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Valuing Resiliency from Microgrids: How End Users Can Estimate the Marginal Value of Resilient Power

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VALUING RESILIENCY FROM MICROGRIDS:

HOW END USERS CAN ESTIMATE THE MARGINAL VALUE OF RESILIENT POWER

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The Cleveland Foundation

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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“Recommendation 1 to [Department of Energy]: Improve understanding of customer and society value associated with increased resilience….”

Consensus Study Report on “Enhancing the Resilience of the Nation’s Electricity System,”
National Academies of Science, Engineering and Medicine,
September 2017.

Executive Summary

Resilient energy systems are becoming a higher priority in the United States. Resiliency has become higher profile recently following a series of major storms in the U.S. Gulf Coast plus cyber-security failures. The U.S. Department of Energy and the National Academy of Science both published reports in September of 2017 on the state of U.S. Grid reliability.

Yet, as noted by the Academy of Science, we still do not really have a sense of the value of resiliency to customers. Most studies have focused primarily on understanding the cost of lost production. Economists have developed strategies for estimating the value of lost load (VOLL) for certain industries based upon the ratio of the gross domestic product for that industry to the total electricity consumed. The VOLL estimate, in this sense, is equivalent to the value of lost opportunity associated with a power outage.

The Study Team used this strategy to estimate the cost of lost load for a broad range of industries, using the North American Industry Classification System (NAICS) to group the sectors. Based upon these estimates, the Study Team determined that certain industries, such as computer systems design, scientific consulting services and legal services incur $80-$100/kWh in lost productivity. Thus a law firm with a 100 kW load would lose $8,000 in an hour. Even some forms of manufacturing, generally considered the most capable of industries to handle interruptible power, suffer around $40/kWh. For instance, a household goods manufacturer with a 10 MW load loses $400,000 in an hour.

However, VOLL is just one way to estimate the value of resiliency to a customer. Another way to estimate value is to identify the costs of building back-up power systems. This can be done by looking at the costs data centers incur by improving their electricity uptime to increasingly higher levels. The Study Team used the Expedient data center “build versus outsource” algorithm, holding all parameters but reliability level constant, and estimated the costs of upgrading the system to each new level. From this, capital investment and labor costs of resiliency can be estimated.

Most data centers seek 99.999% (5-nine) uptime. This is representative of the standard of resiliency needed by many businesses and organizations that have critical infrastructure requirements, such as communication industries, military bases, and emergency management. The cost of achieving 5-nine reliability can be estimated for Northeast Ohio by first looking at the state of resiliency for the local utility, Cleveland Electric and Illuminating Company (CEI). Based upon the outage records reported to the Public Utility Commission of Ohio (PUCO), the Study

Team determined that CEI has averaged around 99.93% uptime over the past 8 years. This excludes power quality problems, such as voltage sags, which are not reported to the PUCO.

To get from 99.93 to 5-nine reliability, a customer would have to spend the equivalent of around 5-6 cents/kWh on an ongoing basis. This assumes that all equipment built has a 15-year life, except for the uninterruptible power supply (UPS) system (battery and controls), which have a 5-year life. This also assumes 6.5% rate for the cost of money.

A business that hooks up to a microgrid would be able to avoid all or most of these costs. The UPS and back-up power systems required could be replaced in whole or in part by the microgrid, which would be able to provide full resiliency. Other costs may also be avoided in whole or in part through a microgrid, such as demand and transmission charges, and business interruption insurance premiums.

I. Introduction

This report is part of a general microgrid planning evaluation for Cleveland, Ohio undertaken by Cleveland State University and Case Western Reserve University, underwritten by the Cleveland Foundation.[1] The evaluation has been undertaken in collaboration with Cuyahoga County and the City of Cleveland. This report focuses on one of the more important questions posed in building a microgrid: what is the marginal value of reliable power to end users?

Microgrid systems are often identified as a strategy for enabling a more rapid adoption of renewable power generation. Microgrids promise to better capture the value of distributed but intermittent power sources through electricity storage and smart control systems. Yet the opportunity to build microgrid infrastructure is accelerating due not just to improvements in storage and control systems, but also due to cheap natural gas from shale development. Importantly for microgrids, natural gas generation plants also provide "flexibility and fuel efficiency."[2] New natural gas plants are better suited than traditional generation to respond to the "faster pace of grid operations driven by variable generation."[3] In short, natural gas is making it easier to include intermittent generation in the power grid. This will be especially true when used in microgrids, where systems can be optimized through state of the art storage and controls used in concert with natural gas generation.

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[1] The Microgrid Cleveland Study Team, referenced as "µGrid Cle," consists of Cleveland State University's Energy Policy Center (Urban College), Case Western Reserve University's Great Lakes Energy Institute, Cuyahoga County and the City of Cleveland, and several consultants. The principal researchers and authors of this document are: Andrew R. Thomas, Robert A. Simons, Rajiv Choski, and Mark Henning, Cleveland State University; Grant Goodrich, Ken Loparo, Alexis Abramson and Reza Jamalzadeh, Case Western Reserve University; Ali Ahmed, Green Strategies, LLC; Marc Divis, Cleveland Thermal; Michael Foley, Cuyahoga County; Glenn Krassen, Bricker & Eckler; Anand Natarajan, City of Cleveland and John Juhasz, Telepath Systems, Inc.

[2] A. Silverstein, "If I'd Written the DOE Grid Study Recommendations," *Utility Dive*, October 7, 2017, found at: http://www.utilitydive.com/news/silverstein-if-id-written-the-doe-grid-study-recommendations/506274/

[3] *Id*.

However, an important near-term promise that microgrids offer today is reliable power. Microgrids use a combination of distributed generation, batteries and advanced control systems to ensure that power is always available and dispatched in the amounts and condition required to manage the local load. They are capable of separating from the main grid during a power outage, going into an "island" mode, and thereby providing their customers with power during general grid outages.

But this sort of electrical system resiliency costs more. How much more depends upon the circumstances and the complexity of the potential microgrid scope. Inevitably, it leads end users to ask: what is resilient power actually worth to me? Putting numbers on the cost of outages to consumers can be difficult. Much depends upon the duration of the outage, the type of business involved and the timing of the event.

Yet it is important to end users that the added value of resiliency be estimated. It is also important that such estimates be relatable to businessmen, such as on a per-kWh basis. Many end users develop their energy procurement strategy without understanding the nuance of energy system design or costs.

There are several ways for an end user to go about assessing the value of resiliency. One relatively straightforward way is to observe how business interruption insurance changes as a result of acquiring resiliency. It is probably too early to project how microgrids will affect business interruption insurance – there are only around 15 microgrids in operation in the United States that have commercial end users.[4] We can expect, however, that this will be a relevant future metric for companies that are looking to build or join a microgrid. The extent to which the microgrid controller warrants delivery of power will likely affect insurance premiums.

