Photo from Getty Images, 1339485674.

Understanding Resilience Valuation for Energy Systems:

An Overview of the NYSERDA-NREL Research Collaboration

The NYSERDA-NREL collaboration resulted in three reports released in 2023:

Resilience Insights from New York State Stakeholders

Measuring and Valuing Energy Resilience: A Literature Review

Applications of Measuring and Valuing Resilience in Energy Systems

Introduction

Energy resilience has become a national priority as Americans experience more frequent power outages attributed to climate change, extreme weather, and cyberevents. Energy system owners and operators recognize that they must prepare differently for outages today than they did in the past. Decision makers at all levels face unique challenges and opportunities in effectively and equitably executing a transition to more-resilient power systems. The New York State Energy Research and Development Authority (NYSERDA) recently added resilience to its mission statement.[1] The authority engaged with the National Renewable Energy Laboratory (NREL) in a collaborative effort to: (1) understand options for measuring and valuing resilience investment benefits, and (2) inform how resilience could be operationalized across NYSERDA initiatives and program areas.

Since 2010, every county in New York State has been affected by at least one federally declared weather disaster. From 2010 through April of this year, New York State has experienced 46 extreme weather events costing $1 billion or more (in Consumer Price Index-adjusted terms). Climate change is leading to more acute disruptive events, and New York communities are experiencing weather hazards and conditions they have not previously encountered. Power systems must be resilient against non-climate hazards as well. The four main categories of disruptive events are natural hazards, technological or mechanical failure, human attack, and operational failure. In recent years, the northeast region of the United States has made most improvements in power system resilience to natural hazards compared to outages from the other three event categories (Ankit et al. 2022).

The costs of acute shock and chronic stress events—as well as the costs of taking steps to prevent and mitigate the damages and disruption of events—are substantial. Pursuing all risk mitigation options is unrealistic from both a cost and efficiency perspective, but many solutions offer critical customer and societal benefits. Quantifying the costs and benefits of resilience

[1] https://www.nyserda.ny.gov/About/Tracking-Progress

investments allows decision makers to avoid net negative solutions and to make informed decisions about where to direct scarce investment dollars for optimal outcomes.

For over 15 years, NREL has worked with organizations and communities to develop resilience assessments and plans that have a quantifiable impact on social welfare through health, safety, and economic measures. Research related to measuring, valuing, and justifying resilience investments has grown out of NREL's place-based initiatives and is an important and ongoing area of exploration.

The NYSERDA–NREL collaboration includes several components. This document presents an overview of the research activities and outputs, which are covered in depth in the reports linked on this page. The first phase was leading and synthesizing discussions with internal and external stakeholders toward codifying a common understanding of resilience, followed by a literature review on monetization and valuation strategies for power sector resilience. These two components are the foundation for a third project on opportunities to measure and value resilience in New York State, coupled with illustrative examples.

Defining Resilience

Resilience is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions (Hotchkiss and Dane 2019). NREL developed this definition for resilience based on stakeholder input from more than 200 individuals from local, state, and federal government entities, building on Presidential Policy Directive #21.

In 2022, stakeholders in New York State were asked to react to NREL's resilience definition and to reflect on whether, and how, this definition resonates with their own work. The interviews, led by NREL researchers, revealed general alignment with the definition, with minimal deviation from the language presented. Instead, many stakeholders—representing state agencies, authorities, utilities, and regulators—noted that it resembled definitions and practices used in their respective organizations and program areas. The research team synthesized the 34 interviews to examine the degree of shared understanding around resilience, identify opportunities to address common challenges, and align stakeholder interests to better serve New York State's services, systems, and residents. We discuss several of the recurring themes from these interviews below.

There was consensus among the interviewees that resilience is a broader concept than reliability. Due to the lack of resilience metrics or valuation frameworks available, many of the interviewees were more familiar with reliability metrics than resilience metrics, especially those in the electricity sector. Understanding whether an investment results in the intended benefit (e.g., withstanding shocks or rapidly recovering from an outage) was a common knowledge gap identified by the participants.

Climate change can also generate economy-wide risks through disruption to business models, emergencies for community members, cascading failures from extreme events, and increased litigation. Several interviewees considered the ability to anticipate, prepare for, and adapt to "changing conditions" a more important aim than returning to the status quo after a disruption. This was in reference to the consequences of climate change, as well as the expected changes coming from New York State's clean energy transition. Deep decarbonization will significantly affect specific sectors and the economy as a whole, especially carbon-intensive sectors like ground and air transportation, maritime shipping, construction, power generation, and all downstream beneficiaries of these sectors.

