Quantifying Resilience Value of Solar plus Storage in City of Reno

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***Abstract*—This paper summarizes the development and implementation of resilience valuation metrics for solar plus storage in the City of Reno. The proposed resilience valuation metrics are intended to assist local governments, policy makers, and building owners in making well-informed decisions and plans for resilience enhancement of power supply. The valuation metrics are developed based on historical data of extreme events, historical outage data, cost of outages, and classifications of critical loads to determine the likelihood, expected duration, and average cost of outages. Events that last for less than 24 hours are not considered in developing metrics for resilience valuation. The proposed approach enables resilience valuation based on selected parameters such as sites, types and characteristics of critical loads, and size of solar and energy storage systems. The ten regions in the continental United States and territories identified by the Federal Emergency Management Agency (FEMA) are used to classify types of extreme events at different locations. Although resilience value of solar plus storage alone may not justify investments in some resilience enhancement projects, the stacked value (resilience value, revenue, avoided costs, etc.) of solar plus storage during their lifetime will be an important measure in weighting different investment alternatives. The proposed resilience valuation approach is demonstrated on a Public Safety Center in City of Reno.**

***Index Terms*—Energy storage, extreme events, resilience metrics, resilience valuation, solar energy**

I. Introduction

The frequency of extreme events, both natural and man-made, has recently increased, causing prolonged power outages to major pieces of power system equipment [1], [2]. These events have brought significant concerns about the reliability and resilience of power supplies, which can damage major equipment such as substations, transmission lines, and power plants. This calls for developing resilience evaluation and valuation methodologies and metrics to both measure the resilience of a given system and monetize the resilience to help decision makers choose between different alternatives. Upfront costs associated with resilience enhancement can be a challenge to local governments. Therefore, the first step toward incorporating resilience in decision making processes is to develop resilience valuation metrics and methods to compare planning and operation alternatives and to provide techno-economic justifications for resilience enhancement.

Several methods have been proposed for resilience valuation. Existing resilience valuation methods can be summarized as follows.

Bottom-up/Survey-based Methods. Bottom-up approaches measure the value of resilience based on customer behavior and preference. Survey-based methods are generally employed to estimate how electricity outages affect customers. Generally, value of lost production and outage related costs which result from power outages are used to estimate direct the cost of an outage. To determine the value of power loss on the residential sector, surveys ask residential customers a series of contingent valuation questions. Survey questions typically focus on customers' willingness to pay or accept higher fees in exchange for improved and more reliable service.

Bottom-up methods are classified into two approaches as follows [3], [4]. *Stated preference method:* This method is developed based on customer surveys from their hypothetical willingness to pay for better service [5]. Stated preference approaches include contingent valuation method [6], conjoint analysis [7], and discrete choice experiments (DCE) [8]. Conjoint analysis and DCE ask respondents to choose between different options for better service [7]. *Revealed preference/market-based methods:* These methods use real world data to estimate power interruptions [9]. These methods are classified mainly into defensive behavior and damage cost methods.

Economy-wide/Macroeconomic Approaches. Economy-wide approaches measure the value of resilience based on the effect of power interruptions on economic regions using indicators such as employment and economic output. There are two major types of regional impact modeling indicators: input-output (I-O) methods and commutable general equilibrium (CGE). I-O methods evaluate the public policies that affect the whole society. The I-O method has the capability to estimate induced and indirect economic effects (e.g., purchasing power from end users) caused by the direct policy change. The I-O method itself cannot directly provide the value of the resilience; rather, it provides the important economic information regarding the impact of extreme events.

Value of Lost Load. Value of lost load (VoLL) method uses a

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contingent valuation method to estimate the value of avoided power outages. VoLL is an economic metric that provides information about cost of a power outage, and it represents an approximate price that a customer is willing to pay in exchange of better service or avoided power interruption. Several factors can be included in the VoLL such as damage to equipment, lost supplies, lost data, and health and social impacts. VoLL is affected by context and attributes of power interruption such as customer type, outage duration, timing (time of day and the season of the year), magnitude of the outage, and geographical location [5], [10], [11].

