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Improving the estimated cost of sustained power interruptions to electricity customers

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ABSTRACT

Electricity reliability and resiliency have become a topic of heightened interest in recent years in the United States. As utilities, regulators, and policymakers determine how to achieve optimal levels of electricity reliability while considering how best to prepare for future disruptions in power, the related issue of how much it costs when customers lose power remains a largely unanswered question. In 2006, Lawrence Berkeley National Laboratory developed an end-use based framework that estimates the cost of power interruptions in the U.S that has served as a foundational paper using the best available, yet far from perfect, information at that time. Since then, an abundance of work has been done to improve the quality and availability of information that now allow us to make a much more robust assessment of the cost of power interruptions to U.S. customers. In this work, we find that the total U.S. cost of sustained power interruptions is $44 billion per year (2015-$) –25% more than the $26 billion per year in 2002-$ (or $35 billion per year in 2015-$) estimated in our 2006 study.

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1. Introduction

Since we completed our first paper on the total cost of power interruptions in 2006 [1], interest in electricity reliability and resiliency in the United States has increased dramatically. The White House issued a *National Electric Grid Security and Resilience Action Plan* that describes activities the country is taking at the federal level to strengthen the security and reliability of the power system [2,2a]. In 2017, the Department of Energy issued a *Staff Report to the Secretary on Electricity Markets and Reliability* that highlights the importance of future investments in the power grid to ensure a reliable and resilient grid. A report issued by the National Academy of Science titled *Enhancing the Resilience of the Nation's Electricity System* in 2017 presents a series of overarching and specific recommendations intended to increase the resilience of the U.S. power system from events that result in outages that last several days, weeks or even months [3]. Among them, large-scale blackouts as well as widespread and long-duration interruptions resulting from catastrophic weather events, have highlighted the question of what is required and how much it will cost to maintain or improve electricity reliability, bringing it to the forefront of discussions among utilities, their customers, state utility regulators, and policy makers.

Recent reports have highlighted severe weather as the leading cause of power outages in the United States [4,5]. With more frequent severe or catastrophic U.S. weather events such as Hurricane Harvey, Irma, or Maria occurring, many electricity customers are focused on the issue of electricity reliability. Some customers are willing to pay to prevent unwanted power interruptions, and others wonder why utilities are not more reliable. Purchases of diesel backup generators have increased, both in the residential and commercial/industrial sectors [6,7]. Utilities are spending more on vegetation management and storm hardening, including tree trimming and upgrades to poles and fixtures. One of the key causes of the 2003 blackout was insufficient tree trimming [8–10]. Some utilities are considering whether there is economic justification for undergrounding their distribution lines to reduce exposure to environmental hazards [11,12].

These recent changes coupled with the ability to significantly improve the representation and quality of the input components of our previous cost estimate gave us reason to revisit our work of more than a decade ago. In this study we wanted to determine whether any of these recent changes were impacting the economic cost of power interruptions in the United States.

This paper is structured as follows: Section 2 describes the improvements in data now available to support an updated estimate

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Acronyms

CAIDI	customer average interruption duration index
CDF	customer damage function
EIA	United States Energy Information Administration
IEEE	Institute of Electrical and Electronics Engineers
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index

of the national cost of power interruptions; Section 3 highlights studies conducted since our 2006 literature review; Section 4 reviews the framework that we developed in 2006 and the updated assumptions in the current study; Section 5 updates our 2006 base-case estimate of a $26 billion (2002-$) cost attributable to sustained power interruptions in the United States; Section 6 explores a set of sensitivity cases using a step-by-step method that updates one element of the estimate at a time, with a focus on sustained interruptions, including Monte Carlo uncertainty analysis; and Section 7 summarizes our findings including some concluding remarks.

2. Background

In 2006, Lawrence Berkeley National Laboratory (Berkeley Lab) developed an end-use-based framework for estimating the costs of power interruptions to U.S. electricity customers [1]. Our work found that the total cost of sustained power interruptions was $26 billion (2002-$).[1] This estimate considered all electricity customers in the residential, commercial, and industrial sectors across all U.S. census regions. Note that our 2006 study considered both sustained interruptions as well as momentary, or interruptions lasting less than 5 min. With a better understanding of the challenges utilities still face in their ability to adequately monitor momentary interruptions with the current technologies deployed, we have since determined that the estimated cost of momentary interruptions was too speculative to include in the current work. Our 2006 study acknowledged that there was significant uncertainty in the publicly available information at that time and showed that using better information could either lower our estimate by a factor of almost 4 or increase it by a factor of almost 2 when decreasing or increasing the average duration and frequency of power interruptions by one standard deviation, respectively.

In just the last decade, Berkeley Lab research has expanded the understanding and representation of reliability information in the United States. Expanding on pioneering efforts by the Institute of Electrical and Electronics Engineers (IEEE) Distribution Reliability Working Group and the National Association of Regulatory Utility Commissioners to develop a consistent approach for reporting reliability information, Berkeley Lab in 2008 examined current practices for collecting and reporting electricity reliability information in the United States [13].

When we prepared our first report on reliability trends in 2012, we studied the portion of reliability metrics reported using a voluntary standard, IEEE 1366 Standard, to define major events and determined that this information was difficult to find in the public domain [14]. IEEE 1366 Standard is a voluntary standard that articulates a consistent set of definitions and procedures for measuring and reporting distribution reliability information, including major events. Berkeley Lab has since worked with the United States Department of Energy and the Energy Information Administration (EIA) to include reporting of reliability metric information as part of EIA Form 861, with a separate section for entities that use the IEEE 1366 Standard. EIA Form 861 requires under Federal law that electric power industry entities annually report information on the status of generation, transmission, and distribution as a way of assessing the state of the U.S. electric power industry.

