Comfort in the Dark: Quantifying the Value of Building Resilience

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ABSTRACT

As our energy system evolves and becomes more complex, and as extreme weather events become more common, it is crucial to identify and quantify the full benefits of energy efficiency, particularly in terms of building resilience. The Northwest Power and Conservation Council (NWPCC) identified a need to better understand the full value provided by energy efficiency measures on building resilience, with a focus on how weatherization can enhance a building's ability to withstand prolonged power outages. This project led to the development of a resilience valuation tool, based on the enhanced ability of a weatherized building to maintain temperature and reduce the need for alternative resources like backup generators. This Excel-based valuation tool is the first of its kind, offering a method to assign a monetary value to the resilience benefits of energy efficiency.

The methodology first determines an avoided cost of resilience by using the cost per emergency kilowatt-hour (kWh) of a backup power system, and then estimates the avoided emergency kWh provided by weatherization upgrades. To validate this approach, EnergyPlus was used to simulate an electrically heated home, both with and without weatherization upgrades, during a series of simulated seasonal blackouts. The study found that weatherization provided resilience benefits of approximately $250 per year, or 1-3 cents per annual kWh saved by the weatherization measures, for the modeled measure set and location. This paper discusses how resilience is factored into power planning work, review the developed methodology, and outline future steps.

Background

Cost-effectiveness of energy efficiency portfolios has become more challenging as regulatory, market, and utility business forces have recently coalesced. Regulatory actions have made LEDs the de facto baseline and left a significant portion of formerly cost-effective lighting equipment no longer a component of portfolios, while stringent building codes and appliance standards have also increased the baseline efficiency of other measures, excluding some of the lowest cost assets available to efficiency programs. Pronounced reductions in the costs of renewable energy have caused a drop in avoided costs of energy, making even moderately priced efficiency equipment less attractive.

In addition, extreme weather events are increasing in frequency with two notable events occurring in the United States in 2021 alone. These events have resulted in property damage, health impacts, and even loss of life. The Northwest heat dome event caused over 400 deaths, with over 50 killed by heat in Multnomah County (Portland, OR), all of whom lacked access to air conditioning at home (reference to Multnomah County study). Winter storm Uri caused over 200 deaths due to cold in Texas, as well as the collapse of the power grid.

With this confluence of factors, the Northwest Power and Conservation Council (Council) in its 2021 Power Plan, recognized that energy efficiency measures can have benefits to buildings beyond energy savings, specifically improving a buildings resilience can offer substantial benefits to buildings occupants (see 2021 Power Plan).[1] The Council identified a need to understand the value these efficiency measures provide toward building resiliency and tasked its Regional Technical Forum (RTF) with exploring the development of a valuation approach. In 2022, the RTF solicited a study to develop a replicable approach to valuing efficiency improvements benefits associated with improved resilience of buildings.

There is a growing body of research surrounding energy efficiency and building resilience as evident with recent publications produced by LBNL (Frick 2021, Franconi and Hong, 2021, 2024) coupled with papers produced by Efficiency Vermont (Efficiency Vermont, 2021). The National Lab research team has multiple building-resilience studies currently in progress, with some findings already published and additional reports and papers due to be published over the coming months.

Some jurisdictions outside the Northwest include other indirect attributes that receive standardized, quantified valuation for inclusion in cost-effectiveness testing. These additional cost-effectiveness components include non-energy impacts (NEIs), carbon abatement costs, or the individual components representing NEIs (health, safety, comfort, productivity). These metrics are incorporated into cost-effectiveness testing, either through an indirect dollar-per-avoided-unit-of-energy basis, or collectively as a percent-of-total-benefits adder (Pigg et all, 2021). In at least some cases (like Massachusetts), these NEIs include what we have defined here as resilience impacts (event-based health and safety impacts), though they have not been explicitly defined as resilience impacts. As a result, it may be difficult to definitively say that another jurisdiction does NOT include resilience impacts. They may be implicitly included in their NEIs, depending on the methodology used to calculate their NEIs, without being called resilience impacts.

