and unavailable, and inconveniences and economic losses they might suffer [5]. Also, the surveys appear to have done little to minimize cognitive biases [23-25], and do not allow the realistic expression of preferences that may be incomplete (i.e., not defined over all states of the world), uncertain (i.e., unable to provide an exact WTP), and heuristic (i.e., focusing only on some aspects of the decision problem). Second, it is also not trivial to understand the value of having a small amount of power that could serve peoples' high priority (HP) demands (e.g., a few lights, air conditioning during summer, or furnace pump or blower during cold winter), compared to full power that also supports somewhat lower priority (LP) demands (e.g., using a speaker dock, DVD/video player, and LED TV to play a game). Most importantly, past studies of residential customers have only asked respondents about outages that last a few hours (i.e., generally ≤24 hours), providing little information relevant for investment decisions that would minimize the impact of WLD-outages. The costs per kW of lost services during longer duration outages –many hours, several days, or even weeks –are likely to be very different than the costs of brief outages, so simply scaling up the results is not appropriate.

To address this issue, we have developed and demonstrated a set of improved methods that help residential customers think systematically about the value they attach to reliable electric services during WLD-outages and illustrated how the results could be used to explore when the incremental investment could become cost-effective. While we have described a technically plausible strategy by which it would be possible to implement full or partial backup service if a distribution system with distribution generation is intact, in this thesis we have not concerned with the technical, economic or regulatory details of how that might be done. Instead, we have focused on assessing people's carefully considered WTP for such services.

The four major contributions of this thesis are:

1. Development of a face-to-face and web-based survey frameworks that can be used to elicit informed judgments from residential customers in the context of a wide variety of hypothetical outage scenarios including outages of different durations, in different seasons, different locations, with different levels of backup service coverage, and under a variety of emergency conditions;
2. Performance of a series of analyses that explore when the incremental investments to provide such services may be justified on economic and social grounds and development of ideas about how to recover the costs of upgrades in a way that is socially equitable;
3. Discussion of ongoing controversies about the reliability of the estimates from contingent valuation method and risk perceptions among the public, whether and how much some of those influence people's preferences for reliable electric services, and how the elicited preferences can be used as inputs for further decision-making problems; and,

4. Proposal of a strategy that considers preference uncertainty in a benefit-cost analysis using societal preference intervals and implementations of the strategy for public valuations of implementing smart grid technologies along with a discussion of why incorporating such uncertainty into societal decision-making is important.

2. Assessing the Cost of Large-scale Power Outages to Residential Customers

Residents in developed economies depend heavily on services provided by electricity. While distributed resources and a variety of new smart technologies can increase the reliability of that service, adopting them involves costs, necessitating tradeoffs between cost and reliability. An important input to making such tradeoffs is an estimate of the value customers place on reliable electric services.

We develop an elicitation framework for helping individuals think systematically about the value they attach to reliable electric service. Our approach employs a detailed and realistic blackout scenario, full or partial (20A) backup service, questions about willingness-to-pay using a multiple bounded discrete choice method, information regarding inconveniences and economic losses, and checks for bias and consistency.

We apply this method to a convenience sample of residents in Allegheny County, Pennsylvania, finding that respondents valued a kWh for backup services they assessed to be high priority more than services that were seen as lower priority ($0.75/kWh vs. $0.51/kWh). As more information about the consequences of a blackout was provided, this difference increased ($1.2/kWh vs. $0.35/kWh), and respondents' uncertainty about the backup services decreased (Full: $11 to $9.0, Partial: $13 to $11). There was no evidence that the respondents were anchored by their previous willingness-to-pay statements, but they demonstrated only weak scope sensitivity.

In sum, the consumer surplus associated with providing partial electric backup service during a blackout may justify the costs of such service, but measurement of that surplus depends on the public having accurate information about blackouts and their consequences.

The work presented in this chapter was a joint effort with M. Granger Morgan and Alexander L. Davis and was published in the journal *Risk Analysis* in February 2018 [26].

2.1 Introduction

American society depends on electric power for many individual, household, and commercial activities, making our individual and collective vulnerability to power disruption a key question for policy analysis. Most causes of power outages, such as lightning strikes, falling trees, squirrel electrocutions, or vehicles crashing into poles, cause little prolonged disruption to daily life. These events result in short-term and local power outages, as evidenced by the median power outage in the United States lasting less than 3 hours in 2014 [27]. On the other hand, WLD-outages do occur and impose considerable private and social costs. Examples include the ice storm that hit Southern Québec, Ontario, and Northern New York in 1998 and the extensive outages in the Southeast United States and Caribbean caused by hurricanes such as Harvey, Irma and Maria. These large outages are not limited to extreme weather events, but can also result from a large solar mass ejection (for example, the geomagnetic storm on the United States and Québec power grids which caused a blackout in 1989 [28, 29]) as well as physical and cyber-attacks on grid infrastructure [30].

While preventing blackouts altogether is too costly for most service territories [31], new technologies make it possible to sustain critical social services and serve HP customer demands during an extended blackout, for example, by islanding distribution feeders using DG, distribution automation, and smart meters [1]. However, implementing such capabilities would require incremental investment, and have benefits that are uncertain and difficult to quantify. For this reason, an understanding of the value people place on the services that would be lost during such events is essential for sound decision-making.

In this chapter, we develop and demonstrate an elicitation framework to obtain the informed judgments of residential customers about their WTP for the full and partial backup service in the event of an extended outage. We illustrate the method with a study of respondents' valuations of a hypothetical 24-hour power outage on a hot summer weekend in western Pennsylvania. In the study, we test the following two hypotheses:

- **H1:** Providing respondents with detailed information about the circumstances of an outage and helping them think through the costs they are likely to experience will lead to more consistent and less uncertain assessments of the value of backup services;
- **H2:** Respondents will value the first 20A of service to meet their HP demands much more than they value service to meet LP demands (>20A).

We focus only on service for individuals, but the approach can be generalized to many other outage scenarios, including how people value providing service to others in their communities and to support critical social services (emergency services, food stores, gas stations, etc.).

2.2 Methods

2.2.1 Overview of the survey design

Our elicitation procedure was designed to help residential customers think carefully about a specific large-scale outage and systematically reflect on how much they value their full and partial backup service during that outage [22]. The approach helps respondents understand what services would and would not be available in their homes and communities, their personal load profiles as a function of time of day (under normal circumstances or with the full backup service), HP domestic loads they could operate with the partial backup service (under limited availability), and economic losses they might suffer. The framework also allows respondents to express uncertainty in their preferences and incorporates consistency and bias checks to determine the reliability of responses. Figure 2-1 summarizes the design of our elicitation approach.

Figure 2-1. Overview of the face-to-face survey elicitation design indicating the information and exercises that we provided in three different stages and showing when we pose questions about willingness-to-pay (WTP).

In the introduction of the survey, we asked respondents to imagine that a large regional blackout occurred on a hot summer weekend as a result of severe weather events in the Midwest (Figure 2-2; see Appendix A for the full blackout scenario). Although there was an outage, Pittsburgh's power system was not directly damaged, so power would be restored in 24 hours. Full and partial backup service were then described to respondents, where the full backup service would provide all the electric power respondents would normally have used, while the partial backup service would provide only 20A service for the entire house.[2]

[2] Before we conducted the actual interviews, we considered a number of electric appliance combinations. Based on the results, we chose 20A as the amount of electricity needed to cover bare necessities. As indicated in Figure 3-3, this could be simply implemented by upgrading circuit breakers. See Chapter 3.2 for more technical details.

Figure 2-2. The hypothetical blackout scenario. We told respondents that that there were several tornadoes (left) which struck big power lines in the Midwest (right) and resulted in a large regional blackout that spread to the entire Mid-Atlantic and Northeastern parts of the United States (middle).

After introducing the scenario and backup services, we elicited respondents' WTP for the full and partial backup service using a MBDC method, an approach that provides a range of bids that respondents are asked to accept or reject (see Chapter 2.2.2 for more details on why we selected MBDC instead of other traditional elicitation techniques or discrete choice modelling) [32, 33]. Figure 2-3 shows the WTP question used in the study. The range of values from $0 to $75 was chosen based on the range of results from a pilot study, and a "not sure" column was included to allow respondents to express uncertainty about their WTP [34]. For each question, respondents indicated their maximum "sure" WTP (the upper limit from the "yes" column) and maximum "not sure" WTP (the upper limit from the "not sure" column). If a respondent had a very high WTP and marked the entire "yes" column, we asked a follow-up question: "What is the largest amount you would be willing to pay to receive the service?"

	Would you be willing to pay this amount to get full service on a hot summer weekend day?		
	Yes	Not sure	No
Less than $5	☑	☐	☐
$5 to $9.99	☑	☐	☐
$10 to $14.99	☑	☐	☐
$15 to $19.99	☑	☐	☐
$20 to $24.99	☑	☐	☐
$25 to $29.99	☐	☑	☐
$30 to $34.99	☐	☑	☐
$35 to $39.99	☐	☑	☐
$40 to $44.99	☐	☑	☐
$45 to $49.99	☐	☐	☑
$50 to $54.99	☐	☐	☑
$55 to $59.99	☐	☐	☑
$60 to $64.99	☐	☐	☑
$65 to $69.99	☐	☐	☑
$70 to $74.99	☐	☐	☑

Figure 2-3. Example response format used in eliciting respondent's WTP. In this example, the respondent indicates that he or she would surely pay at least $25 and might be willing to pay as much as $45 for the full backup service during the blackout.

Following this initial WTP assessment, we provided information describing the services that would and would not be available in respondents' homes and communities during the blackout. For example, Table 2-1 shows that battery-powered radios and emergency services (including 911) would be available during the blackout, but electric appliances that do not run on batteries, as well as most stores and restaurants without backup generators, would not operate during the blackout.

Table 2-1. List provided to respondents of services that will and will not work in homes and communities when the power is out for the entire region.

In your home		In community	
Will work	Will not work	Will work	Will not work
• Old style telephones that have a rotary dial • Anything that runs on a battery, as long as the battery lasts (e.g., radios, flashlights, laptop computers, and cell phones). • Natural gas and all normal water and sewer services.	• New style telephones that include a plug to a power outlet. • All electrical appliances that cannot also run on batteries, including air conditioners and blowers that circulate air. • Cable and internet service.	• Emergency service including 911 (via cell phone or rotary dial phone). • Hospitals, police stations, and other places that have backup generators. • TV and radio stations (most have backup generators). • Natural gas and all normal water and sewer services. • Bus service. • GPS service.	• Traffic signals. • Street lights. • Banks and ATMs. • Most gas stations (pumps need electricity). • Food stores (lights, refrigeration, and cash registers will not work). • Most restaurants (very few have backup generators). • Elevators in buildings without backup. • Ventilator fans and lighting in traffic tunnels. • Electric trolley service. • Airport – major delays.

Next, we asked respondents to play a card stacking game that helped them construct their daily load profiles under normal and limited conditions (in this case, 20A). Respondents were given a set of cards corresponding to common household appliances. The height of each card was proportional to the amount of power used by that appliance. For example, a typical microwave oven consumes 1500 Watts or 12.5A at 120V, so the height of microwave oven card was 12.5 cm (left side of the Figure 2-4-A). We divided the day into morning, mid-day, evening, and late evening, and asked respondents to select the appliances they would likely use in each time period. The height of each stacked column represents the maximum electricity consumed in each period if all appliances are used at the same time (right side of the Figure 2-4-A).[3] Once respondents created their normal load profiles, they were then asked to select a set of HP appliances from their stacked columns to fit under the 20A limit (Figure 2-4-B). Upon finishing

[3] In some cases, not all appliances would be used at the same time; so, this method provides an upper bound on load. Dealing with the possible time sequence of appliance usages would have added a great deal of complication, without yielding significant additional insight. We did not mention this issue and most respondents did not bring it up. We wanted respondents to focus on the demands they considered most important, especially when they initially did not understand the concept.

the game, respondents were asked a second time for their WTP for both the full and partial backup service.

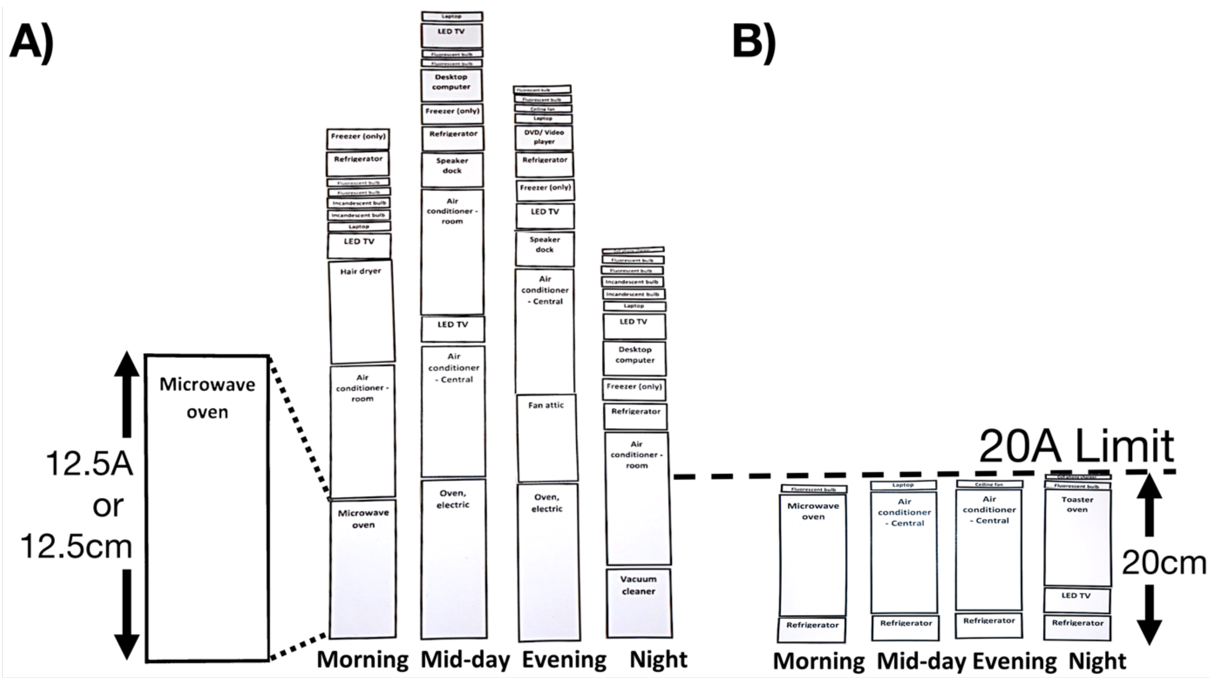

Figure 2-4. The electric appliance card stacking game. A) The height of each card for an appliance or device is proportional to the power consumed, and each respondent built his or her normal electricity consumption profiles for four time-periods by using the appliance cards; B) Each respondent selected his or her high priority (HP) loads to fit under the 20A limit.

Finally, we asked respondents to think about the monetary losses that they would incur as a result of the 24-hour blackout. To do this, we reproduced a recommendation from the United States Department of Agriculture regarding perishable foods in refrigerators, and asked respondents to estimate the value of perishable food they have in their refrigerators and would likely lose in the 24-hour outage. This exercise was followed with a third and final set of WTP questions, again asking respondents to evaluate their WTP for the full and partial backup service.

Compared to the other survey designs, our framework has four major advantages: 1) the framework can inform respondents about the consequences of a blackout in their home (e.g., value of perishable food and frozen water pipes) and communities (e.g., shopping malls, restaurants, grocery stores, and gas stations will not work); 2) the framework can help respondents understand their priorities for electric services (e.g., furnace blower or additional lighting) and reflect on their preferences for backup services; 3) the framework can allow the realistic expression of preferences that may be incomplete (i.e., not defined over all states of the world), uncertain (i.e., unable to provide an exact WTP), and heuristic (i.e., focusing only on some aspects of the decision problem); and, 4) the framework can provide decision-makers with numbers that come from more informed and engaged members of the public, reflect the uncertainty in what people want, and can be aggregated in a number of ways to access alternative policies.

2.2.2 Elicitation format to obtain respondents' preferences

To determine the most appropriate elicitation technique, we started by comparing the traditional elicitation techniques that have been used in previous studies. As discussed in Chapter 1.1, studies generally use one of four methods –revealed preference; stated preference; production function method; and case studies of historical blackouts– to estimate customer outage costs. Among these, the stated preference method has been the most widely used for residential customers. The contingent valuation method asks respondents to state their WTP for a hypothetical service or product, asking respondents to make a direct assessment. While stated preference studies have several inherent issues such as hypothetical bias, Arrow *et al.* [35] argue that a study that is carefully designed and properly conducted may provide a useful input into decision-making processes.

Because contingent valuation studies have several sources of uncertainty [36], the elicited values of a commodity or service using different elicitation techniques can yield different estimates.

Cameron *et al.* also compare elicitation techniques used in contingent valuation studies and argue that each technique has advantages and disadvantages relative to a given good or service [25]. Here, we focused on open-ended technique and dichotomous choice technique, two of the most widely used techniques in value of lost load studies. Previous studies using open-ended approach in other contexts have posed questions like, “what is the most that you would be willing to pay for a 3.5-ounce Cadbury solid milk chocolate bar?” [37]. While seemingly straightforward, the method has several well-documented limitations. The most important is that respondents have difficulty providing a precise number, and often do not feel confident with the numbers they do give, especially for things that are not familiar. Additionally, there is no incentive for respondents to provide their actual values. Indeed, they may believe that lower numbers may lead to lower prices. Thus, respondents tend to not respond to the question (because of its difficulty) or to under-report their values (for strategic reasons). In dichotomous choice approach, respondents are asked “will you be willing to pay $X for the chocolate bar?” [37]. Dichotomous choice can reduce strategic bias if done with an incentive-compatible mechanism [23]. However, a respondent’s agreement to a specific bid does not necessarily give their maximum WTP; instead a yes for a given bid provides a lower bound on WTP. Thus, the power of dichotomous choice approach is relatively low [38], and a larger sample size is required to identify the underlying distribution of WTP and accurately assess where respondents switch from “yes” to “no” [39]. Additionally, respondents may be anchored by the first dollar amount they are asked to accept or reject (called “starting point” bias) and may have a tendency to agree (called “yes-saying” bias).

As previously addressed, we assumed that people have rough preference for reliable electric services during WLD-outages even in the beginning of the study, and the information and exercises we provide would help them better articulate their values, even if some of them had previously experienced long-lasting outages (because they may not have fully learned which services are and are not available in their communities and which electric appliances are critical and noncritical for them). However, we expected that some of the uncertainty will remain even after providing the information and exercises as respondents may have additional interpretations of the scenario beyond the description provided in the survey (for instance, how hot will it actually be and what if having no TV is enjoyable). Thus, forcing respondents to condense the uncertainty into a single response may result in inaccurate inferences about collective decision-making (e.g. concluding that the society would accept the policy even if the society might be unsure).

Because traditional elicitation frameworks do not allow respondents to express their imprecise preferences, we used multiple bounded discrete choice method, which increases the dimensions of both bid prices and decision responses, instead because of its apparent benefits. First, multiple bounded discrete choice provides a table which allows respondents to vote on a wide range of reference thresholds with more response options, allowing us to gather more data from each respondent and providing a more precise estimate of WTP per respondent[4] [40]. Second, the method addresses the high cognitive load of open-ended response mode by only requiring simple "yes" or "no" answers to small ranges rather than the provision of a point estimate over the (infinite) range of positive numbers[5] [34, 40]. Third, we allowed respondents to express uncertainty in their WTP by including a "not sure" column. Finally, Roach, Boyle and Welsh compare results from three different elicitation techniques –open-ended technique, dichotomous

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[4] Discrete choice technique requires a larger sample size to achieve a distribution of WTP because the method asks respondents only one time if they are willing to pay the specified amount and receive the product (or service) or not.

[5] Under open-ended format, respondents feel high cognitive loads because they have to answer specific numbers; thus, it generally ends up with a serious underestimation with a high level of uncertainty and higher non-response rates [23].

choice technique, and multiple bounded discrete choice method with three different ranges– and observe that all the results from multiple bounded discrete choice method fall between the estimates from open-ended technique and dichotomous choice technique [32]. We expected that using multiple bounded discrete choice could help avoid both the potential underestimation problem from open-ended technique (due to cognitive loads and strategic bias) and overestimation from dichotomous-technique (due to yes-saying bias), thus can provide more reliable estimates.

There are some drawbacks to multiple bounded discrete choice method. For example, Roach, Boyle and Welsh report that welfare estimates can be affected by the range of bids (range bias) [32], while they argue that a carefully designed survey can reduce some of the bid design effects. Also, Alberini, Boyle, and Welsh suggest that the order of presentation can have a significant effect [33]. Thus, following to the previous studies' recommendations, we conducted the pilot tests to check whether the elicitation question works without providing additional information and whether for our scenario the range ($0 to $75) covers most of respondents' preferences. See Appendix A for the WTP questionnaires that we designed and used in the actual study.

Finally, we should note that discrete choice modeling has been used to estimate consumers' preferences for electricity services (for example, for understanding residential customers' preferences for electric service plans [41] and improved electricity services [42]). However, we did not consider the use of discrete choice modeling to be appropriate to the problem of assessing the cost of long outages. *First*, we believed that peoples' preferences for reliable electric services are uncertain and incomplete when they only bring to bear their prior knowledge, thus it is difficult to use a single cardinal utility function to incorporate the preference uncertainty because the utility function is not deterministic. Respondents are probably able to judge rather accurately how they value a Cadbury chocolate candy bar versus a KitKat bar, however, without a great deal of assistance to think things through, most have very little basis to judge the relative costs of a 3-day mid-week outage with outdoor temperatures averaging 29°F *versus* an 8-day outage during a cold spell with outdoor temperatures averaging 12°F.

Second, under the discrete choice study settings, researchers need to abstract away significantly from what will actually happen during a blackout when presenting various scenarios. In working through many scenarios, none can be described (or absorbed) in detail; for instance, a survey cannot provide detailed information about what would be available with 20A vs 40A service and what social services are available after 1-day vs 4-days within a reasonable amount of time. Finally, in all such cases, unless respondents receive help in understanding more about the consequences of outages and backup services, their preferences and values are almost certainly uncertain and incomplete. Thus, abstracting away significantly from what will actually happen in the blackout and presenting a number of scenarios (with likely learning effects during the experiment) may lead to mechanical and uninformed responding rather than enlightening people about their world and their preferences in relation to that world.

Third, respondents' value of reliability is determined by many factors (not only by interruption-related factors but also by customer-related factors such as respondents' perceived level of reliability and their demographic characteristics), and there may exist behavioral incoherence (e.g., making choices using lexicographic semi-orders or heuristics). In such cases, differences across people will be washed out by aggregating over individuals to produce a single average utility function -for example, if 50% of people make their choices only based on price whereas the other 50% make their choices only based on the amount of power, the average will end up implying precise tradeoffs in aggregate that none of the participating individuals is willing to make. Thus, using the resulting estimated cardinal utility function over an attribute space would be implausible and unverifiable in the case of value of reliable electric services during WLD-outages.

2.2.3 Assessment of bias and consistency

In addition to providing the information needed to assess respondents' value of the backup services, we tested two important effects that have cast doubt on WTP numbers from contingent valuation studies: scope insensitivity and anchoring [43]. Respondents are scope insensitive if their valuations of a given good or service do not reflect its magnitude. For example, Desvousges *et al.* report that people assigned very similar values (~$80) to protect 2,000, 20,000, and 200,000 birds from being killed by oil spills, suggesting that they cared about protecting the birds, but did not have a precise dollar per bird value in their minds [44]. Anchoring bias occurs when WTP estimates are influenced by irrelevant numerical information. For example, in a classic study, respondents gave higher estimates of the percentage of African countries in the United Nations after they provided an arbitrary high number in an unrelated task, compared to respondents who were asked to give an arbitrary low number [45].

To test for scope insensitivity and anchoring, we used a 2x2 between-subjects design with repeated measures on the second factor, as shown in Figure 2-5. Respondents were randomly assigned to Group 1 or Group 2 by a virtual computer-generated coin-toss (http://www.random.org). Group 1 first gave their WTP for the full backup service, and then moved on to the partial backup service, whereas Group 2 responded in the reverse order. If respondents are scope insensitive, Group 1's initial WTP for the full backup service and Group 2's initial WTP for the partial backup service should not differ, suggesting respondents care about getting service, but do not have a specific dollar-per-amp (or dollar-per-kWh) figure in their minds. If respondents are biased by anchoring, Group 2's WTP for the full backup service should be smaller than Group 1's, as the partial service WTP question for Group 2 anchors respondents on a lower number for their full service WTP. Using the same reasoning, Group 1's WTP for the partial backup service should be greater than Group 2's WTP for the partial backup service.

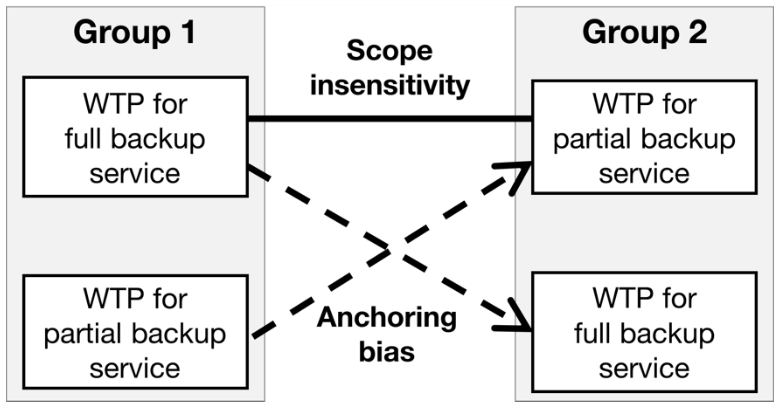

Figure 2-5. Experimental design. Group 1 completed the WTP question for the full backup service and then completed the WTP question for the partial backup service. Group 2 completed the WTP questions in the reverse order. Scope insensitivity (solid line) predicts that the WTP for full backup service in group 1 should not be different from the WTP for the partial backup service for Group 2. Anchoring (dashed arrow) predicts that the WTP for the full backup service for Group 1 is greater than the WTP for the full backup service for Group 2 (which would be anchored by the lower number preceding it). Similarly, anchoring predicts that the WTP for the partial backup service for Group 1 (with a larger number preceding it) is greater than the WTP for the partial backup service for Group 2.

We also developed two additional conditions to check the consistency of respondents' preferences. Our first check was whether WTP for electricity backup per kWh were greater than or equal to the normal electricity cost (i.e., $0.11/kWh), as the value of electricity should not be decreased by a blackout.[6] Second, for the same respondent (as opposed to across experimental

[6] In the elicitation, we did not tell the respondents about the normal price of electricity to avoid anchoring them on a value we provided.

groups), the WTP for the full backup service should be greater than or equal to the partial backup service, as the former encompasses the latter.

2.3 Results

To recruit a diverse sample within Allegheny County, the study was advertised through local community organizations and online through Craigslist and the Center for Behavioral Decision Research at Carnegie Mellon University. Individuals were required to be 25 years or older, had to have lived in Allegheny County for at least three years, and have at least one other adult living in their household.[7] All interviews were conducted in a face-to-face format between July and August 2015. The respondents completed the three sections of the survey individually at their own pace. Interviews took one hour on average. Once the interview was completed, the respondents were compensated $10 for their time. We recruited 73 eligible respondents (Group 1: *n*=38, Group 2: *n*=35). We excluded three interviews because one respondent did not meet the eligibility criteria, one already owned a number of backup generators, and one could not understand the WTP response mode. The conclusions do not change if we include the first outlier (WTP results were similar to the averages), and no results could be calculated for the other two.[8] [9]

[7] In other words, we recruited residents of Allegheny County who have a sense of their domestic budget and experience paying their electric bills, have lived long enough in, and are familiar with, the region and its power system, and are electric consumers. The criteria for eligibility were tested in the pilot study, and slightly modified before the actual implementation.

[8] The second outlier was completely off-grid, thus the hypothetical outage scenario and the assumptions for the backup services were not applicable (this respondent refused to answer the survey). The third outlier's answers were not at all consistent (e.g., "not sure" WTP were lower than "sure" WTP but higher than "no" WTP), so we could not calculate the value to service HP and LP demands and the respondent's range of uncertainty.

[9] In addition to the main results from the analyses of the respondents' WTP, we performed additional analyses to compare the respondents' WTP by demographic category (household income and housing types) and level of preparedness for an outage (whether they had backup generators, battery power devices, etc.). We found that the respondents' WTP were slightly influenced by income levels, but not by other variables. We also compared the respondents' WTP in relation to their outage experiences during their lifetime, but we did not observe any significant difference.

We compared the demographic information of the survey respondents with census data for Allegheny County, Pennsylvania. The survey sample was similar with respect to income and race but had fewer men and middle-aged individuals than the local population. The average age of the respondents was 43 (SD=16), 56% were female, and 33% were non-white. On average, the respondents had lived in Allegheny County for 20 years (SD=18). About 73% lived in the Greater Pittsburgh metropolitan area, and 27% of the respondents lived in the suburbs.

2.3.1 The value of service for loads of high and lower priority

Our first result is that the respondents valued backup service for their HP demands more than that for their LP demands, and as they received more information, their WTP for the partial backup service to meet HP demands (≤ 20A) increased, while their WTP for power to serve LP demands (> 20A) decreased slightly.

We calculated the amount that the respondents were sure they were willing to pay to meet HP demands in the following way: 1) We used the upper bound of the highest box the respondents checked in the "yes" column of the WTP question for the partial service (see Table 2-2 for the WTP summary), 2) estimated the respondents' electricity consumption by summing up the multiplication of the amount of electricity that each appliance consumes, the number of each selected appliances, and the time that each appliance would be turned on,[10] and 3) divided the maximum WTP for the partial backup service by the amount of power consumed by the appliances they selected within the 20A limit. Thus, the value of meeting HP demands would be $\frac{WTP_{partial}}{Electricity\ consumption\ within\ 20A\ limit}$. For example, if a respondent indicated his/her maximum

[10] Because we only asked the respondents to estimate their demands at four specific times of the day, we did not have their actual total consumption. Instead, we used three different sets of plausible assumptions and computed the average of the three values in order to estimate the total electricity consumption. However, the ability to purchase capacity during the blackout is also important. For that, we also conducted the same analysis for capacity charge (for kW).

willing to pay of \$25 for 10kWh (from the partial service), the value of serving HP demands would be $\frac{\$25}{10} = \$\,2.5/kWh$. Next, we calculated the amount that the respondent was sure (s)he was willing serve LP demands by: 1) Using the upper bound of the highest box that the respondents checked in the "yes" column of the WTP question for the full service (maximum WTP for the full service; see Table 2-2 for the WTP summary), 2) subtracting that number from their maximum WTP for the partial service, and 3) dividing by the amount of power consumed by the appliances they selected without any limit, minus the power consumed by appliances they selected within the limit.[7] Thus, the value of serving LP demands would be $\frac{WTP_{full} - WTP_{partial}}{Electricity\ consumption\ without\ limit - Electricity\ consumption\ within\ 20A\ limit}$. For the example in Figure 2-3, because the respondent indicated that (s)he was willing to pay up to \$45 for 70kWh (from the full service), his/her value of serving LP demands would be $\frac{\$45-\$25}{70-10} = \$\,0.33/kWh$.

Table 2-2. Summary of the "sure" WTP for the full and partial backup service.

		Min	Median	Mean (M)	Max	SD	N
Initial	Full backup (\$/day)	**0**	**30**	**39**	**150**	**31**	**73**
	Partial backup (\$/day)	**0**	**20**	**23**	**80**	**17**	**73**
Middle	Full backup (\$/day)	**0**	**40**	**48**	**200**	**42**	**73**
	Partial backup (\$/day)	**0**	**25**	**33**	**100**	**24**	**73**
Final	Full backup (\$/day)	**0**	**40**	**51**	**200**	**41**	**73**
	Partial backup (\$/day)	**0**	**30**	**37**	**100**	**24**	**73**

Table 2-3 summarizes the sure amount the respondents were willing to pay per kWh for serving HP and LP demands, and Figure 2-6 shows each observation. We compared the values using the Wilcoxon Signed-Ranks tests (Wsr) [46]. We report the statistic V, which describes the smaller of the sum of positive signed ranks and the sum of negative signed ranks, for the initial WTP (V_i), middle WTP (V_m) and final WTP (V_f), as well as the difference between middle and initial

(V_{mi}), and final and middle (V_{fm}).[11] As Figure 2-6 shows, the respondents report a significantly higher WTP to serve HP demands than their LP demands at all stages (Wsr, V_i=554, paired Cohen's D=0.21; V_m=270, D=0.67; V_f=212, D=0.75; all $p < .05$), and the values to serve HP demands significantly increased as the survey progressed (Wsr, V_{mi_HP}=80, D_{mi_HP}=0.58; V_{fm_HP}=137, D_{fm_HP}=0.21, both $p < .05$). In contrast, the values to serve LP demands significantly decreased from initial to middle assessments (Wsr, V_{mi_LP}=695, $p_{mi\_LP} < .05$, D_{mi_LP}=0.12), but did not differ between middle and final assessments (Wsr, V_{fm_LP}=297, p_{fm_LP}=.77, D_{fm_LP}=0.026).

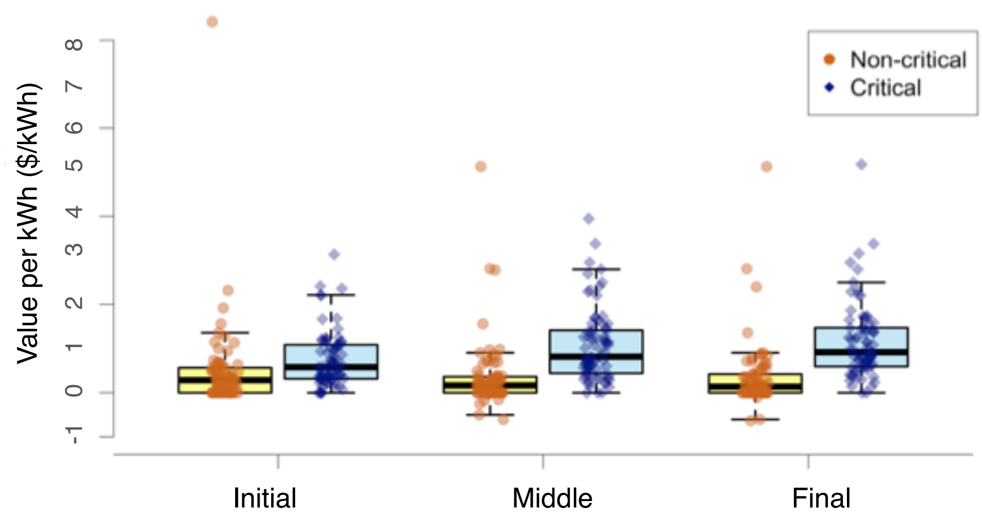

Figure 2-6. Distribution of the value per kWh to serve lower priority (LP) and HP demands by stage over the course of the study (LP: left at each stage (yellow), HP: right at each stage (blue)). Boxplots show the median, interquartile range, and whiskers at 1.5 times the interquartile range (or the greatest/smallest number). Yellow circles indicate the value of LP demands for each respondent, and blue diamonds indicate the value of HP demands for each respondent at each stage.

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[11] The test statistic for the Wsr (V) is defined as the smaller of the sum of the positive ranks (V^+) or the negative ranks (V^-), where the sum of V^+ and V^- equals the sum of all the ranks ($\frac{n(n+1)}{2}$) if no ranks are tied. If the test statistic significantly deviates from the critical value, we rejected the null hypothesis that the two samples were drawn from the same population distribution [46].

Table 2-3. Summary of the "sure" value per kWh, to serve high priority (HP) and lower priority (LP) demands.

		Min	**Median**	**Mean (M)**	**Max**	**SD**	**N**
Initial	$/kWh of the HP demands	0.00	0.58	0.75	3.1	0.63	73
	$/kWh of the LP demands	0.00	0.29	0.51	8.4	1.0	73
Middle	$/kWh of the HP demands	0.00	0.82	1.1	3.9	0.84	73
	$/kWh of the LP demands	-0.61	0.17	0.36	5.1	0.79	73
Final	$/kWh of the HP demands	0.00	0.92	1.2	5.2	0.88	73
	$/kWh of the LP demands	-0.63	0.14	0.35	5.1	0.76	73

Thus, by the end of the process (as well as at the other stages), on average, the respondents placed a higher value on serving their HP demands (Mean (M)=$1.2/kWh) than that of their LP demands (M=$0.35/kWh). Furthermore, their WTP to serve HP demands significantly increased by 56% (from $0.75/kWh to $1.2/kWh) as they came to better understand the inconveniences and monetary losses they might suffer. We found that several respondents decreased their WTP as the survey progressed (full: 8 or less, partial: 9 or less), indicating the respondents felt free to either increase or decrease their WTP.

2.3.2 Uncertainty in WTP assessments

We operationalized the respondents' uncertainty about their WTP as the difference between the upper bound of the highest box that the respondents checked in the "not sure" column of the WTP questionnaire, and the upper bound of the highest box that the respondents checked in the "sure" column. For example, in case of Figure 2-3, the respondent checked "yes" up to $24.99, "not sure" up to $44.99, and then "no" afterwards. Then, the respondent's range of uncertainty would be $\$44.99 - \$24.99 = \$20$. There were 5 (partial backup service) and 13 (full backup service) respondents who were willing to pay higher than $75 in the final stage, after which we asked for a single number that best represented their WTP. Because we were not able to obtain a range of uncertainty for these respondents, we excluded them from the uncertainty analysis.

Table 2-4 summarizes the results, and Figure 2-7 compares the range of uncertainty between different backup services and stages. We also compared the results using the Wsr and reported the statistic V for the difference between initial and middle (V_{im}), middle and final (V_{mf}), and initial and final (V_{if}) for each backup service, as well as the level of uncertainty in initial (V_i) and final (V_f) stage between the backup services.[12] In the initial stage, the respondents were slightly more uncertain about the partial service than the full backup service (Wsr, V_{i}=237, p=.44, paired Cohen's D=0.16). Comparing the initial to middle stage, the respondents became less uncertain, and the decrease was more pronounced in the partial backup service case (Wsr, V_{im_full}=263, p_{im_full}=.17, D_{im_full}=0.19; $V_{im\_partial}$=522.5, p=.06, $D_{im\_partial}$=0.21). Comparing the middle and final stages, the information regarding the respondents' monetary losses slightly decreased their uncertainty about both backup services, but the deceases were not statistically significant (Wsr, V_{mf_full}=165.5, p_{mf_full}=.66, D_{mf_full}=0.082; $V_{mf\_partial}$=261, $p_{mf\_partial}$=.34, $D_{mf\_partial}$=0.14). Over the course of the entire study, the respondents decreased their uncertainty in their WTP for both the full and partial backup service by 16% and 23%, respectively (Wsr, V_{if_full}=300.5, p_{if_full}=.07, D_{if_full}=0.26; $V_{if\_partial}$=628, $p_{if\_partial} < .05$, $D_{if\_partial}$=0.28). Yet, even by the end of the study, uncertainty about the unfamiliar ideas of the partial backup service remained slightly higher than that for the full backup service (Wsr, V_f=101, p_f=.16, D_f=0.18).

