Applications of Measuring and Valuing Resilience in Energy Systems

Sean Ericson, Nicholas Grue, Eliza Hotchkiss,
and Maxwell Brown

National Renewable Energy Laboratory

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5R00-83841
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Suggested Citation

Ericson, Sean, Nicholas Grue, Eliza Hotchkiss, and Maxwell Brown. 2023. *Applications of Measuring and Valuing Resilience in Energy Systems*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5R00-83841. https://www.nrel.gov/docs/fy23osti/83841.pdf.

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Golden, CO 80401
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Acknowledgments

The authors would like to thank Anna Brown, Bob Mack, and Hetvi Dave for the opportunity to work with New York State organizations focusing on resilience and energy security. The authors would also like to thank Nelson Yip and Christopher Jones of Consolidated Edison for their input into the case studies.

List of Acronyms

AC	air conditioning
BCA	benefit-cost analysis
CHP	combined heat and power
ConEd	Consolidated Edison
DOE	U.S. Department of Energy
EV	electric vehicle
FEMA	Federal Emergency Management Agency
Hazus	Hazards United States
IPCC	Intergovernmental Panel on Climate Change
NREL	National Renewable Energy Laboratory
NRI	National Risk Index
NYC	New York City
NYPA	New York Power Authority
NYSERDA	New York State Energy and Research Development Authority
p.u.	per unit
PV	photovoltaics
RCP	representative concentration pathway
TPRA	Transmission Probabilistic Reliability Assessment
VoLL	value of lost load

Executive Summary

The electricity sector is vulnerable to numerous hazards that are being exacerbated by climate change, which can cause an increase in the hazards' frequency and intensity. Consumers, system regulators, system operators, and communities are now preparing to mitigate the increased risks posed by climate change. New York State's energy infrastructure resilience can be increased with targeted investments including but not limited to installing emergency backup systems, integrating microgrid solutions, weatherizing buildings, increasing energy efficiency, adding redundancy, investing in restoration and recovery, and hardening critical components. Such investments can reduce the likelihood, impact, and consequences of disruptive events but can also increase capital and operating costs.

A barrier to prioritizing investments in resilience is that there is no widely established method for quantifying and assigning the benefits of resilience investments across various stakeholders. Decision-makers need better information detailing the value of resilience improvements. Developing methods to quantify, value, and price resilience helps meet resilience needs in an effective manner that also supports broader societal welfare. This report lays out considerations for quantifying and valuing resilience, discusses the current state of resilience valuation tools, and provides case studies of resilience projects that demonstrate how resilience attributes could be measured while highlighting broader, project-specific challenges to increasing resilience. Further, we present insights into methods and challenges to measuring, valuing, and enacting resilience investments. One way to quantify resilience involves using a probabilistic risk assessment, which is the process of identifying hazards, estimating their frequency of occurrence, identifying vulnerabilities, and estimating the severity of impacts. There are five steps to determining the expected costs of disruptive events, and in turn, determining the value of resilience, which are similar to NREL's energy resilience assessment methodology (Anderson et al. 2019). NREL's methodology fits within the probabilistic risk assessment framework.

Hazards are the underlying disruptive events that a decision-maker wants to build resilience towards. Scenarios are the potentially multiple timing, duration, geographic scope, and intensity instances of a hazard. Occurrence frequencies can be expressed as the annual likelihood that a given scenario will occur. Impacts can be the physical damages from a given scenario. Finally, consequences are the economic and societal costs associated with an event. Resilience valuation tools are becoming increasingly useful to help assess the cost from more frequent and intense disruptive events. Several resilience valuation tools are currently available, but further research in methods as well as hazard- and asset-specific considerations are needed. Resilience valuation approaches suffer from lack of historic data from extreme events, leading to increased uncertainty and low confidence in ultimate valuation estimates. More publicly available information on occurrence frequencies and better integration of climate change forecasts into resilience valuation tools can improve the quality of estimates. Improving the ease of use and reducing the cost burden of using resilience valuation tools would increase the number and variety of resilience projects that can be modeled.

In addition to presenting the five-step framework for resilience valuation and discussing resilience valuation tools, we present four case studies relevant to the New York State Energy Research and Development Authority (NYSERDA) coverage area that highlight the opportunities and challenges of resilience and resilience valuation. The first case study focuses on resilience to heat waves for residential customers. It discusses how resilience upgrade costs and benefits are allocated and examines the impact of individual choices on the energy system and society. The case study suggests that purchasing individual air-conditioning (AC) units provides an inexpensive and effective means to reduce the dangers of extreme indoor temperatures. However, low-efficiency AC units can both contribute to climate change and stress the grid during peak temperatures, leading to potential outages. Similarly, purchasing higher efficiency heat pumps and increasing building energy efficiency can reduce emissions, reduce grid stress, increase passive survivability during grid outages, and provide long-run cost savings. However, these investments can have higher upfront costs, and those who benefit are not always the same as those who make the investments.

The second case study focuses on the interactions of electric vehicle (EV) adoption and grid resilience. EVs present an additional grid load whose charging, if uncoordinated, could disrupt grid operations during peak loads but also present a significant source of potential load flexibility, which offers grid resilience benefits. EVs, with grid operator coordination, can provide backup power to critical loads and help mitigate the costs of extended outages. Additionally, EVs' zero tailpipe emissions provide the additional resilience benefit that using EVs instead of generators for backup power removes the chance of carbon monoxide poisoning, which is a significant cause of harm during extended outage events. However, EVs also present a potential challenge to resilience planners to ensure that sufficient electricity supply is available for EV users to evacuate or travel during disaster events.

The third case study discusses how Consolidated Edison used resilience valuation to allocate funds for grid hardening. Superstorm Sandy exposed the vulnerability of the distribution network to flooding. In response, Consolidated Edison spent more than a billion dollars to mitigate the risk of future flooding. Allocating funds toward solutions that provided the highest net resilience benefits substantially improved the effectiveness of these investments.

The final case study focuses on distributed energy microgrids. More specifically, it discusses the New York Prize competition and follows the evolution of the City of Albany's planned Empire State Plaza microgrid project. This case study demonstrates how resilience benefits from microgrids can be valued and discusses the need to consider multiple decision criteria such as air quality and climate change goals when planning resilience investments. In this project, planners face an important trade-off between systems that offer the most resilience and systems that offer the most emissions reductions. Placing generators in close proximity to critical loads comes with the unwanted effect of increasing emissions near local populations.

Climate change is leading to an increase in extreme weather events, resulting in a greater prevalence of long-duration power outages. This threat to the electric grid is causing a reassessment of how electricity is generated and distributed. More outage events increase the need for and value of resilience solutions such as microgrid systems. At the same time, combating climate change requires a shift away from fossil fuel generation and toward cleaner generation sources.

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1 Introduction

The electricity sector is vulnerable to a variety of hazards, such as intense storms, heavy precipitation, icing, flooding, drought, mechanical failures, and physical and cyber threats. Climate change is increasing the frequency and intensity of some of these hazards, with the likelihood of exceeding historical 100-year flood levels in New York City (NYC) projected to double by 2050 (Orton et al. 2019) and the number of days above 90°F projected to increase from a baseline of 8 days per year to a middle range of 39 to 52 days per year by 2050 (NYDEC 2021). Major power outage events between 2003 and 2012 in the United States resulted in an estimated $22 billion to $41 billion in damages per year (Executive Office of the President 2013), and sustained power interruptions currently cause an estimated $43 billion to $62 billion in damages per year (Lacommare et al. 2018). Hurricane Sandy alone caused an estimated $19 billion in damage to NYC and $50 billion in total damages across the United States (Bloomberg 2013). In addition to the economic and financial costs, recovery can take years, and some regions may never fully recover after a disaster. An increase in extreme weather events, along with aging infrastructure, are further increasing the prevalence and costs of disruptions (Reidmiller et al. 2018; Sanstad et al. 2020).

Efforts are underway to mitigate the risks posed by climate change (New York State 2021). In 2019, New York State passed the Climate Leadership and Community Protection Act (Climate Act), which sets goals to reduce the carbon footprint and improve resilience (*New York State Senate Bill S6599* 2019). In 2021, the New York State Energy Research and Development Authority (NYSERDA) added resilience[1] to its Mission Outcomes and Strategic Focus Areas (NYSERDA 2021b) and has initiated steps toward the goal of integrating climate risk and resilience considerations into relevant programs to better anticipate, prepare for, and recover from climate and other related shocks and stresses. Resilience solutions such as installing emergency backup systems, integrating microgrid solutions, weatherizing buildings, increasing energy efficiency, improving demand management, adding redundancy, investing in restoration and recovery, and hardening critical components can reduce the likelihood, impact, and consequences of disruptive events; however, these solutions can also come with increased capital or operating costs (Consolidated Edison 2013; Zamuda et al. 2019). Actors in the electricity sector have long focused on reliability, which includes using metrics such as the System Average Interruption Duration Index (SAIDI), or duration of the average customer interruption, and System Average Interruption Frequency Index (SAIFI), which indicates how often the average customer experiences an interruption. Climate change, however, is creating a landscape with new risks and extreme consequences. While reliability refers to the ability of the power grid to provide power during normal operations, resilience extends reliability to include the low-probability, high-consequence events that apply stress to a system potentially over a large temporal and geographic scale.

Developing methods to quantify the value of resilience helps meet resilience needs in an effective manner and in a way that supports goals of broader societal welfare. Given limited resources, decision-makers need to balance goals surrounding climate change, equity and

[1] We use the definition of resilience as "a system's ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions through sustainable, adaptable, and holistic planning and technical solutions" (Hotchkiss and Dane 2019).

inclusion, employment and economic opportunity, and public health and safety. Resilience investments should demonstrate "significant and measurable short and long-term benefits that balance or exceed the costs" (National Research Council 2012). Resilience projects can sometimes require trade-offs with other dimensions such as economics, environmental considerations, and social goals, or can positively benefit multiple dimensions at the same time.

Comparing the costs of installing, operating, and maintaining a resilience investment to its benefits helps planners determine which resilience measures are worth implementing and when. Cost-benefit analyses allow decision-makers to compare resilience investments consistently and comprehensively (Kallay et al. 2021) and are a requirement for many federal and state resilience grants. For example, the Federal Emergency Management Agency's (FEMA's) Hazard Mitigation Assistance grants "require that mitigation measures demonstrate cost-effectiveness" in order for applicants to be eligible for funding (FEMA 2022a). FEMA grant applicants are required to use a Benefit-Cost Analysis (BCA), which is a method that calculates the future risk reduction benefits of a hazard mitigation project compared to its costs (e.g., a project is considered cost-effective when a Benefit-Cost-Ratio for that project is 1 or greater). Some criticisms of BCA methodologies include the challenge of large projects with longer time horizons failing to account for inflation, interest rates, cash flow, and net present value (Graves 2007).

New York's Climate Leadership and Community Protection Act (Climate Act) was passed in 2019 and is one of the most ambitious and comprehensive pieces of climate and clean energy legislation passed by any state. The legislation calls for a "40% reduction in statewide greenhouse gas from 1990 levels by 2030 and an 85% reduction by 2050" (NYS 2021). In addition, the legislation requires 70% of electric generation to come from renewable sources by 2030 and a 100% renewable grid by 2040. Meeting these emission reduction targets requires a significant transition away from fossil fuel use, which in turn requires a major shift in the electricity sector. These changes present both opportunities and challenges for energy and social resilience. Integrating resilience capabilities alongside investments to transform New York into a clean energy economy will prepare New York to be able to effectively address the threats of climate change. Failing to invest in resilience or investing in resilience projects that do not align with the broader mandated environmental and societal goals could lead to a failure to meet emissions targets.

A barrier to prioritizing investments in resilience is that there is no widely established method for quantifying the benefits of resilience investments (DOE 2017). There is no single metric or set of metrics that encompasses all decision-making requirements (RAND Corporation 2015). Instead, metrics can vary based on the electricity sector, geography, and time scale under study, as well as the needs of the individual, community, company, or system. According to DOE (2017) "there is a clear need for a set of commonly used methods for estimating the costs and benefits of reliability and resilience investments." Similarly, NYSERDA (2019a) states that "decision-makers need concrete information detailing the value of resilience improvements to encourage them to raise the issue to a higher priority."

This report lays out a framework for quantifying and valuing resilience, discusses the current state of resilience valuation tools, and provides case studies of resilience projects to demonstrate how resilience attributes and performance can be measured and highlight broader challenges to increasing resilience. It provides reflections and insights into methods and challenges to measuring, valuing, and enacting resilience investments.

Section 2 presents the general framework for valuing resilience investments. It discusses the five primary determinants of resilience value: (1) the underlying *hazards*, (2) the relevant *scenarios*, (3) the *occurrence frequencies*, (4) the *physical impacts*, and (5) the economic and societal *consequences*. Section 3 discusses the current state of resilience valuation tools and where research efforts to support resilience valuation could be most beneficial. Section 4 discusses the process and challenges of applying the resilience framework through four illustrative case studies. The case studies represent examples of resilience investments occurring in New York State along with the valuation process of these resilience investments. Each case study focuses on a unique hazard and sector while discussing challenges to valuation along with additional data or research that could support the quantification of resilience. The case studies presented are mitigation options for heat waves, the resilience potential and challenges of electric vehicles (EVs), hardening grid distribution assets to flood risk, and the benefits and challenges of microgrid energy solutions.

2 Considerations for Quantifying Resilience

Quantifying the value of resilience is necessary to translate abstract descriptions of resilience benefits into decision-supporting quantitative approaches. When an organization is considering implementing resilience solutions, whether installing new backup generators or addressing community environmental or social pain points, any new investments can come with increased upfront capital costs or long-term operational costs. Understanding how to balance investment costs against the values and benefits that new investments can provide to an organization or community can paint a broader picture of the benefits of resilience investments compared to traditional techniques for evaluating new investments (Hotchkiss et al. 2023). By properly measuring the specific benefits of resilience investments against the cost of non-action, the true value of resilience-focused investments can be exposed.

Investments in resilience should always improve the ability to prepare for, withstand, and recover quickly from events, including those with a low probability of occurrence, but a high impact. The U.S. Air Force's 5Rs framework describes attributes of resilient systems in terms of being robust, redundant, and resourceful, and having an ability to respond and recover quickly to a disruptive event (Department of the Air Force 2021). The value of a resilience investment is the difference in expected costs between the old system and the system with the improved resilience attributes once the risks associated with disruptive events are considered. There are several approaches to quantifying resilience, with methods varying by factors such as data requirements, geographic scope, and whether the method applies to a specific hazard or is hazard agnostic. At present, there is no standardized approach for policymakers or energy project developers to value energy resilience investments (NARUC 2019).

One way to quantify resilience investments involves utilizing a probabilistic risk assessment, which is the process of identifying hazards, estimating frequency of occurrence, identifying vulnerabilities, and estimating the severity of impacts (NYC Emergency Management 2019). A probabilistic risk assessment asks decision-makers to answer three questions: (1) What disruptive events can occur? (2) How likely are they to occur? and (3) What are the associated costs? (National Academies 2017). Determining relevant hazards and associated scenarios answers the first question. Determining the occurrence frequency of each scenario answers the second question. To answer the third question, it is useful to first determine the physical impacts of an event, and then determine the economic and social costs of these impacts (RAND Corporation 2015).

