Wake of the Flood? Valuing Resilience Benefits of Energy Efficiency During Power Outages

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ABSTRACT

In recent years, extreme weather events interacting with the built environment have resulted in significant loss of life (e.g. NW heat dome event and winter storm Uri). When extreme weather events are coupled with power outages, people experience extreme heat or cold in their buildings, which can result in death. Poor building quality exacerbates these extremes and upgrades to the building envelope can mediate the building's thermal response, increasing resilience and safety for customers during outages. Our team created a novel methodology to quantify the economic benefit of building resiliency during power outages, building on previous work. Using 1000s of building simulation runs, the team analyzed building responses to power outages under a variety of weather conditions, including extremes. By comparing a reference model before and after an upgrade, the team was able to estimate the avoided costs of backup generation to hold the baseline model to the indoor air temperature of the efficient model. The results of the building simulation effort were paired with Northwest region-specific power outage weather condition frequencies to produce an estimate of resiliency benefits associated with a variety of building shell upgrades. The team observed a strong correlation between long duration outages and weather below freezing, likely linked to winter storms causing power outages. With a marginal size of diesel backup generator avoided cost approach, the team found savings of between 0.3 and 1.5 cents/kWh saved. The paper provides other states, utilities, and interested parties with the necessary information to quantify building resiliency benefits for residential energy efficiency upgrades.

Introduction

There is growing consensus that building resilience delivers real value during power outages. However, quantifying these benefits has proven difficult. In 2022, Apex worked with the Northwest Power and Conservation Council to develop an approach to valuing building resilience during outages. This work included a significant literature review and interviews with a variety of experts in the field. The ultimate output from this work resulted in a spreadsheet tool called the Resilience Valuation Tool (RVT), which successfully quantified a value of building resilience for attic insulation and a suite of measures in one location, Boise, ID. The work also identified areas for potential improvements, including:

- Potential changes in valuation methodology – the team identified multiple possible approaches to valuation, some of which could potentially improve upon the initial approach.
- Improved locational valuation of resilience – the team hypothesized that areas with higher outage frequencies would have higher value derived during outages
- Improved estimates of outage frequency and duration by weather type – the team used relatively coarse EIA outage data from recent years with rough estimates of weather distributions.

- Potential changes to avoided cost methodology.

In 2024, Apex worked with the Northwest Power and Conservation Council to make improvements to the approach and produce an updated RVT, in advance of consideration of valuing resilience in the upcoming power plan. While the approach has been designed to be applicable to the upcoming power plan, the same set of tools and approaches could be used in most places in the United States.

Recent Literature

The authors started this effort by reviewing recent literature in this space, published in the last few years, since the first version of the resilience valuation tool (RVT) was published. The authors were hunting for updates to approaches for improving the resilience valuation approach and for any available data to compare results to. Details of which improvements were adopted are found below in the approach section, while results of the review are summarized in Table 2 below.

Table 2. Resilience Literature Review Summary

Document (with hyperlinks embedded)	**Overall Resilience Guidance**	**Resilience Valuation Approach**	**Resilience Value**
ACEEE Valuing Resilience Benefits in Utility Building Retrofit Programs (Srivastava, 2024)	Varies based on cited study	Two main approaches included PNNL and Apex study	PNNL and Apex results
NREL Measuring and Valuing Resilience: A Literature Review for the Power Sector (Leddy, 2023)	Varies based on cited study	Overall logic maps to PNNL and Apex approach	None calculated
PNNL/NREL Enhancing Resilience in Buildings Through Energy Efficiency (Franconi, 2023)	Recommended valuation for benefit cost calculations based on efficient upgrade measure costs against benefits	Value of: life, energy savings, building impacts	Based on whole home EE levels, benefit cost ratios with and without EE upgrades
EE Vermont Energy Resilience Return on Investment (Ross, 2021)	Recommended valuation for benefit cost calculations based on efficient upgrade measure costs against benefits	Based on VOLL.	None calculated
NREL Customer Damage Function Tool (Gilroy, 2022)	Tallies up facility level costs to value resilience improvements	Summation of facility costs incurred due to outage	Site specific

Of note, the long-awaited PNNL/NREL study was released in 2023, which pursued a direct valuation approach to quantify the economic benefits of resilience. They were able to quantify the benefits of resilience in new commercial buildings built under different codes. ACEEE conducted their own literature review , summarizing the building benefits of resilience. They pointed to the previous Apex study and the current PNNL/NREL study as being exemplars of two different approaches to valuing resilience: direct impacts and avoided costs. The following revised approach section lays out potential approaches to solving various problems in quantifying building resilience benefits and the selected approach for this study.

