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Understanding the Cost of Power Interruptions to U.S. Electricity Consumers

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Prepared for

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Abstract

The massive electric power blackout in the northeastern United States and Canada on August 14-15, 2003 resulted in the U.S. electricity system being called “antiquated” and catalyzed discussions about modernizing the grid. Industry sources suggested that investments of $50 to $100 billion would be needed. This report seeks to quantify an important piece of information that has been missing from these discussions: how much do power interruptions and fluctuations in power quality (power-quality events) cost U.S. electricity consumers? Accurately estimating this cost will help assess the potential benefits of investments in improving the reliability of the grid.

We develop a comprehensive end-use framework for assessing the cost to U.S. electricity consumers of power interruptions and power-quality events (referred to collectively as “reliability events”).

The framework expresses these costs as a function of:

- Number of customers by type in a region;
- Frequency and type of reliability events experienced annually (including both power interruptions and power-quality events) by these customers;
- Cost of reliability events; and
- Vulnerability of customers to these events.

The framework is designed so that its cost estimate can be improved as additional data become available.

Using our framework, we estimate that the national cost of power interruptions is about $80 billion annually, based on the best information available in the public domain. However, there are large gaps in and significant uncertainties about the information currently available. Notably, we were not able to develop an estimate of power-quality events. Sensitivity analysis of some of these uncertainties suggests that the total annual cost could range from less than $30 billion to more than $130 billion. Because of this large range and the enormous cost of the decisions that may be based on this estimate, we encourage policy makers, regulators, and industry to jointly undertake the comparatively modest-cost improvements needed in the information used to estimate the cost of reliability events. Specific areas for improvement include: coordinated, nationwide collection of updated information on the cost of reliability events; consistent definition and recording of the duration and frequency of reliability events, including power-quality events; and improved information on the costs of and efforts by consumers to reduce their vulnerability to reliability events.

Acknowledgments

The work described in this paper was funded by the Office of Electric Transmission and Distribution, Energy Storage Program and by the Assistant Secretary of Energy for Energy Efficiency and Renewable Energy, Office of Planning, Budget, and Analysis of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. We acknowledge the guidance and direction provided by Imre Gyuk and Sam Baldwin, U.S. DOE. We also gratefully acknowledge comments on an early draft of this work provided by Anne-Marie Borberly-Bartis, John Boyes, Ali Chowdhury, Ken Friedman, Charles Goldman, Julie Gorte, Doug Hale, Scott Hassell, Pat Hoffman, Bill Howe, Joseph Iannucci, Leora Lawton, Chris Marnay, Philip Overholt, Marek Samotyj, Rich Scheer, Michael Sullivan, Jane Thornton, Kent Van Liere, and Mary Beth Zimmerman.

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Acronyms and Abbreviations

CBECS	Commercial Buildings Energy Consumption Survey
C&I	commercial and industrial
CPI	Consumer Price Index
DOE	U.S. Department of Energy
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
hr	hour
LBNL	Lawrence Berkeley National Laboratory
MAIFI	Momentary Average Interruption Frequency Index
MECS	Manufacturing Energy Consumption Survey
min	minute
NAICS	North American Industry Classification System
NEMS	DOE/EIA’s National Energy Modeling System
PRS	Population Research Systems
RECS	Residential Energy Consumption Survey
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
sec	second
SIC	Standard Industrial Classification

Executive Summary

The massive electricity blackout in the northeastern United States and Canada on August 14-15, 2003 rekindled public interest in the reliability of the electricity grid. Following the outage, the U.S. electricity system was called "antiquated" and likened to that of a third-world nation. Industry sources suggested that investments of $50 to $100 billion would be needed to modernize the grid. This report seeks to quantify an important piece of information that has been missing from these discussions: how much do power interruptions and power-quality events cost U.S. electricity consumers? Accurately estimating these costs will help to assess the potential benefits of investments in improving the reliability of the grid.

We develop a comprehensive end-use framework for assessing the cost to U.S. electricity consumers of power interruptions and power-quality events. This framework, which can be readily updated as additional data become available, expresses annual power-interruption and power-quality costs (referred to collectively as "reliability events") as a function of the:

- Number of customers by class and region;
- Duration and frequency of reliability events experienced annually (including both power interruptions and power-quality events) by customers;
- Cost of reliability events, by event type, customer class, and region; and
- Vulnerability of customers to reliability events.[1]

We use the framework to review previous estimates of the national cost of power interruptions and power quality, including those developed by the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE), which range from $26 billion to $400 billion annually. Our analysis shows that key assumptions underlying these early estimates reveal potentially significant biases; many of these biases cannot be fully understood until better information is collected than is currently available on the elements that contribute to the costs of reliability events.

Following our review of existing estimates, we use the best information currently available in the public domain to develop a new estimate of the national cost of power interruptions. We do not include power-quality events. Our base-case estimate of the national cost of power interruptions is approximately $80 billion annually as shown in Figure ES-1, broken down by customer class. Table ES-1 summarizes the information used in developing our estimate.

---

[1] The vulnerability of customers to reliability events is included because it is an important component of the cost of reliability events. However, because there are no reliable, current data on customer investments in reliability-enhancing technologies (e.g., back-up generation, batteries, power-conditioning equipment), this component is not currently incorporated in our estimates or sensitivity analyses.

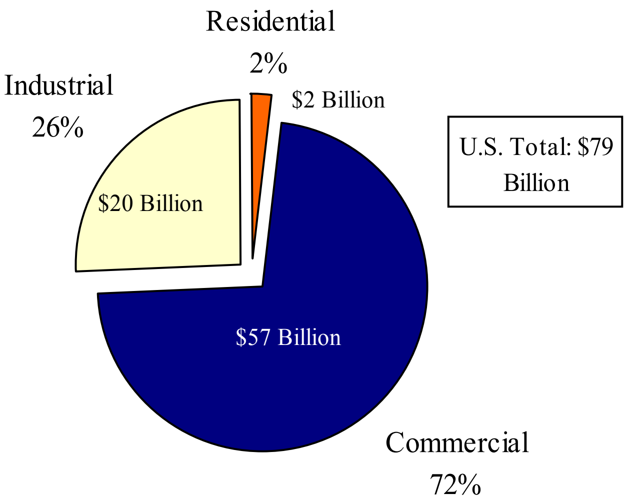

Figure ES- 1. LBNL Base-Case Estimate of the Cost of Power Interruptions by Customer Class

Our analysis shows that:

- The majority of outage costs are borne by the commercial and industrial sectors;
- As a result, although there are important variations in the composition of customers within each region, the total cost of reliability events by region tend to correlate roughly with the numbers of commercial and industrial customers in each region; and
- Costs tend to be driven by the frequency rather than the duration of reliability events.

Related to this last finding, our work reveals the importance of short-term, momentary interruptions, which last 5 minutes or less. Figure ES-2 shows that (more frequent) momentary power interruptions have a stronger impact on the total cost of interruptions than (less frequent) sustained interruptions, which last 5 minutes or more.

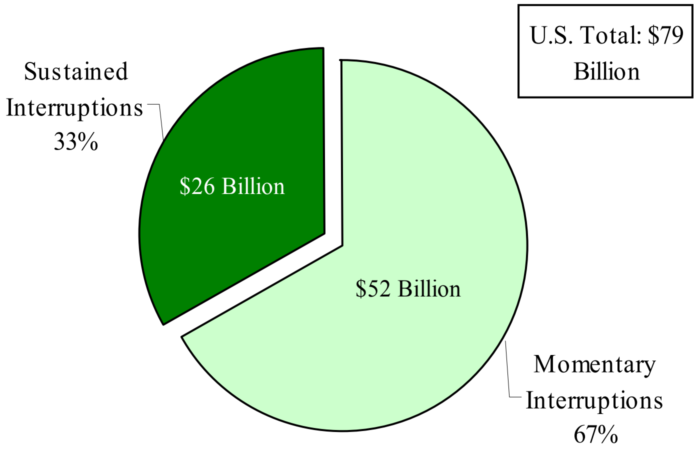

Figure ES- 2. LBNL Base-Case Estimate of the Cost of Power Interruptions by Type of Interruption

This finding is consistent with the observation that the "down-time" associated with a power interruption can be as or more important than the duration of the interruption, itself.

Consistent with our review of prior estimates, we also find in developing our own estimate that there are significant gaps and uncertainties in the information currently available to support any estimate of the national cost of power interruptions. (Table ES-1 summarizes the uncertainties and their effects.)

To understand the effects of these uncertainties, we performed a sensitivity analysis of our base case in which we varied key parameters used in our calculation in order to quantify the impact of these variations on our results. Figure ES-3 shows the resulting total cost of power interruptions for each of the following variations:

- Assuming that the duration and frequency of reliability events varies by region, based on the limited region-specific data we collected;
- Assuming that the duration and frequency of reliability events is one standard deviation greater and less than the values used in our initial estimate, based on the total sample of data we collected;
- Assuming that all outages are valued based on the assumption that they occur on a summer weekday afternoon or summer weekend night; and
- Assuming that the commercial and industrial sectors experience a disproportionately lower duration and frequency of reliability events than the residential sector.

