VALUING RESILIENCE IN ELECTRICITY SYSTEMS

Recent natural disasters resulting in long-duration power outages have highlighted the United States' increasing dependence on electricity, as well as the increasing vulnerability of the electric system. As utilities and system operators develop plans to upgrade current electricity systems and build new ones, they need ways to quantify, value, and monetize the resilience provided by different system designs.

Quantifying Energy Resilience

A resilience metric is used to quantify the ability of an energy system to prepare for and adapt to changing conditions, and withstand and recover rapidly from disruptions (Table 1). No one definition or metric can be applied broadly; rather, the appropriate metric depends on goals, event context, hazards, scale, and perspective. For example, a community may want to measure the number of essential services impacted during an outage, like hospitals, shelters, or gas stations. A military base, however, may want to measure how long its critical load can be served with backup generation. To inform planning and investment decisions, we need performance-based metrics that consider the likelihood that a hazard and its consequences will be realized, and the temporal evolution of the corresponding outage event.

Performance-based metrics can be used to measure the potential impacts of a resilience investment. For example, consider a military base that uses building-tied diesel generators and on-site fuel storage to power its critical loads during an outage. The resilience of this system can be measured in the number of hours the diesel generators can sustain the load. The duration could be increased through various options, such as building additional on-site fuel storage, integrating renewable energy and storage alongside the diesel generators in a microgrid configuration, and incorporating energy efficiency measures to reduce critical load. Figure 1 shows how survivability increases from five to nine days at no additional life cycle cost by adding solar and storage to extend the supply of available backup power.

Reliability versus Resilience

Reliability is the ability to maintain power delivery to customers in the face of routine uncertainty in operating conditions, as in cases of fluctuating load and generation, fuel availability, and outage of assets under normal operating conditions. Reliability events typically result in shorter outage durations (seconds to hours) and smaller areas of impact (facilities, campuses, or neighborhoods).

Resilience focuses on preparing for, absorbing, adapting to, and recovering from low-probability, high-consequence disruptive events. Resilience events typically result in longer outage durations (days to months) and larger geographic areas of impact (states, regions, or islands). As a result, they could lead to cascading impacts in other critical infrastructures and parts of the economy.

Table 1. Evaluating a Resilience Investment Requires Quantifying, Valuing, and Monetizing Its Impact on System Resilience

Quantifying Resilience	Valuing Resilience	Monetizing Resilience
A resilience metric measures how resilient an energy system is. Performance-based metrics quantify the consequences that could be avoided as a result of a resilience investment: • Customer outage time (hours) • Load not served (kilowatt-hours) • Number or percentage of customers experiencing an outage (# or %) • Number of critical services (e.g., hospitals or fire stations) without power (#) • Time to recovery (hours) • Cost of recovery ($)	Determining the value of a resilience investment (in dollars) is an essential component of cost-benefit analysis. An accurate resilience value involves determining the avoided costs of an outage, including the direct and indirect costs incurred by the service provider, customers, and society: • Loss of utility revenue ($) • Cost of grid damages ($) • Cost of recovery ($) • Avoided outage cost ($) • Loss of assets and perishables ($) • Business interruption costs ($)	Resilience monetization determines what portion of the resilience value can be realized in cash flow to finance project implementation. Beyond the improved resilience itself, such an evaluation should consider all available revenue streams associated with the investment: • Reduced insurance rates • Reduced mortgage rates • Government incentives • Grid services value • Resilience payment from site host

	Generator	Solar PV	Storage	Life Cycle Cost	Outage
1. Base case	2.5 MW	-	-	$20 million	5 days
2. Lowest cost	2.5 MW	625 kW	175 kWh	$19.5 million	6 days
3. Proposed system	2.5 MW	2 MW	500 kWh	$20 million	9 days

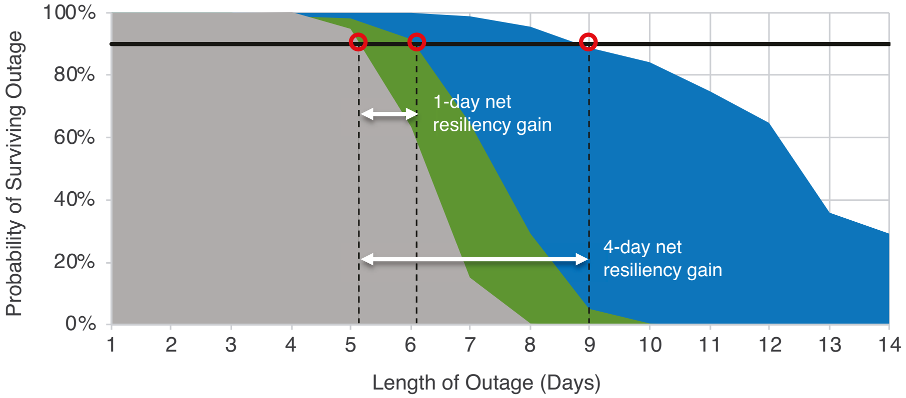

Figure 1. The metric of days of survivability is used to quantify the resilience benefit of adding solar and storage to existing diesel generators in a microgrid.

