I’ve Got the Power: The Value of Resilience for All-Electric Single-Family Homes

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ABSTRACT

Extreme weather events and the resulting power outages can lead to weather-related illnesses, emergency room visits, and even death, and can result in property damage such as spoiled food and medications. Electricity provided by battery storage systems during outages can mitigate these and other effects, especially for all-electric homes.

A study is underway on behalf of the Massachusetts energy efficiency program administrators (PAs) to assess resilience-related non-energy impacts (NEIs) from battery storage measures offered through a strategic electrification and energy optimization program for low- and moderate-income residential customers residing in single-family homes. NEIs are additional impacts of energy efficiency programs beyond the energy savings attributable to installing energy efficiency measures. Participating customers receive home weatherization services with heat pumps, battery storage, and solar photovoltaic systems. The study assesses NEIs that accrue to program participants from having an uninterrupted electricity supply from the program-supplied battery during a grid power outage. Rather than assessing each NEI individually, the study employs a top-down approach, which uses the concept of the Value of Lost Load (VoLL) –– an estimate of the price that customers are willing to pay for uninterrupted electricity — to monetize all NEIs as a whole. The study used three years of detailed outage data in the PA’s service territory to determine the timing and length of each outage and the probability of affected customers. Building Energy Optimization (BEopt) software is used to develop seasonal customer load profiles to estimate the kWh of electricity supplied by the battery system during each outage.

Introduction

The frequency and intensity of extreme events and resulting power outages has been increasing and is predicted to continue increasing (Apex Analytics 2022a; Levenson 2023; Ericson et al. 2022, Macmillan et al. 2022). Outages, particularly during extreme weather events, can lead to weather-related illnesses, emergency room visits, and even death, and can result in property damage such as spoiled food and medications. Electricity provided by battery storage systems during a power outage on the grid can mitigate these and other effects, resulting in non-energy impacts (NEIs). NEIs are additional impacts (positive or negative) of energy efficiency programs beyond the energy savings attributable to installing energy efficiency measures that can be factored into program cost-effectiveness testing. NEIs can accrue to program participants, program administrators or society at large. For example, society may realize environmental benefits and positive economic impacts from energy efficiency programs. Participants may realize benefits such as increased comfort, health or safety impacts, or reduced water usage. In this paper we are focused on program participant NEIs.

This study, conducted on behalf of the Massachusetts energy efficiency program administrators (PAs), is assessing resilience-related NEIs from battery storage measures offered as part of a strategic electrification and energy optimization program for low- and moderate-income residential customers residing in single-family homes. The study assesses benefits that accrue to program participants from having an uninterrupted electricity supply from the program-supplied battery during a grid power outage. Rather than assessing each NEI individually, the study employs a top-down approach, which uses the concept of the Value of Lost Load (VoLL) –– an estimate of the price that customers are willing to pay for uninterrupted electricity — to monetize all NEIs as a whole. Three years of outage data (2020 through 2022) in the PA's service territory is used to determine the timing and length of each outage and the probability of a customer being affected by it. Building Energy Optimization (BEopt; NREL 2023) software is used to develop seasonal customer load profiles to estimate the kWh of electricity that can be supplied by the battery system during each outage to meet an affected customer's critical load.

The Massachusetts-based Cape Light Compact's (CLC's)[1] Cape and Vineyard Electrification Offering (CVEO) is a strategic electrification and energy optimization offering for low- and moderate-income residential customers[2] residing in single-family homes that combines home weatherization with heat pumps, battery storage, and solar photovoltaic (PV) systems. Participating customers will (1) convert their oil, propane, or electric resistance heat to cold climate air source heat pumps and convert their fossil fuel cooking appliances to electric cooking appliances, (2) install solar PV systems to support electrification of their heating systems, and (3) weatherize their homes. For a subset of these customers, the CLC will install battery energy storage for demand response and resiliency.

The CVEO offering provides incentives that cover 100% of the cost of battery storage for low-income customers and moderate-income customers residing in deed-restricted properties. The CLC plans to install two batteries in each participating low-income and deed-restricted moderate-income property and one battery per non-deed-restricted moderate-income property. The two-battery system is designed to power the CVEO-provided heat pump during an outage, but households that receive one battery may not experience all of the resilience NEIs, as CLC anticipates that the single battery configuration will not power the heat pump during all outages.[3]

Defining and Quantifying Resilience

Resilience is often defined from the perspective of a power system and its ability to adapt and recover from acute disruptions. The focus is generally on preparing the system for low probability, high-consequence disruptive events that result in outages lasting hours, days, or even months that lead to widespread impacts on critical infrastructures and the economy (Apex Analytics 2022b; NREL 2022; Macmillan 2022).[4]

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[1] The Cape Light Compact is a Massachusetts-based energy services organization operated by the 21 towns on Cape Cod and Martha's Vineyard and Dukes County. The Compact's mission is to provide energy efficiency programs, consumer advocacy, and renewable competitive electricity supply to its 200,000 customers. Eversource is the electric distribution company that delivers electricity to all Cape Light Compact customers.