[12] Because the number of respondents with "sure" WTP higher than $75 for the full and partial backup service in the end of the study did not match (5 respondents for the partial backup service and 13 respondents for the full backup service in the final stage), we dropped the respondents with WTP higher than $75 for the *full* backup service and compared the ranges of uncertainty. For the comparisons between stages, we dropped the WTP higher than $75 for *each* backup service in the end of the study (i.e., 5 respondents from the partial backup service and 13 respondents from the full backup service) to compare the ranges of uncertainty within each service.

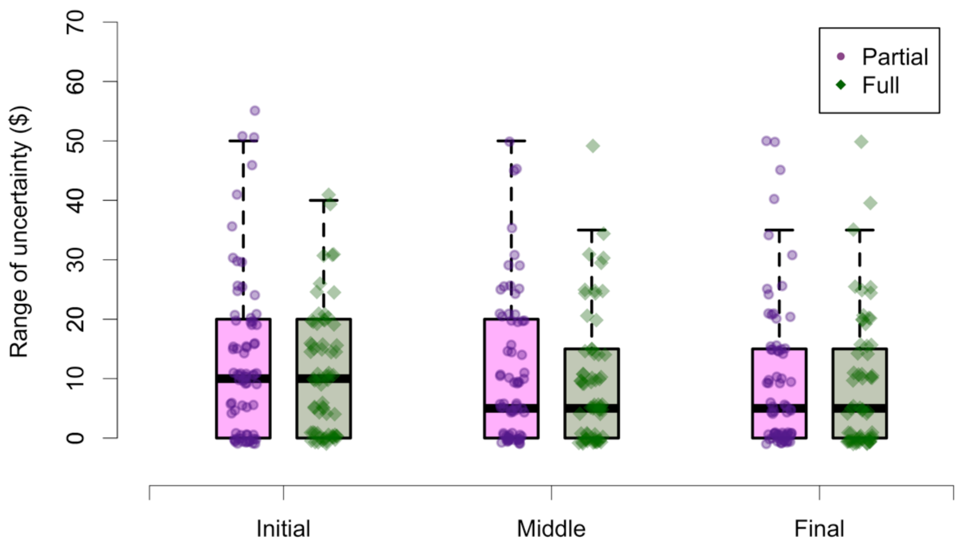

Figure 2-7. Distribution of the range of uncertainty in the partial (purple circle) and full (green diamond) backup service with boxplots after dropping the respondents who had WTP higher than $75 at each stage and backup service (partial: left at each stage (pink), full: right at each (green)). Purple circles indicate the range of uncertainty for the partial backup service for each respondent, and green diamonds indicate the range of uncertainty for the full backup service for each respondent at each stage.

Table 2-4. Summary of the ranges of uncertainty after dropping the respondents who had WTP higher than $75 in the final stage.[10]

								Percentages that		
		Number of respondents	Mean (M)	SD	Median	Min	Max	Not sure > Sure	Not sure = Sure	Not sure < Sure
Initial	Partial	68	13	13	10	0	55	72%	28%	0%
	Full	60	11	10	10	0	40	70%	30%	0%
Middle	Partial	68	11	12	5.0	0	50	66%	34%	0%
	Full	60	9.6	11	5.0	0	50	67%	33%	0%
Final	Partial	68	11	13	5.0	0	50	59%	41%	0%
	Full	60	9.0	11	5.0	0	50	57%	43%	0%

In summary, the information provided by the survey protocol helped respondents better understand the blackout scenario, its consequences, and the backup services. On average, it reduced the range of uncertainty for both the full ($11 to $9.0) and partial backup service ($13 to

$11). The greater uncertainty for the partial versus full backup service likely reflects the respondents' different familiarity with the two options. While the standard deviations and the ranges of uncertainty were fairly high, a primary reason for this was the large heterogeneity across people in their WTP due to different electricity use profiles, demographics, and needs. More discussions about heterogeneity and further analysis are provided in Chapter 2.3.3.

2.3.3 Consistency and bias checks

We introduced two conditions to check the internal consistency of respondent's WTP assessments. Results are summarized in Table 2-5. First, we compared the WTP for backup service per kWh with the normal electricity cost (assuming an average electricity rate of $0.11/kWh). At the beginning of the survey, 8 respondents valued the full backup service lower than their normal electric services, as did 6 respondents for the partial backup service. By the end of the survey, these numbers dropped from to 4 (for full) and 2 (for partial). Second, no respondent gave a higher WTP for the partial backup service than the full backup service at the beginning of the survey, but 6 did in the middle and 3 did by the end. Thus, by the end of the survey, 90% of the respondents gave responses that suggested well-reasoned, systematic preferences.

Table 2-5. Number of inconsistencies from two consistency checks.

	Number of inconsistencies					
	Partial backup service			Full backup service		
	Initial	Middle	Final	Initial	Middle	Final
Normal electricity cost ($/kWh) > Electricity backup cost ($/kWh)	6	3	2	8	7	4
WTP for the partial backup > WTP for the full backup	Initial		Middle		Final	
	0		6		3	

Next, we tested scope sensitivity by comparing the WTP distribution for those first asked to give their partial WTP versus those first asked to give their full WTP in the initial stage. Because this test was between-subjects, the respondents were not influenced by any prior numerical information when making their judgments. Scope insensitivity implies that there will be little difference between the WTP distributions for those two groups. Although Group 1 gave a higher average value for the full backup service (M=\$35, SD=29) than Group 2 gave for the partial backup service (M=\$27, SD=20), the result of a two-sample Kolmogorov-Smirnov (KS) between the two groups were not statistically significant ($KS\text{-}D_{full\_partial}=0.17$, $p_{full\_partial}=.68$). More in-depth analysis about scope insensitivity is provided in Chapter 2.3.4.

Then, anchoring bias would be present if the respondents' later WTP estimates are influenced by their earlier estimates. The null hypothesis is that initial WTP distributions of the same backup service were drawn from the same population distribution ($H_0: X_{1_{initial_j}} = X_{2_{initial_j}} where j = full, partial$). We conducted two-sample KS tests and compared Group 1's and 2's cumulative distribution functions, as shown in Table 2-6. In all the cases, the null hypotheses cannot be rejected (two sample KS-test, $KS\text{-}D_{full=}0.22$, $p_{full=}.35$; $KS\text{-}D_{partial=}0.19$, $p_{full=}.49$). Importantly, Group 1 started with higher WTP (from the full backup service question) but resulted in lower numbers than Group 2, which was the opposite of an anchoring effect. Thus, we conclude that the order of introducing two backup services neither anchored nor influenced the respondents' WTP.

Table 2-6. Summary of KS tests for anchoring bias with summary of initial WTP results from two groups for the partial (left) and full backup service (right).

		Partial backup				**Full backup**			
	N	Mean (M)	SD	KS-D	*p*	M	SD	KS-D	*p*
Group 1 (Full first)	38	\$19	14	0.19	.49	\$35	29	0.22	.35
Group 2 (Partial first)	35	\$27	20			\$45	33		

2.3.4 Multiple linear regression analysis and scope sensitivity

We used multiple linear regression to model the respondents' final WTP for the full and partial backup service. To do this, we: 1) included regressors in the model if they reduced the root mean-squared prediction error according to 5-fold cross-validation, 2) examined the correlations between the regressors, 3) conducted principal component analyses on the regressors,[13] 4) checked for necessary transformations of the regressors, and 5) modeled the final WTP as linear functions of selected variables and components which minimize the sum of squared residuals (Figure 2-8). Both models provide reasonable estimates of respondents' final WTP (adjusted $R^2_{partial}$=0.40, $p_{\text{partial}} < .05$ *and* adjusted R^2_{full} =0.38, $p_{\text{full}} < .05$) and perform substantially better than simple models only with intercepts (according to 5-fold cross validation). We also used a multi-level model with varying intercepts by respondent (Figure 2-9) [47].

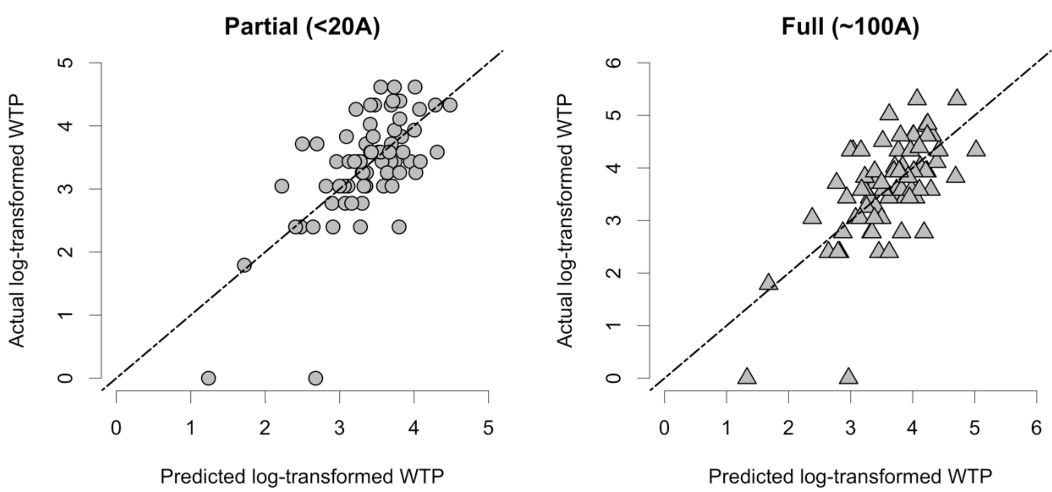

Figure 2-8. Predicted log-transformed WTP against actual log-transformed WTP in the final stage (partial: left and full: right) using multiple linear regression analysis against actual final WTP, including two extreme outliers who were not interested in using both backup services.[14]

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[13] If a regressor is not strongly correlated with other regressors, we did not transform the regressor. However, for some regressors that are strongly correlated with each other, we: 1) scaled (set standard deviations to 2) centered (shifted means to 0), and 3) conducted a principal component analysis to find a linear combination that explains the most variance of the group of variables.

[14] There were 7 (partial backup service) and 11 (full backup service) respondents who had absolute difference between actual and predicted values larger than 1 in the final stage. The two most extreme outliers were the respondents with

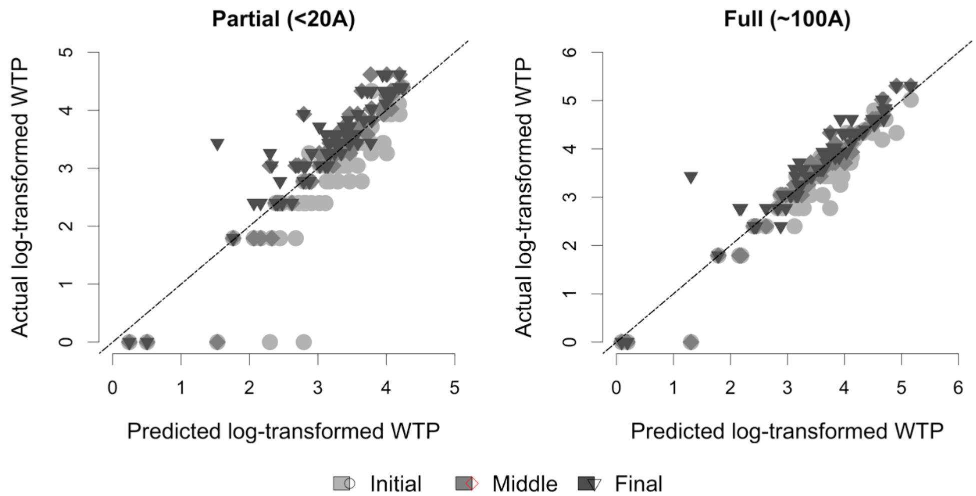

Figure 2-9. Predicted log-transformed final WTP against actual log-transformed final WTP (partial: left and full: right) using regression models with varying intercepts by respondents, including two extreme outliers who were not interested in using both backup services.[15]

A likely reason for the lack of statistical significance of the scope sensitivity test was the large heterogeneity across people in their WTP (variance of random intercepts across the respondents are 0.64 (partial backup service) and 0.78 (full backup service)). Using the regression models with varying intercepts (Figure 2-9, including the outliers), we estimate that heterogeneity, and provide a more precise estimate of scope sensitivity by comparing Group 1's WTP for the full backup service and Group 2's WTP for the partial backup service. In this model, we included a factor variable for the randomly assigned group (1=Group 1, 2=Group 2). If this variable was

zero WTP for both backup services (Cook's $D_{partial}$=0.41, 0.036 (M=0.021), $Leverage_{partial}$= 0.34, 0.10 (M=0.10); D_{full}=0.27, 0.24 (M=0.018), $Leverage_{full}$=0.32, 0.10 (M=0.11)). While removing the two outliers increased some of the variables' coefficients (e.g., value of perishable food), the coefficients of other variables decreased (e.g., electricity consumption under 20A limitation) because they had almost opposite preferences. The number of responses for the full and partial backup service are different because of some non-responses in the case of the partial backup service.

[15] There were 3/2/2 (partial backup service, in the initial/middle/final stages) and 1/1/1 (full backup service, in the initial/middle/final stages) respondents who had absolute difference between actual and predicted value larger than 1. The two most extreme outliers had zero WTP in the initial stage, but then increased their numbers (to \$30 and \$50, respectively) in the final stage.

statistically significant, then respondents would be scope sensitive across their three choices. However, this was not the case ($p \geq .37$).

To determine whether we had enough respondents to adequately detect scope sensitivity, we calculated the required sample size needed to reject the null hypothesis of no scope sensitivity 80% of the time with an alpha level of 0.05 by using the effect sizes obtained in the study. According to the result (using a two-sample t-test), we would need 226 respondents from each group (mean difference=0.26, pooled SD=1.0; WTP results were log-transformed before the calculation).

2.4 Discussion

2.4.1 Study results and policy implications

First, our results suggest that the value of serving HP demands for a one time 24-hour outage (M: $0.75/kWh) was significantly higher than that of LP demands (M: $0.51/kWh) even when they only brought their prior knowledge to the assessment. Second, as the respondents received additional information, they placed higher value on sustaining services they considered HP (M: $0.75/kWh to $1.2/kWh), whereas the value they attached to LP demands slightly decreased (M: $0.51/kWh to $0.35/kWh). Third, the respondents' uncertainty about their WTP decreased as they worked their way through the protocol (full: $11 to $9.0, partial: $13 to $11 on average), suggesting that they progressively understood more about the backup services, and how much they cared about those services. Finally, our checks suggested that the vast majority of respondents (90%) were consistent and systematic about their preferences and were not biased by their previous WTP responses. However, the respondents demonstrated only weak sensitivity to the magnitude of service provided (scope sensitivity).

So far, our study is most similar to Sullivan, Schellenberg and Blundell which combines individual study results conducted by major utilities, and derives a customer damage function for industrial, commercial, and residential customers [21]. The average interruption cost can be estimated as a function of interruption attributes and customer characteristics (using the constructed customer damage functions which can be applied to estimate interruption costs as a given season, day of week, timing of interruption, duration, geographical region, and customer type). While the results analyzed by Sullivan *et al.* cannot be simply compared to the results obtained in this study [20, 21],[16] our survey framework has three major improvements with policy implications. First, we can assess the difference between the value for the first few kWh and the last amount consumed [48]. Using the considerable amount of consumer surplus, distribution utilities and other relevant parties, such as regional authorities and local or state governments, can substantially reduce interruption costs if they continue to supply at least a small amount of electricity during such outages. In the event of WLD-outages, the benefits from implementing partial backup services and covering customers' bare necessities will become even greater.

Second, the survey framework highlights the benefits of information about outages and associated costs, especially when respondents are not familiar with the issue. If we assume that

[16] The studies only consider the differences between full backup service or nothing and divide the elicited WTP by the average electricity demand (1.5kW for power demand and 1.5kWh times interruption durations for the energy consumptions; the numbers are derived from dividing the average residential customers' annual electricity consumption by 8760 hours) to calculate the "cost per average kW" and "cost per unserved kWh". However, the unit value of the first little portion of electricity is likely to be worth more than the value of last amount consumed. Moreover, in addition to the large seasonal and regional variations in people's electricity demands, their consumptions may be substantially changed during WLD-outages. For instance, people consume more electricity during summer for air conditioning; also, our study respondents consumed 3.5kWh per hour on average, which is more than twice of the numbers that Sullivan, Mercurio, and Schellenberg used [20].

the cost increases proportionally to the duration, scaling the Sullivan, Schellenberg and Blundell's results to a 24-hour outage suggests a cost of $46 (by using the simple linear interpolation: $3.9 + \frac{(\$32 - \$3.9)}{16\ hours - momentary(0\ hour)}(duration) = 3.9 + 1.8(duration)$) [21]. While the estimated cost is higher than our study's initial "sure" WTP for the full backup service (M: $39), it is less than the number we got from the final stage (M: $51). Importantly, the increase comes from the HP demands (Wsr, $V_{if_{partial}} = 64.5$, $p_{if\_partial} < .05$), not from the LP demands (Wsr, $V_{if_{(full-partial)}} = 462$, $p_{if\_(full-partial)} = .13$). This result suggests that the information did not simply increase the respondents' WTP values, but it actually helped them to better understand which demands were most important to them and why sustaining service to those demands is important [49]. Thus, our study reemphasizes the need for information when eliciting values to serve HP and LP demands.

Finally, our approach demonstrates that respondents expressed a significant amount of uncertainty about their preferences, but part of that uncertainty could be reduced with additional information. Yet, uncertainty persisted throughout the study (full: $9.0, partial: $11 on average), illustrating the need for frameworks that can incorporate the uncertainty of public preferences into decision-making.

2.4.2 Limitations

We note three limitations of the study. First, there are some drawbacks associated with multiple-bounded discrete choice method [25]. For example, Roach *et al.* determine that welfare estimates can be affected by the range of bids available to respondents (range bias [32]), and Alberini, Boyle and Welsh suggest that order of presentations can have a significant effect [33]. While we alleviated some of the range bias by using the follow-up question, we could not eliminate the range bias entirely, and still had a small peak near $75 (the maximum for the multiple-bounded discrete choice procedure).[17] Second, we found that the respondents' income levels only slightly influenced their WTP for backup services, suggesting they were either not constrained by their ability to pay, or were not considering the other possible uses of their money [50]. Third, because the length of the interviews precluded our exploring WTP for the partial service levels of other than 20A, we were not able to trace out the full shape of the consumer surplus.

2.5 Conclusion

Low-probability high-consequence interruptions in electric services of large spatial scale and long duration can give rise to enormous economic and social costs, including loss of life.[18] These costs can be reduced if a small supply of electricity can be provided during such outages. However, providing this capability requires incremental investments. One important input to determining whether and where such investments might be warranted is an informed judgment by residential and other customers of the value of such service as reflected through judgments about their WTP. The method we have developed and demonstrated in this chapter points the way to obtaining such informed judgments.

[17] We compared the "sure" WTP distributions without the follow-up question (categorizing all the respondents with WTP higher than $75 as "maximum sure WTP is $75" group) and with the follow-up question (assuming their maximum WTP answers from the follow-up question as their "sure" WTP) and observed reductions in the $75 peak (65% from the full service and 45% from the partial service in the final stage). Thus, the follow-up question helped alleviate the range bias.

[18] According to the Energy Information Administration, more than 85% of outages to the bulk electric system are caused by severe weather (e.g., thunderstorms, hurricanes, and blizzards); the annual cost of power outages caused by these events is estimated to be $18 to $33 billion [51].

3. Providing Limited Local Electric Service during a Major Grid Outage: A First Assessment Based on Customer Willingness-to-pay

While they are rare, widespread blackouts of the bulk power system can result in large costs to individuals and society. If local distribution circuits remain intact, it is possible to use new technologies including smart meters, intelligent switches that can change the topology of distribution circuits, and distributed generation owned by customers and the power company, to provide limited local electric power service. Many utilities are already making investments that would make this possible.

In the previous chapter, we observed consumer surplus associated with providing partial electric backup service (i.e., customers value the first bit of power more per kWh than the last bit), and the value of the first few kWh is significantly increased as respondents received additional information. The considerable amount of consumer surplus suggests that a region might be able to substantially reduce interruption costs if distributed utilities or other relevant parties could find a way to continue to supply at least a small amount of electricity and cover most customers' bare necessities.

To that end, we estimate the required service payment to implement the ability to provide a low-amperage backup to all residential customers and/or full backup service to some critical social services, compare the willingness-to-pay that would be required to justify the backup service with the measured willingness-to-pay distribution, and explore when the incremental investments are needed to implement these capabilities. Under many circumstances, upgrades in advanced distribution systems could be justified for a customer charge of less than a dollar a month (plus the cost of electricity used during outages) and would be less expensive and safer than the proliferation of small portable backup generators. We also discuss issues of social equity, extreme events, and various sources of underlying uncertainty.

The work presented in this chapter was a joint effort with M. Granger Morgan and Alexander L. Davis and was published in the journal *Risk Analysis* in February 2018 [52].

3.1 Introduction

Because the services provided by electricity have become critical in modern society, power outages can result in large economic and social costs. While they are rare, blackouts of large geographic extent with durations of several days or more occur more frequently than one might think (Figure 3-1) [30, 53-55]. In the past, such blackouts have been caused by extreme weather and by faults and errors in the operation of the bulk power system. With a changing climate, the frequency and intensity of extreme weather events is expected to increase [55-56]. Large future outages could also be caused by terrorist events and by large solar mass ejections [55, 57-58].

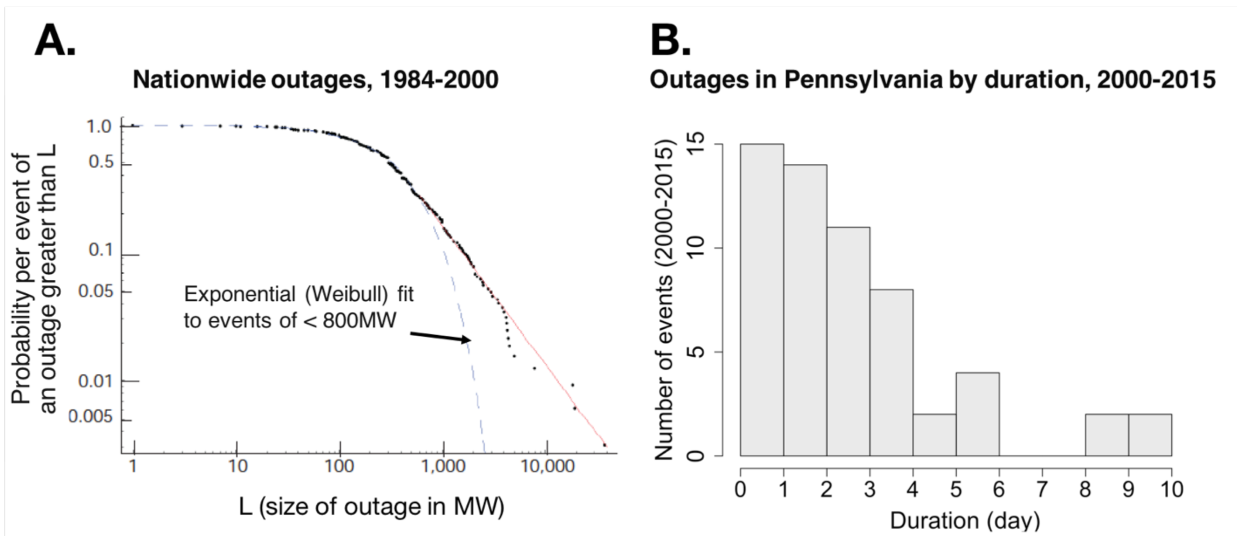

Figure 3-1. Large blackouts are more common than one might expect. A) Distribution of large blackout in the United States during the period from 1984 to 2000 (data compiled by North American Electric Reliability Corporation, figure reproduced from Talukdar *et al*. [53]). B) Distribution of large blackouts (outages affecting more than one distribution utility or more than one state) in the state of Pennsylvania during the period from 2000 to 2015 (data compiled by [54]).

In Chapter 2, we developed and demonstrated a method for helping individuals think systematically about their WTP to avoid the effects of WLD-outages. For simplicity in developing and demonstrating the method, we focused on the amount that individual homeowners would be willing to pay to avoid service interruptions only to their own home (i.e. not their neighbors or near-by critical social services). In addition to asking about the full service, we also asked respondents about their WTP to retain a low-amperage (e.g. 20A) service during an outage. The study results suggest that the respondents valued their HP demands much more than their LP demands. Hence, the social benefit of providing many customers with a small amount of electricity to cover their HP demands (such as lights or air conditioning during summer) is likely greater than serving a few customers full power to also meet their LP demands (such as using a speaker dock, DVD/video player, and LED TV to play a game). Although we only considered an outage of 24 hours on a hot summer weekend, the method could be applied to longer time periods and different times of year.

Many distribution systems now have installed automation that allows utilities to automatically change the topology of the distribution networks, for example changing the location from which a circuit is fed, isolating a damaged portion of a circuit, or connecting two circuits together [1]. More advanced automated sectionalizing switches (such as S&C electric company's IntelliRupter®)[19] and related protection devices can communicate with each other, sense direction of current flow, and adapt appropriately as the configuration of a distribution feeder changes. Many systems are also installing smart meters that allow utilities to connect and disconnect customers remotely [59]. Finally, growing amounts of gas-fired DG are being installed, often with combined heat and power (CHP) [60-63]. With modest upgrades to such systems, including backup battery power for control circuits and meters, the ability to synchronize DG when an

[19] See for example http://www.sandc.com/en/products--services/products/intellirupter-pulsecloser-fault-interrupter/. Accessed on Apr 05, 2018.

isolated feeder being repowered (i.e. local black start),[20] and some modest reprogramming or upgrading of some protection systems [64-67], it would be possible to operate a distribution feeder as an isolated island using DG to provide a low-amperage service to homes and selected HP demands in the event of an outage in the bulk power system. This is illustrated in Figure 3-2.

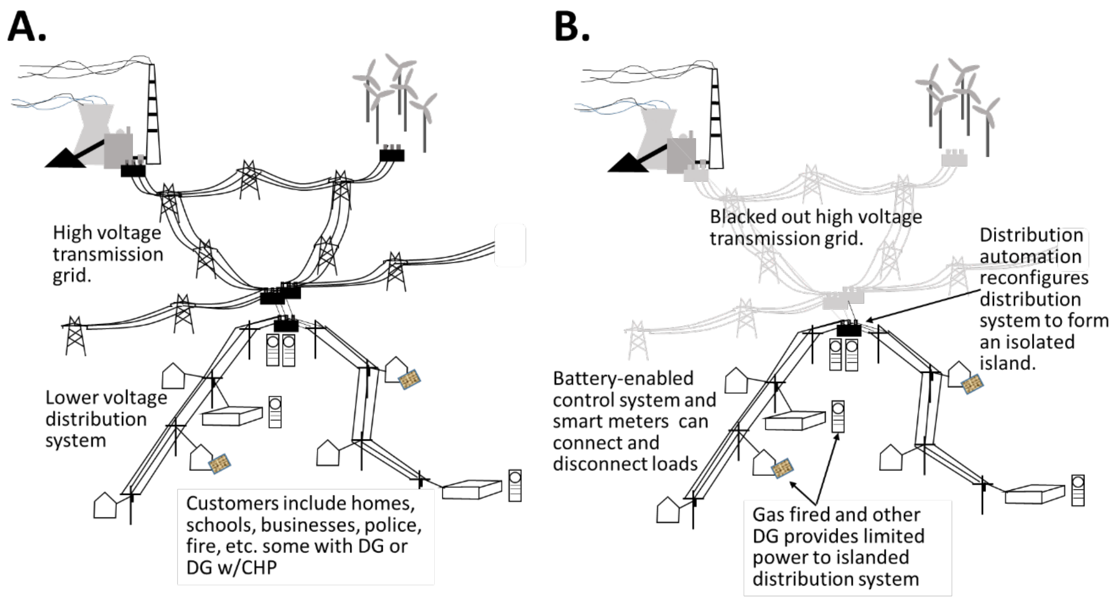

Figure 3-2. A) Conventional power system with high voltage grid feeding distribution systems**;** B) Illustration of the way in which distribution automation, smart meters, and distributed generation (DG) could be used to create an island with limited local electric service when power is not available from the bulk power system. The smart meters need to have battery backup so that they can drop loads and not reconnect until the DG has been brought up and synchronized.

In this chapter, we perform a series of order of magnitude calculations to illustrate how values elicited in the previous chapter can be used to illustrate how values elicited in the previous chapter can be used to inform investment decisions about the distribution system upgrades that

[20] Here we are not considering individual roof top PV (which with present inverter designs and regulations only operate when there is grid power) or small-scale DG (of the sort that individual residential customer might install). Rather our focus is on larger micro-turbines and CHP systems of the sort that medium sized and larger institutions and utilities might deploy [61].

could make service provision more robust in the event of major outages. Whether investing in such upgrades makes sense depends on the following three factors: 1) an assessment by the community of the likely future frequency and duration of possible large widespread outages; 2) the incremental cost of system upgrades to make a low-amperage service available; and 3) the willingness of individuals and the community to cover the costs of the necessary incremental investments. A key issue in our mind is *whose* WTP? While many high-end homes have their own backup generators fired by natural gas these days, many people cannot afford such systems. Also, in addition to the individual costs imposed by power outages, there are broad social costs including loss of injuries and deaths especially from vulnerable segment of the population. Hence, we also concern about issues of social equity and the possibility that we could move to a society of haves and have nots with respect to reliable electric power and the services it makes possible.

3.2 Required Technical Features to Provide a Low-amperage Backup Service

While the incremental investment needed to support a low-amperage backup service during a WLD-outage may be too excessive for many service territories, some regions with a significant risk of WLD-outages may be interested in introducing emerging technologies and enhancing their power system resiliency to better deal with those events. There are several strategies to make the distribution power system more reliable and resilient:

- *Hardening critical but vulnerable infrastructure*: While few extreme events can affect the entire region, in most cases, some parts of a region are likely to be particularly susceptible to severe damages compared to other areas (e.g., transformers and substations in regions of low conductivity and high latitudes are more likely to be damaged by induced currents from massive coronal mass ejection). In this case, the region can use either statistical models or simulation-based models to identify the vulnerable infrastructure and harden them. In addition, the system may also need to increase its level of physical and cyber protection (such as increasing physical surveillance and adopting improved integrated electric surveillance technologies).

- *Enhancing system operation and control*: This will be easiest, and least expensive for distribution systems that have already deployed intelligent distribution automation, which allows utilities to automatically change the topology of the distribution networks (for example changing the location from which a circuit is fed, isolating a damaged portion of a circuit, or connecting two circuits together [1]).
- *Establishing redundancies:* There are several regions where extreme weather events can simultaneously damage several critical system components and trigger cascading failures. In such cases, the regions do not only need to upgrade their distribution systems but also need to add redundancies. For instance, the systems would be able to consider changing feeder configuration from radial to loop, adding redundant power lines, and interconnecting a feeder to its neighboring feeders [68, 69].
- *Developing restoration strategies so that the system can restore failed system components and power faster*: While hardening physical assets reduces vulnerability of the regions, improving resiliency is often viewed as a cost-effective strategy [70]. Regions can increase their systems' resiliency by conducting preparedness planning and training, monitoring and inspecting facilities, allocating more mobile command and repair vehicles, dispatchable generation resources (e.g., truck-mounted mobile emergency generators [71]) and repair crews, procuring spare critical system components, and managing vegetation [69, 70].

Because we assumed that the hurricanes left the entire Pittsburgh's distribution system intact in the hypothetical outage scenario (see Chapter 2.2.1 for details), we only considered enhancing system operation and control, specifically introducing smart grid technologies and enhancing system operation and control (see Figure 3-2 for illustrations). However, if the region is expected to suffer extreme events that can also damage critical distribution system components, the system should also consider implementing other strategies.

To provide a low-amperage backup service via islanded distribution feeders by enhancing system operation and control, a region does not only need to deploy bi-directional automated sectionalizing switches and related protection devices but also need to upgrade smart meters. Smart meters have been widely deployed already, but current smart meters cannot automatically adjust or control power consumptions. Several utilities and manufacturers are now experimenting and deploying advanced smart grid technologies that employ internet-of-things technologies to better monitor, manage and control end-user's energy consumption over lower level, thus it would be possible to control residential customers' demands at circuit level or per-appliance level in the near future (see Eaton's smart energy management circuit breaker for an example [72]). Also, recent smart meter communication and control studies suggest that smart meters with wireless communication capabilities can limit or cut loads at the distribution level [73, 74]. Once the technologies are fully developed and mature, distribution utilities would be able to send signals remotely to turn off all the non-prioritized branch circuit breakers or non-prioritized electric appliances (i.e., LP demands) so that residential customers' consumptions can always fall below the predetermined level (such as 20A in our case). Until then, as a *transitional* measure, we propose upgrading traditional smart meters to smart meters with two different circuits which can replace binary (on-off) load shedding. For instance, as shown in Figure 3-3, a low-amperage service capability can be achieved by a smart meter which could be commanded to automatically feed two main circuit breakers (100A for normal circumstances and 20A for emergent circumstances). There also exist several other ‘load clipping’ strategies that can be used as transitional measures, such as Sparkmeter which cuts loads off using a mechanical relay when current exceeds the pre-specified limit [74].

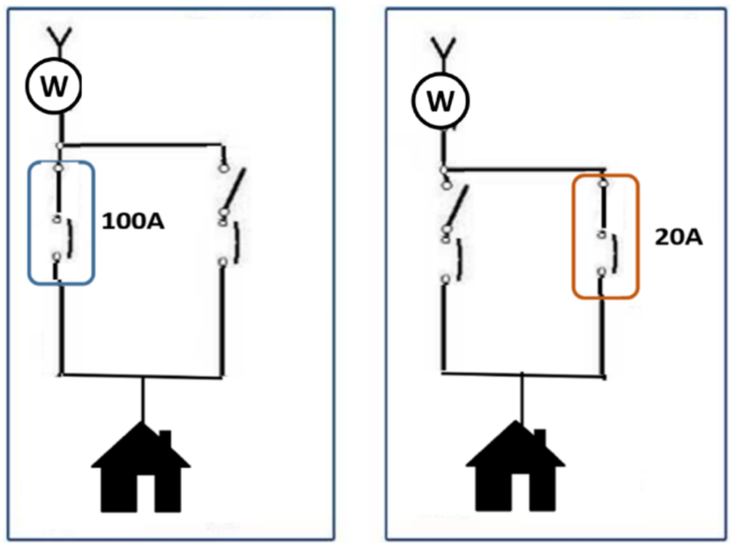

Figure 3-3. Concept diagram of a smart meter with two circuit breakers with different limits. Customers can receive electricity from regular limit for their normal electricity consumptions (left), but when a power outage occurs, they will receive limited amount of electricity from the other limit with low-amperage (right).

3.3 Order of Magnitude Estimates for One and Five-day outages

For the purpose of illustration, we considered implementing a low-amperage backup service for a distribution feeder that serves 2,500 customers. Following the strategies suggested by Narayan and Morgan [1], we assumed that either the distribution utility itself has sufficient DG to supply 20A service to all 2,500 customers on the islanded feeder(s) ($20A \times (120V - 220V) \times \frac{1}{1000} kW/A \cdot V \times 2{,}500 \approx 6MW - 11MW$), or that it has contracted with private DG owners who can supply that much power in the event of an outage. In either case, we assumed that most of the time these DG units are being used for non-emergency purposes so that it is only necessary to cover the cost of emergency generation during the outage.

To estimate the cost to upgrade control and protection equipment for a feeder, we have consulted with the director of distribution planning for a major urban utility that has already deployed intelligent distribution automation (including bi-directional smart sectionalizing switches that can sense the direction of current flow communicate with each other) and smart meters. The total cost of upgrades to the feeder and operation of the associated DG was on the order of $100,000 for a feeder covering 2,500 customers with additional annual operation and maintenance (O&M) costs of approximately 5 percent of this initial capital cost (i.e., $5,000). We assumed that these technologies last 20 years based on Narayanan and Morgan [1]. Of course, as noted below, if these cost estimates are optimistic or if some of the necessary upgrades have not already been accomplished and are charged to adding the ability to supply emergency service, costs could be higher.

We assumed that basic smart meters are already in place,[21] and if done in bulk, upgrading them by adding batteries for continuous operation in the event of a power outage, and a control circuit that can switch a main breaker from a high-amperage service (e.g., 100A) to a low-amperage service (e.g., 20A) would require an additional investment of $50 per meter (based on consultation with circuit breaker companies, including labor cost, smart meter cost, and backup battery; see Figure 3-3 for illustration and Chapter 3.2 for the technical details). Again, we assumed a lifetime of 20 years based on Narayanan and Morgan [1]. Because longer widespread

[21] Utilities have been deploying smart grid devices and technologies (including upgrading transmission and distribution system with enabling local distribution automation). Major electric utilities already have installed more than 50 million smart meters nationwide [59, 65-67]. In addition to being used for billing, these meters provide real time measurement of customer loads to help monitor and improve power system management.

outages are rare, here we assumed that customers will limit their loads manually (i.e. turn off appliances and open breakers) to meet the 20A constraint.

Finally, we assumed the cost of power produced by DG during an outage is 1.5 times that of grid power under normal circumstances (i.e. \$0.11/kWh$\times$ $1.5 \times \$\,0.17/kWh$).[22] We set the daily electricity cost per residential customer per day as \$9.8 ($20A \times 120V \times \frac{1}{1000} Wh/kWh \times 24hours \times \$\,0.17/kWh$), and assumed that the charge for electricity occurs when there is an actual outage. To adjust cost to present value, we used an interest rate of 3%.

If there is no consideration of when the outages occur (i.e., no consideration of time value of money), the required service payment per household per outage is simply the sum of total investment cost divided by the number of outages during the lifetime and the electricity cost (as shown in Table 3-1 below). However, because power outages occur randomly and the value of money declines over time, we modeled the occurrence of 24-hour outages using a Poisson arrival model.[23] We considered the case of a 24-hour outage that occurs on average once every 5, 10, and 20 years (i.e., the intervals between successive outages are Poisson distributed with $\lambda = 0.2, 0.1, and\ 0.05$). Because the occurrence of outages is probabilistic, in a few realizations of the model, outages occur much less or much more frequently than these mean values.

[22] In many parts of the United States, the levelized cost of electricity from gas fired DG is close to or actually competitive with the cost of grid power. We assume that long-term contracts have been put in place to secure power from DG in the event of a blackout. For further discussion, see Narayanan and Morgan [1].

[23] The use of a Poisson arrival model is a standard way of dealing with the occurrence of random events in which the occurrence of one such event is not affected by the occurrence of other random events, and the events are assumed to occur with a known constant rate ($\lambda = 0.2, 0.1, and\ 0.05$). However, climate change is expected to increase the frequency and intensity of severe weather events (Karl, Melillo and Peterson, 2009). In such case, non-homogeneous Poisson process or Markovian arrival process could be used to incorporate the time varying arrival rate.