In 2015, the Department of Energy commissioned Nexant to update the customer damage functions (CDFs) that form the backbone of the online Interruption Cost Estimate calculation tool. This update entailed including additional utility customer surveys in the tool and improving the parsimony of the statistical regressions. Additionally, in 2015 Berkeley Lab commissioned a report to evaluate the current inventory of back-up generators that customers purchase to protect against the impacts of power interruptions. Berkeley Lab also issued a 2016 update of our 2012 assessment of electricity reliability trends. This update found that reliability is worsening, especially when major events are included, and that this worsening trend is likely a result of an increase in severe weather events [5].

We applied this extensive research on electricity reliability over the past decade to the current interruption-cost update. We are now able to use a more sophisticated approach for estimating the cost of power interruptions; that is, we can now account for the uncertainty of some of the input values using Monte Carlo simulation. Given the nature of the input parameters to our estimation framework, it makes sense to construct the results as a range of possible outcomes and their associated probabilities of occurrence. The outcomes reflect the most likely estimate based on the best available data, along with less likely and even extreme possible estimates that could result from various circumstances. Structuring the results in this way allows us to use a likely range of values instead of relying on a single value. Given the uncertainty in the input parameters, this presentation of results increases their usefulness for decision makers assessing electricity service reliability.

3. Recent studies

Since our 2006 report was released, some studies have focused on the issue of severe weather impacts. We discuss those studies briefly here and summarize their highlights in Table 1. Although none of these studies claim to comprehensively represent all types of interruptions or all electricity customers, they contribute to our understanding of outages and their costs are symbolic of the recent focus on the influence of severe weather on the cost of power interruptions.

A 2012 U.S. congressional report summarizes results from other studies and, based on this literature review, estimates that storm-related interruptions in the United States cost between $20 billion and $55 billion annually. That report draws from a Primen 2001 study [15] that we discussed in our 2006 report and extrapolates to derive a weather-focused estimate. The congressional report also cites our 2006 study and presents the base-case estimate for sustained interruptions ($26 billion), noting this estimate includes both weather and non-weather causes [16].

A 2013 White House report prepared by the President's Council of Economic Advisors and the United States Department of Energy also focuses on severe weather. The White House report states that power interruptions due to severe weather between 2003 and 2012 cost the U.S. economy an average of $18 billion to $33 billion annually. This study asserts that severe weather is the leading cause of power interruptions and that this pattern is likely to increase

[1] Sustained interruptions are interruptions of power lasting more than 5 min. We do not estimate a cost to customers from momentary interruptions, which are interruptions of power lasting 5 min or less.

Table 1
Summary of recent studies on the cost of power outages and comparison to the current Berkeley Lab study.

Name of Study	Author and Date	Notable Highlight	How Berkeley Lab Study Differs
Weather-Related Power Outages and Electric System Resiliency	Richard J. Campbell (Congressional Report) August 2012	• Summarizes external studies stating storm-related outages cost the U.S. an average $25–$55 billion annually • Focuses only on seasonal storms • Includes only sustained interruptions • Reference to studies done 10+years ago	Considers all sustained interruptions, not just those from storms Uses updated information to derive a year-2015 estimate
Economic Benefits of Increasing Electric Grid Resilience to Weather Outages	Executive Office of the President (White House Report) August 2013	• Estimates that U.S. weather-related costs average $18–$33 billion annually • Notes that during significant weather years, the above estimate could increase to $75 billion • Uses 2009 Sullivan et al. value-of-service data (28 customer surveys by 10 major utilities between 1989 and 2005), which do not include long-duration outages lasting >8 h, yet applies this CDF to storms lasting up to 20 days • Focuses on 14 major storms • Evaluates years 2003–2012 • Uses Form DOE/OE-417 outage distribution data	Uses 2015 Nexant work with updated CDFs (34 customer surveys by 10 major utilities between 1989 and 2012) Focuses on year 2015 Considers all sustained interruptions1, not just those from weather events Uses sub-hourly data to assess distribution of interruption durations
A Huge Distribution Opportunity	Paul J. Feldman February 2015	• Finds that $112 billion in costs of outages is roughly one-third of $364 billion that U.S. customers pay for electricity service	

because of climate change, resulting in costs that could reach up to $75 billion during significant weather years. This report uses 2009 value-of-service data from Sullivan et al. (2009) and the Interruption Cost Estimator tool to estimate the cost of 14 severe storms between 2003 and 2012 [17]. Focusing on just these severe weather events, the White House study gives a range of estimated costs of power interruptions in each year. One notable drawback to this approach is that the data used in the Interruption Cost Estimator calculations do not include large-scale interruptions, so that study incorrectly applies the cost that would have been estimated for these severe weather occurrences [4].

In 2015, an article in Electricity Policy by Paul Feldman of the Midwest Independent System Operator highlighted the need for electricity distribution system improvements [18]. With nearly $364 billion in reported revenue from sales of electricity to U.S. customers in 2012, Feldman scales up our $79 billion estimate of power-interruption costs from 2006 to $112 billion at 2013 consumption levels and asserts that this dollar amount represents nearly one-third of the total that customers pay for service. Feldman's article is a plea to state regulators and policy makers to invest in the distribution system to reduce these costs [18].

Table 1 highlights what we consider to be the notable differences among these three reports and identifies how our current study compares to these reports.

4. The Framework for Assessing the Cost of Power Interruptions

The framework presented in the 2006 study consisted of a simple mathematical formula that is expressed as follows:

$$\text{Cost of Power Interruptions (COPI)} = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{i,j} \times E_{i,j} \times O_{i,j} \times V_{i,j} \quad (1)$$

where,

m = the number of customers in each customer class
n = the number of regions
i, j = indices for customer class and region, respectively
C = total number of electricity customers in customer class i for region j
E = the frequency of sustained power interruption events in one year for each region and customer class sector
O = the cost per interruption as a function of interruption duration by customer class for each region
V = vulnerability factor

This study applies the framework using both updated data and information as well as an improved method of assessing the uncertainty we find in the dependent parameters used in this expression.