Valuing Resilience

While quantifying resilience is necessary, it is not enough. Resilience investments often take the form of a cost-benefit decision, so we must be able to weigh the cost of an investment against the value, or benefit, it provides. In some cases, resilience value will change investment and operational decisions (Figure 3).[1] In Figure 1, outage survivability increased from five to nine days, but we do not yet know what losses we avoided and whether the financial benefit was more than the investment cost.

Multiple resources provide data on the costs associated with potential resilience improvements, but information on the value of resilience is limited. The most common metric for valuing resilience is value of lost load (VoLL), which may include loss of assets and perishables, business interruption costs, and recovery costs. Preliminary estimates of VoLL for power outages can be made based on national outage survey data collected by utilities. However, these estimates are typically only applicable for short-duration outages of less than one day, and they typically do not account for how costs vary over the course of an outage event.[2] More accurate (but more time-consuming) characterizations can be made by using surveys to collect data on the consequences of an outage at a specific site.[3] This results in a customer damage function, which describes how the cost of an outage varies over time for different event scenarios.[4] Resilience can also be valued by a customer's willingness to pay, but information on what individuals and society are willing and able to pay to avoid the consequences of disruptive events is limited.

Beyond the time- and customer-dependent VoLL, accurately determining the value of a resilience investment requires an evaluation of the likelihood and extent to which it would help mitigate the consequences of an outage. In general, there is an inverse relationship between the level of rigor and ease with which such an analysis can be performed. Therefore, stakeholders must determine the ideal approach across the spectrum, keeping in mind that it may be important to avoid letting the best analysis be the enemy of a good analysis.

Value of Lost Load

VoLL describes the costs associated with electric grid outages and represents an approximate price that consumers are willing to pay for uninterrupted electricity. VoLL is typically measured in units of dollars/kilowatt-hour, and it can be multiplied by the lost load to estimate the total cost of an outage. Established VoLL estimates—which primarily reflect outages of less than one day—range from $1/kWh to $300/kWh, and they vary with the attributes and context of an outage (e.g., timing, duration, season, region, and location).

For long-duration events, it is critical to understand how the VoLL varies over time and by customer class. For example, a grocery store may experience high costs from loss of spoilable stock in the first days of an outage, but after that costs will level off as there is less stock left to spoil. By contrast, the VoLL for a National Guard site may be low during the first days of an outage, but climb exponentially higher as Guard members are activated to respond to the causes and impacts of a long-term outage (Figure 2).

The most informative version of the VoLL will depend on its application and the decision it is informing. For example, a system or site operator seeking to minimize the financial consequences of a long-duration outage would likely be interested in the functional form of the time-varying VoLL, which demonstrates at what point the costs begin to grow more rapidly. However, a city planner or insurance company may be more interested in the integrated value of the VoLL over the course of the outage, which provides a snapshot of the overall consequence. Both examples are based on the same underlying information, but the ultimate presentation of the metric depends on the information sought by a given stakeholder.

Figure 2. VoLL varies over time and by type of customer.

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[1] Laws, Nicholas, Kate Anderson, Nicholas A. DiOrio, Xiangkun Li, and Joyce McLaren. 2018. "Impacts of Valuing Resilience on Cost-Optimal PV and Storage Systems for Commercial Buildings." *Renewable Energy*, Nov. 2018, vol. 127, pp. 896-909. https://doi.org/10.1016/j.renene.2018.05.011.

[2] "Interruption Cost Estimate (ICE) Calculator." n.d. Lawrence Berkeley National Laboratory and Nexant, Inc. Accessed August 2019, https://icecalculator.com/.

[3] Electric Power Research Institute (EPRI). 1996. "Outage Cost Estimation Guidebook." TR-106082, May 22, 1996. https://www.epri.com/#/pages/product/TR-106082/?lang=en-US.

[4] Ericson, Sean and Lars Lisell. 2018. "A flexible framework for modeling customer damage functions for power outages." *Energy Systems*, Nov. 2018, pp. 1–17, https://doi.org/10.1007/s12667-018-0314-8.

