Increasing Manhattan's Energy Resilience through Storm Hardening

Consolidated Edison's East 13th Street Substation Storm Hardening Project, New York

JUNE 2024

BERKELEY LAB

GRID DEPLOYMENT OFFICE

Disclaimer

Authors

Alan Sanstad, Lawrence Berkeley National Laboratory (LBNL)

Nichole Hanus, LBNL

Sunhee Baik, LBNL

Peter Larsen, LBNL

Acknowledgments

This report is provided as an educational resource. It was prepared by Lawrence Berkeley National Laboratory for the U.S. Department of Energy Grid Deployment Office. We are grateful for the ongoing support from U.S. Department of Energy (DOE) staff including David Parsons, Michele Zemplenyi, and Angelena Bohman. We would like to thank the following individuals for their constructive feedback on earlier drafts of this manuscript: Mike Ragona (Con Edison), Kirsten Verclas (National Association of State Energy Officials), and Olivia Lee (Grid Deployment Office). Finally, we thank Joe Eto (Berkeley Lab) for his internal review. All errors and omissions are the responsibility of the authors. Any views expressed in this document are those of the authors and do not necessarily represent those of their employers or the stakeholders profiled in this case study.

Summary

- In October 2012, Tropical Storm Sandy caused unprecedented damage to the electrical infrastructure of Consolidated Edison of New York, Inc. (Con Edison), resulting in loss of power to more than two million of the utility's customers in and around New York City. While power was restored to 50% of affected customers within three days and 90% within eight days, full restoration took about two weeks.
- At the Battery in Lower Manhattan, Sandy caused a record storm surge, resulting in flooding and failure of Con Edison's East 13th Street Substation. This failure caused about 220,000 customers to lose power in lower Manhattan.
- In Sandy's aftermath, Con Edison began developing a comprehensive, long-term storm hardening plan under the auspices of the New York Public Service Commission (NYPSC), with the goal of reducing the utility's vulnerability to future extreme weather. The NYSPC formed a special multi-stakeholder "Storm Hardening and Resiliency Collaborative" to work with the utility on developing new methods and procedures for large-scale storm hardening.
- Working over three years in parallel to standard rate case proceedings, this Collaborative produced, among other things, a Risk Assessment and Prioritization model and a Cost-Benefit model that was adopted by Con Edison storm hardening planning. Among other features, this approach used avoided customer interruption cost information from the Lawrence Berkeley National Laboratory's Interruption Cost Estimate (ICE) Calculator.
- Using these models, Con Edison and the Collaborative determined that hardening of the East 13th Street Substation was the highest priority resilience project among more than 100 developed by the utility.
- A hallmark of the project was that the Substation was re-engineered to a higher standard of flood risk protection than Con Edison had previously used: The new standard was the Federal Emergency Management Agency's Base Flood Elevation plus an additional three feet.
- Con Edison began the project in 2013, with an estimated duration of three years. Due to various delays, it took over six years, and was completed in 2019 at a final cost of $188 million.
- Although the activities described in this case study occurred several years ago, they are relevant to current resilience planning efforts, inasmuch as certain underlying considerations have not changed in determining how this type of planning should be conducted:
    - The case study highlights the importance of institutional factors in determining how resilience investments are developed, evaluated, and decided upon, and how

complex technical issues in electric utility resilience planning can be grappled with in ways not readily available in the adversarial[1] utility rate case context.

- Going forward, the key engineering performance test of the East 13th Street project will be whether the Substation withstands the storm surge level for which it was designed. The project is an example of how resilience investments can be viewed as insurance against a "low-probability/high-consequence" event.
- It also illustrates the importance of adapting regulatory processes and utility technical methods to address the risks of events of this type involving extreme weather, including those exacerbated by climate change.
- The formation of the Storm Hardening and Resiliency Collaborative was an important institutional innovation enabling Con Edison to substantially expand and improve its storm hardening planning methods and practices.