Therefore, there are five steps to determine the cost of disruptive events and determine the value of resilience:

1. Identify *hazards*
2. Determine relevant *scenarios*
3. Determine *occurrence frequency* of each scenario
4. Calculate the *impact* of each scenario
5. Quantify the *consequence* of impacts.

Subsections 2.1 through 2.5 discuss specifics of each step, and 2.6 discusses quantitative formulations for determining a value of resilience.

2.1 Hazards

Hazards, also referred to as threats, are the underlying disruptive events a resilience investment is intended to protect against. NYC Emergency Management (2019) defines a hazard as "a source of potential danger or an adverse condition that could harm people, our socioeconomic systems, or our built and natural environments." Hazards are anything that can damage, destroy, or disrupt the energy system, and can be natural, technological, or caused by human activity (Stout et al. 2019; Anderson et al. 2019; Hotchkiss and Dane 2019). Natural hazards include extreme weather events, droughts, and other weather-related disasters. Technological hazards include mechanical failures, such as a power plants tripping offline, and structural failures, such as a bridge collapse. Human-caused hazards include operator error, and physical and cyber-attacks.

The first step for any resilience analysis is to identify the relevant hazards of concern. NYC Emergency Management (2019) focused on the following seven natural hazards during a recent evaluation of risks for New York City:

- coastal erosion
- coastal storms
- earthquakes
- extreme heat
- flooding
- high winds,
- winter weather.

Hazards of concern vary by sector, location, and time. For example, coastal areas are more at risk of hurricanes than inland areas, and hurricanes are only a threat during certain times of the year.[2] Incorporating additional hazards helps identify the full threat landscape, but comes at the cost of additional required time, effort, and expertise for data collection, modeling, and analysis. It may be more effective to choose a small number of hazards to analyze in detail instead of attempting to analyze all potential hazards, and it can be beneficial to choose hazards based on which are most impactful, most likely to occur, and which hazards the resilience investments are intended to mitigate. The possibility of never-before-seen hazards, sometimes referred to as black swan events, should be kept forefront when evaluating resilience investments to help characterize potentially unforeseen effects of these unknown or unknowable events.

2.2 Scenarios

A scenario consists of the timing, duration, geographic scope, and intensity of an event. Given the *hazard* of heat waves, a *scenario* could be a heat wave lasting five days with a daily peak temperature of 95°F and high humidity, causing a dangerous heat index, impacting NYC. Multiple scenarios can be modeled for a single hazard to capture differences in factors such as duration or intensity, and a scenario can be a compilation of multiple hazards in the case of coincident disasters, such as a heat wave occurring during a global pandemic and coupled with a

[2] It is worth noting, however, that climate change is altering the seasonal norms for hurricanes and other weather events, which can mean historically calm times of the year can in the future be interrupted by unseasonal hazardous weather.

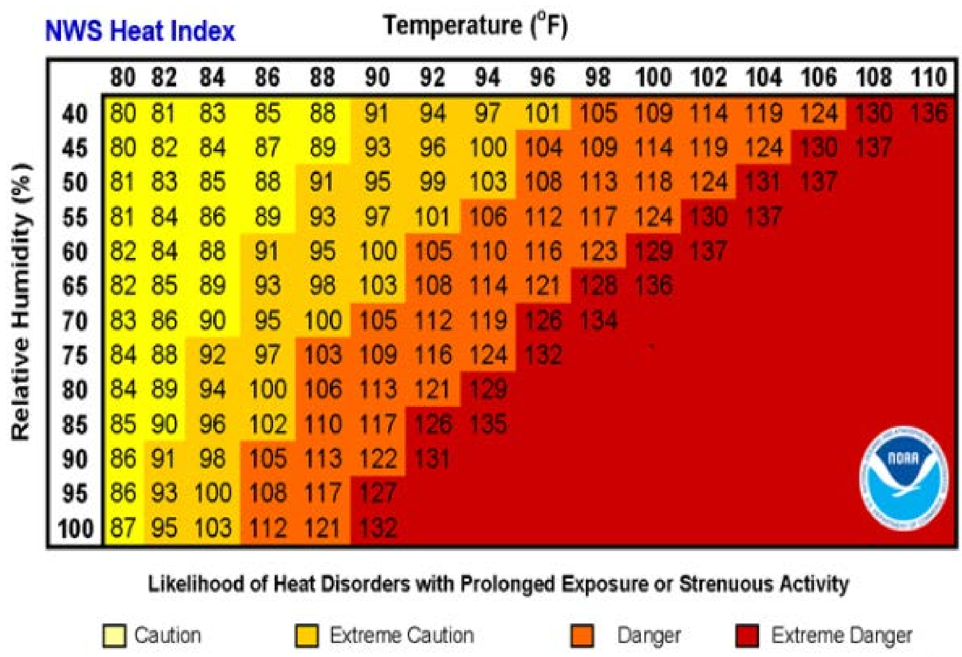
long-duration power outage. Scenarios may also be agnostic to the underlying hazard, such as with modeling power outages independent of the root cause the outage.

Disruptive events have a set of characteristics, which often vary over the event duration, that influence the size of their impact. Modeling every potential combination of the various characteristics of an event can result in too many scenarios to evaluate in a useful way. An intensity metric that captures the relative strength and danger of a disruptive event can reduce the number of scenarios while maintaining the spectrum of possible impacts. Table 1 displays characteristics and example intensity metrics used for a variety of hazards, though this list is not exhaustive.

Table 1. Event Characteristics and Example Intensity Metrics for Select Hazards

Hazard	Characteristics	Example Metrics
Heat wave	Temperature, Humidity	Peak / average heat index Peak / average air conditioner set point temperature Hours above threshold
Cold wave	Temperature	Minimum temperature Hours below threshold Average heater set point Peak cold index
Hurricane	Wind speed, air pressure, storm surge	Saffir-Simpson Hurricane Wind Scale
Flooding	Crest height time series	Peak crest height
Tornado	Wind speed and tornado size	Enhanced Fujita Scale
Winter Weather	Precipitation, wind speed, snowfall	Winter Storm Severity Index
Earthquake	Slip, energy released, magnitude, intensity	Moment magnitude scale, Modified Mercalli Intensity Scale
Power outage	Customer outages	Total customer outage hours, Average outage duration
Strong winds	Wind speed time series	Beaufort Scale

The Heat Index, an example of which is shown in Figure 1, demonstrates how intensity metrics are commonly used and can translate a multidimensional concept (such as the dynamics between air temperature and humidity) into a single value that directly informs potential impacts.



	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Figure 1. National Weather Service Heat Index

Credit: National Oceanic and Atmospheric Administration.

2.3 Occurrence Frequency

Occurrence frequency is the annual likelihood a given scenario will occur, such that a one-in-one-hundred-year event has an occurrence frequency of 0.01. Determining occurrence frequency is a required step to quantify risk and value resilience. Occurrence frequency depends on both the hazard and scenario, with some hazards being more likely to occur than others and scenarios of higher intensity, duration, and geographic scope being more impactful but generally having a lower occurrence frequency.

Occurrence frequencies can be based on historical rates or based on simulations. A variety of federal, state, and private sources collect and aggregate historical occurrence frequencies for natural hazards. Table 2 provides a summary of sources for select natural hazards used to determine annual frequencies for FEMA's National Risk Index (FEMA 2021c). For NYC specifically, the NYC Hazard History & Consequence Tool provides a database for historical hazard events to impact the city.[3]

[3] https://nychazardhistory.com/Default.aspx

Table 2. Data Sources for Select Hazards

Hazard	Source Data	URL
Heat Waves, Cold Waves, Winter Weather	National Weather Service	https://www.weather.gov/
Coastal Erosion	Coastal Erosion Hazard Area Permit Program	https://www.dec.ny.gov/lands/86541.html
Earthquakes	U.S. Geological Survey	https://www.usgs.gov/programs/earthquake-hazards/hazards
Flooding	National Flood Insurance Program	https://www.fema.gov/flood-maps/national-flood-hazard-layer
Hurricanes	NOAA HURDAT2	https://www.nhc.noaa.gov/data/
Power Outages[4]	EAGLE-I™ DOE OE-417	https://eagle-i.doe.gov https://www.oe.netl.doe.gov/oe417.aspx
Strong Winds	National Weather Service, Severe Weather Database Files	https://www.spc.noaa.gov/wcm/

Figure 2 displays the historical annual frequency of occurrence by census tract for select natural hazards. Winter storm events are most likely to occur in the northern and western parts of New York, while heat waves are most likely to occur in the NYC area. Flooding and hurricanes are clearly most prevalent in coastal regions and near rivers. Because of such differences in occurrence frequency, it is important to base resilience valuations on the specific location of where the investment will occur.

[4] Estimated outage frequencies and recurrence intervals by region are provided in Ericson et al. (in review).

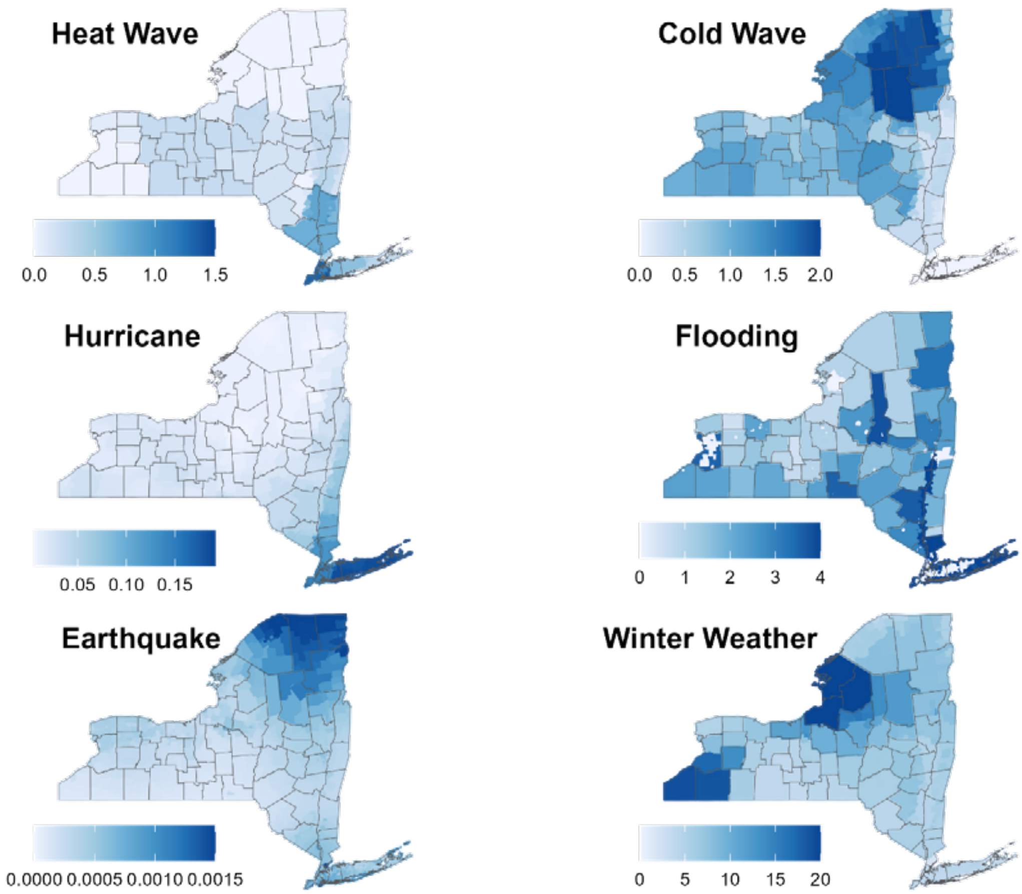


Figure 2. Annual occurrence frequency by census tract for select natural hazards

Data from National Risk Index (Rogers et al. 2019).

Historical occurrence frequencies of hazards are not good indicators of future occurrence frequencies. The future frequency of many hazards is expected to increase due to climate change (Preston et al. 2016). Moreover, determining occurrence frequency from historical information can be difficult because of the low frequency and short historical records of some hazards, which can skew estimates. In lieu of historical events, models can be used to simulate the frequency of low probability events and project future frequencies given climate change.

The frequency and intensity of several future extreme weather hazards are linked to future temperatures, which in turn are linked to future emissions paths (Allan 2021). New York State temperatures increased an average of 1.53°F (0.85°C) between 1995–2014, relative to 1850–1900 averages. Depending on future emissions, temperatures are expected to increase by an additional 1.17°–1.35°F (0.65°–0.75°C) between 2021 and 2040, and 1.35°–2.79°F (0.75°–1.55°C) by 2041–2060 (Allan 2021). Future emissions pathways have a large impact on long-term 2081–2100 temperatures, with expected temperature increases relative to the 1995–2014 period ranging from 1.0°–6.4°F (0.55°–3.55°C). Figure 3 displays how increases in temperatures impact the likelihood of extreme heat. When considering the impacts of hazards such as heat waves and flooding, which are directly affected by average air temperature and sea level rise, considering the exacerbating effects of climate change is critical to avoid underestimating the impacts of these hazards in the future.

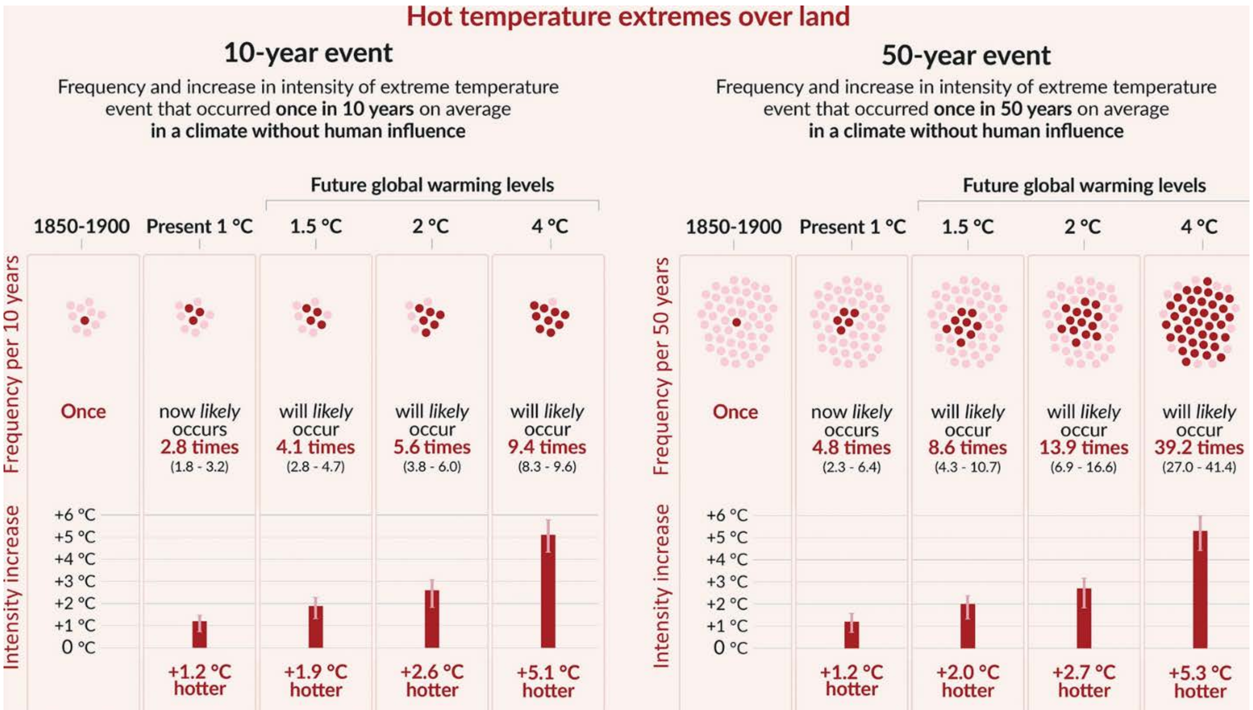


Figure 3. Impact of average temperature increases on heat wave likelihoods and intensity

Figure from Allan (2021).