Many stakeholders stated that resilience planning must have a local dimension and equity impact to better serve frontline communities. Health and climate disparities are evident during major hardships when under-resourced communities struggle to withstand, respond to, and rapidly recover from disruptions. There was agreement among the interviewees that resilience solutions are most effective when they reflect a given population's lived experiences and cultures and when community input shapes the vision of success. Knowledge of local infrastructure, the availability and quality of information, social and economic networks, and environmental resources and risks (among other factors) must complement national best practices.

Participating Organizations

NYSERDA and NREL are indebted to the New York State stakeholders who volunteered their time for the interviews and shared their expertise. All comments in this summary came from members of one of the following organizations, though they are intentionally not attributed.

- ConEdison
- National Grid
- New York Independent System Operator
- New York State Department of Environmental Conservation
- New York State Department of Financial Services
- New York State Department of Public Service
- New York State Department of State
- New York State Office of General Services.

How Can Resilience Be Measured?

Quantifying the value of resilience is necessary to translate abstract concepts into real-world decisions. Any new investment can come with increased capital costs or long-term operational costs. Traditional cost benefit analysis techniques like those used during utility energy master planning processes usually would not provide an organization or community with a complete picture of the benefits of a resilience investment to balance against the investment costs (Hotchkiss et al. 2023). By properly measuring the impacts of resilience—or lack thereof—the true value of resilience-focused investments can be uncovered.

Resilience Versus Reliability

NREL's stakeholder interviews demonstrate that reliability is well-understood across New York State agencies, but expanding views on resilience will require new and accessible tools, data, and evaluation practices. Resilience and reliability are two interrelated yet distinct concepts. Reliability typically deals with routine, shorter-term events, while resilience focuses on low-probability, high-consequence disruptions. There can also be trade-offs between reliability and resilience, although a more resilient system is generally more reliable.

Resilience Metrics

Resilience metrics are in their nascent stage, and there is no one-size-fits-all resilience measurement. At a high level, resilience metrics can be categorized as either qualitative or quantitative. Qualitative metrics often take the form of attributes describing the characteristics that make a system more resilient (e.g., robustness, resourcefulness, redundancy), and quantitative metrics are typically performance-based (describing how a system performed during a disruptive event) or outcomes-based (describing the consequences of a disruptive event).

To capture resilience as accurately as possible, however, we must apply metrics to a specific scenario and often combine available metrics. Quantitative metrics provide crucial additional detail to qualitative attributes like robustness or redundancy. For example, the available megawatts of spare capacity in a grid system help describe that system's robustness (Watson et al. 2015; Willis and Loa 2015). To help measure the qualitative attribute of response, we can use quantitative metrics—for example, megawatts of curtailable load or number of linemen on call to respond to grid restoration (Willis and Loa 2015).

Resilience metrics can also be combined in other ways. Bhusal et al. (2020) and Cicilio et al. (2021) combined qualitative and

Reliability		Resilience
The ability **to meet the electricity needs** of end-use customers, even when events reduce the amount of available electricity	**Definition**	The ability to **anticipate**, **prepare for**, and **adapt to changing conditions** and **withstand**, **respond to**, and **recover rapidly from disruptions**
Uncertainty associated with fluctuating load and generation, fuel availability, and failure of assets **under normal operating conditions**	**Event Characteristics**	**Low-probability, high-consequence events** that represent black-sky operating conditions and apply stress to a system over a large scale
Seconds to hours	**Outage Duration**	**Days to months**
Concentrated area (e.g., one facility, campus, or neighborhood)	**Spatial Extent**	**Large geographic region** (e.g., states, regions, or islands)
Losses largely limited to **unserved load for a subset of customers**	**Economic Losses**	Losses arising from both **lost load and cascading impacts to the economy** (such as degraded water quality or delivery due to power loss)

Figure 1. Differentiating reliability and resilience

quantitative metrics into two main categories of resilience strategy: operation-based and planning-based. Operation-based resilience strategies implement protection schemes and keep the system operational during and following a disruptive event, while planning-based methods target electrical grid expansion and hardening to withstand predicted disturbances. The exact choice of metric for a resilience analysis will always depend on relevant baseline and intended upgrades.