Revised Approach

Estimation of building resilience valuation requires identifying the critical components and this literature review is aligned with each of the components. Valuing resilience requires identifying: the **events** that would trigger a building needing to be resilient, the **efficiency measures** that provide resilience benefits, the **pathways** by which impacts occur, and the **valuation logic** to estimate the resulting resilience value. The research addressed each of these components:

Measures and Pathways

The prior RVT modeled two of several representative EE measures identified by the Northwest Regional Technical Forum that are likely to provide resilience benefits. The PNNL paper modeled three whole home scenarios – an existing home, a new code-built home, and an above code home. The updated RVT effort modeled each of the envelope upgrade unit energy savings measures in use in the Northwest:

- Attic insulation
- Wall insulation
- Basement/crawlspace insulation
- Windows
- Infiltration reduction

For the updated RVT, the team also developed a repeatable workflow and process that could be used to create resilience values for future energy efficiency measures.

Valuation Approach

Valuation involves the quantification of value based on a dollar per resilience impact. The original RVT used an **Energy Valuation Approach** to estimate the energy savings (kWh) of the energy-efficient technology relative to a baseline system during a resilience event and then multiplied by an estimate of energy value during events (expressed as $/kWh) to monetize the impacts of resilience associated with each event. In contrast, the PNNL/NREL paper adopted a **Direct Impact Valuation Approach.** Direct Impact approaches consider the direct costs associated with experiencing an extreme event. Direct impacts can be categorized as occupant-based (survivability/loss of life, physical health, productivity) and building-based (frozen pipes, spoiled food, energy savings). The PNNL/NREL paper included a valuation of (a) loss of life (at $10mm per life), (b) energy savings, (c) greenhouse gas savings, and (d) property damage.

Our prior literature review, supplemented with a scan of more recent resilience valuation publications, continued to show that though alternatives to energy valuation approaches are proposed for resilience valuation, there still doesn't appear to be either an agreed upon methodology or a practical application of direct impact valuation approaches to value resiliency, with the exception of the PNNL/NREL direct impacts approach.[1] This includes a well thought out documentation of an approach by Efficiency Vermont which includes a preferred VOLL approach to valuation and an NREL-conducted literature review summarization of resilience valuation approach which includes both VOLL and energy valuation approaches. The following table summarizes and compares the key resilience inputs and logic used between the original RVT, the updated RVT, and the PNNL/NREL paper.

[1] While the PNNL/NREL direct impacts approach does work for their code-based application, the authors felt it could not be easily extrapolated to the energy efficiency retrofit measure application in the Northwest.

Table 1. Comparison of Resilience Valuation Approach and Input Assumptions

Input	Component	Source		
		Apex (original)	Apex (new)	PNNL/NREL
Weather data	Daily weather to estimate event frequencies	NOAA + NCDC	NOAA + NCDC	NASA and NOAA
	Wx files for building SIM	Modified Larson/Sharpe (NWC) files (Larson, 2022)	Unmodified Larson/Sharpe (NWC) files	NASA and NOAA
Outage data	Outage occurrences	EIA 861 reliability	Eagle-I data (Brelsford, 2024)	OE Form 417
	Joint Probability (wx x out)	Professional judgment and probability distributions	Eagle-I/OE417 data x NOAA + NCDC wx data	Severe weather incidents in OE417 data
Valuation approach		Avoided cost of backup energy	No change	Impact Valuation - "direct impacts"
Valuation metrics		Cost of backup diesel generator	Cost of backup generator or storage/solar system	Value of LoL, property damage, ee savings, loss of life
Building Simulation		EnergyPlus used for all building simulations		

