Link Fellowship Report

Electric Reliability, Distributed Energy Resources (DERs), and Opportunities for Customer-Sited Solar and Storage in Modern Electric Systems

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1. Introduction

“This [Federal Energy Regulatory Commission] order has absolutely nothing to do with subsidies. This is all about unleashing the power of our markets. We're talking about smaller energy resources located in our homes, our businesses, within communities. What our rule did was say, `You know what, these smaller assets should be able to join together through the power of technology and compete in our wholesale electric markets, just like the large power plant down the street.' This action, in my view, is revolutionary and will help us pave the way for the grid of the future. It makes our grid more nimble, flexible and ***reliable****."*

Statement by FERC chairman Neil Chaterjee on order 2222
October 5, 2020

At the turn of the 21st century, the electricity system started to transform. Regulators opened up electric generation to competition and renewable electricity, particularly wind and solar, entered a period of rapid cost decline (Borenstein and Bushnell, 2015). At the same time the popularity of distributed, rather than centralized, supply of electricity grew, giving end consumers new options to meet their electricity demand locally. The dramatic cost decline of solar technologies made it more economic to install solar generators at individual households (Barbose et al., 2021a), and technological development of battery storage has led to even more options for the local supply and control of electricity by the residential sector (Kittner et al., 2017; Barbose et al., 2021b).

Amidst these regulatory and market transformations are increasing concerns about the underlying reliability of modern electricity systems. In high-income countries, interruptions in power supply are rare and electricity systems are generally viewed as highly reliable (Arlet, 2017). In the past decade, however, United States natural disasters such Superstorm Sandy in the Northeast, Hurricane Maria in Puerto Rico, electricity-induced wildfires in California, and polar-vortex weather conditions in Texas have led to increasing calls for grid hardening of the transmission and distribution systems (Walton, 2017; Schwartz et al., 2021). These weather events comport with the growing consensus that climate change will increase strain on the reliability of electricity grids (Chen et al., 2017; Brockway and Dunn, 2020) and have shown that modern electricity systems remain vulnerable to long-duration outages which are extremely costly for societies which rely on electricity services (Sanstad et al., 2020).

Given this context, my Link Fellowship project investigated opportunities for solar and storage technologies to provide power locally and mitigate the customer impacts of power outages. Could these new distributed technologies be used to improve electric supply resilience at individual households? I categorize my research into two distinct parts that both aim to answer pieces of this broad question. The first part critically examined state-of-the-art approaches to estimating the economic value of electric reliability while developing novel techniques to improve on prior estimation strategies. While performing the first portion of my research project, I realized that the resilience benefits of behind-the-meter solar-plus-storage systems (BTM PVESS) are poorly understood, especially for residential customers, owing to lack of data and methodological challenges. To fill this gap, in the second portion of my research project, I applied techno-economic methods to quantify the backup power potential of solar and storage resources in the residential sector given diverse building stock conditions across the United States.

2. Summary of Results

My research project began with a critical literature review of various approaches to measuring the economic value of electric reliability. I found that prior strategies which aim to estimate the economic value of electric reliability (i.e. "The Value of Lost Load" or VoLL in industry terminology) either rely heavily on modeling assumptions that are often oversimplified and hard to verify or are based on survey techniques that have often been found to be biased (Sanghvi, 1982; Schroder and Kuckshinrichs, 2015). To build upon this literature, I worked to develop a revealed preference approach using empirical observations of backup power purchases (e.g. solar and storage technologies). This approach relied on quasi-experimental variation in power outages from the public safety power shutoffs (PSPS) that occurred in California in 2019 (depicted in Figure 1) to estimate the effects of blackouts on backup power adoption.