Because resilience events are characterized as low-probability yet high-consequence, resilience metrics would ideally be expressed in risk-based terms. A risk-based resilience approach considers interactions between the likelihood of an event occurring and the severity of that event's consequences, should it occur.

Risk-Informed Resilience Assessments

Frameworks for quantifying resilience are typically based on three questions: (1) What disruptive events can occur? (2) How likely are they to occur? and (3) What are the associated costs? (National Academies of Sciences, Engineering, and Medicine, 2017). One example framework, called a probabilistic risk assessment, follows the logic that risk equals probability multiplied by consequence, which is a well-established risk assessment methodology commonly used in the aerospace, nuclear, and electricity industries (Stamatelatos and Dezfuli 2011; Fullwood and Hall 1988).

NREL's resilience assessment methodology uses elements of a probabilistic risk assessment. It follows a cyclical process to assess baseline conditions, and both identify and score relevant hazards and vulnerabilities to understand the risks (i.e., consequences). Mitigation strategies are then developed to address the risks most likely to occur or that will have the greatest consequences, as shown in Figure 2. (Anderson et al. 2019).

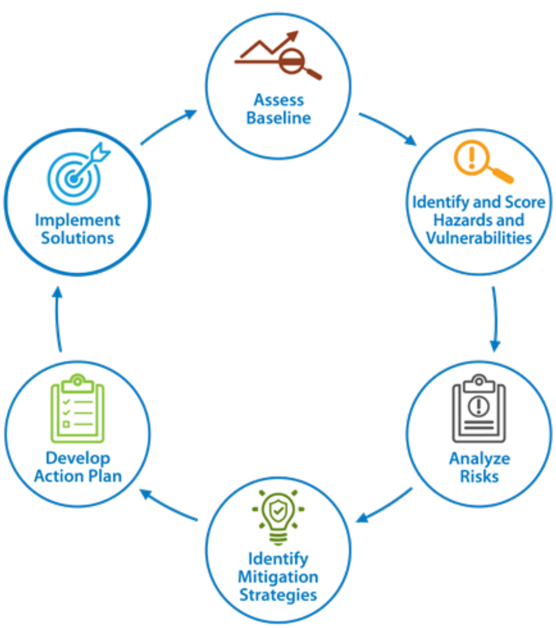

Figure 2. Resilience assessment methodology *NREL 2019*

Resilience Methodologies

The literature review provides a high-level overview of analysis methodologies that could be used to assess current resilience enhancement strategies. The leading options include N plus M redundancy (where N represents the minimum number of independent components needed to operate, and M is the number of redundant components kept available to replace the failure of a component N), network theory, layer of protection analysis, and probabilistic risk assessment. A key shortcoming among these methodologies is their current exclusion of cascading failures, although there are some recent improvements to these considerations.

Several methods for monetizing resilience by assigning a dollar value are surveyed in the literature review. These methods include value of lost load, customer damage functions, cost-benefit analyses, and consequence valuations. The indirect and intangible costs (e.g., loss of life, hospitalizations, loss of economic stability) of disruptive events on communities, however, often makes straightforward valuation difficult.

As stakeholders examine resilience valuation techniques, it is important to understand intended upgrades and specific context for the resilience investment under investigation. Once an analysis methodology is selected, mitigation techniques, approaches, or strategies can be examined that address either one high-risk issue or multiple resilience gaps. The first step is to establish a system baseline in order to estimate the cost of each mitigation against the change in system reliability, resilience, or risk. Mitigation and resilience solutions will depend on the system, aspect of systems, or geographic location being assessed and should be identified using subject matter experts (e.g., electrical engineers, grid operators, emergency managers, community leaders) and validated for feasibility and priority by stakeholders. More information on the full resilience planning and implementation process is included in NREL's *Resilience Roadmap* (Hotchkiss et al. 2019).

When NREL researchers interviewed New York State stakeholders to gain their perspectives on resilience, many expressed an interest in financial valuation strategies. For example, the financial consequences of a power disruption could include the value of lost services or goods due to lost supply of power. To use the value of resilience in practice, however, organizations need to quantify the baseline resilience of their existing systems and then track impacts from resilience investments against this baseline. One stakeholder suggested measuring lost tax revenue and New York State gross domestic product attributed to power disruptions. Another interviewee was interested in measuring the aggregated cost of repairing a vulnerable system over decades of maintenance compared to an upfront investment in storm hardening. Several interviewees raised challenges around measuring the costs and benefits of resilience, including nonfinancial benefits, such as social and health advantages, and misalignment between who pays and who benefits. As a result of this emphasis on the valuation of resilience, the second half of the literature review focuses specifically on value and monetization strategies. Likewise, *Applications of Measuring and Valuing Resilience in Energy Systems,* the third publication in the series, reviews several strategies available to New York State stakeholders.

