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ORIGINAL PAPER

Evaluating the Potential Impact of Smart Grid Funding on Reducing the Economic Impact of Large Outage Events in the United States from 2003 to 2017

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Abstract
This paper examines the trends in electrical disturbances and how these trends influence decision-making. Funding for the smart grid from government grants has enabled almost $9.5 billion dollars worth of spending geared toward installing smart meters and self-healing and reconfigurable assets, to increase the resiliency and reliability of the electrical grid. Using Value of Service, we find that the cost of outage events has reduced during the deployment of the smart grid and generated positive net present value, reasonable payback periods, and a respectable rate of return.

Keywords Power outages · Smart grid · Power trends · Asset replacement · System reliability · Risk management

Introduction

Power Outages

Society's reliance on electricity increases each day, with the adoption of power-intensive products such as electrically powered vehicles, mobile phones, and modern public transit. Thus, when power disruptions occur they not only leave us in the dark, they also inhibit our ability to continue the activities that are integral to our daily lives [1, 2]. A study initiated by the Lawrence Berkeley National Lab concluded that power outages could cost the U.S. economy $80 billion every year [3]. It is believed that power outage events are increasing due to older electric assets and the lack of ability to identify outage events in real-time and potential failures before they occur.

This has led the United States Congress to allocate $4.5 billion to the U.S. Department of Energy (DOE) to make investments in the electrical grid aimed at increasing the resilience and reliability of the system [4]. One of the stated goals of the smart grid program was to reduce the occurrence of large outage events and their impact on electricity customers. Subsequently, this has led us to the question of whether there have been noticeable trends showing improvement in large power outages and whether consumers are losing less money from power disruptions. If consumers are seeing a reduction in outage frequency and duration, then the smart grid was a good investment for the government.

Investing in the Smart Grid

In the mid-2000s, it was recognized that sizable investments in the United States' electric power infrastructure, or the grid, were a critical necessity to keep the lights on. As the nation's electric demand continues to increase, the grid was put at risk to fail [5].

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Investment in the grid to make it smarter would result in a grid that would function more efficiently and deliver power at a service level needed for modern applications.

Goals for the Smart Grid include:

- Reducing large outage events
- Ensuring the grid's reliability
- Maintaining affordability for customers
- Reinforcing the U.S.'s global competitiveness
- Accommodating growing renewable and traditional energy sources
- Allowing for a reduction in the power system's carbon footprint
- Introducing advancements and efficiencies yet to be envisioned.

Spending for the smart grid in the U.S. has totaled \$9.5 billion (Fig. 1), with projects funded through grants (\$4.5 billion) from the DOE.

An Overview of Smart Grid Technologies

A smart grid is the enhancement of the electric grid to incorporate sensors, feedback devices, monitoring, and control devices to enable efficient grid operation (Table 1) [6]. These technologies are designed to bring the U.S. electric grid into the twenty-first century.

Overview

In this paper we set out to determine whether consumers are seeing a tangible financial benefit measured by the reduction in economic cost of power outages before and after the smart grid was implemented. Section "Literature Review" provides a brief literature review of existing articles about the smart grid. Section "Background on DOE Data" describes the available DOE Outage Data and some of the trends seen in this data. Section "Method" outlines the method we use to evaluate whether consumers are seeing an economic benefit from the smart grid. Section "Results and Discussion" contains the results and a discussion. Finally, Section "Future Work and Conclusion" concludes and discusses future work and potential policy implications.

Literature Review

A review of existing literature shows no previous academic journal articles evaluating the benefits of the smart grid from an economic perspective. Articles on smart grid focus on a variety of topics, primarily the functionality and technologies used to implement the smart grid (Tuballa and Abundo) [7]. Some articles suggest that smart grid technology will play an important role in reducing greenhouse gas emissions (Peng et al.) [8]. Other articles highlight the public policy issues that are lagging behind as smart grid technology is being deployed and implemented (Blumsack and Fernandez) [9]. Privacy issues are being raised with the smart grid, particularly the implementation of smart meters that collect customer energy usage (McDaniel and McLaughlin) [10]. Previous work has examined some of the frequency and duration of outages, but with the installation of