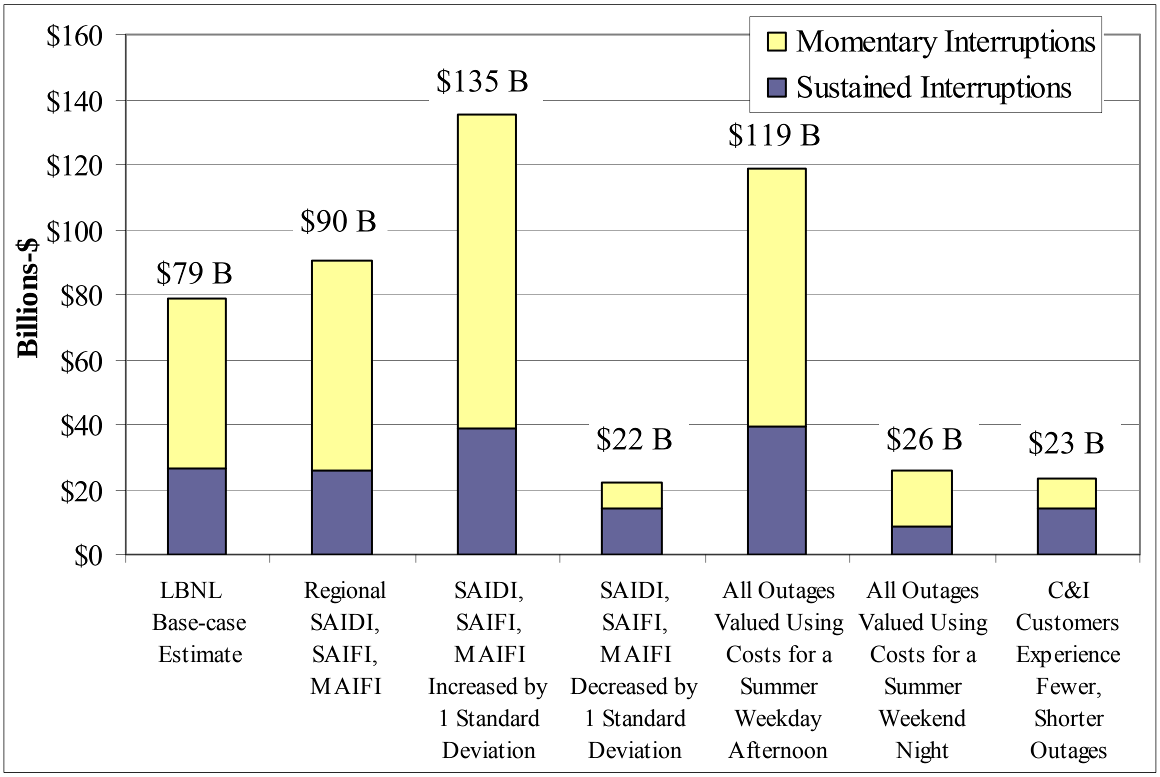

Figure ES- 3. Summary of U.S. Cost of Power Interruption Sensitivity Cases

We find that the annual cost of power interruptions:

- Could be as low as $22 billion or as high as $135 billion when we consider a reasonable range in the annual duration and frequency of power interruptions, which addresses both gaps in the data for certain regions and possible year-to-year variations in reliability;
- Might be calculated to be as high as $119 billion if all reliability events are (incorrectly) assumed, as is typical in many studies, to occur during summer weekday afternoons when power usage and costs are high; and
- Could be as low as $23 billion when we take into consideration that larger commercial and industrial customers typically experience fewer and shorter interruptions than do residential and smaller commercial customers, which results from the design of many utility distribution systems.

In view of the large range of plausible estimates and the enormous cost of the private and public decisions that will be based on them, we encourage policy makers, regulators, and industry to work to jointly work to undertake the modest-cost activities that are needed to improve the information that is available on reliability events and their costs.

Specific areas for improvement include:

- Coordinated, nationwide collection of updated information on the cost of reliability events to customers;
- Consistent definition and tracking of the frequency, duration, timing, and number and type of customers affected by reliability events, including power-quality events; and
- Collection of information on efforts by customers to reduce their vulnerability to reliability events through investments in technology (such as back-up generators and energy storage) and other measures.

Table ES- 1. Review of Assumptions Used to Develop LBNL Base-Case Estimate of the Cost of Power Interruptions

	Source of Information Used in This Study	Uncertainties in These Sources of Information	Assessment of the Impact of These Uncertainties
Customers	Customer classes (residential, commercial, and industrial) and populations as defined and estimated by the U.S. Energy Information Administration (EIA) for 10 regions of the U.S. (with California treated separately).	Customer classes defined by EIA (residential, commercial, industrial) are not consistent with customer revenue classes used by utilities (residential, small and medium commercial and industrial (C&I), and large C&I).	No clear direction in bias.
Duration and Frequency of Reliability Events	Trimmed means for three major industry reliability indices collected from an on-line search of utility and state PUC websites. SAIDI[1] Mean = 106 min. Std. Dev. = 54 min. N = 162 SAIFI[2] Mean = 1.2 Std. Dev. = 0.5 N = 162 MAIFI[3] Mean = 4.3 Std. Dev. = 3.6 N = 52	SAIDI, SAIFI, and MAIFI are not collected consistently and are often collected using inconsistent definitions.	No clear direction in bias.
		SAIDI and SAIFI data sometimes exclude major events (such as those caused by large storms).	Likely bias is to underestimate costs.
		SAIFI data sometimes include MAIFI data.	Likely bias is to overestimate costs.
		SAIDI, SAIFI, and MAIFI exhibit year-to-year variability.	No clear direction in bias.
		SAIDI, SAIFI, and MAIFI data are typically reported for an entire population, not by customer class.	Likely bias is to overestimate costs (larger customers typically experience greater reliability).
		SAIDI, SAIFI, and MAIFI data difficult to find for all regions.	No clear direction in bias.
		SAIDI, SAIFI, and MAIFI do not distinguish the time when interruptions occur.	No clear direction in bias.

		Information on power-quality events was not included in this analysis because information on power-quality events suffers from all of the above limitations to an even greater degree than SAIDI, SAIFI, and MAIFI.	Likely bias is to underestimate costs.
Cost of Reliability Events	Customer damage functions for three customer revenue classes (residential, small and medium C&I, and large C&I) were developed through a separate national study of utility outage-cost surveys conducted by Population Research Systems and Lawrence Berkeley National Laboratory (2003). In total, more than 60,000 survey responses from 24 past utility studies were combined to estimate customer damage functions.[4]	Customer damage functions were estimated by consolidating a large number of independent utility outage-cost surveys. Although survey methods were similar, they were not identical. Changes in customer costs since the time of the original surveys have not been examined. Utility surveys do not capture infrastructure costs associated with widespread major outages (e.g., the Northeast blackout on August 14-15, 2003).	No clear direction in bias. No clear direction in bias. Slight bias toward underestimating costs (major outages are rare events.).
Vulnerability to Reliability Events	Not used in this study because of the absence of reliable information on customer investments in reliability-enhancing technologies (e.g., back-up generators and energy storage) and other measures.	Comprehensive information on customer investments in reliability enhancing technologies (such as back-up generators and energy storage) is not available.	Likely bias is to overestimate costs.

[1] System Average Interruption Duration Index

[2] System Average Interruption Frequency Index

[3] Momentary Average Interruption Frequency Index

[4] Customer damage functions express the cost of outage as a function of outage duration, season, time of day, annual electricity use, and (depending on the customer class) household income or number of employees.

1. Introduction

The massive blackout in the northeastern United States and Canada on August 14-15, 2003 rekindled public interest in the reliability of the electricity grid. Following the blackout, the U.S. electricity system was called “antiquated” and likened to that of a third-world nation. Industry sources suggested that investments of $50 to $100 billion would be needed to modernize the grid (Fialka 2003; Schieffer 2003). This report seeks to quantify an important piece of information that has been missing from these discussions: how much do power interruptions and fluctuations in power quality (power-quality events) cost U.S. electricity consumers? Accurately estimating this cost will help assess the potential benefits of investments in improving the reliability of the grid.

From a customer’s perspective, electricity reliability problems come in a variety of forms. Interruptions or outages during which voltage drops to near zero for periods of time ranging from a few seconds to several hours are the most visible problems and affect the widest range of electricity-consuming equipment. Less apparent are smaller voltage deviations, either above or below nominal voltage, which influence the operation of only some types of equipment depending on the magnitude and duration of the variations. These smaller deviations are aspects of power quality.[2] It is important to consider both outages and power quality problems because from a customer’s perspective both can affect the cost of unreliable electricity.