The authors' recommended valuation approach is to calculate a value of resilience as the product of the marginal cost of providing electricity ($/kWh) for outage events using a customer-owned back-up generation system and the expected backup electricity (kWh) avoided during resilience events by EE upgrades. The authors propose this "avoided cost of outage energy" as an analog to to avoided costs of energy frequently used in energy efficiency cost-effectiveness testing. It is equivalent to the counterfactual cost of providing an equivalent service. While it is true that many people do not install backup generation, installation of backup generation is the most common way in which people currently provide thermal comfort during outages. Similar to calculation of avoided energy costs, our approach uses the cost of a marginal increase in the size of the required backup generation, rather than the cost of a single backup generation system. This is the same approach that we recommended in the original RVT. The updated RVT allows additional backup system options (and associated incremental costs) and improves the modeling workflow to iterate on various locations and EE measures.

After a comprehensive review of the literature and an assessment of the advantages of different valuation approaches, the team decided to proceed with the continued use of the energy valuation approach, which utilizes marginal abatement costs.

The equation below summarizes the calculation of savings from each of a series of annual events, including the

$$Annual\ event\ value\ (\$)\ =\ Marginal\ avoided\ cost\ (\frac{\$}{avoided\ resilient\ kWh})\ *\ Event\ hours/year\ *\ resilience\ savings\ /\ hour\ (kW))$$

We identified two main backup-system options[8] for consideration:

1. Backup generator (either diesel or gasoline system)[9].
2. Solar with backup batteries.

Apex adopted the marginal cost of electricity produced by a choice of backup generators, allowing a user to choose between a conventional diesel/gasoline generator and a solar/battery system. During an extreme cold event, electrically heated homes will consume up to 200 kWh per day, which is higher than current solar/battery systems can supply (unless installing a massive system). **Resilience Events**

These are the events that would trigger a building needing to be resilient, meaning a power outage combined with weather that would cause the building to no longer be able to maintain temperatures conducive to human health and well-being. The authors describe events in terms of the outage duration, weather, and event frequency, defined as the "joint probability" of outage and weather. The literature review in this area focused on the PNNL/NREL paper, showed that their teams modeling approach to resilience valuation applied two resilience event types – a shorter two-day 48-hour outage and one week-long (168 hour) long-duration outage and modeled joint probabilities with extreme weather based on a upper and lower threshold of 2.5%-5%. The PNNL paper relied on granular and regional outage data combined with federal weather data, which helped inspire a new review for improved joint probability for the RVT. In the original iteration of the RVT, Apex created a matrix of various Resilience Events, combining the outage duration (five unique outage durations, ranging from 8 hours to 4 days) and the weather (ten unique weather events, focusing on increasingly extreme weather conditions). Our updated RVT approach expands on the PNNL paper's granular and regional outage data approach to estimating joint probability. The updated RVT approach utilizes granular regional outage data and calculates a joint probability of weather and outage, combining location-specific actual weather data with the same time period.

Outage Duration

Outage duration is the length of the outage in a building. The PNNL/NREL defined two outage durations – a short two-day event and a longer duration week-long event. The revised RVT approach uses four outage durations of increasing length: 8 hours, 24 hours, 48 hours, and 96 hours. The original RVT effort showed that resilience benefits drop as outages get longer, because most of the benefits occurred during cold weather in winter, and while a well-insulated home maintains temperature for longer, most of the temperature benefit occurs in the first 48 hours. As a result, the authors did not feel the need to include an additional outage length longer than 96 hours.

Weather

The weather experienced by a building during an outage includes categories such as temperature, solar radiation, and wind speed. For event matching purposes, weather is defined based on the average outdoor temperature during the duration of the outage. In the revised RVT, Apex worked to align the extreme weather category definitions with those used in the extreme weather study conducted for the RTF,[3] with an additional lower frequency, higher amplitude category included.

Weather statistics vary both within a year and between years. The statistics for weather extremes predict the likelihood of a temperature condition being met or exceeded during a given year. Apex included both typical (mild, winter, and summer) and extreme (very cold/hot, extreme cold/heat, record cold/heat) weather cases in the Resilience Events.