Figure 1. **Left**, Con Edison service territory map;[2] **Right**, East 13th Street Substation complex[3]

[1] While evocative, the term "adversarial" is used here in a technical sense, in the same way that other types of legal or regulatory systems might be described as, e.g., "administrative." An adversarial process is "where each side vies for the neutral [party's] favor." Peskoe, A. 2017. *Alternative Dispute Resolution at Public Utility Commissions*. May 24. https://eelp.law.harvard.edu/wp-content/uploads/Alternative-Dispute-Resolution-at-PUCs-Harvard-Environmental-Policy-Initiative.pdf

[2] Selectra. 2023. Callmepower.com. https://callmepower.com/ny/utility/conedison

[3] Consolidated Edison Company of New York Inc. 2013. *Substation Hardening. Presentation*; Appendix G in Consolidated Edison Company of New York Inc. (Con Edison). 2013. *Storm Hardening and Resiliency Collaborative Report*. December 4. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={E6D76530-61DB-4A71-AFE2-17737A49D124}

Table 1. Con Edison case study summary information

Threat	High storm surge caused by extreme weather
Location	New York City, New York
Reliability/resilience project	Hardening substation at East 13th Street against flooding, including: • Installing internal removable flood barriers • Sealing penetrations in control room and elsewhere • Elevating control cabinets in pumphouses and cooling plants • Elevating control room, additional control pumphouse and cooling plant cabinets, and diesel generators above the designated flood elevation • Relocating relay cabinets to near transformers using micro-processor relays and fiber optic connections • Isolating critical operational controls and circuits in transformer control cabinets • Upgrading and replacing transformers
Key stakeholders	• Consolidated Edison • New York Public Service Commission • Storm Hardening and Resiliency Collaborative • Consolidated Edison customers, NGOs, private companies, trade associations
Cost	$188 million
Metrics used to assess investment	• Likelihood of reducing power interruption risk due to flooding during extreme weather • Estimated project cost • Benefits: Reduced risks of power interruption impacts on customers (in terms of value of lost load) and damage to critical infrastructure
Evaluation framework	• Storm hardening Risk assessment and Prioritization Model • Cost-Benefit Model • Expert judgement
Timeline (concept to completion)	2013-2019

Background

Utility and regulator

Consolidated Edison of New York, Inc. (Con Edison) is a regulated, investor-owned utility providing electricity, natural gas, and steam heat to New York City and Westchester County. Con Edison is regulated by the New York Public Service Commission (NYPSC), which is authorized by state law to oversee the production, sale, and distribution of electricity, natural gas, and steam throughout New York State, and to regulate rates for these energy services.

Precipitating event

Tropical Storm Sandy made landfall near Atlantic City, New Jersey, on October 29, 2012. The wide extent of the storm's high winds, an extremely high tide, and the angle of its onshore arrival made Sandy unusually destructive, leading to unprecedented storm surges and flooding. Twenty percent (20%) of New York City's land area was flooded, exceeding the "100-year" floodplain boundaries designated by Federal Emergency Management Agency (FEMA) maps by nearly 50%. More than two million Con Edison customers lost power, including two-thirds of those served by overhead systems affected by wind and tree damage, and some 80,000 public housing residents. While power was restored to 50% of affected customers within three days and 90% within eight days, full restoration took about fourteen days.[4,5]

At the Battery in Lower Manhattan, Sandy caused a record storm surge, resulting in flooding and failure of Con Edison's East 13th Street Substation. This failure caused about 220,000 customers to lose power in lower Manhattan.

Regulator and Utility Processes and Responses

Con Edison's initial post-Sandy storm hardening proposal

In the aftermath of Storm Sandy, Con Edison proposed a portfolio of new storm hardening projects in a general rate case filing in January 2013. An initial set of these were completed by June of that year. Concurrently, however, in the rate case context, some stakeholders argued that the hardening plan was too ambitious and expensive, while others thought that the utility should develop and implement a bigger, "comprehensive and longer-term approach to [storm hardening] investment, much of which would be in infrastructure expected to last for most of this century." Moreover, stakeholders noted that "changing climate conditions are likely to affect Con Edison's ability to provide reliable service without major disruptions."[6]

A key point of dispute during the proceedings was the criterion Con Edison should use to evaluate hardening against flooding risks. In the aftermath of Sandy, the utility increased the stringency of its flood risk criterion. However, during rate case hearings following the January filing, several parties including state government agencies and non-governmental organizations argued that Con Edison's criterion was inadequate and that a higher threshold should be required.