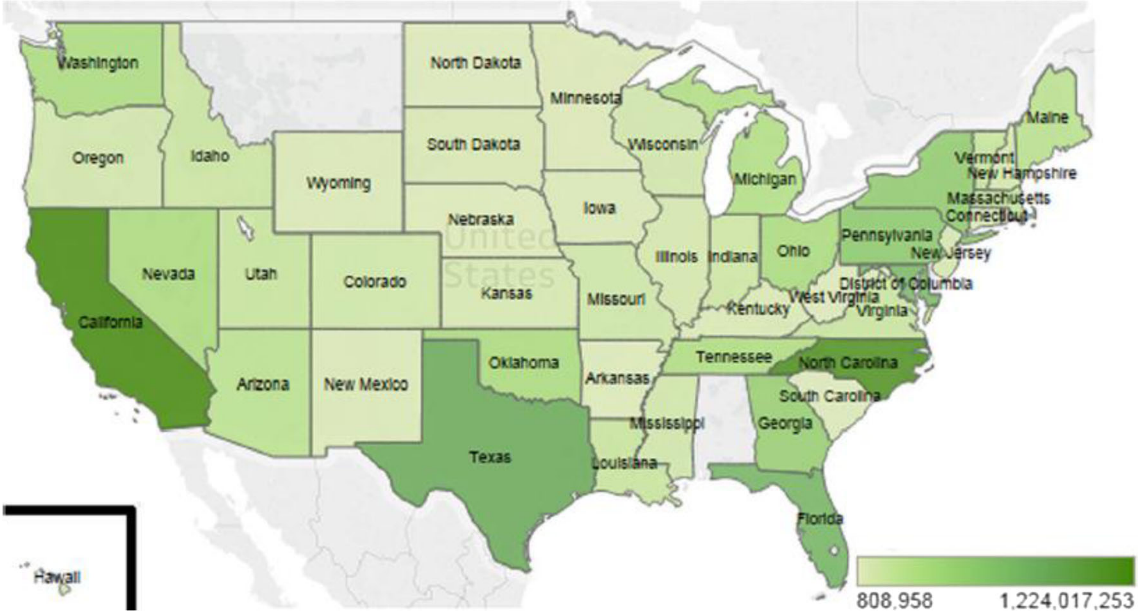


Fig. 1 Smart Grid spending in the United States reported [in \$US]

Table 1 Smart grid technologies at a glance

Asset	Description
Advance interruption switch	Switches that can detect and clear faults more quickly or without traditional reclosing sequence
Advanced metering infrastructure	Electricity meters that use two-way communications to collect electricity usage and deliver information to the customer
Phasor measurement technology	Phasor technology enables the system operator to collect and analyze synchrophasor data
Load monitoring	Technology that can measure and communicate line, feeder, and/or device-loading data via a communication network in real-time
Distribution automation	Distribution Devices that can be used to perform automatic switching, reactive device coordination and other feeder operations/control

smart grid assets, a refresh of this work seems prudent [11, 12].

The Department of Energy has published several whitepapers to help readers understand the benefit of the smart grid (Booz Allen Hamilton et al.) [13]. The benefits are described as reducing losses to society from power outages, reducing operation and maintenance cost for utilities, and consequently reducing electricity prices for customers. A news article in Scientific American titled "Debate Continues on Smart Grid Benefits versus Massive Costs" has raised the possibility that smart grid deployment to consumer homes could cost between $338 and $467 billion over the next 20 years, and potentially deliver a value of $1.3–2 trillion in benefits over this period to customers [14]. This article gives us a good perspective to base our analysis. Customers were promised roughly a 1-to-3 cost-benefit ratio in deploying the smart grid. The data collected from the DOE evaluated in this paper will show that

Table 2 Descriptive statistics for DOE data 2003–2015

Outage Reason	Avg. Duration in Hrs	Avg. Customers Affected	Avg. Customer Cost	Count of Outage
Cold	19	262,000	$347,271,000	1
Cyber, Sabotage, Suspicious, Vandalism	14	2,800	$1,125,700	19
Earthquake	14	132,700	$142,281,300	4
Equipment	41	57,500	$30,333,000	60
Fire	55	103,200	$120,455,400	9
Fuel/Supply	151	70,000	$7,180,400	2
Generator	5	21,800	$16,268,400	1
High Winds	49	137,200	$170,635,900	59
Hurricane/Tropical	109	490,100	$634,730,100	65
Ice storm	34	190,400	$175,809,700	114
Inadequate Supply	8	23,300	$30,936,900	3
Interruption	3	85,300	$61,433,000	11
Lightning	7	185,000	$193,906,700	3
Load Loss	2	104,500	$21,110,800	1
Load Shedding	10	109,400	$74,152,200	49
Major Storms/Severe Weather	67	170,700	$212,810,200	710
Other/Unknown	14	582,700	$772,052,000	13
Physical	9	31,200	$21,291,100	7
Public Appeal	34	117,100	$154,193,400	12
Reduction	14	243,000	$178,249,100	6
System Operation	5	31,700	$15,045,700	9
Transmission	8	179,500	$193,347,800	22
UnControlled	11	100,100	$66,996,100	8
Wildfire	3	528,300	$362,010,400	6
Winter	63	196,800	$209,354,700	17

Fig. 2 The number of outage events from 2003-2017 reported from DOE OE-417

whether there is any evidence that smart grid delivers the benefits some are projecting (Tables 2).