2.4 Impacts

We define impacts as the physical damages from a given event. The physical damages can result in financial, physical and mental well-being, and other short- or long-term consequences. Examples of impacts include the number of homes damaged in a storm or the number of customers without power during a blackout. Impacts depend on intensity (strength of hazard), exposure (who and what is impacted), and vulnerability (the susceptibility to damage).

2.4.1 Intensity

Intensity is a measure of strength of a disruptive event. Scales such as Saffir-Simpson for hurricanes, the Modified Mercalli Intensity Scale for earthquakes, the Enhanced Fujita Scale for tornadoes, and the Beaufort scale for high winds help capture non-linearities in intensity and are valuable for relating scenarios to impacts. Figure 4 describes the relationship between hurricane categories and damages from the hurricane event.

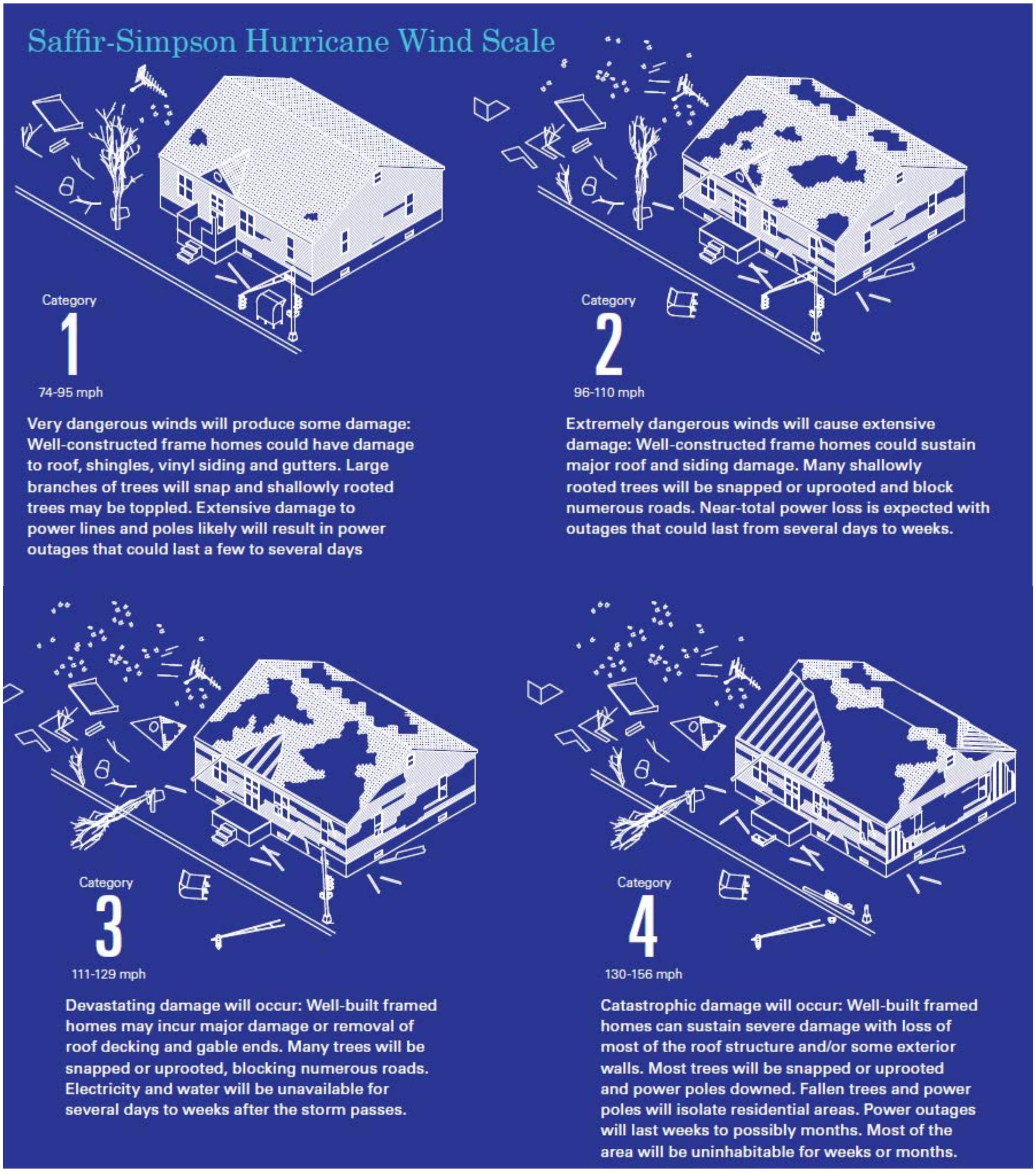


Figure 4. Saffir-Simpson Hurricane Wind Scale relationship between categories and impacts

Figure from NYC Emergency Management (2019).

2.4.2 Exposure

Furman et al. (2019) indicate that "exposure typifies the scope of damage in terms of who or what may be damaged." Exposure is the number of people, buildings, and infrastructure affected by an event. Greater exposure to a disruptive event results in more impacts. Exposure depends both on the geographic scope of the event and on the population density and density of assets.

NYC has particularly high exposure given it has the highest population density of any major city in the United States, with over 27,000 people per square mile. The building stock of NYC is also exceptionally dense, with approximately one million buildings with total floorspace of over 5 billion square feet and 3.2 million residential housing units (NYSERDA 2021a). The high density of buildings increases the ambient temperature by several degrees, an effect known as the urban heat island, which also increases the intensity of heat waves (NYSERDA 2021a). Also, its location next to the coast also places it at higher risk of flooding and storms, as occurred during Hurricane Ida in 2021 (Beven II et al. 2022); specifically, there are 71,500 buildings in NYC in the 100-year flood plane, which is among the highest in any city in the United States (Department of City Planning 2014).

New York energy infrastructure has significant exposure to storm events, and the exposure will continue to increase as a result of climate change. During Hurricane Sandy, 11 Manhattan electrical distribution system networks and 3 Staten Island load areas were shut down due to substation flooding (Consolidated Edison 2013). Tropical Storm Isaias caused widespread power outages in the Tri-State area, with hundreds of thousands of people experiencing outages throughout NYC, Long Island, New Jersey, and Connecticut (ABC7 NY 2020). In many of these locations, resentment among customers against their utilities resulted in lawsuits, including a nearly $30 million dollar fine against Eversource Energy and The United Illuminating Company for failing to sufficiently prepare and respond to the storm (Malo 2021).

According to sea level rise projections, Consolidated Edison's (ConEd's) 1-foot of sea level rise risk tolerance threshold may be exceeded as early as 2030. Of ConEd's total 324 substations, 75 of those, as well as 32 gas regulators, and 5 steam generation stations would be exposed to flooding during a 100-year storm if sea levels rose 3 feet (Consolidated Edison 2019). Because 100-year flood events are occurring more frequently, historical data is less helpful to "future proofing" infrastructure to future conditions.

2.4.3 Vulnerability

Vulnerability is "the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt" (Pörtner et al. 2022). Vulnerability captures risk factors that influence the susceptibility of various stakeholders to damage when exposed to a given event (Furman et al. 2019). Vulnerable populations, such as elderly people and historically marginalized populations, face both a higher likelihood of experiencing negative impacts from a disaster as well as greater barriers to recover quickly after an event (Flanagan et al. 2011). Adaptation measures and resilience improvements can reduce vulnerability to hazards, thereby reducing the impacts of disruptive events. Resilience enhancements can reduce vulnerabilities through preventing adverse events from occurring, improve redundancy to enable systems to continue operating, and improve the speed of recovery when a disruption occurs (DOE 2017).

Identifying the people, buildings, communities, and regions most vulnerable to a given hazard can facilitate the allocation of resilience and adaptation resources (Nayak et al. 2018). Individual characteristics such as a person's age, health, education, and income level, a building's material and vintage, or an asset's quality and maintenance determine its vulnerability to a disruptive event. In addition to individual attributes, community, environmental, sociodemographic, and behavioral characteristics contribute to vulnerability (Nayak et al. 2018).

Engineering and physics-based models can be used to assess building and asset vulnerabilities, and socioeconomic models can capture differences in population vulnerabilities. Figure 5 displays the Heat Vulnerability Index for NYC, which highlights the relative vulnerability of the population in each area. The darker colors in the figure indicate a greater proportion of the population that are vulnerable to hazardous heat waves.

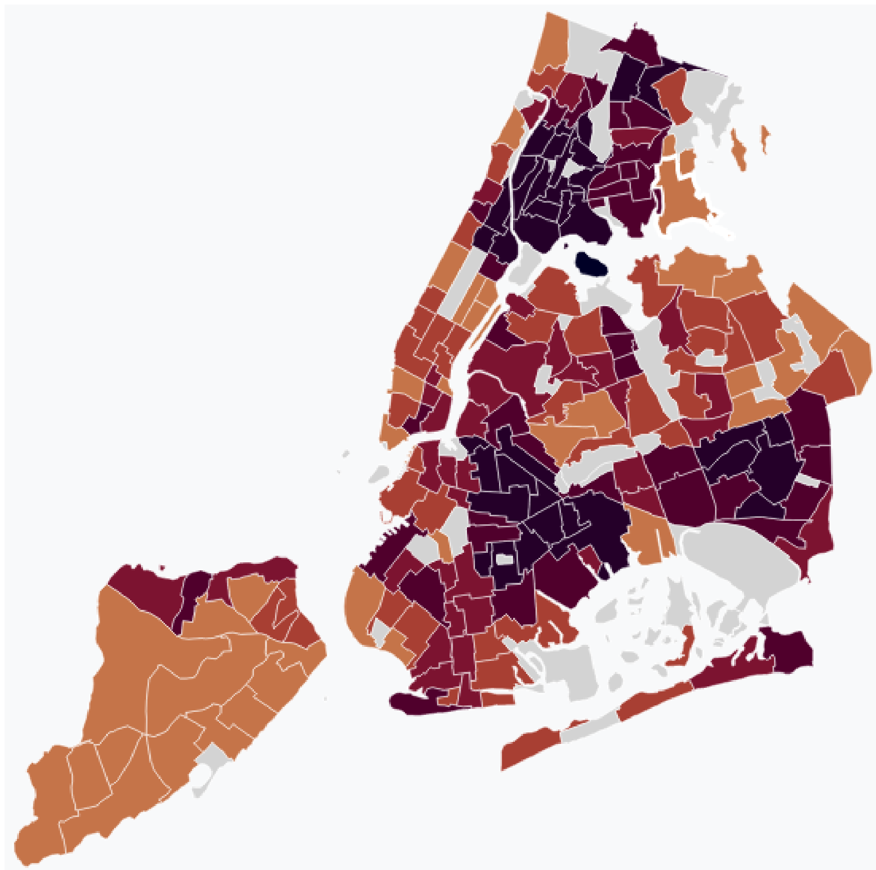


Figure 5. Heat Vulnerability Index for New York City

Figure from NYC Department of Health (2022). Darker color indicates higher vulnerability.

2.5 Consequences

Consequences are the economic and societal costs associated with an event. Consequence metrics convert physical impacts into societal costs and are measured in terms of economic values (such as the dollar value of damages or business interruption) or societal values (such as lost lives or lost time). Consequences will vary by stakeholders, hazards modeled, and operational decisions taken (Watson et al. 2014).

There is no single consequence metric that works in all circumstances. Instead, a variety of metrics can be applied to different cases. Because investment costs are measured in dollars, measuring the benefits of resilience in dollars facilitates cost-benefit analysis. Some impacts, such as building damages or lost production, are relatively straightforward to assign dollar values while other impacts, such as discomfort, increased health risks, and lives lost, do not have easily calculated monetary costs associated with them.

Costs can be categorized as *direct* costs (costs that are a direct result of damage from the event), *business interruption costs* (opportunity costs of lost production/operations), and *indirect costs* (induced costs and ripple effects) (Meyer et al. 2013), and costs can come from the effects of a disaster (*damage costs*) and from preparing for a disaster (*risk mitigation costs*). *Tangible costs* have a direct dollar value attached, while *intangible costs* do not have a direct market value, meaning costs must be inferred by other means. Figure 6, adopted from Meyer et al. (2013), displays each cost category and provides examples of each.

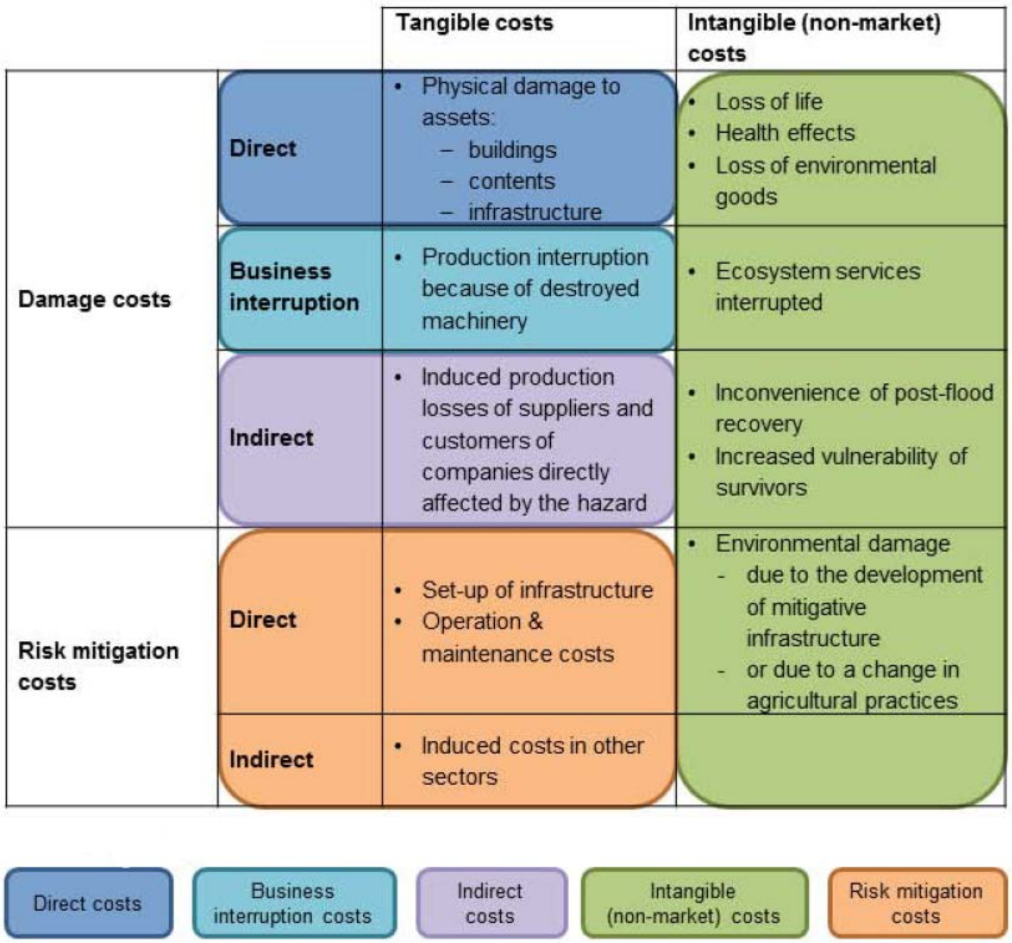


Figure 6. Matrix of cost types

Figure from Meyer et al. (2013).