During the past decade, there have been several efforts to assess the national cost of power interruptions and power quality. During the 1990s, the Electric Power Research Institute (EPRI) estimated the national cost of $26 billion per year based on a figure that had been presented at a power-quality conference (Electric Power Research Institute 1993). Later, EPRI extrapolated from this figure and began reporting power-interruption costs of $50 billion per year (Douglas 2000). During the same period, a U.S. Department of Energy (DOE) study offered cost of reliability estimates ranging from $150 to $400 billion per year, based on an extrapolation from a single utility value-of-service study (Swaminathan and Sen 1998). Finally and most recently, EPRI prepared a new set of cost of power interruption and power quality estimates ranging from $119 billion to $188 billion per year; $119 billion per year is the figure most often quoted from that study (Primen 2001).

Little has been done to systematically analyze the accuracy of these estimates. This paper presents a framework for assessing the strengths and weaknesses of past estimates and characterizes the uncertainties inherent in past and future estimates of the economic cost of power interruptions and power quality. We illustrate the use of this framework by drawing on existing data from a variety of sources to develop a new estimate of the total economic cost to U.S. electricity consumers, not including power quality. We examine uncertainties and gaps in the information used to develop this estimate to define a range of plausible estimates that might be expected from future calculations. We also explore issues that may have introduced bias into

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[2] Power quality refers to the degree to which power characteristics align with the ideal: 120-V or 480-V (in the U.S.), 60-Hz., sinusoidal voltage and current waveform, with current and voltage in phase. Power quality problems therefore encompass not only variations in voltage magnitude but also a host of other, more subtle deviations from the ideal. Harmonics are one example. Harmonics are integer multiples of the fundamental frequency that are imposed on the fundamental frequency and can affect certain types of equipment, such as adjustable-speed drives.

prior estimates. These examples allow us to pinpoint key sources of uncertainty inherent in any estimate of these costs. Based on the uncertainties we identify, we prioritize future data collection activities whose results can be used to refine estimates of these costs.

The paper is organized into five sections following this introduction:

- **Section 2** describes the basic framework for estimating the cost of power interruptions and power quality.
- **Section 3** uses the framework to evaluate the three published estimates described above.
- **Section 4** uses publicly available data from a variety of sources to create an independent estimate of the cost of power interruptions to U.S. electricity customers (not including power quality).
- **Section 5** uses sensitivity analysis to explore the significance of the uncertainties in the initial estimate developed in Section 4.
- **Section 6** summarizes our findings and conclusions and offers recommendations for improving future estimates.

Energy Storage and Electricity Reliability

This report was sponsored by the United States Department of Energy’s (DOE) Office of Electricity Transmission and Distribution, in part, to quantify the possible financial benefits if electric energy storage (storage) is used to improve electric service reliability.

Storage can attenuate most manifestations of poor power quality and in some cases can provide direct electrical “support” to the grid (transmission and distribution systems). For generation and transmission systems storage can be an important tool to maintain system stability. At the local/electricity distribution level, storage can absorb, filter out or otherwise compensate for many types of poor power quality and can provide power during longer duration interruptions lasting for a few minutes to a few hours.

Storage may be a superior solution for reliability enhancement if conventional utility options to improve reliability are limited or constrained and/or for locations where noise, air emissions, zoning, or fuel-related issues limit use of generation-based solutions. Furthermore, unlike generation-based solutions most storage (system) types respond instantaneously to power quality events and to outages.

2. An End-Use Framework for Estimating the Economic Cost of Power Interruptions and Power Quality

This section describes an end-use framework for estimating the economic costs of power interruptions and power quality to U.S. electricity consumers. The framework relies on a simple mathematical expression that determines the economic cost of power interruptions and power quality as follows:

$$\text{Cost of Power Interruptions and Power Quality} = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{p} N_{i,j} \times F_{i,j,k} \times C_{i,j,k} \times V_{i,j,k}$$

where,

N = number of electricity customers, by customer class for each region
F = the frequency of reliability events by type of event experienced annually by customers by customer class for each region
C = the cost per event by type of reliability event per customer by customer class for each region (2002-CPI-weighted dollars/event)
V = the vulnerability of customers to each type of reliability event by customer class for each region (a fraction between 0 and 1)
m = the number of customers in each customer class
n = the number of regions
p = the type of reliability event
i,j,k = indices for customer class, region, and type of reliability event, respectively

The simplicity of this formula belies the complexities involved in estimating the value of each of the four variables in the equation. The remainder of this section briefly summarizes some of the issues that can arise in developing the information needed to use this framework to estimate the cost of power interruptions and power quality. Table 1 summarizes some of the uncertainties associated with defining and gathering accurate data about each of the variables used for the quantification of the cost of power interruptions and power quality to U.S. electricity customers.

2.1 Customers

The number of customers considered when estimating the cost of power interruptions or power quality will have a significant impact on the accuracy of the estimate. Significant uncertainty can result from differences in how customers are defined. Customer definitions can include any one of the following: a single electricity account with one (or more) meters, such as a single-family detached residence; a single site/facility with multiple accounts, each possibly consisting of multiple meters, such as an apartment building; or multiple premises under common ownership, each with one or more accounts/meters, such as a chain of retail establishments.

Table 1. Sources of Uncertainty in Estimating the Cost of Reliability Events

Variable	Sources of Uncertainty
Customers	Customers and customer classes are not defined consistently
Reliability Events	All reliability events are not always counted: • Are power quality events and momentary interruptions included? • Are outages from major natural events included? Aggregate or system level reliability measures do not describe the reliability experienced by customers on different classes of service or served by different distribution system designs. Aggregate of system level reliability measures suppress the geographic and temporal distribution of reliability events among the affected population of customers.
Cost of Reliability Events	Some costs may not be counted accurately or may not be counted at all: • How accurate are estimates of customers' "willingness to pay" for unquantifiable "inconvenience" factors associated with outages? • Are business losses accurately counted so that only net losses (i.e., excluding offset costs) are included? • How do we account for societal/infrastructure costs, e.g. costs associated with emergency response due to a widespread outage?
Vulnerability to Reliability Events	Customer investments in technologies or measures to reduce their exposure to reliability events are not collected routinely.

Customer sectors are also not defined consistently. As we explain in detail in Section 5.1, it is difficult to reconcile data from sources that use different customer classification systems. For example, customers can be classified according to revenue accounts ("small and medium light and power" and "large light and power") or according to end-use forecasting categories (or market segments) made up of groupings of North American Industry Classification System (NAICS) codes. (Energy Information Administration 1990).

2.2 Reliability Events

Assessment of reliability involves looking at electromagnetic deviations from the ideal service that the U.S. electricity distribution system is designed to provide: a pure 60-cycle per second alternating current at a designated voltage (120 volts for residential customers or 480 volts for many commercial or industrial customers). Any deviation from this standard that causes customers' equipment to fail or malfunction can be considered a reliability 'event.' Power interruptions (sometimes called outages or blackouts), which occur when voltage falls to zero for more than a few seconds, are the reliability problem with which most individuals have the greatest direct experience and are the key phenomena represented in utility reliability statistics.

While many utilities maintain detailed records of customer outage experience in their outage management systems, these data are usually reported in summary in the form of reliability event indices (Kueck et al. 2004). The System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) describe the duration and frequency, respectively, of *sustained* interruptions experienced by customers of a utility in one year (IEEE 1995; IEEE 1999). According to IEEE, a "sustained interruption" is defined as any interruption that lasts at least five minutes and is not classified as a momentary interruption.

The SAIDI index represents the average length of time customers are interrupted and is defined as,

$$\text{SAIDI} = \frac{\text{Sum of customer (sustained) interruption durations for all customers}}{\text{Total number of customers served}}$$

The SAIFI index represents the total number of customer interruptions per customer for a specified electric supply system and is defined as,

$$\text{SAIFI} = \frac{\text{Total number of customer (sustained) interruptions for all customers}}{\text{Total number of customers served}}$$

There are other reliability indices, too, but SAIDI and SAIFI measurements are the two indices most commonly used by utilities and industry experts to report on the quality of service based on duration and frequency of electricity outages[3]. In this paper, SAIDI and SAIFI data are used to quantify the magnitude of duration and frequency of sustained electricity interruption events for a typical year.

Although SAIDI and SAIFI are useful for assessing the costs and effects of power interruptions, these data are often either not collected by utilities or are collected inconsistently (Warren et al. 2003). That is, the information collected by utilities, if it is collected (and reported) at all, varies in the details or variables that are recorded. Thus, a major source of uncertainty is that many reliability events that have measurable cost consequences for the customers who experience them are simply not counted.