The PNNL study relied on two publicly available weather datasets to identify historical extreme temperature events. The two weather datasets include the NASA POWER (Prediction of Worldwide Energy Resources) project (Stackhouse, 2021; Sparks, 2018), and NOAA's Local Climatological Data (NOAA, 2021). The PNNL study relied on a weather modeling (Ouzeau et al., 2016) methodology, which uses a combination of the top 0.5%, 2.5%, and 5.0% temperatures to identify extreme weather events (i.e., heatwaves). According to the PNNL paper, "*the historical weather data are scanned to flag temperatures exceeding the 0.5% of all recorded measurements (hot or cold for heat and cold waves respectively), then the data are scanned forward and backward from the 0.5% measurement. If the temperature stays in the top or bottom 2.5% of recorded temperatures, it is included as part of an extreme event. If the temperature falls outside the 2.5% temperature measurements but stays within the 5% highest or lowest recorded temperatures, the heatwave can continue with other neighboring heatwaves*." The PNNL paper's weather thresholds are summarized in Figure 1 below.

Threshold	Extreme Heat Event (Percentile)	Extreme Cold Event (Percentile)
Detection (T_{pic})	99.5	0.5
Duration (T_{deb})	97.5	2.5
Interruption (T_{int})	95.0	5.0

Source: Ouzeau et al. 2016

***Figure 1**. PNNL Paper Weather Thresholds*

Apex believes the PNNL's paper approach to extreme weather events is a narrower definition for joint probability calculation and recommends instead using a simplification of the existing RVT weather classification and data sources, eliminating the most extreme, lowest frequency weather event, fully aligning with Larson/Sharpe extreme weather files produced for use in the Northwest instead. The original RVT included an extreme weather event that was equivalent to approximately a one year in 30 to one year in 50 frequency. However, outages associated with this sort of weather are extremely rare and the previous RVT showed that very little value was derived during these events, when other events were much more frequent and created more expected value. The revised RVT incorporates these changes.

Event Frequencies and "Joint Probability"

The expected frequency (i.e., annual probability of occurrence) of each resilience event is necessary to establish the average value of resilience. As noted earlier, it is difficult to forecast the correlation of power outage events with specific temperature weather, because most of the outage events are not caused by bulk power system failures, but rather by other natural hazards or events, some of which are correlated with cold or hot weather (e.g. ice storms, windstorms, thunderstorms) and some of which are not (e.g. earthquakes, floods).

Previously, Apex used EIA-861 outage data,[4] a normalized distribution of outage lengths for different customers within a given outage event, across 8 discrete outage lengths, ranging from about 0.1 times the mean outage length up to 3.5 times the mean outage length, and recent major outage events from EIA data in the Northwest and assigned the weather type coincident with the outage (e.g., was it summer or winter and was the weather random or correlated). Apex used this admittedly anecdotal data and professional judgment to assign proportions of outage distribution to each associated weather type. Interviewed experts agreed with the general idea of outages being more common in the winter.

The PNNL study utilized the DOE electric disturbance events form, specifically the OE-417 outage data. The PNNL study assumed that outages recorded in this dataset affected the entire state and assumed full and simultaneous power restoration to all customers. As noted in their paper, "*these assumptions will produce an overestimation of power outage frequency and duration.*" Furthermore, the PNNL paper conducted scenario analysis to develop low, medium, and high bounds for power outages, informed by the OE-417 data. The PNNL paper adopted the "medium" case. The paper concluded that additional work is needed to refine the power outage data assessment and the joint probability estimation.

Apex researched the OE417 data and identified another outage dataset, Eagle-I data. This outage data originates from DOE Oak Ridge National Lab and includes 15-minute interval county-level outage data. There are advantages and disadvantages to each outage data source, summarized in Table 3 below.