Calculations and Tools for Valuing Resilience

In *Applications of Measuring and Valuing Resilience in Energy Systems,*, the authors present various approaches to calculating the value of resilience. With finite resources and time, comparing investment options using these calculations can help identify the highest-benefit investment for a given scenario. Resilience valuation tools can perform these calculations and other types of analysis that would otherwise be cost-prohibitive. Improving these modeling tools and providing technical support will further reduce the burden of exploring mitigation options at a site—particularly for under-resourced communities exploring resilience upgrades.

The *Applications* report summarizes the resilience valuation tools currently available and describes their uses and limitations. A nonexhaustive list includes offerings from diverse organizations such as the City Resilience Index from the Rockefeller Foundation,[2] the National Risk Index from the Federal Emergency Management Agency (FEMA),[3] and the Customer Damage Function Calculator[4] and Technical Resilience Navigator[5] of the Federal Energy Management Program.

For a resilience tool to produce accurate results, it needs to be methodologically sound, use accurate data that reflects on-the-ground realities, and be employed by a trained user to operate the tool correctly and effectively. The magnitude of data and the level of expertise required often present major barriers to conducting resilience analyses. Determining sensible defaults, integrating relevant datasets, and setting up tools in a user-friendly manner can reduce user burden while generating a robust result.

Understanding the Value of Resilience

Resilience Investments and Valuation Potential

How we value resilience depends on the type of resilience investment system planners intend to implement. Types of resilience investments range from system hardening measures to strategies aimed at improving recovery time and processes.

System hardening and backup power systems are some of the most traditional resilience investments. Research has shown that 90% of power outages originate in the distribution system, so hardening is an integral first step in helping create distribution systems with resilient loads (Bai et al. 2017). Backup power systems are a fundamental resilience investment, which is why resilience valuation is often focused in this area.

Resilience is as much a characteristic that applies to processes as it does to infrastructure, so strategy and operations are essential topics for further valuation research. A well-designed system can fail if it is not operated in a resilient manner. The literature also points to how demand response and flexibility programs can strengthen power system resilience. Demand response methods are an efficient tool for dealing with the uncertainty of distributed generation and improving overall system resilience (Kahnamouei et al. 2021; Khalili, Bidram, and Reno 2020).

New York Case Studies

Energy sector stakeholders—from customers to utilities to regulators—are already making resilience investments in response to current trends and a changing future. Through the NYSERDA–NREL collaboration, resilience experts reviewed four case studies to understand how decision makers are applying a resilience framework in their cost-benefit analyses.

The four cases studies covered in depth in *Applications of Measuring and Valuing Resilience in Energy Systems* are: home resilience to heat waves, electric vehicles and grid resilience, distribution system hardening to high heat risks, and distributed energy microgrids.

The heat risk case study, focused on Consolidated Edison (ConEd), describes the utility's use of the Network Reliability Index (NRI) and the Transtmission Probabilistic Reliability Assessment for understanding the likelihood and impacts of longer-term, more severe outages. With future climate change impacts and higher likelihood of high-heat events, ConEd is expecting to see many more occurrences of the NRI metrics being above 1.0 per unit,

[2] https://www.rockefellerfoundation.org/report/city-resilience-index-2/
[3] https://hazards.fema.gov/nri/
[4] https://cdfc.nrel.gov/
[5] https://trn.pnnl.gov/

their threshold for the likelihood of feeder band failure. This means a greater intervention in the electrical grid will be required to address potential risk of feeder failure.

In terms of a resilience assessment, the hazard is an extreme heat event. ConEd delineated scenarios of potential future risks of the event in the timeframes of 2030, 2050, and 2080 using different climate models and found an increased occurrence frequency of extreme heat events. The impact is a greater number of networks exceeding the NRI per unit threshold and stressing the grid, and the consequence is a higher likelihood of grid failure.

The NRI metrics help ConEd identify vulnerable sectors of the electrical grid network that warrant intervention to improve resilience. The Transmission Probabilistic Reliability Assessment provides a process for prioritizing investments of certain components of the sub-transmission system.