[2] Low-income customers are households with annual income at or below 60% of state median income and moderate-income are households with annual income of 61% to 80%of state median income.

[3] At this time the CLC does not know what equipment in the home will be connected to the battery storage.

[4] The NREL paper provides a brief overview of potential resilience performance metrics that quantify the resilience of an energy system is. Examples include customer outage time (hours); load not served (kWh); number or

Resilience can also be understood from the perspective of a home and the home's ability to withstand disruptions.[5] A recent study by Apex Analytics (2022b), completed for the Regional Technical Forum (RTF), provides a definition of resilience from the perspective of a home or building and in relation to energy efficiency measures: the ability for buildings to prepare for, mitigate, and recover from the negative occupant and/or physical impacts of infrequent—but extreme—events (e.g., extreme weather and/or electricity grid outages).

In the case of battery storage, this study focused on the battery storage system's ability to provide uninterrupted electricity supply during an outage and provide benefits to the building occupants or owners. Residential resilience impacts can be quantified using two types of approaches: top-down or bottom-up.

A typical **bottom-up approach** involves identifying and quantifying the array of potential impacts, including health and safety impacts (e.g., avoided thermal stress or avoided failure of medical equipment) and property impacts (e.g., avoided food and medicine spoilage, avoided pipe freezing, avoided basement flooding, etc.).

A common **top-down approach** involves estimating VoLL, or the average price per kWh that customers would be willing to pay to avoid the disruption of electricity supply. VoLL can be multiplied by the lost load to estimate the total cost of an outage. Another top-down approach, which is cost-based, involves determining the marginal abatement cost, or the cost of a baseline alternative investment that delivers the same services (Apex Analytics 2022b).

For our study we use VoLL to monetize the resilience benefits from avoided disruption of electricity supply attributable to the battery storage.

Estimating VoLL Attributable to CVEO Participants

VoLL is an estimate of the costs associated with electric grid outages and represents an approximate price that customers are willing to pay per kWh for uninterrupted electricity (NREL 2022). In other words, VoLL is the value of unserved energy, and quantifies the value of impacts perceived by customers during power outages. VoLL is a key input to the monetization of the resilience NEIs.

The Team reviewed recent literature on VoLL and conducted a review of studies that used a bottom-up approach to estimate resilience NEIs as a way to assess the top-down estimate. From our review we identified the *2021 Self-Generation Incentive Program (SGIP) Energy Storage Market Assessment Study*[6] as providing an applicable estimate of VoLL for the CVEO study population (Verdant Associates 2022).

The 2021 SGIP study conducted a web-based willingness to pay (WTP) survey to estimate VoLL for residential SGIP participants that adopted battery storage and solar PV as well as a stratum of non-SGIP households that had adopted solar PV but not battery storage. The surveys of non-SGIP solar non-storage households provide data from customers who had not installed storage but were experienced with Distributed Energy Resources (DERs). The SGIP

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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 ($). The most common metric for valuing resilience is VoLL, which may include loss of assets and perishables, business interruption costs, and recovery costs.

[5] A home can also provide resilience to the power system.

[6] The SGIP is a program of California's major investor-owned utilities (IOUs) that provides financial incentives for the installation of behind the meter (BTM) distributed energy resources (DERs) and energy storage technologies that meet all or a portion of a customer's electricity needs. Over the past decade, energy storage has experienced a significant increase in budget allocation within the SGIP (Verdant Associates 2022).

study Team hypothesized that these non-SGIP customers were more likely than the general population to be at least somewhat familiar with battery storage and thus able to provide insights into their potential motivations and barriers to battery storage adoption.

The VoLL from the non-SGIP solar non-storage population represents the best estimate of incremental VoLL attributable to battery storage that we identified in the literature applicable to the CVEO participants. Importantly, the 2021 SGIP included separate estimates of VoLL for those with medical needs[7] and those without. Table 1 presents the WTP-based VoLL estimates from the SGIP study. We assumed that 14% of the CVEO population had a medical need based on the *Low-Income Multifamily Health- and Safety-Related NEIs Study* (Three Cubed and NMR Group 2021) to calculate a weighted VoLL estimate of $13.82/kWh.