Table 3-1. The required service payment per household per outage by the number of outages during the lifetime of technologies (i.e., 20 years). We assumed that upgrading the distribution system requires an investment of $100,000 and an investment of $50/meter to upgrade smart meters when the number of residential customers served by a feeder is 2,500.

	Number of outages during the lifetime									
	1	2	3	4	5	6	7	8	9	10
Required service payment per household per outage	$90	$45	$30	$23	$18	$15	$13	$11	$10	$9

3.3.1 Order of magnitude estimates for the 20A partial backup during 24-hour outages

While the primary motivation for implementing a capability to provide limited emergency power backup service using isolated distribution feeders is to mitigate the individual and collective consequences of WLD-outages, the WTP estimates in Chapter 2 were for a 24-hour outage. Hence, we first did the analysis for such a period, and then make assumptions to extend the analysis to longer periods (will be presented more in Chapter 3.3.3 below).

In this first estimate of the benefit from the backup service, we assumed that all the residential customers make fixed payments at the time of each outage. Thus, the net benefit that results from implementing the backup service is:

$$Net\ benefit = Total\ benefit - Total\ cost$$

$$= Total\ service\ payment - System\ upgrade\ cost - Annaul\ O\&M\ cost - Smart\ meter\ upgrade\ cost - \ Total\ fuel\ cost$$

$$= \sum_{i=1}^{n} \frac{2{,}500 \times Service\ payment\ by\ each\ customer}{1.03^{Year_i}} - 100{,}000 - \sum_{i=1}^{20} \frac{5{,}000}{1.03^{i}} - 50 \times 2{,}500 - \sum_{i=1}^{n} \frac{9.8 \times 2{,}500 \times Year_i}{1.03^{Year_i}}$$

where n=number of outages during the lifetime, and $Year_i$*= Year when the* i^{th} *outage occurs.*

The WTP of residential customers for the 24-hour partial backup service were found to be lognormally distributed (logarithmic mean=3.4, logarithmic standard deviation=.84).[24]

The upper parts of Figure 3-4 display the results of the 10,000 simulations using the different levels of WTP (x-axis) and the outage frequencies (once every 5, 10, or 20 years on average, from left to right). When we drew realizations using the Poisson arrival model, we encountered some in which no outage occurs, and some in which several occur. To simplify this order of magnitude assessment, we have excluded realizations in which no outage occurs, and cases in which more than three times as many occur as expected during the 5, 10 and 20-year intervals.[25]

Each point in the upper figure indicates the net revenue (i.e., total customers' payments minus the cost of system upgrades and the cost of electricity) when the outage occurs, and all the customers make the fixed and promised payments right after the outage. A point greater than zero indicates that the investment can be recovered through service payments, whereas a point less than zero indicates that the backup service would require some form of subsidy. The shaded areas are polygons that connect the minimum and maximum net revenue at the given WTP level using the truncation explained above. The bottom part of Figure 3-4 displays the cumulative distribution of WTP, with the vertical lines indicating the required service payment per residential customer per outage that is needed to justify the private low-amperage backup service.

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[24] We used the KS goodness of fit test to calculate the maximum difference between the elicited distribution and the lognormal distribution. Since the two distributions do not significantly deviate from each other (KS-D=.13, p=.18), we assumed that the fitted lognormal distribution appropriately represents the WTP distribution [46].

[25] If the region does not experience any outage during the lifetime, there is no way to recover the system upgrade costs. Also, we do not consider very extreme cases (outages occur 3 times or more often than the given average). The percentage of realizations that were removed were 36% (once every 20 years on average), 17% (once every 10 years on average), and 9.9% (once every 5 years on average).

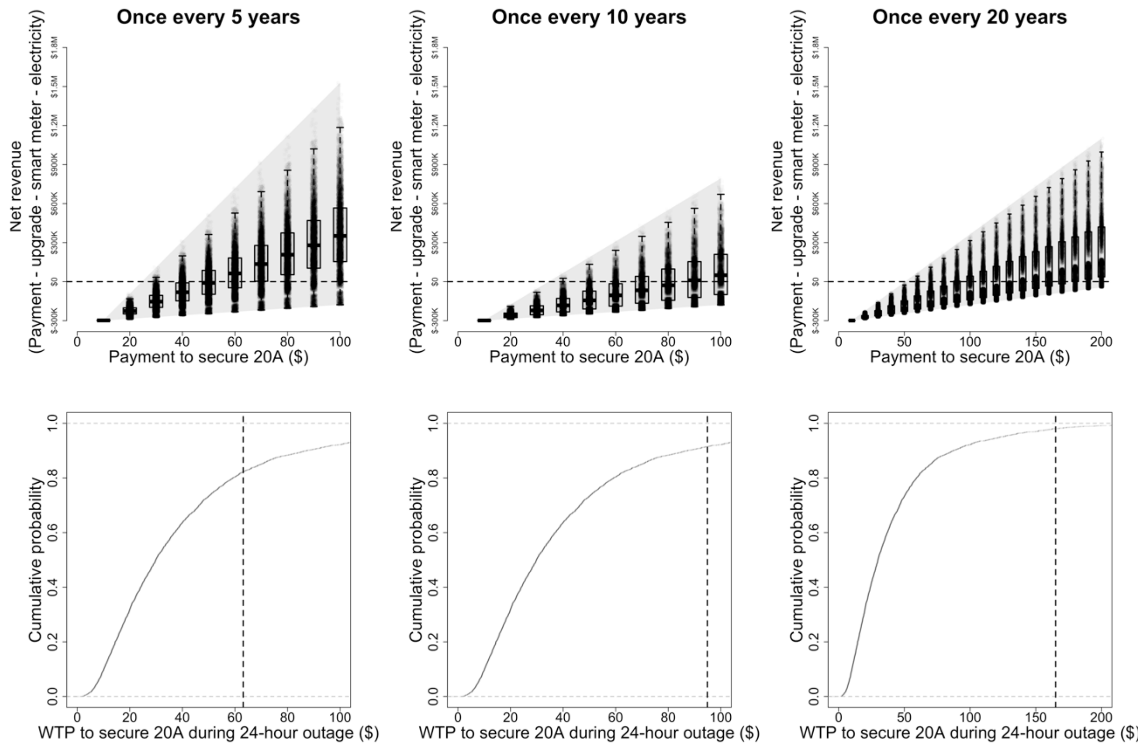

Figure 3-4. The upper panel shows the differences between the residential customers' payments to secure the private low-amperage backup service and the actual cost of providing the service for 10,000 realizations of the modeled outages under three different outage frequency scenarios (once every 5, 10 and 20 years). Each point indicates the net revenue when the outages occur according to the Poisson process, and the shaded area indicates the range of net revenue under the assumptions outlined in the text. We assume that upgrading the distribution system requires an initial investment of $100,000 and $5000 for annual O&M, and an investment of $50/meter to upgrade smart meters when the number of residential customers served by a feeder is 2,500. The lower curve shows the cumulative lognormal WTP distributions fitted to the results measured from Allegheny county residents. The vertical dotted lines represent the WTP that would be required to justify the partial backup service if the outage occurs at the mean of the generated Poisson random variables. Upgrades for outages once every 5 years on average can be justified at $63/customer/outage, for once every 10 years on average at $95/customer/outage, and once every 20 years on average $170/customer/outage.

If the region suffers a 24-hour outage once every 5 years on average, the backup service can be justified by a relatively low service payment. Assuming that the region is expected to suffer the outages at the mean of the generated Poisson arrival random variables, the backup service can be justified when all residential customers pay $63, which is at or below the value of WTP for 18% of them.[26] When the outage occurs on average once every 10 years or 20 years, the region would suffer fewer outages; thus, a substantial increase in the service payment is needed to justify the backup service ($95/customer/outage for 10 years and $170/customer/outage for 20 years which is only below WTP for 8.0% and 2.0% of the customers). Still, implementing the backup service is more cost effective than buying a small portable generator and storing diesel or gasoline for fueling (~$270 for purchasing a generator and ~$52/outage for gasoline if gasoline costs $3/gallon).[27]

3.3.2 Consideration of neighbors and critical social services

Power that is supplied to one's own home is not the only thing most people care about. We assumed that larger critical social services, such as hospitals, have their own emergency backup power, and the DG capacity exists to sustain other critical social services [1, 30, 55, 75]. A discussion of critical social services that depend on the availability of electric power (can be found in Chapter 8 of a recent National Academy report [30]).[28]

It is unclear whether WTP would be higher or lower in order to assure some continuing power for neighbors and other local services (emergency services, cash machines, drug and convenience stores, gas pumps, etc.). The answer could depend on both behavioral factors and the outage duration. As Table 3-2 shows, even if customers' WTP to secure their private backup

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[26] In the case of once every 5 years, the average occurrence times of the first, second, third, and fourth outage are year 4.9, year 10, year 15, and year 21, respectively. Since the lifetime of technologies are 20 years, we assume that the region would suffer three outages during the period. Similarly, in the case of once every 10 years, the region will suffer two outages at year 7.1 and year 17, and in the case of once every 20 years, the region will suffer only one outage at year 8.8.

[27] See for example http://www.amazon.com/DuroStar-DS4000S-4-Cycle-Portable-Generator/dp/B004918MO2. Accessed on Apr 05, 2018.

[28] Table 8.1 in this National Academy Report list critical social services by category including: emergency services; medical services; communication and cyber services; water and sewer; food; financial; fuel; non-emergency government services; transportation systems; lighting; and, building operations [30].

service are low, the backup service might still be justified if people attach high values to supplying power for neighbors and other local services. On the other hand, if customers' value for the private backup service is high enough, the distribution utility might also cover the critical social services without additional revenue.

Table 3-2. The required level of increase or decrease from the given service payment to justify the backup service (in percentage).

	Customers' payments to secure the private backup service								
	$20	$40	$60	$80	$100	$120	$140	$160	$180
Once every 5 years	220%	58%	5.2%	-21%	-37%	-47%	-55%	-61%	-65%
Once every 10 years	370%	140%	48%	19%	-5.1%	-21%	-32%	-41%	-47%
Once every 20 years	730%	310%	180%	110%	65%	38%	18%	3.2%	-8.3%

Because we did not know what people's preferences would be, we explore the issue parametrically by assuming, on the high side, that all the customers might be willing to pay 20% more to assure that both their neighbors and critical social services are supplied (i.e., value the social low-amperage backup service as high as 20% of the value of their private demands), whereas, on the low side, they might decrease their WTP by 20% because now they can fulfill some of their private HP demands through the sustained critical social services and/or going to the homes of neighbors with backup power.

Figure 3-5 summarizes the cost effectiveness of implementing a private and social low-amperage backup service for 24-hour outages varying WTP by $\pm$20%. The shaded area indicates the range of WTP that would be required to justify the backup service if a 24-hour outage occurs at the mean of the generated Poisson random variables (the left edge is the results when residential customers are willing to pay 20% more, and the right edge is the results when they are willing to pay 20% less). The results are not dramatically different than those for the case of only private backup service. Of course, this thought experiment does not include the non-monetary community benefits which might be large, especially as the duration of an outage increases.

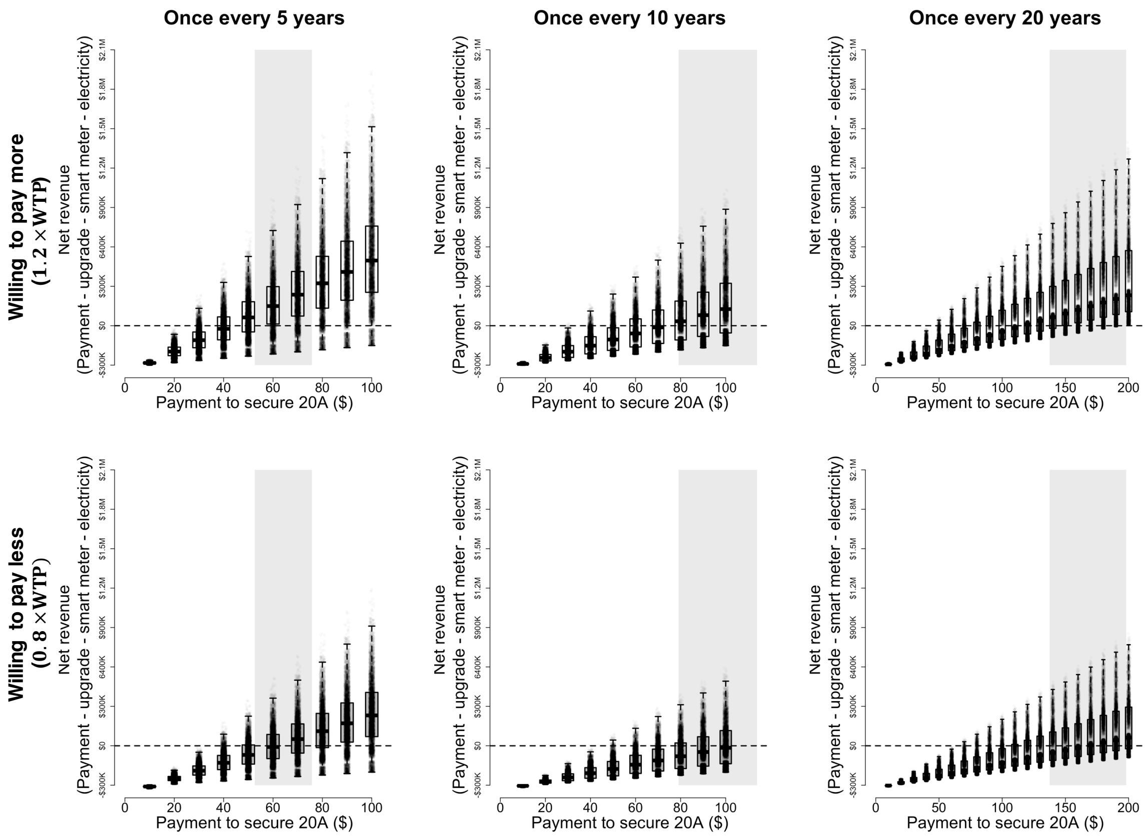

Figure 3-5. Results similar to those shown in the upper portion of Figure 3-4 in which WTP are increased by 20% (above) and reduced by 20% (below) given the possibility that the power to neighbors and to local critical social services without emergency power can both increase and decrease individuals' preferences. Here we use the generated Poisson random variables and the truncation explained in Chapter 3.3.1, and the boxplots show the median, interquartile range, and whiskers at 1.5 times the interquartile range. If a region suffers a 24-hour outage once every 5 years on average, the backup service can be justified at $53-76/customer/outage; once every 10 years on average case can be justified at $79-110/customer/outage; and, once every 20 years on average would require $140-200/customer/outage.

From the forgoing, we concluded that in some communities, a low-amperage backup service can be cost-effective if a 24-hour outage occurs at least once every 20 years. Implementing a low-amperage backup service appeared to be more cost effective (and certainly safer) than having each homeowner buy a ~$280 portable or stand-by generator and refuel the generator (~$52/outage), even in the case of decreased WTP due to sustained critical social services.[7] As might expected, the results changes when we explored the sensitivity of these findings to the assumptions made to the number of residential customers served by a feeder, the distribution system upgrade cost per feeder, and the cost of advanced smart meter.

3.3.3 Order of magnitude estimates for longer outages

In the absence of WTP estimates for longer outages, we performed a simple order of magnitude calculation to see how the results of Chapter 3.3.1 might change for longer outages. For purposes of illustration, we examined an outage lasting 5 days (120 hours), roughly the mean of the large-scale and severe outage durations affecting more than one distribution utility or affecting more than one state (Figure 3-1-B) in the western Pennsylvania region.

We considered the three cases: 1) people find strategies to adapt, so that the WTP for a five-day outage is only four times that for a 24-hour outage ("Low case"); 2) the WTP for a five-day outage is five times that for a 24-hour outage ("Mid case"); and 3) because it becomes increasingly inconvenient the longer the outage persists, the WTP for a five-day outage is eight times that for a 24-hour outage ("High case"). We generated three different sets of lognormal random variables for each case by multiplying the WTP results in the previous chapter by 4, 5 and 8 and then refit the lognormal distributions.

Following the same procedure outlined above, Figure 3-6 reports the results for a private 20A backup service against longer five-day outages. Compared to the 24-hour outages (Figure 3-4), implementing the backup service for longer outages can be justified in more scenarios, and becomes more affordable. If the 5-day outage occurs once every 5 years on average, even a service payment around $100 per residential customer per outage (which is the same as $20/residential customer/day) can justify the low-amperage backup service and includes between 56 and 84% of the residential customers without subsidies. If the outage is expected to occur once every 10 years, a residential customer would need to pay slightly less than $130 per event (i.e., around $26/residential customer/day), and between 43 and 75% of the customers would be willing to use the backup service without subsidies. However, if the outage occurs only once every 20 years on average, each residential customer would have to pay $200/outage (i.e., $40/residential customer/day), and in such case, the service is affordable between only 25 and 56% of the residential customers without subsidy.

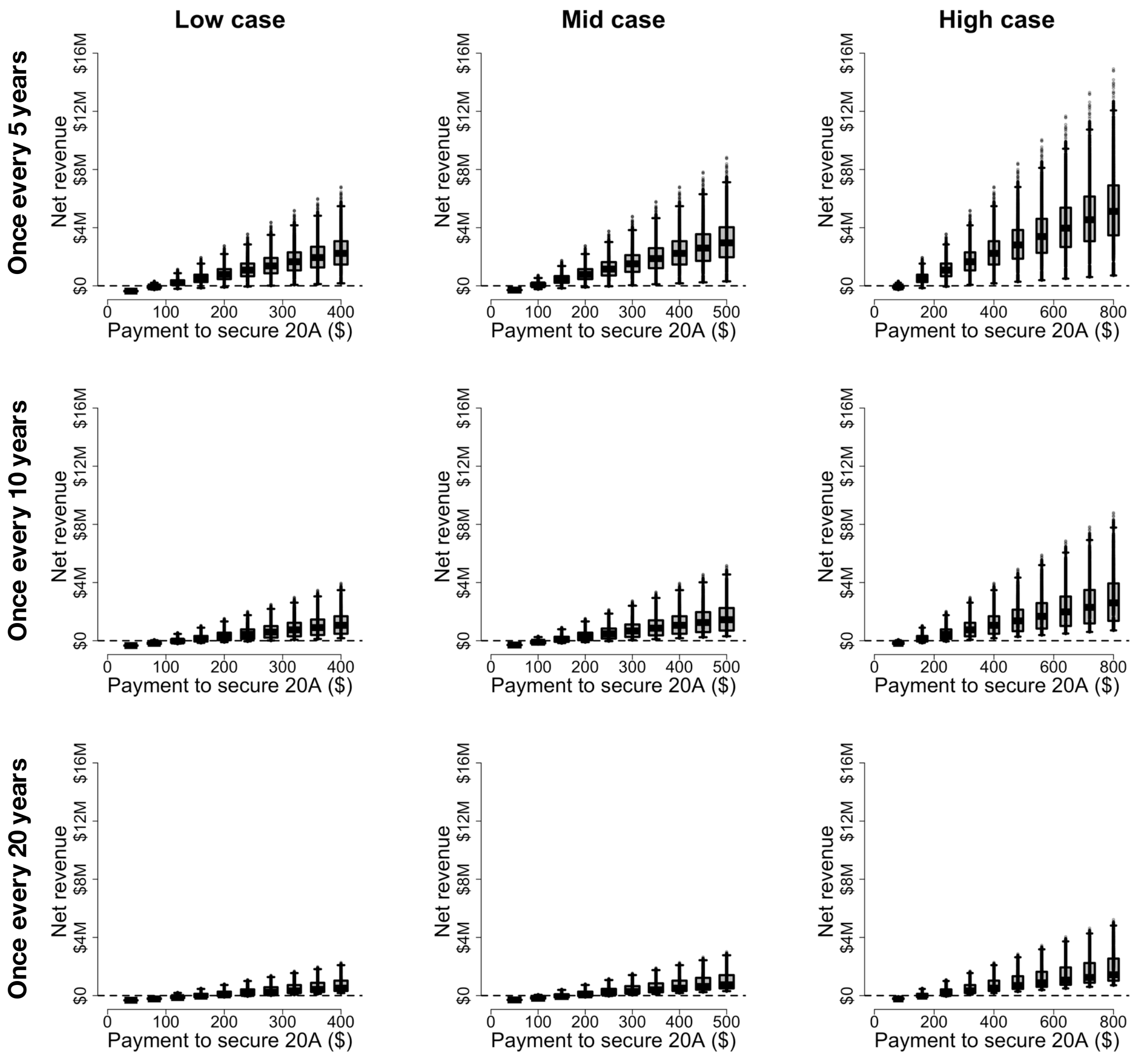

Figure 3-6. Plots similar to those shown in Figure 3-4 for three outage frequency scenarios for outages of five days assuming low (x4 one day), middle (x5 one day), and high (x8 one day) values of WTP.

In summary, as one might expect, implementing a low-amperage backup service becomes more economically feasible if the region is expected to suffer more and longer WLD-outages. While not reported here, it appeared that implementing a backup service to serve both social and private HP demands can be justified without subsidies in most cases. In addition to the monetary benefits, the value of sustaining HP demands for longer outages would be even greater than that for shorter outages. Across most of these scenarios, the 20A backup service is still more cost effective, and certainly much safer than having each individual homeowner buy a small portable generator (~$270) and fuel (~$52/outage). While the backup service becomes more affordable for residential customers, the payment (from $75 to $130, depending on the outage frequency and how much more the residential customers are willing to pay) still imposes a financial burden on low-income households, who are likely to be the most vulnerable segment of the population.

3.4 Equity and Other Important Considerations

3.4.1 Questions and equity

While some of the variation in WTP in the previous chapter is likely due to different assessments of the degree of inconvenience that an outage would produce, some is likely related to ability to pay. Understanding private WTP is important in assessing the viability of backup service; however, an approach that provides a service only to those prepared to pay for it raises issues of social equity. If a community were to implement a system of the sort discussed here, it should cross-subsidize service to very low-income individuals and families that would likely be among the most vulnerable segment of the population.

Here, we considered two different methods to recover the system upgrade costs. Under the first option, the backup service provider adds a very small (< $1) monthly “backup service insurance charge” to all customer bills. For some low-income households who are already covered under various financial assistance programs for energy bills, we assume that those programs would also cover the costs for the insurance. The second option is to cover the incremental cost of the upgrade with general tax revenues on the grounds that much of the benefit will accrue to the community as a whole. In such cases, the equity issue is automatically resolved to the extent that taxes and subsidies are roughly proportional to individuals' incomes and wealth levels. In either case, each residential customer would be responsible for paying for the power they consume during outages (in our example assumed to be $9.8/residential customer/day).

Under these assumptions, we conducted a back of the envelope calculation for the low-amperage private backup service against outages. As Table 3-3 shows, the system upgrade requires an initial subsidy of $120 per customer (a one-time installation fee) or $0.66 per month per customer during the entire 20-year system lifetime. Given that the utilities' fixed customer charge associated with cost of providing grid services for residential customers are ~$10 per month on average, most would probably view an additional $0.66 per month to implement a low-amperage backup service to be acceptable [76]. The table also reports the customer charges for the emergency electricity consumed if the outages occur at the mean of the generated Poisson random variables.

Table 3-3. Two methods to subsidize the required system upgrade costs to implement a low-amperage backup service and the estimated electricity cost per residential for 24-hour and 5-day outages. The costs for system upgrades and annual operation and maintenance are covered by tax revenues, and the backup service provider only charges residential customers to cover the electric costs. The electricity cost is $9.8/residential customer/day and each residential customer will pay when there is an actual outage at the interest rate of 3%, and the outages occur at the mean of the generated Poisson random variables.

	Once every 20 years	Once every 10 years	Once every 5 years
Monthly backup service insurance charge.	$0.66/month	$0.66/month	$0.66/month
Required subsidy per residential customer (if instead of monthly insurance it is covered as a one-time fee for installation at the beginning of the lifetime).	$120	$120	$120
Expected value of total electricity cost per residential customer during the lifetime (for 24-hour outages).	$7.6	$14	$22
Expected value of total electricity cost per residential customer during the lifetime (for 5-day outages).	$38	$69	$110

While there are minor differences between the methods of financing the system upgrades and who is directly responsible for supporting low-income and vulnerable people, both methods can be implemented without excessive burden to either residential customers or the region without raising a serious equity issue. A low-amperage backup service can generate non-monetary benefits that we do not consider in the assessments which would make backup service more feasible and more advantageous.

Some especially disaster-prone regions might be able to secure funds from Federal stimulus and disaster relief programs to cover upgrade costs. For example, in the past, the American Recovery and Reinvestment Act invested $400 million to develop energy assurance plans for natural disasters ("Enhancing State Energy Assurance Planning" and "Enhancing Local Government Energy Assurance program"), and the Disaster Relief Fund from Federal Emergency Management Agency has funded disaster support and mitigation activities [77, 78].

3.4.2 Other considerations relevant to valuing of backup service

Because we adopted the results from the previous chapter, all of the preceding discussion assumes that outages occur under circumstances that, while they may be inconvenient and uncomfortable, do not pose a serious risk of death or major property losses. However, there are situations in which such risks do exist.

The WTP values that we employed in this chapter came from respondents in Southwestern Pennsylvania, where electric power is fairly reliable, and only few respondents have experienced long power outages. Results from regions that have suffered more frequent and longer outages (e.g., New Jersey shore, parts of Florida, etc.) might be quite different.

Moreover, outages in extreme winter weather can cause deaths and major property damages (e.g. frozen water pipes). The 1998 ice storm in Québec, Ontario and the Northeastern United States blacked out 2.3 million customers (some for many weeks), caused damages of ≥ $4.4 billion, and 44 deaths (mostly because of carbon monoxide poisoning [29]). Similarly, extreme heat waves of the sort that hit Chicago in 1995 can be catastrophic. The Chicago event resulted in 700 deaths, mostly among vulnerable population who did not have air conditioning or could not afford substantially increased electric costs [79, 80]. In these and similar situations, such as after a major hurricane, the WTP values discussed above are almost certainly lower bounds since supplying a limited amount of electricity can determine the life and death and the level of injury of people, especially from the vulnerable population groups.

Second, in the previous chapter, we found that the survey respondents had relatively imprecise preferences, and the information and exercises we provided helped them better translate those into values for WTP. However, in many cases, uncertainty and inconsistencies persisted throughout the study. There are two possible explanations for the respondents' uncertainty: 1) incomplete understanding in the current survey design, and inferences about the scenario beyond what we provided; and 2) a mismatch between a respondent's perceptions and actual situation (such as, how extreme they perceive the scenario to be and how different the external environment is compared to what they expected) can also affect their numbers. While we may be able to further reduce some of the cognitive challenges and uncertainty by providing additional help, we cannot completely eliminate uncertainty. Instead, incorporating the inherent uncertainty in respondents' preferences into the analysis and understanding when and how much the uncertainty can change the cost-effectiveness of the investments would be helpful to develop resilient decisions.

3.5 Limitations of This Analysis

We have assumed that the distribution utility has already implemented a full suite of intelligent distribution automation and that there is already a significant amount of connected DG, some of which can be freed up for emergency use in the event of a WLD-outage. In distribution systems for which those assumptions are not true, costs could be considerably higher if needed upgrades are allocated against the emergency backup service. Because of the limited nature of the WTP data available from the companion study our analysis has focused on the choices of individual customers. However, the primary motivation for implementing the system we have outlined is not to deal with the sorts of brief outages that occur regularly in many distribution systems but rather to address issues of individual *and* collective social vulnerabilities that can result from WLD-outages in the bulk power system. While we have discussed some of the relevant issues in Chapter 3.3, before any community choose to implement such a system, these issues should receive considerably more consideration and elaboration.

3.6 Conclusion

The order of magnitude estimates we have outlined in this chapter suggest that implementing the ability to provide a low-amperage backup service via islanded distribution feeders may make sense in some regions that face a significant risk of frequent or long outages. While not considered in the analysis, a low-amperage backup service can generate substantial non-monetary benefits, the value of which will grow as outages becomes longer. However, even in systems that already have smart meters, distribution automation, and DG, upgrades will require investments of ≥$300,000 per feeder. Thus, it will be important to consider the best and most equitable way to cover costs and adequately address equity and ethical issues. Spreading those costs over time in the form of a "monthly backup service insurance charge" may be one attractive way to cover costs, when such retrofits appear to be desirable.

4. Estimating Residential Customers' Costs of Widespread and Long-duration Power Outages in Regions Facing Significant Risks

In order to explore respondents' willingness-to-pay under a variety of scenarios in different locations more efficiently, we develop a generalizable web-based survey framework that allows researchers or decision-makers to elicit residential customers' willingness-to-pay for reliable electric services in the context of their own interests and needs. Here, we report on the web-based tool we have built and the experimental design of the study we have initiated.

In this first implementation, we posit two hypothetical outage scenarios (a massive solar storm and a series of terrorist attacks), both of which result in a 10-day outage during freezing winter weather, and elicit the economic and social preferences for reliable electric services from a representative sample of Northeastern United States residents. In addition, we test four research hypotheses to the controversies associated with risk perceptions, contingent valuation method, and people's actual WTP to avoid power outages.

The web-based survey framework could help researchers and decision-makers explore preferences for reliable electric services under a variety of scenarios and allow users to construct an outage damage function for residential customers. Results from such studies should serve as an input to decision-making problems about when and whether upgrades to advanced distribution systems might be justified on economic and social grounds in at least some regions of the United States where the relative probability of outages is high and the population and local and regional governments are risk averse.

4.1 Why Develop a Web-based Survey Framework?

Previously, we have developed a face-to-face elicitation framework that can help residential customers think carefully about a specific WLD-outage and reflect systematically on how much they would value their full and partial backup service during that outage, applied this method to a convenience sample of residents in Allegheny County, Pennsylvania, and then illustrated how the results could be used to explore when the incremental investment could become cost-effective.

The face-to-face interviews in our Pittsburgh survey worked quite well, but the study has three important shortcomings. First, the method required a great deal of interview time (averaging ~1 hour per interview), so it cannot be readily applied to explore other scenarios. Second, the Pittsburgh study only considered an outage of 24 hours on a hot summer weekend when there is no significant chance of loss of life or property. However, the consequences of having almost no backup services for longer periods (e.g., a week or more) are likely to be very different than that of shorter periods (e.g., a day or two), both economically and socially [55, 75]. As Figure 3-1-A and -B indicate, such outages do occur, more often than expected. Third, in our initial design we focused only on individual homeowners' WTP to avoid service interruptions to their own homes. In the absence of WTP estimates for supporting neighbors and critical social services, we explored the issue by making plausible extrapolations from the 24-hour WTP results (varying respondents' WTP for their private demands by $\pm$20%); however, such analyses could be substantially improved if the actual values were available.

To overcome some of these shortcomings, we develop a web-based interview tool that makes it easier to conduct studies exploring WTP of residential customers under a variety of scenarios in different locations for different durations. Online surveys are considered to be cost-effective, time-efficient, easy to use and administer, and able to reach a larger population sample [79-86]. At the same time, such surveys also have drawbacks such as low response and completion rates, sampling bias, and issues involving privacy and ethics [85, 87-92]. Using the tool, we conduct an online survey and a mail-out survey with residents in the Northeastern United States and elicit their value of reliable electric services in the event of WLD-outages caused by two emerging threats to the major electric power system: a massive solar storm and a series of terrorist attacks.

Using the elicited preferences, we delve more deeply into the controversies surrounding contingent valuation methods and risk perceptions. Specifically, we test the following four research hypotheses:

H1: Compared to the respondents who have never experienced outages or only experienced brief outages, the respondents who have experienced long-lasting outages have more articulated preferences. Thus, their preferences for reliable electric services are less uncertain and influenced by the given information;

H2: The respondents' WTP for reliable electric services during the hypothetical outage that was caused by a man-made disaster (terrorist attacks) are higher than that caused by a natural hazard (a massive solar storm);

H3: The respondents' preferences for sustaining their HP demands and supporting their communities (either by directly helping their vulnerable neighbors or by sustaining critical social services) are not strongly related to each other and the different types of preferences are explained by different variables;

H4: The respondents recruited through Amazon Mechanical Turk (MTurk) and the others recruited through address-based sampling have the identical preferences.

4.2 Issues Concerning the Reliability and Validity of Contingent Valuation Estimates

Over the last several decades, researchers have used stated preference methods to elicit individuals' preferences for goods or services. Among the stated preference methods, contingent valuation method, has been most widely used because the method captures non-use values without relying on other data such as travel costs [23]. Contingent valuation method has been applied in many areas including valuations of environmental goods and their improvements (for instance, see [93-95]), health risk reductions [96], cultural heritages [97], public goods and services [98], and new products or services that will soon be released in the market.

While Arrow *et al.* argue that a contingent valuation study can measure WTP even for a hypothetical product or service if the study is carefully designed and properly conducted according to the suggested guidelines [35], there are ongoing controversies about the reliability and validity of contingent valuation estimates. Previous studies suggest that values elicited using different techniques could be deviated from each other [24]. Other studies report that contingent valuation estimates can be influenced by several factors including level and nature of information provided [99] and altruism [100-102]. In addition, there are several behavioral factors that may influence people's risk perceptions [103, 104], but there has been no study investigating whether and how much the types and characteristics of risks influence respondents' preferences.

4.2.1 Previous studies on respondents' prior experience and familiarity

Contingent valuation method has been extensively used for non-use non-market valuations, but previous studies indicate that contingent valuation studies have several sources of uncertainty

[36], and respondents' underlying preferences differ across elicitation formats especially for things that are not familiar [25]. For instance, Schulze *et al.* [24] review previous contingent valuation studies using different elicitation techniques (mostly open-ended and dichotomous choice) and report that the WTP values elicited using dichotomous choice technique have almost the same value as those elicited from open-ended questions when respondents are familiar with the given commodities or services and have many "real rounds of experience" (e.g., for river rafting and outdoor recreations [105]) whereas the elicited values of goods or services that respondents may never have systematically considered before exhibit a considerable amount of uncertainty (for instance, preservation of wilderness areas where commercial development and public uses are currently prohibited [106]).

As we previously discussed, people are assumed to have rough but not well-articulated value of a low-amperage backup service during WLD-outages (see Chapter 1.2 for details), and the respondents from Pittsburgh face-to-face interviews expressed substantial amount of uncertainty about their preferences even after we provided the information and exercises (see Chapter 2.3.2). However, because there were only few respondents who experienced long-lasting outages, we were not able to fully explore whether and how much respondents' previous experiences influence their value of reliable electric services. As we had larger sample sizes recruited from the entire Northeastern United States (where some of the regions have suffered more frequent and longer outages than Pittsburgh), we divided the respondents into two groups based on the duration of their longest power outage experience and compared the groups' economic and social preferences and their levels of uncertainty. We also discussed whether helping them better understand the given situations and their consequences decreases the gap between the two groups if there is any.

4.2.2 Previous studies on framing of risks

Previous studies of risk perceptions show that several factors could influence people's risk perceptions and assessments: gender, age, culture, socioeconomic status, ethnicity, type of risks, level of dread, knowledge, familiarity, voluntariness, controllability, and number of people exposed to the risks [103, 107-116]. For natural hazards and man-made disasters, Brun suggests that risk perceptions of man-made disasters could be adequately explained by voluntariness and severity of consequences whereas natural hazards also need novelty of the event as factors [112]. Dziegielewski and Sumner and Beutler *et al.* report that people may fear more about terrorist attacks than natural hazards because they are more difficult to predict, control, and take precautionary measures [117, 118].

While it is reasonable to assume that people perceive natural hazards and man-made disasters and attribute responsibility for the consequences of the disasters differently [112, 119], to our knowledge, no previous studies has directly compared individuals' preferences for risk reductions from natural hazards and man-made disasters that result in same consequences. In this study, we compared respondents' preferences for mitigating natural hazards and man-made disasters that yield almost the same consequences to see whether the framing of risks influence respondents' economic and social preferences for reliable electric services.

4.2.3 Previous studies on private and social WTP

Previous value elicitation studies report that people's WTP for public goods and services may show more cognitive bias than that for private goods and services. While some of the difference arises as people are often less familiar with making public choices than expressing their private preferences [106], some of the difference may result from other factors. Previous studies on consumer-citizen distinction (i.e., people take a citizen perspective expressing how they care about the issues instead of revealing their actual preferences) suggest that people often base on altruistic motives and social welfare when they construct their preference functions instead of reflecting their self-interests and actual preferences [100-102, 120-122]. Other studies suggest that people often behave as reciprocal altruists as their utility and preference are not solely determined by their wealth maximization models but also by their moral and ethical values [123, 124]. These studies suggest that people's WTP for reliable electric services for public goods and services could be different from that for private goods and services, thus more attention to the influence of the types of demands seems warranted.

To explore whether the type of demands (i.e., for themselves vs for society) and who the beneficiaries are matter, we compared the respondents' economic and social preferences for reliable electric services. While it is expected that the respondents' WTP to (directly or indirectly) support their communities would be more uncertain and complicated than that to sustain their HP demands, we assumed that they are comparable with each other because of the following reasons. First, before respondents answer the social WTP questions, we provided the information about the outage scenarios and their consequences with two (private) WTP assessments. Thus, their WTP for society is expected to be more knowledgeable about what would happen, which causes their WTP for society to be more articulated. Second, following to previous studies' suggestions, we framed the study as 'market-like' situations (by framing respondents as 'customers' instead of 'citizens' and adopting a referendum style contingent valuation method), recruited electric customers who have lived in the regions that are directly affected by the events, and assured respondents that the results would be used to inform policy decision makings [125-127]. Also, providing a backup service to sustain critical social demands and to help vulnerable populations in respondents' communities incorporate both 'altruistic motive' and 'personal self-interests' as all the community residents have access to the critical social services and can be supported by the assistance program when they are in need of help in the future. That means respondents' WTP for society does not solely based on their altruistic motives but is also based on personal self-interests. Third, because previous studies suggest that people become more generous and less coherent in non-monetary allocations (such as spend more time or share more burden of harm and discomfort [128, 129]), we measured respondents' preferences in monetary terms. Under these assumptions, we compared the three different types of preferences one by one with each other, and identified what variables are associated with the different types of preferences.

4.2.4 Previous studies on recruitment strategies

There are several strategies to recruit survey respondents including using face-to-face interviews, mail surveys of randomly selected households, telephone surveys with probability samples, web-panels (which are usually probability-based; e.g., Knowledge network and the Gallup panel), and crowdsourcing platforms (e.g., MTurk, Qualtrics and SurveyMonkey). While MTurk is the largest and most often used subject-recruiting tool due to of its low-cost time-efficiency, MTurk users are assumed to be different than the general population [130]. The discrepancy between the respondents recruited using different strategies lead researchers to examine representativeness of samples and reliability of results, but the conclusions are quite mixed. For instance, Weinberg, Freese and McElhattan are able to obtain very similar results between probability-based panels (Knowledge Network) and users recruited via a crowdsourcing platform (MTurk) even though demographic differences exist [131]. However, Redmiles *et al.* conduct a survey with respondents recruited through three different channels (via telephone, MTurk, and a web-panel company) and find that there exists a significant difference between the online survey (recruiting MTurk users and census-representative web-panels) and telephone survey (using probability samples) [132]. However, the authors argue that the difference may not be solely due to the demographic differences but rather to other factors such as internet skills and behaviors.