4.1. Number of customers (C)

As in our 2006 study, the customer count data for year 2015 was taken from EIA Form 861 [19]. Many of the input data used in this analysis are provided by U.S. Census region, as shown in Fig. 1. Table 2 shows the number of customers by census region and

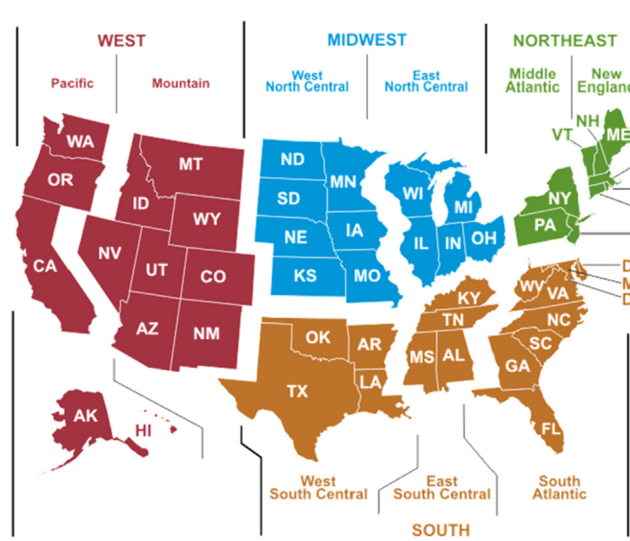

Fig. 1. Map of U.S. Census regions.

Table 2
Number of customers by sector and region, year 2015 (and total percentage change from year 2001), shown in millions of customers.

Census Division	Residential	Commercial	Industrial	Total
New England	6.3	0.9	0.0	7.2
Middle Atlantic	15.9	2.3	0.0	18.2
East North Central	19.8	2.5	0.1	22.3
West North Central	9.3	1.4	0.1	10.8
South Atlantic	26.8	3.7	0.1	30.5
East South Central	8.2	1.4	0.0	9.6
West South Central	15.4	2.2	0.2	17.8
Mountain	9.4	1.4	0.1	10.9
Pacific	18.7	2.4	0.2	21.3
TOTAL	**129.8 (13.6%)**	**18.0 (20.4%)**	**0.8 (-47.2%)**	**148.6 (13.6%)**

customer demand sector, as well as the percentage change from the year 2001, the year of data for our previous study, to the year 2015.

The vast majority (87%) of total U.S. electricity customers are residential with the remaining 13% from the commercial or industrial sectors. Yet, as we discuss later, the cost of power interruptions is driven by costs in the commercial and industrial sectors. This fact highlights the need to accurately represent interruptions by customer class, an area of focus for future research.

Overall, the number of electricity customers increased by more than 13% from year 2001 (the year used in our 2006 study) to 2015. However, the total number of customers in the industrial sector is roughly half the number we used in the 2006 study. In the 2006 study we assumed that customers defined in EIA's "Other" category were part of the industrial sector. According to EIA, beginning in 2003, the "Other" category was eliminated and, among other changes, the street and building lighting customers in the "Other" category were assigned to the commercial sector, and agricultural and irrigation sales were assigned to the industrial sector. This change results in a much smaller number of industrial customers in the current study (0.8 million customers) compared to the number in the 2006 study (1.6 million customers). This change has a significant impact on the estimated cost of power interruptions because the interruption costs in the industrial sector are much higher than those in the residential and commercial sectors. Our analysis documents the incremental effect of this definition change on the estimated cost of power interruptions, as explained in Section 6.

4.2. Reliability data

4.2.1. Duration of sustained interruptions, SAIDI

A key input to our framework's outage-cost component is the duration of each customer interruption, which is represented at a high level in this study using SAIDI. In our 2006 study, we used an average SAIDI based on a small convenience sample of utilities taken from public sources. Our current study is able to draw from a much larger pool of utilities and to represent the likely mix of individual outage durations rather than using a single average value. [2]

Beginning in year 2014, EIA began collecting reliability data from utilities (for performance year 2013) as part of EIA Form 861 [19]. The reliability data collected represent more than 1000 investor-owned utilities, cooperatives, and municipalities across the United States. In this work, we only consider the subset of utilities that reported reliability information including major events. We also filtered to include only those utilities who reported this information using IEEE Standard 1366 as this standard ensures that we are using data that are reported in a consistent way.

In the current study, we use the data from the large number of entities reporting via EIA Form 861 to estimate the year 2013–2015 weighted average SAIDI. We considered a subset of 434 utilities that reported their reliability information using the IEEE Standard 1366, which as we mentioned earlier represents is a voluntary standard designed to report electricity reliability in a consistent manner. From these data we calculated the customer-weighted averages for each of the nine census regions, as shown in Table 3. This approach is a dramatic improvement over the single average SAIDI used in our 2006 study based on a rudimentary online web search not specific to each U.S. state or region. The current study collected data from state regulatory entities or from utilities directly and benefits from more widespread data reporting practices over this time period. In all regions, the average SAIDI used in the current study is higher than the average SAIDI of 106 min that we used for all regions in the 2006 study.

4.2.2. Frequency of sustained interruptions, SAIFI

To reflect the average number of sustained power interruptions experienced by all U.S. utility customers, we also used EIA Form 861 to derive SAIFI [19]. As with SAIDI, this is a dramatic improvement over how SAIFI was represented in our 2006 study where we applied the same single average SAIFI value to all regions based on publicly available information gathered at the time that was not represented for each U.S. region or as widely reported (see Table 4).

4.3. Cost per outage (O)

Accurate individual outage costs are key to estimating the cost of power interruptions in our framework. Studies by Refs. [20–25] have assessed various cost perspectives (i.e., customer, utility, regulatory) on maintaining electric reliability. These studies focus on customer surveys administered by utilities as a source for estimating costs of individual outages because these surveys account

Table 3
Average annual 2013–2015 customer-weighted interruption duration (SAIDI, including major events), by region.