The VoLL estimate from the SGIP study is for the solar PV customers thinking of adding battery storage in California. Given this and the recent wildfires in California and the associated risk of losing power for extended periods of time, this VoLL estimate is likely an upper bound for the true VoLL for the CVEO program participants. That said, the CLC territory (Cape Cod and the island of Martha's Vineyard) are affected by coastal storms and cold winters, which could justify such a high VoLL for the CVEO participants who may be more concerned about catastrophic weather events than the average US household.

Table 1. VoLL Estimates Based on Willingness to Pay for Whole House Battery Storage, 2021 SGIP Market Assessment

Study Population	VoLL ($ / kWh), 2022 $USD
Solar without storage, medical needs	$20.05
Solar without storage, no medical needs	$12.80
Solar without storage, Weighted	$13.82

We also developed another estimate of VoLL for residential customers in Massachusetts using the Lawrence Berkeley National Lab's (LBNL's) Interruption Cost Estimate (ICE) calculator, a free, web-based, interactive tool for estimating interruption costs associated with power outages (Sullivan, Schellenberg, and Blundell 2015). The ICE calculator is a widely used tool designed for electric reliability planners to estimate interruption costs and the benefits associated with reliability improvements. It provides estimates of cost per interruption event, per average kW, per unserved kWh, and the total cost of sustained electric power interruptions.

The ICE calculator analyzes data from existing customer interruption cost (CIC) studies and organizes the results into a usable format and meta-database for utilities and other stakeholders seeking to develop outage cost estimates. This meta-database became the basis for the ICE calculator released in 2011. The meta-analysis was updated in 2015 with data from several more recent studies and LBNL made subsequent improvements to the ICE calculator. In its current form, the ICE calculator uses data from 34 US-based studies (a total of 105,000 customer surveys) completed by 10 utilities between 1989 and 2012 (See Sullivan et al. 2009; Sullivan, Schellenberg, and Blundell 2015; Schellenberg and Larsen 2018). The Team notes that, because the ICE calculator is based on relatively older studies, current customer preferences and the value they place on uninterrupted power may be different as a result of changes in the frequency and length of outages and electric end uses over time.

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[7] A participant was defined as having a medical need if they stated their household has a health-related need that requires electricity to power medical equipment.

The ICE calculator allows the user to enter state-specific inputs to estimate a VoLL specific to residential customers in that state. In developing an average VoLL estimate from the ICE calculator, we used a three-year average (2020–2022) of Customer Average Interruption Duration Index (CAIDI) based on the EIA-861 data for Eversource (US EIA 2023b).[8] CAIDI is the average interruption duration time for those customers that experience an interruption during the year. Since the ICE calculator produces numbers in 2016 dollars, we inflation-adjusted the results to express them in 2022 dollars.

We conferred with the LBNL Team to determine that the 2009 version of the ICE calculator—which is still available through the ICE calculator website—included an input for the percentage of households with medical needs. This allowed the Team to develop separate estimates of VoLL for households with and without medical needs (Table 2). The weighted VoLL estimate based on the ICE calculator is $2.77/kWh in 2022 dollars using the same assumption of 14% for the share of population with medical need based on the *Low-Income Multifamily Health- and Safety-Related NEIs Study* (Three Cubed and NMR Group 2021).

The VoLL estimate from the ICE calculator is for the average residential customer in Massachusetts. Since participants self-selecting into the CVEO program and adopting battery storage would be expected to have a higher VoLL compared to the average residential customer in Massachusetts, the ICE calculator-based VOLL estimate should be treated as a lower bound for the actual VoLL for the CVEO program participants.

Table 2. ICE Calculator Estimates of VoLL, Households with and without Medical Needs

Study Population	VoLL ($ / kWh), $2022
ICE calculator, households with medical needs	$3.25
ICE calculator, households without medical needs	$2.69
ICE calculator, weighted	$2.77

Configuration of BEopt Prototypical Models

The Team used the Building Energy Optimization (BEopt) software (version 3.0.1) to develop seasonal customer load profiles, including solar generation from the program-supported PV system, for three prototypical modeled CVEO participant homes (NREL 2023). BEopt is an energy modeling software tool designed to find optimal building designs. In typical use, it evaluates a supplied building design by exploring myriad measure option combinations to generate sets of measures that can meet various efficiency goals such as the cost-effective construction of zero net energy (ZNE) homes. Other key aspects of BEopt 3 include a system conducive to rapid prototyping, and the generation of detailed time series load data. Our model assumes that the participating homes will only have a critical load connected to the battery system during outages. The critical load is the equipment load that must be met during a grid outage (see Table 3).

In Table 3, the Team presents the critical loads for various end uses relative to the normal load. The Team notes that additional strategies such as lowering thermostat or water heater set points, or removing hot water heaters from the critical load could further reduce critical load during an outage.

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[8] The three-year average CAIDI was 5.5 hours.