In this study, we recruited respondents not only using MTurk but also address-based sampling (via postal mail) to obtain a more representative sample of Northeast residents [133]. By comparing the respondents, we examined whether the recruitment strategies result in different results, and if there is any difference, what accounts for the differences between the two groups.

4.3 The Web-based Survey Design

To obtain the judgments of individuals about their economic and social preferences for a low-amperage backup service in the event of a WLD-outage, we modified our earlier design and completed multiple rounds of pilot testing to minimize the potential influences from the visual and verbal elements [134].

Figure 4-1 below summarizes the design of our elicitation approach. In this study, we focused on one scenario for each of the two emerging threats that result in the same consequences: a WLD-outage that lasts long enough during cold winter and impose significant economic and social costs.[29] One of the major differences between the face-to-face survey and the web-based survey

[29] Among the five representative risks which could result in widespread losses of electric power for extended periods of time (a series of physical and/or cyber-attacks on the bulk power system, solar storm disruption of the bulk power system, seismic events, tropical cyclones, and ice storms), we have focused on the two emerging threats for following two reasons. First, there have been several efforts to estimate the economic and social impacts and mitigate the impacts of three existing threats [136, 138, 141], but fewer studies have devised strategies to mitigate the risks posed by terrorist attacks and large solar mass ejection to the bulk power system, and none have explored individual customers' WTP for such events. Second, because the threats could cause a major disruption to the bulk power system *without* damaging distribution circuits, providing a low-amperage backup service with modest system upgrades is most straightforward for these cases.

is that we dropped the full backup service and only provide the partial backup service. We removed the full backup service because: 1) the results from our first study already suggested that the value of serving HP demands was significantly higher than that of LP demands, 2) most regions do not have sufficient DG to serve full power to all residential customers during WLD-outages (installing enough DG would be technically feasible but, in most cases, not economically viable), and 3) the respondents did not display anchoring bias but demonstrated only weak scope insensitivity. Accordingly, we only asked respondents' WTP for the partial backup service, thus, unlike our face-to-face interviews, we cannot test for scope insensitivity in results from this study. However, scope insensitivity turned out not to be a serious problem (see Chapter 2.3.3 for details). We kept a consistency check for whether the WTP for electricity backup per kWh is greater than or equal to the normal electricity cost ($0.11/kWh).

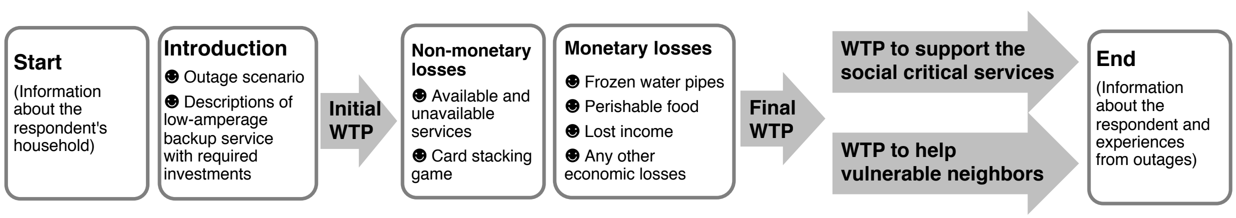

Figure 4-1. Overview of the web-based survey elicitation design indicating the information and exercises that we provided in three different stages (white boxes) and when we posed WTP questions (grey arrows).

4.3.1 Overview of the web-based survey framework

In the introduction, we asked respondents to assume that one of the two emerging threats have damaged a number of critical high voltage transformers and caused a WLD-outage across the Northeastern and Midwestern United States and Southeastern Canada during a period of very cold winter weather. This initial scenario states that it will take 10 days for power to be fully restored in the affected regions. We also asked respondents to assume that federal and state governments have declared a state of emergency in response to the event so that they can evacuate severely ill or injured patients or residents with disabilities immediately and distribute essential commodities within few days (see Figure 4-2 below).

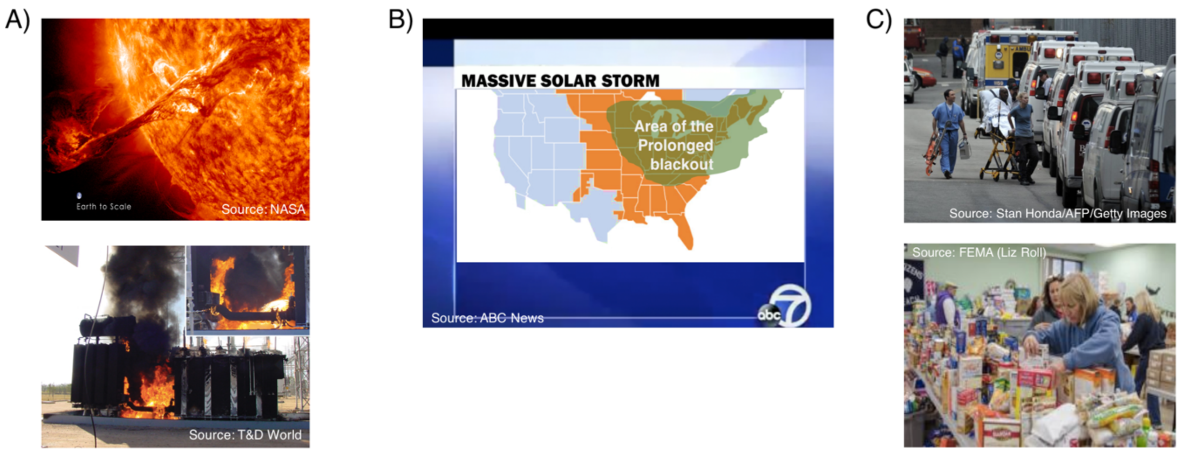

Figure 4-2. Example images used in the video briefings for our survey instrument for the case of a hypothetical solar storm blackout. A) We told respondents that there was a massive solar storm that hit the earth during the early morning hours (top) and damaged critical high voltage power transformers (bottom). B) We assumed that the event caused a 10-day large regional blackout across the northeastern and Midwestern United States and Southeastern Canada. C) We also told respondents that federal and state governments have declared a state of emergency so that they can immediately evacuate severely ill or injured patients and residents with disabilities and distribute emergency supplies. The only difference between the solar storm and a second scenario involving a terrorist attack is the cause of the blackout (we assumed that the large regional blackout was occurred by a series organized terrorist attacks on electric power system while all the other information remained the same).

After introducing the blackout scenario, our tool then explains that people living in the affected region can receive low-amperage backup service through "smart grid" technology. After introducing the scenario and the low-amperage backup service, we first asked respondents' WTP per day to receive the backup service for their own electricity consumption during the 10-day outage using a multiple bounded discrete choice method (see Figure 4-3-A below) and then checked whether they understand they need to pay what they have indicated in the table (i.e., their WTP per day) multiplied by the duration of WLD-outages (in our case, 10 days) to receive the backup service during the entire period of outages (see Figure 4-3-B below). For any respondent whose WTP is very high and marks the entire “yes” column, we first checked whether they understand they need to pay more than $1,000 during the 10-day outage and then asked a follow-up open-ended question: “what is the number that best represents the maximum amount you would be definitely be willing to pay (per day)?”.

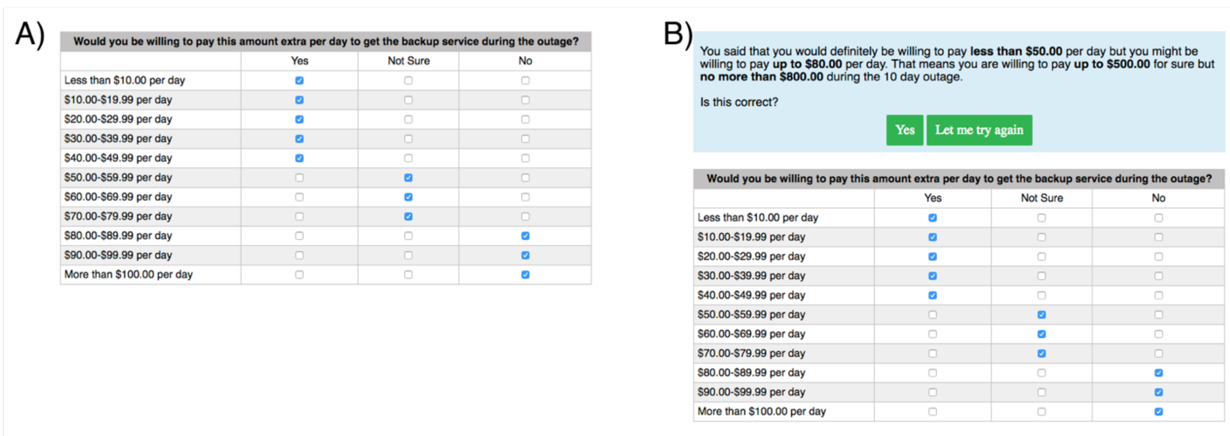

Figure 4-3. Example response format used in eliciting respondent’s WTP. A) In this example, the respondent indicates that (s)he would surely pay at least $50 per day and might be willing to pay as much as $80 per day for the low-amperage backup service during the 10-day blackout. B) After the respondent indicates his or her WTP using the table, a blue follow-up box comes up above the table to make sure that the respondent really understands the concept of total service payment (in this case, the respondent needs to pay up to $500 for sure but no more than $800 since the outage duration is 10 days).

Following this initial WTP assessment, we provided information describing what services will and will not be available in respondents' homes and communities during the blackout. After that, we asked respondents to engage in an "electric appliance stacking game" which is similar to the one we used in our face-to-face interviews (see Figure 4-4 below). In this way, respondents can construct their personal load under limited availability (< 20 Amps for the entire house) as a function of time of day.

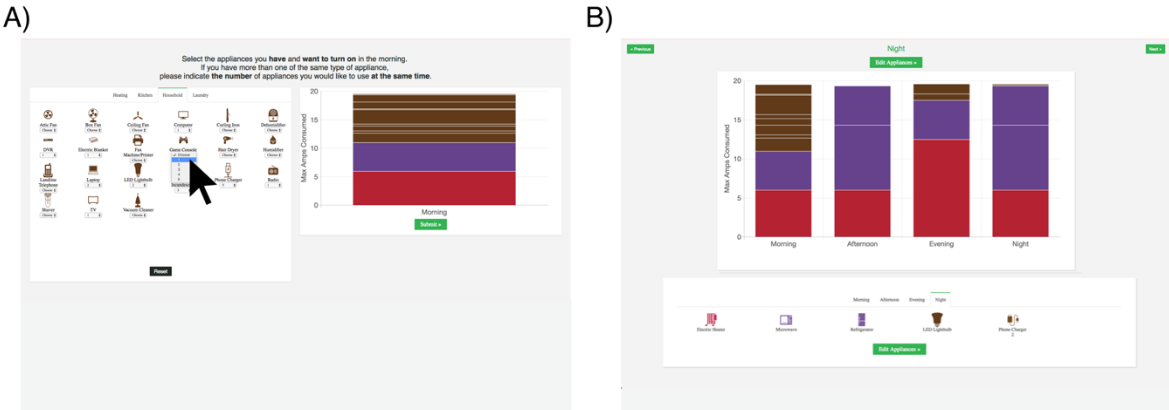

Figure 4-4. The online version of electric appliance stacking game. A) Each respondent was asked to select electric appliances (s)he had and wanted to use during each time period. Each electric appliance belongs to one of the four subcategories (heating, kitchen, household, and laundry). After an appliance is selected, the system stores its power consumption data. The height of each bar in the graph on the right side is proportional to the resulting current in Amps. The respondent can select any combination of electric appliances as long as the total current required is under the 20 Amps limit. B) After constructing their electricity consumption profile, the respondent had an opportunity to review the selected appliances and revise his or her selections if needed.

Because these first scenarios involve a 10-day blackout with temperatures below freezing, we next explained and asked respondents to estimate their economic losses including frozen water pipes, lost perishable food, lost income, and any other economic losses. Figure 4-5 shows the images we used to help respondents understand the risks of frozen water pipes, and how they can store and consume food safely during the outage. These exercises were followed by a second private WTP question for the backup service.

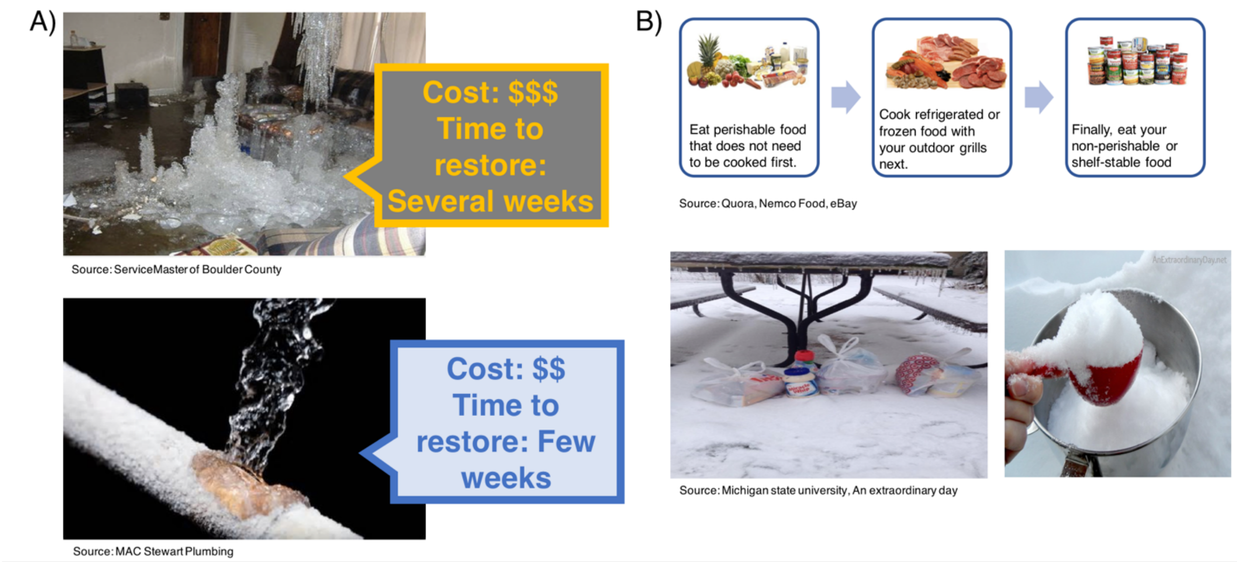

Figure 4-5. Example images used in the video explaining the monetary losses that respondents may suffer during the hypothetical blackout. A) We explained that respondents' water pipe will start to freeze and burst if they cannot get some heat or drain their pipes, and getting repairs done once the power comes back will take many weeks and costs a lot (top); we also told them that they can sufficiently reduce their monetary losses and repair time if they can manage and drain most of the system (bottom). B) We introduced several strategies to consume respondents' perishable and non-perishable food until they receive emergency supplies from government (top) and to store their perishable food safely utilizing the cold weather (bottom).

Finally, we posed two questions that ask about the social value of backup service. Assessing the viability of backup service using the respondents' WTP to sustain their HP demands is important, but an approach that provides a service only to those who are prepared to pay for it raises issues of social equity. We told respondents to assume that many key private and public social services will not be prepared to cope with a WLD-outage [55, 75]. In other words, only a few critical private and social services that have their own backup generators and enough fuel or emergency backup supply contracts can be minimally operated (such as a few gas stations which have emergency backup generators, 911 and related dispatch centers and hospital emergency rooms), but most other services will not work immediately or may stop working after a few days. Having very few critical private and social services during an extended blackout would not only impose costs on individuals but also impose large collective social costs, especially for vulnerable segments of the population who may not be prepared for such outages. To that end, we asked respondents' WTP to support their neighbors directly (by supporting their vulnerable neighbors) and indirectly (by sustaining critical social services in addition to what they want to pay for their own private demands) and wrap up the study.

See Appendix B for the actual survey framework, and the full online survey can be accessed at http://power.andrew.cmu.edu:5021/, select "Individual participants with participation code" and then enter **"TestSurvey2018**".

4.3.2 Web-development technical details

Rather than using one of several existing standard (textual) survey platforms (e.g., Qualtrics, Survey Monkey, or Google Forms), we developed our own web-based survey platform to support responsive and interactive functions (such as informative popup messages, online electric appliance stacking game, and responsive WTP questions using multiple bounded discrete choice method and follow-up open -ended questions). 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 survey is divided into several pages to reduce the loading time, and the load on the web browser. In order to provide a consistent look and feel throughout the survey, all pages use the same basic design template defined in CSS files provided by a professional designer. Some pages provide informative pop-up messages or additional questions based on the respondent responses. These features are programmed in JavaScript. Some parts of the design and features use Bootstrap library.

There are several features implemented in the platform to maintain integrity of the survey responses: 1) input validation, 2) timestamps, 3) flow control.

- **Input Validation**: The server validates submitted responses from a respondent using a predefined set of validation rules for each page and question. Whenever a respondent wishes to move on to the next page by clicking the next button, the browser transmits the response to the server in a HTML POST request. The server will enforce a set of validation rules for each request. If the response passes all the validation checks, the response will be saved in the database and the respondent will be allowed to move on to the next page. Otherwise, error message(s) will be returned to the respondent's browser to instruct the respondent to fix the error(s). Most of validation rules are specified in Validate.JS framework format, but some of them are manually programmed in the server code.
- **Timestamps**: The server stores a timestamp when a respondent starts the survey and completes the survey. This allows the administrator to verify whether the respondent has taken a reasonable amount of time to answer the questions, and to reject responses that are completed too rapidly or too slowly.
- **Flow Control**: To maintain consistent experience with the survey across all respondents, the server also validates whether a respondent accesses and answers questions in the proper order. This will prevent respondents from skipping a page or returning to a page to modify their answers.

The survey platform allows several methods for a respondent to start the survey. Different methods exist for each of the different ways the respondents are recruited and compensated for participating in the survey. A respondent recruited from MTurk needs to provide their worker-id. A respondent recruited through an organization needs to select their organization name and provide the organization-specific code. The administrator can add or remove organizations as needed. A respondent recruited from mail-out surveys or through social media would provide the validation codes provided in the recruiting advertisements. The information used by each respondent is stored in the database to provide compensation after completion of the survey.

Once a respondent provides the log-in information, the respondent is presented with the informed consent form with the agreement questions (stage 1 of Figure 4-6) and the questions to determine their eligibility conditions (stage 2 of Figure 4-6). If the responses are not satisfactory, the respondent will be marked ineligible to participate the study, and the browser will redirect the respondent to the final page. If a respondent is eligible, then the server will internally conduct two coin-flips to determine which of the two outage scenarios to use and the order of social WTP questions and store the result of flips in the database (see Figure 4-7 below). When the respondent reaches the stage of the survey that is customized to an outage scenario, or social WTP questions, the server will use the result in the database to render appropriate page to the respondent's browser.

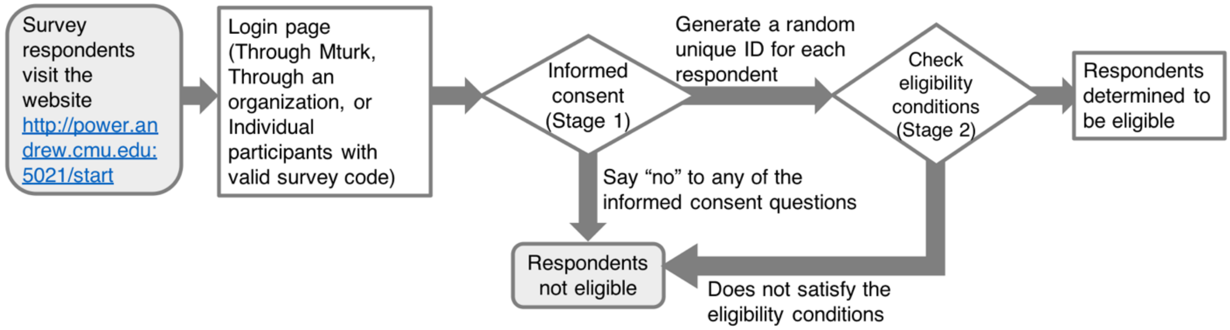

Figure 4-6. Sequence to create the survey and check the eligibility conditions.

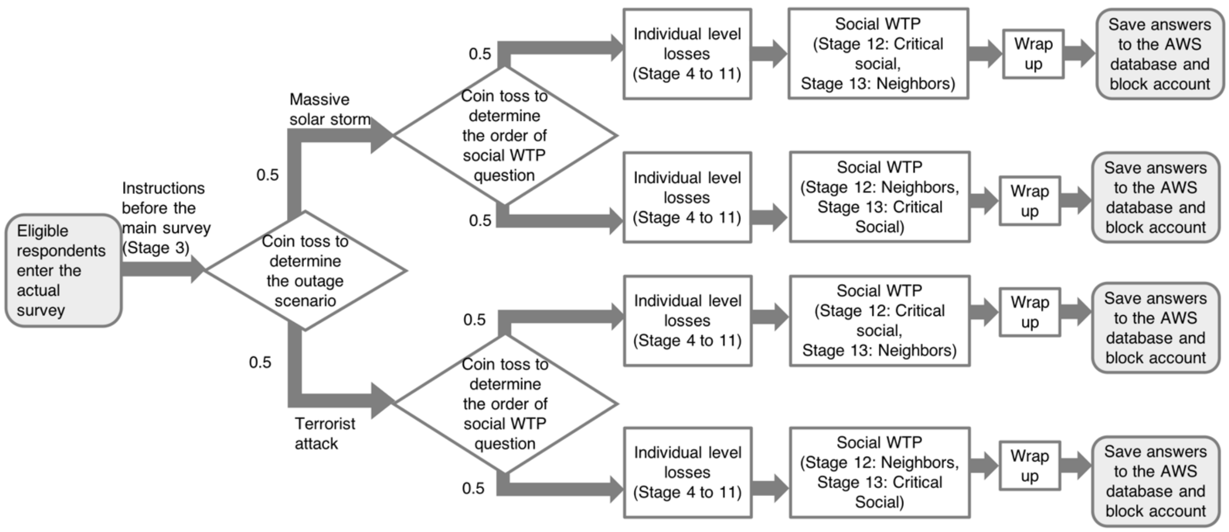

Figure 4-7. Sequence of interactions for the eligible survey respondents as the survey proceeds.

There are two crucial components of our survey that are not provided by the conventional survey platforms: the specialized response modality for WTP questions and the electric appliance card stacking game. The screen capture of the response modality interface for WTP questions is shown in Figure 4-3. It involves a collection of three columns of checkboxes in a table. It has been enhanced to make it easier for respondents to express their WTP. Whenever the respondent checks/unchecks a checkbox, a JavaScript code automatically checks/unchecks other boxes in the table to maintain invariants. For example, if the respondent is willing to pay up to $50, then the respondent must also be willing to pay any amount less than $50. Thus, when the respondent checks $40-50 checkbox, the code will also automatically check $0-10, $10-20, $20-30, $30-40.

As described in Chapter 4.3.1, the electric appliance stacking game is a digitized version of the game. The screen capture of the game is shown in Figure 4-4. Both screens (Figures 4-4-A and 4-4-B) contain a list of names along with graphical depictions of household appliances. The properties of an appliance (icon, name, electricity consumption) and the list of appliances used in the game can be customized by the administrator. A chart library called Chart.JS has been used to generate the bar charts. Most of the interaction occurs in first screen (Figure 4-4-A). Whenever the respondent selects a new appliance or changes the number of appliances to use, the code recalculates the consumption and rolls back to the previous state if the consumption exceeds the pre-specified limit (which is 20 Amps in this study), otherwise the height of the bar in the chart will be adjusted to reflect the updated selections and the respondent's electric consumptions. When a user submits their selection by clicking the next button in the first stage without including some of the critical appliances (e.g., heater, water heater, or refrigerator), the game will show a confirmation message to remind the user that (s)he is missing what may be considered a critical appliance. Also, if a respondent does not select any appliance from Heating, Kitchen or Household category, the game also will show another confirmation message as a reminder. A second screen will display all information collected from respondents to date: a bar showing electric consumption per time period, and a list and number of appliances selected for each time period. The exercise is then repeated for each of the four time-periods.

4.4 Results

Using our web-based elicitation framework, we conducted two rounds of surveys with residents from the Northeastern United States, with each round of respondents recruited in two different ways. In the surveys, the respondents were asked to imagine a hypothetical 10-day outage that occurred during winter, and then to indicate their WTP for reliable electric services. To participate in the study, the respondents were required to be: 1) 25 years old or older, 2) have lived in the Northeast region of the United States for at least two years (including Connecticut, New Hampshire, New Jersey, New York, Maine, Massachusetts, Pennsylvania, Rhode Island, and/or Vermont), and 3) be aware of their electricity bills.

We recruited the respondents using MTurk along with an address-based sample of Northeastern electricity customers [133]. To select households in the address-based sampling, we first used https://openaddresses.io/ to randomly draw addresses proportional to the population of the nine states, and then verified that each address is a valid residential address. We sent a recruitment letter to the selected addresses with a $2 prepaid cash incentive that asks them to participate in the web-based survey. After one week, we sent a follow-up postcard as a reminder [133]. Among the 2,000 selected residential customers, 128 were returned as undeliverable, and 75 eligible residents completed the survey (response rate: 4.0%). The first round of surveys with respondents recruited through MTurk was conducted in early January 2018 (204 respondents), and the second round of surveys with randomly selected Northeastern residents was conducted between February and March 2018 (75 respondents).

In line with previous studies, our MTurk respondents were also younger, earned less, and had lived in their current residency for shorter periods of time than those who were recruited via address-based sampling (demographic information is summarized in Table 4-1 below). We also asked whether the respondents had any life-critical medical devices (such as an oxygen ventilator) in their homes. Only 4.5% of the respondents had such medical devices. 75% of them had some form of backup even though most of those only last for a day or less. The time required to complete the online surveys averaged 43 minutes. The respondents were compensated $10 for their time once the survey was completed. About 90% of the respondents passed all the three attention check questions.

Table 4-1. Demographic information of the web-based survey respondents.

		Total	MTurk	Mail
Age (years)		M=41, SD=13	M=37, SD=10	M=51, SD=14
	Between 25 to 29	62	58	4
	Between 30 to 39	103	87	16
	Between 40 to 49	40	33	7
	Between 50 to 59	45	17	28
	Between 60 to 69	22	8	14
	Between 70 to 79	6	1	5
	Above 80	1	0	1
Race				
	African	22	21	1
	Asian	16	13	3
	Caucasian	217	152	65
	Hispanic	13	11	2
	Others	11	7	4
State				
	CT	6.1%,	6.4%,	5.3%,
	MA	13%,	12%,	13%,
	ME	3.2%,	2.9%,	4.0%,
	NH	2.5%,	2.5%	2.7%,
	NJ	17%,	16%,	20%,
	NY	31%,	33%,	25%,
	PA	23%,	23%,	24%,
	RI	2.9%,	2.5%,	4.0%,
	VT	1.1%	0.98%	1.3%
Years respondents had lived in the state		M=30, SD=17	M= 27, SD=15	M=36, SD=21
Years respondents had lived in their current houses or apartments		M=11, SD=11	M=9.8, SD=14	M=14, SD=9.1
Income level				
	Under $17,000:	6.8%	7.8%	4.0%
	$17,001 to $30,000:	13%	15%	8.0%
	$30,001 to $46,000:	13%	15%	6.7%
	$46,001 to $75,000:	29%	33%	20%
	$75,001 to $148,000:	28%	25%	35%
	Above $148,00:	10%	4.4%	27%
House type				
	Apartment	24%	30%	6.7%
	Duplex	9.7%	9.8%	9.3%
	Attached	65%	58%	84%
	Others	1.4%	2.0%	0
Having life-critical medical devices				
	No	267	192	75
	Yes without any backup	3	3	0
	Yes with any forms of backup	9	9	0
Total		279	204	75

4.4.1 The value of serving high priority demands and preference uncertainty

As in our previous work described in Chapter 2, we assumed that the respondents already have rough preferences for reliable electric services even in the beginning of the survey and that their WTP become more articulated and certain as they better understand the consequences of the given WLD-outage scenarios. In order to confirm this underlying assumption, we asked the respondents' preferences right after introducing the scenarios and the specifics of low-amperage backup service ("initial" stage) and after providing the information and exercises ("final" stage) and tested whether their values of sustaining private HP demands increased while their preference uncertainty reduced as the survey progressed.

Table 4-2 below summarizes the amount the respondents were surely and might be willing to pay to sustain their HP demands and their preference uncertainty about their WTP for the low-amperage backup service. We first compared the respondents' initial and final value per kWh to serve their HP demands using the *paired* Wsr tests and found out that their values per kWh were significantly increased as the survey progressed ("sure" $V_{if\_per\ kWh}$=1262, $D_{if\_per\ kWh}$=0.46; "not sure" $V_{if\_per\ kWh}$= 1971, $D_{if\_per\ kWh}$=0.25; all p<.05). In order to better understand how their preferences had changed, we plotted the respondents' initial values against the final values. As can be seen from the slopes (the curves in Figure 4-8), the respondents increased their "sure" value for reliable electric services by ~40% whereas their "not sure" value was uniformly increased by \$0.6/kWh ("sure" $value\_per\_kWh_{Final}$=0.10+ 1.4·"sure" $value\_per\_kWh_{Initial}$ compared to "not sure" $value\_per\_kWh_{Final}$=0.59+ 0.99·"not sure" $value\_per\_kWh_{Initial}$; the blue dashed lines in Figure 4-8-A and B). While there were some respondents who indicated very high WTP per day (18 respondents in either one of the stages) or zero WTP (18 respondents in either one of the stages), more than 85% of the respondents' preferences laid within the predetermined range of $0-$100/day.

Table 4-2. Summary of the respondents' maximum "sure" and "not sure" WTP per day and value per kWh to sustain their HP demands, and their range of uncertainty in the initial and final stage.

		"Sure"				"Not sure"				Uncertainty ("Not sure" - "Sure")			
		Min	Mean (M)	SD	Max	Min	M	SD	Max	Min	M	SD	Max
Initial	$/day	0	32	33	300	$0	48	50	600	0	16	35	540
	$/kWh	0	1.1	1.2	8.3	$0	1.6	1.7	15				
Final	$/day	0	48	54	500	$0	66	84	1000	0	18	62	900
	$/kWh	0	1.6	1.9	14	$0	2.2	2.9	33				

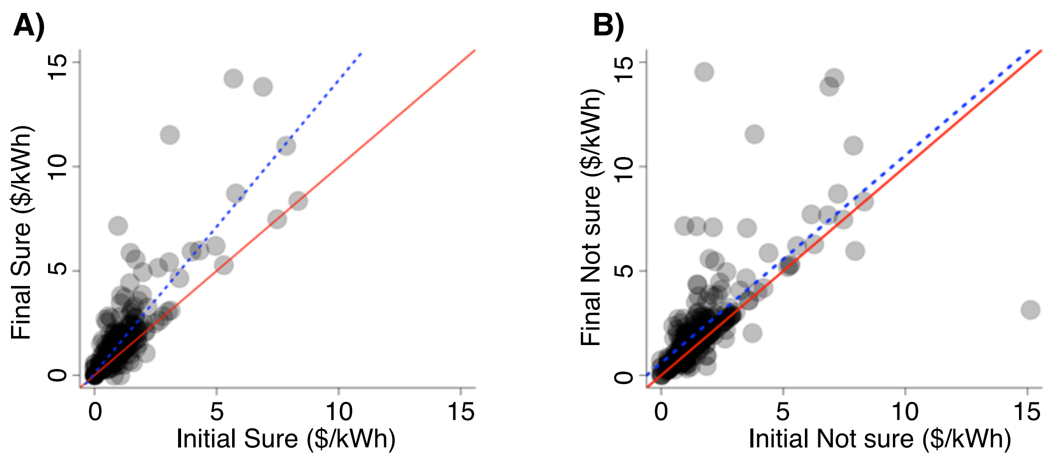

Figure 4-8. A) Scatter plot of the maximum "sure" value per kWh to serve private HP demands during the WLD-outages in the beginning of the study against the value after we provided the information and exercises. The regression line (dotted blue line) is compared with the slope of 1 (solid red line). B) Scatter plot of maximum "not sure" value per kWh in the initial stage against the value per kWh in the final stage. The dotted blue line represents the regression line, and the solid red line represents slope of 1.

We also compared the respondents' preference uncertainty between the two stages (differences between "not sure" and "sure" WTP per day) using the *paired* Wsr tests, but their preference uncertainty was not significantly changed (from $16/day to $18/day, $V_{Uncertainty\_per\_day}$=2575,

$D_{Uncertainty\_per\_day}$=0.087, $p_{Uncertainty\_per\_day}$ =.35).[30] The main reason for the indifference is that the majority of the respondents did not have any preference uncertainty in both stages (49 out of 261) or kept the same amount of uncertainty (116 out of 261). Among the respondents who made changes in their preference uncertainty, the increase (36 out of 261, M=$62/day, SD=150) was more pronounced than the decrease (60 out of 261, M= -$14/day, SD=9.7). However, after removing two outliers who markedly increased their preference uncertainty (the increase in preference uncertainty ≥ $400/day), the change in preference uncertainty became negligible (from $M_{Uncertainty\_initial}$=$14, $SD_{Uncertainty\_initial}$=15 to $M_{Uncertainty\_final}$=$14, $SD_{Uncertainty\_final}$=21).

In summary, the respondents' value of sustaining their HP demands were significantly increased as the survey progressed, and their preference uncertainty were remained the same. While the preference uncertainty result was different from that of our previous study, the difference may be attributed to the changes in the settings (online versus face-to-face interviews), extended pool of the survey (entire Northeastern United States vs Pittsburgh), and hypothetical outage scenarios (10-day outage during a cold winter vs 1-day outage during a hot summer weekend). The fact that some respondents did not change or increase their values suggests that they were not simply responding in a way they thought we wanted them to do.

4.4.2 Influences from the respondents' previous outage experience

To determine whether people's previous experiences influence their preferences, we divided the respondents into two groups. One group was consisted of the respondents who had lost power for longer than one day ("Experience group") and the other group was consisted of the others who

[30] We excluded 18 respondents whose WTP 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 range of uncertainty. 5 respondents had very high preferences from the beginning of the study, and 13 respondents became very interested in the backup service after they received information and exercises.

had lost power for shorter than one day or had never experienced any power outages ("No-experience group"). Table 4-3 below summarizes the two groups' WTP for reliable electric services.

Table 4-3. Summary of the respondents' maximum "sure" and "not sure" value per kWh to serve their HP demands and WTP per day to support their communities during the 10-day WLD-outages, divided by their previous longest outage experiences (whether their longest outages lasted longer than one day or not).

		"Sure"				"Not sure"			
		Min	M	SD	Max	Min	M	SD	Max
Experience group (n=173)	Initial ($/kWh)	$0	$1.1	1.4	$8.3	$0	$1.7	1.9	$15
	Final ($/kWh)	$0	$1.7	2.3	$14	$0	$2.3	3.3	$33
	Critical social services ($/day)	$0	$18	20	$100	$0	$25	23	$100
	Helping neighbors ($/day)	$0	$18	19	$100	$0	$28	25	$100
No-experience group (n=106)	Initial ($/kWh)	$0	$1.0	0.80	$5.3	$0.15	$1.5	1.1	$6.8
	Final ($/kWh)	$0	$1.5	1.2	$6.0	$0.15	$2.0	1.9	$15
	Critical social services ($/day)	$0	$16	18	$100	$0	$26	24	$100
	Helping neighbors ($/day)	$0	$18	19	$100	$0	$28	27	$100

We first compared the two groups' value of reliable electric services using the two-sample KS tests. The results suggest that the maximum "sure" and "not sure" value per kWh of the Experience group were slightly higher than those of the No-experience group in the initial stage ("sure" KS-$D_{\text{Initial\_per kWh}}$=0.11, $p_{Initial\_per\_kWh}$=0.42, "not sure" KS-$D_{\text{Initial\_per kWh}}$=0.086, $p_{Initial\_per\_kWh}$=0.72). While both groups significantly increased the value they assessed for sustaining their HP demands (Experience group: M=$1.1/kWh to $1.7/kWh ("sure") and $1.7/kWh to $2.3/kWh ("not sure"), No-experience group: M=$1.0/kWh to $1.5/kWh ("sure") and $1.5/kWh to $2.0/kWh ("not sure"); paired Wsr p<0.05 for all the four cases), the gap between the two groups slightly increased as the survey progressed ("sure" KS-$D_{\text{Final\_per kWh}}$=0.16, $p_{Final\_per\_kWh}$=0.07; "not sure" KS-$D_{\text{Final\_per kWh}}$= 0.11, $p_{Final\_per\_kWh}$=0.45). Yet, the two groups' preferences for sustaining the critical social services and helping vulnerable neighbors in their communities were not different ("sure" KS-D_{Social}=0.058, p_{Social}=0.98, "not sure" KS-

D_{Social}=0.053, p_{Social}=0.99; “sure” KS-$D_{Neighbor}$=0.056, $p_{Neighbor}$=0.98; “not sure” KS-$D_{Neighbor}$=0.074, $p_{Neighbor\_per\_kWh}$=0.86).

To further understand the potential influences of the respondents’ previous experiences on their WTP to sustain private HP demands, we further divided the respondents into eight groups based on their longest outage experiences (see Figure 4-9 below). The value per kWh distributions were highly overlapped with each other and were not significantly different from each other, but the Experience group represented wider and stronger preferences in both directions (i.e., have some respondents with very high or low value per kWh). There may be two explanations for the difference in the ranges of preferences. On one hand, there are some respondents who had never experienced nor systematically considered WLD-outages may have an incomplete understanding of the survey design. This may make the No-experience group respondents’ value their reliable electric services slightly lower than that of Experience group respondents’ even though they were less prepared against long-lasting outages, expected more future outages, and expected to suffer more inconveniences from hypothetical outages of various durations (see Table 4-4 below). On the other hand, the differences could also be resulted from the mismatches between the respondents’ perceptions and actual situations, such as how extreme the respondent perceives the scenarios to be or how different the external environment is compared to what they have experienced and expect. The Experience and No-experience group respondents’ preference distributions highlight the importance of determining who the respondents are and designing the survey to reduce the uncertainty and inconsistencies that the target respondents are expected to suffer.