The approaches to estimating consequences break down into economy-wide modeling (often called regional modeling) versus bottom-up modeling (NARUC 2019). Economy-wide approaches use macro-econometric, input-output (I-O), or computable general equilibrium models to estimate the cost of a large-scale impact on economic activity (Baik et al. 2021). Economy-wide models can capture the interactions between industries to provide an accurate estimate of total impacts of a disruptive event. Computable general equilibrium models in particular are able to account for adaptive responses and resilience measures taken to reduce the impacts of disruptive events (Baik et al. 2021). However, economy-wide models can lack transparency and be challenging to calculate, costly to implement, and hard to interpret (Baik et al. 2021).

Bottom-up approaches use aggregations of specific outage impacts to determine the combined consequence of a disruptive event. One of the most used and simplest bottom-up approaches is to use a fixed ratio to translate each type of impact into consequences. Power outage studies often use a fixed value of lost load (VoLL), measured in dollars per MWh of lost load during power outages. As an example, FEMA calculates a VoLL for hospitals based on the average cost of transporting and treating patients at the nearest hospital, and then uses this VoLL combined with assumptions on outage probabilities[5] to estimate the benefit for generator hazard mitigation projects to be $6.95 per building gross square foot in urban areas and $12.62 in rural areas. Other examples of fixed values include average costs of repairs per building from frozen pipes or flooding, and cost per person per day for displaced populations.[6]

More advanced consequence metrics can incorporate customer-specific attributes along with non-linearities (e.g., increasing at a non-uniform rate) in the cost of impacts. Consequences can be non-linear in impact intensity due to damage thresholds, such as replacing an entire roof after more than 5% of the roof is damaged (FEMA 2021a). Consequences can increase non-linearly in impact area due to interactions between individual impacts, such as widespread disruptions leading to traffic jams, supply disruptions, and constraints on recovery resources. Finally, consequences can be non-linear in impact duration due to damage thresholds, such as food spoilage, negative health impacts leading to increasing consequences over time, or mitigation strategies such as bringing in backup generators reducing consequences over time (Ericson and Lisell 2020).

Intangible costs can be calculated using valuation methods such as revealed preference and hedonic pricing (Meyer et al. 2013). There is a rich literature from health and environmental economics on valuing intangible costs such as lost life (Kip and Aldy 2003; Rogers et al. 2019; Timothy and McConnel 2002). Using multiple decision criteria or non-monetary metrics can also facilitate decision-making without the need to place a dollar value on difficult-to-estimate costs, such as morbidity and mortality.

One last consideration for determining consequences is to define the relevant entities and jurisdictions, which then informs which costs are inside and outside of scope (DOE 2017). For example, an insured homeowner pays their deductible in the event of a disaster, and the insurance company pays for the cost of repairs minus the deductible. Determining the relevant scope is especially important for considering which resilience investments to pursue. Some resilience solutions have positive spillovers while others have negative external impacts. For example, a fossil fuel powered backup generator has negative externalized impacts on the air and environment. Separations among who is affected by hazards, who pays for resilience, and who is positively and negatively impacted by resilience investments can lead to suboptimal decisions.

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[5] The calculations assume a 5-year recurrence interval for 1-day outages and 50-year recurrence intervals for 4-day outages. These values seem to be based simply on guesses of outage frequency, underscoring the difficulty of finding outage duration data.

[6] FEMA suggests the hourly rate of $33.94 should be used to measure the value of hours spent by individuals on disaster-related activities (FEMA 2016).

2.6 Calculations to Value Resilience

Risk is defined as the expected consequences due to hazard events over a given time frame, generally annual or over the analysis period.[7] Figure 7 displays the general structure for calculating risk, where different hazards have potentially numerous scenarios, varying frequencies of scenarios, and potentially numerous impacts and consequences that can be quantified or characterized. Risk may be comprised of multiple hazards, each of which can have multiple associated scenarios. Each scenario has a frequency of occurrence and results in a set of impacts. These impacts result in economic and societal consequences.

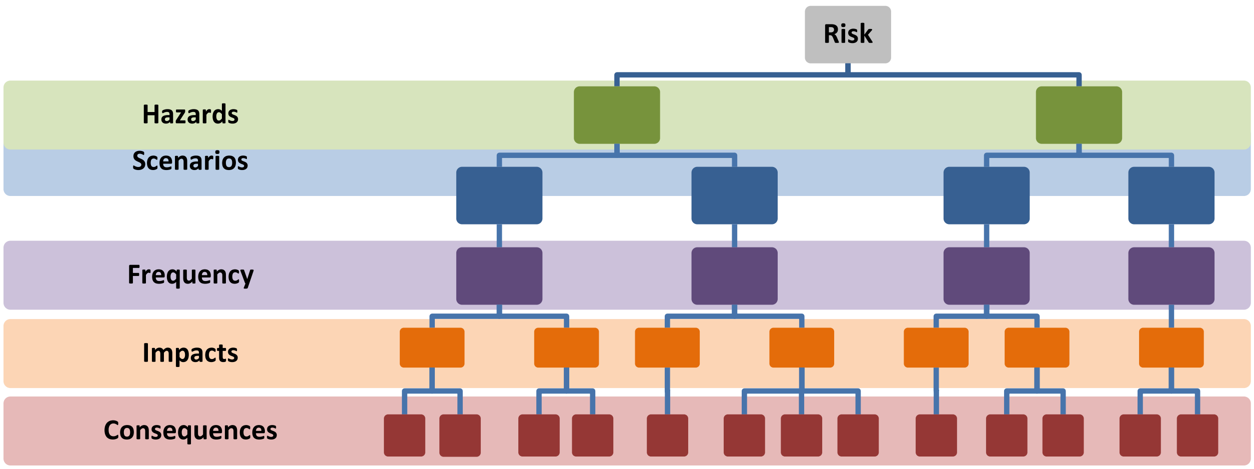

Figure 7. General structure of calculating risk

For considering the calculation of risk and its role in valuing resilience, the annual risks in a given project year y are the sum of consequences multiplied by their respective annual frequency of occurrence. Denoting h as a set of hazards, s as a set of scenarios, y as a year index, F as an occurrence frequency, I as impacts, and C as consequences as a function of resilience r and impacts $I_{h,s,y}$, annual risks can be calculated by Equation 1:

$$R_y(r) = \sum_{h,s} F_{h,s,y}(r) \times C\left(r, I_{h,s,y}(r)\right) \tag{1}$$

The occurrence frequency and impacts of an event can vary with project year due to changes in exposure and vulnerability along with changes in the natural environment including climate change. Consequences may be a non-linear function of the underlying impact, which in turn depend on the given hazard, scenario, and level of resilience. In practice, consequences are often given as a fixed multiple of impact, such as a fixed cost per building damaged, MWh of dropped

[7] We are using the term risk as it is used in literature on disaster planning, where risk denotes downsides to be avoided. Finance and investment literature often uses the term risk to denote volatility or uncertainty, which has both upside and downside potential.

load, or lost person-hours. If a fixed consequence multiplier is used, then Equation 1 can be rewritten in the format of Equation 2 when denoting *i* as impact types:

$$R_y(r) = \sum_{h,s} F_{h,s}(r) \times \sum_{i} I_{h,s,i}(r) \times C_i(r) \quad (2)$$

The total risk over the lifetime of a project, R', can be estimated by taking the present value of annual risks across the lifetime of the project. Letting *Y* denote total project lifetime and *d* denote the discount rate, then total risk is given by:

$$R'(r) = \sum_{y=1}^{Y} \left(\frac{1}{1+d}\right)^{y} R_y(r) \quad (3)$$

A word of caution regarding discount rates is in order. It is common practice to include both time preferences and risk aversion in the discount rate.[8] Risk aversion means that uncertain benefits are discounted more heavily, but also means that uncertain costs are discounted less heavily. Because occurrence frequencies, impacts, and consequences are highly uncertain, it may be prudent to use a low discount rate when calculating risks. This is the opposite of the case of uncertain benefits, where high uncertainty generally coincides with a high discount rate. This situation weights risks and consequences in an unrealistic way, which can skew the return-on-investment calculations.

The value of resilience is the reduction in risk due to the resilience investments. Thus, if resilience investments increase the level of resilience from r_0 to r_1, then the benefits of these investments are given by:

$$Benefits = R'(r_1) - R'(r_0) \quad (4)$$

The benefits equation is included here as an example of how it could be applied. Use of functions like those listed above can help bring greater clarity when quantifying the potential benefits of investing in resilience-improving solutions. With finite resources and time, comparing multiple investments in resilience using calculations like these can help ensure the highest benefit investment is selected for a given scenario.

8 Risk aversion uses the financial definition of risk and denotes a preference for certainty over uncertainty.

3 Resilience Valuation Tools

Resilience valuation tools are an important component of quantitative resilience analysis. They support researchers and decision-makers in identifying hazards, determining vulnerabilities, calculating risks, and evaluating resilience solutions. Resilience valuation tools vary in terms of the scope of analysis, input demands, and type of analysis performed. The scope of analysis is generally either a specific site or a broad geographic area. Input demands vary with the detail of analysis and amount of precalculated defaults used, with a higher input demand increasing the difficulty of using the tool but also potentially increasing the accuracy of the tool. The type of analysis performed can be a qualitative assessment of risks or mitigation options, a quantitative estimate of risk or value of resilience, or a full cost-benefit analysis of a resilience investment.

This section outlines different types of tools and discusses the current state of resilience valuation tools and future research needs. We provide examples of how tools determine hazards, scenarios, frequencies, impacts, and consequences, and describe the uses and limitations of current tools. Table 3 displays a non-exhaustive list of resilience and risk management tools in use today.

Table 3. Commonly Used Resilience Tools

Tool	Organization	Description
Benefit Cost Analysis (BCA) Toolkit	FEMA	Excel tool that performs benefit-cost analysis for resilience upgrades and mitigation investments.
City Resilience Index	Rockefeller Foundation	Helps cities understand and respond to challenges in a systematic way.
Customer Damage Function (CDF) Calculator	NREL	Resource for facility owners and resilience planners to understand the costs of an electric grid outage at their site. The calculator provides a process to elicit facility outage vulnerabilities and estimates how costs vary with outage duration.
Hazard Mitigation Cost Effectiveness Tool	Federal Transit Administration	Evaluates the benefits and costs associated with undertaking the design, construction, and operations and maintenance of capital planning projects that incorporate resilience.
Hazus	FEMA	Provides standardized tools and data for estimating the physical, economic, and social impacts from earthquakes, floods, tsunamis, and hurricanes.
Interruption Cost Estimate (ICE) Calculator	Lawrence Berkeley National Laboratory	Tool designed for electric reliability planners at utilities, government organizations, or other entities interested in estimating interruption costs and/or the benefits associated with reliability improvements.
National Risk Index	FEMA	Data set and online tool to help illustrate the U.S. communities most at risk for 18 natural hazards.
Regional Economic Accounting (REAcct)	Sandia National Laboratories	Input-output model incorporating geospatial computational tools and site-specific economic data to provide impact-zone estimates of acute disruptive events.
REopt	NREL	Recommends the optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings, resilience, emissions reductions, and energy performance goals.
Resilience Roadmap	NREL	Offers comprehensive guidance for federal, state, and local entities to effectively convene at the regional level for adaptable and holistic planning.
System Advisor Model (SAM)	NREL	Techno-economic software model that facilitates decision-making for people in the renewable energy industry.
Technical Resilience Navigator (TRN)	Pacific Northwest National Laboratory	Provides a systematic approach to identifying energy and water resilience gaps and developing and prioritizing solutions that reduce risk.

3.1 Geospatial Risk Assessment Tools

Geospatial risk assessment tools combine spatial information on historical or projected future hazards with geographic information such as population, building stock, and critical infrastructure. Geospatial risk assessment tools are designed to help users better understand how hazard risks vary by location, determine potential losses from disasters, and identify areas and strategies for mitigating the potential impacts and consequences (FEMA 2021a). They also provide a standardized methodology to compare risk estimates across regions, which can help guide the allocation of resources (FEMA 2021d). Examples include the City Resilience Index, FEMA's Hazus (Hazards United States) model, the Interruption Cost Estimate (ICE) Calculator, the National Risk Index, and REAcct.

Hazus shows the general steps geospatial tools use to assess hazards, scenarios, frequencies, impacts, and consequences. Hazus is a risk modeling methodology developed by FEMA that provides standardized tools and data for estimating the physical, economic, and social impacts from earthquakes, floods, tsunamis, and hurricanes (FEMA 2021d). The final output of Hazus is a "loss estimate," which describes the "scale and extent of damage and disruption that may result from a potential event" including direct costs to repair and replace damaged buildings, loss of function to critical facilities, and damages from induced hazards such as flooding and fires caused by an earthquake event (FEMA 2021b). Table 4 shows the close link between the steps in Hazus to calculate loss estimates and the five steps used to determine the cost of disruptive events and determine the value of resilience discussed in Section 2.

Table 4. Relating Steps for Hazus Analysis to Hazards, Scenarios, Frequencies, Impacts, and Consequences

Step	Hazus
Hazards	User specifies which hazard or hazards to model as the first step to conducting an analysis (FEMA 2022b). Calculates the impact and consequences for earthquakes, floods, hurricanes, and tsunamis.
Scenarios	User selects the area to be studied (census tract, county, or state level) and specifies the hazard scenario (FEMA 2022c).
Frequency	Occurrence frequencies depend on the hazard type being modeled. Some models require a single event to be specified, while other hazards can be run for a range of event types, which connect into the frequency of the respective events. For example, the flood model allows for 10-year, 25-year, 50-year, 100-year, and 500-year return period floods to be modeled simultaneously (FEMA 2022c).
Impacts	Combines user inputs, geospatial information on buildings and vulnerable structures, and models that relate event intensity to a variety of impacts. This allows Hazus to compute the probability distributions for damage to different classes of buildings, facilities, and system components, which allows impacts to be estimated (FEMA 2021b).
Consequences	Calculates the cost to repair or replace damaged buildings, cars, infrastructure, and goods. It also calculates impacts to the population along with additional indirect economic losses (FEMA 2022b, 2022c).