Table 3. Critical Loads Relative to Normal Load

End Use	Critical Load as Percentage of Normal Load
Space conditioning, hot water, refrigerator, freezer, ventilation	100%
Miscellaneous plug loads, lighting	50%†
Clothes washer, clothes dryer, dehumidifier, dishwasher	0%

† Evaluation Team assumption to cover key uses such as medical equipment, minimal lighting, phone chargers.

The Team used microdata from the U.S. Energy Information Administration's (EIA's) 2020 Residential Energy Consumption Survey (RECS) to estimate the average heated square footage of three single-family home types in Massachusetts, for households with annual income less than $75,000 per year (Table 4) (US EIA 2023a).[9] To account for the diversity of types of single-family homes in the CLC territory and associated variations in critical load, the Team developed estimates of the load profile separately for the three single-family home types shown and then used the percentage of each single-family home types in Massachusetts (Table 4) to develop a single, weighted estimate across all single-family home types.[10] The individual home type load profiles were created by exporting the modeled hourly energy consumption data of a typical year for the whole home and various sub-systems such as space heating. This consumption data is influenced by the home characteristics, local climate, and the standard appliance usage schedules developed by NREL and included in BEopt.

Table 4. Massachusetts Single-family Home Characteristics, 2020 RECS (Households with Annual Income <$75,000)

Home Type	% of Single-Family Homes (Massachusetts)	Average Heated Square Footage (Massachusetts)
Small single-family detached	68%	1,327
Large single-family detached	20%	2,792
Single-family attached	12%	1,538
TOTAL	100%	1,648

Source: U.S. Energy Information Administration's (EIA's) 2020 Residential Energy Consumption Survey (RECS)

The Team used several sources to configure the building characteristics of the weatherized prototypical CVEO homes used in BEopt models, which affect the energy efficiency (and load) of the homes to determine post-weatherization building characteristics (see Massachusetts PAs 2018; NMR Group 2020). Table 5 presents the key building characteristics that affect the load of the prototypical homes and the source for the modeled values.

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[9] Income categories used by RECS do not align well with the income thresholds used by the Massachusetts PAs to determine if a household qualifies for their low- and moderate-income (LMI) offerings. An income cutoff of $75,000 is the closest to the LMI thresholds used by the Massachusetts PAs.

[10] Because we do not know the home characteristics of the program population, we created a weighted estimate to reflect the average program-eligible population.

Table 5. Assumed Building Characteristics of Prototypical CVEO Homes

Building Characteristic	Value	Source
Attic insulation R-value	60	Massachusetts Building code
Heating system: air source heat pump	15.2 SEER2 / 8.1 HSPF2	Program requirement[11]
Water heater: 50-gallon heat pump water heater	3.30 UEF	Program requirement[12]
Above-grade wall insulation R-value	13	Program weatherization field guide (Massachusetts PAs 2018), Expert judgement
ACH50	8.3	NMR Group 2020
Duct Leakage	6.5	Program weatherization field guide, Building Performance Institute (personal communication)
Window Area (fraction of floor area)	18%	Standard assumption, existing option in BEopt
Lighting	100% LED	Program weatherization field guide (Massachusetts PAs 2018)

The Team estimated PV generation with the BEopt software and specified the PV system and battery systems according to CVEO specifications detailed in the order from the Massachusetts DPU (2023a, page 12):

- PV system: The models assumed an installation size of 7.43 kilowatts ("kW") direct current ("DC") (or 7.10 kW alternating current ("AC") per household).
- Battery storage: Per battery, the model assumed a power rating of 5.0 kW and a usable capacity of 13.5 kWh

Based on the results of the BEopt modelling, we estimated the average seasonal load profile of the critical load of each home type (see Figure 1 in the "Estimating Battery Resilience NEIs" section for the results) for a small detached CVEO home, which is the most common type of single-family home in Massachusetts occupied by households with annual income less than $75,000. Given Massachusetts' cold climate, the program was most concerned about providing sufficient battery back-up for winter outages during peak heating demand, and so the Team disaggregated the data by season to ensure that any insufficiencies during winter would not be obscured in an annual average.[13]

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[11] https://www.masssave.com/en/heat-pump-qualified-list

[12] https://www.masssave.com/en/residential/rebates-and-incentives/heat-pump-water-heaters

[13] The team notes that summer peak load does not exceed spring peak load. This may be due to a combination of relatively mild summers in the CLC territory and higher loads during morning hours in spring that may reflect the heating load from heat pumps.

Estimating Grid Outages

The Team determined the average number, length, and season of outages in the CLC service territory,[14] as reported in the Eversource service territory outage data reported to the Massachusetts DPU for 2020 through 2022 (Massachusetts DPU 2023b). Since Eversource is the electric distribution utility for the CLC customers, the outage data for CLC towns are reported with the Eversource service territory outage data. This time period included outages from both a Nor'easter[15] in October 2021 (Barry 2021)) and a major winter storm, Winter Storm Kenan, in January 2022 (FEMA 2022).