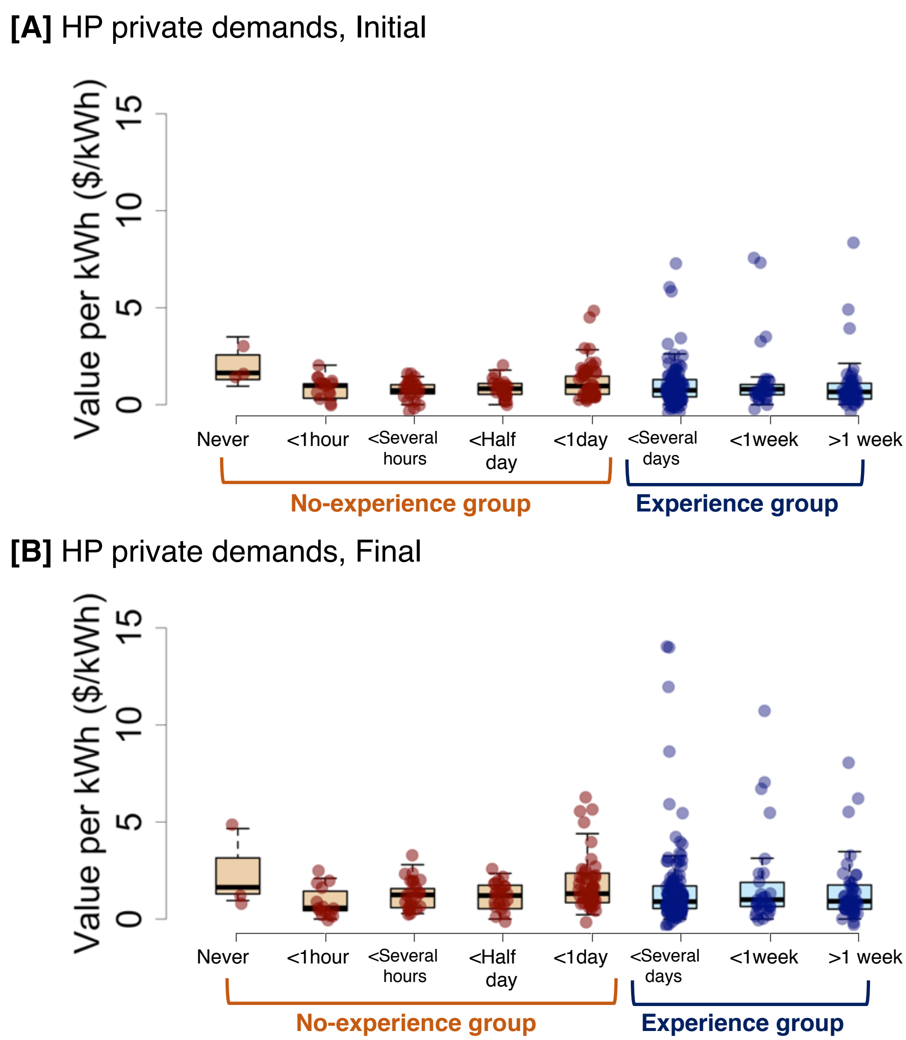

Figure 4-9. The distribution of the respondents' maximum "sure" value per kWh to serve HP demands in the initial (A) and final stage (B) divided by their longest outage experience.

Table 4-4. Level of preparedness, monthly electricity bills, and risk perceptions of the No-experience and Experience group respondents.

	No-experience group	Experience group		
		Moderate weather	Summer	Winter
Total number of respondents	106	56	36	81
Number of respondents with strong preferences (value per kWh >$5 in the final stage)	4	8	2	2
Number of respondents with weak preferences (value per kwh<$0.5 in the final stage)	19	10	8	17
"Sure" WTP per day for				
Private HP demands (final)	M=$46, SD=37	M=$59, SD=82	M=$50, SD=59	M=$41, SD=46
Critical social services	M=$16, SD=18	M=$13, SD=13	M=$19, SD=17	M=$20, SD=24
Neighbors	M=$18, SD=19	M=$15, SD=19	M=$19, SD=17	M=$19, SD=20
"Sure" Value per kWh (for private demands, final stage)	M=$1.5/kWh, SD=1.2	M=$2.2/kWh, SD=3.1	M=$1.6/kWh, SD=2.2	M=$1.3/kWh, SD=1.5
Number of respondents who have any forms of generators	24 (23%)	21 (38%)	9 (25%)	24 (30%)
Monthly electricity bill				
Moderate weather	M=$90, SD=44	M=$99, SD=56	M=$89, SD=54	M=$100, SD=55
Summer	M=$120, SD=66	M=$150, SD=89	M=$140, SD=96	M=$150, SD=99
Winter	M=$140, SD=86	M=$150, SD=93	M=$130, SD=95	M=$150, SD=94
Expected level of inconveniences from outages (From 1: not at all to 5: Extremely)				
Less than several hours	M=2.0, SD=0.83	M=1.7, SD=0.75	M=1.6, SD=0.68	M=1.8, SD=0.75
Less than one day	M=2.9, SD=0.88	M=2.6, SD=0.89	M=2.6, SD=0.73	M=2.7, SD=0.90
Less than several days	M=4.0, SD=0.91	M=3.6, SD=0.91	M=3.7, SD=0.79	M=3.7, SD=0.88
Less than one week	M=4.6, SD=0.76	M=4.4, SD=0.71	M=4.3, SD=0.71	M=4.4, SD=0.76
Less than few weeks	M=4.9, SD=0.56	M=4.8, SD=0.44	M=4.8, SD=0.38	M=4.8, SD=0.43
Longer than few weeks	M=4.9, SD=0.59	M=4.9, SD=0.30	M=4.9, SD=0.23	M=5.0, SD=0.16
Expected number of WLD-outages in the future				
Within 1 year	M=0.16, SD=0.37	M=0.36, SD=0.86	M=0.19, SD=0.47	M=0.47, SD=0.84
Within 5 years	M=0.66, SD=1.3	M=3.3, SD=13	M=0.86, SD=1.1	M=2.6, SD=6.9
Within 20 years	M=2.1, SD=5.2	M=23, SD=130	M=2.4, SD=2.8	M=7.8, SD=19
Within 50 years	M=4.0, SD=12	M=101, SD=670	M=4.3, SD=4.0	M=28, SD=140

To sum up, the respondents who had experienced long-lasting outages had stronger preferences to sustain their HP demands, and the increase of the value of reliable electric services from the Experience group was more pronounced as we provided the information and exercises. The results are somewhat inconsistent with previous studies reporting that people who are more familiar with the given commodity and service and have more prior knowledge would be less influenced by information and exercises but revealed two important facts: 1) even if the respondents had previously experienced long-duration outages, they still needed the information and exercises to better articulate their values, and 2) the slight difference between the two groups may not only be caused by the No-experience group respondents' incomplete understanding but also caused by the Experience group respondents' perceptions which are influenced by their previous experiences. These findings indicate that researchers need to specify who their respondents will be and understand what they need for their value articulations before designing their survey frameworks.

4.4.3 Influences from the framing of the risks

To understand the influences on the framing of risks, we elicited the respondents' preferences for the low-amperage backup service against two different types of risks: a series of organized terrorist attack and a massive solar storm. While both risks result in very similar consequences, their causes are quite different. Man-made disasters are assumed to be more avoidable or preventable than natural hazards (although prior preparations can mitigate the impacts of both), but people are assumed to be more threatened by terrorist attacks as man-made disasters can be occurred everywhere and their potential damages can be bigger than that of any natural hazards [117, 118].

To test whether people's preferences vary depending on the causes of an outage, we divided the respondents into two groups and completed the same survey under each outage scenario. We compared the preferences of each group using the two-sample KS tests. Table 4-5 summarizes the value of backup services for each group of respondents. As can be clearly seen from Figure 4-10, the two groups' preferences were not significantly different in the initial stage ("sure" KS-$D_{\text{Initial\_per kWh}}$=0.075, $p_{Initial\_per\_kWh}$=0.83; "not sure" KS-$D_{\text{Initial\_per kWh}}$= 0.10, $p_{Initial\_per\_kWh}$=0.43), and the minor gap between the groups was further narrowed as we provided the information and exercises ("sure" KS-$D_{\text{Final\_per kWh}}$= 0.074, $p_{Final\_per\_kWh}$=0.84; "not sure" KS-$D_{\text{Final\_per kWh}}$=0.083,

$p_{Final\_per\_kWh}$=0.73). While most of the respondents' preferences for sustaining their own private demand were in the reasonable range ($0-6/kWh), the outage scenarios extended the range of preferences differently. The solar storm scenario substantially increased several respondents' value per kWh in both stages and levels of certainty (number of respondents who had higher than $6/kWh: 4 (initial, sure), 8 (initial, not sure); 9 (final, sure), 13 (final, not sure)). In case of the terrorist attack scenario, only affected a few respondents' value per kWh with uncertainty (number of respondents who had higher than $6/kWh: 3 (initial, not sure), 4 (final, not sure)); yet, the increase in the terrorist attack scenario in the final stage was more pronounced ($0-$33/kWh). In the social WTP analysis, the two groups' preferences for supporting the critical social services ("sure" KS-D_{Social}= 0.055, p_{Social}=0.98, "not sure" KS-D_{Social}=0.072, p_{Social}=0.86) and helping their vulnerable neighbors ("sure" KS-$D_{Neighbor}$=0.047, $p_{Neighbor}$=1, "not sure" KS-$D_{Neighbor}$=0.066, $p_{Neighbor}$=0.93) did not show any significant differences.

Table 4-5. Summary of the respondents' maximum "sure" and "not sure" value per kWh to sustain their HP demands and WTP per day to support their communities during the 10-day WLD-outages that were caused by two different types of risks.

		"Sure"				"Not sure"			
		Min	M	SD	Max	Min	M	SD	Max
Solar storm (n=145)	Initial ($/kWh)	$0	$1.2	1.4	$8.3	$0	$1.7	2.0	$15
	Final ($/kWh)	$0	$1.8	2.4	$14	$0	$2.2	2.4	$14
	Critical social services ($/day)	$0	$17	21	$100	$0	$25	25	$100
	Helping neighbors ($/day)	$0	$18	20	$100	$0	$27	27	$100
Terrorist attack (n=134)	Initial ($/kWh)	$0	$0.94	0.82	$5.3	$0	$1.5	1.2	$7.9
	Final ($/kWh)	$0	$1.4	1.3	$6.0	$0	$2.2	3.2	$33
	Critical social services ($/day)	$0	$17	17	$100	$0	$26	22	$100
	Helping neighbors ($/day)	$0	$17	18	$100	$0	$28	25	$100

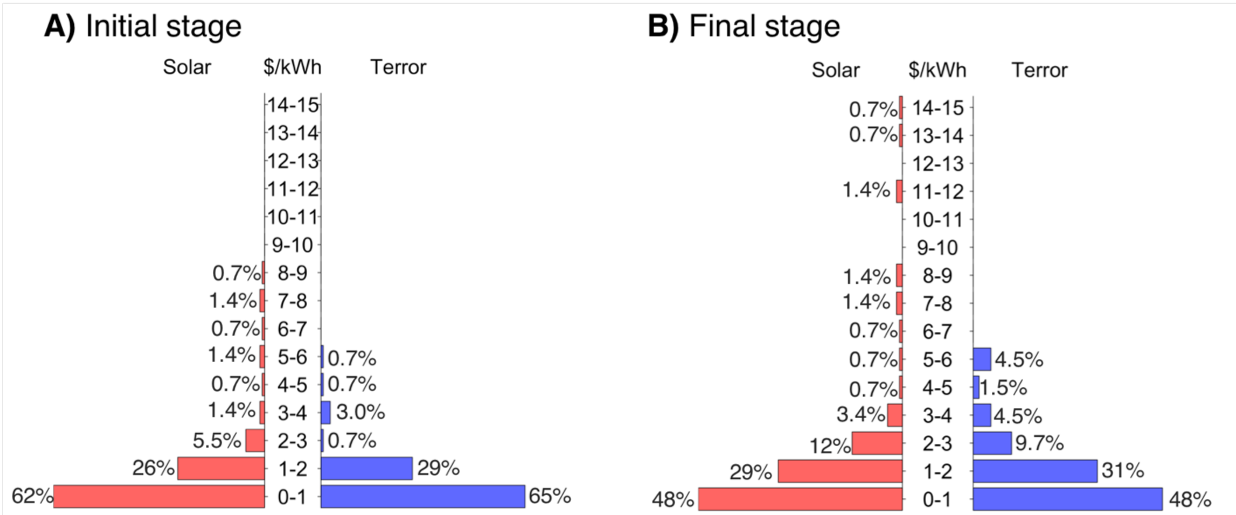

Figure 4-10. A) Pyramid diagram for the respondents' maximum "sure" value per kWh when they face WLD-outages that were occurred by a massive solar storm (left, red) or by a series of terrorist attacks (right, blue) in the initial stage. B) Pyramid diagram for the respondents' maximum "sure" value per kWh during the WLD-outages that were occurred by a massive solar storm (left, red) or by a series of terrorist attacks (right, blue) in the final stage.

We concluded that most of the respondents were not appreciably influenced by the framings of risks. For the value of lost load studies that construct customer damage functions, this finding implies that they can focus more on other factors such as characteristics of outages (such as under what weather condition an outage occurs and how long it takes to restore the power) and customer-related factors (including customers' demographic characteristics and their levels of preparedness and risk preferences) rather than the type of risks. However, the type of risks still requires careful analyses as they may extend ranges of preferences, and we should note that the ranges could also be determined by other factors such as respondents' risk perceptions and averseness, levels of preparedness, previous WLD-outage experiences, and hypothetical bias. More discussions about the customer damage functions are provided in Chapter 4.5.2.

4.4.4 Influences from the types of demands and strategies to support communities

Understanding private WTP is important in assessing the viability of the backup service for residential customers but understanding how much people are willing to pay to assure others in their communities is also important as such estimates can be used as an input in determining the viability of backup services for communities. While we elicited the respondents' WTP for sustaining their HP demands and for directly and indirectly supporting their communities, the relationships between the different types of demands are not fully understood. To determine whether the types of demands and strategies to support communities influence the respondents' WTP, we first compared their WTP per day results (see Table 4-6 below for the summary). The paired Wsr test results suggest that the respondents' preferences for sustaining their HP demands were significantly higher than that for supporting their communities ("sure" W_{Privae_Social}=26592, $D_{Private\_Social}$=0.54, $W_{Private\_Neighbors}$=25440, $D_{Private\_Neighbors}$=0.52; "not sure" W_{Privae_Social}=27952, D_{Privae_Social}=0.0.46; $W_{Private\_Neighbors}$=27664, $D_{Private\_Neighbors}$=0.43; all p<.05).[31] The private and two types of social preferences were barely correlated with each other ("sure" Kendall τ_{Privae_Social}=0.049, $\tau_{Private\_Neighbors}$=-0.033; "not sure" τ_{Privae_Social}=0.034, $\tau_{Private\_Neighbors}$=-0.014; see Figure 4-11-A and B below). However, the respondents' WTP for directly and indirectly helping their communities were not noticeably different ("sure" $W_{Social\_Neighbor}$=4311, $D_{Social\_Neighbor}$=0.063, $p_{Social\_Neighbor}$=0.36; "not sure" $W_{Social\_Neighbor}$=4890, $D_{Social\_Neighbor}$=0.13, $p_{Social\_Neighbor}$=0.08) and were highly correlated with each other ("sure" $\tau_{Social\_Neighbor}$=0.62; "not sure" $\tau_{Social\_Neighbor}$=0.67; see Figure 4-11-C below).

[31] Part of the reason is because we did not ask the respondents who had very high social WTP (i.e., willing to pay more than $100 per day for sustaining critical social services or helping vulnerable neighbors) about their upper bounds. However, compared to sustaining private HP demands (18 respondents for sure and 32 respondents for unsure), only a few respondents had very high WTP (sustaining critical social services: 4 respondents for sure and 8 respondents for unsure; helping vulnerable neighbors: 2 respondents for sure and 13 respondents for unsure).

Table 4-6. Summary of the respondents' maximum "sure" WTP per day to sustain their HP demands in the final stage and to serve their critical demands during the 10-day WLD-outages.

	"Sure"				"Not sure"			
	Min	M	SD	Max	Min	M	SD	Max
Private HP demands in the Final stage ($/day)	$0	$48	54	$500	$0	$66	84	$1000
Critical social services ($/day)	$0	$17	19	$100	$0	$25	23	$100
Helping neighbors ($/day)	$0	$18	19	$100	$0	$28	26	$100

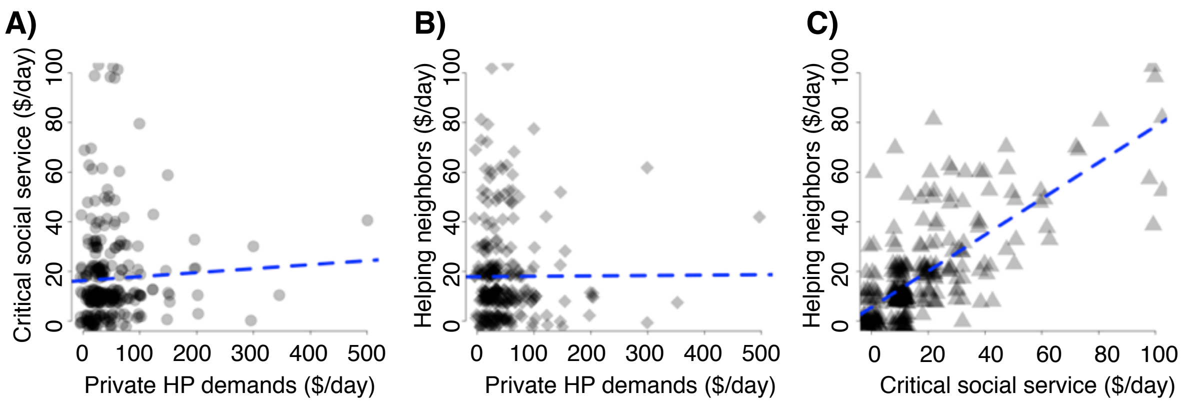

Figure 4-11. A) The respondents' WTP per day to sustain the respondents' HP demands in the final stage against their WTP per day to sustain the critical social services. B) The respondents' WTP per day to sustain HP demands in the final stage against their transformed WTP per day to support vulnerable neighbors in their communities. C) The respondents' WTP per day to sustain the critical social services against their WTP per day to support vulnerable neighbors in their communities.

To better understand what makes the respondents' underlying preferences for sustaining their HP demands and supporting communities different from each other, we modeled the relationships between the square-root transformed respondents' WTP per day from other relevant variables. To conduct the multiple linear regressions, we: 1) selected regressors that reduce the root mean-squared prediction error according to 5-fold cross validations, 2) examined the correlations between the selected regressors and conducted principal component analyses if required,[32] and 3) modeled the square-root transformed WTP per day as linear functions of the selected variables and components which minimize the sums of squared residuals. As Table 4-7 below shows, the respondents' value of sustaining HP demands can be well explained by the variables that are related to incomes (their income levels and whether they and their household members can get paid during the outages even though they cannot work), electricity consumptions (their electricity consumptions under the 20A limit and their estimated electricity bills during hot summer and cold winter), and risk perceptions of outages in the future. However, their WTP for their communities was only partially explained by the income-related variables and other variables.

[32] If a regressor is correlated with other regressors (such as expected inconvenience during outages last longer than several hours), we first scaled and centered the data, and then conducted principal component analysis to find a linear combination that explains the most variance of the group of variables.

Table 4-7. Summary of the multiple linear regression analyses to predict the square-root transformed respondents' maximum "sure" WTP per day to sustain their HP demands and support their communities.

	Private HP demands	Critical social services	Vulnerable neighbors
Constant	6.1*** (0.19)	3.5*** (0.14)	3.6*** (0.15)
Income (Income level, Income recovery for the respondents and their household members)	0.56*** (0.15)	0.25* (0.11)	0.23 * (0.11)
Expected inconvenience during outages that last longer than several hours	0.37** (0.13)		
Expected number of outages in the future	-0.59 . (0.31)		
Variables related to electricity consumption (electricity consumptions under 20A consumption, estimated electricity bill during hot summer and cold winter)	0.41** (0.14)		
Having stand-by generators		-1.6 . (0.95)	
Having preschool child(ren) in their households			-0.51 . (0.29)
Residual standard error	2.9 on 240 DF	2.3 on 276 DF	2.4 on 276 DF
Multiple R-squared	0.14	0.029	0.026
F-statistic	9.4 on 4 and 240 DF	4.1 on 2 and 276 DF	3.7 on 2 and 276 DF
p-value	<0.05	<0.05	<0.05

In order to better understand the relations between the respondents' WTP and the income-related variable, we plotted their income levels against their square-root transformed maximum sure WTP per day. As the first row of Figure 4-12 shows, the respondents' WTP to sustain their HP demands was moderately correlated with income levels ($r_{\text{Sqrt\_Private\_Income}}=0.24$) and their own or their household members' income recovery (i.e., whether they or their household members can get paid during the outages even though they cannot work; $r_{\text{Sqrt\_Private\_Respondents'\_Income recovery}}=0.16$, $r_{\text{Sqrt\_Private\_household\_members'\_Income recovery}}=0.12$). As both variables reflect the respondents' ability to pay, their WTP to pay to sustain their HP demands increased with higher income levels ($Y_{\text{Sqrt\_Private}}=0.53\cdot\text{Income level} + 4.1$) and getting paid ($Y_{\text{Sqrt\_Respondents'\_Income recovery}}=1.0\cdot\text{Getting paid} + 5.8$, $Y_{\text{Sqrt\_Household members'\_Income recovery}}=0.86\cdot\text{Getting paid} + 5.9$). Also, the pairwise combinations of the respondents' WTP per day between the different income level groups suggest that the low-income groups' WTP (income level 1 and 2) was significantly lower than that of high-income groups' (income level 5 and 6) whereas the mid-income groups' preferences (income level 3 and 4) were in the middle of the two groups and were not significantly different from the other two groups' preferences (see Table 4-8). The differences between income levels became more apparent after we adjusted the respondents' WTP for their household incomes (by dividing the total WTP for the backup services by the median of each tax bracket; see Table 4-8 below). This result implies that there are income effects and equity issues in the private backup service.

However, the respondents' WTP for their communities was not different across the income levels. The respondents from the lowest income group were willing to pay almost equal amount of money for sustaining the critical social services and helping other vulnerable neighbors as they were less prepared against long-lasting outages, more vulnerable to the blackouts, and need the supports the most to sustain their lives during the outages. Yet, in other income levels, the respondents' WTP for sustaining critical social services and helping vulnerable neighbors were not different across the income levels and significantly lower than that for their HP demands. Regarding the respondents' income recovery, their WTP for their communities were still related to their own and their household members' income recovery ($r_{\text{Sqrt\_Socialservice\_Respondents'\_Income recovery}}=0.11$, $r_{\text{Sqrt\_Socialservice\_household\_members'\_Income recovery}}=0.10$, $r_{\text{Sqrt\_Neighbor\_Respondents'\_Income recovery}}=0.11$, $r_{\text{Sqrt\_Neighbor\_household\_members'\_Income recovery}}=0.10$). The respondents were willing to spend some amount of money regardless of their income levels, and their WTP for supporting their communities was closely related to their altruisms.

Table 4-8. Summary of the WTP per day to sustain the respondents' private HP demands and support their communities and their total WTP for the backup services as proportions of annual household incomes for each income level and the results from Wilcoxon Signed Rank tests (within each income level) and two-sample Kolmogorov-Smirnov tests (between different income levels).

		Income 1 (<$17K)	Income 2 ($17-30K)	Income 3 ($30-46K)	Income 4 ($46-75K)	Income 5 ($75-148K)	Income 6 (Above $148K)
Private (WTP per day, proportion of annual household income)		M=$22/day, 2.5%	M=$43/day, 1.9%	M=$44/day, 1.2%	M=$41/day, 0.68%	M=$54/day, 0.48%	M=$76/day, 0.51%
Social (WTP per day, proportion of annual household income)		M=$17/day, 2.1%	M=$13/day, 0.53%	M=$23/day, 0.61%	M=$15/day, 0.24%	M=$26/day, 0.14%	M=$25/day, 0.17%
Neighbor (WTP per day, proportion of annual household income)		M=$17/day, 2.0%	M=$15/day, 0.63%	M=$21/day, 0.54%	M=$18/day, 0.30%	M=$17/day, 0.15%	M=$21/day, 0.14%
Significantly different among the types of demands within the income level		No	Yes (Private-Social, Private-Neighbor)	Yes (Private-Social, Private-Neighbor)	Yes (Private-Social, Private-Neighbor)	Yes (Private-Social, Private-Neighbor)	Yes (Private-Social, Private-Neighbor)
Significantly different from higher income level group(s) without adjustment	Private	Income 5, 6	Income 6		Income 6		
	Social						
	Neighbor						
Significantly different from higher income level group(s) after adjustment for income	Private	Income 3, 4, 5, 6	Income 3, 4, 5, 6	Income 4, 5, 6	Income 5		
	Social	Income 2, 3, 4, 5, 6	Income 3, 4, 5, 6	Income 4, 5, 6	Income 5, 6		
	Neighbor	Income 2, 3, 4, 5, 6	Income 4, 5, 6	Income 4, 5, 6	Income 5, 6	Income 6	

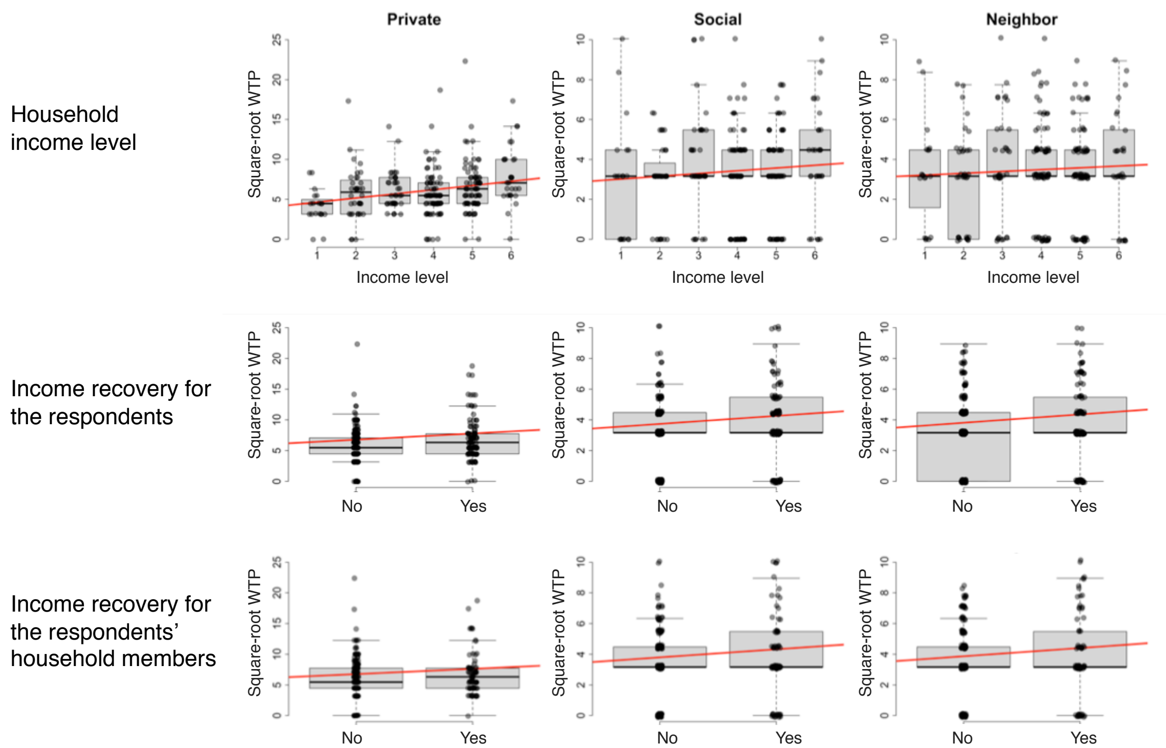

Figure 4-12. Left column) The square-root transformed respondents' maximum "sure" WTP per day to sustain their HP demands against their household income levels (top), their income recovery during the outages (middle), and their household members' income recovery during the outages (bottom). The red lines indicate the regression fits on the square-root transformed scale. Center column) The square-root transformed respondents' maximum "sure" WTP per day to sustain the critical social services against their household income levels (top), their income recovery during the outages (middle), and their household members' income recovery during the outages (bottom). The red lines indicate the regression fits on the square-root transformed scale. Right column) The square-root transformed respondents' maximum "sure" WTP per day to support vulnerable neighbors in their communities against their household income levels (top), their income recovery during the outages (middle), and their household members' income recovery during the outages (bottom). The red lines indicate the regression fits on the square-root transformed scale.

To conclude, the respondents' preferences for private demands were more straightforward and easier to understand, but their preferences for society were harder to predict as such preferences were more related to their altruistic motivations and other variables that were not measured in the study. Thus, we concluded that the respondents' WTP for sustaining their HP demands and supporting communities were not related to each other, and one cannot be inferred from the other. This analysis illustrates the importance of clearly specifying the type of demands when designing survey frameworks and using the right combinations of variables to properly analyze the elicited preferences. Also, the respondents' WTP for the private backup were moderately correlated with their ability to pay and exhibited income effects. While the results suggest that the lower income groups' WTP to sustain private HP demands were substantially lower than that of higher income groups', this occurred not simply because the lower income groups can withstand the given hypothetical outages but also because they cannot afford the high service payments. Thus, decision-makers should pay additional attention to the social equity issues when they use the estimates as an input to further decision-making problems.

4.4.5 Influences from the recruitment strategies

Previous studies reveal that respondents recruited from internet-based convenience samples can be different from the general population, and the difference can lead to discrepancies between other respondents who are recruited via different strategies thus undermining the reliability of study results. To test whether there is a difference between the respondents who were recruited through two different channels, we divided the respondents based on the recruitment strategies (address-based sampling and MTurk) and compared the two groups' preferences. Table 4-9 summarizes the two groups of respondents' maximum "sure" and "not sure" value per kWh to sustain their HP demands and their maximum WTP per day for supporting their communities.

Table 4-9. Summary of the address-based sampling and MTurk respondents' maximum "sure" and "not sure" value per kWh to sustain their HP demands and WTP per day to support their communities.

		"Sure"				"Not sure"			
		Min	M	SD	Max	Min	M	SD	Max
Address-based sampling (n=75)	Initial ($/kWh)	$0	$1.0	1.1	$5.7	$0	$1.5	1.4	$7.1
	Final ($/kWh)	$0	$1.5	2.0	$14	$0	$2.0	2.1	$14
	Critical social services ($/day)	$0	$18	19	$100	$0	$26	24	$100
	Helping neighbors ($/day)	$0	$15	16	$80	$0	$26	26	$100
MTurk (n=204)	Initial ($/kWh)	$0	$1.1	1.2	$8.3	$0	$1.7	1.8	$15
	Final ($/kWh)	$0	$1.6	1.9	$14	$0	$1.5	3.1	$33
	Critical social services ($/day)	$0	$17	19	$100	$0	$25	23	$100
	Helping neighbors ($/day)	$0	$19	20	$100	$0	$28	26	$100

The two-sample KS test results suggest that there was a slight difference in the beginning of the study ("sure" KS-$D_{\text{Privae\_Initial}}$=0.16, $p_{Privae\_\text{Initial}}$=.14; "not sure" KS-$D_{\text{Privae\_Initial}}$=0.14, $p_{Privae\_\text{Initial}}$=.21), but providing the information and exercises reduced the gap between the two groups ("sure" KS-$D_{\text{Private\_Final}}$=0.10, $p_{Private\_Final}$=.61; "not sure" KS-$D_{\text{Private\_Final}}$=0.12, $p_{Private\_Final}$=.38). Most of the respondents' preferences were laid in the reasonable range ($0-6/kWh) and the preferences between two groups were not significantly different. However, the preference range of MTurk respondents for sustaining their HP demands were wider than that for address-based sampling respondents in both initial (MTurk: $0-8.3/kWh for sure and $0-15/kWh with uncertainty compared to address-based sampling: $0-5.7/kWh for sure and $0-7.1/kWh with uncertainty) and final stage (MTurk: $0-14/kWh for sure and $0-33/kWh with uncertainty compared to address-based sampling: $0-14/kwh for sure and with uncertainty). While there were more MTurk respondents whose preferences exceed the $0-6/kWh range, the proportions of such respondents were actually quite similar (MTurk: 2.0-4.4% in the initial stage, 3.4-6.4% in the final stage; address-based sampling: 0-2.7% in the initial stage, 2.7-5.3% in the final stage). There was no major differences between the two groups' social preferences ("sure" KS-

D_{Social}=0.079, p_{Social}=.89; KS-$D_{Neighbor}$=0.089, $p_{Neighbor}$ =.78; “not sure” KS-D_{Social}=0.081, p_{Social}=.86; KS-$D_{Neighbor}$=0.095, $p_{Neighbor}$=.70), and their ranges of preferences for society were very similar to each other.

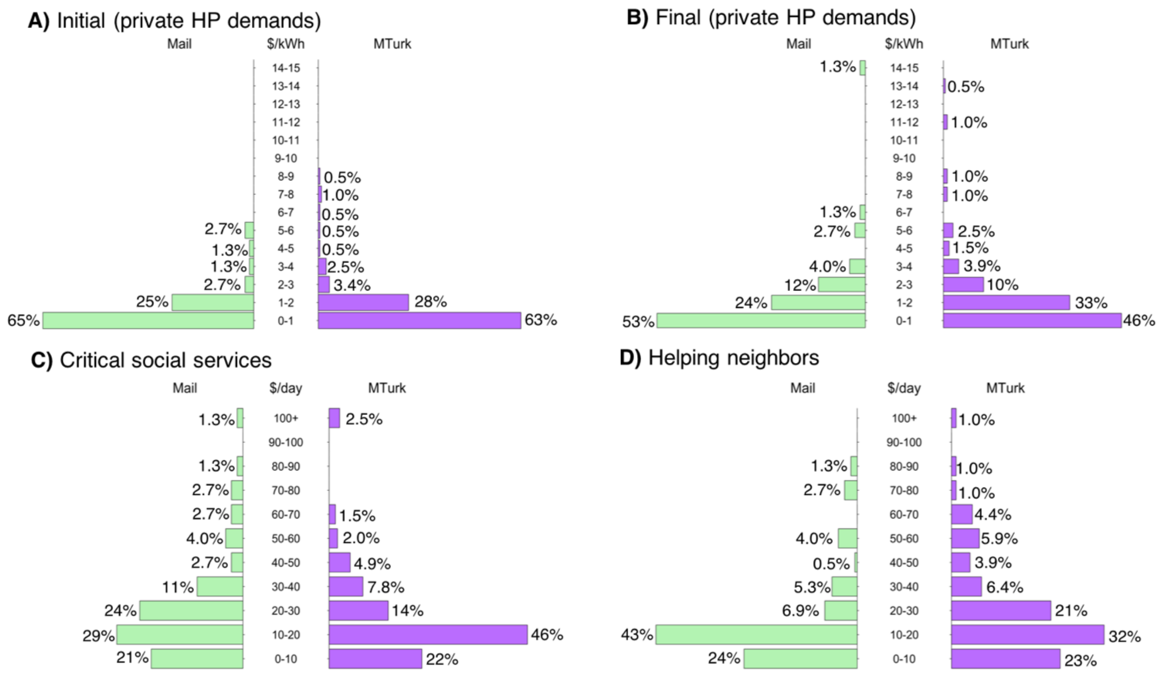

Figure 4-13. Pyramid diagram for the private and social preferences for reliable electric services from the respondents who were recruited from address-based sampling (left in each panel, light green) and MTurk (right in each panel, purple). The distribution of two groups of respondents’ maximum “sure” value per kWh for sustaining private HP demands in the initial stage (A) and final stage (B), and their maximum “sure” WTP per day to support critical social services (C) and to help vulnerable neighbors in their communities (D).

While there was no significant differences between the MTurk and address-based sampling respondents, we found that helping the respondents better articulate their values and preferences can decrease the small gap between the two groups. This finding may help researchers who have limited resources and cannot recruit respondents using several different strategies to have sufficiently representative samples as they can reduce the potential gaps by survey designs and implementations.

4.5 Discussion

4.5.1 Study results and policy implications

To elicit people's WTP under a variety of scenarios in different locations more efficiently, we have developed a generalizable web-based survey framework. Using the framework, we elicited the value of reliable electric services during a WLD-outage that poses a serious risk of economic and social losses. As reported in Chapter 2, our study results suggest that the value of sustaining private HP demands was significantly increased as the respondents received the information, participated in the exercises, and better articulated their values (M: \$1.1/kWh to \$1.6/kWh for sure, \$1.6/kWh \$2.2/kWh with uncertainty) without significantly increasing nor decreasing the respondents' preference uncertainty (from \$14/day to \$14/day on average after removing 18 respondents whose preference uncertainty cannot be obtained and 2 respondents who preference uncertainty changes were far above the reasonable range). Both the value of serving private HP demands and preference uncertainty in the final stage were higher than that of our Pittsburgh face-to-face interviews (Pittsburgh study M: \$1.2/kWh and \$11/day), but the differences could have been resulted from the different survey settings, size and composition of the pools, and characteristics of the hypothetical outages (both interruption-related and environmental factors).

The results indicate four major implications. First, both those with and without experiences learned more about their preferences. Those who did not have any experience increased their "sure" values from \$1.0/kWh on average to \$1.5/kWh as a result of learning more about the hypothetical outage scenarios, and those who had experience increased their "sure" values from \$1.1/kWh to \$1.7/kWh. The respondents with previous experiences significantly increased their WTP as the survey progressed and showed a more pronounced increase compared to others without experiences are slightly different from what previous studies have demonstrated. Here we suggest three explanations for the different findings. First, the hypothetical outages might be different from what the respondents have experienced. For example, about half of the respondents who have experienced outages that lasted longer than several days, experienced the outages under moderate weather or during hot summer, whereas our hypothetical outage scenarios assumed a cold winter weather. Second, the respondents may not have fully understood the outages they experienced. For instance, residents of some counties in New York, who lost water, electricity and heat for 2 to 3 weeks during the extended outages occurred by Hurricane Sandy [135], may have more prior knowledge as they were able to learn the various consequences of WLD-outages. However, others who only lost electricity for few days without losing other services during Hurricane Sandy may not be able to consider the consequences of the WLD-outages before we provide the information and exercises. Finally, the respondents may have misremembered or forgotten what they have experienced. WLD-outages that take at least several days to restore power are rare, and it is likely that the outages that resulted in similar consequences to our scenarios happened so long ago (for instance, the North American Ice Storm of 1998 occurred 20 years ago, and the 2011 Halloween nor'easter occurred 7 years ago). Thus, even if the respondents experienced similar event in the past, they might have needed more information to recall their old experiences.

Second, the respondents' WTP for sustaining their HP demands and supporting their communities were significantly different, and the different types of WTP were explained by different variables. The respondents' WTP for sustaining their private demands were significantly higher than that for sustaining critical social services and helping vulnerable neighbors in their communities except for the respondents in the lowest income group (M: $48/day compared to $17-$18/day for sure). Also, the different types of preferences were barely correlated with each other ("sure" Kendall τ_{Privae_Social}=0.049, $\tau_{Private\_Neighbors}$=-0.033). Furthermore, the results of multiple linear regression suggest that the respondents' WTP for private backup service can be explained best by their ability to pay, their electricity consumptions, and their risk perceptions about the outages in the future whereas their WTP for supporting communities was more related to their altruistic motivations and other variables that were not measured in the study. This result demonstrates why it is important for researchers to clearly define the types of demands (i.e., private or social WTP) and use the right variables to analyze the elicited preferences.