Figure 8 gives the structure of the Hazus earthquake model, displaying the delineation between impacts and consequences, where the physical damages are the impacts of an earthquake, and the direct and economic and social losses are the consequences of an earthquake. Clarifying the difference between impacts and consequences is especially useful for incorporating non-linear consequences, such as repair costs increasing after a major event due to material and manpower shortages.

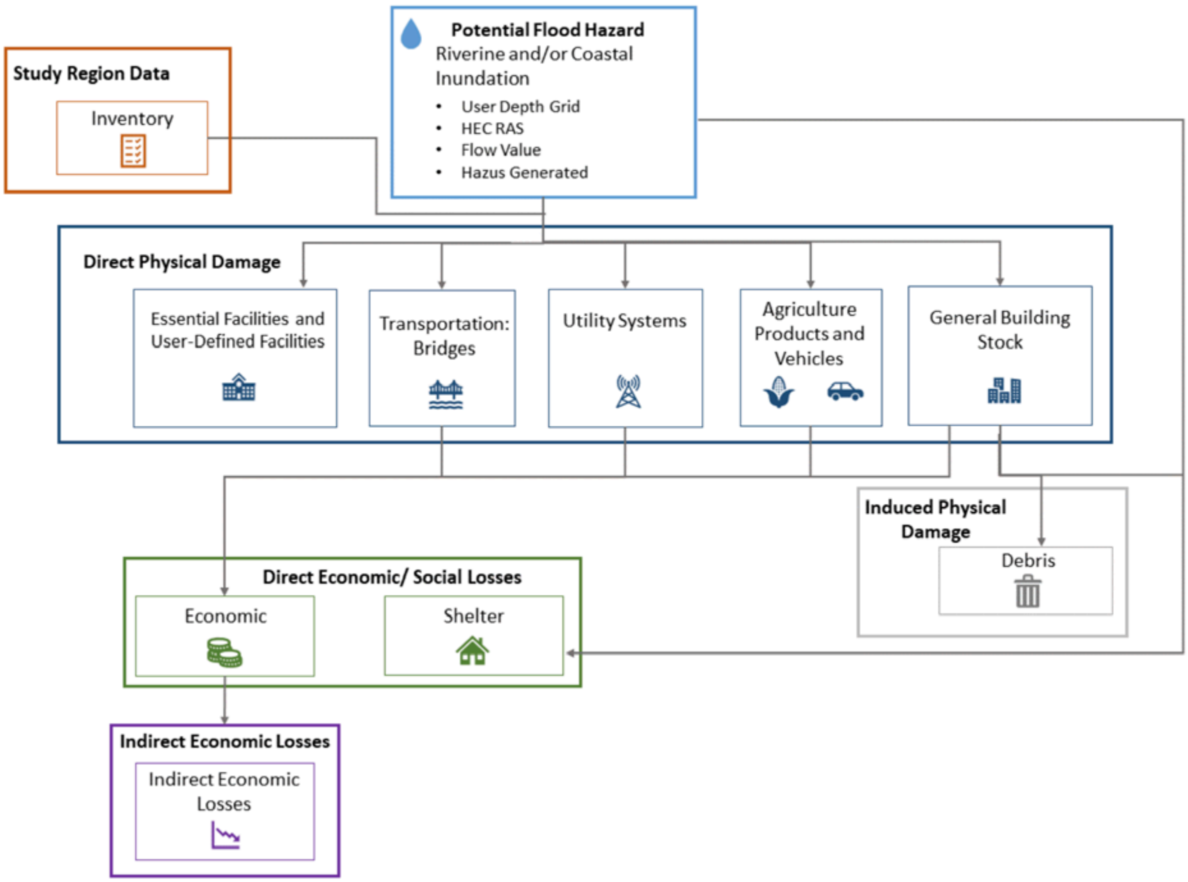

Figure 8. Hazard model structure for flood hazards

Figure from (FEMA 2022c).

Geospatial risk assessment tools such as Hazus provide valuable information on the relationship between location and risk. At the same time, they can suffer from the large amount of information required for analysis along with the complexity of the underlying models. The ability to model hazards at any location in the nation requires large national-scale data sets. These data sets may contain inaccuracies at the local level, which can lead to errors.

Significant time, effort, and expertise are often required for a successful analysis. Hazus documentation states that "any risk modeling effort can be complex and would benefit from an input of an interdisciplinary group of experts," suggesting a representative team of 13 different types of experts (FEMA 2021b). Geospatial hazard models can be limited because of the challenge and cost of bringing together such a broad team of specialists.

Hurricane Sandy provides a stark example of the potential challenges and pitfalls of modeling large-scale hazards through geospatial models. Hurricane Sandy caused an estimated $19 billion in damage to NYC and $50 billion in total damages across the United States (Bloomberg 2013). Meanwhile, the Hazus modeling of damages from an event like Hurricane Sandy included in the Hazus Loss Library[9] is only $190.5 million for New York State. There is room for improvement when using these types of models because underestimating losses and damages is a common result, but they provide approaches to quantify inaction. Models are only as good as the data entered, so miscalculations and underestimations often point to a need for more complete data sets and better interpretation of results related to hazard frequencies, impacts, and consequences.

3.2 Facility-Level Resilience Tools

Facility resilience tools help facility owners and resilience planners assess the hazard risks and value of mitigation at a given location or set of locations. These tools can be used to compare various mitigation investments and compare the benefits of improved resilience to the cost of investment. Examples of facility-level resilience tools include the BCA toolkit, the Customer Damage Function Calculator, the Hazard Mitigation Cost Effectiveness Tool, REopt, the Resilience Roadmap, the System Advisor Model, and the Technical Resilience Navigator.

FEMA's BCA Toolkit shows the general steps facility-level resilience tools use to assess hazards, scenarios, frequencies, impacts, and consequences, which are outlined in Table 5 below. The FEMA-developed BCA Toolkit is an Excel tool that performs benefit-cost analysis for resilience upgrades and mitigation investments. A positive FEMA BCA evaluation, where the benefits exceed the costs, is required to be eligible for Hazard Mitigation Assistance Funding (FEMA 2011).

Table 5. Relating Steps for FEMA BCA Analysis to Hazards, Scenarios, Frequencies, Impacts, and Consequences

Step	Implementation in FEMA BCA
Hazards	User selects among 19 hazard types, with mitigation options available depending on which hazard is selected.
Scenarios	When hazard historical occurrence frequencies are available, then scenario intensities are based on occurrence frequency, such as the height of a 100-year and 500-year flood. Otherwise, user inputs intensity.
Frequency	Incorporates historical frequency information when available. User has to specify frequencies if historical values are unavailable or if future frequencies are different from historical values.
Impacts	Calculates expected damages from flooding and winds, though user is required to input site-specific information of building properties before and after the mitigations. Other hazards require user to input impacts of event.
Consequences	User inputs values such as the cost to repair or replace damages to the facility along with the cost from loss of function. These costs are then multiplied by the expected impacts and frequencies to calculate the expected consequences before and after mitigation.

[9] The Hazus Loss Library can be accessed at https://hazards.fema.gov/hll.

The FEMA BCA Toolkit is straightforward to use, but the quantity and precision of inputs required for an effective calculation can require significant effort and expertise (NHMA 2021). External consultants and experts are often needed to run an analysis, which places additional costs on the user (NHMA 2021). A report that details recommendations to enhance FEMA's grant process (NHMA 2021) states:

> The BCA has deterred applicants from pursuing some projects, especially complex projects, which contradicts the intention of FEMA's hazard mitigation funding programs. The BCA prevented one innovative project from reaching the submission…Given the complexity of the project, the sub applicant could not conduct the BCA internally, nor could it secure the resources to complete the BCA externally.

This is a general challenge of facility resilience models, where the time, effort, and expertise to conduct analysis can be cost-prohibitive. This is especially problematic for smaller scale resilience upgrades and for poorer communities with fewer resources. More curated publicly available data sets as well as additional support made available for resilience analysis could help reduce the burden of exploring mitigation options at a site. This in turn could help increase the number of mitigation and resilience solutions implemented.

3.3 Research Needs

There is a growing need for resilience valuation tools to help inform investment decisions to mitigate the cost from increasingly frequent and intense disruptive events. For a resilience tool to produce accurate results, it needs to be methodologically sound, use accurate data that reflects on-the-ground realities, and a be employed by a trained user to operate the tool correctly and effectively. The results of these tools may be scrutinized by regulators, stakeholders, and the public, meaning the outcomes of the analysis will need a high level of transparency and, when needed, description of caveats. Additional research and support can develop additional capabilities, improve data quality, make tools more user-friendly, and train users in best practices. Some research and methodologies that have historically only existed in academic or hypothetical settings can benefit real-world resilience planning and should therefore be socialized to interested parties and the general public.

One of the most challenging aspects of conducting resilience analysis is the magnitude of data and the level of expertise required. The required data and expertise present major barriers to resilience investments. Making tools faster and simpler to use and providing additional support and training for users can help increase the number and variety of resilience projects that can be modeled. Determining sensible defaults, integrating relevant data sets, and setting up tools in a user-friendly manner can reduce the burden on the user.

3.3.1 Hazard Needs

The first step of any resilience analysis is to identify relevant hazards. However, many tools do not identify the hazards most relevant to a given location or region. In fact, it is often the case that multiple hazards that are relevant to a single location must be modeled using multiple, separate tools, each with their own unique data and training requirements. At the same time, other tools present all potential hazards without helping the user identify which are most relevant to consider. Additional work can help resilience tools to have more integration between hazard types and more filtering of hazards to the ones most important to model.

3.3.2 Scenarios

Sites face a range of potential scenarios that the resilience planner should consider, but most resilience tools only model a single user-defined scenario. Modeling an overly mild scenario can result in insufficient preparation and risk management, while modeling a doomsday scenario can result in over expenditures on mitigation and a distorted understanding of the likelihood of disruptive events. Providing information on a range of scenarios increases computational needs and modeling complexity. In addition, it can become more challenging to visualize and interpret multiple scenarios.

Probably the best example of the value of incorporating multiple scenarios comes from consensus forecasts for hurricanes, where forecasts are produced by combining an ensemble of model runs. The visualization and statistical estimates of multiple forecasts in a single output helps resilience planners assess areas most likely to be affected and the range of potential impacts. Additional work could take a similar approach to a wider range of hazards along with how these hazards impact the electricity sector.

3.3.3 Occurrence Frequency Needs

Resilience valuation tools are only as good as the data that goes into them. Any quantitative assessment of risk requires occurrence frequencies, but frequency data are often not available. There is a clear need for additional data on the likelihood, intensity, impacts, and costs of historical hazards. Historical events are used to calibrate and validate models, and inaccuracies in historical outage costs lead to inaccuracies in resilience tools. A lack of publicly available information on power outage frequencies is a major barrier to valuing grid resilience (Ericson et al. 2022). Similarly, many of the outage cost surveys used to determine outage consequences are more than 20 years old (Sullivan et al. 2019). Information on the types of costs various hazards cause and the historical performance of various mitigation investments supports resilience planners in guiding resources to where they will provide the most value.

Climate change has increased the uncertainty around disruptive events. The likelihoods of future heat waves and flooding are not the same as historic frequencies, though there is a great deal of uncertainty around what future likelihoods will be. Connecting resilience valuation tools with high-quality forecasts of future climate events supports the ability of decision-makers to prepare for the future. Additional work can also help determine how a changing climate will impact the supply, demand, and distribution of energy, which can then support resilience planning.

3.3.4 Impact Needs

Connecting scenarios to impacts is a critical component of resilience modeling. There is a need to better understand how disruptive events impact energy systems. This is particularly important for resilience planning because many resilience investments do not change the likelihood or intensity of the event but instead reduce the impact these events have.

3.3.5 Consequence Needs

A major challenge to resilience assessments is the lack of information on the cost of disruptive events. While some data sets do exist, they are incomplete and often lead to incorrect estimates. While private companies such as in the insurance industry may have better quality proprietary information, resilience researchers, municipalities, and communities do not have access to such information. Additional work can improve the quantity and quality of cost information from historical events.

Another important avenue for research is to connect equity considerations into consequence metrics. There is a growing awareness that differences in susceptibility and vulnerability to outages should be considered in planning. Research to develop, calculate, and integrate energy equity metrics into resilience planning can help protect populations who are most at risk to disruptive events.

4 Case Studies

This section provides select case studies that highlight the opportunities and challenges of resilience and resilience valuation. Each case study demonstrates how specific aspects of resilience valuation can fit into the broader considerations for quantifying resilience laid out in Section 2. In addition, each study discusses how resilience fits into the broader landscape of the electricity sector. The first case study describes the potential benefits of air conditioner usage for customer resilience to heat waves. The second case study describes potential challenges and opportunities that EVs can provide to the grid during normal and emergency times. The third case study describes the real-world metrics that ConEd uses for grid resilience. The final case study discusses the New York Prize competition and the Empire State Building microgrid project.

4.1 Home Resilience to Heat Waves

This case study focuses on alternative steps to decrease the impact of heat waves on residential customers. It discusses how resilience upgrade costs and benefits are allocated and examines the impact of individual choices on the energy system and society. Purchasing individual AC units provides a cheap and effective way to reduce the dangers of extreme indoor temperatures. However, low efficiency AC units can both contribute to climate change, and stress the grid during peak temperatures, leading to potential outages. Purchasing higher efficiency heat pumps and increasing building energy efficiency can reduce emissions and grid stress, increase passive survivability during grid outages, and provide long-run cost savings. However, these investments can be costly, and those who benefit are not always the same as those who make the investments.

4.1.1 Heat Wave Hazards

High ambient temperatures cause a wide range of negative health impacts including increased mortality, higher emergency room and hospital visits, adverse pregnancy outcomes, negative mental health impacts, and reduced physical work capacity and motor-cognitive performances (Ebi et al. 2021; Gasparrini et al. 2015). Heat waves are a leading cause of weather-related deaths in the United States and are particularly dangerous in large cities due to the urban heat island effect, which causes urban temperatures to be several degrees hotter than surrounding areas (Ebi et al. 2021; Lundgren-Kownacki et al. 2018).

Climate change has increased the frequency, duration, and intensity of heat waves (Collins et al. 2013), with the number of heat waves in American cities tripling since 1960 (Sun et al. 2020). Daily maximum summer temperatures have increased 0.2°F per decade in Central Park between 1900 and 2013, and daily maximum summer temperatures at LaGuardia have increased an average of 0.7°F per decade between 1970 and 2013 (González et al. 2019). Figure 9 visualizes the multidecadal measured temperatures and trend lines. Continued warming is projected to lead to further significant increases in heat wave occurrence and impacts, particularly in high emissions scenarios (González et al. 2019). Absent emissions reductions and adaptation, NYC may see thousands of additional annual heat-related deaths in the coming decades (Gasparrini et al. 2017).