At one extreme, widespread power losses resulting from major natural events (primarily storms but also hurricanes and earthquakes) are sometimes not included in the same data categories as more routine power losses. As a result, power losses from natural events are not always included in data used for cost estimates. At the other extreme, momentary fluctuations in power (or

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[3] The North American Electric Reliability Council is a source of information on major customer outages stemming from events affecting the bulk transmission system (for example, an unplanned loss of demand greater than 300 MW.) See http://www.nerc.com/~oc/pds.html. However, most outages are small and occur on utility distribution systems. Utility reporting systems, in principle, record both types of outages.

power-quality events) and momentary interruptions or losses of power for less than five minutes are not reported as reliability events by many utilities. Clearly, these differences in reporting conventions make it difficult to compare reliability data and performance among different utilities.[4]

The MAIFI index is a useful measure for assessing the frequency of momentary interruptions. However, the data are not as commonly collected and, therefore, more difficult to find. Consistent with IEEE's definition of a sustained interruption, a momentary outage is defined as any event lasting less than five minutes. The MAIFI index is therefore defined as,

$$\text{MAIFI} = \frac{\text{Total number of customer momentary (< 5 min) interruptions for all customers}}{\text{Total number of customers served}}$$

Nevertheless, because SAIDI, SAIFI, and MAIFI are reported as an aggregate of all events in a given year, these indices alone cannot be used to determine the frequency, duration, or timing of individual reliability events. As we will discuss next, this practice is at odds with the costs customers experience as a result of reliability events, which have been found to vary as a function of the duration and timing of reliability events.

Along the same lines, SAIDI, SAIFI, and MAIFI data do not distinguish between the types of customers experiencing reliability events. Due to the design of electricity distribution systems, larger commercial and industrial customers tend to experience fewer and shorter power interruptions than do smaller commercial and residential customers.

While SAIDI, SAIFI, and MAIFI capture those reliability events during which voltage drops to zero, for many customers, subtle deviations in power quality pose a far more significant reliability problem than these interruptions (because they occur more frequently). The most common small deviation is a voltage "sag" – a drop in (but not complete loss of) voltage for a short period of time (i.e., from a few cycles to a few seconds).[5] Voltage sags can be caused by natural events (e.g., trees falling on power lines or lightning striking lines or transformers), utility activities (e.g., routine switching operations or human error), or customer activities (e.g., starting of large motors).

Despite the growing importance of power quality as a class of reliability events, the situation for information on power quality is even worse than it is for SAIDI, SAIFI, and MAIFI. Indices for power quality events are under active discussion by the industry. However, at this time, there has

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[4] There is some confusion in the literature regarding the definition of "sustained" and "momentary" interruptions for the purpose of reporting them as reliability events. We have relied on the IEEE Trial-Use Guide for Electric Power Distribution Reliability Indices (IEEE 1999), which defines momentary interruptions as zero-voltage (or voltage < 10%) events lasting 5 minutes or less (no minimum duration is specified). The IEEE Recommended Practice for Monitoring Electric Power Quality (IEEE 1995) defines the duration of momentary interruptions as zero-voltage events lasting between 0.5 cycles to 3 seconds and sustained interruptions as "any interruption not classified as a momentary interruption." A momentary interruption event (for reporting purposes), therefore, may encompass more than one momentary (or sustained) interruption, provided service is restored within 5 minutes.

[5] EPRI's landmark study of power quality found that voltage-related power quality events accounted for 90% of all power quality events (Electrotek Inc. 1996).

been only one comprehensive study of power quality, and the data collected for it are now over 10 years old (Electrotek Inc. 1996). Currently, there are no ongoing data collection efforts for power quality in the public domain (Electric Power Research Institute 2003).

In addition to data availability concerns, some of the challenges for studies of power quality include:

- Power quality events can be caused by activities on both sides of the customer meter.
- Utility distribution systems were never designed to provide perfect power quality.
- Sensitivity to power quality events depends on the characteristics of the customer.

2.3 The Cost of Reliability Events

Estimating the costs that customers experience as a result of outages involves several sources of uncertainty. Typically, outage-cost estimates are based on surveys that assess the costs that customers say they will experience under different outage circumstances (Lawton et al. 2003). One source of uncertainty in these estimates is the degree to which the costs customers report in surveys under hypothetical circumstances correspond with the costs they actually would experience under such circumstances. No studies have been done to validate the results obtained from these surveys and this is a significant source of uncertainty in the cost estimates that have been prepared to date.

Assessing actual costs is complicated by the differing impacts of reliability events on the different classes of customers – residential, commercial, or industrial – that are affected by an event. We break costs down into three categories: costs borne by residential customers, costs borne by non-residential (commercial and industrial or C&I) customers, and costs borne by the infrastructure of society in general.

Costs experienced by residential customers are difficult to quantify. Although out-of-pocket costs for consumable goods, such as candles, flashlight batteries, prepared food (i.e., eating out), and food spoilage, are easy to quantify, the other "costs" borne by residential customers are experiential in nature, such as resetting clocks, changing plans, and coping with inconvenience, fear, anxiety, etc. Analytical techniques to estimate these costs typically involve contingent valuation, which includes so-called "willingness to pay" and "willingness to accept" approaches as a means of addressing experiential costs in deriving outage costs for residential customers. The findings developed through application of contingent valuation methods have been controversial due to concerns regarding bias in the responses provided by customers to the hypothetical nature of situations they must rely on.

Customer Vulnerability to Power Quality Events

The cost of power quality events is not included in the LBNL base-case estimate of the cost of power interruptions because systematic information on the frequency and nature of power quality events is not readily available and because the impact of these events on customers' equipment is both changing and not spread evenly throughout the population.

Assessment of power quality involves looking at electromagnetic deviations from the ideal service that the U.S. electricity distribution system is designed to provide: a pure 60-cycle per second alternating current at a designated voltage (120 volts for residential customers or 480 volts for many commercial or industrial customers). Any deviation from this standard that causes customers' equipment to fail or malfunction is considered a power quality "event."

Deviations in voltage are the most frequent power quality event. The IEEE classifies these events according to both the duration of an event, as well as by the degree of voltage deviation from the service standard. See Figure 1.

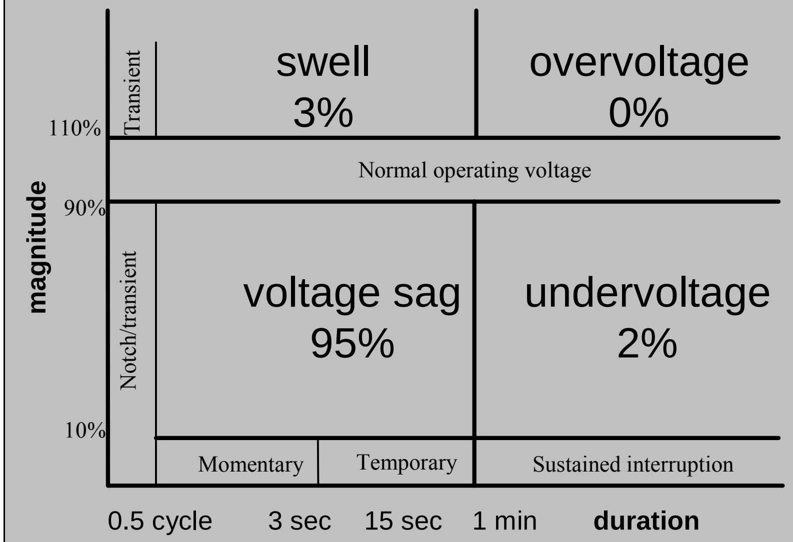
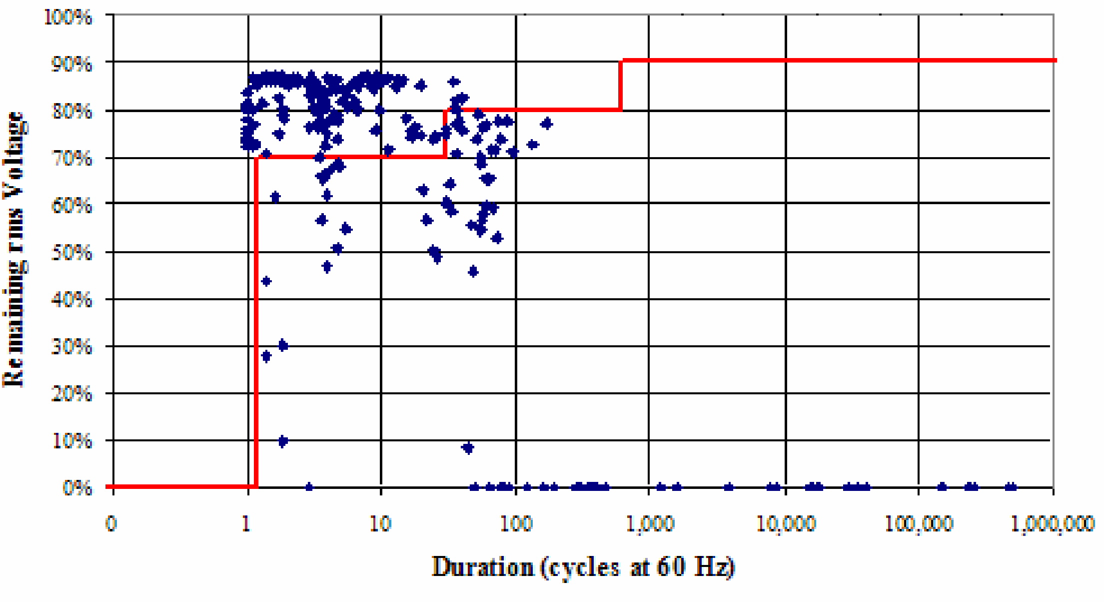


Figure 1. Voltage Deviation as a Function of Duration of Event

Although in the past most electricity-consuming devices could "ride through" voltage sags (e.g., a light bulb might dim momentarily), many of the electricity-consuming devices associated with today's digital economy (e.g., equipment controlled by programmable logic chips) cannot tolerate a partial drop in voltage for even a fraction of a second. Voltage sags may cause this equipment to shut down and remain off even after service is restored to normal levels. Voltage sags are rapid and not easily detectable by an untrained observer, and so consumers may not realize that a power quality 'event' caused their equipment to fail or stop operating. Currently, voltage sags are not included in reliability statistics reported by utilities (e.g., SAIDI, SAIFI, and MAIFI).