Another strategy, developed by the National Renewable Energy Laboratory, is instructive. NREL examined the value that energy storage has in reducing "demand" charges. Demand charges[5] are designed to enable the utility to recover costs associated with having to maintain

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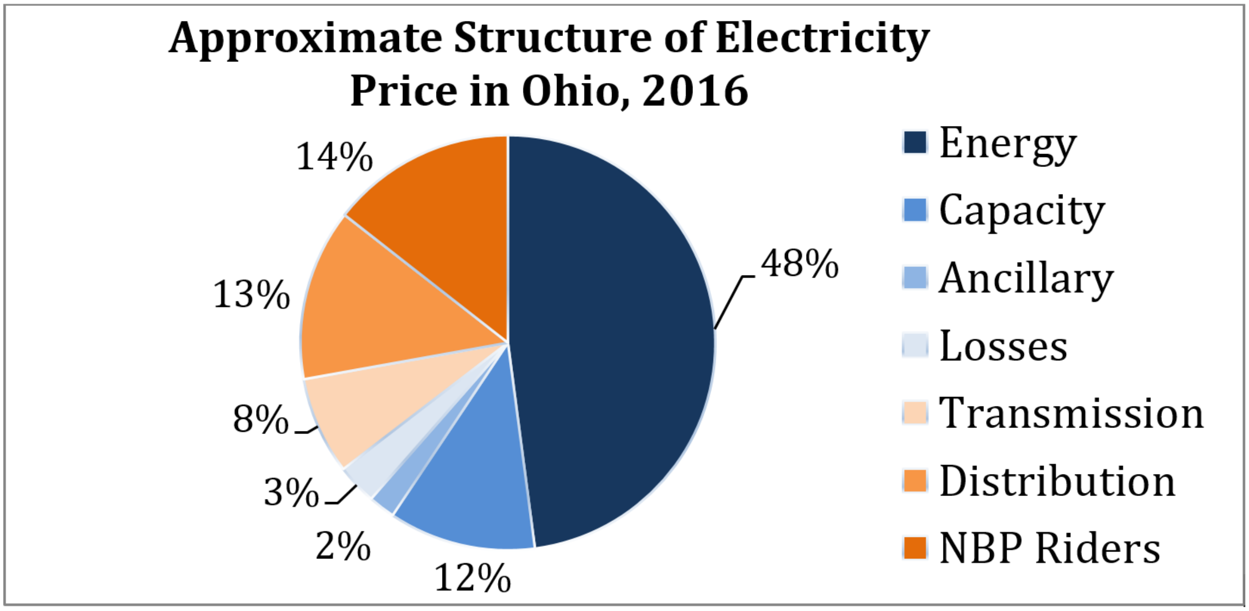
[4] The estimate of 15 microgrids with commercial loads comes from a compilation of several reports, including the following: "Microgrids & District Energy: Pathways to Sustainable Urban Development." *Pace Law.* (n.d.). Accessed August 24, 2017, http://energy.pace.edu/publications/microgrids-district-energy-pathways-sustainable-urban-development; "New York State Microgrid Inventory." *Navigant Research* (on behalf of the New York State Smart Grid Consortium). (2015). Accessed August 24, 2017, nyssmartgrid.com/wp-content/uploads/NewYorkStateMicrogridInventory_2015-08-1331.pdf; and *Microgrid Knowledge.com*, a website devoted to tracking developments in microgrids.

[5] Many utilities use the term demand charge and capacity charge" interchangeably, and some utilities have both demand and capacity charges. In deregulated markets, it is common to use the demand charge to recover for standby distribution assets, while the capacity charge is used to recover for standby generation assets. Both often are determined through a complicated formula that consider such things as peak load contribution, ratchets and other accounting devices. PJM Interconnect, the Regional Transmission Organization for the Mid-Atlantic states, compares its capacity charge to a parking lot for a big box store: parking must be available to accommodate "Black Friday" shopping, even though much of the lot will be vacant the rest of the year. *See* "Capacity Markets," *PJM Learning Center*, found at: https://learn.pjm.com/three-priorities/buying-and-selling-energy/capacity-markets.aspx

infrastructure so that it can deliver power during peak demand periods. This infrastructure – which includes wires, transformers, substations and other equipment -- may otherwise be idle, and as a result expensive to build and maintain. The end user's demand charge normally is determined by its maximum monthly usage during a short interval of time, such as 15 minutes.

Demand charges are most commonly assessed to commercial and industrial users, and are not trivial. NREL determined that 25% of commercial customers pay demand charges greater than $0.015/kWh.[6] Moreover, there may be another utility charge for standby power: end users may also have to pay a "capacity" charge. Capacity charges are similar to demand charges, except that they are designed to compensate the utility for maintaining standby generation to supply peak customer requirements. In Ohio, a typical commercial customer pays around 13% of its total electrical cost as a distribution charge, of which the demand charge is a significant portion, and another 12% of its total cost in capacity charges (*see* Figure 1). This could mean another penny per kWh cost for a customer.

Figure 1. Cost Structure for Mercantile (over 750,000 kWh/yr) Consumers in Ohio, 2016.



Source: Scioto Energy (2017). Assumes: 47% load factor for Secondary, 67% load factor for Primary Power Customers.

Having back up power, in the form of batteries, uninterruptible power supply systems and local generators, may be able to reduce both demand and capacity costs. Through these systems end users can shave its own peak demand and also reduce coincident peak contribution during peak

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[6] *See* J. McLaren et al, "Identifying Potential Markets for Behind the Meter Battery Energy Storage: A Survey of the U.S. Demand Charges." National Renewable Energy Laboratory (2017) https://www.nrel.gov/docs/fy17osti/68963.pdf See also: E. Wood, "Wondering if Energy Storage Can Reduce Your Demand Charges," Microgrid Knowledge, August 24, 2017, found at: https://microgridknowledge.com/demand-charges-energy-storage/

grid times, such as hot summer afternoons. Utilities charge more for capacity when the end user's peak requirements coincide with peak demand on the grid.

But constraining demand or capacity charges require end users to actively manage their use in response to weather changes and other events. Further, it is not entirely clear how demand charges will be assessed within a microgrid. Microgrids may be able to disengage from the grid not only during outages, but also, for economic reasons, during peak grid demand. Indeed, microgrids may even be able to sell excess power into the grid during times of peak demand. Accordingly, the savings that microgrids supply to end users from demand or capacity charges will be highly dependent upon circumstances.

Two other ways can be used to estimate the added value of resiliency: (1) determining the value of lost load (i.e. lost business opportunity) and (2) determining the value of avoided costs. This study has undertaken to examine ways these estimate the value of resiliency for end users through these two strategies. To do this, we must start first with an understand of how resilient the grid currently is in its present form.

II. Current Levels of Grid Resiliency

To understand the value of resiliency to customers, we must first consider the current status of resiliency in terms of the frequency and duration of loss (or diminishment) of power supply. Once we understand these, we can compare this to what level of resiliency would be desirable, and then assess the costs of achieving that level.