Region	Customer-Weighted Average SAIDI	n
New England	275	13
Middle Atlantic	229	12
East North Central	281	78
West North Central	208	101
South Atlantic	233	76
East South Central	218	47
West South Central	220	38
Mountain	122	36
Pacific	149	33
U.S. Total	214	434

[2] The calculation of SAIDI (and SAIFI) aggregates individual interruptions. As such, it is misleading to interpret a SAIDI value as representing the average duration of interruptions, as this is represented by CAIDI. Instead, SAIDI represents the average amount of time, in total, that customers are, on average, without power.

Table 4
Average annual 2013–2015 customer-weighted frequency of power interruptions (SAIFI, including major events), by region.

Region	Customer-Weighted Average SAIFI	n
New England	2.1	13
Middle Atlantic	1.1	12
East North Central	1.2	78
West North Central	1.2	101
South Atlantic	1.7	76
East South Central	2.4	47
West South Central	1.7	38
Mountain	1.0	36
Pacific	1.0	33
U.S. Total	1.3	434

for differences in factors such as outage duration, time of day, customer type, and size. Utility customer surveys that represent the customer perspective on how they value power interruptions are used for this study because we believe these surveys are the best available source for these data. However, as Larsen (2016) points out, surveys conducted by utilities likely reflect an inherent bias that we hope to address in future research [12].

Our analysis relies on CDFs developed by Nexant in a 2015 study update that collected data from numerous customer utility surveys collected across the United States [26]. The CDFs provide costs per outage for each duration of interruption, by end-use sector, as a function of numerous utility characteristics .

Fig. 2 shows the costs per customer outage by census region used in the CDFs for residential, commercial, and industrial customers, and for individual interruptions of varying duration lasting up to 16 h [3] These costs consider the time of day and year as well as regional differences in electricity consumption.

Using EIA Form 861, Table 5 shows the average electricity consumption by census region and sector, as input to the CDFs to generate the outage costs [19]. The degree of variability by region directly reflects the variability we see in Fig. 2. In addition, the more variable electricity usage in the industrial sector is reflected in the greater variability of this sector's outage costs.

Our previous study of the cost of power interruptions assumed a fixed outage duration and associated cost. In the current study, we developed a parametric modeling technique based on real-time outage information from as many as 40 utilities across the United States. This approach uses a distribution to account for differences in the costs of various outage durations, which also accounts for the fact that outage durations are not uniformly distributed and that the relationship between cost and duration is nonlinear. We then applied these costs to the 2012 reliability information from Ref. [5].

Table 6 shows the estimated weighted average cost per sustained outage using annual electricity usage, annual partitioning of time of day and year, and the distribution of interruption durations. This table represents the average cost of a sustained outage by customer class and region considering the distribution of outage durations likely experienced in each U.S. region. Because we use a different approach to derive the sustained outage costs in the current study compared to the approach used in our 2006 study, it is difficult to make direct comparisons between the results from the two studies in this area. However, in general, the outage costs for sustained interruptions are higher in the current study as a result of the higher SAIDI values described earlier.

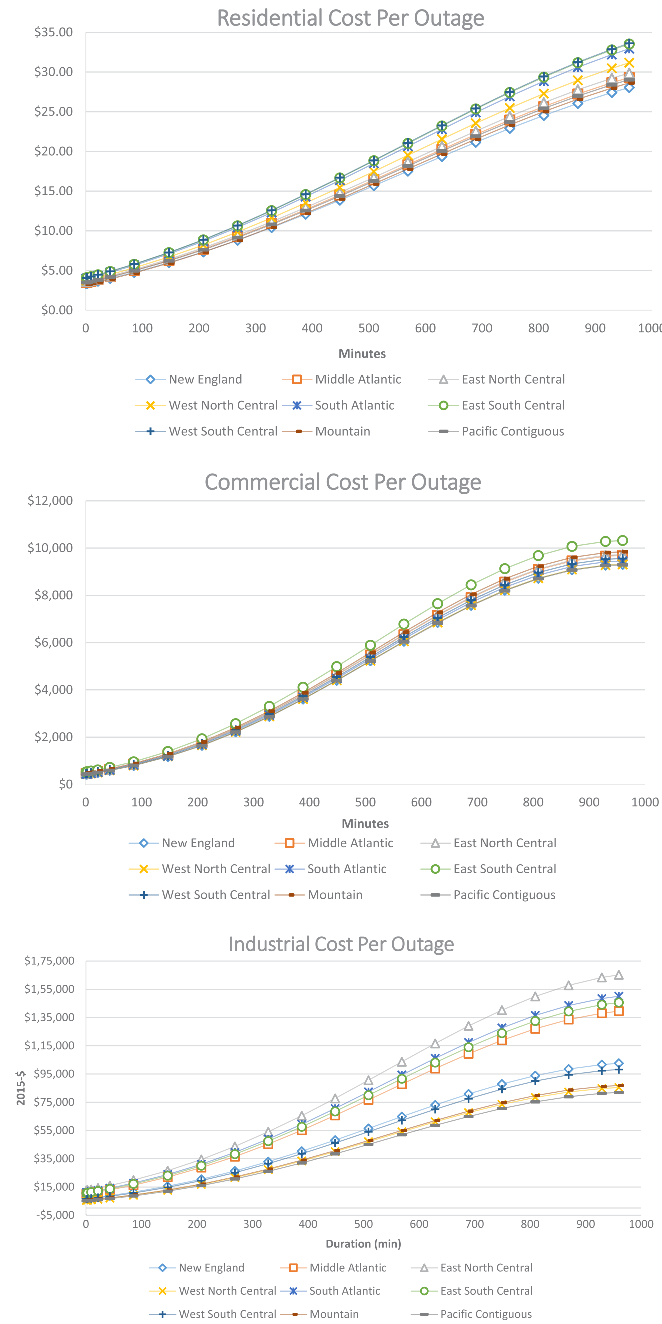

Fig. 2. The average cost per customer outage for residential (top), commercial (middle), and industrial (bottom) by region as a function of an interruption duration (minutes).