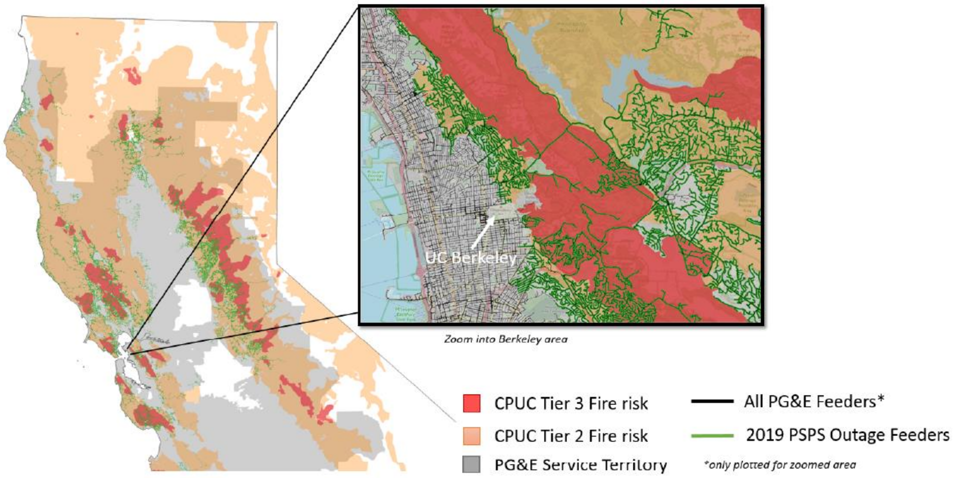

Figure 1: Maps of 2019 PSPS outage feeders (green) in Northern California combined with fire risk areas. Tier 3 risk (red) is higher than Tier 2 (orange).

I developed a regression discontinuity design which compares neighboring electricity customers who live on different distribution feeder lines and therefore experienced differing amounts of PSPS power outages. The power outage discontinuities I found are significant and depicted in Figure 2, subset by urban density levels. I then analyzed whether that discontinuity in outage hours led to corresponding discontinuities in solar and storage adoption. Surprisingly, I found statistically insignificant increases in the adoption of battery technologies in the metro and micro urban density categories. In the rural areas, however, I found that adoption of storage increased by 0.11 kWh after the 2019 PSPS events in the treatment group, a 360% increase from the control group. This result was significant at the 5% level. I combined the 0.11 kWh storage increase estimate with an assumption of storage costs of \$650/kWh-battery to estimate the increased electricity cost paid by homeowners who experienced power outages. Lastly, I estimated the total amount of lost load that resulted from the 2019 PSPS events. I applied a difference-in-difference analysis of the electricity lost as a result of outages and found that for every incremental outage hour during the PSPS events, households lost roughly 0.5 kWh of demand. The rural discontinuity in outage hours is 14, which combined with the 0.5 kWh estimate of lost load per outage hour, results in 7 kWh lost across our treatment discontinuity. Finally, I combined this estimate of lost load with the estimate of the incremental increase in storage purchases to calculate a VoLL in units of $/kWh. All of these numerical results were combined to estimate a VoLL of $0.8/kWh, lower than estimates previously found in the literature.

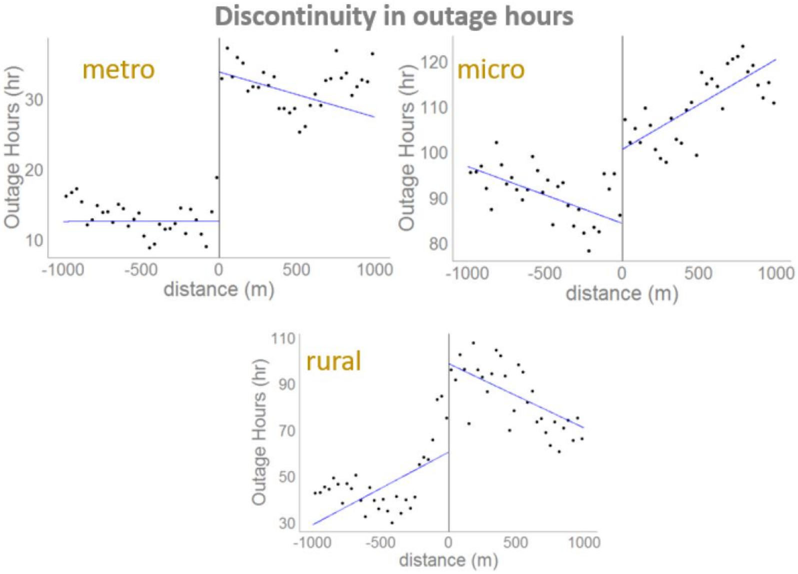

Figure 2: Graphical regression discontinuity results on outage hours across feeders by different land density categories. Distance of 0 meters signifies the boundary between two different feeders in the data sample.