Many urban areas have a choice of an investor-owned utility or a municipally owned utility for delivery of electricity. Cleveland, Ohio, for instance, has two distribution utilities: Cleveland Electric and Illuminating Company (CEI) and Cleveland Public Power (CPP). CEI is a subsidiary of FirstEnergy, Inc. and is regulated by the Public Utility Commission of Ohio (PUCO). CPP is a municipally owned utility, and is not subject to PUCO oversight, but rather has local government oversight.

For purposes of estimating the reliability of the existing grid, CEI serves as useful guide for understanding likely outages. This is so for two reasons. First, because Cleveland is relatively safe from natural disasters compared to other urban areas,[7] CEI serves as a conservative example for estimating downtime. Second, CEI reports its outages to the PUCO. Cleveland's municipal utility, Cleveland Public Power, is not required to file outage reports with PUCO, even though it is likely to be at least as resilient as the investor-owned utility. Municipal utilities tend to have fewer

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[7] *See e.g.* E. Bamforth, "Cleveland Ranks No. 2 in Safety from Natural Disasters," *Cleveland.com*, September 8, 2017, (citing CBS News), found at: http://www.cleveland.com/metro/index.ssf/2017/09/cleveland_ranks_2nd_in_list_of.html

interruptions because power lines are below ground and because customers are located closer together.[8]

Table 1 shows the average annual number of interruptions per customer served and average minutes per customer interruption between 2014 and 2016 for Ohio investor-owned electric utilities. These were estimated using data reported to the Public Utilities Commission of Ohio (PUCO).[9]

Table 1. Average Annual Frequency and Duration of Outages for Ohio's Investor-Owned Electric Utilities, 2014-2016.

Utility	Average Interruptions per Customer	Average Minutes per Customer Interruption
Cleveland Electric Illuminating Company	2.7	73.4
Ohio Edison	2.4	48.1
Toledo Edison	2.1	46.4
Ohio Power	2.7	80.7
Duke Energy	2.7	77.1
Dayton Power & Light	2.3	59.1

Source: Public Utilities Commission of Ohio[10]

The outages can be further refined based upon how they are reported. This includes the following types of outages:

> *Major events.* These encompass any calendar day when an electric utility's system average interruption duration index (SAIDI) exceeds a *major event day threshold* as defined by the Institute of Electrical and Electronics Engineers (IEEE) in their "IEEE Guide for Electric Power Distribution Reliability Indices."[11] The method for determining this threshold is to add 2.5 standard deviations to the average[12] of an electric utility's daily SAIDI performance during the most recent five-year period.[13] The SAIDI index can be characterized as indicating the total duration of interruption for the average customer.[14]

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[8] *See "*EIA data show average frequency and duration of electric power outages." *U.S. Energy Information Administration*. (2016). Accessed July 27, 2017, https://www.eia.gov/todayinenergy/detail.php?id=27892. Underground lines reduce risk from vandalism, storms, tree/limb falls, animals or other incidents.

[9] Investor owned utilities must report outages in compliance with the Ohio Administrative Code Rule 4901:1-10-10 also known as *Rule 10.*

[10] *See id.* Note that the investor owned utilities do not report all events together, as we have done here. So if one looks at the PUCO reports, one would not see a chart like this. This was created by compiling different data.

[11] Ohio Administrative Code Rule 4901:1-10-01.

[12] In practice, the average of the natural logarithms of the SAIDI index for a given utility is used to determine the major event threshold.

[13] This is known as the IEEE 2.5 Beta Method.

[14] Robinson, David G., Douglas J. Arent, and Larry Johnson. "Impact of distributed energy resources on the reliability of critical telecommunications facilities." In *Telecommunications Energy Conference, 2006. INTELEC'06.*

> Major events can therefore be described as outages where the average customer experiences a disruption lasting far longer than what is normal for a typical outage, such as those resulting from severe weather.
>
> *Transmission outages.* This describes any outage involving facilities that would be included in rate setting by the federal energy regulation commission (FERC).[15]
>
> *Momentary interruptions.* This describes electricity disruptions with a duration of five minutes or less.[16]
>
> *Distribution outage.* The Rule 10 reporting procedure does not use this term, but rather just describes the remaining outages as those not falling into the first three categories. For lack of a better descriptive term, we deploy this term as a catchall to indicate sustained interruptions within the distribution system lasting more than 5 minutes that are caused by neither major events nor transmission outages.

It is important, however, to recognize that utility reported outages *do not include "brownouts."* Brownouts refer to deteriorations in power quality, such as sags in voltage, that frequently have the same effect as a power outage, especially for businesses that rely on computers, including, among other industries, those that use sensitive devices, clean rooms, and data.[17]

Average interruptions per customer in Table 1 were calculated as the sum of two indices: (1) the system average interruption frequency index (SAIFI) for transmission, distribution and major outages using data found in the Rule 10 reports that investor-owned utilities file annually with PUCO;[18] plus (2) the momentary average interruption frequency index (MAIFI), as estimated[19] by the American Public Power Association among municipal/cooperative power utilities for "momentary" outages of five minutes or less.[20] The national MAIFI was determined to be 1.35

28th Annual International, pp. 1-7. IEEE, 2006. SAIDI reports do not typically include long duration outages. However, the PUCO requires that these are reported in Ohio, even if they are not in the SAIDI numbers. Accordingly, we were able to include long duration outages in our analysis for Cleveland Electric & Illuminating Company uptime.

[15] *See* fn 9*, supra.*

[16] *Id.*

[17] Power quality can be affected by frequency changes, voltage swings, and localized harmonics. *See* M. Hartfiel, "UPS Cures for Power Quality Problems, March, 2001, found at: http://www.ecmweb.com/content/ups-cures-power-quality-problems

[18] Rule 10 filings can be downloaded at: http://dis.puc.ohio.gov/CasesByIndustryPurposeStatus.aspx?indcode=EL&purpcode=ESS&status=OPEN&count=(32%20cases)

[19] MAIFI cannot be calculated directly for Ohio investor-owned utilities given that there is no requirement to report the number of customers interrupted during momentary outages for Rule 10 reports to PUCO.