4.4. Vulnerability (V)

In our 2006 study, we were not able to consider the impact of customer-initiated purchases of equipment designed to protect against the impacts of power outages. Recent work has highlighted the importance of installing protective devices to shelter against possible interruptions, especially critical infrastructure [27].

In the current study, we considered the impacts of customer-installed backup generators designed to protect against the effects of electricity interruptions. Those customers that adopted this type of equipment were assumed to have no sustained power interruptions.

[3] We used an earlier study by Nexant to adjust the Interruption Cost Estimator tool-generated costs per interruption by commercial and industrial (C&I) classification to a commercial or industrial end-use sector [15].

Table 5
Average annual consumption per customer by region and sector, 2015.

Region	Average Annual Consumption (megawatt-hours)		
	Residential	Commercial	Industrial
New England	8	61	696
Middle Atlantic	8	71	1672
East North Central	9	75	3575
West North Central	11	72	736
South Atlantic	13	85	1789
East South Central	14	67	3832
West South Central	14	89	996
Mountain	10	69	898
Pacific Contiguous	8	72	456
Pacific Noncontiguous	7	53	2475
U.S. Total	11	76	1181

Table 6
Weighted average cost per customer for a sustained interruption, by sector and region (2015-$).

Weighted Outage Cost	Residential ($)	Commercial ($)	Industrial ($)
New England	9.9	2570	16,342
Middle Atlantic	7.7	1988	19,311
East North Central	9.4	2662	35,843
West North Central	8.2	1995	12,861
South Atlantic	10.4	2711	25,718
East South Central	8.9	1975	29,083
West South Central	8.8	2057	14,944
Mountain	5.9	1434	10,565
Pacific	6.1	1443	7449
U.S. Average	8.2	2009	16,259

Berkeley Lab enlisted a market research firm to estimate the market penetration of backup generator units by size/type, customer class, and region [6]. By determining what fraction of electricity customers use this equipment to protect against power interruptions, we were able to adjust the outage costs to represent the population of customers that have secondary resources designed to reduce their exposure to electricity disruptions.

Table 7 shows the share of total U.S. installed generating capacity that has installed a backup generator in each region. The percentages in these tables were directly applied to our framework. In general, this table shows that a relatively modest share of the total installed generating capacity has an alternating-current backup generator unit installed across regions and sectors of the U.S., especially in the residential sector and Mountain region. The installation of backup generator s in the industrial sector, however, makes up 18% of the total installed capacity in the U.S. The Mid-Atlantic region shows higher adoption rates, perhaps due to the increased vulnerability to hurricanes in this region.

Table 7
Share of total U.S. installed generating capacity of backup generators by region, 2014.

Region	Residential	Commercial	Industrial	Total
New England	1%	14%	14%	9%
Mid-Atlantic	19%	23%	52%	28%
East North Central	2%	14%	11%	9%
West North Central	1%	86%	12%	6%
South Atlantic	11%	19%	10%	13%
West South Central	1%	7%	18%	6%
East South Central	1%	7%	18%	6%
Mountain	1%	4%	15%	4%
Pacific	3%	18%	22%	13%
U.S. Total	5%	19%	18%	11%

Source: Frost and Sullivan 2015; 2015 Electric Power Annual.

5. Estimating the cost of sustained power interruptions

In this section, we present the updated U.S. cost of power interruptions based on the various data input updates described in Section 4. The effect of incrementally updating each input is discussed in Section 6, including consideration of uncertainty in our base case.

Fig. 3 shows that the updated cost of sustained power interruptions by sector totals $44 billion (2015-$), a 25% increase from the 2006 study result (when correcting for changes in dollar-year). When extrapolated to all U.S. electricity customers, the updated base-case estimate shows that the cost of power interruptions is driven by the higher estimated costs perceived by commercial and industrial customers. The increase from the 2006 study is primarily driven by a significant worsening of the regional reliability. A modest increase is also attributed to a steady increase in customer population over the years coupled with modest decreasing influences from the definitional changes between the commercial and industrial sectors. Use of the updated CDFs is also a contributing factor.

Fig. 3 shows that nearly 97% of the total is attributed to costs in either the commercial or industrial sector, with only 3% from the residential sector. As mentioned in Section 5, this is true despite the fact that nearly 90% of total customers across these three sectors are residential. This result reflects the much more costly consequences of losing power to commercial and industrial customers, despite the much smaller number of commercial and industrial (C&I) customers relative to the residential sector. These disparate costs experienced by different customer types underscore the need to better understand the reliability experiences of these different classes.

Fig. 4 shows the cost of sustained power interruptions by region and sector. The regional cost of power interruptions exhibits a similar pattern to what we found in the previous study, with higher costs in the South Atlantic and West South Central regions and lower costs in the New England, West North Central, and Mountain regions. This pattern is driven by the commercial and industrial population more than by any regional distinctions in the perceived costs of outages.

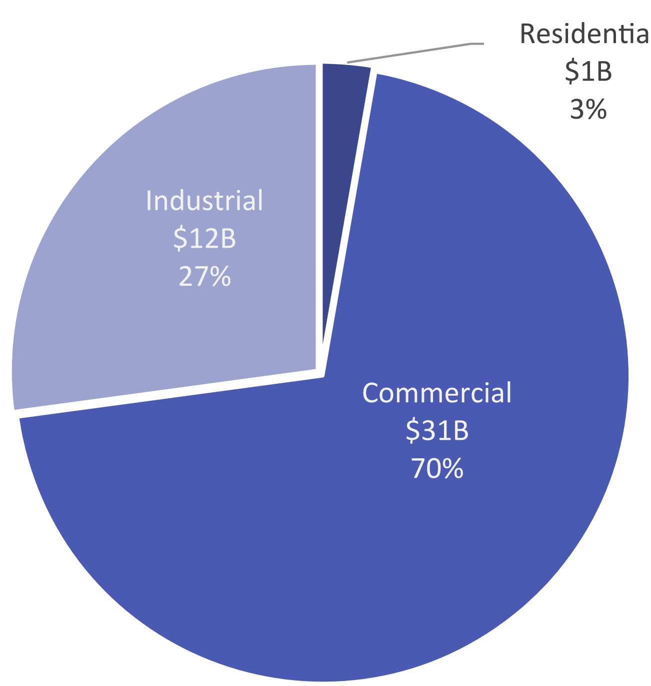

Fig. 3. Updated U.S. base-case cost of sustained power interruptions for all customers, by sector.