Background on DOE Data

DOE Reporting Data

The Department of Energy (DOE) requires electrical disturbance events interrupting more than 300 MW or 50,000 customers reported to the DOE, through the use of Form OE-417 (https://www.oe.netl.doe.gov/oe417.aspx). Additionally, events such as cyber security attacks, vandalism, voltage reduction, and voluntary reduction are also required to be reported to the DOE, even if no outage occurs. The DOE's mandatory reporting requirements are designed to meet national reliability and security goals. The DOE uses these data to understand how electrical disturbance events affect the electric supply infrastructure. The DOE's Energy Information Administration uses the data to report out monthly on electric disturbances and emergencies. Lastly, the data can be used to develop legislation, Congressional reports, and serve as the basis of DOE investigations.

According to the DOE guidelines, electric utilities that operate as control area operators and/or reliability authorities (e.g. CAISO), must submit documentation within 72 hours of an electrical disturbance event. The information recorded on OE-417 includes the duration, magnitude, number of customers, cause of the outage, and date and time that the event began and ended. The range of the dataset available from the DOE covers 2002–2017. Although the data begins in 2002, that year's data has an unusually small number of disturbance events (22) and extremely large outage

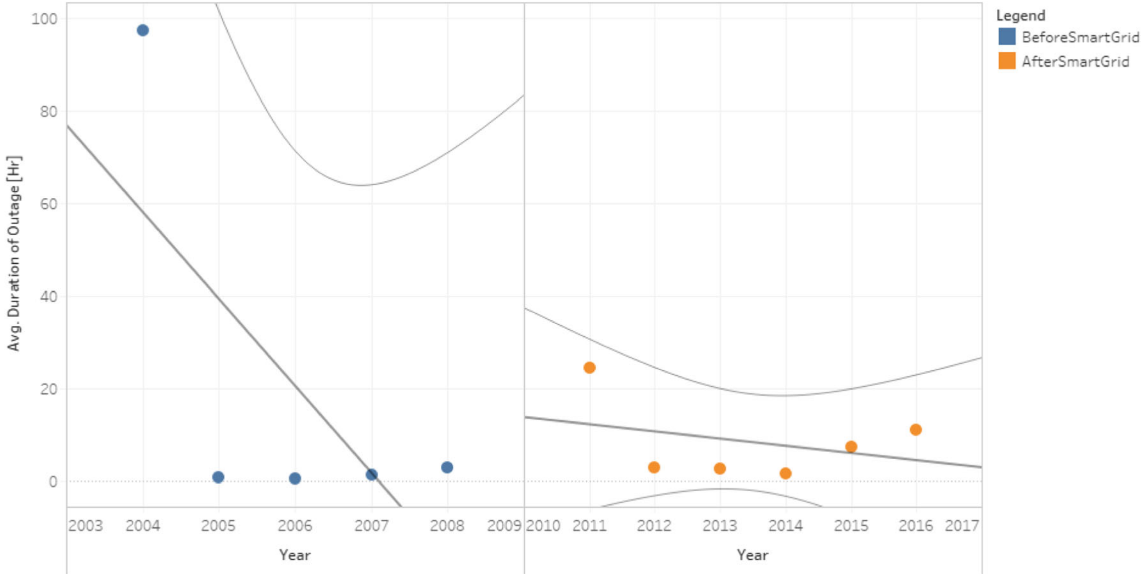


Fig. 3 The average duration of outage events from 2003- 2017 calculated using DOE OE-417 data

durations for small magnitude events. The low number of events causes us to suspect problems with data quality. Consequentially, we have decided to remove 2002 from our analysis.

Descriptive Statistics on DOE Outage Data

Weather is the largest and leading cause of outages (Table 2).

Figures 2, 3, and 4 show the total number of outage events per year recorded in OE-417, the average duration of an outage event and the average number of customer impacted.

Smart Grid Funding Data

Smart grid funding ranges from 2011 to 2016 (Tables 3). Programs deployed during this period have a total value of approximately $9.5 billion.

Method

To evaluate whether smart grid funding reducing the financial impact large outages, we first need to understand the economic impact an outage has on customers. This can be done using a metric called the value of service to the customer, defined as the amount of money the customer loses when a power outage occurs. The economic impact a customer experiences is based on many factors, but typically customer type (Residential, Small, Medium, and Large Business) and duration are the two most important factors (Tables 3, 4, 5 and 6).