Apex staff – at the time of this study in 2022, were unable to identify any publicly available studies that demonstrate a methodological approach or recommendation around valuing (i.e., monetizing) resilience, whether based on a dollar per avoided unit of energy, as a percentage adder, or any other basis. Dr. Hong (LBNL) noted the lack of any resilience valuation during an interview and noted this in one of his papers: "Costs are challenging to estimate due their dynamic nature and wide variations in installation costs and other factors. Cost/benefit analysis is even more challenging when considering non-energy benefits such as thermal resilience, health, and productivity. More work is needed in the future to perform a comprehensive analysis to quantify these non-energy benefits." (Hong et all, 2021)

After a comprehensive review of literature and an assessment of the advantages of the different valuation approaches, the team categorized various valuation approaches from the literature into two main kinds: **Energy Valuation** and **Direct Impacts.**

Energy Valuation approaches first estimate the energy savings (kWh) of the energy-efficient technology relative to a baseline system during a resilience event. Then it estimates an energy value during events (expressed as $/kWh) to monetize impacts of resilience associated with each event. Based on Apex team's literature review and concurrent discussions with

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[1] Available at: https://www.nwcouncil.org/2021-northwest-power-plan/

resilience experts, we identified **three Energy Valuation approaches**: **Value of Lost Load (VOLL)**, **marginal abatement cost**, and **bulk system adequacy.**

Direct Impacts approaches consider the direct costs associated with experiencing an extreme event. Direct Impacts can be categorized as occupant-based (physical health, loss of life, productivity) and building-based (frozen pipes, spoiled food).

Apex developed a resilience valuation method using ***marginal abatement costs***. The remainder of this section provides details on this approach. The alternative approach options (direct impacts, energy valuation using VOLL and bulk system adequacy) are summarized and reviewed in the Appendix to the longer study.

Resilience Valuation Approach

There are several components that require identification to estimate a building resilience value. Valuing resilience requires identifying: the **events** triggering a building's need for resilience, the **efficiency measures** that provide resilience benefits and the **pathways** by which impacts occur, and the **valuation logic** to estimate the resulting resilience value:

- **Resilience Events**: events that trigger a building needing to be resilient. Currently defined Resilience Event scenarios, which illustrate and bracket the types of real-world events that can drive resilience value. The methodology recommends a distribution of weather and duration for power outages but excludes extreme weather events where the power is on.[2]
- **Efficiency Measures and Pathways**: an overview of representative energy efficiency measures that may provide resilience benefits and two EE measures for which resilience value was estimated in the Resilience Valuation Tool. For each measure, we present the pathways that result in resilience impacts.
- **Valuation:** The final step is to develop the valuation logic that establishes a dollar benefit per resilience impact value. The proposed 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 back-up generation system and the expected backup electricity (kWh) avoided during resilience events (as defined in the next section) by EE upgrades. This approach further uses building simulation models to estimate the backup electricity avoided during each of the events for a particular EE upgrade. This recommended approach was implemented in the valuation tool for two weatherization upgrade options.

Resilience Events

Through our review of the literature and discussions with Council staff, we decided on the following definition of a **Building Resilience Event: a long-duration power outage combined with weather conditions that cause typical homes to fail to provide an essential**

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[2] This paper is focused on quantifying building resilience benefits occurring during power outages. Energy efficiency can also provide building resilience benefits when the power is on, and efficiency provides grid-level resilience. These impacts can be captured in other benefit streams, e.g. health and safety benefits for building resilience during events with the power staying on and capacity value for grid resilience. The Council will continue to consider whether and how to improve its valuation of resilience in resource planning.

service of keeping people and property safe. While the literature review also identified significant value associated with some EE measures that increase cooling availability during extreme hot weather events, these measures require the power be on. Therefore, this type of event was excluded from the event definition for the scope of this study; it remains an opportunity for future research efforts.

Apex created a matrix of various Resilience Events (i.e., scenarios) as the coincidence of **outage duration** and **weather**. As a starting point, we included all combinations of identified outage durations and weather. To the extent that weather may be correlated with power outages, some combinations of outage and weather may be more common than others. Also, not all combinations have substantive resilience impacts for all measures; for example, energy modeling showed that outages occurring during mild weather have minimal resilience impacts and that outages occurring during hot weather were rare and resulted in only modest impacts in the Northwest.

Outage Duration

Outage duration is the length of the outage in a building and only outages that are long enough to cause significant building impacts are included (i.e., at least 6 hours). A summary of the outage scenarios used in the tool Apex developed, Resiliency Valuation Tool (RVT), are detailed in Table **1** below.

Table 1. Outage Scenario and Ranges

Outage	**Duration**	**Model Event**
Short	Partial day (6-12 hours duration)	8-hour
Medium	1 day (12-36 hours duration)	24-hour
Long	Multiple days (36-72 hours duration),	48-hour
Extended	Several days (72+ hours duration)	96-hour
Extended Rolling Blackouts	Several days of rolling blackouts (72+ hours duration)	96 hours w power cycling on and off every 3-hours

Weather

Weather during the outage impacts the building resilience. As well as temperature, other weather parameters including humidity, solar radiation, and wind speed impact building loads and ultimately building resilience impacts. Weather is also used to describe an event and is defined based on the average outdoor temperature during the duration of the outage. Apex worked to align the extreme weather category definitions with those used in the extreme weather study conducted for the RTF.[3]

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 and extreme weather cases in the Resilience Events, detailed as follows.