In addition to the absence of systematic information on the frequency and type of power quality events, the vulnerability of electricity-consuming devices to these events is changing. Industry has developed guidelines that can be used to specify the tolerance of equipment to voltage sags of varying types. Figure 2 includes an example of such a guideline, known as the CBEMA curve. This guideline specifies a region or class of voltage events (in terms of duration and degree of voltage deviation) within which equipment is designed to operate normally. Figure 2 also displays power quality events recorded during a recent DOE-sponsored pilot demonstration of a new power quality monitoring system in California's Silicon Valley. With respect to these guidelines, the figure confirms that equipment specified to meet them should ride-through many of the recorded events. However, the figure also confirms that there were many events outside the "zone of protection" specified in the guideline. A total of 263 sags and 51 interruptions were recorded; of these, 104 were events below the CBEMA curve.

This figure illustrates a key challenge for estimating the cost of power quality events. Information is needed on the frequency and type of power quality events experiences by customers, as well as on the vulnerability of customers' equipment to these events. As we were not able to develop systematic information on either type of information, we did not include an estimate of the cost of power quality events in the LBNL base-case.



Source: (Eto et al. 2004)

Figure 2. Findings from a Recent Demonstration of a Power Quality Monitoring System in California's Silicon Valley Displayed Against the CBEMA Curve.

Costs experienced by non-residential customers or firms are, in principle, simpler to estimate. Basic accounting categories, including labor and materials costs and lost revenues, are straightforward (though not necessarily easy) to determine for work interruptions caused by power losses. Significant work has been done to articulate clear cost categories for recording this information.[6] It is important to assess these costs carefully and focus on net losses; for example, lost revenues might be partially offset by scheduling an extra shift to make up for lost production.

A subtle issue that has gained increasing recognition is that losses to businesses are not in direct proportion to the duration of a reliability event (Eto et al. 2004). The relevant factor is the length of business or production downtime caused by an outage of any length. A partial loss of voltage or voltage sag can cause the same amount of downtime as a complete one hour loss of power, if, for example, machines need to be rebooted or production needs to be restarted. This issue poses a major challenge in estimating the economic cost of power interruptions and power quality.

A final category of costs applies when reliability events are widespread and last for extended periods of time. These are costs borne by the "infrastructure" of society, not by individual residential and non-residential customers. Examples of infrastructure costs include costs associated with emergency response or public health and safety activities that may be

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[6] See, for example, (Sullivan and Keane 1995).

necessitated by widespread outages.[7] Surveys that ask customers to report the impacts of reliability events on their individual activities will never capture these costs.

2.4 Vulnerability to Reliability Events

The economic cost of reliability events has led many customers to invest in a wide variety of technologies and to take other measures to reduce their vulnerability to reliability events. At one end of the spectrum, back-up or stand-by generators are probably the most well-known customer investment. However, strip surge protectors should also be viewed in this same category. In between, there are a host of energy storage technologies, such as batteries, that can reduce a customer's vulnerability to power interruption and power quality events. And for power quality especially, there are a host of measures associated with improved grounding practices customers can take to reduce the frequency of these events.

Unfortunately, data on customer investments and other efforts to reduce vulnerability to reliability events are not widely available. Limited market research is available on annual sales of some of these technologies. There have been some systematic efforts to assess the overall vulnerability of customers to reliability events that focus on specific processes (e.g., cleanrooms) or equipment types (e.g., office equipment) that may be especially sensitive to these issues. For more information, please refer to Eto et al. 2001.

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[7] Another factor complicating assessment of infrastructure costs associated with outages is that most large outages are the result of natural events, such as major storms. In these situations, the infrastructure costs (e.g., emergency response, health/human safety) stemming from the loss of electric service are difficult to separate from the (typically, larger) costs associated with addressing the direct effects of the initiating event itself (e.g., storm damage, flooding, etc.). There have been very few instances, for example, where loss of life has been attributing uniquely to the loss of electric service.

3. Assessing Recent Estimates of the Economic Cost of Reliability Events

This section reviews and analyzes three recent and widely cited published estimates of the economic cost of power interruptions and power quality to U.S. electricity customers. In Section 3, we review how others have attempted to address the data and estimation issues identified in this section – e.g., to reconcile differing customer and customer class definitions, address inconsistencies in reporting of outage frequency that might result in omission of short-duration or natural-event outages, and to account for what outage costs are and are not included in reported data. Our analysis is based on the framework and discussion of data limitations described in the previous section. The three estimates are:

- Clemmensen (1993), which was cited extensively by EPRI and others throughout the 1990s
- Swaminathan and Sen (1998), a Sandia National Laboratory report developed for DOE
- Primen (2001), which was developed for EPRI and is currently the main source cited

3.1 Clemmensen's Estimate of $26 Billion per Year

Clemmensen (1993) provided the first-ever power-quality cost estimate of $26 billion for the U.S. manufacturing sector (Electric Power Research Institute 1993). This estimate was adopted by EPRI and subsequently widely cited throughout the 1990s. It is important to note that Clemmensen's estimate was for annual spending on *industrial equipment* to address *power-quality* problems; power-quality problems normally refer to a subset of reliability problems in which voltage drops (in some cases to zero) for a very short period of time, typically for only a few cycles or seconds. Clemmensen's estimate was used by others as a measure of the aggregate cost of *all* power interruption and power quality problems to the U.S. economy even though Clemmensen focused only on power quality and the manufacturing sector. Clemmensen's estimate was later cited by others as the primary basis for an even higher estimate of $50 billion for all power interruption and power quality costs in all sectors. This extrapolation was intended to take into account the effects of inflation since the time of Clemmensen's original work (Douglas 2000).[8]

Clemmensen estimated that 1.5 to three cents of every manufacturing sales dollar was being spent to correct power-quality problems. This estimate was based on consultations with power-quality colleagues and on work by business author Phillip B. Crosby who estimated that the expense of waste in manufacturing could reach as high as 15-25 percent of sales (Crosby 1979).[9] Using 1987 manufacturing sales of $853.6 billion and the top end of the estimated range of power-quality expenditures (three cents per dollar of sales), Clemmensen derived a total cost of $25.6 billion (which was rounded to $26 billion).

Based on the framework and discussion in Section 2 of this report, we offer four observations about Clemmensen's original estimate. For each point, we note the likelihood that the estimate

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[8] This sort of misuse when citing numerical analyses is an example of a larger problem further discussed in Koomey et al. (2002) that details the many examples of the misuse of numerical facts related to energy analysis issues (Koomey et al. 2002)

[9] This reference was provided by Jane (Clemmensen) Thornton in personal communication to Joe Eto on June 7, 2004.

tends to over- or under-estimate power interruption and power quality costs to the U.S.

1. Spending is used as a proxy for costs. From an economic perspective, this discrepancy is similar to the difference between marginal cost and marginal benefit, where spending is valued such that the last dollar spent is equivalent to the benefit from the last dollar of expenditure. That is, a rational consumer would spend no more on fixing a problem than the cost of the problem itself.[10] Bias is toward underestimating total power interruption and power quality costs.
2. Power quality is only a subset of reliability events that have economic impacts on customers; power quality does not normally include losses of power for periods longer than a few seconds. Bias is toward underestimating total costs.
3. The estimate is limited to the manufacturing sector.[11] Bias is toward underestimating total power interruption and power quality costs because the estimate does not include the costs from the commercial or residential sectors.
4. The estimated value of 1.5 to three cents of spending per dollar of manufacturing sales on power-quality equipment is undocumented. It was based only on experience and professional judgment. A recent survey of annual spending on power-quality equipment (by all sectors, not just manufacturing) reported $5 billion in sales (Clemmensen et al. 1999). This recent survey suggests that the figure used in the original extrapolation to develop the 1993 estimate was too high by a factor of about five; a more appropriate range might have been 0.3 to 0.6 cents of annual spending per manufacturing dollar of sales on power-quality equipment.

3.2 Swaminathan and Sen's Estimate of $150 Billion per Year

In a Sandia National Laboratory report, Swaminathan and Sen (1998) estimate U.S. power interruption costs at $150 billion per year. The authors obtained this estimate by extrapolating the results of a 1992 Duke Power outage cost survey to the entire U.S. based on total industrial electricity sales.