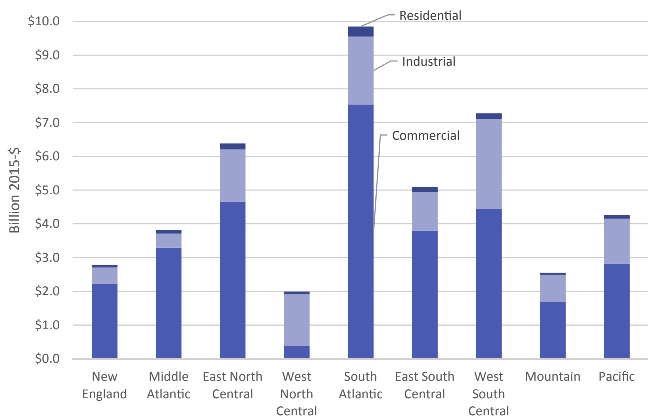

Fig. 4. Updated U.S. base-case cost of sustained power interruptions, by region and sector.

In the next section, we describe in detail the step-by-step changes that we made to our 2006 estimate in order to update the estimate of the cost of sustained power interruptions presented in this study.

6. A step-by-step approach for updating the 2006 study base-case estimate of the cost of sustained power interruptions

This section explains how each of the inputs we described in Section 4 affect the updated $44 billion (2015-$) cost of sustained power interruptions and how the accuracy of the current estimate has improved in relation to our first estimate from 2006. We describe how we carried out a series of step-by-step updates, applying new information, one variable or element at a time, to our 2006 estimate of $26 billion (2002-$), again with a focus on sustained interruptions. These step-by-step updates are shown in a series of cases (1, 2a–2c, 3a–3c, 4), starting with the 2006 study cost estimate as Case 1 for just sustained interruptions. The cases are described below:

- **Case 1** is our $26-billion (2002-$) base-case estimate of the U.S. cost of sustained power interruptions.
- **Case 2a** takes the 2006 study estimate (Case 1) and converts the total from 2002-$ to 2015-$ using the consumer price index, resulting in an estimate of $35 billion (2015 $).[4]
- **Case 2b** takes Case 2a and retroactively applies the reclassifications that EIA imposed in 2003 to estimate what the number of customers in the residential, commercial, and industrial sectors might have been in 2001 (the year from which we took customer count data in our 2006 study) using the subsequently revised EIA classifications. This step decreases the $35 billion cost of power interruptions from Case 2a to $31 billion (both in 2015-$).
- **Case 2c** takes the result of Case 2b and updates the customer count to the most recent 2015 values, keeping all else unchanged. The result increases the cost of power interruptions from the $31 billion value generated in Case 2b to $36 billion (2015-$).
- **Case 3a** builds on Case 2c, updating the CDFs developed by Nexant, which incorporated additional utility customer survey data and improved the regression approach over their earlier version. The resulting estimate of the U.S. cost of sustained power interruptions is $30 billion (2015-$), a 17% decrease from the value generated in Case 2c.
- **Case 3b** applies to Case 3a updated reliability information for SAIDI and SAIFI, not including consideration of vulnerability to power interruptions. Using the customer-weighted averages presented in the previous section, this step more than doubles the U.S. cost of sustained power interruptions to $75 billion (2015-$).
- **Case 3c** adds consideration of vulnerability to Case 3b, which results in an 18% reduction in the estimated U.S. cost of sustained power interruptions.
- **Case 4** takes the output of Case 3c and parses the aggregate SAIDI and SAIFI data into various interruption durations to consider the cost of different length outages and applies the Monte Carlo uncertainty analysis. This produces our updated base-case estimate of $44 billion (2015-$) for the cost of power interruptions in the United States.

Table 8 and Fig. 5 summarize the cases. Looking at what happened in each step reveals that the estimated cost of power interruptions declined as a result of updating the CDFs, decreased, and then increased when correcting for the reclassification of customer classes by EIA and accounting for changes from 2001 to 2015, decreased when accounting for those customers that take extra precautions to prevent power interruptions, and noticeably increased when applying updated reliability metric information, which is consistent with the trend of worsening reliability described in Ref. [5].

Fig. 5 shows the estimated cost of sustained power interruptions for each case by demand sector. In all cases, the commercial and industrial sectors represent 97%–98% of the total cost. As we saw in the 2006 study, although residential customers make up more than 87% of all electricity customers in the U. S., they account for only 2%–3% of the total U.S. cost of sustained power interruptions.

Fig. 6 is a histogram of the uncertainty associated with the base-case estimate of $44 billion (Case 4) and with a plot of the cumulative distribution function. This plot shows that, based on the uncertainty in the SAIDI and SAIFI data (originating from EIA Form 861), the likely cost of sustained power interruptions in the United States is between $35 and $50 billion. By definition, the cumulative distribution function estimates the probability of the cost of power interruptions based on the statistical characteristics of the distribution. Looking at the horizontal and vertical axes of the plot, there is a 10% probability that the estimate is less than $35 billion annually and a 90% probability it is less than $50 billion.