Table 3 Smart grid funding by year

Year	Total Spend ($M)
2011	$1
2012	$188
2013	$3,099
2014	$3,173
2015	$1,764
2016	$1,275

Value of Service

In order to evaluate the effectiveness of the smart grid on reducing major outage events as recorded in OE-417, we calculate the value of service impact that customers experienced from 2003 to 2017 using Eq.1. We also assume that the customer breakdown in any given outage event is roughly 87% Residential, 12% Small and Medium Business, and 1% Large Business. The customer breakdown is based on data from the Energy Information Agency. We use the duration of the event to determine the impact of service based on customer class. Since value of service does not increase linearly, we assign the value of service impact based on the closest match to durations of 0, 1, 4, and 8 hours and their expected cost to different customer classes [15]. We also cap the longest duration at 8 hours, since some studies have shown that the impact of the outage flattens out and does not necessarily lead to additional economic losses to the customer.

Following this methodology allows us to calculate a cost to customers for each outage event listed by the DOE and to sum all cost of all events for each year, to get a cumulative cost of outage value.

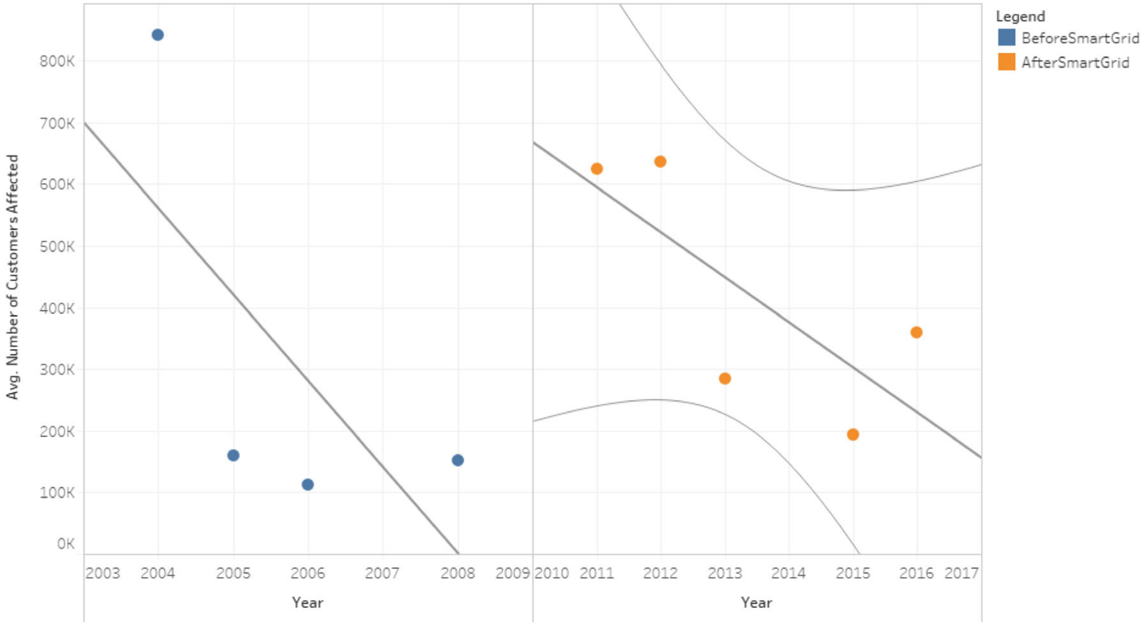


Fig. 4 The average number of customers impacted by an outage event from 2003-2017 calculated using DOE OE-417 data

Table 4 Cost of power outages

Customer Class	Interruption duration			
	Momentary	1 hour	4 hour	8 hour
Residential	\$2.10	\$3.30	\$7.40	\$10.60
Small Business	\$293	\$619	\$2,623	\$5,195
Medium and Large Business	\$6,558	\$12,487	\$42,506	\$69,284

$$COE = N^{*}(A{*}X_a + B{*}X_b + C{*}X_c) \quad (1)$$

Where:

COE = Cost of Outage Event
N = Number of Customers Impacted
A = Percentage of Residential Customers
B = Percentage of Small/Medium Business Customers
C = Percentage of Large Business Customers
X_a = Residential Cost of Interruption
X_b = Small/Medium Business Cost of Interruption
X_c = Large Business Cost of Interruption

Using Value of Service

Once the loss of service is calculated for each year, the pre- and post-smart-grid implementation years are bucketed, and the Total Customer Cost for the periods 2003–2010 vs. 2011–2017 is compared, to see if there is a reduction. The average financial impact to customers is compared from 2003 to 2010 and from 2011 to 2017, and the difference of the two values is used to calculate the Net Present Value. If the smart grid continues to generate this financial reduction in outages from the baseline in the previous period (2003–2010), then we will be able to calculate the net present value (NPV), the break-even period, and the rate of return. In order to protect the data from being confounded by events such as adverse weather that may have occurred in 2003 – 2017, we perform the analysis with and without outage events that were caused by weather.