Using the framework and discussion in Section 2 of this paper, we offer the following three observations about Swaminathan and Sen's estimate. For each point, we note the likelihood that the estimate tends to over- or underestimate U.S. power interruption costs.

1. The extrapolation focused on only the industrial sector. The likelihood is that this results in underestimation of total power interruption costs because the estimate does not include the costs from the commercial or residential sectors.
2. The extrapolation assumes that the U.S. industrial sector at large experiences the same number and type of reliability events and the same costs resulting from these events as the

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[10] However, spending may have been intended to address multiple concerns simultaneously, such as productivity improvements in addition to power-quality solutions, so the portion of the expenditure that can be allocated to address power-quality problems may be less than the total spent.

[11] Interestingly, Clemmensen's original paper also estimated commercial power-quality costs at $13.3 billion, but this figure was never added to the $25.6 billion estimate for manufacturing facilities. The commercial-sector estimate assumed a cost of $20.24/kWh unserved (for a 15-minute outage, from a survey conducted in 1974), and an annual probability of 0.001 for a 15-minute interruption for 1987 commercial electricity use of 658 billion kWh.

population of industrial customers in the Duke Power service territory. A recent study of customer outage costs found that there are statistically significant differences in the costs experienced by industrial customers both among different industrial sectors and among different geographic regions (Lawton et al. 2003). Given the available data, we cannot determine whether Swaminathan and Sen's assumption results in likely under- or overestimation of total power outage costs.

3. Appendix A presents data on the duration and frequency of outages from utility service territories across the U.S. These reliability index data confirm that outage characteristics are not uniform across the country. Anecdotal evidence suggests that the Southeastern portion of the U.S., where Duke Power is located, is subject to more frequent lightning storms than other parts of the U.S., which increases the likelihood that customers in Duke Power's area would experience larger numbers of lightning-related reliability events than customers in other areas of the country. If this were true, Swaminathan and Sen's use of data from Duke Power's service area would likely result in overestimation of the number of outages and therefore the costs that would be likely to apply to the country as a whole. However, based on the information available, we cannot determine conclusively what type of regional-specific bias is introduced by the use of Duke Power service territory data.

3.3 Primen's Estimate of $119 Billion per Year

In 2001, EPRI commissioned and published a report from Primen. This report is the first systematic effort to estimate the national economic cost of power interruptions including power quality (Primen 2001). Building on insights gained from an earlier EPRI-commissioned literature review (Eto et al. 2001), the Primen study addressed several shortcomings of earlier estimates:

- The Primen study was explicitly designed to develop a national estimate; it was not an extrapolation from a smaller geographically confined area, as in the Swaminathan and Sen study.
- It treated power quality along with other reliability events, such as outages, in a consistent manner.
- It was developed, initially, using statistical sampling techniques from a defined population.

The Primen study surveyed 985 firms drawn from three populations of businesses: "digital economy," "continuous process manufacturing," and "fabrication and essential services." Each firm surveyed was asked to provide cost estimates for several distinct power outage scenarios (e.g., loss of power for one second, three minutes, one hour, etc.), all on summer weekday afternoons, plus an estimate of the annual cost of power-quality events. The results from the surveys were weighted to develop estimates for the three surveyed groups. Then, the results were extrapolated to represent an estimate for the nation by assuming that the costs experienced by the non-surveyed population were 25 to 50 percent of the costs experienced by the surveyed populations. Table 2 summarizes results from the Primen study.

Table 2. Summary of Primen Study Results

	Surveyed Populations	Non-surveyed Populations	Total
Power Outages	$46 billion	$58-118 billion	$104-164 billion
Power Quality	$7 billion	$8-17 billion	$15-24 billion
Total	$53 billion	$66-135 billion	$119-188 billion

Based on the framework and discussion in Section 2, we offer the following observations about the Primen estimate. For each point, we note the likelihood that total U.S. power interruption and power quality costs were under- or overestimated.

1. The Primen study assumes that outage costs experienced on summer weekday afternoons can be used to assess outage costs experienced at other times during the year. Most surveys of customer outage costs have found very large differences in costs depending on the time of day, week, and season during which an outage occurs (Eto et al. 2001). Costs associated with outages on summer weekday afternoon are typically the highest because of high electricity usage during this time, largely because virtually all businesses are in full operation and electricity use for space conditioning is at a maximum. Unreliability is not confined to summer afternoons and the use of summer weekday outage cost estimates likely results in overestimation of total power interruption and power quality costs.
2. The Primen study assumes that outage costs experienced by the non-surveyed population are 25 to 50 percent of the costs experienced by surveyed firms. Surveys of outage costs that have controlled for differences in firms have found that costs can differ by a factor of ten to one or more among firms (Eto et al. 2001).[12] The populations surveyed were explicitly selected because they are known to be sectors that are especially vulnerable to electricity reliability events. The resulting bias cannot be established conclusively but likely results in overestimation of total power outage costs.
3. The study did not consider the costs of power interruptions and power quality to residential customers. The result of this omission is likely an underestimation of total power interruption and power quality costs.

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[12] The Eto et al. 2001 study also explored sensitivity to outage costs as a function of process (e.g., cleanrooms), which suggests that it also is important to consider variation in sensitivity within NAICS codes.

4. Deriving a New Estimate of the Economic Cost of Power Interruptions to U.S. Electricity Consumers

This section presents a new estimate of the economic cost of power interruptions to U.S. electricity consumers using the framework introduced in Section 2, not including power quality. Our estimate is based on a review of the best data available in the public domain. Table 3 summarizes the data we used to develop a new estimate of the economic cost of power interruptions to U.S. electricity consumers. As described earlier, the best data available remain subject to important limitations. Accordingly, we identify and explore some of these uncertainties in Section 5.

Table 3. The Data Used to Develop a National Estimate of the Cost of Power Interruptions

Customers	Customer classes (residential, commercial, and industrial) and populations are defined and estimated using data from the U.S. Energy Information Administration for 10 regions of the U.S. (with separate treatment for California.)
Duration and Frequency of Reliability Events	Trimmed means for SAIDI, SAIFI, and MAIFI data collected through an on-line search (N = 162, 162, and 52, respectively.)[13] Within each region, all customers are assumed to experience the same duration and frequency of reliability events because current reporting of SAIDI, SAIFI, and MAIFI does not distinguish between customer classes. Information on power quality events is not included.
Cost of Reliability Events	Customer damage functions for three customer revenue classes (residential, small and medium C&I, and large C&I) are taken from a recent national study of utility outage cost surveys conducted by Population Research Systems and LBNL (Lawton et al. 2003). In total, over 60,000 survey responses from 24 past utility studies were combined to support the estimation of customer damage functions. Customer damage functions express the cost of an outage as a function of outage duration, season, time of day, annual electricity use, and depending on the customer class, household income or number of employees.
Vulnerability to Reliability Events	Vulnerability is not used in this study due to the absence of reliable information on customer investments in reliability-enhancing technologies (e.g., back-up generators and energy storage) and related measures.

4.1 Customers by Customer Class and Region

This sub-section explains how customers are defined in our analysis and discusses the assumptions made in partitioning the population of customers into regions.

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[13] The trimmed mean is a simple data analysis approach designed to remove outliers within a set of observations by deleting a specified percentage of the highest and lowest data points and recalculating the mean of the reduced population of data points.

This study uses residential, commercial, and industrial electricity demand sectors to describe the customer classes. Data on customer population are taken directly from EIA's *Electric Sales and Revenue* publication (Energy Information Administration 2001b):

- The **residential** energy-consuming sector consists of living quarters for private households.
- The **commercial** energy-consuming sector consists of facilities that provide services and includes the equipment of: businesses; federal, state, and local governments; and other private and public organizations, such as religious, social, or fraternal groups, including institutional living quarters and sewage-treatment facilities.
- The **industrial** energy-consuming sector consists of all facilities and equipment used for producing or assembling goods. This sector encompasses: manufacturing [North American Industry Classification System (NAICS) codes 31-33]; agriculture, forestry, and hunting (NAICS code 11); mining, including oil and gas extraction (NAICS code 21); natural gas distribution (NAICS code 2212); and construction (NAICS code 23). Our definition of this category differs from EIA's in that we also include electricity sales sold to/consumed by public street and highway lighting, public authorities, railroads and railways, and users classified as "Other" by EIA.

This study partitions the U.S. into regions so that we can represent variations in outage costs in different areas of the country. The regions correspond to U.S. Census Divisions as mapped by EIA with a slight variation in the Pacific region where we extract California and treat it as a separate region because this is where most of the Pacific region population resides. Figure 3 illustrates the regions used in our study.

The customer population data were taken from EIA's *Electric Sales and Revenue* publication (Energy Information Administration 2003b). The data are reported for year 2001 by state and by demand sector (residential, commercial, and industrial). Using a modified version of EIA's mapping of U.S. Census Division regions, Table 4 shows the number of customers in each region and each sector, including the percent of total by region and sector.