I developed a number of explanations and hypotheses that might explain the small VoLL estimates. The first explanation is that the adoption of battery technology represents just one mitigation option available for our population sample to avoid the impacts of power outages. Other mitigation expenditures include the purchase or rental of fossil fuel based backup power systems, travel costs to friends/family outside of PSPS territory, relocation to alternative housing such as a hotel, and a variety of behavior adjustments that could entail a variety of difficult-to-observe costs. Second, the relative nascence of behind-the-meter battery backup might have affected the salience of the option for battery backup. A third limitation of the above methodology is that it represents the mean outcome within our sample. The specific individuals who purchased batteries in response to the PSPS events would require a higher VoLL to justify such an investment. A fourth and final limitation is that treatment may not solely be the experience of power outages itself, which I focused on in this project, but also the expectation of increased risk of power outages. In other words, neighbors who experienced different outage hours may still have been treated similarly due to the *increase in perceived risk* of power outages. All of these issues are ripe for further exploration in follow-up research that could enhance this novel VoLL estimation method.

After finding that there were mixed results on the adoption of solar and storage (PVESS) as a result of the experience of unreliable electricity, I turned the focus of the project towards understanding the technical capabilities of these systems to actually enhance customer resilience. In this second portion of my project, I developed a methodology to model the performance of solar and storage to provide backup power across a wide range of customer types, geography / climate conditions, and long duration power interruption scenarios, considering both whole-household backup and backup of specific critical loads. I found that PVESS with 10 kWh of storage can meet a limited set of critical loads in most United States counties during any month of the year, though this capability drops to meeting only 86% of critical load, averaged across all counties and months, when household heating and cooling demands are considered critical. Backup performance is lowest in winter months where electric heat is common (southeast and northwest U.S.) and in summer months in places with large cooling loads (southwest and southeast U.S.). Figure 3 summarizes these findings.

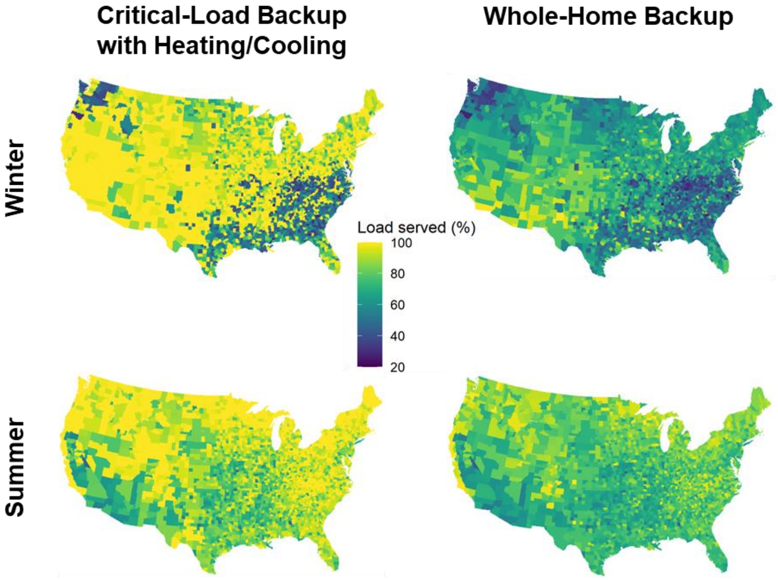

Figure 3: Average percent of load served during 3-day power interruptions simulated for each month, aggregated to the average of winter and summer seasons for a typical home in each county. Critical-Load scenario includes heating and cooling. Assumes PV sized to 100% of annual load, 100% beginning battery state of charge, 10 kWh battery

I also compared outcomes amongst a variety of building stock conditions. Building conditions impact the amount of load the solar and storage system is required to serve. Differences in critical load levels reflect a number of fundamental drivers: (1) Building size, (2) Heating and cooling equipment type (especially electric vs. gas heating), (3) Efficiency levels, and (4) Occupant/behavioral factors (e.g., set points). Focusing on a subset of my results, among homes with electric resistance heating in Harris County, a median of 77% of winter critical load is served, compared to 96% for those with heat pumps and 100% for those with fossil heating. Winter backup performance also varies by roughly 20% depending on infiltration rates (the “leakiness” of the home), while summer performance varies by close to 15% depending on the efficiency of the central air-conditioning system. Differences in temperature set-points in Harris County correspond to a 40% range in winter backup performance and a 20% range in summer performance.