Table 6. CLC Territory Outages, 2020 to 2022

Year	Number of Outages	Average Duration (Hours)	Average Number of Customers Affected	Total Customer-Hours	Total Hours of Outage Experienced by Average Customer
2020	2,307	3.0	166	483,437	2.3
2021	4,722	17.6	127	7,426,010	35.7
2022	891	9.4	512	2,612,281	12.6
Average, 2020 - 2022	2,640	12.4	182	3,507,243	16.9

Source: Massachusetts DPU 2023b

Estimating Battery Resilience NEIs

To estimate the resilience NEIs (defined as the monetized value of all participant benefits from having uninterrupted electricity supply during an outage) the Team first estimated the kWh supplied by the battery system during an outage by combining the BEopt load profiles with the outage timing data by merging on date and hour of day, resulting in a dataset with one row for each hour of each outage[16]. Next, we estimated the NEIs for individual outages for each home type (large detached SFH, small detached SFH, attached SFH) and by number of batteries (one or two) using Equation 1.

Equation 1: NEI per Home per Outage

*NEI per Home per Outage = VoLL_$_{CVEO}$($/kWh) * Total kWh supplied by the battery system*[17] *during the outage * The probability of the home being affected by the outage*

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[14] https://www.capelightcompact.org/wp-content/uploads/2023/05/Let-Marini-05-01-23-CLC-AR-DPU-23-MA-FINAL-CF.pdf
We included outage data for the following localities: the towns of Aquinnah, Barnstable, Bourne, Brewster, Chatham, Chilmark, Dennis, Edgartown, Eastham, Falmouth, Harwich, Mashpee, Oak Bluffs, Orleans, Provincetown, Sandwich, Tisbury, Truro, West Tisbury, Wellfleet and Yarmouth, and Dukes County.

[15] A Nor'easter is a storm along the East Coast of North America. The storms' winds over the coastal area are typically from the northeast. They are most frequent and most violent between September and April. https://www.weather.gov/safety/winter-noreaster

[16] Each home type was modeled twice, once with full load, and once with critical loads only. During an outage, the Team tallied the consumption data of critical load model that could be met before the battery charge was depleted.

[17] A battery system can contain one or two batteries. Total kWh supplied by the battery system is equivalent to the total kWh of lost load avoided.

The probability of the home being affected by a given outage was calculated as the number of customers affected by the outage divided by total number of customers.

Next, we summed all NEIs per home for each home type across all outages in 2020, 2021, and 2022 and calculated a single, weighted average for each year using the share of single-family homes of each type in Massachusetts occupied by households with annual incomes less than $75,000 as the weight. Finally, we took a simple average of the total NEIs per home in 2020, 2021, and 2022 to calculate an average annual NEI per home.

To estimate the annual kWh of lost load supplied by the battery system from the BEopt models and the outage data, the Team considered two different battery management strategies. The first scenario used the standard BEopt battery management strategy, which assumed that the battery storage system is charged by the PV system and discharges throughout the day to offset kWh drawn from the grid. As a result, the battery system does not always have a full charge at the start of an outage. The model allows for the battery to continue to recharge and discharge during an outage if sunlight is available to the PV. Our second battery management strategy scenario assumed that the battery system is configured to always have a full charge at the beginning of an outage. In other words, the battery system would be used for resilience purposes only and would discharge only during outages.

Figure 1 presents the seasonal critical load profile of a small detached single-family CVEO home and the average kWh provided by the battery system during an outage under the first battery configuration, as modeled in BEopt. Figure 2 presents the same critical load for a small detached CVEO home but with the average kWh provided if the battery system were reserved for outage events and always had a full charge at the start of an outage.[18] The difference between the two configurations is most visible during winter where the second battery configuration allows a higher portion of the critical load to be met than the first configuration.

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[18] The average kWh of power provided by the battery system occasionally exceeds the home's average critical load because there could be multiple outages during the same day and hour, so some day-hour records in the dataset are duplicated multiple times. If the outages happened at times when the home's load was higher than average, then the average amount provided by the system will be higher than the average home load for that hour and season.