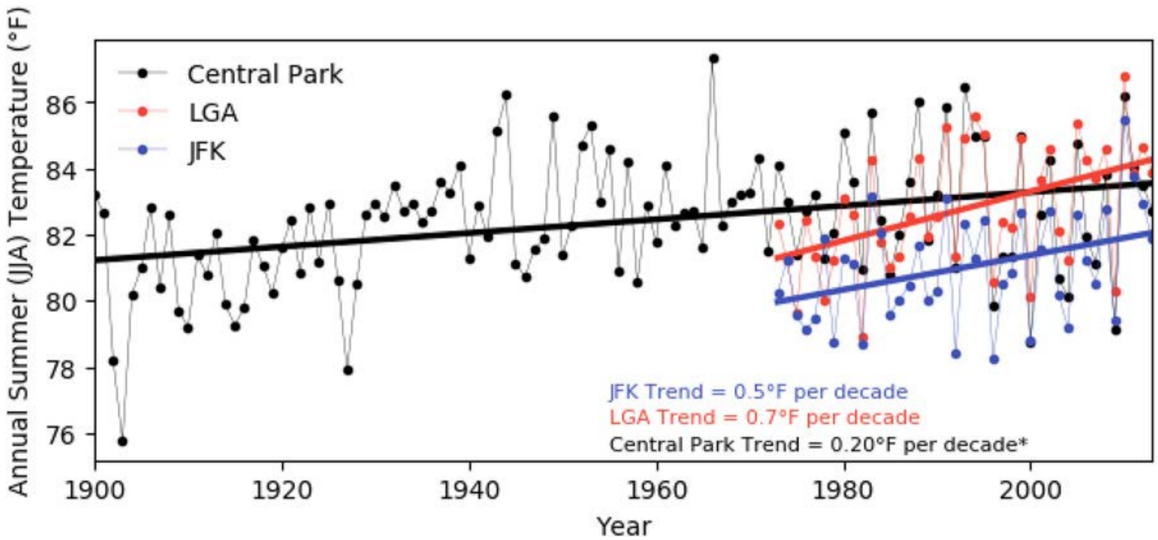

Figure 9. Summer temperature increases for Central Park, LaGuardia, and JFK airports

Figure from González et al. (2019).

Limiting the extent of climate change-induced warming has a significant impact on the risks from future heat waves (Lo et al. 2019). Even if emissions are drastically reduced, past emissions have already ensured considerable warming in the coming decades. Such warming trends will necessitate adaptation strategies. Adaptations to reduce heat risk can be associated with positive or negative externalities. Such additional costs and benefits should be considered when determining which adaptations to pursue.

Air conditioning significantly reduces the negative health impacts of heat waves, and a lack of functioning AC is the predominant cause of overheating during extreme heat events (Baniassadi et al. 2019). Notably, 85% percent of heat stroke deaths in NYC are from customers at home without AC (NYSERDA 2022). NYC has a high prevalence of AC systems—91% of NYC residential buildings have one or more systems for space cooling (NYSERDA 2021a). However, this still leaves hundreds of thousands of residents without AC, and hundreds of thousands more who must ration AC use because of electricity cost concerns. Additionally, residents with older AC units run the risk of the system breaking, which can put the residents at risk during a heat wave event. Increasing the availability of AC and decreasing the cost of AC to low-income customers can improve customer safety during extreme heat events (NYSERDA 2021a).

4.1.2 Air-Conditioning Systems

Most single-family homes use central split-AC systems and most multifamily buildings are generally served by window or packaged terminal AC units (NYSERDA 2021a). Heat pumps provide an alternative means of heating and cooling. Heat pumps are more efficient than traditional gas boilers combined with central or window AC systems, but heat pumps also have higher capital costs. Table 6 displays capital cost estimates for traditional heating and cooling systems and for heat pumps.[10]

[10] Values from 2018 capital cost estimates, so current costs likely vary. Modeled ductless mini-split system requires additional heating source.

Table 6. Representative Capital Costs per Installation in 2018. Values from NYSERDA (2019b).

System Type	Window AC	Central AC	Natural Gas Heating	Ductless Mini-Split	Air-Source Heat Pump	Ground-Source Heat Pump
Single-Family	$660	$3,800	$5,000	$6,100	$19,500	$38,300
Small Multi-Family	$1,300	$5,000	$5,400	$12,200	$20,600	$57,500

Customers deciding which type of system to install weigh higher upfront costs for a more efficient system against lower upfront costs but higher electric bills. However, not all costs and benefits accrue to the homeowner making the investment decision. A clear example is that a more efficient system has lower emissions costs, but these benefits accrue to the broader society and not the homeowner to a sizable amount.

Flat residential rates for electricity disincentivize homeowners from investing in more efficient AC units; an effect known as the "inverse cost shift" (NYSERDA 2019b). The inverse cost shift occurs because heat pumps increase electricity use in the winter and decrease electricity use in the summer. Because the grid peaks in the summer months, reducing the summer peak reduces the need for grid upgrades, even accounting for an increase in winter electricity usage.[11] Residential electricity prices do not reflect these differences in grid value, however, meaning grid benefits for heat pumps exceed the cost savings customers receive.

Finally, the lifetime of an AC unit may not coincide with the time a homeowner is planning to stay in the home. Even if a more efficient system produces sufficient savings to pay off its higher capital costs, a homeowner may still prefer a cheaper but less efficient option if they are planning on relocating and do not think they will be fully compensated for the more efficient system. Rental properties face an even starker separation of upfront costs and monthly bills, with the homeowner paying capital costs and the renter paying utility bills.

Policies such as building codes and incentive payments may be warranted in cases where the value to society of a more efficient AC system is higher than the value accrued to the homeowner (NYSERDA 2019b). Additional policies are especially called for to support lower income households. Customers without AC are more vulnerable to heat waves, as are customers who have AC but are without the budget to operate it (NYSERDA 2021a). Increased energy efficiency of buildings and homes can help ensure that all customers have access to affordable cooling by reducing the need for AC units to run, but also improve passive survivability by maintaining comfortable indoor temperatures even if AC units are unavailable due to power outages.

[11] NYS grid demand is projected to eventually switch from a summer peak to a winter peak given planned electrification policies (Mai et al. 2018).

4.1.3 Energy Efficiency and Passive Survivability

AC can maintain comfortable indoor climate conditions during heat waves, but it can also place additional strain on the electric grid and can lead to reduced resilience in the event of mechanical failure or power outages (Lundgren-Kownacki et al. 2018). AC overreliance also has the potential to lead to maladaptation,[12] leading to a reduction in overall resilience (NYSERDA 2022). Additional electricity use for cooling can make it harder to meet climate goals and can strain the grid during heat waves, increasing the likelihood of blackouts.

Energy efficiency provides a potential means to reduce AC requirements and offers the potential to provide passive survivability. Passive survivability is the ability to maintain thermal comfort during a loss of heating or cooling due to mechanical failure or a loss of power (Baniassadi et al. 2018). Building modeling can simulate indoor temperatures during a heat wave event without cooling to help determine the resilience benefits or consequences of energy efficiency improvements (DOE 2023). More efficient homes require less cooling relative to homes with inferior building insulation characteristics (NYSERDA 2021a). Increased building efficiency can decrease health risks and emissions, and lead to additional grid and resilience benefits. Upgrades to insulation, windows, and airtightness can increase the passive survivability to extreme heat, but also have the potential to increase overheating concerns depending on the specific efficiency upgrades (Baniassadi et al. 2018). Such overheating can occur when efficiency upgrades significantly increase insulation or decrease airflow in the home.

Energy efficiency upgrades interact with energy justice issues in both positive and negative ways. Economic, social, and community characteristics including age, occupation, income, pre-existing medical conditions, building density, and amount of green space impact an individual's vulnerability to heat (Nayak et al. 2018). Marginalized communities and high poverty rates coincide with higher underlying health vulnerabilities, lower building efficiencies, larger urban heat island effects, and low efficiency or non-existent AC. Well-designed energy efficiency programs can help address historical marginalization, reduce energy costs, and increase resilience during heat waves by improving passive survivability and reducing the costs to maintain thermal comfort. On the other hand, overly stringent building efficiency requirements have the potential to raise housing costs, most impacting those who can least afford it. Therefore, to improve resilience to extreme heat, policymakers need to consider the broader socio-economic inequalities and challenges related to costs and feasibility of retrofitting older buildings to bring them up to energy-efficient standards.

4.1.4 Considerations for Calculating the Resilience Value to Heat Waves

This section describes how valuing resilience to heat waves can be quantified using the framework in Section 2 and discusses considerations for inputs for each of the five components.

Hazards: Periods of sustained temperatures that are sufficiently high to cause health impacts.

Scenarios: Scenario information includes geographic location, event duration, ambient temperatures, humidity, and type of building or structure. In addition, scenarios can include

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[12] Maladaptation in this circumstance is the unintended consequence of relying on AC systems that can increase utility costs to the customer and increase greenhouse gas emissions.

events such as grid outages or AC mechanical failures. Because of the large number of dimensions, it is common to run representative heat wave scenarios. Scenario information can be based on historical heat wave data collected from satellites and weather stations. Climate change also has a direct impact on the intensity of heat waves, which calls for integrating climate projections of future heat wave intensities.

Occurrence Frequencies: Heat wave occurrence frequencies can be based on historical temperature data or climate projections of future heat waves. For example, NYC has a baseline of 4 days above 95°F (NYSERDA 2022). From 2020 to 2030, this is projected to increase to 6 to 9 days, and by the 2050s, between 9 and 18 days; by the 2080s, between 12 and 32 days above 95°F are projected (NYSERDA 2022). Because of the impacts of climate change, part of any analysis of heat wave resilience should include a determination of likely future temperatures.

Impacts: Heat waves cause a variety of negative impacts. When determining the benefits of home AC and energy efficiency, however, the relevant impact is the indoor temperature of residential buildings. Building models can model indoor temperatures for different building types and vintages.

Consequences: Unsafe indoor temperatures can have significant negative health consequences, but it can be challenging to place a dollar value on these consequences. Instead of trying to monetize the impacts, an alternative approach is to use specific temperature thresholds for different levels of likely consequences. The benefits of upgrades are then given by the reduction in the likelihood of negative consequences occurring. Figure 10 displays an example application for comparing passive survivability for energy efficiency upgrades to be compliant with Internal Energy Conservation Code or comply with recommendations from Phius (Passive House Institute US). The values are based on simulations of 1,000 residential buildings for each city and assume a power outage coincides with the heat wave (DOE 2022). The results indicate that the baseline or current building practices perform worse than energy-efficient upgrades, where the PHIUS standards perform the best, providing a different metric for resilience that links efficiency to resilience in terms of passive survivability and sheltering in place. This research is new and evolving, so there are many gaps and future areas of research, including damages to buildings and health-related consequences associated with extreme temperatures and lack of energy.

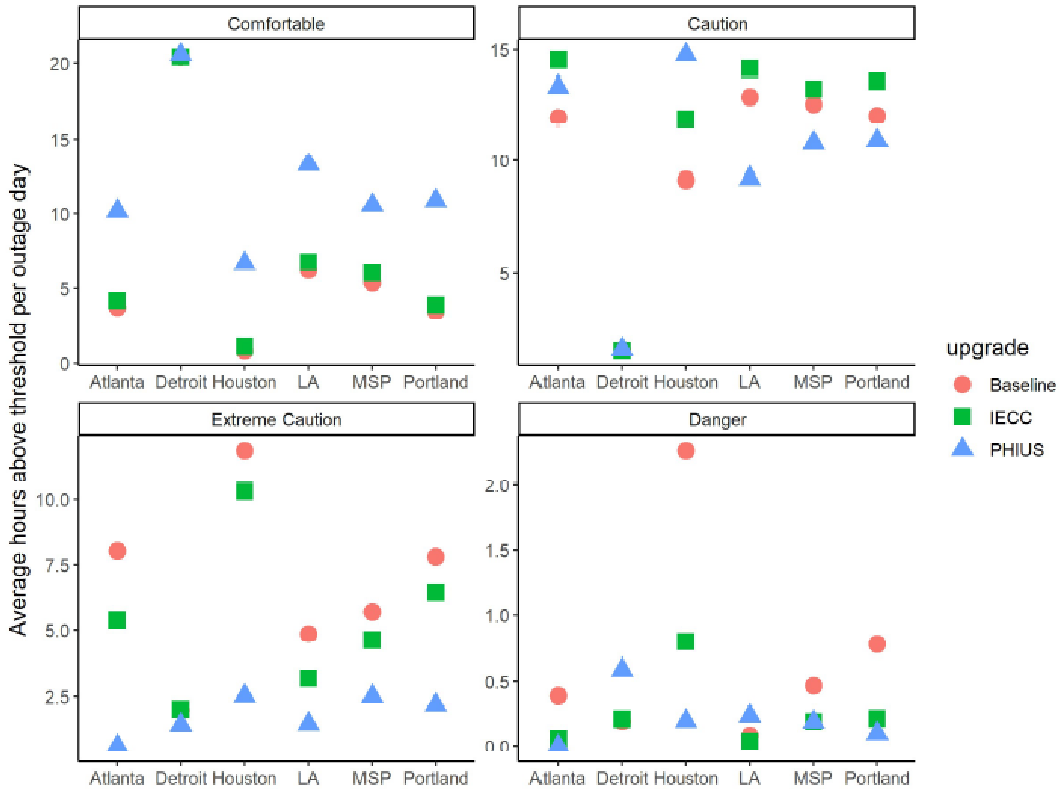

Figure 10. Example thresholds for simulated heat waves in select cities

Figure from DOE (2022).

As is shown throughout this case study, as well as in the summary of the resilience metrics presented earlier, there is a multifaceted perspective toward resilience when considering temperature control and dependence on energy. Multiple trade-offs exist among balancing electricity peak loads across seasons, consumer valuation of upfront installation costs versus both long-term savings and societal benefit, and equipment versus efficiency trade-offs.

4.2 Electric Vehicle Grid Resilience

This case study discusses the relationship between EV adoption and grid resilience. It highlights how coordinated EV charging can help manage grid peaks, and how EVs can improve home resilience during power outages. It also discusses the potential negative impacts of uncoordinated EV charging and potential mobility challenges of EV adoption during extreme events. This case study provides insights into potential rule changes to better value the grid benefits that coordinated EV charging provides along with how potential negative resilience impacts of EVs can be mitigated.