Most existing methods define VoLL in terms of static or constant cost value [5], [12]–[16]. The static VoLL does not vary with the duration of outage and is simply multiplied with the kWh lost load to estimate the value of the cost of power outages. However, the specific relationship of compounding of cost of outage with time is yet to be developed and understood. Development of a temporal (time dependent) relationship between duration of power outage and the cost of outage demands a careful attention to avoid the deviation between the outage recovery cost imposed ($/kWh) to customers and the total economic impact [10], [17]. Developing outage cost estimation model for prolonged outages is a very challenging task mainly due to a lack of outage cost data [7].

This paper proposes resilience valuation metrics for solar plus storage and applies it on a public safety center in City of Reno. The contributions of the paper include development of (a) a methodology for determining likelihood and expected duration of power outages due to extreme events; (b) generic resilience valuation metrics for buildings with and without solar and energy storage systems; and (c) a framework for selecting location-dependent resilience valuation parameters.

The rest of the paper is organized as follows. Section II provides background on resilience valuation efforts. Section III describes the development of the proposed metrics for resilience valuation. Section IV shows the application of the proposed work at a public safety center in Reno and discusses the results. Section V provides concluding remarks.

II. Background on Resilience Valuation

A. Factors impacting cost of outages.

Power interruption is complicated by numerous stochastic variables that affect the cost of power outage [18].

1) Customer Type and Size: Power outage cost depends on who/what experiences the outage. Effect of outage is different for different types and sizes of customers. For example, a short duration outage at a data center can cause much more outage cost than for residential or agricultural customers. Criticality of the load also impacts the cost of power outages. For example, power outage in a critical facility (e.g., hospital, police station, disaster shelter center, etc.) hinders emergency services. Therefore, cost of power outage in critical facilities is much more than that at noncritical facilities.

2) Time of the event: Cost of the power outages is also affected by when an outage occurs. Specifically, time of day, day of the week, and season of the year affect expected outage costs. Residential customers can be less affected by the power outage during the day (both household and leisure activities may be affected) than at the evening while commercial customers can be more affected by power outages during the day (working hours) than during the evening. Similarly, power outage during the working days can have more impact than that at weekends to a commercial customer. Heating, ventilation, and air conditioning (HVAC) use patterns are different in different seasons (due to different weather conditions), which affect power outage impact. For example, a power outage during a mild spring evening is much less impactful than that at hot summer or at bone-chilling cold winter.

3) Scale of Outage (Magnitude): The amount of load lost along with their overall impact affect the total cost of the power outages. The severity of scale of outage depends on consumer type and critical load characteristics.

4) Duration: Cost of power outage is essentially influenced by the duration of the power outage. Long duration power outage have more impacts on all types of customers (residential, commercial, industrial, etc.). Consequences of long duration power outages may include loss of lives, damage to buildings and infrastructure, discomfort, and irritation. Although short duration outages may not have much impact for residential customers, commercial and industrial customers may experience huge loss for both momentary and long duration outages.

5) Advanced warning: If an outage is anticipated, the damage from the power outage could be much less than that if it is unexpected. Advanced warning may help to shift the power use patterns for flexible loads. Based on the advance warning of the outage, damage of outage could be significantly reduced. For example, data can be safely saved, machinery could be safely shutdown, backup resources could be increased, and impacted residential customers can be moved to safe areas.

B. Societal Impact of Power Outages

Here we provide a brief analysis of recently used approaches for power outage cost estimates. Outage cost estimation generally falls into three approaches [5], [11]: (a) estimation of cost based on case studies; (b) survey based approach for outage cost estimation; and (c) economy-wide macroeconomic approaches.

Case studies based methods utilize real power outage repositories (e.g., blackout data) to estimate the power outage cost. These studies are real, provide more accurate estimates, and do not depend on hypothetical assumptions. The major disadvantages of these approaches are: (a) there are a very few outages, specifically, in developed countries; therefore, not enough data for analysis and validation; (b) since most large scale outages are unplanned and unanticipated, it is difficult and expensive to gather the relevant data from the real power outages; and (c) these studies are focused on specific events and locations; therefore, these studies are limited for use in future power outage cost estimation for resilience analysis. For detailed information on outage case studies, refer to [19]–[22].