---

[4] New York City. 2013. *A Stronger, More Resilient New York*. Report of the Special Initiative for Rebuilding and Resiliency, City of New York, June. https://toolkit.climate.gov/reports/stronger-more-resilient-new-york

[5] Consolidated Edison. 2013. *Report on Preparation and System Restoration Performance – [Hurricane] Sandy, October 29 through November 12, 2012.* Report submitted to the New York Public Service Commission, January 11. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7B2D1BF3D9-95DC-4C2D-9F24-6DE65926275B%7D

[6] State of New York Public Service Commission (NYPSC). 2014. *Order Approving Electric, Gas and Steam Rate Plans in Accord with Joint Proposal.* February 21. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={1714A09D-088F-4343-BF91-8DEA3685A614}

Resiliency Collaborative and revised recommendations

In May 2013, NYPSC staff recommended that "in light of the [flood criterion and other] significant issues involved, [Con Edison] should consider convening a collaborative of interested parties." The NYPSC suggested that the collaborative "consider, among other things, what the design standard should be for various aspects of the Company's system and if and how climate change impacts should be incorporated…[and] the best way to build flexibility into its designs."[7]

In the summer of 2013, in the context of the rate case, the NYPSC ordered the formation of a Storm Hardening and Resiliency Collaborative, which would work in parallel to the rate case proceedings.[8,9] Its tasks included consideration of:[10]

- Design standards
- Approach to risk assessment and cost-benefit analysis

The Resiliency Collaborative is an example of an Alternative Dispute Resolution (ADR)[11], which is defined as any new process or practice that is adopted by a public utility commission that "offers less formal means for settling conflicts, sharing information, and reaching a consensus on public policy." In general, ADRs are found to "reduce administrative burdens, obtain higher quality information, and engage regulated entities and stakeholders in the decision-making process."

The Collaborative met from June through October 2013, and issued its initial report in December.[12] Among other things, the Collaborative's report recommended a more stringent flood risk criterion (see "Project details…" section below). During the same period, Con Edison and other stakeholders developed a detailed Joint Proposal on a revised version of the electric, gas, and steam plans filed in its rate case. This Joint Proposal included storm hardening proposals reflecting the Resiliency Collaborative's recommendations; it was approved by the NYPSC in February 2014.

---

[7] NYPSC. 2013. *Prepared Testimony of Staff Policy Panel, in Case 13-E-0030*. May 31. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={E4A4388E-8F67-48B7-85B3-6FA9123F93E6}

[8] Collaborative participants were self-selected. These included interested parties who'd been involved in the 2013 rate case and submitted testimony about such issues as the flood-risk standard.

[9] Collaborative participants were Con Edison, New York State Department of Public Service staff and the New York State Office of the Attorney General, Department of State Utility Intervention unit, and Department of Environmental Conservation, City of New York, County of Westchester, Environmental Defense Fund, Pace University Energy and Climate Center, Columbia University Center for Climate Change Law, New York University School of Law, New York Energy Consumers Council, Consumer Power Advocates, Public Utility Law Project, Utility Workers Union of America Local 1-2, Energy Initiative Group LLC, and the Public Utility Law Practice.

[10] NYPSC. 2013. *Letter, to parties regarding Storm Hardening/Resiliency Collaborative in re Cases 13-E-0030, et al., Consolidated Edison Rate Cases.* July 2.

[11] Peskoe, A. 2017. *Alternative Dispute Resolution at Public Utility Commissions*. May 24. https://eelp.law.harvard.edu/wp-content/uploads/Alternative-Dispute-Resolution-at-PUCs-Harvard-Environmental-Policy-Initiative.pdf

[12] Consolidated Edison. 2013. *Storm Hardening and Resiliency Collaborative Report.* December 4. https://documents.dps.ny.gov/public/MatterManagement/CaseMaster.aspx?MatterCaseNo=13-e-0030

Over the next three years, the Collaborative continued its work and issued two additional reports, in November 2014 and September 2015, respectively.[13,14] Concurrently, Con Edison continued to develop, refine, and implement its storm hardening plan. The NYPSC's approval of the reports was separate from the annual assessment of proposed projects and costs during further adversarial rate case proceedings. Project details were reviewed and argued by NYPSC staff, other state government representatives, Con Edison, and other stakeholders and adjudicated by the Commission.