Table 4. Number of Customers by Region and Sector in 2001

	RESIDENTIAL	COMMERCIAL	INDUSTRIAL	ALL SECTORS	% of Total
U.S. ESTIMATE	114,317,707	14,939,895	1,582,573	130,840,175	
% of Total	(87%)	(11%)	(1%)		
BY REGION					
New England (1)	5,822,935	714,049	62,677	6,599,661	(5%)
Middle Atlantic (2)	15,045,495	2,127,033	103,713	17,276,241	(13%)
East North Central (3)	18,705,754	2,110,172	158,780	20,974,706	(16%)
West North Central (4)	8,287,837	1,139,609	170,937	9,598,383	(7%)
South Atlantic (5)	22,473,797	2,842,220	270,840	25,586,857	(20%)
East South Central (6)	7,356,975	1,135,507	78,545	8,571,027	(7%)
West South Central (7)	12,883,403	1,722,873	292,035	14,898,311	(11%)
Mountain (8)	7,368,280	1,001,310	212,842	8,582,432	(7%)
Pacific (9)	3,922,426	494,778	66,699	4,483,903	(3%)
California (10)	11,841,144	1,559,258	154,261	13,554,663	(10%)

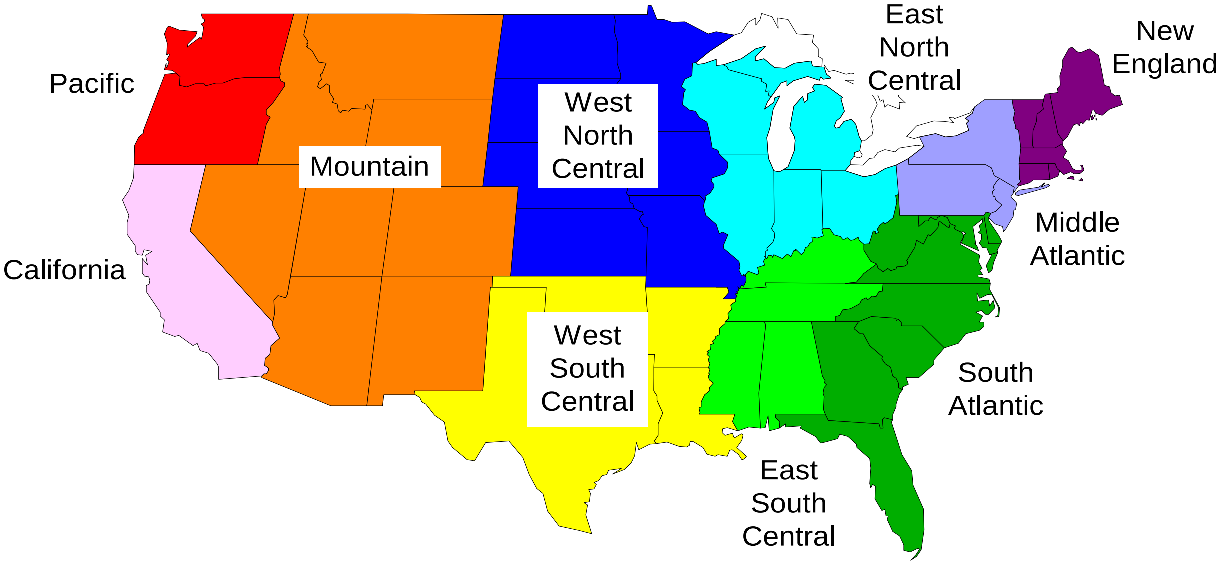

Figure 3. Map of Modified Census Division Regions

4.2 The Duration and Frequency of Reliability Events

Despite the existence of well-defined indices for a majority of reliability events, information on U.S. reliability events is not collected systematically or consistently. The National Regulatory Research Institute reports that only 23 of the 40 surveyed states require annual reporting of reliability statistics (National Regulatory Research Institute 2000). As a result, deriving reliability event data to represent all U.S. regions poses a challenge.

We conducted an on-line search to gather publicly available data on reliability events. We then reviewed the data and implemented a simple data analysis technique to eliminate outliers. Finally, we compared our findings to other published reports on the national duration and frequency of outages.

We obtained 181, 180, 56 observations, for 39, 38, and 9 independent sources of SAIDI, SAIFI, and MAIFI data, respectively, from our on-line search. Figures 4 and 5 present our findings as cross-tabulations. Appendix A contains the regional SAIDI, SAIFI, and MAIFI data we collected.

To address bias introduced by extreme outliers, a simple data analysis procedure called "trimmed means" was used to remove the highest and lowest five percent of observations and then calculate the means of the resulting, reduced population of observations (Mosteller and Tukey 1977). Table 5 compares the means and standard deviations for SAIDI, SAIFI, and MAIFI calculated from both the total set of observations and the "trimmed" set of observations.

Table 5 shows the variation of the means and standard deviations with and without the trimming process. Here we can see that removing the highest and lowest five percent of data points in each data set has a noticeable effect on the resulting average duration of outages. By removing the outliers, the SAIDI average decreases from 122 minutes to 106 minutes, while the SAIFI and MAIFI means change very little. More interesting is the significant reduction in the magnitude of the standard deviation with these three indices. The standard deviation for both SAIDI and SAIFI are roughly halved when ten percent of the outlying data points are removed and is reduced by more than ten percent for MAIFI. This suggests that trimming the highest and lowest five percent of data points helps to significantly improve the robustness of our means.

Table 5. Summary of Trimmed Mean and Total Mean Reliability Event Data

	SAIDI	SAIFI	MAIFI
Trimmed Mean (Standard Deviation)	106 min. (54 min.)	1.2 (0.5)	4.3 (3.6)
Total Mean (Standard Deviation)	122 min. (115 min.)	1.3 (1.0)	4.6 (4.1)

Figures 4 and 5 also include the trimmed outliers to illustrate how much the data can vary and skew the estimated mean. Trimming five percent of the highest and lowest data points provides a more representative average value for these indices by removing the influence of extreme events. For SAIDI, the trimmed mean is 106 minutes as shown by the line, with a standard deviation of 54 minutes and for SAIFI, the trimmed mean is drawn in at 1.2 with a standard deviation of 0.5.

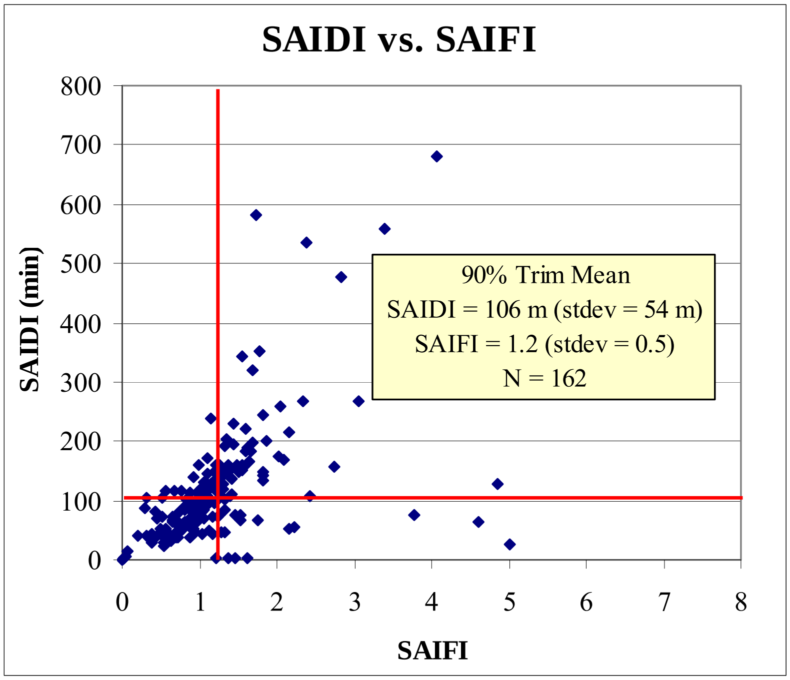

Figure 4. Scatter Plot of SAIDI vs. SAIFI

Figure 5 shows a cross-tabulation of SAIFI vs. MAIFI to identify whether the frequency of sustained interruptions is at all related to the frequency of momentary interruptions. Interestingly, there does not seem to be any visible patterns of increasing/decreasing MAIFI with changes in SAIFI; the occurrence of sustained outages does not appear to have any noticeable impact on the number of momentary outages. The trimmed mean is 4.3 as shown by the line, with a standard deviation of 3.6 based on reducing the number of data points from 56 to 52.[14]