Consequence Metrics

Performance-based metrics, which are measured in physical units such as megawatt hours, do not reflect consequences until they are translated into outcomes-based metrics, which are generally measured in economic units (e.g., U.S. dollars) or health-related units (e.g., mortality). Currency is the most common unit of measurement for consequences because it is relatively straightforward to assign monetary values to impacts like damage to buildings. However, it is more difficult to assign a monetary value to impacts like increased health risks.

For example, an ability to measure resilience benefits in dollars is essential because investment costs are also measured in dollars—monetizing resilience thus facilitates cost-benefit analyses. One approach is to quantify the value of a backup system's resilience as the difference in outage costs with and without that system (Anderson et al. 2021). This quantification framework allows for incorporating duration-dependent customer damage functions into grid- and campus-scale planning and operations. Power outage studies often use a fixed value of lost load (VoLL), measured in dollars per megawatt-hour for load not served. FEMA calculates a VoLL for hospitals based on the average cost of transporting and treating patients at the nearest hospital. Using this VoLL in combination with assumptions on outage probabilities, FEMA has estimated the benefits of generator hazard mitigation projects in hospitals at $6.95 per building gross square foot in urban areas and $12.62 in rural areas. Electric utilities also use VoLL to quantify the monetary losses associated with customer outages.

It is crucial to account for non-linearities in cost with events that are widespread, high-impact, and occur over extended durations, although these costs are more complicated to calculate. The FEMA methodology used above produces values that are linear with respect to MWh of load protected. An example of non-linear impact would be replacing an entire roof once more than 5% of the roof sustains damage (FEMA 2021). Some damage thresholds such as food spoilage, negative health impacts, or inability to go to work have non-linear increasing consequences over time. Meanwhile, mitigation strategies like bringing in backup generators can reduce consequences over time.

Although power outages affect everyone, they severely impact those whose access to electricity is so critical that any interruption can be fatal, pose health risks, or cause permanent damage. Overburdened and underserved communities were noted by New York State stakeholders interviewed as being more vulnerable, given fewer resources to prepare for and cope with extreme weather and climate events. Mitigating risk for these populations was a strong area of concern expressed by several interviewees. The literature review includes a wide range of potential social vulnerability indicators to explore. For example, Zuzak, Goodenough, and Stanton (2023) use the Centers for Disease Control and Prevention's Social Vulnerability Index, while Dugan, Byers, and Mohagheghi (2023) propose less traditional dimensions of vulnerability related to health, preparedness, and evacuation capabilities.

Since the impacts of disruptive events are site-specific, industry-specific, and often business-specific, there is no single consequence metric applicable to all circumstances. Instead it is important to adopt a multilayered approach.

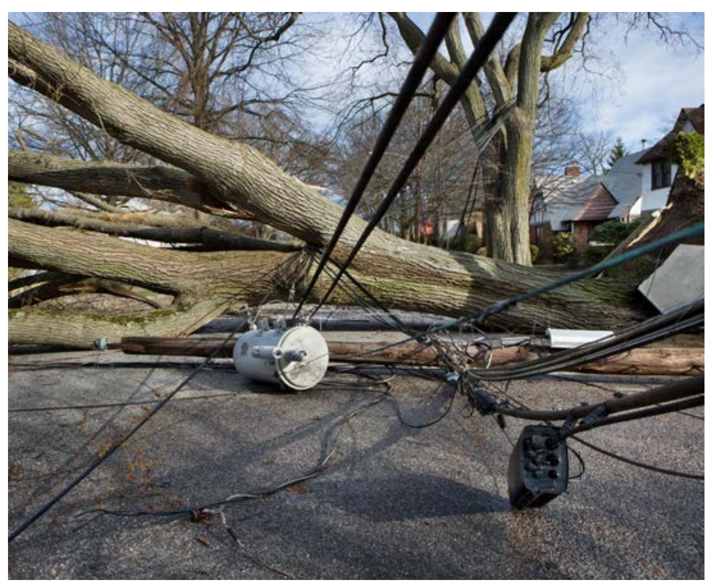

Figure 3. Consequence metrics help account for the impact of disruptions beyond physical damage. *Photo from Getty Images 461097289*

Opportunities for New York State

The research team identified potential opportunities to incorporate resilience planning and to address challenges raised in the stakeholder interviews.