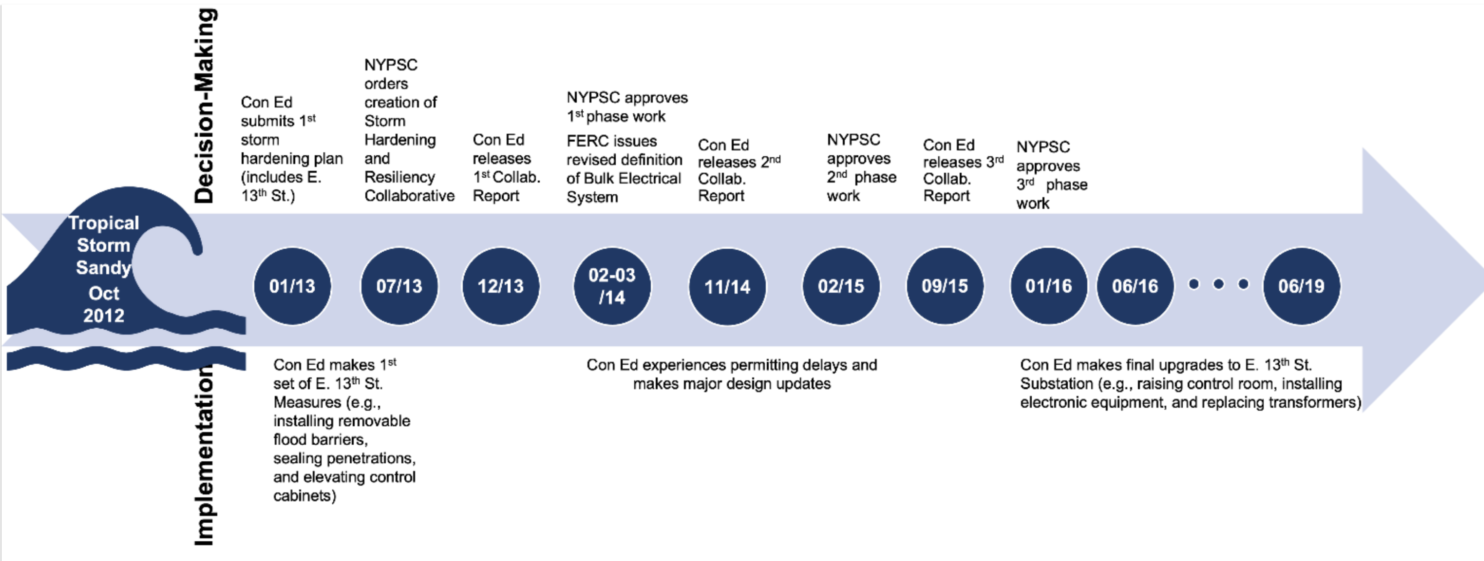

Figure 2. Timeline

Project Prioritization and Valuation

Analytical framework and modeling tools

During its first two years, the Resiliency Collaborative developed and proposed a "Risk Assessment and Prioritization" model and a cost-benefit model to quantify, rank, and value the reduction in risk associated with a set of potential storm hardening projects related to the Con Edison's transmission, substation, underground network, and overhead distribution systems. At a high-level, the analytical procedure was to:

- **Probability:** Estimate the likelihood of significant storms and of resulting wind and/or flood damage to specific Con Edison infrastructure
- **Consequence:** Characterize the physical and economic impacts of such damage

---

[13] Consolidated Edison. 2014. *Amended Storm Hardening and Resiliency Collaborative Phase Two Report.* November 14. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={2137E970-DC34-4630-839C-DD2F08357F2C}

[14] Consolidated Edison. 2015. *Storm Hardening and Resiliency Collaborative Phase Three Report.* September 1. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={0B9E9CB9-0E0E-434B-91F0-82A58FD77A37}

- **Priority**: Run each potential storm hardening project through the Risk Assessment and Prioritization Model and the Cost-Benefit Model to rank them according to (1) risk reduction, (2) cost, and (3) benefit (complemented by expert judgement)

Table 2 in the next section shows the key model inputs that were used to implement this procedure.

Risk and cost-benefit analysis

For substations including East 13th Street, risk reduction from storm hardening projects was calculated in terms of decreased likelihood of the facility failing due to flooding and the resultant decrease in customer loss of power. Using the models described above and the inputs presented in Table 2, these outcomes were computed for residential and commercial customers, as well as for certain customer facilities including critical infrastructure. Benefits of the projects were estimated in terms of reduced customer impacts monetized using avoided cost estimates based on Berkeley Lab research. These benefits were compared to anticipated costs of each project in terms of differences and ratios. In turn, Con Edison ranked these investments in terms of cost-benefit ratios and differences, as well as in terms of risk-reduction-per-dollar-of investment. Con Edison assessed the cost-benefit ratios and risk-reduction-per-dollar-of investment.