Finally, I simulated 500 single-family building models for subset of counties that experienced wide spread long-duration outages within the last 5 years (see list of power outage events below in Table 1). I found that the baseline solar and storage system would have supplied full backup for the majority of building models in the Thunderstorm (TX), PSPS (CA), Derecho (IA), and Hurricane Michael power outage events. The worst outcomes for solar and storage systems occurred for the two winter storm events and Hurricane Florence. Relatively poor performance was observed in Hurricane Florence, driven by the lack of solar production in the first three days of the ~8-day outage event.

I converted the load served metric into a cost of served energy metric, which is an economic indicator representing the levelized cost of providing energy via PVESS during an interruption and is calculated by taking an annualized cost of the PVESS system net of any bill savings and dividing it by the load served by the PVESS over all interruption events for a household in a year. Table 1 below shows the median cost of served energy for the 10 historical events I modeled in our analysis. Each row varies the expectation for how frequent such a wide-spread outage event might occur over the course of the assumed 20-year lifetime of the PVESS system. The above numbers can be compared to average VoLL estimates provided by researchers studying resiliency events, which tend to be between $1-5/kWh for the residential customer class (Baik et. al, 2018; Schroder et. al., 2015). The numbers in the table represent the required VoLL an individual household would need in order to rationalize the purchase of a solar and storage system.

Expected Number of events over PVESS lifetime	2020 Thunderstorm (TX)	2019 PSPS (CA)	2020 Derecho (IA)	2018 Florence (NC)	2017 Harvey (TX)	2017 Irma (FL)	2020 Isaias (NY)	2018 Michael (FL)	2020 Winter Stm (OK)	2019 Winter Stm (WA)
2 (1-in-10years)	$260	$134	$115	$126	$41	$62	$153	$153	$152	$726
20 (Every year)	$54	$17	$12	$14	$4	$6	$16	$16	$18	$98
40 (2 times a year)	$28	$8	$6	$7	$2	$3	$8	$8	$9	$50

Table 1: Breakdown of the cost of served energy ($/kWh) between the historical events with variation depending on assumption of the expected number of events per year

3. Significance and Impact

Policy makers rely on value of lost load estimation in order to perform cost-benefit analyses that inform reliability-enhancing infrastructure investments (e.g. investments to underground distribution and transmission lines). New methods are needed to perform such estimation as current state-of-the-art estimation approaches have a number of shortcomings. Estimates from the regression discontinuity approach developed in this project were lower than those typically found in the literature, suggesting that current cost-benefit approaches might be overvaluing resiliency investments. However, my results should be used with caution by policymakers choosing between different resiliency investments given the shorting comings summarized in the results section above. The central impact of this work, therefore, is the methodological contribution to the literature.

The second segment of my project showed that solar and storage can provide backup power in a number of settings. The advent of new options for customers to procure and supply electricity privately and closer to their point of consumption leads to complex questions for grid planners who aim to make informed regulatory choices that minimize electricity costs while ensuring reliable electric supply. Household installed solar and storage, as currently deployed, benefit the individual homeowner and circumvent public provision of electric reliability that has historically been used within electric regulatory institutions. Though my project did not attempt to address the myriad of questions that customer-sited solar and storage raise, its results highlight various policy tradeoffs in reliability while also informing the relative importance of various drivers of distributed resource adoption.