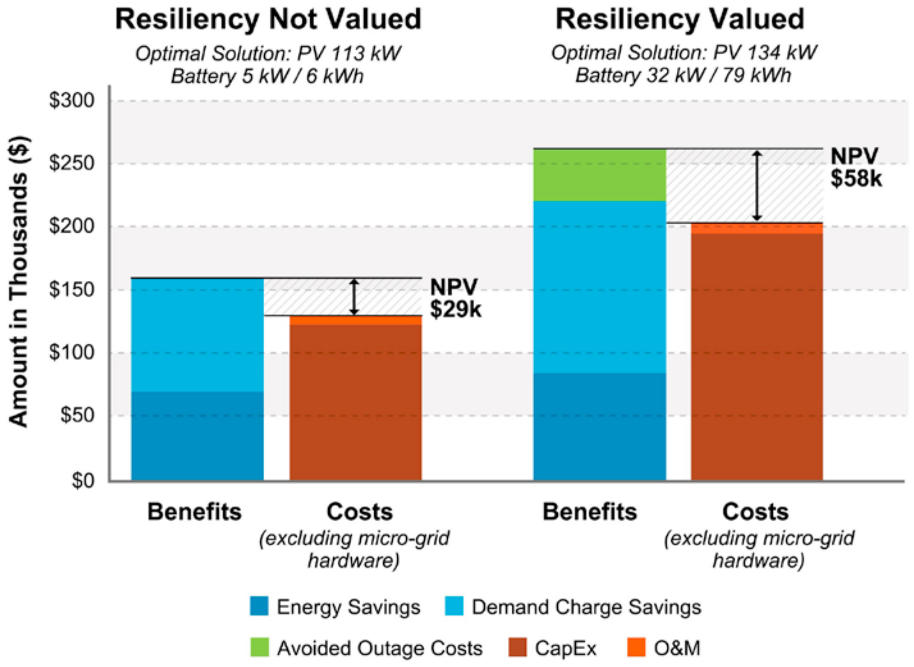

Figure 3. Accounting for the value obtained by mitigating the outage experienced by a facility or campus results in a cost-optimal backup power system that is larger and incorporates longer-duration storage, as modeled in a REopt™ analysis. *Image from "Impacts of Valuing Resilience on Cost-Optimal PV and Storage Systems for Commercial Buildings" (see footnote 1).*

Levels of Rigor in Resilience Analysis

When quantifying resilience, the best approach is to perform a quantitative analysis on the specific system, considering the likelihood of both a given hazard and its consequences. In its ideal form, this requires detailed data on the individual system and its natural environment; a stochastic representation of hazards and consequences; and substantial analytical resources. Since these are not always available, this approach will not always be feasible.

Alternative approaches to consider could include simplifying assumptions (e.g., representative data, deterministic modeling, or spreadsheet analysis), or attribute-based approaches. The latter option, however, doesn't allow for an optimized prioritization of investment options, since it relies on an assumption that a more robust or redundant system will be more resilient.

Monetizing Resilience

After quantifying and valuing resilience, a final challenge lies in monetizing the value associated with a resilience investment. In particular, few tools can be used to monetize the value of resilience into cash flows to finance a project. Grid services are the primary value stream available today, while other potential value streams are limited or unavailable at this time—such as a monthly resilience payment from the site host in exchange for improved resilience, reduction in insurance premiums or mortgage rates to reflect lower risk of damage from loss of power, and incentives to increase resilience and reduce costs of government-funded disaster relief. Table 1 compares quantifying and valuing resilience with monetizing resilience.

Conclusions

As we build the power system of the future and seek strategies for improving the resilience of installations and campuses, integrating the value of resilience into investment and operation decisions is critical. This is challenging, due to the context-specific and diffuse nature of benefits, the difficulty of obtaining the data required to accurately determine the benefits associated with a given investment, and the lack of universally accepted resilience metrics and analysis approaches. Ongoing work focuses on understanding:

- How VoLL evolves over time during a long-term disruptive event, for different customer classes and regions
- The nature of system-wide consequences due to sectoral interdependencies (e.g., water, telecommunications, and natural gas)
- The relationship between distributed energy resources and resilience, particularly in terms of their potential to mitigate long-duration outages
- How to translate the consequences of such an event into associated impacts on societal welfare through health, safety, and the economy.

Though no one metric will cover all resilience planning needs, measuring the benefits of resilience investments, along with establishing valuation methodologies for such measures, will help enhance our ability to monetize investments associated with a more resilient electricity supply.

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