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[3] https://nwcouncil.box.com/v/20220809XtremeWeatherImpsPres

Typical weather cases:

- **Mild**– weather when neither significant heating nor significant cooling is required, generally with average daily temperatures of 55–75 degrees F.
- **Winter weather** – the median temperature conditions experienced during December–February
- **Summer weather** – the median temperature conditions experienced during June–August

Extreme weather cases:

- **Very cold weather** – the kind of very cold weather experienced every year. In 90% of years, weather this cold or colder is experienced at least once.
- **Extremely cold weather** – the kind of cold weather only experienced one year in 10. In 10% of years, weather this cold or colder is experienced at least once.
- **Coldest weather** – this is the coldest weather in the historical record.
- **Very hot weather** – the kind of very hot weather experienced every year. In 90% of years, weather this hot or hotter is experienced at least once.
- **Extremely hot weather** – the kind of hot weather only experienced one year in 10. In 10% of years, weather this hot or hotter is experienced at least once.
- **Hottest weather** – this is the hottest weather in the historical record.

The team used Boise, ID as the weather location for testing the proposed valuation method, because its climate includes both extreme heat and extreme cold conditions. Table 1

Table **2** shows the outside temperature based on an analysis of Boise, ID weather data from 1937 to 2021 for the different outage event lengths identified above. These comprise the set of 45 **resilience events** that were modeled in this study. The different length extreme weather events can typically all be found in a common 5-day period in the historical record (e.g., the hottest 3-day period is usually a subset of the hottest 5-day period).

Table 2. Temperatures (deg F) During Resilience Events (Boise)

	Outage Duration				
Weather	**Short: 6-12 hours (Daily high or low)**	**Medium: 12-36 hours (Daily average)**	**Long: 36-72 hours (3-day average)**	**Extended: 72+ hours (5-day average)**	**Extended Rolling Blackouts (5-day average)**
Hottest Weather (1% annual occurrence)	111	94	91	90	90
Extremely Hot (10% annual occurrence)	108	91	88	87	87
Very Hot (90% annual occurrence)	99	84	81	79	79
Typical Summer	88	73	73	73	73

	Outage Duration				
Weather	Short: 6-12 hours (Daily high or low)	Medium: 12-36 hours (Daily average)	Long: 36-72 hours (3-day average)	Extended: 72+ hours (5-day average)	Extended Rolling Blackouts (5-day average)
Mild Weather (average daily temperature 55-70)	75	65	65	65	65
Typical Winter	25	33	32	32	32
Very Cold (90% annual occurrence)	11	21	23	25	25
Extreme Cold (10% annual occurrence)	-12	-1	1	3	3
Coldest Weather (1% annual occurrence)	-25	-16	-13	-11	-11

Resilience Event Frequencies

The expected frequency (i.e., annual probability of occurrence) of each resilience event is necessary to establish the average annual value of resilience. The frequencies of resilience events combining power outages with extreme weather are highly uncertain. This is a common characteristic of low likelihood, high impact events. In addition, it is difficult to forecast the correlation of power outage events with specific temperature related to extreme weather conditions. Most outage events are not caused by generation and transmission failures to meet high demand, but rather by other natural hazards or events causing failures of the distribution system. Some outages are correlated with cold or hot weather (e.g., ice storms, windstorms, thunderstorms) and some are not (e.g. earthquakes, floods). The team utilized the following approach to estimate the resilience event frequencies:

1. **Create distribution of outage lengths and frequencies.** To develop a distribution of outage lengths and frequencies, Apex estimated event-driven outages using EIA-861 data.[4] To estimate the event-driven hours per utility per year, we used the difference between total and event-driven outage hours by utility, and then divided by the number of event-driven outages per customer. This ultimately results in a mean event duration and number of customers impacted for each year for each utility in the dataset.[5]
2. **Allocate outage hours across different length outages.** Apex examined available publicly reported information on the number of people without power at different points

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[4] Available online in a "Reliablity.xlsx" file within annual zip files at https://www.eia.gov/electricity/data/eia861/.

[5] While it would be preferable to use data from Northwest utilities only, the period of data available from EIA is only since 2013. Given that outage events are likely to be correlated across the Northwest and the desire to find some more rare events, this could be improved in the future. The team considered using national outage data, but ultimately limited the results to Northwest utilities in the dataset.

in time during a major outage (windstorm in Spokane area in 2015).[6] This was used to build a normalized distribution of outage lengths for different customers within a given outage event, across 8 discrete outage lengths, ranging from about 0.1 to 3.5 times the mean outage length. This distribution captures the fact that the actual outage durations for individual customers will vary significantly within an event. The individual outage groups were then summed up based on the outage duration category into which they fell, e.g., all of the customer outages lasting 12-36 hours were assigned to the nominal day long outage event category.