4. Where might this lead?

Future researchers and industry practitioners will continue to analyze trends in backup power adoption as a means to not only to measure the VoLL but also to inform regulatory decisions on grid reliability that balance public and private investments to ensure societal equity. Regulatory institutions acknowledge that electric reliability is a public good and that leaving such reliability investments open to a completely liberalized electricity market without regulatory interventions could result in corresponding market failure and under (or over) investment in reliability. New options for backup power (i.e. solar and storage systems studied in my project) augment the privatized choice set for electric reliability and thereby raise complex questions about how and for whom we plan our grid. Private opportunities for reliability enhancement need not lead to equitable outcomes across society, especially if those technologies remain prohibitively expensive. In a worst case scenario, we could move towards a system where only high-income individuals can achieve the highest levels of electric reliability. Alternatively, these new technologies could be used to benefit electric resiliency for all.

My future research directions aim to build upon the work that began under Link Fellowship funding by analyzing how the household solar and storage adoption will continue to evolve. I have developed a new research project that assesses how electrification of heating, cooking, and water heating pose difficulties for solar and storage systems to provide reliable services to households. Other electrification trends, such as electric vehicle adoption, could support customer resiliency as an important source of backup power. I will consider such challenges and opportunities for household electric reliability while integrating more complex evaluations of load flexibility. The likelihood of load flexibility might be particularly questionable for a customers who rarely think about their hourly electricity consumption. How much are customers willing to engage in day-to-day electricity consumption decision making? This question is central to determining how distributed energy resources are adopted and thereby how the future of the electricity system unfolds. As someone passionate about continuing sustainable energy research, I have accepted a full-time job offer as a research scientist in Lawrence Berkeley National Lab's Electricity Markets and Policy Department. I will be able to continue research that I began while under Link Foundation financial support in this new role.

5. Scholarly Reports Acknowledging Link Foundation Support

- **Gorman, W**., "The quest to quantify the value of lost load: A critical review of the economics of power outages." *The Electricity Journal,* October 2022.
- **Gorman, W**., Barbose, G., Carvallo, JP., Baik, S., Miller, C., White, P., Praprost, M. "County-level assessment of behind-the-meter solar and storage to mitigate long duration power interruptions for residential customers," Working paper, under review at *Applied Energy.*
- **Gorman, W.,** Burlig, F., Callaway, D., Wolfram, C., "A revealed preference estimate of the WTP to avoid power outages: A California case study," in advanced prep.
- **Gorman, W.,** Burlig, F., Callaway, D., Wolfram, C., "Do notifications affect households' willingness to pay to avoid power outages? Evidence from an experimental stated-preference survey in California," in advanced prep.

6. How did the fellowship make a difference?

One major impact of the Link Foundation Fellowship is that it afforded me the opportunity to pursue and develop capabilities in econometric techniques that I did not have before receiving the fellowship funding. As an interdisciplinary scholar with a stronger background in engineering and techno-economic approaches, I wanted to expand my capabilities into economic thinking and methods. Because of the funding, I was able to connect with econometric experts at my university and propose a collaboration in which they would not provide funding but rather a promise to provide their technical expertise to facilitate my training. The two publications exploring revealed preference and stated preference methods to eliciting a Value of Lost Load taught me a tremendous amount about various regression and statistical methods. I do not believe these collaborations would have been possible without the flexibility the fellowship gave me in pursuing projects that could center my development rather than center my prior expertise. This developmental outcome would have been particularly challenging for me without Link Fellowship funding given the timing of my fellowship with the COVID pandemic. The pandemic made in person meetings, presentations, and collaborations difficult to develop, which was an added barrier to starting new collaborative projects. I am very fortunate that funding was not an additional barrier.

In addition to enabling my development into a new area of expertise, the Link Foundation Fellowship also allowed me the freedom to pursue my own independent, interdisciplinary research that was not constrained by a specific project proposal and corresponding set of deliverables. The fruits of this freedom is best observed in my sole authorship of the journal article in *The Electricity Journal* that provides a critical assessment of the Value of Lost Load literature. This work involved a deep, historical literature review of prior approaches to estimating the value of electric reliability as well as general critiques of the overall economic valuation framework. The path towards developing that scholarly report was circuitous and would have been hard to complete without the freedom and openness granted by a fellowship program like the one offered by the Link Foundation.

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