Ultimately, this method also allows us to calculate the maximum spending to avoid these types of events, which will be useful to policy-makers and utilities in the future. The reality is that enough data is not available to evaluate the impact of the smart grid over a long period of time. However, we can make generalizations and projections based on data collected and on the trends that we are seeing now.

Results and Discussion

Cost of Yearly Outages

Figure 5 shows the yearly costs to customers for the years 2003 to 2017. Several years have extremely high values due to "Severe Weather Events" that led to a large number of customers impacted. These values range from approximately \$7 to \$30 billion a year in economic losses (using Eq. 1)

Bucketing Pre- and Post-Smart-Grid

From 2003 to 2010 (pre-smart-grid), the total economic loss to customers from power outages was \$148 billion. From 2011 to 2017 (post-smart-grid), the total loss was

Table 5 The NPV of smart grid with all events

Metric	Total (\$M)	2011	2012	2013	2014	2015	2016	2017	2018	2035
Cash Flow Benefit	\$65,790	\$0	\$0	\$0	\$0	\$3,133	\$3,133	\$3,133	\$3,133	\$3,133
Cash Flow Investment	(\$9,500)	(\$1)	(\$188)	(\$3,099)	(\$3,173)	(\$1,764)	(\$1,275)	\$0	\$0	\$0
Total Cash Flow by Yr	\$0	(\$1)	(\$188)	(\$3,099)	(\$3,173)	\$1,369	\$1,858	\$3,133	\$3,133	\$3,133
PV Benefit	\$27,710	\$0	\$0	\$0	\$0	\$2,390	\$2,234	\$2,088	\$1,951	\$618
PV Investment	(\$7,728)	(\$1)	(\$176)	(\$2,706)	(\$2,590)	(\$1,346)	(\$909)	\$0	\$0	\$0
Total PV	\$19,982	(\$1)	(\$176)	(\$2,706)	(\$2,590)	\$1,044	\$1,325	\$2,088	\$1,951	\$618
Cumulative Total PV	\$0	(\$1)	(\$177)	(\$2,884)	(\$5,474)	(\$4,429)	(\$3,105)	(\$1,017)	\$934	\$19,982
Discount Rate	7%									
NPV 7	\$19,982									
Internal Rate of Return	32%									
Breakeven (Years)	8									

Table 6 NPV of Smart Grid with weather events removed

Metric	Total ($M)	2011	2012	2013	2014	2015	2028	2029	2035
Cash Flow Benefit	$20,727	$0	$0	$0	$0	$987	$987	$987	$987
Cash Flow Investment	($8,225)	($1)	($188)	($3,099)	($3,173)	($1,764)	$0	$0	$0
Total Cash Flow by Yr	$0	($1)	($188)	($3,099)	($3,173)	($777)	$987	$987	$987
PV Benefit	$8,730	$0	$0	$0	$0	$753	$312	$292	$195
PV Investment	($6,819)	($1)	($176)	($2,706)	($2,590)	($1,346)	$0	$0	$0
Total PV	$1,911	($1)	($176)	($2,706)	($2,590)	($593)	$312	$292	$195
Cumulative Total PV	$0	($1)	($177)	($2,884)	($5,474)	($6,066)	$227	$519	$1,911
Discount Rate	7%								
NPV 7	$1,911								
Internal Rate of Return	10%								
Breakeven (Years)	18								

$107 billion. This trend suggests that the economic impact of outages has decreased during the smart grid implementation period.

Examining Fig. 6, we can see that there was a reduction in the cost to customers by $3.1 billion per year for the period of 2011-2017.

If we remove outages due to weather events, the reduction in cost is reduced to $1.0 billion per year (Fig. 7).