Third, the influences from the framing of risks and the recruitment strategies were not significant. The respondents' WTP for reliable electric services were not significantly different for man-made disasters (M: \$0.94/kWh) and a natural disaster (M: \$1.2/kWh) even in the earlier parts of the survey, and the minor gap decreased as the survey progressed (M: \$1.8/kWh and \$1.4/kWh). Similarly, we compared the respondents who were recruited through MTurk and address-based sampling, and their WTP for backup services was roughly the same, and providing information and exercises further reduced the gap (M: \$1.0/kWh and \$1.1/kWh in the initial stage, \$1.5/kWh and \$1.6/kWh in the final stage). The fact that the causes of risks and recruitment strategies that are known to affect respondents' risk perceptions did not affect the respondents' WTP and some of the potential influences from these factors can be further reduced by survey designs and implementations imply that the researchers conducting the value of lost load studies can focus more on other important factors (such as the scope of power outage and extremeness of weather) and use the limited resources more efficiently and effectively.

Fourth, the respondents' WTP exhibited several important issues requiring further analysis such as preference heterogeneity, income effects and equity issues, and the uncertainty in individual preferences. We discussed more about the issue and proposed a strategy that integrates uncertainty in individual preferences into benefit-cost analysis and uses different aggregation rules to make more informed and collective investment decisions (more details are presented in Chapter 5).

It is hard to directly compare the results of this study to other studies' estimates as outage durations, scenarios, underlying assumptions (we elicited the value of sustaining power below 20A whereas other studies have elicited the value of unserved power by asking respondents' WTP for full backup service and divide the estimates with average of residential customers' electricity consumptions), elicitation techniques, and survey designs differ, but the estimated values per kWh from our study (M: $1.6/kWh for sure and $2.2/kWh with uncertainty in the final stage) are close to the lower bound of the range of previous studies' estimates (from $1.3/unserved-kWh for residential customers for a 16-hour long outage [21] to $40/unserved-kWh (by aggregating previous studies on value of lost load from high income countries without providing detailed information such as the durations of outages they considered [11]). However, considering that we made systematic efforts to help respondents fully understand the given outage scenarios and their consequences and to reduce potential biases and tried to be more realistic and conservative (including only focused on residential customers, did not include indirect costs, and specified the outage scenarios and provide information that respondents need for their value articulations so that they do not overstate), our estimates are not underestimated but more precise. Also, compared to using the unserved kWh estimates which simply divide the average of respondents' WTP with the average hourly electricity consumption (which divides the annual electricity consumption by 8760 hours), elicited values from the survey framework can provide more information (e.g., the ranges of preferences from a subset of respondents) and insights (including whether heterogeneity exists, how much interruption-related variables and environmental matter, and whether and how much preference uncertainty affect the decision). Thus, conducting surveys using our framework could lead to more informed decision-making.

4.5.2 Using the web-based survey framework to explore peoples' preferences under a variety of scenarios

While for this dissertation we have focused on the two emerging threats and elicited respondents' WTP to receive 20 Amps limited backup service during hypothetical 10-day outages during a cold winter weather, the survey framework can be generalized to support a wide variety of scenarios including outages of different durations, in different seasons, different locations, different levels of backup service coverage, and under a variety of emergency conditions. Now that we have demonstrated this tool, it is our hope that other researchers, as well as electricity-related decision-makers, will be able to use it to design their own scenarios to elicit the value of reliable electric services in the context of their own interests and needs. For instance, if decision-makers are interested in the value of reliable electric services of a specific customer segment, they would be able to design few outage scenarios that threats the customer segments, customize the information and exercises that might be useful for the customer segments' value articulations, conduct studies, and use the results to develop strategies for enhancing the targeted customers' resilience. Also, the tool can be used to estimate the value of reliable electric services in the event of WLD-outages caused by other representative risks (e.g., earthquakes at West Coast, South Carolina and lower Mississippi, hurricanes in the Southeastern coastal region, and ice storms in the Northeast United States and Southeast Canada region) although those regions also need to make additional investments to implement such capability (i.e., not only enhancing system operation and control but also establishing redundancies, hardening particularly vulnerable system components, or undergrounding electric facilities).

One of the other benefits of the survey framework is that researchers can use the elicited preferences to generate customer damage functions. According to de Nooij, Koopmans and Bijvoet [13] and Sullivan, Mercurio and Schllenberg [20], residential customers' value of reliable electricity is determined by customer-related factors, interruption-related factors, and environmental factors. With a small modification, residential customers' damage function can be written as:

$$Value\ of\ reliable\ electric\ service_{Amount\ of\ electricity\ provided} = f(interruption\ attributes, customer\ characteristics, environmental\ attributes)$$

where

- Customer-related factors: perceived level of reliability and level of preparedness, one's electricity consumptions, level of inconveniences from prolonged outages, and one's demographic characteristics (income, household composition, house type, work from home, etc.);
- Interruption-related factors: The time when an outage occurs (weekday or weekend, weather, and time), the length of an outage, advanced notification of an outage (planned or unplanned), and the reason for an outage; and,
- Environmental factors: the region's level of risks from various natural hazards and system failures, and external/climate conditions during an outage.

For this dissertation, we fixed all the interruption-related factors and some of the environmental factors using two detailed scenarios (i.e., we fixed the outage duration to 10 days, and the amount of coverage was fixed at 20 Amps for all the residential electric customer and the critical social services that will be sustained during the outages are predetermined). However, in collaboration with other utilities and researchers in other regions, it should be possible to generate a customer damage function for residential customers in general. Using the function, decision-makers such as distribution utilities, DG companies and suppliers, backup service providers, and smart-grid companies would be able to explore when upgrades in advanced distribution systems might be justified on economic grounds. Also, the framework could be used to produce estimates about the value of sustaining not only private HP demands but also critical social services (researchers can determine a specific set of social services that they think are important and want to sustain during the entire outage just as we did, but they can also assign some amount of power to social services and cycle on and off critical social services during the outage like Narayanan and Morgan suggest [1]). By using respondents' social WTP to sustain such services, decision-makers and relevant stakeholders may also be able to roughly construct social damage functions and gain insight about how much and how long (if at all) should electricity be provided to the social services.

Our work has been focused on eliciting the value of reliable electric services for residential customers, but the results could also be combined with the interruption costs of industrial and commercial customers. By aggregating the value of reliable electric services from all the electricity customer groups, decision-makers should be able to make more informed investment decisions that incorporates all electricity customers in a region and minimizes the entire economic and social impacts of the region.

4.5.3 Behavioral research needs in eliciting and using peoples' preferences

From a policy-maker's perspective, it is essential to know the trade-offs people are willing to make among different options, such as people's WTP to adopt smart grid technologies and receive some forms of backup services during WLD-outages. While studies eliciting public values and preferences typically assume that respondents are rational and that they can make reliable and consistent judgments, their preferences are often not well articulated, especially for unfamiliar goods or services. Our results suggested that the respondents have rough preferences in the beginning of the study, but they need the information and exercises to better refine and articulate their values and reduce the range of uncertainty in their WTP, and even by the end of the study, there still existed uncertainty in their preferences.

Also, during our face-to-face surveys, we encountered a few respondents whose demographic information and electricity consumption profiles were similar but who had very different reliability preferences. That means there exists large heterogeneity across people in their WTP not only stemming from different electricity use profiles, demographics, and needs but also due to other behavioral factors such as their impressions and experiences (including their own previous experiences and the experiences of others) of the given outage and media exposures to the relevant events. While we were not able to fully address the heterogeneity issue because of the lack of data, we would like to collect sufficient amount of data in the additional rounds of surveys and incorporate the wide range of preferences into policy decision-making.

4.6 Conclusion

Since the mid 1980s, the value-based reliability planning has emerged as an important factor in reliability improvement projects. While they have conducted a number of studies to estimate their customer outage costs, most of the previous studies have focused on outages that last only a few hours, and in many cases, did not involve any systematic effort to help respondents fully consider the various aspects of hypothetical outages with which they may not have had experience or previously considered. Hence, the estimates from those studies are not appropriate to address the question: how much are individuals or society prepared to pay to improve resilience in the face of low-probability power outages of wide extent and long duration? While the work described in Chapter 2 had demonstrated the efficacy of our elicitation approach, conducting the face-to-face interviews is time- and labor-intensive, thus it is not feasible to conduct multiple studies to examine WTP for outages of various durations precipitated by different causes. In order to address that problem, we had developed a web-based elicitation tool that improves our earlier design.

In the first application of the web-based tool, we have not only shown that the tool can elicit the respondents' preferences but also demonstrated the importance of helping respondents better articulate their values. While the tool was used to elicit the value of 20A backup service and WTP for pre-determined critical social services and vulnerable neighbors during the hypothetical 10-day outage, decision-makers can elicit more informed and engaged members of the public in the context of their own interests and needs, and a set of estimates can be used to generate customer damage functions. Thus, the framework should help service providers, utilities, regulators, and other relevant stakeholders to make more informed investment decisions and improve the robustness and resilience of electric power system.

4.7 Future works

In this first application of our web-based tool, we recruited the respondents using MTurk and address-based sampling and tested several research hypotheses. Understanding the preferences of northeastern residents who have not experienced WLD-outages before is important, but it is also important to include people in our sample who have experienced extreme weather events along with WLD-outages so as to assess the extent to which respondents' previous experiences influence their preferences and WTP for reliable electric services, especially for long-lasting outages. One of the most obvious representative events is the extended outages that was caused by Hurricane Sandy. To that end, we are in the process of recruiting a sample of New Jersey residents who experienced the extended outages caused by Hurricane Sandy. The responses from those respondents will help us understand whether and how much their real-life experiences influence on their economic and social preferences for reliable electric services.

In addition, there are several important issues that need to be further explored to make the estimates more reliable and credible. First, we should be able to estimate the influence from hypothetical bias by interviewing some people who have recently experienced WLD-outages and develop some strategies to adjust others' results for that influence. Second, we should be able to determine the variables and characteristics that are really important for the value of load lost studies and hence should be included in future studies. We can do this by conducting a set of small but deep surveys (such as testing whether the geographic extent of the outage, availability of backup power for critical private and social services and coupled infrastructures, and respondents' familiarity with the events make significant differences between groups). Third, we should be able to explore what factors contribute to the large heterogeneity across the respondents in their preferences and how to handle the heterogeneity issue. Finally, we should be able to further explore the relationship between the respondents' needs, income levels and mitigation and preparedness levels with their value of reliable electric services and discuss the equity- and financing-related issues including who should pay for what and how we can resolve the income effects and increase the social benefits.

5. A Method to Include Preference Uncertainty in Benefit-cost Analysis Illustrated with an Application to Minimize Disruptions from a Widespread and Long-lasting Power Blackout

Benefit-cost analysis is widely used to evaluate alternative courses of action that are designed to achieve policy objectives. Although many analyses take uncertainty into account, they typically only consider uncertainty in cost estimates and physical states of the world, while uncertainty about individual preferences, and thus the benefit of policy intervention, is ignored. Here we propose a strategy to integrate uncertainty in individual preferences into benefit-cost analysis using *societal preference intervals*, which are ranges of values where it is unclear whether society as a whole should accept or reject an option. As illustrative examples of this framework, we use public valuations of implementing a smart grid technology to mitigate the impacts of a 24-hour large regional blackout that had occurred on a hot summer weekend and a 10-day outage during a period of very cold winter weather. We find that uncertainty in individual preferences, when aggregated to form societal preference intervals, can substantially change the decision society would make. We conclude with a discussion of where preference uncertainty comes from, how it might be reduced, and why incorporating unresolved uncertainty into benefit-cost analysis can be important.

The work presented in this chapter is a joint effort with Alexander L. Davis and M. Granger Morgan, and submitted to journal *Risk Analysis*.[33]

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[33] Baik, S., Davis, A. L., & Morgan, M. G. (2018). A Method to Include Preference Uncertainty in Benefit-Cost Analysis Illustrated with an Application to Minimize Disruptions from a Large Power Blackout. *Submitted to Risk Analysis.*

5.1 Introduction

From the face-to-face interview and web-based surveys, we found that the value of sustaining HP demands during the WLD-outages is much higher than that for normal circumstances and implementing the ability to provide a low-amperage backup service via islanded distribution feeders may make sense in some regions that face a significant risk of frequent or widespread outages. Because implementing such ability requires substantial investment especially in the beginning of the project [137], and uncertainty in individuals' preferences persisted throughout the study even after providing information about blackouts and their consequences, it is highly desirable to explore the benefits and costs of implementing smart grid technologies to mitigate the impacts WLD-outages while incorporating the uncertainty of the public's preferences into decision-making.

Benefit-cost analysis is widely used in policy analysis and government decision-making to examine whether a specific policy is justified or to compare several alternative policies with different outcomes and time horizons. The most useful analyses take uncertainty into account [139, 140], yet typically only uncertainty about cost estimates and physical states of the world is considered, neglecting uncertainty about the value that the public places on policy outcomes. When a decision is to be made by a single decision-maker who is uncertain about an appropriate value (e.g. the value of a statistical life), the best practice is to use parametric analysis so as to display the consequences of alternative value choices [139]. However, when the values involved are those of a population, no framework exists to incorporate the uncertainty in individual preferences into the societal decision-making process. In this chapter, we propose such an approach, that incorporates preference uncertainty using *individual preference intervals* along with different *aggregation rules*, to express *uncertainty in societal preferences*. Cost estimates are then compared with those societal preference intervals to determine whether society will surely accept (or reject) an option, or whether an additional analytic-deliberative process should be invoked to reach a collective societal decision [142-147].

5.2 Incorporating Preference Uncertainty into Policy Analysis

Benefit-cost analysis typically uses engineering and economic models to quantify the impacts of alternative policy choices in monetary terms. To illustrate uncertainty in societal preferences, we consider the example of augmenting smart grid and DG technologies to allow a region to operate as an isolated island to provide residential electric customers with limited power when none is available from the central grid (see Narayanan and Morgan [1] and Chapter 3.2 for more details). In this case, cost estimates are determined by factors such as the prices of raw materials, manufacturing, labor, and maintenance. The total cost is the sum of the present value of unit prices times the number of required units of each technology. Assuming that engineering analyses can determine the required technology and units with relative certainty, uncertainty in the cost estimates comes from two sources: 1) uncertainty in prices, and 2) errors in estimating the cost function (e.g., knowledge about how technology will evolve in the future is not precisely known).

Quantifying the benefits can be much trickier. The majority of benefits only accrue if a grid blackout occurs but customers continue to receive (some) power. Thus, the expected value of the benefit is $B = P(blackout) \times value(blackout)$ where $P(blackout)$ is the probability of a blackout over a given timeframe and $value(blackout)$ is the value that the public places on the reliable electric services during the blackout. While much effort is spent on estimating the probability of blackouts, (e.g., through simulations [148] or by using bounding analysis [149]), the value of the lost electricity is more difficult to estimate. Typically, the value that the public places on electric services is assumed to be a known quantity that can be elicited using surveys, where customers are asked for their WTP to avoid blackouts [19-21]. Yet, it is not hard to see that there exists uncertainty in these values arising from several sources. Traditional issues include sampling error, where the true distribution of WTP across individuals, or true population average WTP, is unknown from any particular sample of individuals, and statistical inference must be used for the population value. There may also be uncertainty arising from respondents not understanding questions in survey instruments or, despite the efforts made in designing the instruments, respondents may not be able to fully envision the circumstances they would face during a blackout. Both would add measurement error on top of sampling error.

We have found that more fundamental uncertainty in the value of blackouts is present, where members of the public simply do not know exactly how much they value their electric services during a hypothetical blackout. Suppose that there is a large-regional blackout and you cannot get power for 24 hours. We guess that for the 24 hours you would surely be willing to pay $1 to have electricity to power your high priority loads –such as a few lights, your refrigerator, and air conditioning during summer. You also would probably pay $5 or even up to $20. But $40 might give you pause. Is this too much? How much is usually spent on similar goods and services? Unless it is for a very unusual situation (e.g., a planned wedding reception at your home), it is almost certainly too much to pay $500 to get the electricity back for 24 hours. Suppose $150 is the largest amount you might consider, and you are certain you would not pay more. Between these numbers, $40 you would surely pay, and amounts above $150 that you would surely not pay, is a range ($40-150) where you, the decision-maker, are unsure about paying. This is a general pattern we have found in surveying members of the lay public. They tend to have clear bounds to their WTP but are unsure about what they would do between those bounds.

To that end, instead of using a general benefit-cost analysis, we propose an approach to handle individual preference uncertainty and capture that uncertainty in aggregated social preferences. Suppose the population consists of N individuals (in our case, residential electricity customers) indexed i=1,2,...N. Each individual has a lower bound L_i which is the maximum of what they would *surely* trade in exchange for a good or service (i.e., where her mind switches from "definitely buy" to "may consider buying"), and has an upper bound U_i which is the minimum of what they would surely not trade in exchange for the good or service (i.e., where their minds switch from "may consider buying" to "definitely will not buy"). Further, assume that L_i and U_i are measured on an interval scale for all individuals such that L_i and U_i are well-defined up to affine transformations. The range L_i to U_i is the *individual's preference interval* which can be interpreted as the range of values for which the individual is unsure about whether they are willing to pay any amount between L_i and U_i [150-153].

To construct a *societal preference interval* [L, U], representing society's uncertainty about the value of avoiding a blackout (where in this case "society" is everyone served by the feeder), we must aggregate L_i and U_i in some way. If L_i and U_i are measured on an interval scale and individuals are interpersonally comparable so that a change in lower (upper) bounds are equivalent from person to person, then the measures satisfy *cardinal full comparability* [154]. While the most common aggregation from individual to societal preferences is the average, cardinal full comparability also admits other aggregation rules. Two important ones are the minimum and the maximum. There are arguments for and against each one. If, for example, individuals' lower bounds are strongly associated with wealth, then the individuals with greater lower bounds may simply be more affluent. In this case, society might care more about individuals with smaller lower bounds (if no arrangements exist for cross subsidies), and the minimum aggregation function should be used. If, on the other hand, individuals' lower bounds are more strongly correlated with needs (for example, the need for an electrically operated medical respirator), then society might care more about the individuals with larger lower bounds, and the maximum aggregation rule would be more appropriate.

Here we suggest aggregating individuals' preference intervals to construct societal preference intervals. Using the minimum aggregation rule, we calculate *society's minimum preference interval* from the *minimum lower bound* (MinLB=min(L_i)) to the *minimum upper bound* (MinUB=min(U_i); the vertical striped area in Figure 5-1). The same process can be used to construct *society's maximum preference interval* from the *maximum lower bound* (MaxLB=max(L_i)) to the *maximum upper bound* (MaxUB=max(U_i); the horizontal striped area in Figure 5-1). In between the two intervals, it is also possible to construct *the interval of intermediate preference* from MinUB to MaxLB (the dotted area in Figure 5-1). Once the intervals are calculated, it is possible to determine whether society as a whole would definitely reject an option (if the required cost exceeds MaxUB), definitely accept an option (if its cost is lower than MinUB), or are unsure (in between MinLB and MaxUB). Only two of the three possible outcomes permit a definitive decision (accept or reject), while society being unsure means that some form of additional deliberation is needed. In the unsure case, the outcome of benefit-cost analysis might be determined by whether and how strongly respondents' preferences are correlated with their wealth and needs. Here we only consider the most common case when individuals who are the least interested and the most interested in a project are fairly distinguishable and both have some amount of preference of uncertainty, but in general, the number and type of preference intervals are determined by the distance between the two groups of individuals and how much preferences are spread out within each group.

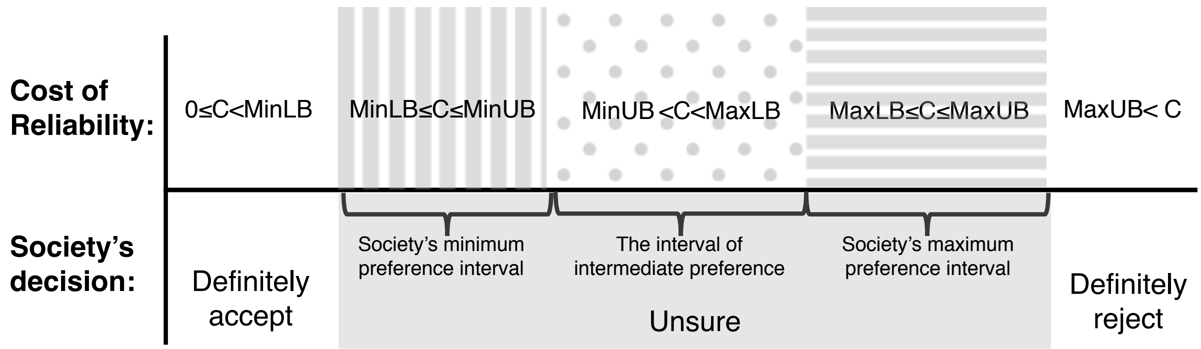


Figure 5-1. Diagram summarizing the three different regions of society's decisions depending on society's preference intervals. If the required cost is lower than the minimum of society's minimum preference interval or higher than the maximum of society's maximum preference interval (i.e., the required cost per individual locates in the white region), society can definitely accept or reject an option. However, if the required cost is within the unsure region (i.e., the required cost is located in the grey shaded region), additional considerations, such as whether and how strongly respondents' preferences are correlated with their wealth and needs, should be addressed before making the decision.

5.3 Case studies: Providing Limited Local Electric service in the Event of Widespread and Long-duration Outages in the Bulk Power System

5.3.1 Study 1: Providing limited local electric backup service against a 24-hour outage

For the purpose of illustration, we considered implementing a low-amperage backup service for a distribution feeder that serves 2,500 customers and the incremental investment cost is recovered through service payments.

To illustrate the approach, we first drew on results from our face-to-face interview with Pittsburgh residents. As seen in Figure 5-2, we used a multiple bounded discrete choice preference elicitation method which allows respondents to express uncertainty in their preferences in the form of an interval (the upper limit from the “yes” column (L_i) to the upper limit from the “not sure” column (U_i)). If a respondent had a high WTP and checked the entire “yes” column, we asked “what is the largest amount you would be willing to pay to receive the service?” and used \$75 as their lower bound and the answer as their upper bound (for instance, if a respondent’s answer is \$100, the respondent’s L_i is \$75 and U_i is \$100).

Using the response mode, we conducted 73 hour-long face-to-face interviews with residential electricity customers in Allegheny County, PA, USA. For illustration, we assumed that these results represent the preferences of all residential customers in the United States (i.e., preferences are the same in all regions), and construct societal preference intervals using the following approach:

- First, we extracted each individuals’ lower and upper bounds for their HP demands ($L_{i\_private}$, $U_{i\_private}$). Figure 5-2-A shows the distributions of $L_{i\_private}$ and $U_{i\_private}$;
- Next, we computed MinLB, MaxLB, MinLB, and MaxUB;
- Then, we constructed the society’s minimum (from MinLB to MinUB) and maximum preference interval (from MaxLB to MaxUB); and,
- Finally, we calculated the interval of intermediate preference range (from MinUB to MaxLB).

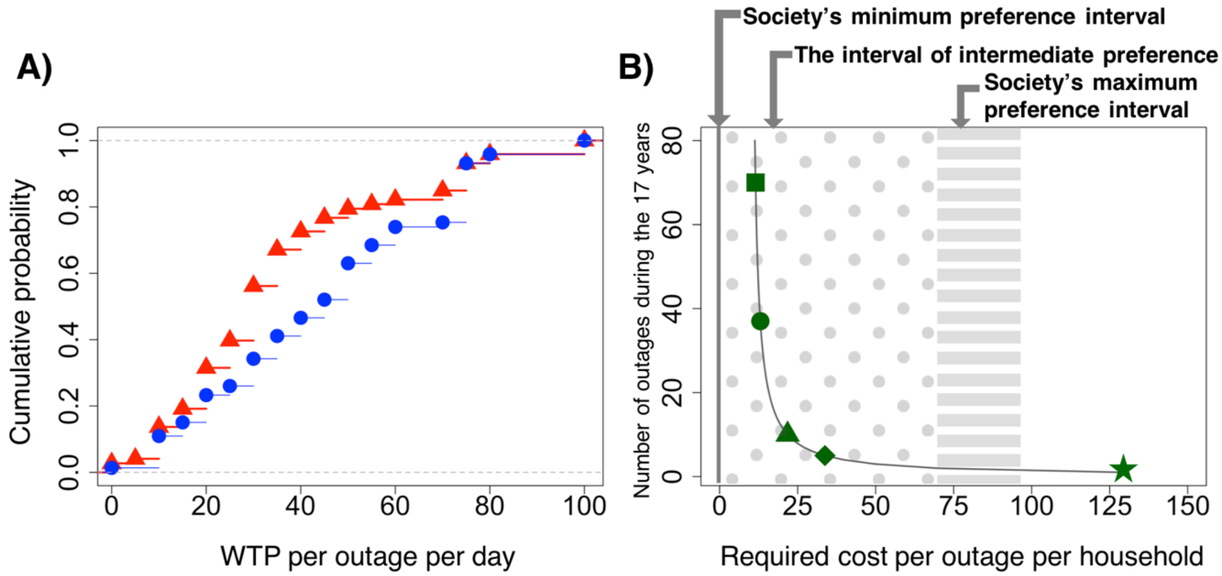


Figure 5-2. A) Cumulative distribution of the respondents who were surely (*L_i,* red triangles) and might (*U_i,* blue dots) be willing to pay for the low-amperage backup service against a 24-hour outage on a hot summer weekend. B) The required incremental cost per residential customer to implement the low-amperage backup service (solid curve) compared to the interval of the society's maximum preference interval (horizontally striped area), minimum preference interval (vertically striped area in Figure 5-1 and the grey line at zero), and the intermediate preference (dotted area). As explained, the points along the curve indicate the cases discussed in the text.

Next, we estimated the costs to provide the low-amperage backup service to residential customers using the following assumptions:

- Either the distribution utility itself has sufficient DG or has contracted with private DG owners who can supply that much power in the event of an outage to supply 20A service to all 2,500 customers. Here we assumed that that most of the time these DG units are being used for non-emergency purposes so that it is only necessary to cover the cost of emergency generation during the outage.
- The total cost of upgrades to the feeder and operation of the associated DG was on the order of $100,000 with additional annual O&M costs of approximately 5 percent of the initial capital cost.

- Basic smart meters for residential customers are already in place, and if done in bulk, upgrading the meters by adding batteries for continuous operation in the event of a power outage and installing a control circuit that can switch a main breaker from a high-amperage service (e.g., 150A) to a low-amperage (e.g., 20A) service costs $50/meter.
- During the outage, the cost of power produced is about 1.5 times than that of grid power under normal circumstances ($0.17/kWh or $9.8/day·residential customer). In order to simplify the calculation, we did not consider the time value of money (i.e., no consideration of when the outages occur).
- The lifetime of these technologies is 20 years.

Under the assumptions, the total cost of implementing the ability to provide the low-amperage backup service can be calculated as follows:

$$\begin{aligned}
&Total\ incremental\ investment\ cost \\
&\quad = System\ upgrade\ cost + Annual\ O\&M\ cost + \\
&\quad\ \ Smart\ meter\ upgrade\ cost\ for\ all\ the\ residential\ customers + \\
&\quad\ \ Total\ fuel\ cost\ for\ all\ the\ residential\ customers \\
&\quad = \$100{,}000 + \sum_{i=1}^{20} \frac{5{,}000}{1.03^{i}} + 2{,}500 \times 50 + \\
&\quad\ \ \sum_{i=1}^{n} \frac{\frac{\$0.17}{kWh} \times 20A \times 120V \times \frac{1}{1000} Wh/kWh \times 24hours \times (outage\ duration) \times 2{,}500 \times Year_i}{1.03^{Year_i}}
\end{aligned}$$

where n=number of outages during the lifetime, and Year$_i$*= Year when the i*th *outage occurs.*

Because different regions face different types of risks, we separated the United States by state and counted the number of major electric emergency incidents and disturbances for each state that: 1) occurred between 2000 to 2017, 2) directly resulted in losses to customers (either demand loss or number of customers affected is greater than zero), and 3) and required ≥ 24 hours to fully restore the power (Office of Electricity Delivery and Energy Reliability, 2018).

Figure 5-2-B shows the cost required per residential customer per outage to implement the backup service on the horizontal axis, plotted against the number of outages on the vertical axis. As an illustrative example, we assumed that individual preferences are the same in all regions and select the following five cases (indicated by points along the curve in Figure 5-2-B): 1) Michigan which experienced the largest number of long outages (70 long outages during the past 17 years, square); 2) Pennsylvania for which the value was elicited (37 outages, dot); 3) four states which experienced the average number of long outages (10 outages, triangle); 4) three states which provide additional insights about the societal investment decision (5 outages, diamond); and, 5) four states which experienced only 1 long outage (star).

As can be seen, the societal decision depends on the individual preferences and aggregation rule. When individuals' WTP is highly correlated with their needs, a decision-maker might make a decision based on the maximum aggregation rule (favoring those who need electricity the most). In this example, the aggregation rule gives us \$75 for the lower bound and \$100 for the upper bound of the society's maximum preference interval (the horizontal striped grey area), thus the society should definitely accept the investment if a region experiences more than 1 long outage. On the other hand, when individuals' WTP is highly correlated with their wealth, a decision-maker might make a decision based on the minimum aggregation rule (favoring those who can pay the least). Since the aggregation rule gives us \$0 for both the MinLB and MinUB, the required cost per outage always exceeds the society's minimum preference interval (the vertical grey line at zero) no matter how many outages occurs in a region. In such a case, society should definitely reject if the minimum aggregation rule is judged most appropriate. In the middle of the two extremes lies an area that experiences more than 1 long outage where the investment cannot definitely be accepted or rejected because the cost curve always lies within the interval of intermediate preference (the dotted grey area). In this case, information might be gained by using the distribution of individuals' lower and upper bounds to determine the proportion of the population who support the policy.

This illustration shows why incorporating preference uncertainty can be important, especially when individuals' preferences for a policy are not sufficiently strong. In some regions that suffer a large enough number of long outages and require relatively low service payments (because the incremental investment cost is evenly distributed across the outages), most individuals are either definitely willing to pay more than the required cost per household per outage or are unsure. For example, if their preferences are the same as those as respondents in the Pittsburgh study, 86% (using lower bounds) to 89% (using upper bounds) of residents in Michigan would support the investment (see Table 5-1 below). Thus, preference uncertainty does not make a significant difference in decision-making. However, in the case of other regions that experience fewer long outages, the required service payment increases, and the proportion of individuals who support the backup service using the two different bounds changes substantially. For instance, in this example, the three states expected to suffer 5 long outages would require ~$34/customer-outage. In this case, the individuals' upper bounds suggest that more than 65% of individuals would be supportive, whereas the lower bound suggests that only 44% of the individuals would be supportive (see Table 5-1 below). A decision based on majority preference would flip depending on both uncertainty in preferences and the aggregation rules.

Table 5-1. Percentage of respondents who would be willing to pay more than the required incremental investment cost per residential customer per outage before and after providing more information and exercises assuming (for illustration) that all respondents have preferences similar to those from our Pittsburgh study. Preference uncertainty arises from using individuals' lower or upper bounds or providing more information and exercises do not substantially influence decision-making in high-risk regions, but low-risk regions' decisions can be substantially influenced by both factors.

		Maximum (76 outages)	Pennsylvania (37 outages)	Average (10 outages)	5 outages	Minimum (1 outage)
Required payment per household per outage		$11	$13	$22	$34	$130
Before providing more information	Lower bound	70	70	44	16	0
	Upper bound	79	79	64	51	0
After providing more information	Lower bound	86	86	68	44	0
	Upper bound	89	89	77	66	0

While we have focused on preference uncertainty, the approach can also be used to incorporate cost uncertainty (Figure 5-3). In our case, the number of customers served by a distribution feeder and the incremental investment cost per distribution feeder to enable islanding are the two largest sources of cost uncertainty. We treated the number of customers served by a feeder (1,500, 2,500 and 3,000 residential customers per feeder [52, 155, 156]) and the incremental investment cost per feeder to enable islanding parametrically (as low as $70,000 and as high as $300,000 [64, 65]). The horizontal error bars on each point in Figure 5-3 indicate the maximum and minimum required costs when the number of outages occurred is fixed. Society should definitely reject the investment if a region experiences less than one large long-duration outage in 17 years because the lowest cost required per household per outage (slightly over $100) exceeds the upper bound of the society's maximum preference interval ($100). Even if a region experiences more than 1 long outage in 17 years, in this example, the region still could not definitely accept the project because the required cost is always higher than the society's minimum preference interval ($0, the vertical grey line), and additional deliberation would be required.

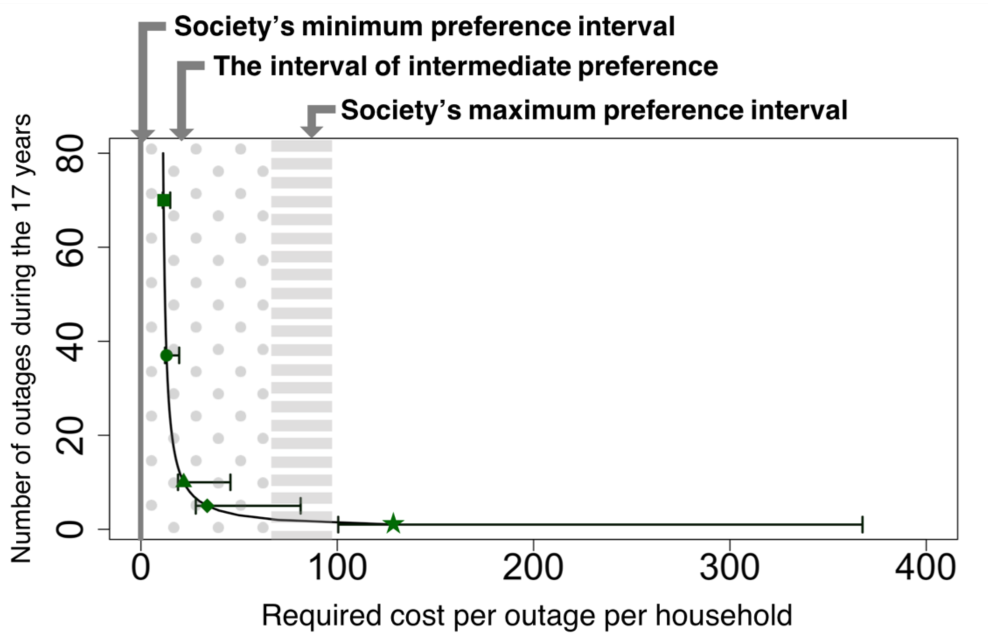


Figure 5-3. Similar to Figure 5-2-B but including uncertainty that arises from cost estimates. The error bar indicates the upper and lower bound of the required cost per residential customer per outage.

5.3.2 Study 2: Assuring both private and social demands during major disruptions to bulk power system

In the face-to-face interviews with Allegheny county residents, we only elicited their preferences for a low-amperage backup service to sustain their own private HP demands against a hypothetical 24-hour outage. However, providing electric backup services is expected to be more feasible if the backup service can serve both private HP demands and critical social demands during WLD-outages. In this illustrative example, we used the elicited value of reliable electric services from the web-based surveys to determine whether and when the incremental investment cost to implement the ability to provide a low-amperage backup service to all residential customers and/or full backup service to selected critical social services can be recovered through service payments.

We first determined whether society as a whole should accept the investment in providing the private low-amperage backup service to residential customers. Similar to what we did in the previous example, we separated the Northeastern United States by state, counted the number of major electric emergency incidents and disturbances for each state, and estimated the required service payment per residential customer per outage. Then, to construct the societal preference intervals, we aggregated the respondents' WTP per day for the low-amperage backup service during the hypothetical 10-day WLD-outages.

Figure 5-4 below shows the required cost per residential customer per outage to implement the backup service on the horizontal axis, plotted against the number of outages on the vertical axis. As the respondents' preferences were mildly correlated with their wealth and needs (see Chapter 4.4.4 for more details), decision-makers need to make a decision based on both aggregation rules. Since the required cost per residential customers per outage for all the nine states laid within the interval of intermediate preference ($0-100, the dotted grey area), the decision-makers cannot make a definite decision, and require additional deliberations.

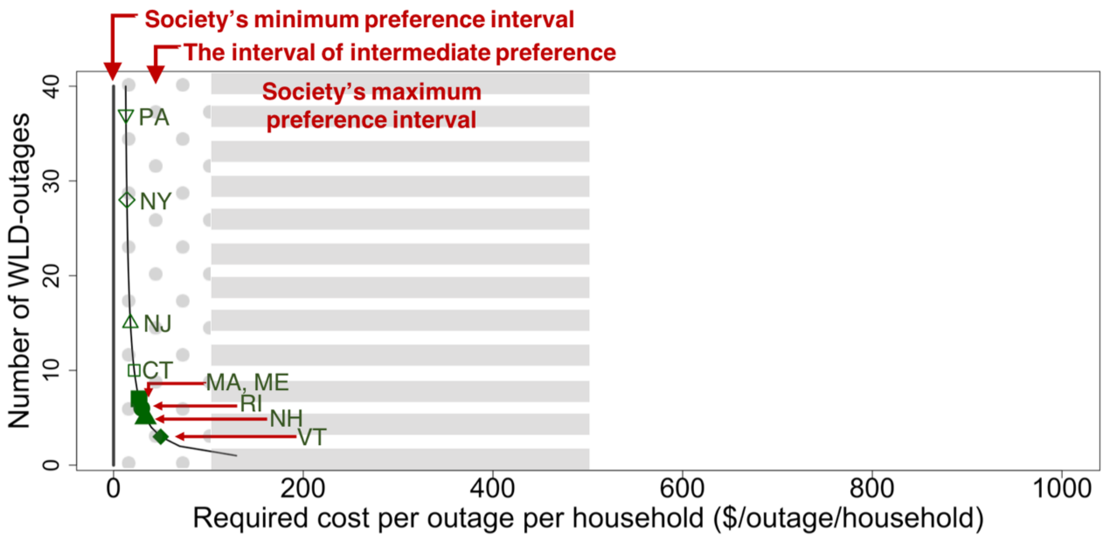


Figure 5-4. Required service payment per residential customer per outage to implement the low-amperage backup service (solid curve) compared to the interval of the society's minimum preference interval (vertically striped area in Figure 5-1 and the vertical grey line at zero), maximum preference interval (horizontally striped area), and intermediate preference (dotted area). The eight points indicate the nine states in the Northeastern United States.

Figure 5-5 below summarizes the proportion of the population who support the policy within each state using the respondents' lower and upper bounds. The results also show why incorporating preference uncertainty into benefit-cost analysis is important, especially when individuals' preferences are not strong. In some regions that suffer sufficient number of WLD-outages, most individuals were willing to pay more than the required cost per household per outage regardless of whether the respondents' lower or upper bounds were being used as the required service payment is relatively low (see Pennsylvania or New York as examples). However, in case of other regions that experience fewer WLD-outages, the proportions of individuals who support the backup service were considerably changed as different bounds were used. For instance, New Hampshire is expected to suffer 3 long outages during the lifetime of technology and requires ~$34/residential customer-outage. In this case, using the individuals' upper bounds suggests that more than 57% of individuals would be supportive of the investment whereas using the lower bounds suggests that only 14% of the individuals would support the policy.