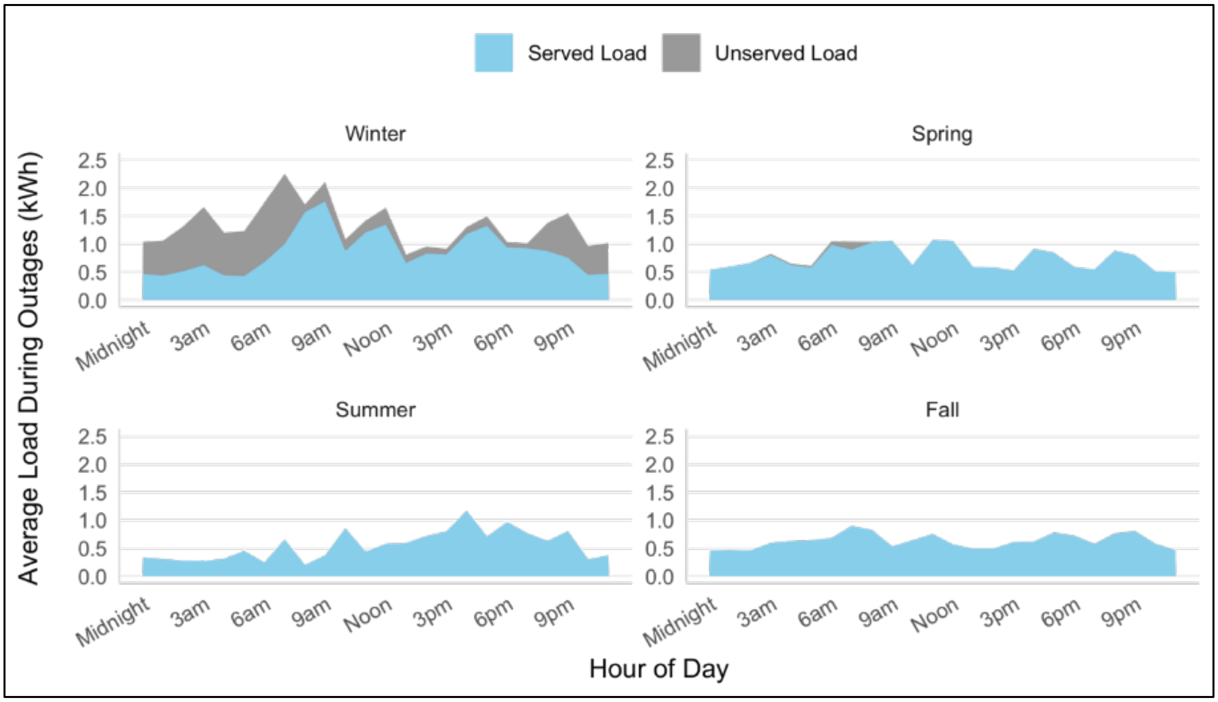

Figure 1. Seasonal Critical Load Profile and Average Load Supplied by a 2-Battery System, Standard Operations, Small Detached CVEO Home