Table 3. Outage Data Source Comparison

Outage Source	Outage Data Source	Outage interval resolution	Customers impacted	MW impacts
EIA 861	Utilities report system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI) non-momentary electrical interruptions and the conditions under which these metrics are collected.	No (just total outage hours and customers impacted)	Yes, total	No
OE 417	The Electric Emergency Incident and Disturbance Report (Form DOE-417) collects information on electric incidents and emergencies. The Department of Energy uses the information to fulfill its overall national security and other energy emergency management responsibilities, as well as for analytical purposes	Full outage interval only	Yes, across event (appears to be maximum # impacted, so is overstated)	Yes
Eagle-I	EAGLE-I is DOE's operational and scalable data and information platform for real-time wide-area situational awareness of the energy sector, providing a centralized platform for monitoring power distribution outage for over 146 million customers; just over 92% coverage of US and Territories.	15-minute resolution	Yes, at 15-minute intervals	No

Modeling Workflow

The team revised the workflow used in the original RVT. With the updated RVT, the team created a semi-automated workflow that enables the modeling of more measures and events than in the previous work.

1. **Summarize outage data integrate weather data.** The team used EAGLE-I outage data combined with historical weather data from NCDC to estimate outage frequencies by duration temperature for each balancing authority location in the Northwest.
2. **Create a new instance of the resilience valuation tool, defining the baseline and efficient cases.**

3. S**et up a new efficient case input file and run using the Residential Energy Efficency and Demand Response tool (REEDR).** REEDR is a parametric analysis front end used by Regional Technical Forum analysts to model energy efficiency measures. REEDR allows up to about 100 EnergyPlus building simulations to be run at a time. Each REEDR run included an efficient case prototype residential building run with all combinations of:
    - 3 heating systems types: gas, electric force air furnace, and heat pump
    - 2 extreme weather files: Miles City, Montana for extreme cold, and Boise, ID for extreme heat
    - 8 outage start days, commencing an outage schedule 4 days on, 4 days off.
      Figure 1 below shows the resulting indoor and outdoor temperatures for one simulation, using the 4 days on, 4 days off outage schedule:

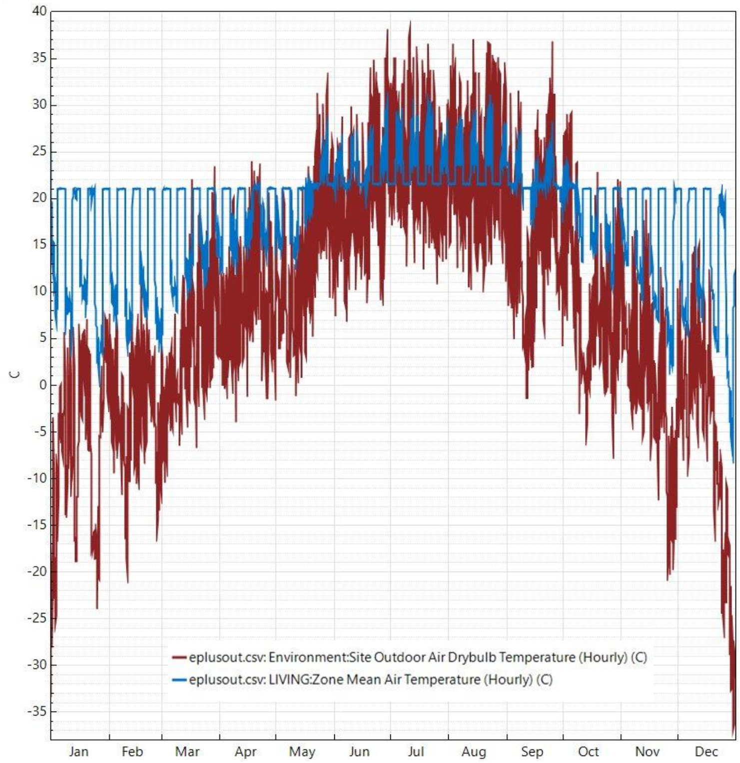

Figure 2. Example Building Simulation Hourly Outdoor Temperature Indoors and Outdoors with 4 Day Outages

By rotating through each of 8 different starting days, along with 2 different extreme weather files, every possible combination of weather and outage could be modeled, e.g., a 4-day outage starting on day 2 of an extremely hot period, followed by a rapid cool down, a 1-day outage on a typical winter day, etc. In addition, each REEDR efficient case run included 10 typical weather runs, one for each balancing authority, combined with each of the same three heating system types, for an additional 30 simulations.