Increase Understanding of Changing Conditions: One energy sector representative explained that historical trends can no longer inform preparedness because new hazards are arising that have not previously been encountered. In this way, resilience must not only reflect lessons learned from the past but also, importantly, anticipate what is coming. Another state agency representative noted that "simply going back to the way we were with additional ability to withstand hazards may no longer be tenable." Environmental justice advocates were particularly reticent to adopt the term "resilience" if resilience is largely accepted to mean maintaining the status quo.

Assist Statewide Coordination and Standards Development: Some stakeholders noted that New York State does not currently have an adaptation plan or statewide standards or codes addressing resilience, although certain municipalities or agencies might operate with their own guidelines. A coordinated approach to statewide standards would help normalize best practices and expectations for all. There was also an acknowledgement that it will be essential to establish standards flexible for both urban and rural communities.

Develop Data Assets to Benefit Investment Decisions: Uncertainties around changing conditions and mitigating solutions often contribute to a reluctance to increase resilience investments. Developing and sharing quality data and success stories would help planners prepare for natural hazards and human-caused events, anticipate long-term trends, and make measurable resilience investments. 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.

Operationalize Resilience Valuation: By properly measuring the impacts of resilience, or lack of resilience investments, energy systems stakeholders can weigh the true value of resilience-focused investments and whether these investments result in the intended benefit. When different agencies follow different resilience frameworks, it is difficult to set common baselines or develop incentives and structures to mitigate risk across interdependent infrastructure. Adopting some common metrics and frameworks, such as those described in the literature review, will facilitate innovative solutions to anticipate, prepare for, and recover quickly from climate-related impacts on the power system. It is also important for standardized approaches to consider flexibility so that these standards can apply to diverse domains and sectors.

Conclusion

Resilience investments can reduce the likelihood, impact, and consequences of disruptive events but also increase capital and operating costs. Investments—whether in physical assets, upgrades, or new operational approaches—are purchased and maintained in dollars, so resilience benefits must also be monetized. The available tools and frameworks can help account for financial and nonfinancial costs or measure targeted resilience benefits. Understanding the methods for valuing resilience in the current research positions New York State to strategically prepare for a more hazardous future.

Other future research themes that emerged from the literature review included: (1) more focus on how human activities tie into both disruptive events and the response to those events (i.e., how human behaviors can increase or decrease a system's risk, vulnerability, or ability to withstand acute shocks), (2) better understanding the linkages between resilience and energy efficiency and how the two objectives can support one another, and (3) how to methodologically keep up with the pace of climate change and associated rapid shifts in disruptive event likelihoods. As Roege et al. (2014) pointed out, the human element of resilience also includes the need for technical experts to supplement data where it is impossible to obtain physical measurements. The human element of resilience acknowledges both the positive and negative ways in which people can impact the ability of a system to prepare for and respond to disruptive events.

A risk-based resilience framework considers interactions between the likelihood of an event occurring and the severity of that event's consequences, should it occur. NYSERDA engaged resilience researchers at NREL to understand the leading options for cost-benefit analyses that will serve energy sector stakeholders as they craft a pathway toward instituting common resilience goals and practices across state agencies. Traditional economic analysis techniques do not provide organizations with insight into mitigation solutions best suited for resilience events that are low probability but can result in severe consequences like longer outage durations, larger impacted areas, and cascading impacts across infrastructure.

As described in NREL's report on *Applications of Measuring and Valuing Resilience in Energy Systems*, New York State stakeholders are hardening the grid in response to an increased rate of heat waves and floods, adding microgrids with renewable energy generation, deriving grid flexibility from electric vehicles, and cutting emissions through energy efficiency solutions, heat pumps, and retrofitted homes. The agencies surveyed in this project reported common obstacles in not having the right data or tools to identify the potential consequences of a power disruption, to quantify the financial and nonofficial losses of an outage, and to measure whether a resilience investment results in the intended benefit. Stakeholders were particularly interested in developing resilience planning with community input and in benefiting disadvantaged communities that bear a greater burden in the aftermath of disruptive events.

The resources developed through the NREL–NYSERDA collaboration can offer valuable insights as New York State stakeholders build consensus around a resilience approach that matches their needs and interests. By implementing the resilience planning process and approaches provided in the different resources, regional stakeholders can work together to better anticipate and prepare for disruptive events and to improve their capacity to recover safely, securely, and promptly.

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