[20] *See* "Evaluation of Data Submitted in APPA's 2013 Distribution System Reliability & Operations Survey." *American Public Power Association*. (2014). Accessed August 19, 2017, *www.publicpower.org/files/PDFs /2013DSReliabilityAndOperationsReport_FINAL.pdf.* This estimate for MAIFI is likely to be conservative given that the APPA's survey participants predominantly serve load in urban areas[20] and, as noted by the Energy Information Administration, municipal utility customers experience the lowest frequency and duration of power outages, which

interruptions per customer per utility. For comparison, in California, where MAIFI is reported for investor owned utilities, the average number of momentary outages per customer was 1.84 in 2015.[21]

Average minutes per customer interruption across all outage types, as seen in Table 1, was determined by adding up the total minutes of power disruption among all customers due to transmission, distribution and major events, which can be gathered from the reports to PUCO. To this number was added an estimate of the total minutes of power disruption among all customers due to momentary interruptions, based on the number of customers served (also available in the PUCO reports) multiplied by the MAIFI of 1.35, times an assumed average duration of 2.5 minutes per momentary interruption.[22]

This total number of minutes (transmission plus distribution plus major plus momentary interruption minutes) of interruption was then divided by the total number of customer interruptions for all outage types. This gives us the average duration per customer per outage. Those numbers are set forth in Table 1. For Cleveland Electric Illuminating Company (CEI), a typical customer averages 2.7 outages per year, with an average duration of 73 minutes.

A more detailed look at estimates for CEI's average annual frequency and duration of outages is set forth in Table 2 using the same method as in Table 1 but for a longer period of time where outages were disaggregated by type into the four categories defined earlier.

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can be attributed to fewer powerline miles per customer and underground distribution lines. *See id, and "*EIA data show average frequency and duration of electric power outages." Accessed July 27, 2017, https://www.eia.gov/todayinenergy/detail.php?id=27892

[21] *See* "California Electric Reliability Investor-Owned Utilities Performance Review, 2006-2015." *California Public Utilities Commission.* (2016). Accessed August 20, 2017, *http://www.cpuc.ca.gov/uploadedFiles /CPUC_Public_Website/Content/About_Us/Organization/Divisions/Policy_and_Planning/PPD_Work /PPD_Work_Products_(2014_forward)/PPD%20Reliability%20Review.pdf.*

[22] The average minutes per customer interruption for a given year were estimated as follows:

i. The number of customer minutes interrupted for momentary interruptions is the number of minutes per interruption multiplied by the number of these kinds of interruptions.
ii. The *number of customer interruptions due to momentary outages* was determined by multiplying the assumed MAIFI of 1.35 by the total number of customers served as found in the Rule 10 reports.
iii. This number of customer interruptions due to momentary outages was then multiplied by the number of minutes per interruption. Momentary interruptions last for 5 minutes or less by definition. However, there is no publicly available data describing the average duration of momentary outages. Therefore, a midpoint value of 2.5 minutes per interruption was used to estimate the *number of customer minutes interrupted due to momentary interruptions*.
iv. For a given year, add together all customer minutes interrupted (including those from sustained outages which are included in the Rule 10 reports) and divide this by the sum of all customer interruptions to arrive at the average minutes per customer interruption across all outage types.

Table 2. Average Annual Frequency and Duration of Outages
for CEI by Outage Type from 2009 to 2016.[23]

	Avg. Total Customer Interruptions per year	Avg. Total Customer Minutes Interrupted per year	Avg. Minutes per Customer Interruption
major event	206,892	167,540,935	624.6
transmission outage	55,146	8,260,191	120.8
momentary interruption	982,933	2,457,332	2.5[24]
distribution outage	733,900	84,305,168	114.5
ALL outages	1,978,871	262,563,626	129.3[25]

Source: Authors (2017).

Table 2 tells us that the most common interruption is the "momentary interruption," which most of us can attest to from casual observation. Our notion of a momentary interruption is often corroborated by the "resetting" of digital clocks. However, "major events" and "distribution outage" make up nearly all of the duration. Those who may value resiliency can from this determine the sort of resiliency that they may require: short term, long term or both. Table 3 sets forth the likely duration of outages based upon the last eight years in CEI territory.[26] Based upon this analysis, interruptions of less than five minutes made up around 36% of the disruptions, and disruptions of 60-180 minutes made up half the outages.

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[23] Rule 10 filings can be downloaded at: http://dis.puc.ohio.gov/CasesByIndustryPurposeStatus.aspx?indcode=EL&purpcode=ESS&status=OPEN&count=(32%20cases)

[24] MAIFI cannot be calculated directly for Ohio investor-owned utilities given there is no requirement to report the number of customers interrupted during momentary outages for Rule 10 reports to PUCO. *See also*, fn 22, *supra*.

[25] Minutes per customer interruption for all outages is a weighted average based on the contribution of each type of outage to the total number of customer minutes interrupted.

[26] The Rule 10 reports disaggregate outages by cause (e.g. animal, equipment failure, human error) along with associated data enabling the calculation of average outage duration for each separate cause. There are more than 20 different outage causes that are reported separately for each of the 3 types of non-momentary outages. This enables the construction of a frequency distribution showing the probability that an outage would last a certain length of time, given that there was a power interruption. Table 2 shows such a frequency distribution table using CEI outage data pursuant to Rule 10 for the years 2009 through 2016. Momentary interruptions were again assumed to have a duration of 2.5 minutes.

Table 3. Frequency of Average Outage Durations for All CEI Power Interruptions, 2009-2016.

t = time in minutes	outage frequency for this duration	probability of duration
$t \leq 5$	39,894	0.357
$5 < t \leq 30$	293	0.003
$30 < t \leq 60$	1,553	0.014
$60 < t \leq 120$	27,644	0.247
$120 < t \leq 180$	28,216	0.253
$180 < t < 240$	3,156	0.028
$240 < t \leq 300$	1,840	0.016
$300 < t \leq 360$	1,020	0.009
$360 < t \leq 420$	1,380	0.012
$420 < t \leq 480$	768	0.007
$480 < t$	5,958	0.053
TOTAL	111,722	1.000

Source: Authors (2017) (using PUCO reports).

The CEI Rule 10 data for this time period can also be translated into a power availability index for Cleveland. The average service system availability index (ASAI) is a commonly used measure of system wide reliability for an electricity distribution utility.[27] This metric represents the total time that service was provided to customers (net of all outages) divided by the total time that service was demanded by all utilities customers. Availability is defined by the number of "nines" for which power is up, such as "4-nines", "5-nines," etc.[28] This simply refers to the percentage of time that a customer can expect to be available, such as 99.99% of the time, or 99.999% of the time, etc.

Given the number of customers served annually by CEI between 2009 and 2016,[29] and the total minutes that service was interrupted across all outage types as found in the Rule 10 reports,[30] the average service availability was around 99.93% over this time period for the area served by the investor-owned utility. This would be equivalent to "3-nines" using the "uptime" industry vernacular for power availability. Availability of at least 5-nines, or 99.999%, in terms of both reliable and resilient power, is the general standard that companies within the telecommunications industry, including data centers, strive to achieve.[31]

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[27] Bichpuriya, Yogesh K., Prashant V. Navalkar, and S. A. Soman. "Benchmarking of reliability indices for electricity distribution utilities: approach and discussion." (2011): 14-14.

[28] Govindan, Sriram, Di Wang, L. Y. Chen, Anand Sivasubramaniam, and Bhuvan Urgaonkar. "Modeling and analysis of availability of datacenter power infrastructure." *Technical Report CSE-10-006* (2010).