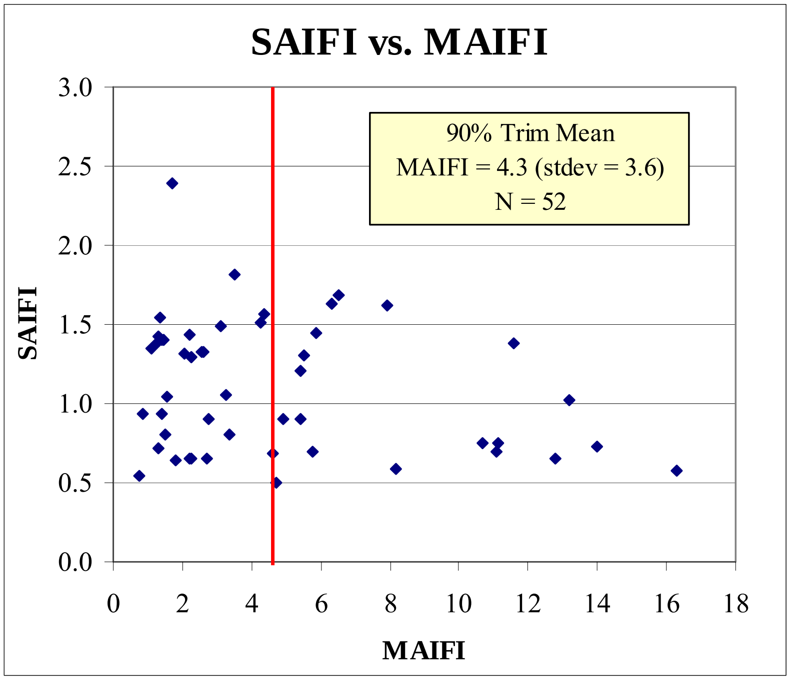

Figure 5. Scatter Plot of SAIFI vs. MAIFI

Several studies have also examined national statistics on SAIDI, SAIFI, and MAIFI. Table 6 compares the findings from these studies to the trimmed means used in our analysis. The trimmed means of 106 minutes, 1.2 and 4.3 for SAIDI, SAIFI, and MAIFI, respectively, are very similar to the estimates reported from external studies shown in Table 6. Hence, our trimmed means are reasonable estimates for calculating the cost of power interruptions to U.S. electricity customers.

Table 6. Summary of U.S. Reliability Event Estimates by External Studies

	SAIFI	**SAIDI**	**MAIFI**
EPRI Report[1]	1.1	107	
IEEE 1995 Survey[2]	1.3	120	5.5
EEI Annual Report[3]			
1998	1.2	118	5.4
1999	1.4	101	11.6

[1] Source: (Electric Power Research Institute 2003)
[2] Source: IEEE 1995 Survey (http://resourceinsight.com/work/naruc_pbr_97.pdf)
[3] Source: Power Sources Manufacturer's Association (http://www.psma.com/HTML/newsletter/Q2_2001/page11.html)

Given the disaggregated framework we have established for evaluating the aggregate cost of power interruptions to U.S. electricity customers, it would be highly desirable to utilize distinct

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[14] This figure does not show the SAIFI trimmed mean in this figure because of the reduced number of points used to accommodate the MAIFI data.

SAIDI and SAIFI values for each customer class. Unfortunately, available literature does not provide reliable information disaggregated in this manner. For the purposes of this evaluation we have assumed uniform application of SAIDI and SAIFI values to all customer classes. Anecdotal evidence suggests that large customers experience higher levels of reliability; hence, our assumption likely exerts an upward bias on our estimate of the cost of power outages. This presumption is further examined in Section 5 when we explore varying reliability event assumptions by customer class.

We did not find similarly comprehensive data on the frequency of power quality events and so elected not to include the costs of power quality events in our initial estimate – a task we leave to future efforts.

4.3 The Cost of Reliability Events

A major challenge for estimating the cost of power interruptions and power quality is the limited information available on the cost of reliability events. We addressed this limitation by relying on findings from a recent study that combined and jointly analyzed the large body of work conducted by utilities to examine the cost of power interruptions to their customers.

Our cost analysis incorporates findings from a recent study published by Population Research Systems (PRS), LLC and Lawrence Berkeley National Laboratory (Lawton et al. 2003), which we will refer to as the "PRS Study." The PRS study is a meta-analysis of 24 independent customer surveys conducted by eight electric utility companies in the U.S. over the past 13 years. Multiple regression analysis techniques were used to combine the survey data into equations that express outage costs per customer as a function of multiple, independent parameters. For more information on this study, please see the text box.

The PRS study developed analytic expressions, called customer damage functions, that express customer outage costs as a function of customer class, region, event duration, and other descriptive variables based on a data set of survey responses from more than 2,000 large C&I, 5,200 small and medium C&I, and 11,000 residential customers. The cost-per-outage-per-customer data were normalized and reported in year-2002 Consumer-Price-Index (CPI)-weighted dollars.

In order to utilize the information developed in the PRS study, we had to reconcile two aspects of the Tobit equations with the data available for our estimate. First, we had to develop a mapping between the regions used in the PRS study with the demographic and firmographic data available for our estimate. Second, we had to develop a consistent method for using the time of day/week and seasonal variables with the information we had on outage frequency, which does not include information on the time when reliability events occur.

4.3.1 Accounting for Regional Variation in Reliability Event Costs

In order to estimate the cost of power interruptions to U.S. electricity customers, we needed to reconcile differences in how the regions were defined in the Tobit regression equations with the collected data we needed in order to estimate this per-outage cost. This sub-section describes how we mapped the regions among these demographic and firmographic data.

Regional variations in outage costs are addressed in our analysis (as described below). We had to determine regional costs for California because we separated California from the Pacific Census Division. To represent California costs, we used energy consumption and worker and establishment population statistics from the Pacific region when California data could not be found. The residential-sector information necessary for the Tobit regression equation was available for California.

Industrial sector annual energy use per worker was available for the four regions that are traditionally reported for the manufacturing sector (West, Midwest, Northeast, and South). The value reported for each manufacturing region was used for all Census Divisions that fall within that manufacturing region. For example, the industrial sector annual energy consumption per worker for the New England and Middle Atlantic Census Divisions is the value for the Northeast-manufacturing region, which includes both of these Census Divisions. Figure 6 shows the relationship between Census Divisions and manufacturing regions.

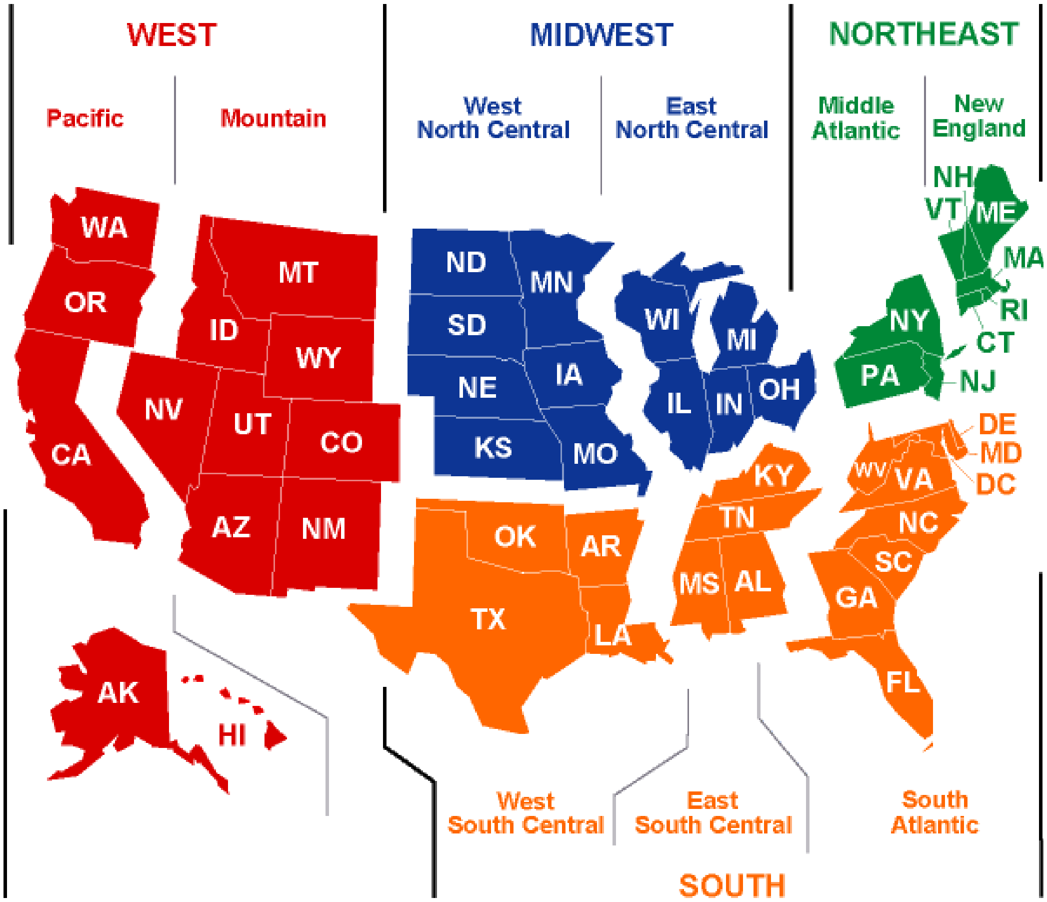

Figure 6. Map Relating U.S. Manufacturing Regions to Census Divisions