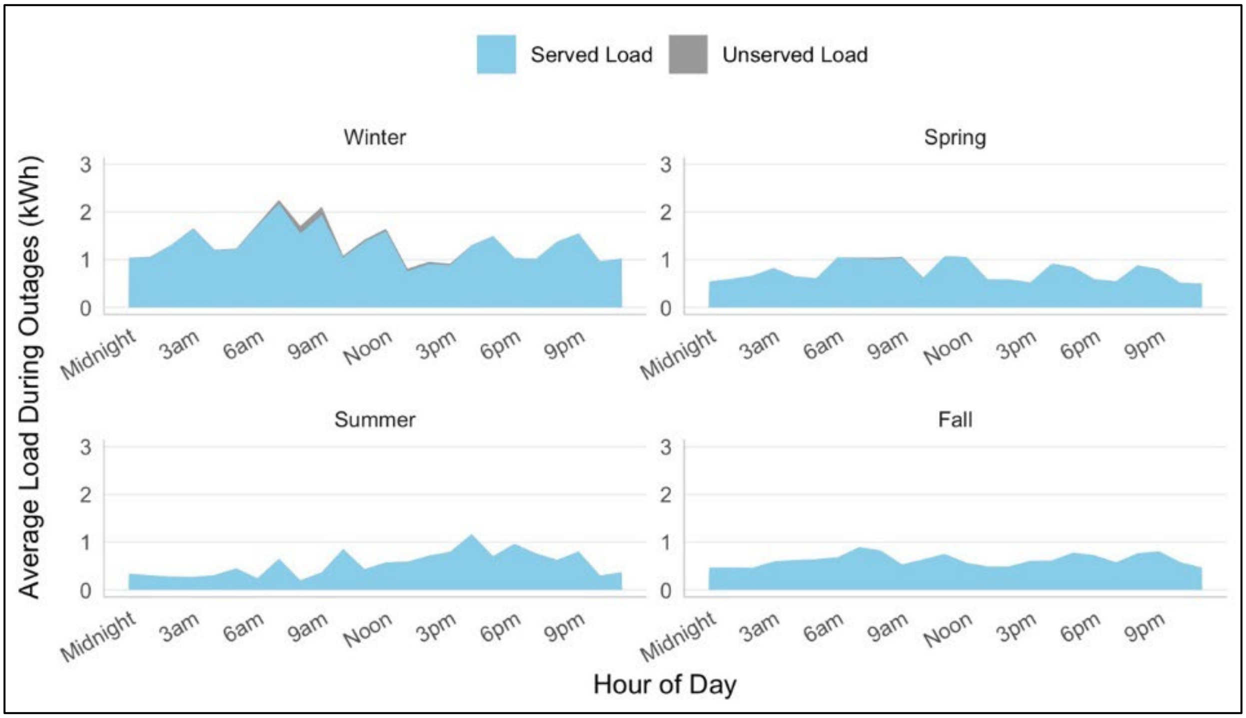

Figure 2. Seasonal Critical Load Profile and Load Supplied by a 2-Battery System Operating from Full at the Start of Outages, Small Detached CVEO Home

The total amount of energy supplied by the battery system during power outages in each study year was calculated using the BEopt modelling outputs joined to the historical outage data as the yearly sum of:

*kWh provided by PV and batteries during each hour of the outage * the percent of customers affected by the outage*

The modelling results were then averaged across the three study years and a weighted average taken across the three housing types per outage, as shown in Table 7 and Table 8.

Table 7. Average kWh Supplied by Battery System during Outages, Standard BEopt Modelling Battery Management Strategy

Home and Battery Type	2020	2021	2022	Weight	Weighted Average of kWh Supplied per Outage (kWh)
Small single-family detached, one battery	1.78	23.21	7.69	68%	10.89
Large single-family detached, one battery	2.23	31.01	9.79	20%	14.34
Single-family attached, one battery	1.92	25.92	8.58	12%	12.14
Average kWh, One Battery					11.73
Small single-family detached, two batteries	1.86	23.33	11.06	68%	12.08
Large single-family detached, two batteries	2.30	38.45	9.91	20%	16.88
Single-family attached, two batteries	2.02	26.03	9.63	12%	12.56
Average kWh, Two Batteries					13.10

Table 8. Average kWh Supplied by Battery System during Outages, Full Charge Modelling Battery Management Strategy

Home and Battery Type	2020	2021	2022	Weight	Weighted Average of kWh Supplied per Outage (kWh)
Small single-family detached, one battery	1.92	23.58	12.67	68%	12.72
Large single-family detached, one battery	2.89	31.44	14.90	20%	16.41
Single-family attached, one battery	2.14	26.34	14.20	12%	14.23
Average kWh, One Battery					13.64
Small single-family detached, two batteries	1.99	23.60	15.99	68%	13.86

Home and Battery Type	2020	2021	2022	Weight	Weighted Average of kWh Supplied per Outage (kWh)
Large single-family detached, two batteries	3.23	39.22	21.50	20%	21.32
Single-family attached, two batteries	2.22	26.37	17.24	12%	15.28
Average kWh, Two Batteries					15.52

From Tables 7 and 8, we use the average kWh provided by the battery system during an outage as an estimate of the kWh of lost load avoided due to having batteries. Table 9 presents the annual NEI estimates using the VoLL estimates from the SGIP study for the two configurations separately for homes with one and two batteries. The annual NEI estimate using the standard BEopt model battery management strategy (the more likely battery management strategy) is $162.08 for a home with one battery and $181.00 for a home with two batteries. The study Team plans to update these estimates once there are more data on several parameters from program implementation data and a survey of CVEO participants: (1) the percentage of the CVEO population with a medical need; (2) battery storage configuration; (3) battery capacity.

Table 9. Resilience NEIs from CVEO Battery Storage (Using VoLL from SGIP Study)

Number of Batteries & Home Type	Battery Management Strategy	Weighted VoLL (A)	Annual kWh of Lost Load Avoided (2020–22 average) (B)	Annual NEI Estimate Per Home (2022$) (A*B)
Single Battery, average home	Standard BEopt model	$13.82	11.73	$162.08
Two batteries, average home	Standard BEopt model		13.10	$181.00
Single Battery, average home	Full charge		13.64	$188.45
Two batteries, average home	Full charge		15.52	$214.46

We also developed annual NEI estimates using VoLL estimated through the ICE calculator. Table 10 presents these NEI estimates using the ICE calculator based VoLL estimates for the two configurations separately for homes with one and two batteries. Since the weighted VoLL estimated from the ICE calculator is about one-fifth of the VoLL from the SGIP study, the corresponding NEI estimates are also about one-fifth of the SGIP-based NEI estimates.