Survey-based approaches perform the end use customer survey to determine the cost of power outages. In these approaches, customers are asked for their willingness to pay for a hypothetical power interruption or willingness to accept the cost for a hypothetical power interruption. The main disadvantages of these approaches include: (a) they are based on empirical assumptions and hypothetical situations; (b) there is a large discrepancy between willingness to pay and willingness to accept values determined which clearly shows confusion of the end use customers; and (c) they are very time consuming and expensive. Significant work, for example [23]–[30], from all around the world have used survey-based methods for the estimation of power outage cost.

Economy wide macroeconomic approaches use economic indicators such as employment rate and regional economic output. Economy based models consider the electricity as input to production of goods. Therefore, the economic indicators can estimate the cost of power outages. Economy based approaches generally use publicly used data and are easier to implement. Economic models are more appropriate for macro level studies. However, they are not very useful for individual customer level studies. It is generally difficult to obtain the cost of power outage for a specific duration from the macro economic approaches. Qualitative and quantitative analyses of power outage cost estimation approaches are provided in [5]. In [11], the authors have provided an approach to estimate the power outage cost. Authors of [31] have incorporated the duration-dependent customer damage functions into energy planning and operations decisions.

Utilities have used the Interruption Cost Estimate (ICE) calculator (an example of survey-based methods) from the Lawrence Berkeley National Laboratory (LBNL) to estimate the interruption cost to value potential benefits of preventive investments [32]. However, ICE Calculator is based on economic surveys of short-term interruptions (up to 16 hours). LBNL team suggests that the estimates obtained from ICE calculator are inappropriate for resilience planning [25] because resilience studies are concerned with longer-duration events (24 hours or more)—the rate of interruption cost increases with the increase of outage time.

Although there are several limitations in determining the long-duration outage cost through the extrapolation of short-duration costs, they are currently the only available means to calculate customer costs for longer-duration outages. As far as we know, there are no credible sources that provide power outage costs for longer-duration outages, which is needed for resilience valuation. In this work, we have used extrapolation techniques to generate the data. Note that these data are used for demonstration purpose only; real data must be used for any actual analysis. A curve fitting approach is used to extrapolate cost data for outages beyond 16 hours using the available cost data for outages up to 16 hours. Using the available data, different types of models are fitted and the model with the least value of root mean squared (RMS) error is used for extrapolation.

III. Resilience Valuation Metric

A methodology for valuing non-energy savings for energy security projects is provided in [33], which is based on the reliability of the commercial power supply and cost of power outages. The report provided in [33] uses reliability indices SAIDI, SAIFI, and ASAI to estimate the avoided cost for outages that mostly last for less than 24 hours. In this paper, we consider events that last for more than 24 hours. We have found that twenty-four hours mark is the approximate point at which the literature makes the distinction between short-duration and long duration outages [18], [24], [26]. As power system resilience evaluation is generally considered for longer-duration outages, we have taken 24 hours (1 day) threshold for resilience evaluation.

A. Response to Extreme Events

To develop a resilience valuation metric, it is important to understand potential degradation and recovery of power supply. For a building (or a group of buildings) to provide power supply robustness (i.e., withstand and absorb), it must have a local energy source (e.g., distributed energy resource or DER). The end goal of this task is to develop resilience valuation metrics for solar plus storage based on (a) providing uninterruptable power supply (withstand) and power supply to critical loads during contingencies (absorb), and (b) reducing amount of interrupted loads (absorb) and interruption time (recover). Several metrics and methods can be used to value resilience. In this work, we have developed two metrics for resilience valuation, which are the expected cost of service interruption due to extreme events (ECOSIEE) and avoided interruption costs due solar plus storage (AICSS).

B. Expected Cost of Service Interruption

The ECOSIEE metric provides a valuation measure to interruption costs. It can also be used to measure the ability of a system to recover from potentially disruptive events. Power outages that last for more than 24 hours are considered for resilience valuation, i.e., events that last for less than 24 hours are included in existing reliability metrics.