If we assume the average value from this updated scenario, the estimated annual U.S. cost of sustained power interruptions is $44 billion (2015-$). That is, applying a distribution of interruption durations (i.e., moving from Case 3c to Case 4 as shown in Fig. 5) reduces the estimate in Case 3c by roughly $18 billion. In other words, replacing the broadly averaged SAIDI and SAIFI values and instead parsing them into likely distributions of various interruption durations results in nearly a 30% reduction in the estimate. This is a key finding as the 30% reduction represents the influence of shorter-duration outages that are less costly.

The Monte Carlo results reflect the treatment of uncertainty in some, but not all, of the framework components based on the characteristic nature of the input information used in this study. The reliability metric data (SAIDI and SAIFI), for example, can be characterized by a standard deviation that represents year-to-year variability by census region and is therefore represented in our analysis. As previously mentioned, the individual outage event cost is a function of outage duration, whose uncertainty we consider. However, we do not represent the uncertainty associated with

[4] Conversion from 2002-$ to 2015-$ was based on a 31.7% inflation change using the U.S. consumer price index: http://www.bls.gov/data/inflation_calculator.htm [26].

Table 8
Summary of step-by-step updates to U.S. cost of sustained power interruptions.

Case	Description	CDF		Customers		SAIDI		SAIFI		Vulnerability		COPI Total	Year $
		Old	New	Old	New	Old	New	Old	New	Old	New		
1	2006 Study Base Case	●		●		●		●		●		$26B	2002-$
2a	Case 1 + conversion to 2015-$	●		●		●		●		●		$35B	2015-$
2b	Case 1 + estimated 2001 customer using updated definition	●		●[a]		●		●		●		$31B	2015-$
2c	Case 2b + 2015 customers	●			●	●		●		●		$36B	2015-$
3a	Case 2c + 2015 CDFs		●		●	●		●		●		$30B	2015-$
3b	Case 3a + updated SAIDI and SAIFI		●		●		●		●	●		$75B	2015-$
3c	Case 3 + vulnerability adjustment		●		●		●		●		●	$62B	2015-$
4	Case 3c + explicit representation of outage durations		●		●		●		●		●	$44B	2015-$
5	Case 4 + Monte Carlo uncertainty analysis		●		●		●		●		●	$44B	2015-$

[a] The customer count data used in this case is a modification from what was used in the 2006 study and estimates what the 2001 customer count would have been using the post-2001 definitions of each customer class.

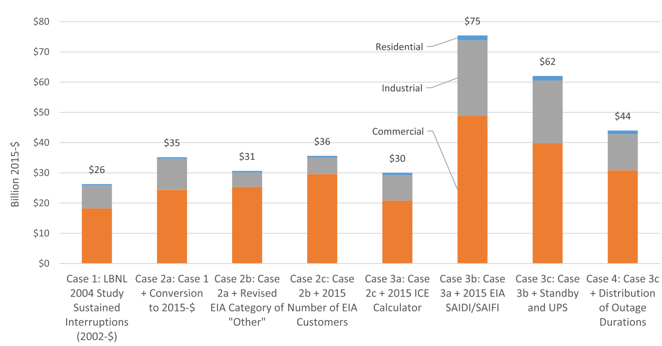

Fig. 5. U.S. cost of sustained power interruptions, by step-by-step case and sector, in billion 2015-$.

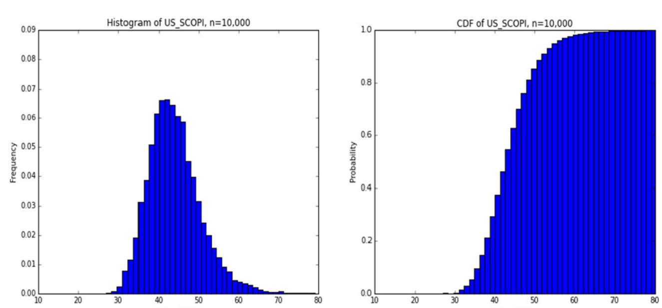

Fig. 6. Updated U.S. cost of sustained power interruptions using Monte Carlo simulation (n = 10,000).

individual outage event costs because we do not know enough about the uncertainty of the various dependent variables (electricity consumption, income, time/date, and industry type, among others) that characterize each customer and outage. We also do not consider the uncertainty of the vulnerability component because of lack of information to explain its variability. Furthermore, the component representing the number of customers was not included in the uncertainty analysis because we felt this parameter is well understood, and therefore has minimal uncertainty to explore.

7. Summary of findings, next steps, and concluding thoughts

Recent large-scale blackouts resulting from severe or catastrophic weather events or from equipment or operational failures have sparked heightened interest in assessing how much it would cost to maintain or improve the reliability of the U.S. electric power system.

Since our 2006 report, interest in electricity reliability has grown. Not only has there been an increase in the public availability of information on electricity reliability, there is also an increased interest in the costs that power interruptions impose on customers. A number of recent events highlight this trend. In 2012, the Department of Energy sponsored the development of a public web-based tool that estimates the economic cost of power interruptions to customers [26]. In 2014, the Energy Information Administration (EIA) began collecting and publishing information from all US electric utilities on their reliability performance [19]. In 2015, Berkeley Lab commissioned a study that estimated the adoption of back-up generation [6].

This report presents an update of our 2006 estimate of the cost of power interruptions to U.S. electricity customers. This work benefits from a strong foundation of updated inputs that represent the current state of reliability in the United States and consider the growing subset of U.S. residents who are purchasing equipment to protect themselves against power interruption impacts.