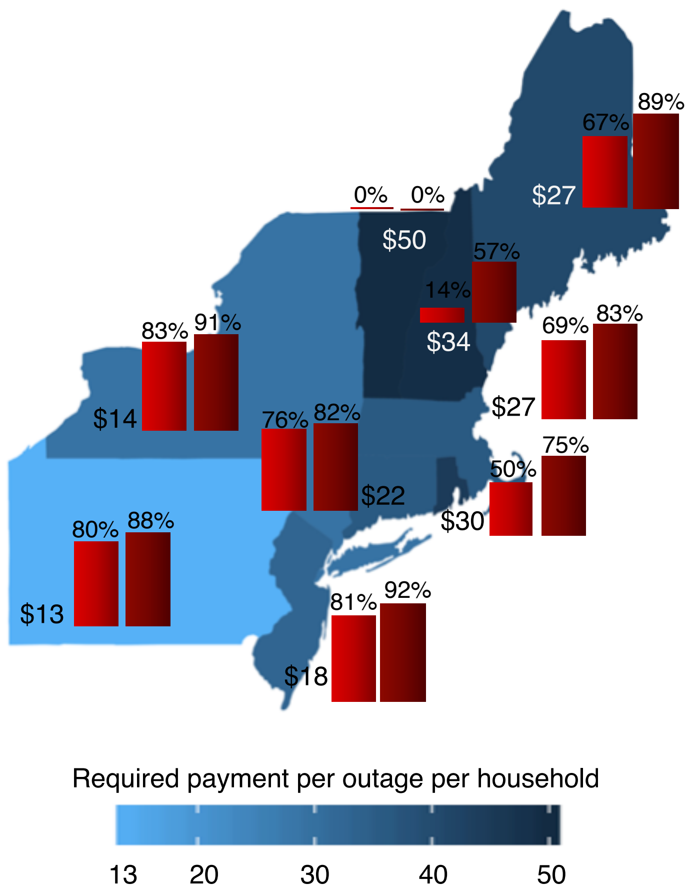


Figure 5-5. Required cost per household per outage to justify the incremental investment and the portion of the respondents who were surely (left red bar graph of each pair, using lower bounds) and might be (right dark red bar graph of each pair, using upper bounds) willing to pay more than the required cost per household per outage in each of the nine states of the Northeastern United states.

Next, we extended the benefit-cost analysis by including the respondents' WTP for supporting their communities. While helping vulnerable neighbors in communities do not change the total incremental investment cost (because the required investment such as upgrading smart meters and distribution system remains the same and the only changes come from who support the low-income households), sustaining predetermined critical social services requires additional investments (such as for sending signals to connect the critical loads following the pre-defined dynamic load schedule). Thus, we made additional assumptions to include such incremental costs:

- Either the distribution utility itself has sufficient DG or it has contracted with private DG owners who can supply that much power in the event of an outage to supply 20A service to all 2,500 customers *and full backup service to selected critical social services on the islanded feeder*.[34] Here we assumed that that most of the time these DG units are being used for non-emergency purposes so that it is only necessary to cover the cost of emergency generation during the outage.
- During the outage, the cost of power produced is about 1.5 times than that of grid power under normal circumstances ($0.17/kWh).
- In case of smart meters for critical social services, battery installations are required to ensure that they are properly disconnected and reconnected. Following to Narayanan and Morgan [1], we assumed that the cost for battery installation is $40/meter.
- In this example, we considered providing full backup service to 1 fire station, 2 police station, 1 drinking water treatment plant, 1 sewage treatment plant, and 15 critical intersections. Following to Narayanan and Morgan [1], we assumed that the fire and police station consumes 60kW when they run at full capacity (during daytime (fire station)/night

[34] If a region does not have sufficient amount of DG capacities to sustain both critical private and social demands, the distribution utility may need to follow its power restoration priorities (critical social services first, power system restoration next, and then private demands). Within the same priority, we assumed that the utilities would focus on restoring power to the greatest number of customers rather than potential profits (i.e., a neighborhood with more residents has higher priority than a wealthy neighborhood with smaller number of residents).

(police station)) and 30kW when they run at partial capacity (during night (fire station)/daytime (police station)); the water treatment facility consumes 1312.5kWh/day and the sewage treatment facility consumes 2187.5kWh/day (assuming that one residential customer consumes 350 gallons per day and drinking water treatment consumes 1.5kW/1,000 gallon and wastewater treatment consumes 2.5kW/1,000 gallon); and, each traffic management system consumes 2kW/traffic light if the region have adopted smart traffic management system and have converted all the signals to LED.

Then, the total cost of implementing the ability to provide the low-amperage backup service for all the residential customers and sustain critical social services can be calculated as follows:

$$
\begin{aligned}
&Total\ incremental\ investment\ cost_{\text{(Private, Social and Neighbor)}} \\
&\quad = Required\ investment\ for\ private\ demands + \\
&\qquad Required\ investment\ for\ critical\ social\ services \\
&\quad = Distribution\ feeder\ upgrade\ cost + \ Annual\ O\&M\ cost + \\
&\qquad Smart\ meter\ upgrade\ cost\ for\ all\ the\ residential\ customers + \\
&\qquad Smart\ meter\ upgrade\ cost\ for\ critical\ social\ services + \\
&\qquad Total\ fuel\ cost\ for\ residential\ customers + Total\ fuel\ cost\ for\ critical\ social\ services \\
&\quad = \$100{,}000 + \sum_{i=1}^{20} \frac{5{,}000}{1.03^{i}} + 2{,}500 \times 50 + 20 \times 40 + \\
&\qquad \sum_{i=1}^{n} \frac{\frac{\$0.17}{kWh} \times 20A \times 120V \times \frac{1}{1000} Wh/kWh \times 24hours \times (outage\ duration) \times 2{,}500 \times Year_i}{1.03^{Year_i}} + \\
&\qquad \sum_{i=1}^{n} \frac{\$0.17/kWh \times (7460kWh\ required\ to\ sustain\ critical\ social\ services\ per\ day) \times (outage\ duration) \times Year_i}{1.03^{Year_i}}
\end{aligned}
$$

where n=number of outages during the lifetime, and $Year_i$*= Year when the* i^{th} *outage occurs.*

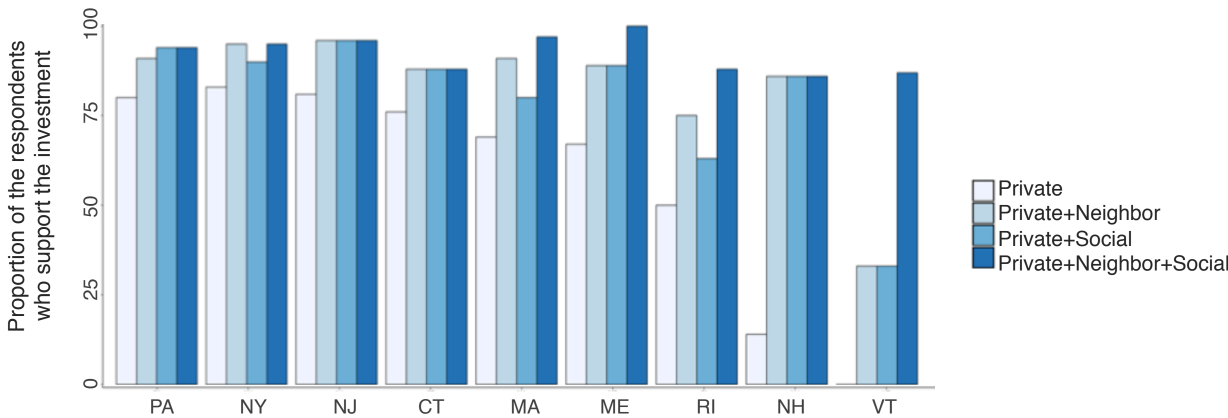
To understand whether sustaining critical social services and helping vulnerable neighbors change the decision society would make, we considered the following three cases: 1) only providing the low-amperage backup service to low-income households; 2) only sustaining critical social services; and, 3) providing the low-amperage backup service to low-income households and sustaining critical social services. In this analysis, we divided the residential electric customers into two groups to address social equity concerns (i.e., not only provide the backup service to those prepared to pay for it): low-income households whose income levels are below the 20th percentile (~500 residential customers under the distribution feeder whose household income is lower than $17,000) and the other households whose income levels are above the 20th percentile (~2,000 residential customers under the feeder whose household income is higher than $17,001). We assumed that the low-income households are supported by low-income home energy assistance program for their normal electricity bills and are not responsible for any forms of backup service (for their low-amperage backup services, for helping other vulnerable members in their communities, and for sustaining critical social services) whereas the other households are not only responsible for their low-amperage backup services but also responsible for helping vulnerable community members and sustaining critical social services.

Similar to the previous case study, we assumed that the elicited preferences represent the economic and social preferences of residents of each of the nine states regardless of outage characteristics (e.g., length of disruptions and weather conditions), and all the responsible customers make fixed payments at the time of each outage. Following to the strategy, we calculated the societal preference intervals for the three cases:

- First, we extracted each individuals' lower and upper bounds for sustaining their HP demands, sustaining critical social services, and helping their vulnerable neighbors ($L_{i\_private}$, L_{i_social}, $L_{i\_neighbors}$, $U_{i\_private}$, U_{i_social}, $U_{i\_neighbor}$). Here, we only considered individuals whose income levels are above $17,000 (i.e., income levels are above the 20th percentile thus responsible not only for sustaining their own private HP demands but also for supporting society);

- Next, we computed MinLB, MaxLB, MinLB, and MaxUB for the three cases (i.e., Min and Max of $L_{i\_private}+L_{i\_neighbors}$, $U_{i\_private}+U_{i\_neighbor}$; $L_{i\_private}+L_{i\_social}$, $U_{i\_private}+U_{i\_social}$; $L_{i\_private}+L_{i\_social}+L_{i\_neighbors}$, and $U_{i\_private}+U_{i\_social}+U_{i\_neighbor}$);
- Then, we constructed the society's minimum (from MinLB to MinUB) and maximum preference interval (from MaxLB to MaxUB); and,
- Finally, we calculated the interval of intermediate preference range (from MinUB to MaxLB).

The results suggest that incorporating both private HP demands and social demands slightly increased the required payment per non-low-income household per outage (additional \$3-\$19/outage/household depending on the state and coverage), and the investment still cannot be definitely accepted (because the required payments per non-low-income household per outage are larger than \$0, the MinLBs for all the three cases) nor definitely rejected (because the required payments per non-low-income household per outage are smaller than the MaxLBs, ranging from \$180 to \$260). However, compared to the investment which only provides residential customers the private low-amperage backup service, the proportions of respondents who support the investment have increased ranging from 6% to 100% depending on the state and coverage (see Figure 5-6 below). In other words, incorporating social demands make the investment more attractive. One thing to note is we only considered the respondents' preferences that are expressed in monetary terms, but securing critical social demands also generates non-monetary community benefits including reduced crime rates, injuries, and death, especially from vulnerable segment of population. Including those benefits would make the backup services more feasible and attractive.



	PA (37 outages)	NY (28 outages)	NJ (15 outages)	CT (10 outages)	MA (7 outages)	ME (7 outages)	RI (6 outages)	NH (5 outages)	VT (3 outages)
Private	\$13	\$14	\$18	\$22	\$27	\$27	\$30	\$34	\$50
Private + Neighbor	\$16	\$17	\$22	\$27	\$33	\$33	\$37	\$42	\$62
Private + Social	\$21	\$22	\$25	\$29	\$34	\$34	\$37	\$41	\$57
Private + Neighbor + Social	\$23	\$25	\$29	\$34	\$41	\$41	\$44	\$49	\$69

Figure 5-6. (Top) Proportion of the respondents who were surely willing to pay more than the required cost per household per outage in each of the state to sustain their HP demands, sustain private HP demands and support vulnerable neighbors, sustain private HP demands and critical social services, and sustain private HP demands and critical social services and support vulnerable neighbors (from left to right in each of the state). (Bottom) Required cost per household per outage to justify the incremental investment in each of the state.

5.4 Discussion

Benefit-cost analysis has been widely used to support decision-making between policy options, but there has been no systematic attempt to incorporate preference uncertainty of the affected population in decision-analyses. Traditional approaches assume no uncertainty in preferences and use averages. Such approaches assume a level of precision in the public's preferences that often does not exist, can hide the tails of the distribution, and neglect income effects. The method that we propose extends the generality of benefit-cost analysis and can help decision-makers understand when society can make a definite decision, and if not, what else needs to be considered before making a societal decision, such as exploring how much preference uncertainty and aggregation rules on individual preference intervals could affect the decision. Thus, the method we propose could help society make more informed and collective policy and investment decisions.

Although the approach generalizes benefit-cost analysis, it remains unclear where such preference uncertainty comes from, and whether it is possible to help individuals resolve the uncertainty. Key issues include the hypothetical nature of contingent valuation studies [157, 158], inherent biases and measurement error in each elicitation technique [159], and qualitative descriptions that are translated differently than intended [160]. Among the likely causes of preference uncertainty, familiarity with the alternatives is probably the most important. Preference uncertainty for goods and services available in the market is usually relatively small [37], while people find it difficult to express preferences over novel alternatives [22, 24, 161]. Such unfamiliarity has been proposed as a reason for violating expected utility theory's axioms, although empirical investigations have found little support for preference uncertainty (in the form of intervals) as an explanation for preference anomalies [34, 162].

The value that the public places on reliable electric services is an ideal case for illustrating the importance of preference uncertainty, where consequences are significant but poorly understood. Although most people are familiar with electric services, many have not experienced long outages, nor thought much (if at all) about losing the services that are usually taken for granted (like heating and refrigeration) during those outages. In our surveys, we provided the respondents with multiple opportunities and detailed information about the prolonged blackouts and the electric services available during the surveys, finding that the uncertainty in respondents' preferences, as measured by the width of their preference intervals, decreased by about 20%, but there still existed preference uncertainty even by the end of the study. This suggests that while some uncertainty in preferences can be resolved by helping respondents think through the various aspects of hypothetical outage and articulate their values, for many respondents there may be an upper bound on the precision with which they can express their preferences for novel services.

5.5 Conclusion

Benefit-cost analysis and other forms of analysis are widely used to compare policies that affect society. While most analyses consider the uncertainty in cost estimates and states of the world, uncertainty in individual preferences is rarely taken into account. Further, because typical benefit-cost analysis treats everyone in a population the same, individuals who need the most assistance and care, both in expressing their preferences, and weighing those preferences once expressed, are often neglected. The method we propose can help decision-makers figure out when society as a whole can and cannot make a definite decision. If society cannot make a definite decision and requires additional deliberation, the method can help decision-makers to explore how much preference uncertainty –the gap resulting from using individuals' lower and upper bounds– and aggregation rules on individual preference intervals could affect the cost-effectiveness of an investment project. The method we propose could help society to make more informed and collective policy and investment decisions.

6. Conclusion and Policy Implications

The dissertation accomplished the following:

1. Developed and demonstrated face-to-face and web-based elicitation frameworks that help residential electricity customers understand what services will and will not be available in their homes and communities, their personal load profiles during normal circumstances and under limited availability as a function of time of day, economic losses they might suffer, and the value of securing critical social services and their vulnerable neighbors, and showed that the framework can be used to obtain the informed judgments of individuals about their economic and social preferences for full or partial electric backup services. While not applied in this work, a similar approach could be applicable for many small commercial customers;
2. Used the elicited preferences to help decision-makers explore whether and when implementing the capability to provide a low-amperage backup service to residential customers and/or full backup service to critical social services can be justified on economic and social grounds;
3. Examined whether and how much several factors that are known to affect respondents' risk perceptions influence their value of reliable electric services and discussed how to make elicited judgments reliable and credible enough to be used in further decision-making; and
4. Proposed a strategy that extends the generality of benefit-cost analysis and treats income effects which are often neglected in traditional approaches and showed why incorporating

uncertainty in individual preferences is important to make more informed and collective policy and investment decisions.

Overall, the dissertation has two major policy implications. First, the fact that respondents significantly increased their WTP for the low-amperage backup service as the survey progressed highlights the importance of assisting people to better articulate their values and preferences. Our study results suggest estimates respondents provide may not be reliable and be more easily influenced by other factors if there is no systematic attempts to help respondents fully consider the various aspects of electrically dependent services and the consequences of the given hypothetical outages. Instead, researchers need to devote sufficient efforts in designing their survey frameworks and ensuring their respondents fully articulated their preferences to obtain informed and reliable results.

Second, it is presumed that the unit value of the first few bits of electricity is more than the last bit but knowing exactly how much more the first few kWh of service is worth should be able to help decision-makers make efficient and effective investment plans for backup services. While we only elicited the respondents' WTP for 20A backup service against pre-defined hypothetical outage scenarios and their WTP to directly and indirectly support their communities under the scenarios and showed how the elicited preferences can be used as an input to investment decision-making problems, researchers and private and public decision-makers could use the framework to elicit values of reliable electric services of their own interests to develop strategies for achieving their desired level of resilience.

To conclude, providing at least limited service to some customers and sustaining critical services during WLD-outages can substantially reduce interruption costs, but there has not been a way to assess the value of such systems. The elicitation frameworks that have been proposed in this dissertation can elicit a critical input –well-reasoned and systematic preferences– to determining whether and where investments to provide such services might be warranted. Insights and methods from this dissertation should be able to assist service providers, utilities, regulators, and other relevant stakeholders to map out the necessary full range of informed judgements and improve the robustness and resilience of electric power system.

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Appendix A. Survey Protocol used for the Face-to-face interview

Attached is Group 1's survey protocol that we actually used in the Pittsburgh study. The only difference between Group 1 and Group 2 is the order of WTP questions for the two backup services (Group 1 always started with WTP for the full backup service question first and then moved onto WTP for the partial backup service whereas Group 2 always started with WTP for the partial backup service and then moved onto the full backup service).

Thank you for your help in this study of the value of reliable electrical services. As stated in the handout, all of your responses will be <u>strictly anonymous.</u> First, you will be asked some basic questions about your household.

Part A. Information about your household

1. **Do you live in an apartment, attached house, or detached house?**

▢ Apartment ▢ Attached house (e.g., duplex or triplex) ▢ House

What neighborhood do you live in? (e.g., Shadyside, Oakmont, Sharpsburg...)

____

2. **How long have you lived in your current house or apartment?** ______ years

How long have you lived in Pittsburgh? ______ years

3. **How many people live in your household, including yourself?** ______ people

How many people are there in your household in each of the following age groups:

Preschool children	__________
K-12 children	__________
Adults under 30 years	_________
30-65 years	__________
Over 65 years	__________

4. **Do you work from home the majority of the time?** (Is your home a place both for business and living?)

▢ Yes ▢ No

If yes, please explain:

____

____

5. **Are there any life-critical devices in your house that require electricity** (e.g., life sustaining medical equipment that runs on electric power)**?**

▢ Yes ▢ No

If yes, do those devices have backup power? How long can they operate without electricity? Please explain:

____

____

Part B. Blackout during a hot summer weekend

1) Hypothetical blackout scenario

In this section, I would like you to imagine the following situation: A large regional blackout occurs on a hot summer weekend at a time when you and your household members plan to spend the weekend at home.

Imagine that it is the middle of August. At sunrise, you wake up and realize that the power is out. Assume that you can find a battery operated radio. It tells you that the power outage is not local, but instead extends across a large region (the gray area on the map below).

The radio says that several tornadoes struck big power lines in Indiana, knocking them down. This caused a blackout that spread to the entire Mid-Atlantic and Northeastern parts of the US (see map above). It also tells you that because the tornadoes did not knock down any power lines in the Pittsburgh region, the power company will be able to restore power within a day (in other words, there will be **no power until sunrise tomorrow morning**).

Before we continue, I would like to ask you a question to make sure you understand the scenario:

1. When will the power come back on?

____

Unfortunately, you and your household members are stuck in Pittsburgh with no electricity in your home. It was hot last night, and today is expected to be one of the hottest days of the year. Please take a moment to describe what you think your day would be like without power, and any strategies you might adopt to cope with the blackout.

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Now, let's go back to our scenario. In addition to paying for the actual electricity you use, your monthly electricity bill includes charges for performing maintenance on the electricity system (e.g., distribution lines, transformers, etc.) and some limited protection of the system against blackouts. However, the bill does not include charges to provide electric services in the event of an unpredictable blackout. In this case, the National Weather Service (NWS) could predict the tornadoes; however, utilities could not prevent the blackout because it was too wide-spread, and they did not have enough time to prepare for the disruption.

Suppose that during the blackout there is a private local service that specializes in disasters and emergencies that can quickly hook up a generator to your house and provide **all** the electric power you would have normally used. Assume your cell phone has enough power to call to get that service and obtain a one-time payment for one day of immediate service provided by the company. You will receive a bill for the payment by mail.

In this case, I would like to know **how much you would be willing to pay** for this one-time service on a hot summer weekend day during the outage. For each of the following questions, please indicate whether you would be willing to pay that amount of money in exchange for the full day of generator service. For example, the first one: would you be willing to pay less than $5 for the full day of generator service? If yes, please check the "Yes" box. If you are not sure, please check the "Not sure" box. If no, please check the "No" box. Now, please repeat this for the remaining rows of the table.

	Would you be willing to pay this amount to get full service on a hot summer weekend day?		
	Yes	Not sure	No
Less than $5	▢	▢	▢
$5 to $9.99	▢	▢	▢
$10 to $14.99	▢	▢	▢
$15 to $19.99	▢	▢	▢
$20 to $24.99	▢	▢	▢
$25 to $29.99	▢	▢	▢
$30 to $34.99	▢	▢	▢
$35 to $39.99	▢	▢	▢
$40 to $44.99	▢	▢	▢
$45 to $49.99	▢	▢	▢
$50 to $54.99	▢	▢	▢
$55 to $59.99	▢	▢	▢
$60 to $64.99	▢	▢	▢
$65 to $69.99	▢	▢	▢
$70 to $74.99	▢	▢	▢

(For respondents whose willingness to pay is higher than $75 or lower than $5)

If you would be willing to pay more than $75, what is the largest amount you would be willing to pay to receive the full day of generator service?

$___________

If you would only be willing to pay an amount that is less than $5, what is the largest amount you would be willing to pay to receive the full day of generator service?

$___________

(For all respondents)

Please explain your response in a brief sentence or two:

____

____

____

Now, let's suppose that there is a different service that uses smart meter technology to give you **some** electricity service during the blackout. This smart grid company can quickly connect your house to their smart power system and provide a **partial** amount of electricity for your entire house (about one-fifth of your normal power).

With this partial service, you would only be able to run **some** of the appliances you might want to use (e.g., you would have enough power to use your refrigerator, one freezer, one laptop, your one cell phone charger, and two lights, at the same time). Assume your cell phone has enough power to call the smart grid company and obtain a one-time payment for one day of immediate but limited power. You will receive a bill for the payment by mail.

In this case, I would like to know **how much you would be willing to pay** for this one-time service on a hot summer weekend day during the outage. For each of the following questions, please indicate whether you would be willing to pay that amount of money in exchange for the partial service.

	Would you be willing to pay this amount to get partial (about one-fifth of your normal power) service on a hot summer weekend day?		
	Yes	Not sure	No
Less than $5	▢	▢	▢
$5 to $9.99	▢	▢	▢
$10 to $14.99	▢	▢	▢
$15 to $19.99	▢	▢	▢
$20 to $24.99	▢	▢	▢
$25 to $29.99	▢	▢	▢
$30 to $34.99	▢	▢	▢
$35 to $39.99	▢	▢	▢
$40 to $44.99	▢	▢	▢
$45 to $49.99	▢	▢	▢
$50 to $54.99	▢	▢	▢
$55 to $59.99	▢	▢	▢
$60 to $64.99	▢	▢	▢
$65 to $69.99	▢	▢	▢
$70 to $74.99	▢	▢	▢

(For respondents whose willingness to pay is higher than $75 or lower than $5)

If you would be willing to pay more than $75, what is the largest amount you would be willing to pay to receive the partial service?

$___________

If you would only be willing to pay an amount less than $5, what is the largest amount you would be willing to pay to receive the partial service?

$___________

(For all respondents)

Please explain your response in a brief sentence or two:

____

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____

2) More information about your home and community during blackout

Next, you will be asked to think about the services that will be available during the blackout in your home and community, as well as the services that will not be available. The table below provides a list of some of the things that will and will not work in your home and community when the power is out for the entire region:

In your home		In community	
Will work	**Will not work**	**Will work**	**Will not work**
Old style telephones that have a rotary dial. Anything that runs on a battery, as long as the battery lasts (e.g., radios, flashlights, laptop computers, and cell phones). Natural gas and all normal water and sewer services.	New style telephones that include a plug to a power outlet. All electrical appliances that cannot also run on batteries, including air conditioners and blowers that circulate air. Cable and internet service.	Emergency service including 911 (via cell phone or rotary dial phone). Hospitals, police stations, and other places that have backup generators. TV and radio stations (most have backup generators). Natural gas and all normal water and sewer services. Bus service. GPS service.	Traffic signals. Street lights. Banks and ATMs. Most gas stations (pumps need electricity). Food stores (lights, refrigeration, and cash registers will not work). Most restaurants (very few have backup generators). Elevators in buildings without backup. Ventilator fans and lighting in traffic tunnels. Electric trolley service. Airport – major delays.

Before we continue, I would like to ask you a few questions to make sure you understand the scenario:

1. Will any of your neighbors or friends in the Pittsburgh area have power from the power company?

☐ Yes ☐ No

2. Will your laptop work if it was charged overnight?	☐ Yes	☐ No
3. Could you use the internet?	☐ Yes	☐ No
4. Could you use a cell phone to call the police in an emergency?	☐ Yes	☐ No
5. Could you spend the day in a local air-conditioned shopping mall?	☐ Yes	☐ No

Now we have listed the services that will be available in your home and community during a blackout. We would like to know if this information changes your willingness to pay for the full service. Would you like to change your willingness to pay?

☐ Yes ☐ No

3) **Appliance card stack game and reasons why the outage would be inconvenient**

Next, you will now consider the ways you consume electricity in a more detailed way. Assume that there is no blackout, and it is an average, hot summer weekend.

Let's start with the morning. The sun has just come up. If the power is on, what kind of appliances would you normally be using? Select the cards with the pictures of every appliance that you would use. If you would be using several lights, select a card for each one. Then place each card on the table above the other cards you have selected to make a column.

Now assume that it is in the middle of the day (afternoon). Again, it is hot, and you and your household members are at home. Once again, please select all the appliance cards and other electrical devices that might be operating if the power is on and stack them above each other to make a column.

Now assume that it is early evening (around dinner time). Remember it is summer so it is probably still bright outside. Once again, please select all the appliance cards and other electrical devices that might be operating if the power is on and stack them above each other to make a column.

Finally, assume that it is late evening, one hour before you go to sleep. Once again, please select all the appliance cards and other electrical devices that might be operating if the power is on and stack them above each other to make a column.

A day-long outage can be very inconvenient. These inconveniences come from many different sources. For example, you might not be able to keep your home at a comfortable temperature (because your air conditioner will not work); you may have difficulty finishing chores (such as the laundry or dishes); and you cannot enjoy some types of leisure or entertainment activities (such as watching the TV or using the internet).

Let's go back to the appliance card stacks that you constructed. Please look over your electric appliances that you selected in each time period. You might feel inconvenienced if you are not able to use any of them. Please take a moment to describe the reasons why an outage might be inconvenient and rank them in order from most to least important.

[**Without any backup service**]

Remember that we talked about a service that could use smart meter technology to give you some electricity during the blackout. However, that service can only provide you with the **partial** amount of electricity for your entire house (about one-fifth of your normal power). Please make a new stack that includes the appliances and other devices that you still want to run during each time period **within the limit**.

Once again, please look over your electric appliances that you selected in each time period. You might feel inconvenienced because you are not able to use other appliances due to the limit. Please take a moment to describe the reasons why an outage with partial backup service might be inconvenient and rank them in order from most to least important.

[**With partial backup service**]

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____
____
____
____
____
____
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Now we have identified how you use electricity during your day with and without partial backup service, and you have listed a number of reasons why the blackout might be inconvenient. We would like to know if this information changes your willingness to pay for the full service. Would you like to change your willingness to pay?

▢ Yes ▢ No

Now, I would like to know how much you value your electric services. Please indicate whether you would be willing to pay the indicated amount of money in exchange for the full day of generator service and partial backup service.

	Would you be willing to pay this amount to get full service on a hot summer weekend day?		
	Yes	Not sure	No
Less than $5	▢	▢	▢
$5 to $9.99	▢	▢	▢
$10 to $14.99	▢	▢	▢
$15 to $19.99	▢	▢	▢
$20 to $24.99	▢	▢	▢
$25 to $29.99	▢	▢	▢
$30 to $34.99	▢	▢	▢
$35 to $39.99	▢	▢	▢
$40 to $44.99	▢	▢	▢
$45 to $49.99	▢	▢	▢
$50 to $54.99	▢	▢	▢
$55 to $59.99	▢	▢	▢
$60 to $64.99	▢	▢	▢
$65 to $69.99	▢	▢	▢
$70 to $74.99	▢	▢	▢

(For respondents whose willingness to pay is higher than $75 or lower than $5)

If you would be willing to pay more than $75, what is the largest amount you would be willing to pay to receive the full day of generator service?

$___________

If you would only be willing to pay an amount that is less than $5, what is the largest amount you would be willing to pay to receive the full day of generator service?

$___________

(For all respondents)

Please explain your response in a brief sentence or two:

____

____

____

	Would you be willing to pay this amount to get partial (about one-fifth of your normal power) service on a hot summer weekend day?		
	Yes	Not sure	No
Less than $5	☐	☐	☐
$5 to $9.99	☐	☐	☐
$10 to $14.99	☐	☐	☐
$15 to $19.99	☐	☐	☐
$20 to $24.99	☐	☐	☐
$25 to $29.99	☐	☐	☐
$30 to $34.99	☐	☐	☐
$35 to $39.99	☐	☐	☐
$40 to $44.99	☐	☐	☐
$45 to $49.99	☐	☐	☐
$50 to $54.99	☐	☐	☐
$55 to $59.99	☐	☐	☐
$60 to $64.99	☐	☐	☐
$65 to $69.99	☐	☐	☐
$70 to $74.99	☐	☐	☐

(For respondents whose willingness to pay is higher than $75 or lower than $5)

If you would be willing to pay more than $75, what is the largest amount you would be willing to pay to receive the partial service?

$___________

If you would only be willing to pay an amount less than $5, what is the largest amount you would be willing to pay to receive the partial service?

$___________

(For all respondents)

Please explain your response in a brief sentence or two:

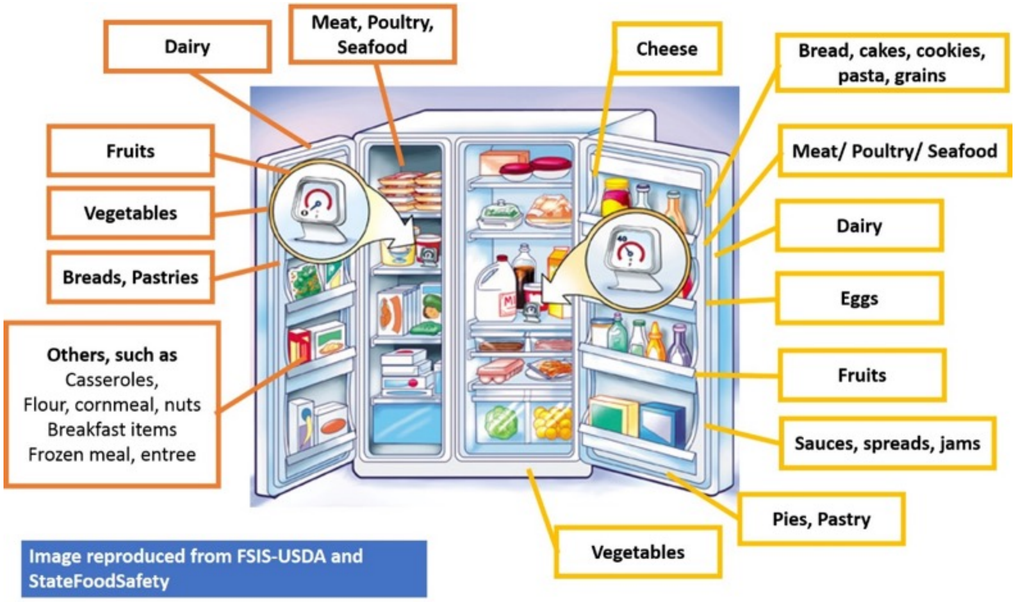
____

____

____

4) Value of perishable food

Next, let's focus on one specific inconvenience: spoiled food. Below we have provided you a picture of the contents of a typical refrigerator/freezer to help you think about the food you have:



The US Department of Agriculture (USDA) says that "perishable food stored in a refrigerator longer than 4 hours without power" should be discarded. Four hours may be too conservative, but if the power is out for a day you will definitely lose some of the perishable food in your refrigerator. Please describe how you feel about the food safety information from USDA and how you would actually respond to the recommendation (e.g., are you going to throw out all the perishable food?).

____
____
____
____

Please use the table below to estimate the value of the perishable food you have, and would need to replace if the power went out for a period of 24 hours.

	Your rough estimate of the value of perishable food that is in your refrigerator:	Your rough estimate of the value of perishable food that will go bad and need to be replaced:
Meat, Poultry, Seafood Raw or leftover cooked, Thawing meat or poultry, Salads: Meat, tuna, shrimp, Chicken, or egg salad, Gravy, stuffing, broth, Lunchmeats, hot dogs, bacon, sausage, dried beef, Pizza – with any topping, Canned hams labeled 'Keep refrigerated', Opened canned meats and fish, Casseroles, soups, stews	$	$
Dairy Milk, cream, sour cream, buttermilk, evaporated milk, yogurt, eggnog, soy milk, Open baby formula	$	$
Eggs Fresh eggs, hard-cooked in shell, Custards and puddings, quiche	$	$
Fruits Opened canned fruits and juices	$	$
Bread, Cakes, Cookies, Pasta, etc. Refrigerator biscuits, rolls, cookie dough, Cooked pasta, rice, potatoes, Pasta salads with mayonnaise or vinaigrette, Fresh pasta, Cheesecake	$	$
Some Pies and Pastry	$	$
Some Vegetables (except raw vegetables)	$	$
Some (soft) Cheese	$	$
Rough sum:	$	$

Just to compare, in 1999 a study conducted in New York found that the average value of perishable food in refrigerators and freezers across the city of New York was about $72, which is just over $100 when adjusted by inflation. Can you suggest why the number you just estimated is higher/lower? Are you willing to change your number (if so, why? and if not, why not?)?

____

____

Losing all the perishable food in your refrigerator may not be the only economic loss you would experience if the power goes out for a day on a hot summer weekend, especially if you work from home or own a home-business. Please explain and estimate any other economic losses you and others in your household might experience in the one-day power outage.

____

____

Now we have thought about the value of perishable food inside your refrigerator and other economic losses. We would like to know if this information changes your willingness to pay for the full service. Would you like to change your willingness to pay?

▢ Yes ▢ No

5) Wrapping it up

We have thought about what it would be like to spend a hot summer weekend day without electricity. Here, I would like you to tell me how much the provided information affected your value of reliable electric services, if at all.

First, please rate the exercises in order of importance regarding how much they affected your value.

	Not at all important	Slightly important	Moderately important	Very important
Information about the services available in your home and community	▢	▢	▢	▢
Appliance card stack game	▢	▢	▢	▢
Reasons why the outage would be inconvenient	▢	▢	▢	▢
Value of perishable food	▢	▢	▢	▢

Finally, now that you have had time to think about all this information, I would like you to once again fill in the table for how much you would be willing to pay to have full service and partial service.

	Would you be willing to pay this amount to get full service on a hot summer weekend day?		
	Yes	Not sure	No
Less than $5	▢	▢	▢
$5 to $9.99	▢	▢	▢
$10 to $14.99	▢	▢	▢
$15 to $19.99	▢	▢	▢
$20 to $24.99	▢	▢	▢
$25 to $29.99	▢	▢	▢
$30 to $34.99	▢	▢	▢
$35 to $39.99	▢	▢	▢
$40 to $44.99	▢	▢	▢
$45 to $49.99	▢	▢	▢
$50 to $54.99	▢	▢	▢
$55 to $59.99	▢	▢	▢
$60 to $64.99	▢	▢	▢
$65 to $69.99	▢	▢	▢
$70 to $74.99	▢	▢	▢

(For respondents whose willingness to pay is higher than $75 or lower than $5)

If you would be willing to pay more than $75, what is the largest amount you would be willing to pay to receive the full day of generator service?

$___________

If you would only be willing to pay an amount that is less than $5, what is the largest amount you would be willing to pay to receive the full day of generator service?

$___________

(For all respondents)

Please explain your response in a brief sentence or two:

____

____

____

	Would you be willing to pay this amount to get partial (about one-fifth of your normal power) service on a hot summer weekend day?		
	Yes	Not sure	No
Less than $5	☐	☐	☐
$5 to $9.99	☐	☐	☐
$10 to $14.99	☐	☐	☐
$15 to $19.99	☐	☐	☐
$20 to $24.99	☐	☐	☐
$25 to $29.99	☐	☐	☐
$30 to $34.99	☐	☐	☐
$35 to $39.99	☐	☐	☐
$40 to $44.99	☐	☐	☐
$45 to $49.99	☐	☐	☐
$50 to $54.99	☐	☐	☐
$55 to $59.99	☐	☐	☐
$60 to $64.99	☐	☐	☐
$65 to $69.99	☐	☐	☐
$70 to $74.99	☐	☐	☐

(For respondents whose willingness to pay is higher than \$75 or lower than \$5)

If you would be willing to pay more than \$75, what is the largest amount you would be willing to pay to receive the partial service?

$___________

If you would only be willing to pay an amount less than \$5, what is the largest amount you would be willing to pay to receive the partial service?

$___________

(For all respondents)

Please explain your response in a brief sentence or two:

____
____
____

Finally, let's consider an extraordinary situation. Suppose it is a special weekend, such as a birthday or anniversary. Several members of your family or friends have flown in from out of town to celebrate a family event. Under this scenario, how much would you be willing to pay for the full service?

	Would you be willing to pay this amount to get full service on a special weekend day during hot summer?		
	Yes	Not sure	No
Less than $5	▢	▢	▢
$5 to $9.99	▢	▢	▢
$10 to $14.99	▢	▢	▢
$15 to $19.99	▢	▢	▢
$20 to $24.99	▢	▢	▢
$25 to $29.99	▢	▢	▢
$30 to $34.99	▢	▢	▢
$35 to $39.99	▢	▢	▢
$40 to $44.99	▢	▢	▢
$45 to $49.99	▢	▢	▢
$50 to $54.99	▢	▢	▢
$55 to $59.99	▢	▢	▢
$60 to $64.99	▢	▢	▢
$65 to $69.99	▢	▢	▢
$70 to $74.99	▢	▢	▢

(For respondents whose willingness to pay is higher than $75 or lower than $5)

If you would be willing to pay more than $75, what is the largest amount you would be willing to pay to receive the full day of generator service?