3. **Allocate outage hours across weather types based on secondary research and professional judgement.** Apex examined 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.

For now, the common set of Resilience Event frequencies were used across all locations in the Northwest and incorporated into the Resilience Valuation Spreadsheet.

Efficiency Measures and Pathways

The Council had already been considering the role of resilience values in planning before the launch of this study. The 2021 Power Plan cost-effective methodology section prepared by the Council discussed resilience.[7] Two tables were presented that “highlight which measures in the 2021 Plan might include one or both of these values”. Theoretically, any measure that improves a building’s ability to ride through a Resilience Event should receive a resilience value. Yet, for this study, only passive measures—those not requiring electricity to operate—were considered for inclusion in this study, a decision made in conjunction with Council staff. Active measures would only work with backup power systems, which are not part of the baseline Resilience Event case.

Each measure considered has resilience impacts via at least one of these pathways:

- Preservation of health/safety
    - Maintenance of space temperatures for health/safety during winter
    - Maintenance of space temperatures for health/safety during summer
    - Other health/safety impacts during outage event (e.g., maintenance of space humidity to prevent mold growth)
- Preservation of property
    - Maintenance of space temperatures to prevent pipes from freezing
    - Other prevention of freezing pipes

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[6] Massive windstorm hits Spokane and eastern Washington, leaving 180,000 homes without power, on November 17, 2015. - HistoryLink.org

[7] See link: https://www.nwcouncil.org/2021powerplan_cost-effective-methodology

- Other property impacts during outage event (e.g., thawing freezer)

The table below presents the measures considered in the development of the valuation methodology and when and how much resilience impact they have. “Mixed” impacts mean that measures may lead to negative or positive resilience impacts, while “High” and “Low” both likely provide positive impacts. “None” indicates the measure has neither positive nor negative impacts.

Table 3. Efficiency Measures Qualitative Resilience Impact Categories

Sector	**Measure**	**In Original Council Recommendation**	**Summer Impacts**	**Winter Impacts**	**Mild Weather Impacts**
Commercial	Window glass	Yes	High	Mixed	None
	Secondary glazing systems	Yes	Low	High	None
Residential	Cellular shades	Yes	Low	Low	None
	Duct sealing	Yes	High	High	None
	Weatherization (Insulation)	Yes	Low	High	None
	Water heater pipe insulation	Yes	Low	Low	Low
	Windows	Yes	High	Mixed	None

Based on this table, and in coordination with RTF staff, Apex developed the Resilience Valuation Spreadsheet to include a single permutation of attic insulation and a more comprehensive weatherization upgrade in a residential building as the two validated resilience test measures.

For a more detailed example of how resilience impacts are derived from EE upgrades, consider the impacts of a weatherization measure. Weatherization upgrades reduce the heat loss (or heat gain) through the building envelope, while leaving some of the other properties of the building (thermal mass and HVAC system capacity) unchanged. The reduction in the heat loss and heat gain (as characterized by the building load coefficients (Krati, 2000)) has a few different practical impacts on the operation of the building that could improve resilience to different kinds of events. The reduction in loads while maintaining the thermal mass means that the building will lose or gain heat more slowly post-retrofit when unheated or uncooled. In addition, the existing HVAC system will have more excess capacity post-retrofit, allowing it to more quickly reach setpoint temperatures after a power outage event. During long-duration events, the reduced heat loss results in the building being able to maintain a more desirable passive operation temperature, potentially preventing the freezing of pipes, or enabling the use of a smaller backup heating or electric generator system.

Figure 1 below shows the simulated difference in temperatures during a four-day outage with very cold temperatures in two identical homes in Boise, one with inefficient envelope characteristics and the other with efficient envelope characteristics after weatherization. During the first day of the outage, starting at hour 24 on the graph, the weatherized home has indoor temperatures about 10 degrees warmer than the non-weatherized home. The non-weatherized home is able to stay above freezing for about 24 hours, while the weatherized home is able to stay above freezing for an extra 24 hours, until the end of the second day of the outage. However, the difference in temperature narrows after the first day and by the end of the fourth day of the outage, there is no substantial difference in temperature between the two homes.