[29] Service demand is calculated as the number of customers served multiplied by the number of minutes per year.

[30] *See* fn 23, *supra.*

[31] Stevenson, Rick. "How Low-Cost Telecom Killed Five 9s in Cloud Computing." *Wired.* (n.d.). Accessed August 22, 2017, https://www.wired.com/insights/2013/03/how-low-cost-telecom-killed-five-9s-in-cloud-computing. See also: *See* "Beyond five nines availability: Achieving high availability with Dell Compellent storage center (Dell Compellent White Paper)." *Dell*. (2012). Accessed August 22, 2017, http://i.dell.com/sites/doccontent/shared-content/datasheets/en/Documents/Compellent_Five_Nines_9_12.pdf

Those same industries that need 5-nines power must also maintain power quality. Utilities generally are responsible for reliability only, and not power quality.[32] Brownouts are typically handled by "Uninterruptible Power Supply" (UPS) systems. These consist of batteries and control systems that can respond instantly to surges, sags and other power quality problems.[33]

Brownouts may not be reported by utilities, but they are of great concern to many end users. While most industrial customers have a general awareness of the costs of power outages, they are commonly less aware of the costs associated with poor power quality. These costs can show up in plant downtown, equipment replacement, lost work in process, additional labor, missed shipment deadlines and so on.[34]

III. Valuing Resiliency

A. Who Needs Resiliency

The easiest way to determine who might pay for energy supply security is to identify who expends what money on power backup facilities.[35] In Ohio, state EPA permit data may be indicative of who may be interested. The permit provisions for air pollution sources under Ohio Administrative Code 3745-31-03(A)(4) set forth the conditions for operation of emergency electrical generation.[36] The Ohio EPA's database of active permits-by-rule for emergency electrical generators powered by fuels such as diesel, distillate oil, and natural gas includes 4,673 records where both the amount of power and the permit holder are identified. These generators have a combined power rating of 1556 MW in Ohio, of which approximately 16.5% is deployed by companies in the Telecommunications and Data Processing & Hosting subsectors, corresponding to the 3-digit NAICS codes 517 and 518, respectively.[37]

Certain types of industries, such as telecommunications and data storage centers (which targets 5-nines service availability),[38] are likely to value resiliency more than other industries, such as traditional manufacturing. For future research, the owners of permitted generation can be mapped to 3-digit and probably 4-digit NAICS levels and those industries using back up power

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[32] K. Olikara, "Power Quality Issues, Impacts, and Mitigation for Industrial Customers, Rockwell Automation, Inc., found at: http://literature.rockwellautomation.com/idc/groups/literature/documents/wp/power-wp002_-en-p.pdf

[33] While UPS systems can handle voltage swings, frequency changes and local harmonics, they may not be able to handle other less common events, such as high ground current, inductive noise, system harmonics, phase imbalance, low power factor, or lightning. *See* Hartfield, "UPS Cures for Power Quality," fn 17, *supra*.

[34] Olikara, "Power Quality Issues," *supra*.

[35] de Nooij, Michiel, C. Koopmans, and C. Bijvoet. "The value of supply security: The costs of power interruptions: Economic input for damage reduction and investment in networks." *Energy Economics* 29, no. 2 (2007): 277-295.

[36] *See* "Permit-by-Rule Fact Sheet (PDF)." Accessed August 8, 2017, http://epa.ohio.gov/dapc/pbr /permitbyrule.aspx

[37] Authors' calculations.

[38] See "IP Telephony: The Fine Nines Story (White Paper)." *Cisco.* (2002). Accesses September 12, 2017, *https://www.cisco.com/c/dam/global/it_it/solutions/pdf/ipcom/5nine_story_wp.pdf*

can be identified. This list can also be compared to economic growth to identify which industries both value resiliency and are also likely to expand.

B. Valuing Resiliency in Terms of Lost Production

Demand for resilient power can be described in terms of the average willingness of electricity consumers to pay to avoid an additional period (e.g. one hour) without power.[39] The willingness to pay for energy security will be determined by a variety of considerations, including the frequency, duration and disruptive effects of the outages. One way to value the resiliency brought by a microgid would be to estimate avoided costs of not having to pay for backup power systems. Those costs are discussed in below. Another way to value resiliency is to estimate the cost of lost productivity. This latter cost is estimated herein below.

This value of electricity supply security to productivity is known as the "value of lost load," or "VOLL."[40] Valuing lost production due to power loss is consistent with the economic notion of opportunity cost. A common method for identifying VOLL for different commercial and industrial customers is through what is known as the "production function approach." This method estimates the consequences of outages through lost production.[41] Under this relatively straightforward model, energy resiliency within a given sector was valued by the ratio of "gross value added" to "electricity consumption:"

Gross Value Added (\$)/Electricity Consumption (kWh)

"Gross value added" was determined from the Bureau of Labor Statistics (BLS) input-output tables that show the flow of commodities from production through intermediate use by industries and then on to purchases by final users. The BLS tables were derived from input-output data initially developed by the Bureau of Economic Analysis (BEA).[42] This ratio provides an estimate for the VOLL for a given industry.[43]

"Electricity consumption" was determined from the Census Bureau's 2012 "Economic Census," which is the most recent source available for the collection of such data across all industries. Consumption was estimated for average electricity purchases by industry. The Census Bureau

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[39] Leahy, Eimear, and Richard SJ Tol. "An estimate of the value of lost load for Ireland." *Energy Policy* 39, no. 3 (2011): 1514-1520.

[40] de Nooij, Michiel, C. Koopmans, and C. Bijvoet. "The demand for supply security." In *Research Symposium European Electricity Markets*. 2003. Accessed August 3, 2017, https://www.ecn.nl/fileadmin/ecn/units/bs /Symp_Electricity-markets/b1_2-paper.pdf

[41] de Nooij, Michiel, C. Koopmans, and C. Bijvoet. "The value of supply security: The costs of power interruptions: Economic input for damage reduction and investment in networks." *Energy Economics* 29, no. 2 (2007): 277-295. This VOLL strategy may not capture all costs of business interruption due to outages.