In 2013-2014, Con Edison assessed its complete list of ~100 proposed storm hardening projects in this way and categorized them into three "risk groups" in descending order of priority and aggregate cost (see Figure 3 below). This analysis became the basis for Con Edison's comprehensive storm hardening planning and for its proposals to the NYPSC in rate cases.

Table 2. Con Edison modeling details

Models	Key inputs
Risk Assessment and Prioritization Model[15]	• Location-based flood probabilities provided by proprietary New York City inundation models • Wind damage probabilities derived from historical wind gust frequency distributions • Costs of storm hardening measures • Estimated power interruption durations with and without hardening measures

[15] From Appendix G in Con Ed. 2013. Storm Hardening and Resiliency Collaborative Report. December 4. https://documents.dps.ny.gov/public/MatterManagement/CaseMaster.aspx?MatterCaseNo=13-e-0030 and Appendix B in Con Ed. 2014. *Amended Storm Hardening and Resiliency Collaborative Phase Two Report.* November 14. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={2137E970-DC34-4630-839C-DD2F08357F2C}

Cost-Benefit Model	• Costs of storm hardening measures (from the Risk Assessment and Prioritization Model) • Estimated power interruption durations with and without hardening measures (from the Risk Assessment and Prioritization Model) • Extrapolated avoided cost (i.e., value of lost load) estimates based on Lawrence Berkeley National Laboratory analysis for the ICE Calculator project.[16,17,18]

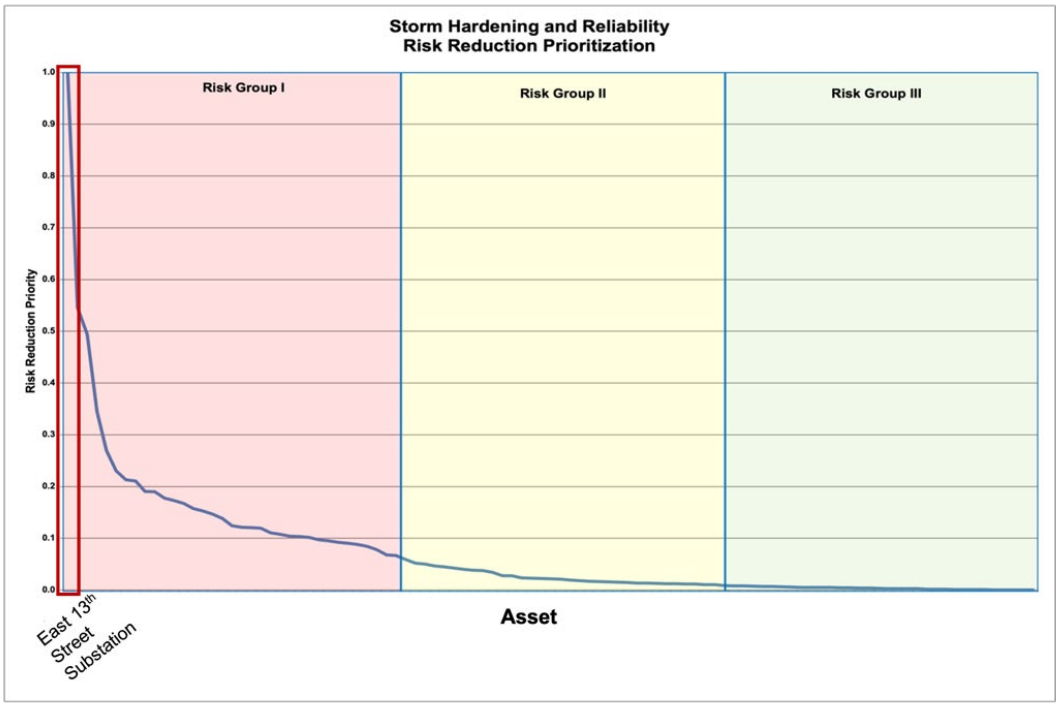

Figure 3. Illustration of Con Edison risk analysis

[16] Cost concepts for electricity resilience valuation are discussed in Sanstad, A. H., et al. 2023. "Electric utility valuations of investments to reduce the risks of long-duration, widespread power interruptions, part I: Background." *Sustainable and Resilient Infrastructure* **8**, Sup. Issue 1, *Adaptive Pathways for Resilient Infrastructure:* 311-322. https://doi.org/10.1080/23789689.2022.2148450