Table 10. Resilience NEIs from CVEO Battery Storage (Using VoLL from ICE Calculator)

Number of Batteries & Home Type	Battery Management Strategy	Weighted VoLL (A)	Annual kWh of Lost Load Avoided (2020–22 average) (B)	Annual NEI Estimate Per Home (2022$) (A*B)
Single Battery, average home	Standard BEopt model	$2.77	11.73	$32.48

Number of Batteries & Home Type	Battery Management Strategy	Weighted VoLL (A)	Annual kWh of Lost Load Avoided (2020–22 average) (B)	Annual NEI Estimate Per Home (2022$) (A*B)
Two batteries, average home	Standard BEopt model		13.10	$36.27
Single Battery, average home	Full charge		13.64	$37.76
Two batteries, average home	Full charge		15.52	$42.98

The Team believes that the true VoLL for the CVEO participants would be closer to the SGIP study's VoLL estimates than the ICE Calculator's VoLL estimates given that CVEO participants all have solar PV and are self-selecting into the program. Therefore, the Team believes that the SGIP-based NEI estimates shown in Table 9 should be used for the CVEO participants. Another more conservative option is to take an average of the SGIP-based NEI estimates and ICE calculator-based estimates in Table 9 and Table 10. The Team does not recommend this option due to the reasoning stated above.

Discussion and Study Limitations

Rather than assessing each resilience NEI individually, the study employed a willingness-to-pay approach that used the VoLL concept to monetize all NEIs as a whole. The study did not directly estimate a VoLL specific to the CVEO program participants. Instead, the study relied on a literature review to identify VoLL estimates applicable to the CVEO program participants. The VoLL estimates identified may not accurately reflect the value the CVEO program participants place on having battery storage to provide uninterrupted power during outages.

- The VoLL derived from the ICE calculator is for the average residential customer in Massachusetts. CVEO program participants may have a higher VoLL than the average residential customer for two main reasons: 1) Participants are self-selecting into the CVEO program and adopting battery storage, and 2) Participants use electricity for heating whereas the average residential customer would use other fuels for heating in a cold-climate state like Massachusetts where space heating is the largest residential energy end use. On the other hand, CVEO participants are low- and moderate-income (LMI) households. Since VoLL is estimated to increase with income, CVEO program participants may have a lower VoLL than the average residential customer in Massachusetts.
- The VoLL from the SGIP study is for non-LMI solar PV customers in California thinking of adding battery storage. Given this and the recent wildfires in California and the associated risk of losing power for extended periods of time and higher incomes for the SGIP program participants, the CVEO program participants are likely to have a lower VoLL than the SGIP participants. On the other hand, the CLC territory has coastal storms and cold winters to contend with, which likely increases the VoLL for the CVEO program participants.

Additional limitations of willingness-to-pay methodologies broadly also apply to this study. The value that low- and moderate-income populations attribute to or receive from a good or service may exceed the amount they are willing or able to pay due to limited income. Willingness to pay is an imperfect proxy for the amount of welfare a person gains from a good or service (Sunstein 2007).

The study analyzed three years of detailed outage data from 2020 through 2022 for the CLC service territory to determine the timing and length of each historical outage and the probability of a given customer being affected by each outage. Three years of outage data may be too short to determine the long-term outage patterns and durations and develop an average annual estimate of the kWh of lost load that can be avoided by battery storage. That said, the Team examined aggregate reliability statistics, including total annual outage hours and average outage duration for a ten-year period from 2013-2022 for the Eversource service territory (US EIA 2023b). We found that the ten-year averages were similar to the three-year averages analyzed in this study. The Team did not forecast future changes in loads and outage patterns attributable to climate change.

Conclusions and Next Steps

The paper presented an approach for monetizing resilience NEIs that accrue to CVEO program participants from battery storage that could be adapted to other programs that support battery storage. It involves estimating the VoLL, which is the average value per kWh that participants would place on uninterrupted electricity supply, and multiplying it by the annual kWh of lost load avoided because of battery storage, to estimate an annual resilience NEI value. For this paper, we adopted an estimate of VoLL from a recent California study of households that had adopted solar PV but had not yet adopted battery storage. It would be possible to update the CVEO NEI estimates by incorporating data on the share of participants with medical need and VoLL values that are specific to participants with and without medical needs.

LBNL is currently updating the ICE calculator with more recent studies and inputs.[19] Once the new version of the ICE calculator is available, the updated VoLL estimates can be used to update the lower bound NEI estimates in the event that the lower-bound estimate is the preferred estimate for the resilience NEIs. It may also be helpful to compare the value of battery storage resilience NEIs from studies that use a bottom-up approach to the NEIs developed through a VoLL-based top-down approach, though the Team notes that we did not find any relevant bottom-up battery storage resilience NEI studies in our preliminary review of the literature.

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