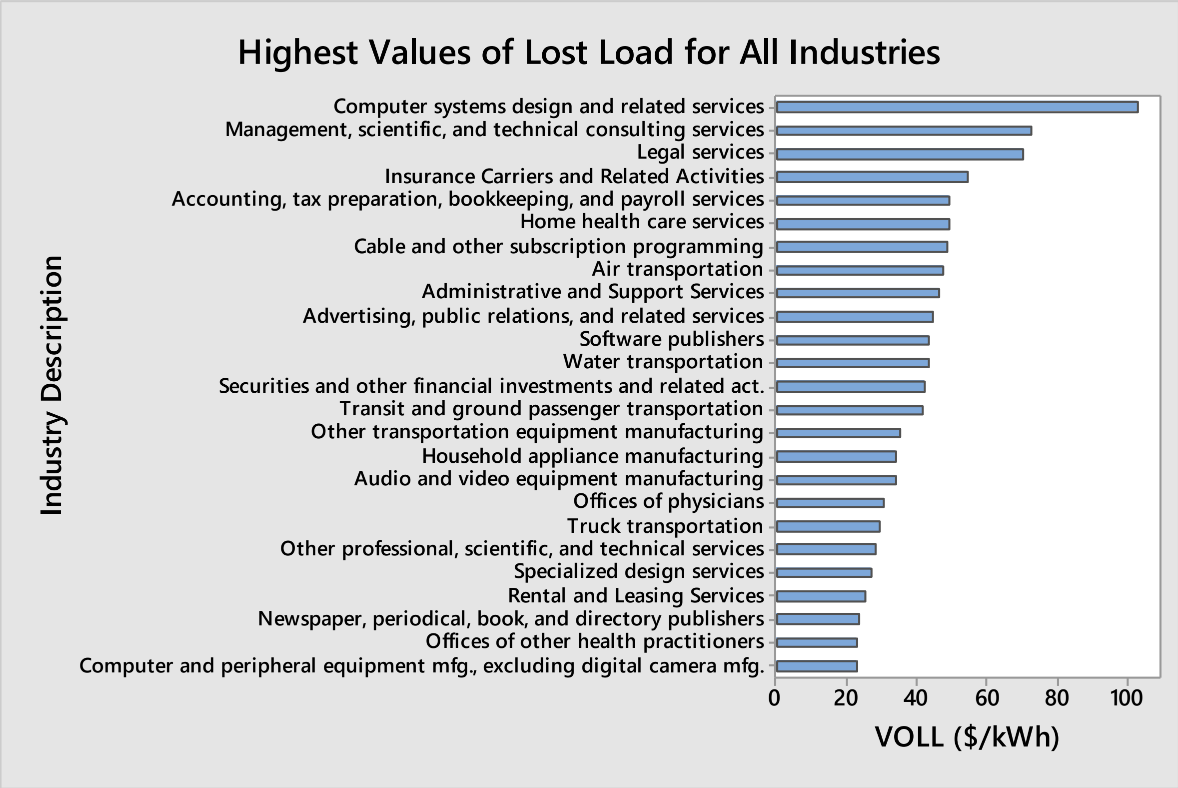
[42] The BLS tables were chosen for this study due to its more detailed industry level classification compared to the original BEA tables (more than 200 sub-industry groupings for the former versus 71 for the latter).

[43] There are a number of limitations to this method of estimating the value of load loss, including the assumption of a linear relationship between duration of disruption and total cost. However, this is a commonly accepted method for valuing load loss among experts*. See* fn 41, *supra*.

collects consumption data by industry in dollars. Only manufacturing industries produces electricity purchase data available in kWh. Accordingly, electricity purchase data for all other industries had to be converted from dollars to kWh by using the manufacturing data to generate a regression.[44] To the extent that manufacturing receives electricity at a lower price than do other industries, electricity consumption may be overestimated for other industries. This in turn lowers the VOLL for non-manufacturers. However, since such a bias would tend to make for lower VOLL numbers for non-manufacturers, it is a more conservative estimate.

The predictors in this regression were total dollar amount of electricity purchased and the number of establishments within a given industry (both of these were known for all industries).[45] Upon estimating electricity purchases in kilowatt-hours for non-manufacturing industries, VOLL was calculated for both manufacturing and non-manufacturing subsectors to the 3- and 4-digit NAICS level. Figure 2 shows the highest VOLL for industries.

Figure 2. Values of Lost Load Per kWh by Industry Description.



Source: Authors (2017). Based upon U.S. Bureau of Labor Statistics (2012) and U.S. Census Bureau (2012).

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[44] The predictive model employed here focuses on association between variables rather than any underlying causal structure that would otherwise require endogeneity (e.g. simultaneous causality) to be addressed. *See* Shmueli, Galit. "To explain or to predict?" *Statistical science* 25, no. 3 (2010): 289-310.

[45] The specified model is $ln(\text{kWh}) = \beta_0 + \beta_1 ln(\text{cost}) + \beta_2 ln(\text{no. of establishments}) + \varepsilon$. The fitted values were exponentiated in order to arrive at kWh predictions for non-manufacturing industries. Fitting the model to the data resulted in an R^2 of 99.09%.

As can be seen, the VOLL numbers indicate that industries that consume a 1 MW load can suffer losses of up to $100,000/hour. Not surprisingly, data heavy businesses, such as law, accounting, banking and insurance firms seem to incur the greatest losses from power outages. Further, VOLL losses for a number of manufacturing industries are non-trivial, due in part to their larger load requirements. For instance, a household appliance manufacturer that uses 10 MW of power is likely to lose $340,000 in a one-hour power outage. Economic development outreach to manufacturers is valued because of job creation and Gross Domestic Product Growth. Accordingly, additional research is needed to identify what manufacturers may value resiliency, and those industries can be targeted for the microgrid.

C. Valuing Resiliency in Terms of Avoided Costs

Another method for estimating the value of resiliency is to calculate the marginal cost for any company to move to incrementally higher levels of power availability. This can be most readily accomplished by estimating the cost of building in-house data centers. The data center company Expedient,[46] in partnership with Intel, provides an online cost calculator for companies that are considering building their own in-house data centers (also known as enterprise data centers). The calculation is based on Expedient's own experience, together with industry benchmarks.[47] This data center cost calculator returns cost estimates for the following levels of expected service availability that coincide with the Uptime Institute's 4-level classification system: [48]

Table 4. Uptime Institute Service Availability Levels.

Level	Service Availability	Annual Expected Time Without Service (in minutes)	Expected Service Time Gained (in minutes)
1	99.671%	1729	--
2	99.741%	1361	368
3	99.982%	95	1266
4	99.995%	26	69

Source: Uptime Institute (2017).

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[46] Expedient operates two 32,500 sq. ft. colocation data centers in the Cleveland area. Such data centers provide computer network services and data storage for companies choosing to outsource their IT.

[47] *See* "The Complete Data Center Build Vs. Buy Calculator." *Expedient*. Accessed September 7, 2017, https://www.expedient.com/data-center-build-vs-buy-calculator

[48] The Uptime Institute refers to these power availability categories as *tiers*, but we refer to them as *levels* here so as not to conflict with our prior description of customer tiers within the Cleveland microgrid. *See also* Nemeth, Evi, Garth Snyder, and Trent R. Hein. 2006. *Linux administration handbook. [electronic resource]*. n.p.: Upper Saddle River, N.J.: Prentice Hall, 2006, c2007. *OhioLINK Library Catalog – LR*, EBSCO*host* (accessed September 8, 2017).