[17] Sullivan, Michael J., and Matthew Mercurio, Josh Schellenberg. 2009. *Estimated Value of Service Reliability for Electric Utility Customers in the United States.* Lawrence Berkeley National Laboratory Report LBNL-2132E, June. https://emp.lbl.gov/publications/estimated-value-service-reliability

[18] At the time, the ICE Calculator estimated costs of power interruptions lasting up to 8 hours. However, Con Edison engaged O'Neill Management Consulting, which extrapolated the values of lost load for outage durations up to 290 hours (12 days). There was no theoretical or empirical basis for this extrapolation. In addition to being focused only on short-run outages, the customer power interruption cost surveys on which the ICE Calculator is based estimate only direct costs to electricity customers. However, widespread, long-duration disruptions such as those caused by Sandy also have indirect effects, as the consequences of curtailing productive activity propagate across the regional economy. These may substantially exceed the direct effects but are not captured by the Calculator. Thus, Con Edison's procedure may have resulted in substantial underestimating of the potential values of resilience investments. (For a discussion of different types of power interruption economic impacts and their estimation, see Sanstad et al., 2023, *ibid.* Footnote 14.)

Project Details: East 13th Street Substation

Con Edison and the Collaborative ranked the East 13th Street Substation as the highest priority project among those it analyzed. As described above, once developed by Con Edison and the Collaborative, the details of the proposed project, and the required expenditures, were evaluated during rate case proceedings on a semi-annual basis, and approved – in some cases with modifications – by the NYPSC.

Following Tropical Storm Sandy, Con Edison adopted a substation flood protection standard of the highest of (1) the observed water level during Sandy, (2) the 2010 Category 1 Hurricane levels as predicted by National Weather Service simulation models, and (3) the 2007 Federal Emergency Management Agency (FEMA) flood maps plus two feet. By June 2013, Con Edison completed several storm hardening measures at the Substation:

- Installed removable flood barriers in relay houses and around diesel generators and transformers
- Sealed penetrations in the control room, at conduits and cabinets around switches
- Elevated control cabinets in pumphouses and cooling plants

As described above, a key issue informing the design and estimated costs of Con Edison resilience projects, including the East 13th Street Substation project, was the appropriate level of flood risk to prepare for – that is, the maximum storm surge level against which to protect facilities. During rate case hearings in the first half of 2013, a number of parties argued for a more stringent "FEMA plus five" feet standard.

In 2013 meetings of the Resiliency Collaborative, most participants agreed that the standard would be increased[19] to FEMA 100-year floodplain as gauged by updated FEMA maps (Base Flood Elevation), plus three feet.[20] It was determined that the additional cost of meeting a FEMA plus five feet standard was too high for the incremental risk reduction that might be gained at East 13th Street and three other substations that had been most affected by Sandy. The Collaborative recommended the FEMA plus three feet standard, which was approved by the NYPSC and adopted by Con Edison.

During 2014-2015, Con Edison also encountered delays in obtaining building permits, higher-than-estimated costs for subcontracts, and the necessity of updating and refining detailed engineering designs as the work proceeded. In addition, the changes at the East 13th Street Substation required upgrading several other substations electrically tied to it in order to meet resilience goals at the latter. Moreover, some of the work had to be accomplished during scheduled feeder outages, which occurred over several years.

---

[19] However, the East 13th Street control room elevation described further down in the text met a standard of FEMA plus nearly seven feet.

[20] Consolidated Edison. 2013. *Storm Hardening and Resiliency Collaborative Report*. December 4. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={E6D76530-61DB-4A71-AFE2-17737A49D124}

The design and engineering changes for the flood standard contributed to increasing the projected cost of hardening the Substation from an initial estimate of $105 million to a revised $121 million.[21] The further delays, additional subcontractor costs, engineering changes, etc., resulted in further project cost increases, with the final total cost tallied at $188 million. These obstacles also extended the project's duration, from a planned completion in 2016 to actual completion in 2019.