4. **Extract space temperature data for each efficient case outage run.** Each efficient case outage run produces an hourly space temperature, which includes times when the space is not conditioned.
5. For each baseline measure condition associated with an efficient case, **create a baseline REEDR input file and run.** In each of the baseline runs, a new set of inputs is run, without the outages, but with the efficient case temperature inputs extracted in the prior step used as the temperature setpoints.

6. **Correct for thermostat hysteresis (optional).** The authors discovered late in the study that the average temperature in EnergyPlus is typically a little bit higher than the thermostat setpoint, which makes a significant difference in results for measures with low electricity savings. This can be corrected for in two different ways. One option is to use an adjustment to the temperature setpoint in the prior step. However, it's difficult to develop the exact adjustment to make. Instead, the team used a correction set of building simulations. In this case, a baseline case with the same efficiency as the efficient case is run with the updated temperature setpoints. This results in a small amount of additional consumption that can be subtracted from the other baseline case runs to remove any bias from the thermostat hysteresis.
7. **Calculate results for each outage type.** For each day with an outage, calculate the change in energy consumption for the day (by subtracting efficient case consumption and hysteresis run consumption from two times the baseline case consumption) and assign it to a temperature bin based on the average daily temperature for the run. Average these results across all days to calculate an average kWh saved/outage hour for each combination of temperature and duration.
8. **Add the results by outage type and baseline and efficient case non-outage annual consumption to the RVT.** When combined with the outage event frequency and assumed avoided cost per outage kWh, this generates an annual value and value per annual kWh saved.

The team then repeated this workflow for each of the measures, using a variety of base and efficient cases, and calculated a resilience value for each case.

Results

In the revised RVT, the study team updated each of the key inputs initially identified, while maintaining the original overall approach of valuing resilience using avoided costs . Using an avoided cost methodology has the advantage of being simpler and easier to understand compared to direct cost approaches, and it is analogous to other avoided cost methodologies currently used in energy efficiency cost-effectiveness testing.

Avoided Costs

The team estimated the avoided costs of outage kWh by balancing authority in the Northwest. Regions with a higher incidence of outages have lower avoided costs per kWh because they incur the same fixed costs per year, but with greater usage of backup generation systems. The team estimated the average avoided costs of outage kWh to be $34/kWh using the marginal change in size of diesel backup generator systems and $121/kWh using the marginal change in size of solar plus battery backup generation systems.

Resilience Event Joint Probability

Across the Northwest, analyzing the Eagle-I dataset, the study team found an average number of 4.7 outage hours per year. Most of these outage hours occurred during longer duration events during the winter months, as shown in Figure 3 below. Very few outages were observed at extremely cold temperatures. However, the sort of region-wide, bulk-power system failure that has a very low likelihood of occurrence is expected to be most likely to occur during these most extreme conditions. The inability to observe these kinds of events does not mean that they do not exist, meaning that this a known bias of the method used.