Other calculator parameters include number of cabinets,[49] total kW of redundant power, evaluation period,[50] the percentage of available power consumed,[51] cost per kWh for electricity, and internet connection speed. In using the calculator to estimate cost differences at different levels of availability, the ratio of "total kW of redundant power" to "number of cabinets" was set at 4:1 for power levels of 1,000 kW, 500 kW, and 250 kW.[52] A power density of 4 kW per cabinet is considered typical for data centers.[53] We also assumed that:

- Servers and uninterruptible power supply (UPS) have 5 year lifetimes[54] while all other data center fixed assets have 15 year lifetimes.[55]
- The proportion of available power consumed was 60%.[56]
- The price of electricity was $0.10/kWh.[57]
- The internet connection speed for the hypothetical data center was 100 Mbps.[58]

Based upon placing the above parameter settings into the Expedient calculator for a 1 MW data center,[59] a table was developed that sets forth the cost of increasing availability by line item of necessary equipment and services. Table 5 shows the added cost resulting from these incremental increases in availability.

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[49] Cabinets are the enclosures that house computer networking servers.

[50] The evaluation period is the expected lifetime for data center components before needing to be replaced.

[51] Percentage of available power consumed is a measure of efficiency. A higher percentage indicates more effective power usage (i.e. less waste).

[52] The calculator maximum for setting total kW of redundant power was 1000 kW.

[53] Rasmussen, Neil. "Calculating Space and Power Density Requirements for Data Centers (APC White Paper 155)." *APC-Schneider Electric*. (2013).

[54] Firms and government units that operate data centers generally replace servers and UPS after 3-5 years. 5 years was chosen by the research team as a more conservative cost estimate for these items. *See* "Information Technology Equipment Life Cycle." State of Michigan. (2011). Accessed September 8, 2017, https://www.michigan.gov/documents/dtmb/ITLifecycle_379666_7.pdf

[55] *See* Koomey, Jonathan. "A Simple Model for Determining True Total Cost of Ownership for Data Centers." *Uptime Institute White Paper.* (2008). Accessed September 8, 2017, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.474.7834&rep=rep1&type=pdf

[56] Expedient states that this is the average percentage for an enterprise data center. *See* hover popup for this parameter data center cost calculator webpage at www.expedient.com/data-center-build-vs-buy-calculator

[57] This was approximately equal to the U.S. Energy Information Administration's electricity price estimate for commercial end-users in Ohio as of June 2017. *See* "Electric Power Monthly." *U.S. Energy Information Administration*. (August 24, 2017). Accessed September 8, 2017, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

[58] The calculator maximum for setting internet connection speed was 100 Mbps.

[59] Ultimately, setting the power level to 500 kW or 250 kW did not affect the eventual value of resiliency in terms of $/kWh.

Table 5. Added Cost Associated with Increased Availability by Line Item[60]
in 2017 Dollars for 1 MW Data Center.

	Difference Between Levels 1 and 2	Difference Between Levels 2 and 3	Difference Between Levels 3 and 4
Engineering and Preparation	61,725	648,109	123,449
Power Systems/Electrical Equipment	730,588	7,671,177	1,461,178
Environmental Controls	159,261	1,672,236	318,521
Security and Monitoring	15,565	163,430	31,129
Core Network Equipment	33,000	346,500	66,000
Electrical Maintenance	53,012	556,621	106,023
HVAC Maintenance	1,984	20,832	3,968
Other Systems Maintenance	1,032	10,831	2,063

Source: Authors (based upon Expedient website).

The last two maintenance items reflect differences in annual operating expenses while all other items represent differences in construction or capital costs.[61] The differences in annual operating expenses were added to the differences in annualized capital costs for each column in order to arrive at a total annual added cost for moving to the next highest level of availability.[62] This total annual added cost was then divided by the total annual kilowatt hours for a hypothetical data center given its power rating and availability level. So, for instance, a 1 MW data center with 99.671% (Level 1) availability would be assumed to have a one-year electrical consumption of:

$$1\text{ MW} \times 24\text{ hours} \times 365\text{ days} \times 0.99671 = 8{,}731{,}180\text{ kWh}.$$

Table 6 shows the resulting marginal cost per kWh in going to the next highest level of availability for a 1,000 kW data center using Expedient's cost calculator. This rate was not different for the other power levels, nor did it change when separately varying percentage of available power consumed or cost per kWh for electricity,[63] while holding the remaining parameters constant.

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[60] More detailed line item costs are available on the Expedient website.

[61] Electrical maintenance, while ostensibly an operating cost, was also considered a fixed cost as it did not vary at all when the calculator parameter for Evaluation Period was adjusted.

[62] Annualized capital costs were determined using the static annuity method where a capital recovery factor (CRF) is calculated for each capital item and is defined as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where i is a discount rate and n is the lifetime of the asset. *See* Koomey, Jonathan. "A Simple Model for Determining True Total Cost of Ownership for Data Centers." *Uptime Institute White Paper.* (2008). Accessed September 8, 2017, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.474.7834&rep=rep1&type=pdf. *See also* Damodaran, Aswatch. "Cost of Capital by Sector (US)." *New York University*. (2017). Accessed September 5, 2017, http://people.stern.nyu.edu/adamodar/New_Home_Page/datafile/wacc.htm

[63] Note that the value of resiliency represents a distinct cost that is related but separate from the cost for electricity.

Table 6. Annual Marginal Cost for Increased Service Availability for 1 MW Data Center.

Change in Service Availability	Total Additional Annualized Cost	Electricity Consumption (kWh) at Higher Level of Availability	Additional Availability at Higher Level	Additional Cost/kWh at Higher Level of Availability (rounded to nearest cent)	Additional Availability per 1-cent/kWh at Next Highest Level
Level 1 to 2	$150,063	8,737,312	0.07%	$0.02	0.040%
Level 2 to 3	$1,575,659	8,758,423	0.241%	$0.18	0.013%
Level 3 to 4	$300,125	8,759,562	0.013%	$0.03	0.004%

Source: The Authors (2017).

These calculations suggest that, based on the experience of one data center service company, some data centers have incurred costs of more than $0.20/kWh in order to move from two-nines to near five-nines availability.[64] By standardizing the percentage of service availability purchased for every 1-cent/kWh at each new level, we see that marginal costs for reliability accelerate with improving availability. This is consistent with what researchers at Penn State University and IBM found in a study of data center availability and infrastructure. In their analysis of the added cost for data centers (a likely microgrid customer), the researchers found that a per-unit of energy cost increase of 25% would be required to move from 3-nines to 4-nines, while a 75% per-unit energy cost increase would be incurred to move from 3-nines to 5-nines availability.[65]

For CEI, we estimated that its reliability (excluding brownouts) averaged around 99.93% over the past 8 years. Using the above charts, we can estimate that improving from this level to 99.999% reliability (the target for data centers) would cost around $0.05 to $0.06/kWh. This is based upon improving 0.04% within level 2 until level 3 is reached, then improving from level 3 to level 4, and then finally improving 0.004% more within level 4.[66] An illustration of the marginal cost