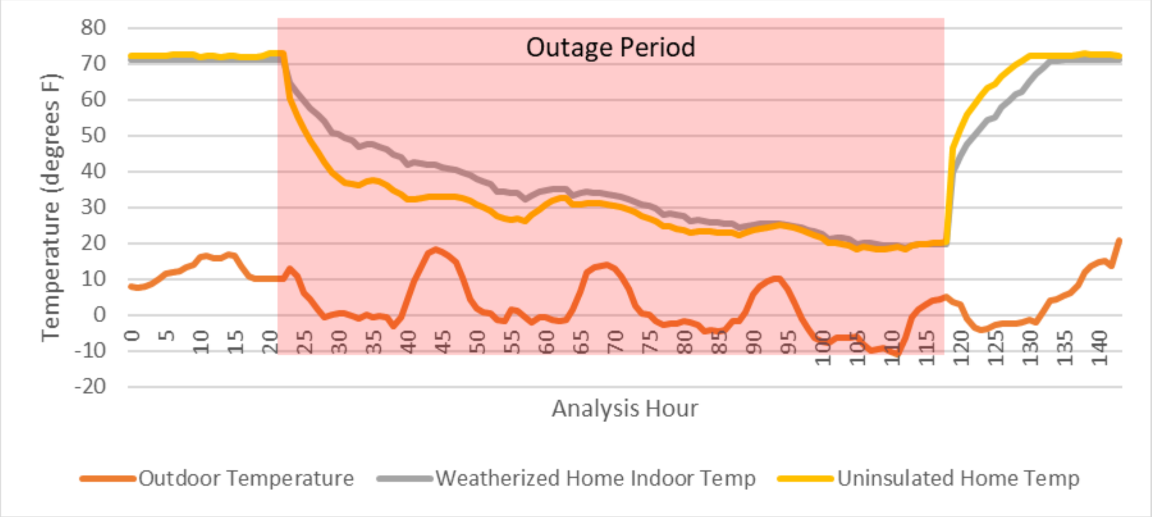

Figure 1. Winter Outage Space Temperature Comparison, Source: Apex building simulation

Energy Valuation Approach

The Energy Valuation approaches share a common set of building energy analysis steps to estimate energy impacts of EE measures, followed by individual approaches for estimating resilience value per kWh. The following formula expresses the general approach:

For each event *i*, calculate Event Resilience Value ($) for each measure *m*, r_{im}:

$$r_{im} = e_{im} * v_i$$

Where e_{im} is the **Measure Energy Impact** (kWh) for each measure *m* during event *i* with respect to a baseline measure case and v_i is the **Resilience Energy Value** ($/kWh).

Note that we expect that Resilience Energy Value could vary across events due to differences in the impacts on home occupants. However, it’s only possible to quantify this using direct impacts, which requires lots of data that did not exist at the time of this study. In the absence of better data, the team recommend assuming the relationship is stable across events, especially as we expect the variation to be small relative to the uncertainty in the Resilience Energy Value generally. Future efforts can research and quantify the variation if additional data becomes available.

Measure Energy Impact Calculation

For each event i and measure m, the authors recommend that the following methodology is used to calculate energy impacts for each indoor-temperature impact measure, e_{im}:

1. **Develop a resilience weather year (RWY)** for each location of interest, which includes defined time periods with all of the hot, cold, and seasonal weather required for the set of resilience events.
2. **Model power outage behavior of efficient case.** Using building simulation prototype models[8] capable of effectively capturing passive building behavior, model the efficient case of the measure without electricity during the event periods (i.e., turn off all electricity-consuming devices, such as HVAC, lighting, etc.) for the RWY. Also include a time period with scheduled power being turned on and off at 3-hour intervals for the rolling blackout case. Extract the set of indoor temperatures attained for each event i $\{T_1 \rightarrow T_j\}_i$ contained within the extreme weather year.
3. **Model alternative HVAC electricity consumption.** The last step is to modify the baseline building simulation input file to use the event indoor temperatures extracted from the efficient case in step 2 as the HVAC setpoints during events, with normal setpoint behavior outside of the events. This model should have electricity turned back on. Extract the HVAC electricity consumption of this model for each of the events. This is the energy impact, e_{im}, equivalent to the energy savings in the case when the baseline building consumes more energy during a resilience event than the efficient building consumes during the same event. The energy impact of the event depicted in Figure 2 below, a 24-hour outage during very cold weather, would be estimated by summing the blue columns from midnight to midnight on the day of the outage.[9]