$___________

If you would only be willing to pay less than $5, what is the largest amount you would be willing to pay to receive the full day of generator service?

$___________

(For all respondents)

Please explain your response in a brief sentence or two:

____

____

____

Part C. Information about yourself and your experiences from outages

How would you categorize yourself in terms of race or ethnicity?

▢ Caucasian ▢ Hispanic ▢ Black ▢ Asian ▢ Other

What was your total household income last year?

▢ Under $10,000 ▢ $10,000 to $30,000

▢ $30,001 to $50,000 ▢ $50,001 to $100,000 ▢ Above $100,000

Who pays for your electricity?

▢ You ▢ Another household member

▢ Your landlord (utility is included in the rent)

If you are paying for your electricity bill, roughly how much do you pay for your monthly electricity bill, on average?

$________/month

If you do not pay your electricity bill, can you roughly estimate how much you think your electricity bill would be?

▢ Yes, it is $_______/month. ▢ No

Can you estimate how much electricity does your household use per day?

____________(kWh) or __________(Amps)

Please describe your experience with power outages in your lifetime:

▢ I have never experienced an outage.

▢ I have experienced one outage.

▢ I have experienced more than one outage.

If you have ever experienced an outage, how long was the longest outage you have ever experienced?

▢ Less than a few minutes

▢ Less than an hour

▢ Several hours. Please explain:____

▢ Less than one half-day. Please explain:_______________________________________

▢ Less than one day. Please explain:____

▢ Less than several days. Please explain:_______________________________________

▢ Less than one week. Please explain:____

▢ Longer than one week. Please explain:_______________________________________

Please tell me about whether you have the following items available to you in the case of a blackout:

▢ Flashlights in easy-to-find places

▢ Wind up or crank operated radio

▢ Wind up or crank cell phone charger

▢ Camping lantern

▢ Camping cook stove

▢ Solar energy storage

▢ Portable generator. Please explain: ____

▢ Stand-by generator. Please explain: ____

▢ Other non-generator. Please explain: ____________________________________

How inconvenient would it be if an outage lasted …?

	Not at all	Slightly	Moderately	Very	Extremely
Less than 1 hour	▢	▢	▢	▢	▢
1 hour to 4 hours	▢	▢	▢	▢	▢
4 hours to 8 hours	▢	▢	▢	▢	▢
8 hours to 1 day	▢	▢	▢	▢	▢
1 day to 3 days	▢	▢	▢	▢	▢
3 days to 1 week	▢	▢	▢	▢	▢
Longer than 1 week	▢	▢	▢	▢	▢

What is your best guess at the percent chance that your home will have at least one blackout that lasts longer than one hour in the:

	% in number (0 to 100)
Next year?	
Next 5 years?	
Next 20 years?	
Next 50 years?	

Thanks very much for your help with this study.

If you have questions or concerns,
feel free to contact:
Sunhee Baik, sunheeb@andrew.cmu.edu

Appendix B. Survey framework for the online surveys

Attached is the survey framework that we actually used for the online surveys. The only differences between the respondents is the hypothetical outage scenario (a massive solar storm vs a series of terrorist attacks) and the order of social WTP questions.

Thank you for your help in this study of the disruptions cause by a large power blackout. First, we will ask you some basic questions about your household and your electricity bill. As we explained in the consent form, all your responses will be **strictly anonymous**.

Information about your household

In what state do you live? ________________

[If respondents do not select one of the Northeast region (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania), they are considered to be ineligible]

How long have you lived in the state? ________________ Years

[If respondents live in the state less than two years, they are considered to be ineligible]

1. What is your age? ________________ Years

[If respondents are under 25, they are considered to be ineligible]

2. Do you have any of the following (select all that applies; if you don't have any, skip this question)?

❑ Backup generator that is connected to the home's natural gas or propane gas line.
❑ Portable generator that needs refueling (e.g., diesel or gasoline).
❑ Solar energy system without battery storage.
❑ Solar energy system with battery storage.
❑ I don't have any of these things.

[If respondents select "Backup generator that is connected to the home's natural gas line or liquid propane gas line", show the following message, and the respondents are considered ineligible]

"Because you have a backup generator that is connected to the natural gas or propane gas line, you would be able to consume the electricity that the generator produces."

[If respondents select "Portable generator that needs constant refueling", show the following message]

"Because you have a portable generator that needs refueling, you can use your own generators until you run out of gas."

[If respondents select "Solar energy generation system without battery storage", show the following message]

"The electricity generated by your solar power generation system is directly connected to the power grid instead of your house. You would not be able to use your solar power system during long-duration outages."

[If respondents select "Solar energy generation with battery", show the following message]

"Because you have solar energy system with battery storage, you would be able to use the electricity generated by your solar power generation. Yet, when the sun does not shine or after sunset, you may not be able to consume electricity if you run out of stored electricity."

3. Are there any life-critical medical devices in your house that require electricity (e.g., oxygen ventilator)**?**

❑ Yes ❑ No

[If respondents select "Yes", show the follow-up question below]

If yes, what are they? Do those devices have backup power? How long can they operate while the power is out? Please explain:

____

4. Do you want to receive the result of this study?

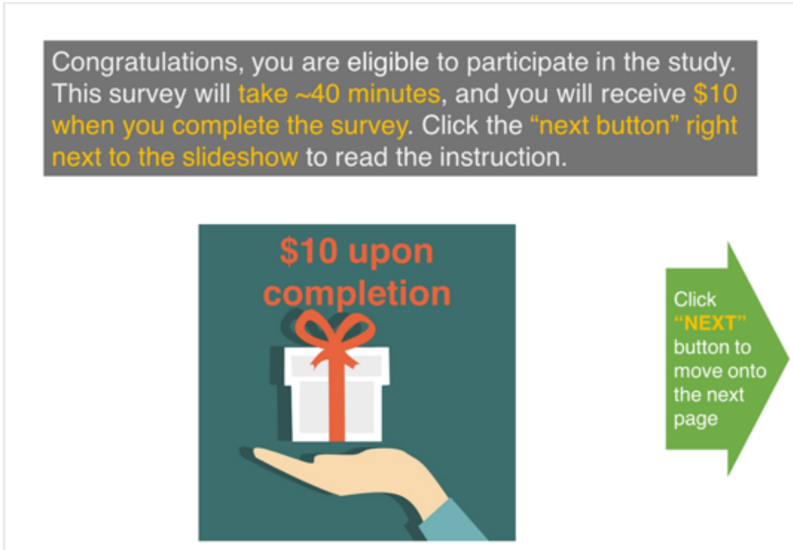
❑ Yes ❑ No

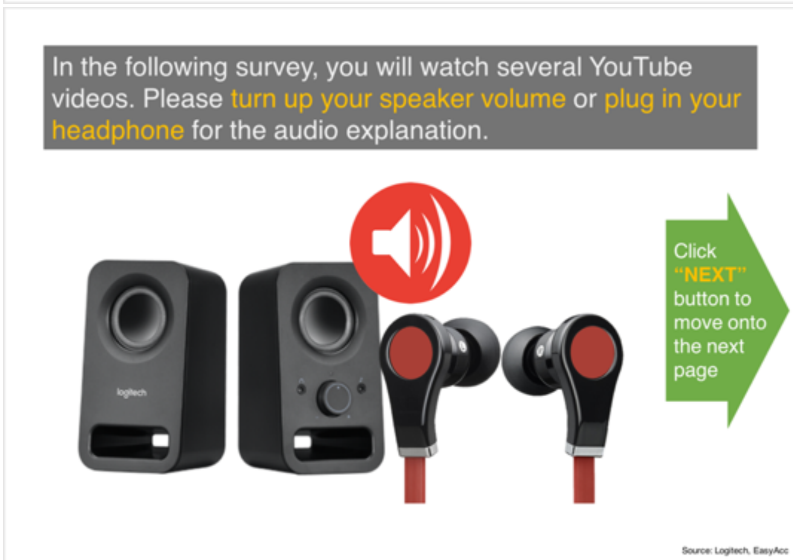
[If respondents select "Yes", show the follow-up question below]

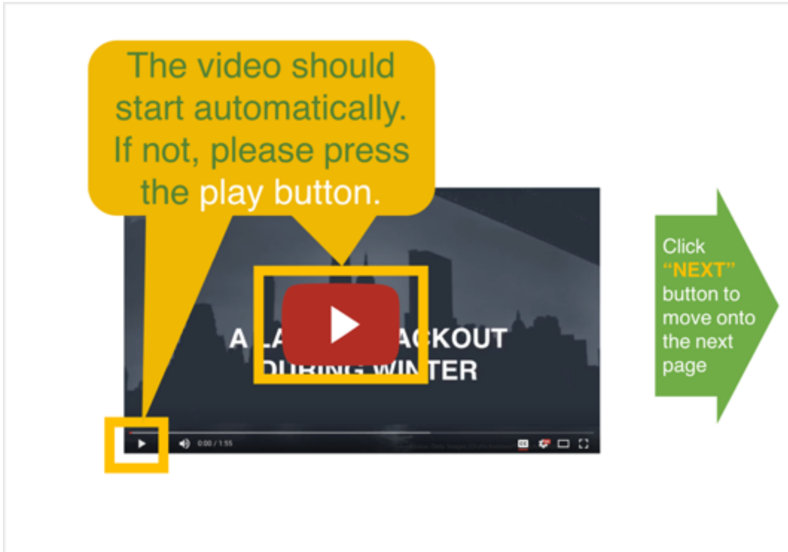
If yes, please provide your email address here: ______________________________________

[Only eligible respondents are allowed to move onto the next page; the ineligible respondents are directed to ineligible-complete page]

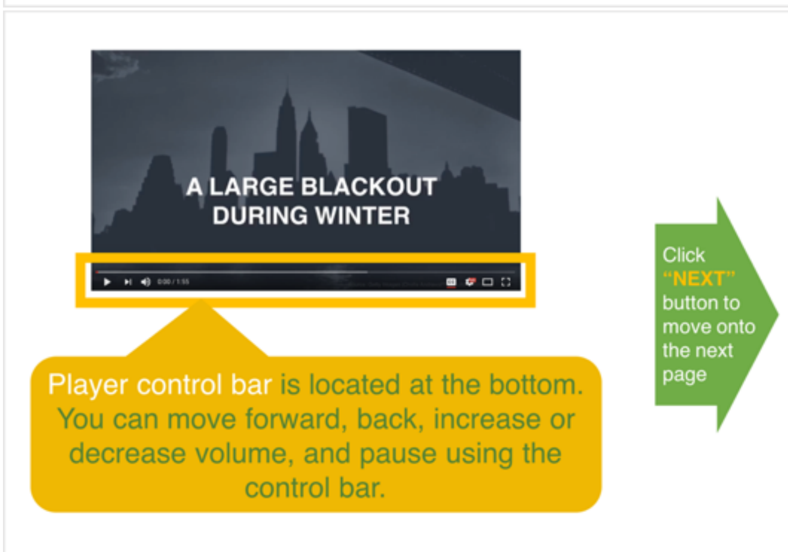
[The instruction for the Youtube videos and the rest part of the survey is provided. Below images are provided as a manual slideshow. Respondents are allowed to move onto the next stage when they reach the final page of the slideshow.]

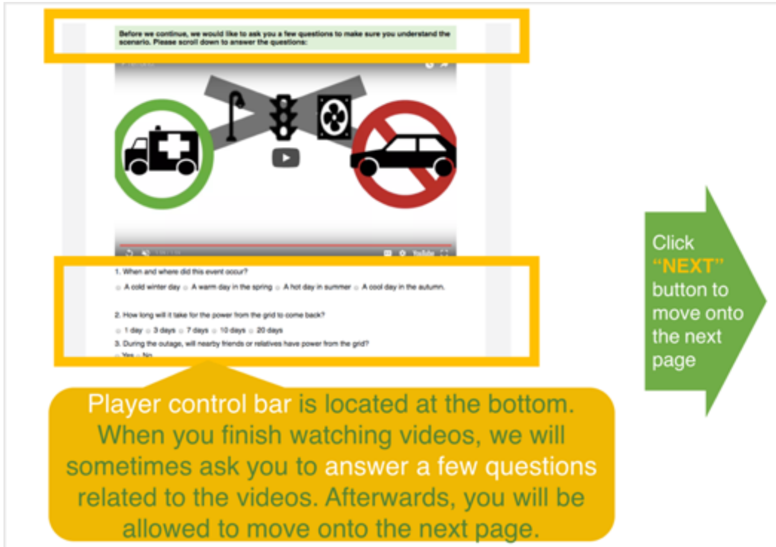


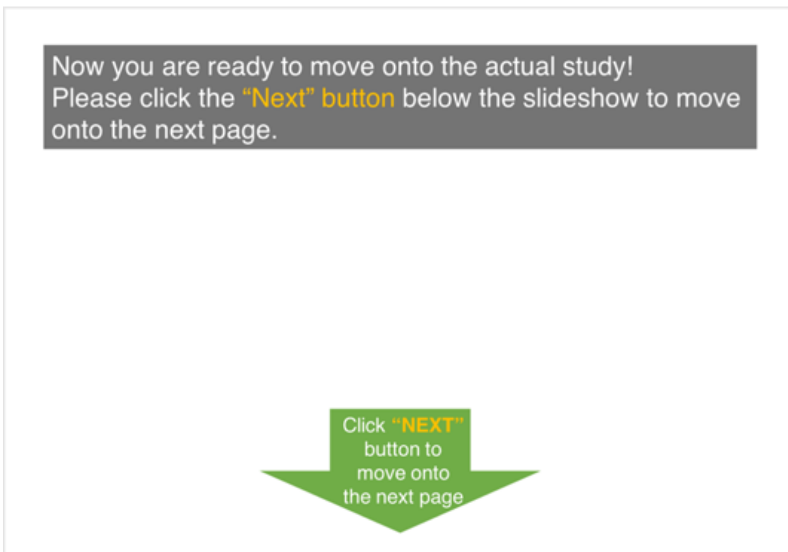



The video should start automatically. If not, please press the play button.
A LARGE BLACKOUT DURING WINTER
Click "NEXT" button to move onto the next page


A LARGE BLACKOUT DURING WINTER
In case you need it, we turned on the closed captions. Feel free to click the CC button on the bottom right corner to turn it off.
Click "NEXT" button to move onto the next page


A LARGE BLACKOUT DURING WINTER
Player control bar is located at the bottom. You can move forward, back, increase or decrease volume, and pause using the control bar.
Click "NEXT" button to move onto the next page


Before we continue, we would like to ask you a few questions to make sure you understand the scenario. Please scroll down to answer the questions:
1. When and where did this event occur?
A cold winter day A warm day in the spring A hot day in summer A cool day in the autumn.
2. How long will it take for the power from the grid to come back?
1 day 3 days 7 days 10 days 20 days
3. During the outage, will nearby friends or relatives have power from the grid?
Player control bar is located at the bottom. When you finish watching videos, we will sometimes ask you to answer a few questions related to the videos. Afterwards, you will be allowed to move onto the next page.
Click "NEXT" button to move onto the next page


Now you are ready to move onto the actual study! Please click the "Next" button below the slideshow to move onto the next page.
Click "NEXT" button to move onto the next page

A blackout occurs during a cold winter

[The Youtube video for the massive solar storm scenario can be viewed at https://youtu.be/edynrZS_3I4. Below is the script for the video]

In this section, we would like you to imagine the following situation: a large regional blackout occurs during a period of cold winter weather. Imagine that it is a cold winter morning. When you wake up, you discover that the power has gone out and the house is already getting cold. You check the news with your cell phone and learn that a massive solar storm, much larger than any we've had in the past 200 years, hit the earth during the early morning hours. This solar storm damaged critical high voltage power transformers and caused a widespread power outage across the Northeastern and Midwestern United States, and Southeastern Canada. Authorities are reporting that it will take 10 days for the power to come back. And the weather is expected to be below freezing for the next 10 days. Federal and state governments have declared a state of emergency that bans all but emergency travel because traffic lights and control systems are not working, most gas stations do not have backup power, and police and other emergency services have their hands full. Thus, you have to stay in your home during the blackout. Governments are planning to evacuate severely ill or injured patients and residents with disabilities immediately. They will also distribute supplies such as food, water, fuel, medications, and batteries to those affected by the outage. However, this will likely take a few days. Fortunately, you have enough food and water in your house to get you and your family through the next few days. Before we continue, we would like to ask you few questions to make sure you understand the scenario.

[Once the video is complete, the follow-up questions below will appear]

Before we continue, we would like to ask you a question to make sure you understand the scenario:

1. When and where did this event occur?

❑ A cold winter day ❑ A warm day in the spring ❑ A hot day in summer ❑ A cool day in the autumn.

[If respondents select "A cold winter day", show the follow-up question below]

You are correct. The (solar storm/terrorist attack) occurs during a cold winter day, and the temperature is expected to be below freezing for the next 10 days.

[If respondents select "A hot day in Summer" or "A warm day of Spring", show the follow-up question below]

Incorrect. The (solar storm/terrorist attack) occurs during a cold winter day, and the temperature is expected to be below freezing for the next 10 days.

How soon will the power from the grid come back on in your region?

❑ 1 day ❑ 3 days ❑ 7 days ❑ 10 days ❑ 20 days

[If respondents select "10 days", show the follow-up question below]

You are correct. The event damaged a number of critical high voltage transformers, and caused a widespread power outage. The authorities reported that it will take 10 days to restore power in your region.

[If respondents select "1 day"/"3 days"/"7 days"/"20 days", show the follow-up question below]

Incorrect. The event damaged a number of critical high voltage transformers, and caused a widespread power outage. The authorities reported that it will take 10 days to restore power in your region.

During the outage, will nearby friends or relatives have power from the grid?

❑ Yes ❑ No

[If respondents select "Yes", show the follow-up question below]

Incorrect. Because a number of critical high voltage transformers were severely damaged, all the electric customers across your region will not be able get electricity for the next 10 days.

[If respondents select "No", show the follow-up question below]

You are correct. Because a number of critical high voltage transformers were severely damaged, all the electric customers across your region will not be able get electricity for the next 10 days.

[Respondents are allowed to move onto the next page after answering all the questions]

[The video can be viewed at: https://youtu.be/Ch7vYek_5dw. Below is the script for the video]

In this section, we would like you to think about what would happen to the power system during the blackout. In our current power system, electricity is generated at power plants and delivered to customers over transmission and distribution power lines. While your monthly electricity bill includes limited protection of the system against blackouts, the bill does ***not*** include things that can protect the system against unpredictable large disturbances and extreme events. However, assume that your local power company has already invested in smart-grid technology. For this reason, while the high voltage power system is not operating your local distribution company can form an isolated island and supply you and others with some very limited power. With this limited backup service, you would only have a small amount of power to run a few critical appliances. Of course, you will have to pay to receive this backup service. Here we would like to know how much you would be willing to pay for such a service during this 10-day outage. For each of the following questions, please indicate whether you would be willing to pay that amount of money. For example, the first one: would you be willing to pay less than $10 per day? If yes, please check the "Yes" box. If you think you might consider using the service if the outage is very inconvenient, please check the "not sure" box. If you are not interested in the backup service at all, please check the "no" box. Please repeat this for the remaining rows of the table. Note that the outage will last 10 days, and your payment will cover your electricity consumption during the entire period.

[Respondents are allowed to move onto the next page after watching the video]

Please indicate whether you would be willing to pay that amount of money in exchange for the partial backup service.

Note that the backup service is separated from your normal electricity consumption. This is a one-time extra payment, and the payment will solely cover your electricity consumption during the outage. You still need to pay for electricity consumed during the rest of the month.

	Would you be willing to pay this amount extra per day to get the backup service during the outage?		
	Yes	Not sure	No
Less than $10 per day	❑	❑	❑
$10-$19.99 per day	❑	❑	❑
$20-$29.99 per day	❑	❑	❑
$30-$39.99 per day	❑	❑	❑
$40-$49.99 per day	❑	❑	❑
$50-$59.99 per day	❑	❑	❑
$60-$69.99 per day	❑	❑	❑
$70-$79.99 per day	❑	❑	❑
$80-$89.99 per day	❑	❑	❑
$90-$99.99 per day	❑	❑	❑
More than $100 per day	❑	❑	❑

[When respondents finish answering the question, show the following prompt and radios above the table]
You said that you would be definitely be willing to pay less than *$((Upper bound of the highest box from the "Yes" column)*) per day but you might be willing to pay up to $(*(Upper bound of the highest box from the "Not sure" column)*) per day. That means you are willing to pay up to *$((Upper bound of the highest box from the "Yes" column)*×10) for sure but no more than $(*(Upper bound of the highest box from the "Not sure" column)*×10) during the entire outage.
Is this correct?

❑Yes ❑Let me try again

[Respondents who click "Yes" are directed to the next page]
[When respondents click "Let me try again", then show the following prompt above the table]
You wanted to revise your answer. Please indicate your willingness to pay again.

More information about your home and community during the blackout
[The video can be viewed at: https://youtu.be/46FyGOJ9JdE. Below is the script for the video.]

If there is a large-scale widespread outage that lasts 10 days, not only will the power be out in your home but also most public and private services that rely on electric power will be out. Let's think about the services in your home first. During the blackout, anything that runs on a battery or natural gas and does not need electricity will work. However, gas heaters will not work because they need electricity to run pumps or blowers. Old style rotary dial telephones will work. Immediately after the outage, most of your electric appliances that cannot also run on batteries will not work. Most modern wireless telephones with a power cord will not work. Cable and Wi-Fi internet service will also not work. This does not include mobile wireless internet connections on your phone. Your gas and electric heater will also not work during the outage. After a few days, you may not have water and sewage treatment services because the authorities only have limited backup power to operate pumps and treatment plants. Now let's think about the services in your community. During the outage, services with enough backup power will minimally work. A few gas stations and some critical social services with emergency backup generators will continue minimal operation. Natural gas service will also work. However, most private and social services will not work immediately. For instance, many banks and ATMs will not work, and most electronic credit card transactions will also be stopped. Most gas stations and local stores will not be open. Social services without backup power such as non-emergency municipal services will not operate. Also, traffic lights and many traffic management systems will not work. Space heating and cooling, and elevators in buildings without backup power will not work. After a few days, services with backup generators will run out of fuel. This could include less-critical in-hospital services, and some fire stations and police stations. Also, TV and radio stations, and cell phone services could stop if they cannot get fuel. Similar to the services in the home, normal water and sewage treatment service also may not be available.

Before we continue, we would like to ask you few questions to make sure you understand the scenario.

[Once the video is complete, the follow-up questions below will appear]

Before we continue, we would like to ask you a few questions to make sure you understand the scenario.
During the blackout:
1 Could you heat your house without using a backup generator?

❑Yes ❑No

[If respondents select "Yes", show the following prompt]
"Incorrect. If there is no backup power or electric service, gas heaters cannot be operated because they need electricity to run a pump or blower. Similarly, electric heaters cannot be operated without electricity."
[If respondents select "No", show the following prompt]
"You are right. If there is no backup power or electric service, gas heaters cannot be operated because they need electricity to run a pump or blower. Similarly, electric heaters cannot be operated without electricity."

2. Could you drive, take a train, or fly on an airplane to escape from the affected region?

❑Yes ❑No

[If respondents select "Yes", show the following prompt]
"Incorrect. Authorities have declared a state of emergency and closed the roads. If you try to drive, you may not be able to refuel your car at local gas stations because most of them do not have emergency backup generators. Also, mass transportation systems including airlines and trains would not have enough fuel, meaning most trips would be cancelled."
[If respondents select "No", show the following prompt]
"You are right. Authorities have declared a state of emergency and closed the roads. If you try to drive, you may not be able to refuel your car at local gas stations because most of them do not have emergency backup generators. Also, mass transportation systems including airlines and trains would not have enough fuel, meaning most trips would be cancelled."

3. Could you use your battery-operated radio (with batteries) to get news and emergency instructions for the first few days if you have any?

❑Yes ❑No

[If respondents select "Yes, show the following prompt]
You are correct. If you have a battery-operated radio with batteries, you would be able to get news and emergency instructions at least for the first few days.
[If respondents select "No, show the following prompt]

Incorrect. If you have a battery-operated radio with batteries, you would be able to get news and emergency instructions at least for the first few days.

4. Could you take money out of ATM machines?

❑Yes ❑No

[If respondents select "Yes, show the following prompt]

"Incorrect. During the outage, most of the financial system will not work, including bank offices and ATM machines."

[If respondents select "No", show the following prompt]

"You are right. During the outage, most of the financial system will not work, including bank offices and ATM machines."

5. Could you go to a local grocery store and purchase important items, such as food and bottled water?

❑Yes ❑No

[If respondents select "Yes", show the following prompt]

"Incorrect. After the outage, most of the financial system will not work, and most grocery stores will not be operating. If you do not have enough cash in advance, you may not be able to purchase items from the grocery store. Even if you have enough cash, it is likely that the stores will be sold out of most items, and most items will not be restocked until the outage is over."

[If respondents select "No", show the following prompt]

"You are right. After the outage, most of the financial system will not work, and most grocery stores will not be operating. If you do not have enough cash in advance, you may not be able to purchase items from the grocery store. Even if you have enough cash, it is likely that the stores will be sold out of most items, and most items will not be restocked until the outage is over."

6. Could you use your (charcoal, propane or gas) grill or camping stove to cook food in a well-ventilated area, such as a back porch, if you store enough fuel and ingredients beforehand?

❑Yes ❑No

[If respondents select "Yes", show the following prompt]

"You are right. Even without electricity, you can light your grill with matches or grill lighters and cook your perishable food with the grill until you run out of fuel."

[If respondents select "No", show the following prompt]

"Incorrect. Even without electricity, you can light your grill with matches or grill lighters and cook your perishable food with the grill until you run out of fuel."

7. Could you go to a near-by heated shopping mall or restaurant?

❑Yes ❑No

[If respondents select "Yes", show the following prompt]

"Incorrect. Because most local shopping malls or restaurants do not have backup generators or enough fuel, they will not be open."

[If respondents select "No" or "Uncertain", show the following prompt]

"You are right. Because most local shopping malls or restaurants do not have backup generators or enough fuel, they will not be open."

8. On the seventh day of the blackout, will water and sewer services be available?

❑Yes ❑No

[If respondents select "Yes", show the following prompt]

"Incorrect. After the first few days normal water supply and sewage service will not be available because they require fuel for pumping and treatment. Even if there is some running water from your faucet(s), tap water may not be safe to drink."

[If respondents select "No" or "Uncertain", show the following prompt]

"You are right. After the first few days normal water supply and sewage service will not be available because they require fuel for pumping and treatment. Even if there is some running water from your faucet(s), tap water may not be safe to drink."

[Respondents are allowed to move onto the next page after answering all the questions]

Reasons why the outage would be inconvenient

[The video can be viewed at: https://youtu.be/6xlT8-LgGwM. Below is the script for the video.]

As previously discussed, smart meter technology can provide you a partial amount of your normal electricity service during the blackout. We would like you to think about how you would use that smaller amount of electricity. In this task, there are four categories of appliances: heating, kitchen, household, and laundry. Let's start with the kitchen category as an example. First select the kitchen tab. Then, select all the appliances you would want to use during the morning period. If you would use more than one, select the number that you would use. When you select an appliance, the electricity consumption on the graph at the right should go up. If you would like to remove that appliance, select "choose." If you want to turn off all of the appliances from one category, click the "reset" button. Notice that the graph only goes up to 20, so if you use appliances that consumer more than the maximum power available, a warning message will appear and the last appliance you chose will be removed automatically. When you are finished selecting the appliances for the morning, press the "submit" button. Here you can review the selected appliances. If you want to add, remove or edit your answer, click "edit appliance" button to revise your selection. Click "next" button to move onto the next time period, and click "previous" button to the previous time period. You will be asked to repeat the task for the afternoon, evening, and night. Please remember the scenario: You are choosing the appliances that you would use if there was a large regional blackout during cold winter weather. Before we continue, we would like to ask you about some of your electric appliances.

[When respondents finish reading the instruction, the following question will show up]

Now we would like you to consider the ways you consume electricity in more detail. Before we start, please tell us if you have any of the following (select all that apply):

Do you have any of the following (select all that apply)?

Water heater	❑ Electric	❑ Gas	❑ Don't have any
Furnace	❑ Electric	❑ Gas	❑ Don't have any
Oven	❑ Electric	❑ Gas	❑ Don't have any

[Respondents are allowed to move onto the next page after answering all the questions]

[In this page, respondents are asked to play the "card stacking game". Please see Chapter 4.3.1 for the details]

Other monetary losses related to the blackout

[The video can be viewed at: https://youtu.be/rxkhypsazrQ. Below is the script for the video]

Now let's focus on the economic or monetary losses that you may suffer. The first is the cost of repairing frozen water pipes. A day or two after the power goes out, the temperature in your house will drop below freezing. Unless you can get some heat, or drain your pipes, your water pipes will start to freeze and burst. That can cause major damage. Repairing that damage will cost several thousands to tens of thousands of dollars. Because lots of other people will have the same problem, getting the repairs done once the power comes back on may take many weeks. If you do not have heat, but can manage to drain most of the system, repairing the damage will still cost between several hundred and few thousand dollars. While your homeowner's insurance may cover part of the damage, how much it covers depends on the terms of the policy and the coverage limits and deductibles. Next, let's focus on another inconvenience: food safety. If this blackout had happened on a hot summer day, storing food that needs refrigeration would be a very serious problem. However, in this could weather you should be able to figure out a way to store perishable food. As we mentioned earlier, it will take several days to receive emergency supplies from the government. Meanwhile, you can only rely on the food that you have stored.

[Respondents are allowed to move onto the next page after watching the video]

Here we will consider other potential monetary losses from an outage.

If the power goes out for 10 days, and you cannot arrange to work, will your employer still pay you?

❑ Yes ❑ No ❑ I am not currently employed.

[If respondents select "Yes" or "I am not currently employed", show the following message]
In that case, you may not need to worry about your lost income.

[If respondents select "No", show the following message]
In that case, how much money will you lose by not being able to work?

$____________ ❑ Cannot estimate

If the power goes out for 10 days, and your household members cannot arrange to work, will they still get paid?

❑ Yes ❑ No ❑ I live alone or I am the only person earning for my household

[If respondents select "Yes" or "I live alone or I am the only person earning for my household", show the following message]
In that case, you may not need to worry about your lost income.

[If respondents select "No", show the following message]
In that case, how much will they lose by not being able to work?

$____________ ❑ Cannot estimate

Finally, please estimate any other economic losses (excluding spoiled food, water pipes, and lost income) that may result from the outage:

____

____

____

Now we have thought about the inconveniences and economic losses that you may suffer as a result of a 10-day large regional blackout. We would like to know if this information changes your preferences.

Please indicate whether you would be willing to pay that amount of money in exchange for the partial backup service.

Note that the backup service is separated from your normal electricity consumption. This is a one-time extra payment, and the payment will solely cover your electricity consumption during the outage. You still need to pay for electricity consumed during the rest of the month.

	Would you be willing to pay this amount extra per day to get the backup service during the outage?		
	Yes	Not sure	No
Less than $10 per day	❑	❑	❑
$10-$19.99 per day	❑	❑	❑
$20-$29.99 per day	❑	❑	❑
$30-$39.99 per day	❑	❑	❑
$40-$49.99 per day	❑	❑	❑
$50-$59.99 per day	❑	❑	❑
$60-$69.99 per day	❑	❑	❑
$70-$79.99 per day	❑	❑	❑
$80-$89.99 per day	❑	❑	❑
$90-$99.99 per day	❑	❑	❑
More than $100 per day	❑	❑	❑

[When respondents finish answering the question, show the following prompt and radios above the table]
You said that you would be definitely be willing to pay less than *$((Upper bound of the highest box from the "Yes" column)*) per day but you might be willing to pay up to $(*(Upper bound of the highest box from the "Not sure" column)*) per day. That means you are willing to pay up to *$((Upper bound of the highest box from the "Yes" column)*×10) for sure but no more than $(*(Upper bound of the highest box from the "Not sure" column)*×10) during the entire outage.
Is this correct?

❑Yes ❑Let me try again

[Respondents who click "Yes" are directed to the next page]
[When respondents click "Let me try again", then show the following prompt above the table]
You wanted to revise your answer. Please indicate your willingness to pay again.

[Consequences for Society]

[Here we will show the video: https://youtu.be/fpYjpedq0jE. Below is the script for the video.]

So far, we have asked about your willingness to pay for electricity in your own home. Now let's think about the critical social services provided by electric power in your community. Many critical social services, such as police and fire departments, water and sewage treatment service, and traffic lights at important intersections would not be available during the outage. How much would you be willing to pay per day to make these critical social services available in your community? Assume that whatever you say, all your neighbors who can afford to pay will also contribute the same amount as you.

[When respondents finish reading the instruction, the following willingness to pay question will show up]

	Would you be willing to pay this amount **extra** to support the critical social services during the blackout occurred by (solar storm/terrorist attacks)?		
	Yes	Not sure	No
Less than $5 per day	❑	❑	❑
$5-$9.99 per day	❑	❑	❑
$10-$19.99 per day	❑	❑	❑
$20-$29.99 per day	❑	❑	❑
$30-$39.99 per day	❑	❑	❑
$40-$49.99 per day	❑	❑	❑
$50-$59.99 per day	❑	❑	❑
$60-$69.99 per day	❑	❑	❑
$70-$79.99 per day	❑	❑	❑
$80-$89.99 per day	❑	❑	❑
$90-$99.99 per day	❑	❑	❑
More than $100 per day	❑	❑	❑

[When respondents finish answering the question, show the following prompt and radios above the table]

You said that you would be definitely be willing to pay less than *$((Upper bound of the highest box from the "Yes" column)*) per day but you might be willing to pay up to $(*(Upper bound of the highest box from the "Not sure" column)*) per day. That means you are willing to pay up to *$((Upper bound of the highest box from the "Yes" column)*×10) for sure but no more than $(*(Upper bound of the highest box from the "Not sure" column)*×10) during the entire outage.

Is this correct?

❑Yes ❑Let me try again

[Respondents who click "Yes" are directed to the next page]

[When respondents click "Let me try again", then show the following prompt above the table]

You wanted to revise your answer. Please indicate your willingness to pay again.

[Consequences for Society]

[Here we will show the video: https://youtu.be/VgrpCW8vgO4. Below is the script for the video.]

Now let's think about members of your community who may not have enough money for the backup service. How much would you be willing to pay per day so that these members of your community will have access to partial electricity service during the blackout? Assume that whatever you say, all your neighbors who can afford to pay will also contribute the same amount as you.

[When respondents finish reading the instruction, the following willingness to pay question will show up]

	Would you be willing to pay this amount **extra** to support some members in your community during the blackout occurred by (solar storm/terrorist attacks)?		
	Yes	Not sure	No
Less than $5 per day	❑	❑	❑
$5-$9.99 per day	❑	❑	❑
$10-$19.99 per day	❑	❑	❑
$20-$29.99 per day	❑	❑	❑
$30-$39.99 per day	❑	❑	❑
$40-$49.99 per day	❑	❑	❑
$50-$59.99 per day	❑	❑	❑
$60-$69.99 per day	❑	❑	❑
$70-$79.99 per day	❑	❑	❑
$80-$89.99 per day	❑	❑	❑
$90-$99.99 per day	❑	❑	❑
More than $100 per day	❑	❑	❑

[When respondents finish answering the question, show the following prompt and radios above the table]

You said that you would be definitely be willing to pay less than *$((Upper bound of the highest box from the "Yes" column)*) per day but you might be willing to pay up to $(*(Upper bound of the highest box from the "Not sure" column)*) per day. That means you are willing to pay up to *$((Upper bound of the highest box from the "Yes" column)*×10) for sure but no more than $(*(Upper bound of the highest box from the "Not sure" column)*×10) during the entire outage.

Is this correct?

❑Yes ❑Let me try again

[Respondents who click "Yes" are directed to the next page]

[When respondents click "Let me try again", then show the following prompt above the table]

You wanted to revise your answer. Please indicate your willingness to pay again.

[Wrap up]

Information about yourself and your experiences from outage

1. How would you categorize yourself in terms of race or ethnicity?

❑Caucasian ❑Hispanic ❑Black
❑Asian ❑Other. Please explain: ___________________

2. What was your total household income last year?

❑Under $17,000 ❑$17,001 to $30,000 ❑$30,000 to $46,000
❑$46,000 to $75,000 ❑$75,000 to $148,000 ❑Above $148,000

3. Do you live in an apartment, attached house, or detached house?

❑Apartment /Condominium ❑Multi-Family homes (duplex or triplex, etc.) ❑Single-family house ❑ Others

How long have you lived in your current house or apartment? ________________ Years

4. How many people (including yourself) are there in your household in each of the following age groups?

Preschool children: ________________
K-12 children: ________________
Adults under 30 years: ________________
Adults between 30 to 65 years: ________________
Adults over 65 years: ________________

5. Please tell us about whether you have the following items available to you in the case of a blackout:

❑Flashlights in easy-to-find places
❑Wind up or crank operated radio
❑Wind up or crank operated cell phone charger
❑Camping lantern
❑Camping cook stove
❑Portable generator.
❑Stand-by generator.
❑Other non-generator.
❑Solar energy generation that is directly connected to the grid (i.e., 'grid-tied').
❑Solar energy generation with storage that actually allows you to use power when the grid power is off.

6. Please roughly estimate your monthly electric bill during:

The off-peak seasons (spring, fall)? $_________/month ❑Cannot estimate
The summer? $_________/month ❑Cannot estimate
The winter? $_________/month ❑Cannot estimate

7. How long was the longest power outage you have ever experienced?:

❑Less than a few minutes
❑Less than an hour
❑Several hours.
❑Less than one half-day.
❑Less than one day.
❑Less than several days.
❑Less than one week.
❑Longer than one week.

[If respondents select "Several hours", "Less than one half-day", "Less than one day", "Less than several days", "Less than one week", and "Longer than one week", show the following message]

What was the weather like during that outage?

❑Hot summer
❑Mild weather (Spring, Fall)
❑Cold winter

8. How inconvenient would it be if an outage lasted …?

	Not at all	Slightly	Moderately	Very	Extremely
Less than several hours (~4 hours)	❑	❑	❑	❑	❑
Several hours to one day	❑	❑	❑	❑	❑
One day to three days	❑	❑	❑	❑	❑
Three days to one week	❑	❑	❑	❑	❑
Longer than 1 week	❑	❑	❑	❑	❑
Few weeks (1-2 weeks)	❑	❑	❑	❑	❑
Less than few weeks	❑	❑	❑	❑	❑

9. How many major solar storms that cause a large-scale power outage would you expect in the:

	Number (greater than or equal to zero)
Next 1 year?	
Next 5 years?	
Next 20 years?	
Next 50 years?	

[When respondents finish answering all the questions and click submit button, they are moved to the completion page]
Thanks very much for your help with this study. If you have questions or concerns, feel free to contact the project manager, Sunhee Baik, sunheeb@andrew.cmu.edu.

[If respondents are considered as ineligible, we moved them to the ineligible-completion page.]

Unfortunately, you are not eligible for the survey at this particular time. Yet, thank you for your interest. If you have questions or concerns, feel free to contact the project manager, Sunhee Baik, sunheeb@andrew.cmu.edu.