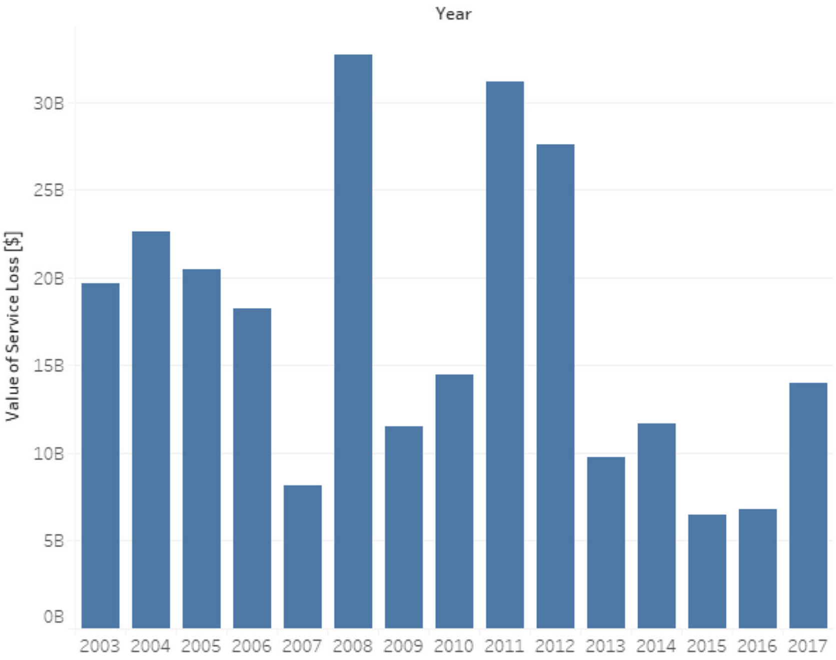
NPV, IRR, Break-Even

If we assume that the reduction in cost to customers from outage events observed in 2011–2017 will continue for several years, at either a $3 billion or a $1 billion per year annual reduction from the baseline previously observed, then we should generate a positive NPV, and have a reasonable rate of return and break-even period.

Calculating these economic metrics, using the fact that the smart grid continues to generate a $3 billion reduction in outages from the baseline in the previous period (2003–2010), the investment will have a break-even period of 7 years with a 32% rate of return and a $19.9 billion net present value (Tables 5).

In the case where benefits are only $1 billion annualized (when weather events are removed), examining the net present value of this scenario shows that we can expect a break-even period of 18 years, an internal rate of return of 10%, and an NPV of $1.9 billion (Tables 6).

Fig. 5 The total economic impact to customers by year from power outages from 2003-2017



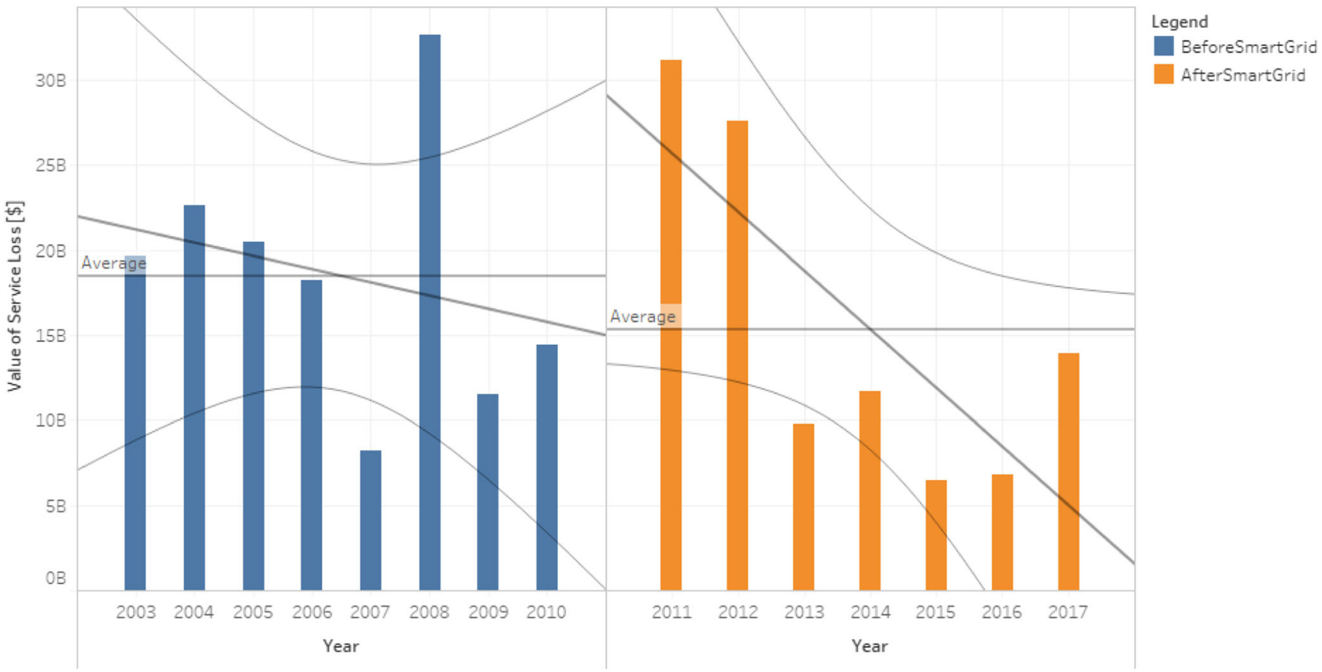


Fig. 6 The total economic impact to customers by year from power outages from 2003-2017, segregated pre-and-post smart grid

Cumulative Spending vs. Outage Events

Trending the cumulative spending from 2011 to 2016 and compounding each year for a total of $9.5 billion against the number of outage events observed each year, we see a reduction in outage events (Fig. 8). In general, the cumulative spending on the smart grid increased to a maximum of approximately $9.5 billion, whereas the number of outage events decreased over this period, from about 300 events to 150 events.