4.2.1 A Changing Transportation Landscape

EVs are entering a phase of rapid adoption. Global sales increased, on average, 78% annually, from 0.23 million in 2013 to more than 7 million in 2019 (L. Muratori, et al. 2021). This number is expected to climb to more than 20 million sales by 2025, with up to half of passenger cars sold in the United States being EVs by 2030 (BloombergNEF 2022). EVs are instrumental in decarbonizing road transport, which currently accounts for 16% of emissions (IEA 2022). EVs have zero tailpipe emissions and are approximately 3 to 4 times more energy efficient than comparable gas-powered vehicles (A. Muratori, et al. 2021). Therefore, EV adoption is an integral part of meeting climate goals and slowing climate change as a result of improving air quality and tailpipe emissions.

Switching millions of vehicles from being powered by gas and diesel to being charged by electricity will have a marked impact on the grid. The average passenger EV requires around 12 to 14 kWh per day of electricity to charge (Zhang et al. 2018), which is equivalent to roughly 40% of an average home load. In a high-electrification scenario, where most cars are transitioned to EVs, transportation would grow from its current level of 0.2% of electricity to 23% of total U.S. electricity demand, which could potentially lead to a large increase in peak loads (Mai et al. 2018).

While the grid impacts of EV adoption will likely be significant, they are also manageable. According to A. Muratori, et al. (2021) "Expected changes in U.S. electricity demand as a result of vehicle electrification are not greater than historical growth in load and peak demand." Grid reliability and resilience are less dependent on total load and more dependent on the volatility and uncertainty in load. A large increase in unexpected load during peak periods can make the grid more challenging to manage, while an increase in flexible load can increase grid reliability.

4.2.2 Coordinated Charging

The effect of EVs on grid operation depends on how EV charging is managed. Customers will often charge vehicles as soon as they arrive home after the workday, which has the potential to spike electricity demand during peak hours (Muratori 2018; Szinai et al. 2020). This can result in additional strain to the distribution network, requiring costly upgrades. It can also result in expensive peaking plants being turned online, or in more extreme cases, a spike in peak demand could result in load shedding.

EV charging as well as their potential use as electricity storage provide an opportunity for substantial load flexibility. Level 2 charging, which allows charging up to 240 volts over the usual 120 volts for Level 1 charging (DOT 2022), is becoming the common form of residential charging and allows customers to add 10–20 miles of range per hour. This means there is flexibility when night home charging occurs for most residential customers given that charging can be completed faster. Public and office located charging stations provide additional opportunities to charge EVs during daylight hours when solar generation is highest, providing a degree of grid flexibility to help demand meet supply (Mai et al. 2018).

Rapid ramping of electric generators can decrease their reliability, and generators that are run more sporadically are often less reliable than generators that run consistently. Therefore, leveraging EV load flexibility to smooth demand can increase grid reliability. Another means through which EVs can increase grid reliability is by voluntarily avoiding charging during peak grid hours, such as during heat waves. This form of flexibility is already being implemented in some regions. The California Independent System Operator sent Flex Alerts to EV owners during the summer of 2022 asking residents to avoid charging between 4 p.m. and 9 p.m. (Albeck-Ripka 2022). Similarly, Tesla owners in Texas were sent in-car alerts encouraging them to not charge between 3 p.m. and 8 p.m. during heat waves (Lambert 2022).

Leveraging the potential load flexibility that EV adoption offers requires a shift in market rules and operations. Time-of-use rates offer one avenue to encourage efficient EV charging by increasing the cost of charging during peak hours to incentivize EV owners to shift charging to cheaper off-peak hours. More advanced "smart charging" programs, where a third party aggregates EV charging to participate in demand response programs, offer an additional avenue to shift charging times in response to grid needs.

There are a variety of technical challenges to coordinated EV charging that can be alleviated through policies. For example, in August 2022, the California Public Utilities Commission updated its protocols to allow EV residential submetering, which allows separate metering of EV charging without the need to install a costly second utility meter (Balaraman 2022). This change provides the opportunity to increase EV charging responsiveness to grid conditions. Smart policies and regulations can leverage the positive synergies between grid operations and EV charging while avoiding negative cost and reliability impacts of additional EV loads.

4.2.3 Vehicle to Load

While most experts believe that vehicle charging has the highest current and future potential impact, EVs can also draw down stored energy to charge other loads, known as vehicle to load (Brown and Soni 2019). Vehicle to load provides potential resilience benefits during power outages and natural disasters. EVs have sufficient stored energy to power a home for several days and power critical loads for even longer.

Some EVs can be used as a home backup system during power outages given the right equipment. The Ford F-150 Lightning, for example, can power a home for up to 10 days. Converting an EV into a home backup system does require additional investments, however. In the case of the F-150, it requires the installation of a "home integration system," which costs around $4,000, along with additional installation costs. Given that a home generator can cost $10,000–20,000 dollars to install, these costs still may be worthwhile for some customers, though it means that backup power from EVs are currently the exception rather than the rule.

A more cost-conscious solution is to plug critical appliances such as refrigerators, fans, space heaters, sump pumps, or computer and phone charging ports directly into the EV through extension cords, along with using the EV for heating or cooling. Such measures can substantially reduce the risk of long-duration power outages. Residential outage costs largely consist of impacts from food spoilage, damage due to a loss of power to the sump pump, and loss of power to electronics, in addition to the nonmonetary death from heat stroke. Direct charging from the EV can largely avoid each of these costs, providing an important benefit of EV adoption.

Using EVs as a source of backup power provides the additional benefit of zero source emissions. The rates of carbon monoxide poisoning increase more than ninefold during power outages due to the use of backup generators indoors, along with running gas-powered vehicles indoors to make use of charging and AC (Worsham et al. 2022). Greater use of EVs as a source of power during outages could therefore lead to a reduction in deaths associated with power outages and natural disasters.

4.2.4 Mobility Considerations

Vehicle transportation is the primary mode of evacuation from natural disasters. As such, it is important to consider whether the transportation network is sufficiently designed to allow for evacuation in the event of a power outage. According to Adderly et al. (2018), "evacuation distances for those escaping the affected areas may exceed the range of an electric vehicle on a single charge, and charging stations could become swamped or unavailable due to outages." Gas pumps do not work without power, so gas-powered vehicles are also dependent on the electric grid. Understanding the opportunities EVs provide for emergency response or evacuation is important, even if not well understood. When power is lost to gas stations, EVs could potentially provide mobility when needed.

However, the dependence on a functioning electrical grid is especially pronounced for EVs because of the fact that gas-powered cars currently have longer ranges than EVs, and that there are much lower backup power requirements for gas stations than for charging stations. Additionally, EVs tend to experience reduced driving ranges during cold weather, which would reduce the benefits of EVs during a grid outage overlapping with severe winter weather. Several states, including New York, New Jersey, and Florida, require certain gas stations located near major evacuation routes to be capable of operating using backup power (Adderly et al. 2018). There is currently no equivalent requirement for EV charging stations.

Technology, policy, and planning can each help alleviate EV range concerns during grid outages. Decreasing battery prices and increasing battery densities are expected to increase vehicle ranges. Expanding the network of DC fast charging stations can further help speed up charging, which can support larger-scale evacuation given that power is available. Similar policies to the requirements of backup power for gas stations can be implemented for charging stations at critical locations to further improve resilience. Leveraging the positive aspects of EVs while mitigating challenges related to EVs will support resilience and make people safer when natural disasters do strike.

4.2.5 Considerations for Calculating Resilience of Electric Vehicles

Hazards: Hazards for EV resilience can include any events that disrupt the electrical grid, including weather or human-caused events.

Scenarios: Important scenario factors include duration of event and level of EV charge. If the EV owner is given forewarning of the event, they can pre-charge their battery in anticipation of an outage.

Occurrence Frequency: Dependent on hazard; potentially exacerbated by grid peaks likely to increase in frequency due to increasing temperatures.

Impacts: Impacts from EVs on peak grid periods can be beneficial or problematic, depending on the charging approach for the EVs. A coordinated response to peak grid conditions that prevent EVs from charging during these particularly high load periods can reduce grid overloading. More long term, a coordinated EV charging approach can reduce the need for utility construction of additional power generators in the region (Meyers 2010).

EVs can also play a role during a power outage, with both potentially positive or negative impacts. A fairly obvious negative is that residents would be stranded if their EV is not charged, and a grid outage prevents charging of the vehicle. A potential positive, however, is if advance notice allows residents to charge their vehicles ahead of a disruption, and the vehicles are equipped to provide vehicle-to-grid charging that can power a home equipped with a microgrid. (Federal Energy Management Program n.d.).

Consequences: The consequences of demand response can be a decrease in electricity load for the utility and also financial incentives for EV owners. Fleet EVs and bus EVs used by the University of Delaware and the White Plains, New York, school district as part of demand response programs have successfully used bidirectional charging. In the case of the University of Delaware, the school has received payments for the grid services their EVs provide (Federal Energy Management Program n.d.). In the case of power outages, EVs can either provide positive or negative impacts. EV owners utilizing their vehicle batteries for power and heat can avoid health impacts of a loss of power, which is what occurred after the 2011 earthquake near Fukushima, Japan. While electricity service was restored to roughly 90% of the region within a week of the earthquake, only around 50% of the gas stations were operational by that time. Therefore, electric vehicles were able to provide transportation and vehicle-to-building services while other forms of fuel were still unavailable (Nissan Motor Corporation 2019).

Conversely, evacuations for large-scale weather hazards such as hurricanes can be stifled by EVs that are not able to charge using existing charging infrastructure (Feng et al. 2020)

4.3 Distribution System Hardening to High-Heat Events

ConEd, an investor-owned utility serving NYC and Westchester County, uses reliability metrics and processes to inform resilience planning in the development of infrastructure reliability plans. The metrics and processes cover both the distribution system—using the Network Reliability Index (NRI)—and the sub-transmission system—using the Transmission Probabilistic Reliability Assessment (TPRA). Although power system reliability normally encompasses disruptions that are more frequently occurring and have lower potential consequences, the NRI and TPRA also help determine the likelihood and impacts of longer-term or more severe outages. To date, the metrics used by ConEd are hazard-specific and have only been applied to measure reliability and resilience to extreme heat. Certain aspects of the methodology could apply to other hazards but have not been applied to other hazards so far.

In preparation for their climate adaptation and resilience implementation plan, ConEd completed an initial climate vulnerability study in 2019. In this study, the NRI was used to anticipate the grid's performance during hypothetical extreme heat events, and TPRA was used to estimate summertime rates of transmission load drop due to extreme heat. By identifying areas where closer monitoring and evaluation is necessary for building new design considerations into its system, ConEd is positioning itself to better address and anticipate upgrades, making the electric infrastructure more resilient to future threats from extreme weather events, especially to rising temperatures.

According to Wang et al. (2008), "ConEd's network customers see an interruption about once every 100 years, which is approximately 100 times better than the national average." The high network reliability is because of a unique design where only one substation is used to supply electricity to each network in a series of 59 underground networks consisting of cables, joints, transformers, and other related equipment. Power travels along 27-kV and 13-kV feeders from ConEd's substations, which interface with transformers that then connect to a low-voltage secondary distribution system. This redundant design allows ConEd to deliver electricity to its customers while maintaining high levels of reliability that negate any incidental failure in two feeders at a single time.

An example of how the NRI can be used to estimate failure due to heat waves can be seen where four feeders serving a section of a network are analyzed by bands. During a heat wave where two of the four disrupted feeders are in the same "band," one of the two disrupted feeders would normally begin serving the load dropped by the other feeder due to the disruption. The frequency measured in this example captures how often the distribution network will be in an "NRI state" during a set time period. To be in an NRI state, ConEd considers a heat wave to be when the weighted three-day average dry-wet temperature variable equals or exceeds 80°F.

This NRI metric focuses on the "NRI state" scenario applied to primary distribution feeders, given that failure in primary feeders can indicate that widespread disruption is occurring across the distribution network, which can cause ripple-effect damage or cascading failures to secondary distribution systems. The NRI measures this failure scenario as "per unit" (p.u.) of standard reliability, which simply indicates the likelihood of feeder band failure. For example, an NRI of 0.001 means that the network could see the NRI state once every thousand years, or that the current year has a one-in-one-thousand chance of experiencing the "NRI state." A 1.0 p.u. NRI is the maximum threshold of acceptable risk for ConEd. Any part of the network with an NRI at or higher than 1.0 p.u. would merit intervention.

To date, ConEd has maintained its network such that it has not exceeded the NRI threshold of 1.0 p.u. Future climate change scenarios indicate extreme heat events will be more common, however, and ConEd's internal models show that its networks' NRI will begin to exceed a p.u. of 1.0 by 2030. Under either Representative Concentration Pathways (RCP) scenarios 4.5 and 8.5 from the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report, the number of networks (i.e., underground cables, joints, transformers, and other related equipment) that are likely to exceed an NRI of 1.0 p.u. will likely equal at least 10, if not more, by 2050. Figure 11 shows ConEd's projections of risks associated with future extreme heat scenarios (2018 base case through RCP 8.5), as calculated using the NRI metric.

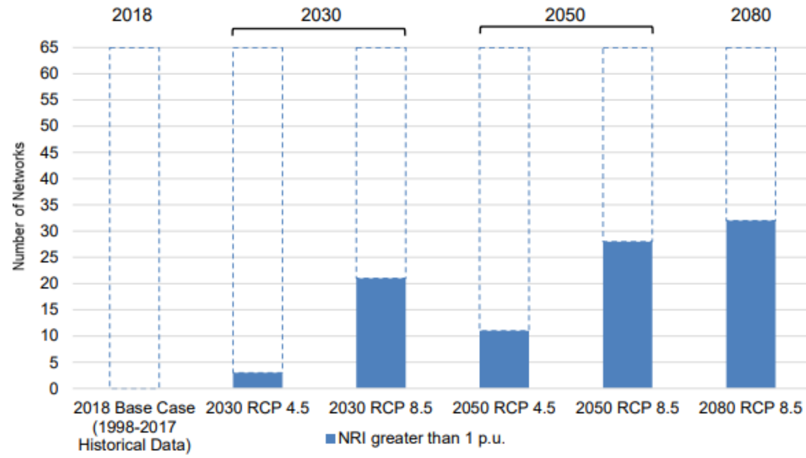

Figure 11 Projected increase in NRI metric by climate change scenario (2030, 2050, 2080)

Source: ConEd 2019.

In addition, and in support of the NRI metric, ConEd also uses TPRA as a process for prioritizing investments to certain components of the sub-transmission system (e.g., transformers, circuit breakers, or spans of cable). Although NRI is a metric that has a specified threshold, as stated previously, TPRA is more of a software-based process for prioritizing certain types of activities that address identified needs for improvement. ConEd categorizes these activities as ranging from high-level planning, such as long-term equipment procurement, down to the installation of new equipment itself (Consolidated Edison 2021a). The TPRA software relies upon historical failure rates to model which of the sub-transmission substations are most likely to cause a load drop. ConEd uses the term load drop to refer to losses in load (e.g., an appliance using electricity) anytime between June and August, after countermeasures such as voltage reduction or demand response have been deployed (Consolidated Edison 2021b).

4.3.1 Considerations for Calculating Grid Resilience to High-Heat Events

Hazards: Extreme heat event impacts on critical grid infrastructure.

Scenarios: Scenarios are delineated depending on the particular RCP and time frame for consideration. RCPs 4.5 and 8.5 are considered, and time frames 2030, 2050, and 2080 are considered.