The following variables are used in the development of the proposed ECOSIEE metric:

- Outage duration, D, which depends on disaster type; in this work, D is considered at least 1 day, i.e., $D \geq 24$ hours. D is a vector with dimension of $(1 \times n_d)$, where n_d is number of intervals of the studied period.
- Season, S, where the year is divided into four seasons (spring (Sp), summer (Su), autumn (Au), and winter (Wi)). Each season is divided into three periods: morning, afternoon, and night. Therefore, S is a vector with dimension of (1×12), i.e., 4 seasons and three periods per day.
- Load types: essential (Es), priority (Pr), and discretionary (Di) loads.

Other factors can be included in this metric such as scale of outage, advanced warning, and time of the event. These factors can be modeled with the amount of the lost load. For example, advanced warning can reduce damage and loss of critical loads; scale of outage can impact the amount of lost load; and events during weekday or weekend have different cost of outages.

To develop this metric, consider a matrix of outage cost, $C(S, D)$, which is a function of outage duration, season, and load type. The dimensions of this matrix is $(12 \times 3n_d)$, which can be expressed as follows,

$$C(S, D) = [C_{Es}(S, D) \quad C_{Pr}(S, D) \quad C_{Di}(S, D)] \tag{1}$$

where $C_{Es}(S, D)$, $C_{Pr}(S, D)$, and $C_{Di}(S, D)$ are respectively cost of interruption matrices for essential, priority, and discretionary loads for the set of time intervals and four seasons. These matrices have dimensions of $(12 \times n_d)$, i.e., four seasons with n_d outage intervals in each season.

Cost of interruption of essential loads for element i of the season vector and element j of outage duration vector, $CIC_{i,j}$, can be expressed as follows,

$$CIC_{i,j} = C_{i,j}(S, D) \tag{2}$$

Cost of interruption of essential and priority loads, $CICM_{i,j}$, for same outages of (2) can be expressed as follows,

$$CICM_{i,j} = C_{i,j}(S, D) + C_{i,j+n_d}(S, D) \tag{3}$$

In (3), we increase the index j by n_d because the priority load belongs to $C_{Pr}(S, D)$ in (1).

Cost of interruption of all loads, $CIAL_{i,j}$, for same outages of (2) can be expressed as follows,

$$CIAL_{i,j} = C_{i,j}(S, D) + C_{i,j+n_d}(S, D) + C_{i,j+2n_d}(S, D) \tag{4}$$

In (4), we increase the index j by n_d and $2n_d$ because the priority and discretionary loads belong to $C_{Pr}(S, D)$ and $C_{Di}(S, D)$, respectively, in (1).

The proposed ECOSIEE index can be calculated as follows:

$$\text{ECOSIEE} = \sum_{i=1}^{12} \sum_{j=1}^{n_d} P_{i,j}\{x_i : x_i \in X_{ex}\} C_{i,j} \tag{5}$$

where $P_{i,j}\{x_i : x_i \in X_{ex}\}$ is the probability of service interruption duration D_j during season S_i due to extreme events, where X_{ex} is the set of service interruptions due to extreme events; and $C_{i,j}$ is cost of service interruption for interruption duration D_j during season S_i. In (5), the summation is taken over 12 periods because we consider four seasons with three periods in each day, i.e., morning, afternoon, and night.

C. Resilience Value of Solar plus Storage

Avoided interruption costs due solar plus storage (AICSS) can be used to measure the resilience value of solar plus storage. The metric of AICSS provides a measure for avoided costs due to the ability of a system to withstand contingencies without suffering operational compromise, which can be offered by solar plus storage.

The underlying concept of calculating the AICSS is similar to calculating the expected cost of service interruption due to extreme events (ECOSIEE) except that it represents the difference between the cost of interruptions with and without adding solar plus storage. In other words, the duration of outages in the matrix given in (1) must be updated to represent outages avoided due to solar plus storage rather than total outage time. In other words, the new outage duration in (1) will be less than the original outage duration. For each event, the time during which the solar plus storage system can provide power supply and corresponding outage cost (if solar plus storage are not added) are used to calculate the AICSS. Mathematically, AICSS can be represented as follows.

$$\text{AICSS} = \sum_{i=1}^{12} \sum_{j=1}^{n_d} P_{i,j}^{mod}\{x_i : x_i \in X_{ex}\} A_{i,j} \tag{6}$$

where $A_{i,j}$ is avoided cost of service interruption due to solar plus storage for *potential* interruption duration D_j during season S_i.