Future Work and Conclusion

There are several pieces of future work that our analysis has brought to light.

Electricity Costs

Along with reduced outages for customers, reduced energy prices were another promise made by the smart grid. Future papers could examine electricity rates to determine if smart

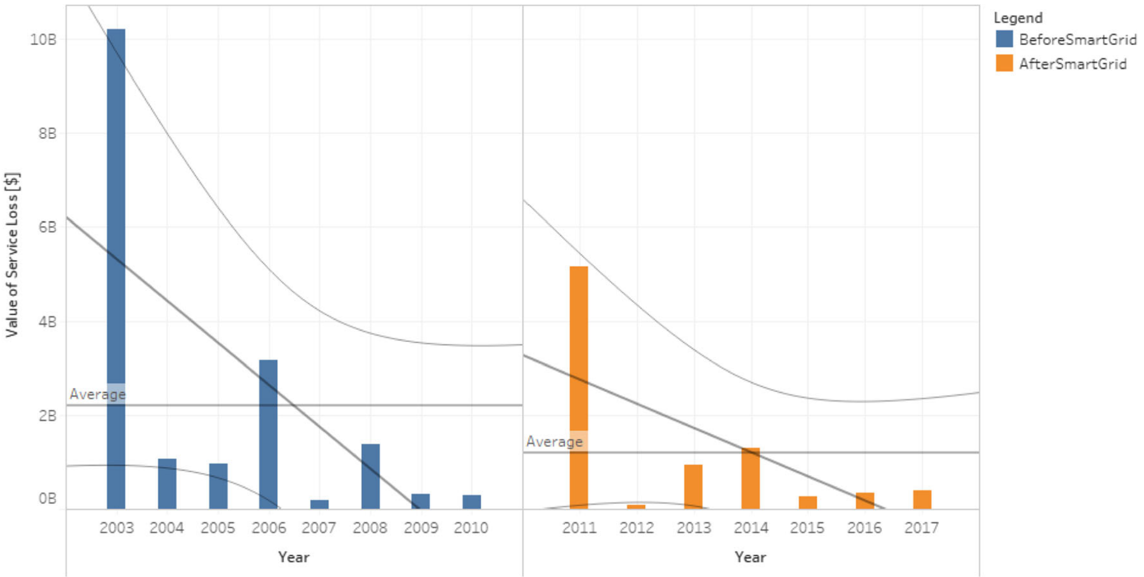


Fig. 7 The total economic impact to customers by year from power outages from 2003-2017, segregated pre-and-post smart grid, with weather related outage events removed

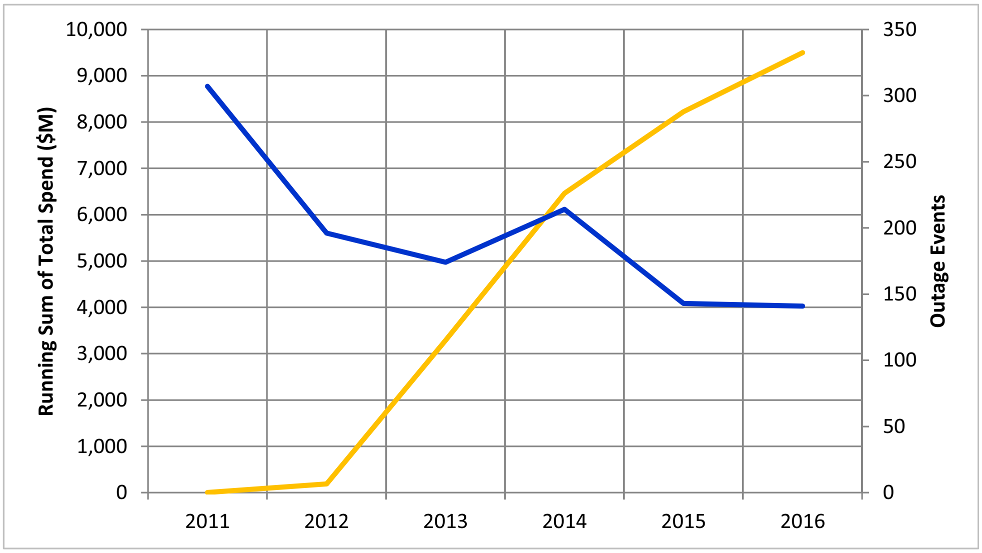


Fig. 8 In general we see that as the cumulative spending (graphed in *gold*) on smart grid increased the number of outage events decreased over this period of time from about 300 events to 150 events (graphed in *blue*)

grid technology has had an influence on increasing or reducing the rates that customers pay.