Occurrence Frequencies: An increased occurrence of extreme heat events will cause more frequent NRI states for ConEd grid sectors.

Impacts: Electrical distribution system failure can cause damage to utility and customer assets and harm to customers during high-heat events.

Consequences: ConEd uses the NRI metric and TPRA to determine which sectors of their grid require intervention and to prioritize investments to reduce the probability of outages or load drop.

4.4 Distributed Energy Microgrids

This case study focuses on distributed energy microgrids. It discusses the New York Prize competition and follows the evolution of the planned City of Albany Empire State Plaza microgrid project. It highlights how resilience benefits from microgrids can be valued and discusses the need to consider multiple decision criteria, such as air quality and climate change goals, when planning resilience investments.

4.4.1 Initial Proposal

The originally planned Empire State Plaza microgrid project was a combined heat and power (CHP) plant consisting of two 8-MW gas turbine generators. The generators would provide electricity and heating to the Empire State Plaza complex, which includes the New York State Capitol building, Times Union Center, and surrounding buildings in the Empire State Plaza where around 11,000 state government employees work. A primary benefit of the proposed CHP plant cited in the original proposal was that "it can remain in operation during loss of utility supplied electricity and/or the loss of the natural gas fuel supply" (Cogen Power Technologies 2015). The generators would be run primarily using natural gas but would also have fuel oil stored on-site to operate the turbines for at least seven days during a natural gas disruption (Cogen Power Technologies 2015).

The Empire State Plaza microgrid was part of the New York Prize competition, a multistage competition process administered by NYSERDA and supported by the Governor's Office of Storm Recovery to award prize money to implement microgrid development plans (NYSERDA 2015). The original competition design consisted of three stages. Stage 1 offered up to $100,000 to support microgrid feasibility studies, Stage 2 provided up to $1 million to support detailed engineering, financial, and business plans, and Stage 3 was set to award up to $5–$7 million for microgrid build-out and construction (NYSERDA 2015). Stage 1 approved funds for 83 feasibility studies in July 2015, and Stage 2 approved funds for 11 designs in April 2017. Stage 3 was originally planned for the end of 2019 but was cancelled before funds were awarded because of a prevalence of fossil-fuel systems in the final stage, which went against New York climate goals. Resilience benefits ranked high on the list of motivating factors for many of the proposed microgrid projects in the New York Prize, with most of the microgrids first conceived in response to severe weather events that resulted in extended power outages (NYSERDA 2017). The Empire State Plaza microgrid was selected for Stage 1 and Stage 2, and after the third stage of the Prize program was cancelled, the Empire State Plaza microgrid was one of the only projects to continue development.

4.4.2 Addressing Emissions Challenges

Microgrids can provide cost-effective resilience during power outages and major storm events. However, they can also exacerbate challenges of meeting emission reduction goals. Climate change is causing an increase in disruptive events, which increases the need for on-site power generation to enhance resilience. Climate change is also driving the need to cut greenhouse gas emissions. As seen in Table 7, the Empire City Plaza microgrid projected benefits from reduced electricity and heating costs exceeded the projected capital and operations costs, meaning the project could provide net financial benefits along with resilience benefits. At the same time, the proposed project would generate significant CO_2 emissions during operations. In addition, siting the gas turbines close to critical loads also sites emissions close to population centers, which can lead to health impacts from SO_2, NO_x, and particulate matter. The societal damages from emissions were projected to more than offset the benefits of reduced grid emissions, leading to annual net emissions costs of $486,440.

Future iterations of the Empire State Plaza proposal did lower CO_2 emissions by roughly 25,600 tons per year, assuming grid emissions remained constant at 2018 levels (New York Power Authority 2018). However, New York State is planning to reduce greenhouse gas emissions by 40% by 2030, enhance energy efficiency in the state by 600 trillion British Thermal Units (TBTUs), and generate half of the state's energy from renewable sources. This would reduce emissions savings, further decreasing the project value. While the proposed Empire State Plaza CHP plant was relatively efficient and would provide resilience value, the emissions that would have been produced were not in line with New York State climate goals.

Table 7. Annualized and Present Value of Costs and Benefits for the Originally Proposed Empire City Plaza Microgrid (Cogen Power Technologies 2015).

	Annual Value ($2014)	**20-Year Present Value ($2014)**
Design + Installation	$1,238,000	$15,370,000
Fuel Costs + O&M	$9,900,000	$112,227,000
Emissions Damages	$8,250,000	$126,000,000
Total Costs	**$19,388,000**	**$254,000,000**
Generation + CHP Fuel Savings	$13,050,000	$147,900,000
Avoided Emissions	$7,763,560	$119,040,300
Other Savings	$1,353,000	$15,360,000
Total Benefits	**$22,166,000**	**$282,000,000**
Net Emission Costs	**$486,440**	**$6,959,700**
Net Benefits	**$2,778,000**	**$28,200,000**

Emissions concerns related to the Empire State Plaza microgrid led to significant opposition from environmental and community advocates. The consensus among opposition groups was that the state should explore renewable options instead of the continuing emissions from fossil fuels by installing the gas turbines. Albany County legislator Merton Simpson summarized such concerns by stating that the proposed CHP plant "will poison us a little slower, a little less and a little more efficiently. We're asking that you not poison us" (French 2017). The third stage of the New York Prize was cancelled in large part because of the high fraction of proposed microgrids that were primarily powered by diesel and natural gas. This funding was instead reallocated to projects that could more directly address the needs of emission reductions.

4.4.3 Renewable Energy and Resilience Benefits

As part of the New York Prize Stage 1, emission reductions were called out specifically within the feasibility studies as a sought-after benefit of microgrids (NYSERDA 2017):

> *[W]hen incorporating energy-efficient and low- or no-emission technologies, the microgrid gets to the root problem of climate change and environmental protection by*

reducing greenhouse gas emissions and dependence on fossil fuels in two important ways: supporting the viability and deployment of renewables, such as solar power, and reducing energy waste. A positive environmental impact should be among the main microgrid goals.

However, renewable energy options were initially seen as too expensive and unable to provide sufficient resilience to be considered viable for microgrids. When the New York Prize competition began in 2015, renewable energy sources required significant grants, utility energy credits, and/or other credits in order to be cost-effective (NYSERDA 2017). The landscape for the cost challenge has shifted markedly in recent years. Costs for commercial rooftop photovoltaics (PV) fell by 70% between 2010 and 2020, and utility-scale PV costs fell by 80% over the same period (Feldman et al. 2021). Battery system costs have experienced even more dramatic cost declines. Solar PV costs are forecasted to decline by an additional 43% between 2020 and 2030, and utility-scale battery storage costs are forecasted to close to 50% over the same time period (Vimmerstedt et al. 2022). Thus, renewable energy projects that would have been cost-prohibitive when first proposed for the New York Prize in 2015 may now be the least-cost solution today.

While renewable energy costs have declined significantly, space considerations still pose a challenge to using renewable energy resources to provide resilience in urban settings. An important factor for success originally identified in the New York Prize feasibility studies was that "successful microgrid proposals were those that had compact physical size," with the important loads to be supplied by the microgrid "located within close proximity to the generation sources" (NYSERDA 2017). Renewable energy sources often require large open spaces and are not easily cited within cities.

In the case of the Empire State Plaza Microgrid project, several challenges were identified regarding renewable resources. Battery storage systems were excluded because of their "very high capital costs which resulted in payback periods well beyond the replacement life of the batteries" (Cogen Power Technologies 2015). Solar generation was also eliminated because of costs and insufficient roof space or available acreage to site PV close to loads. An analysis by the New York Power Authority (NYPA) estimated that around 1,000 acres of solar panels, more than every roof in downtown Albany, along with a 1- to 2-acre battery, would be required to provide equivalent resilience from renewable sources. Other renewable sources such as wind and geothermal have similar siting challenges.

Power outages primarily occur due to disruptions to the transmission or distribution grid, meaning resilience is increased when microgrid generation sources are located close to critical loads. The large land areas often required for renewable projects still pose a challenge to siting the generation source for renewable microgrids close to critical loads. Solutions such as battery storage may offer a way to locate renewable energy on-site, but battery storage is often cost-prohibitive for providing long-duration power. At the Albany location, the proposed microgrid was designed to provide seven days of backup power. Even if the critical loads were only half of average loads, it would require a 1.4-GWh battery system to provide equivalent resilience.

4.4.4 Finalized System and Lessons Learned

In 2019, because of environmental concerns surrounding the proposed CHP plant, the NYPA decided to change course (French 2019). The new plan is for the development of a 30-MW remote-solar array located in Oneida County, which can provide up to half of Empire State Plaza's power needs. The NYPA selected DG Development & Acquisition, a subsidiary of NextEra to develop the off-site solar array, which is planned to be completed in 2023 (NYPA 2021). On-site solar panels and electrical energy storage will also be added (DeMichele and Groll 2019). In addition, $16 million is planned to install LED lighting, and $30 million will electrify one of the steam-driven chillers to reduce local natural gas use by 18%.

There is an important trade-off between systems that offer the most resilience, which require generation to be located close to critical loads and often require diesel or natural gas generators, and systems that offer the most emissions reductions, which often requires renewable generation and electrification. The new proposal is more in line with New York's commitment to reduce emissions and address climate change, but the changes do not provide the same level of resilience in the event of a major disruptive event as the originally proposed CHP plant offered. The eventual cancellation of the New York Prize competition highlights the more general tension between the dual requirements of system resilience and emission reductions.

Climate change is leading to an increase in extreme weather events, resulting in a greater prevalence of long-duration power outages. This threat to the electric grid is causing a reassessment of how electricity is generated and distributed. More outage events increase the need for and value of resilience solutions such as microgrid systems. At the same time, combating climate change requires a shift away from fossil fuel generation and toward cleaner generation sources.

4.4.5 Considerations for Calculating Resilience of a Microgrid

The New York Prize competition used a standardized process to calculate potential resilience benefits from major power outages (IEc 2015).

Hazards: The calculation is agnostic of the *hazard* causing the power outage.

Scenarios: There is a single *scenario* type, which was a power outage of a fixed duration. The outage duration is not fixed ahead of time, but instead was set to the minimum duration, which would make the system have a non-negative net present value.

Occurrence Frequency: The *occurrence frequency* is assumed to be an annual major outage event.

Impacts: Impacts are based on site critical loads. Loads from fire stations, emergency medical services, hospitals, police stations, wastewater treatment plants, water services, and electric services are treated separately from other loads. Table 8 displays the impacts estimated by the FEMA methodology for each service category. The microgrid system was assumed to reliably meet load during major outage events, and existing backup generators were assumed to fail 15% of the time.

Consequences: Consequences for the services listed above are based on methodologies developed by FEMA (FEMA 2011, 2016). The value of maintaining other commercial and industrial services is based on estimates from the ICE Calculator.[13] Both the FEMA methodology and the ICE Calculator methodology produce values that are linear with respect to MWh of load protected.

Table 8. Benefits Estimated by the FEMA Methodology. Table adapted from IEc (2015).

Service Category	**Impacts Estimated**
Fire	1. Value of property losses from fires, due to increased response time 2. Value of lives lost and injuries suffered from fires, due to increased response time.
Emergency Medical	1. Value of lives lost from cardiac arrest, due to increased response time.
Hospital	1. Value of extra time spent getting to emergency department or waiting to be seen 2. Value of extra distance traveled to get to emergency department 3. Value of lives lost from acute myocardial infarction or unintentional injuries, due to increased time before emergency department treatment.
Police	1. Tangible and intangible cost of property crimes 2. Tangible and intangible cost of violent crimes.
Wastewater	1. Lost economic productivity due to a loss of commercial wastewater service 2. Welfare loss from lost residential service.
Water	1. Lost economic productivity due to a loss of commercial water service 2. Welfare loss from lost residential service.
Electric Power	1. Lost economic productivity due to a loss of commercial electric service 2. Welfare loss from lost residential service.

The approach to valuing resilience used for the New York Prize competition can be applied to a broad variety of microgrids. However, it assumes major outages occur annually and does not incorporate estimates of outage durations. Determining the likelihood of outages by duration is essential for estimating the value of resilience that a system is expected to provide (Ericson et al. 2022). A project that generates fewer economic returns may end up being preferred once its full resilience value is accounted for.

13 https://icecalculator.com

5 Conclusions

The costs of shock and stress events, such as a storm or heat wave, as well as the costs of taking steps to prevent and mitigate the damages and disruption of events are both substantial. Pursuing all risk mitigation options is unrealistic from a cost and efficiency perspective. At the same time, pursuing risk mitigation options that generate positive net benefits can provide customer and societal benefits. Quantifying the costs and benefits of resilience investments allows decision-makers to avoid net negative solutions and to make informed decisions about where to direct scarce investment dollars for optimal outcomes.

This report lays out considerations for quantifying and valuing resilience, discusses the current state of resilience valuation tools, and provides case studies of resilience projects in New York that demonstrate how resilience attributes can be considered and highlight broader challenges to increasing resilience. There are five steps to determine the cost of disruptive events and in turn determine the value of resilience:

1. Identify *hazards*
2. Determine relevant *scenarios*
3. Determine *occurrence frequency* of each scenario
4. Calculate the *impact* given a scenario
5. Quantify the *consequence* of a given impact.

Addressing each of these areas will help with creating a strategy for reducing consequences and vulnerabilities.

There is a growing need for resilience valuation tools to help mitigate the cost from increasingly frequent and intense disruptive events. Several resilience valuation tools are currently available, but there is still much additional work and research to be done. Developing methods to quantify, value, and price resilience helps meet resilience needs in an effective manner, and in a way that supports broader societal welfare. Resilience valuation tools are only as good as the data that goes into them. More publicly available information on occurrence frequencies, and better integration of climate change forecasts into resilience tools would improve the quality of estimates. Improving the ease of use and reducing the cost burden of using resilience valuation tools would increase the number and variety of resilience projects that can be modeled. As mentioned previously, separation among who is affected by hazards, who pays for resilience, and who is positively and negatively impacted by resilience investments can lead to suboptimal decisions, but these consequences are not clearly quantified and pose another area needing additional research.

Climate change is leading to an increase in extreme weather events, resulting in a greater prevalence of long-duration power outages. This threat to the electric grid is causing a reassessment of how electricity is generated and distributed. More outage events increase the need for and value of resilience solutions, such as microgrid systems. At the same time, combating climate change requires a shift away from fossil fuel generation and toward cleaner generation sources. Similarly, there are trade-offs between different goals and sources of resilience; for example, the AC case study demonstrates that increasing AC adoption can help with adaptation to extreme weather events but increases electricity load during peak periods.

Decision-makers should use tools, methodologies, and frameworks to measure and value resilience to determine which mitigation solutions to implement given limited available resources. These decisions should incorporate the full positive and negative impacts to avoid maladaptive investments. Disruptions are inevitable, and it is infeasible and/or impractical to protect against all potential hazards. However, well-considered investments in resilience will allow us to recover faster and stronger when disruptive events do strike.

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