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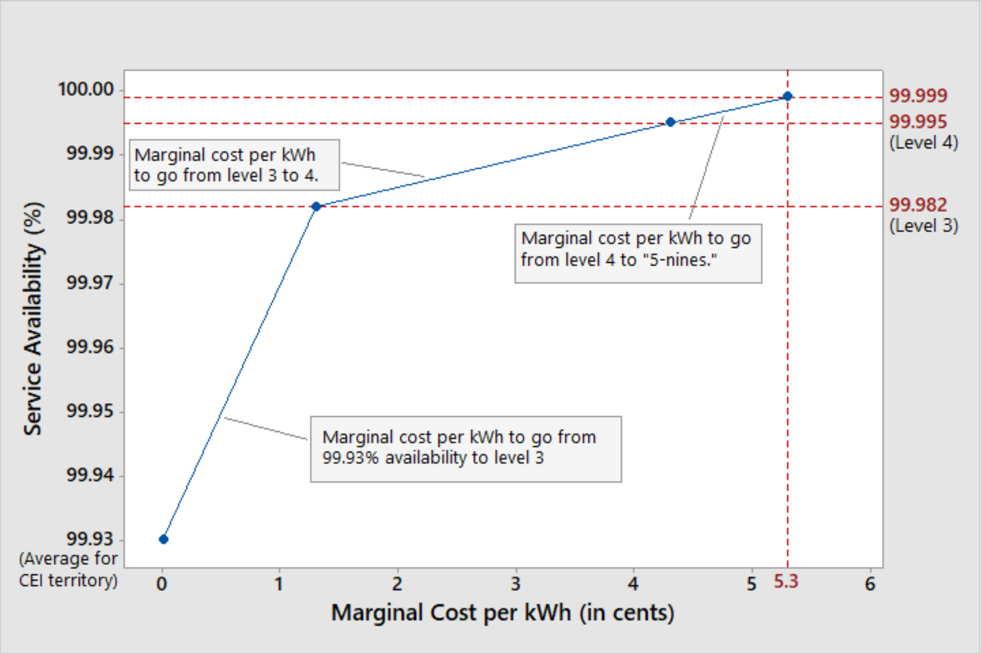
[64] The Uptime Institute levels do not improve evenly. The improvement between levels 1 and 2 is 0.07%, 2 to 3 0.24% and 3 to 4 0.01%. This explains in part why there is an uneven cost increase for improved resiliency levels. Overall, each cent per kWh is purchasing less availability as one moves up from one level to the next.

[65] Govindan, Sriram, Di Wang, L. Y. Chen, Anand Sivasubramaniam, and Bhuvan Urgaonkar. "Modeling and analysis of availability of datacenter power infrastructure." *Technical Report CSE-10-006* (2010). For instance, the cost of additional uninterruptible power supply (UPS) infrastructure to raise reliability from 3 nines to 4 nines would be an additional $6000 per rack (a unit of measure for physical computer center framework). This means a cost increase from $18,000 to $24,000 per rack. *See id.*

[66] Assuming that CEI offers 99.93% availability on average, Table 4 tells us that this corresponds to level 2 reliability since it is more than 99.741% for level 2, but less than the 99.982% associated with level 3. If, for example, a commercial customer of CEI's decided to build an in-house data center on its premises, our research represented in Table 6 indicates that it would spend around an extra 1-cent-per-kWh to increase its power availability by 0.04% from 99.93% to 99.97%. We considered this to be close enough to the threshold of 99.982% for level 3 since the average of 99.93% was brought down by a year of particularly low availability in 2012 and that the four most recent years had availability of at least 99.95%. After spending 1-cent-per-kWh to get to level 3, the company could then pay $0.03 (3.4 cents before rounding) to move to level 4 and its availability of 99.995%, as seen in Tables 10 and 12. At this level of availability, it would cost a company wanting to increase service availability 1-cent-per-kWh for every additional 0.004% of reliability. If the commercial customer in our example

associated with this incremental improvement in service availability for CEI's territory can be seen below in Figure 3. This gives us a rough estimate ($0.053/kWh) of the added value for resiliency offered by a microgrid that provides 5-nine reliability. Notably, the microgrid would also provide protection against brown outs, which protection is not included in the 99.93% estimate.

Figure 3. Marginal Cost of Additional Service Availability in CEI Territory.



While the Expedient calculations are for adding additional levels of power resiliency for data-center facilities, similar costs would likely be incurred by any company or operation that would seek to install additional power resiliency. The significance of these costs must be taken into account by any company that is considering options for increasing the resiliency of their power.

These estimates of marginal costs of resiliency are conservative. The base uptime of 99.93% is likely generous for most distribution utilities, not only because CEI is located in a region that has few natural disasters, but also because it does not include brownouts and other unreported power quality problems. Moreover, even though CEI has averaged 99.93% uptime over the past 8 years, it is important to remember that CEI does not warrant delivery of that much uptime. Nor does it provide 99.93% uptime for quality power. Accordingly, for those who need 5-nine power reliability, the 5-6 cents/kWh cost is likely to be on the low side. If you assume that for quality time, the uptime is closer to the Level 2 rate of 99.741%, the cost for reaching five 9s is over $0.20/kWh.

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decided to spend this penny, it would have spent $0.01 + $0.034 + $0.01 = 5.4 cents in order to get to 99.93% + 0.04% + 0.013% + 0.004% = 99.999%, also known as 5-nines.

Finally, this analysis makes no attempt to value the environmental or security values of resiliency. Technologies that enable a more rapid transition to renewable power generation will of course also provide value as an extrinsic avoided cost. Like other environmental costs associated with the commons, these costs are difficult to quantify. That does not mean they should be ignored, however. Likewise, resiliency also has value for national and local security. This value is also difficult to quantify, and is not included in this study.

IV. Conclusion

The national discussion about the value of resiliency is in the early stages. These discussions are important because we are, as a society, rethinking how the grid of the future will look. Before we invest heavily into grid edge technologies that improve reliability, we need to know what value these will provide. This knowledge will guide us in optimizing grid systems, and in understanding what investments we need to make where.

We have reason to believe, however, that for many businesses that require reliable and high quality power, resiliency is worth at least 5 cents/kWh, and probably a good deal more. The national average commercial cost of electricity in the United States was around 11 cents/kWh in August 2017.[67] This means that a microgrid operator that seeks to attract commercial businesses should probably target a price of around 15-16 cents/kWh or lower for 5-nine power. Much will depend, of course, on local market conditions.

But this price only reflects part of the value of resiliency to the end user. There is additional value added from opportunities gained (measured by the VOLL), lower business interruption insurance premiums, and possibly reduced or avoided demand, capacity and transmission charges. These additional values are likely to be made more clear as microgrids and other resilient systems become more common.

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[67] U.S. Energy Information Administration, Electric Power Monthly, August 2017. Accessed August 24, 2017, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a.