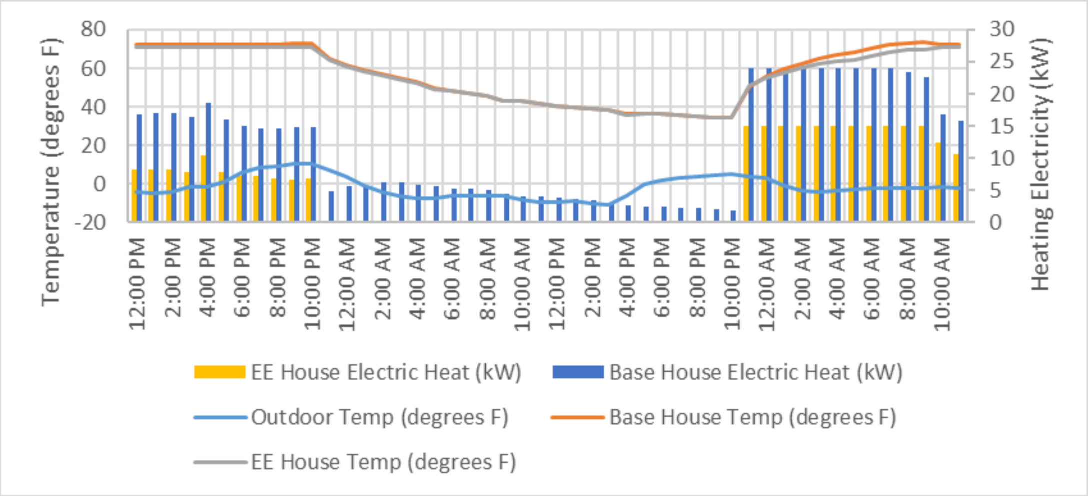

Figure 2. Temperature and Heating Electricity for Two Day Period During 24 Hour Outage

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[8] For the draft valuation tool, Apex used EnergyPlus for building simulation because it captures passive building operations better than most building simulation engines.

[9] There are two additional cases of energy savings in conjunction with events that have been purposely left out of impacts. During the return to setpoint after an outage ends, the efficient building consumes less energy. However, these energy savings are less impactful than the energy savings during the outage. As a result, these impacts are not included in the resilience benefits at this time. During a rolling outage, this reduction in energy consumption during recovery from an outage has very valuable benefits. However, these benefits should be part of winter peak capacity benefits.

Resilience Energy Valuation

Marginal abatement cost refers to the cost of a baseline alternative investment that delivers the same services, analogous to using the cost of new combined-cycle gas generation plant to estimate avoided costs of electricity or demand. The National Standard Practice Manual (NESP, 2020) defines avoided cost as "the costs of those electricity and gas resources (e.g., generation, transmission, and distribution system infrastructure) that are deferred or avoided by the DERs being evaluated for cost-effectiveness." In the case of power outage, the avoided costs of energy represent the avoided costs of supplying additional backup electricity. The energy efficiency investment allows for the installation of an incrementally smaller backup power system.

Multiple experts interviewed during this study agreed with our proposal to apply the same principle to resilience benefits by defining an alternative standard backup power system and using that to develop a marginal abatement cost. In order to use marginal abatement cost, one must define both the alternative investment characteristics and whether the average cost per unit, the marginal cost per unit, or the total cost of the equipment should be used, as described below.

- **Total cost of equipment:** The total cost of backup system equipment. Using the total cost would not take into account the fact that the backup system typically provides many more benefits to occupants (e.g., lights, hot showers, cold food) compared to the weatherization EE services of making the space 55 degrees instead of 45 degrees. For example, if a backup power system costs $20,000, then for this analysis, it would be the assumed resilience value of the EE improvements per household. One approach to limiting this value to the value of the resilience would be size the generator to only be able to deliver the same benefits as the energy efficiency.
- **Average cost per unit:** The average cost per unit divides the total equipment annual ownership cost (including equipment, maintenance, fuel, etc.) by the energy delivered (in kWh) during the average year. This value is then multiplied by the kWh required to provide the same measured resilience metric as the EE measure. For example, if the levelized cost of backup power is $200/kWh and the expected kWh required each year for attaining the same level of resilience with EE is 10 kWh per household, then the resilience value of EE is $2,000 per year per household.
- **Marginal cost per unit:** The marginal cost per unit compares the incremental cost savings associated with being able to downsize the backup power system due to the addition of EE. For example, if the downsized backup power system with EE costs $12,000 instead of $20,000, with annual ownership costs of $1,200 instead of $2,000 then the resilience value of EE is $800 per year per household.

The team recommend using the marginal cost per unit (marginal cost of abatement) at this time, but a case could be made for using the average cost per unit instead. Anderson (Anderson et all, 2018) identified three main backup-system options for consideration:

1. Backup generator.
2. Solar with backup batteries.

3. Hybrid system with solar, generator, and backup batteries.[10]

Recommended Approach: Use marginal cost of electricity produced by large backup diesel generator with large aboveground fuel tank. This choice may seem surprising, given the economic benefits of the renewable energy hybrid system (REHS) advocated by Anderson et al. However, the typical use case in the Northwest is assumed to be a home using electric heating. During an extreme cold event, electrically heated homes will consume up to 200 kWh per day, which is much higher than that assumed in the Anderson paper. Expected baseline system characteristics:

- 20 kW diesel generator with 100-gallon fuel tank.
- Weatherproof enclosure.
- Automatic transfer switch.