D. Calculation Procedure

The following steps are used to calculate the resilience valuation metrics.

1) Collect data which include historical outage data, extreme event data according FEMA regions (it can be divided into smaller zones if need be), typical critical load profiles, solar radiations in a given site, and outage costs.
2) Analyze data as follows: remove all events that last for less than 24 hours; filter outage data based on common disasters in a given region; and create probability distribution functions for outages, which can capture both likelihoods and duration of outages.
3) For passive buildings, which do not have local DERs (e.g., solar plus storage in this case), calculate resilience value by summing up multiplications of likelihood, duration, and cost of outages. This value can be used to calculate how much can be lost if solar plus storage are not integrated to a building or center.
4) For active buildings, which have DERs, calculate the difference between resilience value before and after adding DERs, which represents the resilience value of DERs.

IV. Case Study

The proposed resilience valuation metrics are used to estimate the value of resilience of solar plus storage at the Reno's Public Safety Center (114,500-square-foot building). The City's new Public Safety Center will be located in a retrofitted building originally occupied by a newspaper company. The new facility will house Reno's police and fire services, as well as evidence storage and other services.

Sequential Monte Carlo simulation with the importance sampling approach is used to estimate the average annual interruption cost due to extreme events.

Outage duration: the mean time between outages and mean time of outages are calculated using outage data in FEMA region 9 (California, Nevada, and Oregon). The total number of events recorded since 2002 till 2020 in region 9 is 471 events.

Based on the outage data, the mean time between outages and mean time of outages for all events are respectively 346.58 hours and 21.97 hours. When considering only outages that last for more than 24 hours, the mean time between outages and mean time of outages are respectively 1839.36 (76.64 days) and 61.67 (2.57 days) hours—these values represent the entire region. Scaling up or down these numbers to match a specific area within a region will be required. For example, mean time between outages and mean time of outages at building in a city is less than mean time between outages and mean time of outages of a FEMA region.

Load and DER size: The total annual electricity consumption of the Public Safety Center is estimated to be 4.2 GWh. The peak demand of the building is 1,427 kilowatts (kW) in August when air conditioning loads are the highest, and 402 kW in December. In this case study, the critical load is assumed to be 15% of the building hourly load, which corresponds to 215 kW as a peak critical load (15% of 1,427 KW). The cost of interruption is calculated for the cases before and after installing solar plus storage. The size of the battery is 215 kW/1,720 kWh and the size of solar PV is 430 kW. The requred area to install PV panels with size of 430 kW is about 32,000-square-foot, which would approximately occupy 28% of the roof of the building.

Based on the above values and parameters, the total cost of interruption per year before adding the solar plus storage is $2,475, and total cost of interruption per year after adding the solar plus storage is $150. Therefore, the avoided interruption cost per year due solar plus storage (AICSS) is $2,325. It is worth mentioning here that the cost of power interruptions after adding solar plus storage is not zero because we included solar energy variability in the analysis—i.e., if power outages occur during cloudy days, the PV system cannot supply the demand and same time fully charge the battery.

V. Conclusion

This paper has provided a resilience valuation approach for solar plus storage. The approach was based on Monte Carlo simulations of extreme events utilizing Importance Sampling technique. Resilience value of solar plus storage was estimated based on likelihood of power outages and expected outage times due to extreme events in a given FEMA region, expected cost of outages, and critical load characteristics. The proposed approach was used to estimate the resilience value of solar plus storage in a facility owned by the City of Reno, Nevada. Although resilience value of solar plus storage alone may not justify capital investments, stacked value of resilience value, revenues, renewable energy credits, etc. may justify an investment. Also, resilience valuation can be used to compare investment alternatives.

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