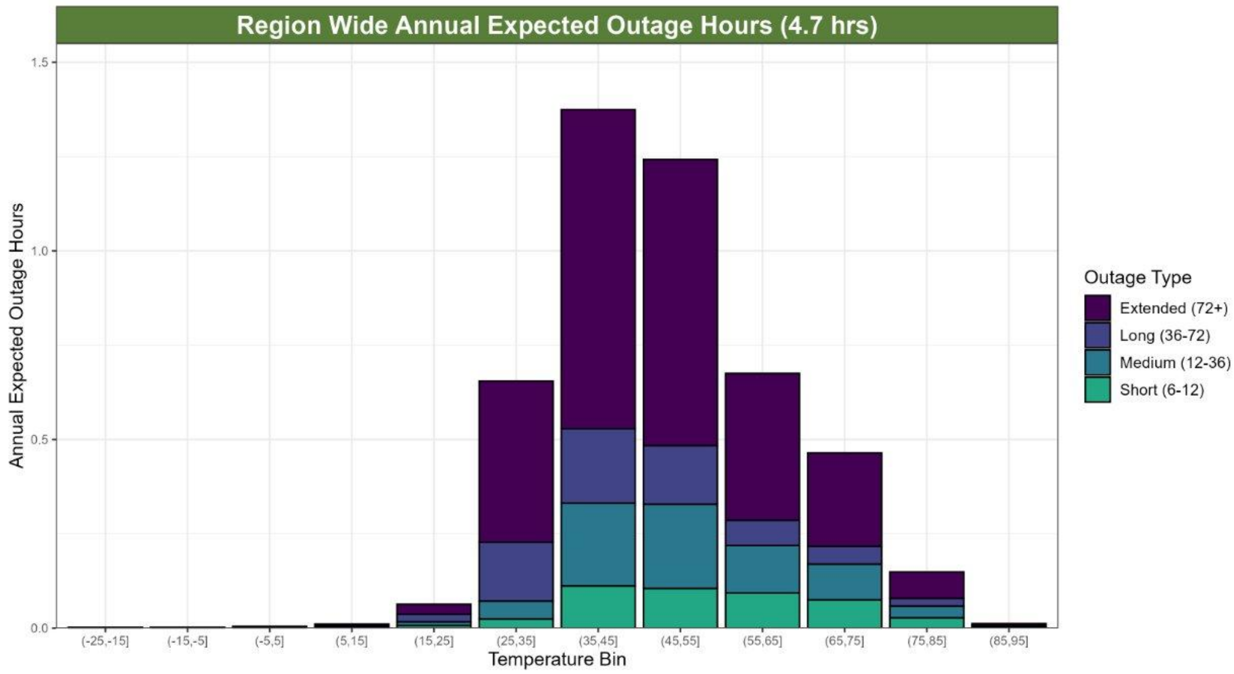

Figure 3. Northwest Region Expected Outage Hours by Daily Average Temperature and Duration.

Annual Resilience Value

Across the region, the team found a range of resilience values by measure. Figure 4 below shows the value of resilience across a suite of envelope measures for an air source heat pump, using a diesel generator for the avoided cost of outage energy. While values vary by measure, for this case, they are all within the same order of magnitude, 0.3 to 0.7 cents/kWh.

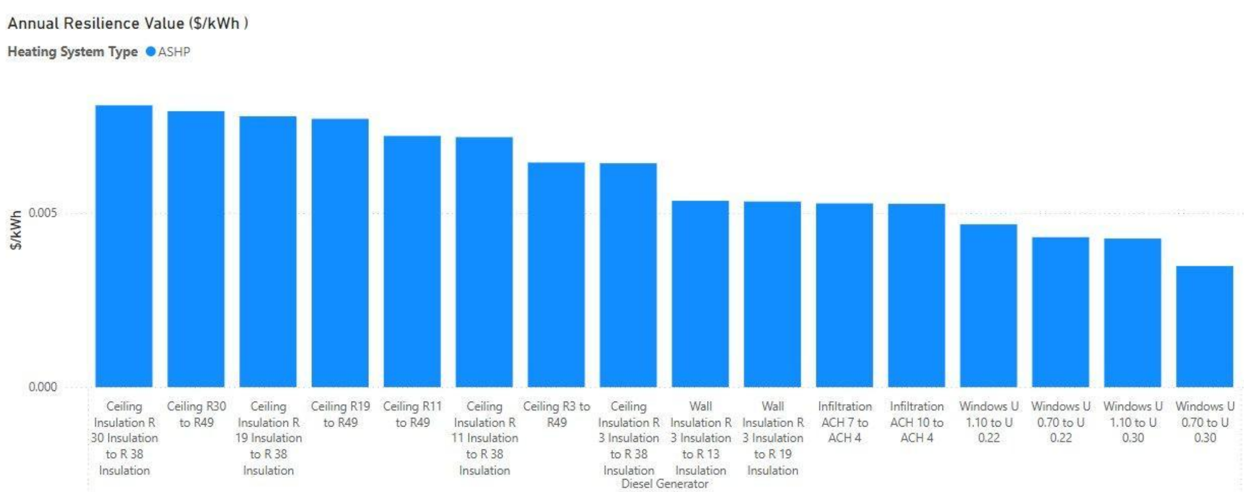

Figure 4. Air Source Heat Pump Resilience Value per Annual kWh Saved – Diesel Backup Generator Avoided Cost

Heating types with higher usage of electricity have higher benefits per kWh saved, with homes with gas furnaces having very low benefits in this framework. In addition, using solar and storage to set the avoided cost of outage energy results in roughly 5X higher value of resilience, as shown for a ceiling insulation measure in Figure 5 below.