The following provides the recommended calculation methodology, which is included in the Resilience Valuation Spreadsheet for the ease of future updates.

For a typical backup diesel generator running at typical loading, the generator is about 20% efficient at producing electricity, with 125,000 Btu/gallon of #1 diesel assumed. The generator is then capable of producing 100 gallons * 125,000 Btu/gallon / 3,412 Btu/kWh * 20% = 730 kWh on a tank of fuel, enough to supply 240 kWh for 3 days or 150 kWh for 5 days, at which point additional fuel will be required. In the case of a long-duration outage with limited fuel supplies (e.g., Puerto Rico during Hurricane Maria), this system will fail to provide benefits when the fuel supply runs out. This is where the REHS system would definitely perform better—during natural disasters. A true long-duration power outage system in the Northwest would probably require a non-electricity heat source be added. Fuel-switching is considered outside the scope of this study.

The installed cost of the expected system is approximately $25,000, but if properly maintained (essential to ensure it works during an emergencies), it can be expected to last 30 years, given the low usage.

Annual maintenance costs are assumed to be $500. Annual maintenance costs include scheduled annual oil changes, fuel conditioning, weekly automated testing, and 20 gallons/year of diesel consumed for testing. With a 3.75% real discount rate,[11] annual maintenance costs, and

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[10] Anderson et al identified a critical weakness in traditional backup generators: "*The current cornerstone of resiliency, fossil fuel backup generation, is useful for riding out short outages, but for longer outages these systems are vulnerable to refueling supply chains that can be, and have been, compromised due to physical damage of transportation and distribution infrastructure.*" They then went on to quantify the benefits of their proposed solution: *"Renewable energy hybrid systems (REHS) can serve as an alternative or supplement to existing forms of backup power, extending limited fuel supplies and providing greater system redundancy."* They concluded that the optimal backup power system in most cases is actually an REHS, which includes a mixture of solar, battery, and generator to deliver during an extended outage. Backup generators alone have much lower initial capital costs, but they fail during some outage events. At this time, it's unclear if the resilience benefits associated with EE most closely resemble those provided by backup generator systems (primarily short duration) or REHS (short and long duration).

[11] Consistent with the 2021 Plan.

annual fuel consumption at a cost of diesel fuel of $5/gallon, the annualized cost of ownership of this system is $1,909.

Based on EIA outage data, as analyzed in the tool, the average annual event-based outage experienced by a home in the Northwest in recent years is 3.5 hours. With the system running at 4 kW on average, then the annual kWh provided by the system is 14 kWh.

This baseline system has been compared to a similar system sized half as large. The difference in costs between the two systems is the marginal cost. The system that is half as large produces 7 kWh less per year and costs $1590/year, $318/year less than the large system. Dividing the change in annual generation by the change in annual cost between the two systems gives a marginal cost per kWh of $45.39. **This gives a marginal abatement cost of $45.39/kWh.**

Example Valuation Results

The methodology was implemented in the Resilience Valuation Tool[12] and tested for a single-family home in Boise, ID with window AC units and an electric forced air furnace, for a ceiling insulation upgrade alone and for a whole home weatherization suite of measures, including ceiling insulation, crawlspace insulation, wall insulation, air sealing, and window retrofits. Example results from this application of the tool for the whole home weatherization option are shown below, applying the marginal abatement cost of $45.39/kWh to each scenario and including a sub-selection of a few records from high, moderate, low, and zero value events. The event energy savings per home represent the total modeled kWh savings for each scenario. These are then divided by the outage duration to get the energy savings per home per event hour. Expected annual outage hours per home were estimated using the analysis of outage data and assumptions about coincidence of weather with this outage data. This is multiplied by the energy savings per home per even hour to estimate the expected annual energy savings per home, which is then multiplied by the marginal abatement cost to estimate the expected annual value in dollars.