Specific enhancements drawing from these developments have been incorporated into this report (as presented in section 6) including the following:

1 Use of more consistently reported reliability metrics that focus on the IEEE Standard 1366 now included in EIA Form 861; we used the most current year of data available
2. Representation of the mix of interruption durations and frequencies likely experienced by customers and thereby applying a range of individual outage costs instead of a single outage cost to represent outage duration (SAIDI) and frequency (SAIFI)
3 Use of updated CDFs to reflect individual outage costs based on a broader pool of utility customer surveys and a more sophisticated statistical regression modeling approach
4 Consideration of the vulnerability of customers to utility service interruptions, i.e., accounting for customers who have installed backup generators to protect themselves from the effects of a power interruption

We find that:

- The total U.S. cost of sustained power interruptions is $44 billion per year (2015-$) — 25% more than the $26 billion per year in 2002-$ (or $35 billion per year in 2015-$) estimated from sustained interruptions in our 2006 study.
- The majority of the costs (70%) are borne by customers in the commercial sector. See Fig. 3. This is due to the high cost of

power interruptions on a per customer basis, coupled with the large number of customers in this sector. The industrial sector accounts for 27% of the total cost. Although the cost of power interruptions on a per customer basis is more than it is for commercial customers, there are far fewer industrial customers. Finally, residential customers account for only 3% of the total cost. Despite the fact that 90% of all customers are residential, the costs they experience on a per customer basis are low.
- Accounting for customers who take extra measures to ride-through power interruptions by installing backup generators results in an 18% decrease in the estimated cost of sustained interruptions.
- Replacing the broadly averaged SAIDI and SAIFI values with estimated distributions of various interruption durations results in nearly a 30% reduction the cost of sustained power interruptions - this finding suggests the influence of shorter-duration outages that are less costly.
- In view of the greater base of information available to develop a revised estimate of the total cost of power interruptions, we are also able to use formal methods to estimate the uncertainty in our estimate due to year-to-year and utility-to-utility variability in reliability. We find that with a 90% confidence level that the total U.S. cost of sustained power interruptions is between \$35–\$50 billion per year (2015-\$).

These findings result from the following specific enhancements to our 2006 estimate:

- A steady rate of increase in the total number of electricity customers (approximately 1% per year) is directly tied to a 14% increase in the cost of sustained power interruptions since our last estimate in 2006. In our step-by-step update process, updating the customer count in Case 2b increased the cost of outages from \$31 billion (2015-\$) to \$36 billion (2015-\$) (Case 2c).
- Updating the CDFs to incorporate additional utility customer survey data and an improved modeling approach resulted in a significant decline in the cost of sustained power interruptions in our step-by-step update process, i.e., a 16% decrease from \$36 billion (Case 2c) to \$30 billion (Case 3a).
- Updating the reliability data (SAIDI and SAIFI) in our step-by-step process increased the cost of sustained power interruptions to \$75 billion (Case 3b) from \$30 billion (Case 3a). This is a finding consistent with the conclusions of the [5] study that reliability is getting worse over time.
- Accounting for customers who take extra measures to shelter themselves from power interruptions by installing backup generators reduces the estimated cost of sustained power interruptions by 18% from Case 3b to \$62 billion (Case 3b).
- Using a more sophisticated approach to represent the reliability using a mix of various interruption durations and frequencies (and thus various mixes of individual outage costs) reduced the cost of sustained power interruptions by 29% (from Case 3c at \$62 billion to Case 4 at \$44 billion, both in 2015-\$).

7.1. Next steps

While we believe this study presents the most accurate and comprehensive estimate of the total cost of power interruptions to U.S. electricity customers based on the best available data in the public domain, there remain several areas where improved data and methods would lead to improved precision. First, more granular information on reliability is needed that considers how power interruptions result in costs to electricity customers. Power interruption information should identify what types of customers are affected, e.g., commercial or residential, and when and for how long their electric service is interrupted. Second, updated information that is national in scope is needed on the costs customers incur when their power is interrupted. Special attention should be paid to augmenting survey-based approaches that have been traditionally used for collecting this information with newer methods that are designed specifically to estimate the costs associated with long-duration and widespread power interruptions.

7.2. Concluding thoughts

This work is predicated on the understanding that power interruptions have economic consequences. Our work has sought to quantify regional variations in the customer classes that bear direct and readily quantifiable economic consequences from power interruptions. Discussions pertaining to the cost of power interruptions naturally lead to questions of what, if anything, should be done and who should be responsible for such costs.

In this regard, we believe that it is useful to recognize that addressing the costs of power interruptions is actually a shared responsibility involving multiple entities. Often, the overall responsibility for managing reliability rests with the utility, which in conjunction with the regulator or oversight authority, then determines how much to spend on efforts such as storm hardening, equipment upgrades, or automated outage-management systems to maintain a standard of reliability for customers. However, in some cases, the costs are more appropriately addressed jointly by the utility in conjunction with the local, state, or even federal government, especially when the cause involves severe or extreme weather, which affects more than just the electric infrastructure of a community or region. It is also important to keep in mind that the costs can be addressed, at least in part, when customers take direct action by investing in mitigation options such as installing a back-up generator.

As we conclude, it is important to keep in mind that the cost estimate we present is not intended to represent the amount of money that needs to be spent or even should be spent in the U.S. to eliminate all reliability costs related to power interruptions. It is neither economically viable nor technically feasible to invest billions of dollars to create an electricity system free of outages. Instead, our estimated cost of power interruptions is meant to put into perspective the decisions that utilities, regulatory agencies, local government, and policy makers need to make when prioritizing the needs and safety of U.S. electricity customers. With this study, decision makers now have an updated tool that they can use to better understand the economic implications of power interruptions in the U.S. that enable them to assess regional distinctions. We hope this study can also serve to inform how any country outside the U.S. could establish and apply a similar framework as a means of thinking about how different customer sectors differ in their valuation of the same power interruption. Recent work like Larsen et al., 2016 [27] can be used together with the framework we developed as a way of helping to identify areas where future investments in reliability can be most beneficial to customers. We believe this information could help inform decision makers as they consider investments or rate designs that are better aligned with a customer's willingness to pay for lost power [28–30]. As we continue to advance the work and are able to consider suggested next steps, this framework will become increasingly more powerful, especially when reliability information parsed by customer class can be incorporated. We hope that our work will help inform these important decisions, which must and will be made by public and private decision-makers both individually and in conjunction with one another.

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