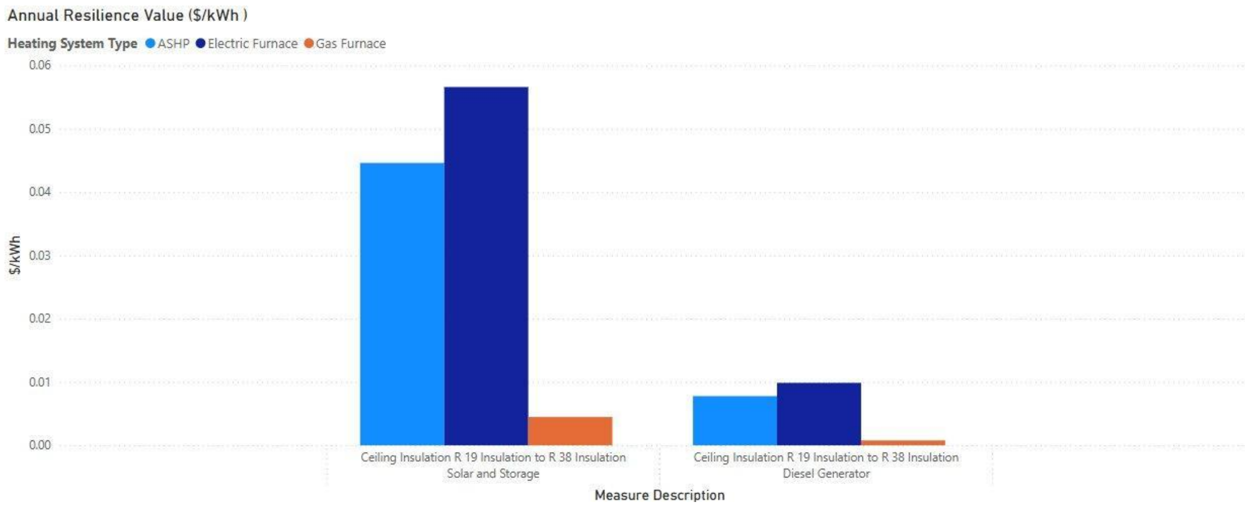

Figure 5*. Ceiling Insulation R19 to R38 Valuation for Solar and Storage vs Diesel Generator Valuation Approach*

Across regions, avoided cost per outage kWh is inversely correlated with annual outage hours, so outage values using this approach are not dramatically higher in areas with more outages.

Conclusions and Recommendations

The authors have demonstrated that an avoided cost approach to valuing building resilience enables the quantification of resilience benefits. The choice of alternative outage mitigation technology has a highly impactful effect on the overall value, with solar and storage-based avoided costs coming in five times higher than diesel generator avoided costs. Using the avoided cost approach in this paper, higher outage frequency was not strongly correlated with higher value per annual kWh saved.

Using a diesel generator as an alternative for avoided costs and a heat pump for the heating system results in a resilience value ranging from approximately 0.3 to 0.7 cents per kWh for the range of measures tested in this study. Using this methodology, most of the resilience value is derived from extended outage events that occur during winter weather, which is not especially extreme. We expect to see similar results in other climates that experience at least occasional winter storms.

While the avoided cost approach to valuing resilience may be the most practical approach at this time and the approach the authors recommend for valuing resilience benefits now, the direct cost approach has some significant advantages and might prove to be more accurate. In particular, the avoided cost approach doesn't deal well with the non-linearity of direct impacts, during which mortality may rapidly increase beyond a certain threshold. Quantifying direct impacts is difficult, but long-term research in this area should be supported.

When calculating the joint probability of weather and outage, researchers should use the longest time period possible and expand or summarize across larger geographic areas if the time period is too short. Estimating the frequency of infrequent events should be considered to have higher uncertainty at finer timescales and geographies. In the Northwest, the authors recommend using a single region-wide value due to these uncertainties in smaller geographies. Lastly, building resilience benefits should be considered for addition to societal benefits in jurisdictions that incorporate these sorts of host customer benefits into their cost-effectiveness testing.

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