Table 4. Selective Scenario Results from Resilience Model

Outage Type	Weather	Assumed Outage Duration (Hours)	Event Energy Savings per Home (kWh)	Energy Savings per Home per Event Hour (kWh)	Expected Annual Outage Hours per Home	Expected Annual Energy Savings per Home (kWh)	Expected Annual Value ($)
Day	Typical Winter	24	50.88	2.12	0.5874	1.2453	$56.52
2day	Typical Winter	48	78.58	1.6371	0.2728	0.4465	$20.27
Extended	Coldest	96	133.88	1.3946	0.0222	0.031	$1.41
Day	Mild Weather	24	0.87	0.0364	0.1762	0.0064	$0.29
2day	Extremely Hot	48	2.39	0.0499	0.0055	0.0003	$0.01
Extended	Extremely Hot	96	6.75	0.0704	0.0044	0.0003	$0.01
Short	Hottest	8	0.05	0.0069	0.0077	0.0001	$0.00

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[12] The tool and user guide are available on the RTF website at https://rtf.nwcouncil.org/other/energy-efficiency-resilience-valuation-methodology-study/

Short	Extremely Hot	8	0.09	0.0108	0.0077	0.0001	$0.00
Short	Very Hot	8	0.01	0.0007	0.0232	0	$0.00
Extended Rolling	Typical Summer	96	7.24	0.0754	0	0	$ -
Short	Mild Weather	8	---	0	0.1162	0	$ -
Total/ Average	**Total/ Average**	**All**	**N/A**	**1.7753**	**3.162**	**5.6136**	**$254.77**

Note $254 total exceeds sum of rows expected annul value shown due to limited display of only 11 of hundreds of rows of valuation.

The results show that almost all (~98%) of the resilience benefits occur during winter weather. This is a function of both the higher incidence of outages during the winter and the higher energy impacts associated with winter outages.

When the total annual value of resilience ($254.77) is divided by the estimated annual energy savings of the EE measure (5.6136 kWh), the resulting values of the resilience per annual energy impact were estimated as 1.4 cents per kWh for the whole home weatherization suite vs 3.2 cents per kWh for the ceiling insulation alone. This implies that there could be a significant interactive effect on the resilience impacts between measures. Measures with savings more focused on winter will have higher resilience impacts per kWh. In particular, window retrofits will reduce solar gains as well as conductive and radiative heat loss. During sunny winter weather, the additional solar gains associated with the baseline windows become larger than the conductive and radiative heat loss during outages, because the temperature difference is reduced.

We recommend a future assessment of windows separate from other envelope measures, as window measures with lower SHGC may actually have negative resilience impacts compared to window measures with higher SHGC.

Conclusions

Recent storms, power outages, and extreme weather events have shown that climate models' prediction of greater frequency and intensity of weather events is already a reality; coupled with the potential for extended duration power outages, the need for increased building resilience has never been greater. While we are convinced that the value of resilience impacts is non-zero, validated through this project via the Resilience Valuation Tool, significant assumptions were required to estimate valuation using this approach. Table 3 summarizes the sources of uncertainty, our assessment of the uncertainty level (high, medium, low) and future improvements that could be considered to reduce uncertainty. Work is already underway (as of spring 2024) to address the largest sources of uncertainty with plans for a new resilience valuation tool to be released later in 2024.

Table 5. Resilience Sources of Uncertainty

Component	**Uncertainty**	**Considerations**
Event – duration	Low	Duration is discrete, but various events need to be mapped to discrete events.
Event – weather	Medium	The range of likely weather events in the near future is likely not that different from the recent past. However, climate change is causing a shift in extremes.

Event – frequency	High	Frequency of weather and outages and their correlation is highly uncertainty and would be a good area for further research. Within the modeling approach used, there is uncertainty around the distribution of customer outage lengths and the frequency of outages, especially long duration outages. Rolling blackout frequency is low, but highly uncertain.
Measures	Low	Measures are relatively straightforward – more work will be needed to develop all of the different measures and measure variants.
Valuation – Abatement	Medium	Costs of equipment and costs per kWh both carry uncertainty. Annual kWh provided per generator capacity/size is also uncertain.

The team has also identified the following opportunities for streamlining further efforts to estimate resilience impacts for different measures:

1. Exclude mild weather events. Mild weather impacts were minimal.
2. Model a suite of similar measures and use one impact value from the stack of measures.
3. Consider dropping all of the summer events, if the distribution of longer duration outages across weather types can be confirmed in some way. Summer impacts were in the order of 2% of the total.
4. We also considered recommending dropping the most extreme events from the analysis.

The Council's 2021 Power Plan recognized not all the power system benefits have been fully quantified for energy efficiency, leading to the development of an approach for quantifying the impact energy efficiency has on building resilience. While the valuation approach developed may continue to have areas of uncertainty and there will likely continue to be improvements, this tool provides a first of its kind approach to determining a value for the resilience impacts of energy efficiency. As noted, Apex is supporting efforts to update the tool, including providing multiple options for back up generator, and addressing other areas of uncertainty where possible. This work is expected to provide data to support the Council, RTF, and the region in its continued assessment of energy efficiency potential and its value to the system.

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