Individual Utility Comparison

A more utility-by-utility evaluation of the smart grid could be made using reliability data and individual spending. This analysis would be quite complex, since utilities would have to provide the amount of funding that they spent each year on smart grid technology and the associated reliability statistics for each year, as well as the overall spend. Utilities that spend money on the smart grid should see a noticeable improvement in their reliability statistics in the size, frequency, or duration of the events.

Re-Thinking Risk

One finding of our work is that perhaps there is an minimal amount of outages that society is willing to accept. Resources in society are limited, and at some point the payback period and diminishing returns necessitate a maximum cap on spending. The focus of future work may well shift from simply reducing outages to calculating the least-impact outage situation for a given area and setting that as a new policy goal.

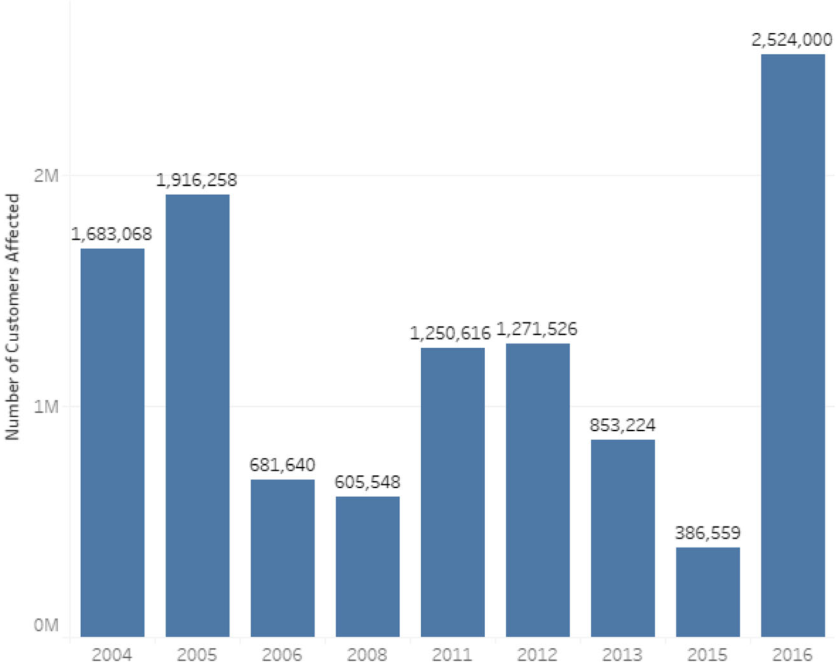


Fig. 9 The total number of customers impacted by outage events in Puerto Rico from 2004 to 2016

Infrastructure Investments

The U.S. utility grid is getting smarter, but it is also getting older. When weather events were removed, we see that the benefit of the smart grid declined, which is reasonable considering that certain outages can only be mitigated through changes in generation capacity and replacing aging infrastructure. Assets such as poles, conductors, and transformers are the ones that typically fail and lead to high reliability impact outages. Storms are the biggest cause of power outages in the United States, and weatherizing assets and strategic undergrounding could be a focus to mitigate outages. However, funding for these types of programs doesn't come from smart grid funding grants from the DOE, but from the traditional rate case processes. Perhaps there could be federal grants targeted at addressing system reliability issues caused by weather or system imbalances.

Puerto Rico

In 2017, Puerto Rico suffered a terrible outage event after Hurricane Maria hit the island, leading to a prolonged island-wide blackout [16].

This event is not uncommon in Puerto Rico's recent history. The data we have trended from the DOE clearly shows that Puerto Rico has had large power losses each year, which impacted millions of customers in several years (Fig. 9). Yet Puerto Rico did not receive any smart grid funding. This is a serious oversight that needs to be addressed by future smart grid funding.

Conclusion

Our analysis has shown that smart grid investments have had a noticeable benefit on reducing the number and economic impact of large outage events observed in the United States during the implementation of smart grid assets (2011–2016). This suggests that the investment was a good public decision and is realizing billions of dollars in benefits. While the smart grid does not eliminate all outages, it may have reduced the impact of severe events, which in turn has reduced the economic cost of outages to customers.

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