During 2016-2019, Con Edison made the following modifications to the East 13th Street Substation:

- Elevated the control room, additional control pumphouse and cooling plant cabinets, and diesel generators above the designated flood elevation
- Relocated relay cabinets to near transformers using micro-processor relays and fiber optic connections
- Isolated critical operational controls and circuits in transformer control cabinets
- Upgraded and replaced transformers

The East 13th Street Substation storm hardening project was completed in 2019, three years later than its original schedule. The engineering performance of a project of this type is gauged by its success in preventing flood damage resulting from storm surges. Since Tropical Storm Sandy, the most severe weather event affecting the Con Edison service territory was Hurricane Isaias in August 2021. This storm caused minimal storm surges in Manhattan and, therefore, did not test the hardening implemented at the East 13th Street Substation. Going forward, the key engineering test of the project will be whether the Substation withstands the storm surge level for which it was designed, should it occur.

Lessons Learned

This case study highlights the importance of institutional factors in determining how resilience investments are developed, assessed, and decided upon.[22] Most utility reliability and resilience investments are developed, proposed, and adjudicated in the context of general rates cases, which are typically adversarial proceedings. These are not always well-suited to addressing novel, complex technical problems such as those exacerbated by climate change. In particular, the case illustrates the need to adapt regulatory processes to grapple with "low-probability/high-consequence" events that lead to widespread, long-duration power interruptions. The formation of the Collaborative was an important institutional innovation enabling Con Edison to substantially expand and improve its storm hardening planning methods and practices.

---

[21] Also contributing to the cost increase was a March 2014 the Federal Energy Regulatory Commission revision of the definition of "Bulk Electrical System," which resulted in new requirements for East 13th Street's 138kV transmission facilities.

[22] This topic is further discussed in Leibowicz, B. D., et al. 2023. "Electric utility valuations of investments to reduce the risks of long-duration, widespread power interruptions, part II: Case studies." *Sustainable and Resilient Infrastructure* **8**, Sup. Issue 1: *Adaptive Pathways for Resilient Infrastructure.* https://www.tandfonline.com/doi/full/10.1080/23789689.2022.2138163

Appendix

Con Edison storm hardening Risk Assessment and Prioritization[23,24]

Con Edison defined risk in terms of:

- P: the population (number of customers) affected by an interruption
- D: outage duration
- I: the event impact in terms of event customer hours, $I = P \times D$
- p: the probability of flood or wind damage to a Con Edison infrastructure asset or facility

The risk (R) associated with an outage was:

- $R = p \times I$, expected event customer hours

The details of how this formula was applied varied among asset types (substations, overhead, transmission). A key difference was how duration (D) entered the calculations. For overhead and transmission assets, storm hardening measures were assumed to reduce D. For substations such as East 13th Street, it was instead assumed that facility failure due to flooding would cause a 96-hour outage, and the effect of hardening measures was to reduce the likelihood of this occurring – i.e., reduce the likelihood of a 96-hour outage (as opposed to reducing the duration). (The reason for this specific duration was not documented.) The steps in estimating risk reductions were as follows:

1. Assume asset life of 20 years
2. Estimate the 20-year probability of flooding exceeding the asset's i) existing design, and ii) the proposed design incorporating storm hardening
3. Calculate the impact of a 96-hour power interruption in terms of I (note: given the assumption described above, this was unchanged by the prospective storm hardening measure)
    a. Impacts for residential, commercial, and total populations (their sum) were estimated directly, i.e., $I = P \times D$
    b. For residential high-rise buildings, hospitals and public health facilities, critical infrastructure, and public safety facilities served by a particular substation (such as East 13th Street), Con Edison calculated "infrastructure population equivalents" using a formula the sources/justification of which were not

---

[23] Consolidated Edison. 2013. Storm Hardening and Resiliency Collaborative Report. December 4. https://documents.dps.ny.gov/public/MatterManagement/CaseMaster.aspx?MatterCaseNo=13-e-0030

[24] Consolidated Edison. 2014. *Appendix R - Amended Storm Hardening and Resiliency Collaborative Phase Two Report.* November 14. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={2137E970-DC34-4630-839C-DD2F08357F2C}

documented. (The formula converted numbers-of-facilities of each type into these equivalents.) The formula $I = P \times D$ was then applied to these equivalents.

4. The sum of residential and commercial customer population, and total infrastructure equivalents (summed across the facility types just mentioned), times 96 hours, were multiplied by the probability of flooding failure before and after the storm hardening measure. The expected risk reduction from the measure was defined as the difference between the two. That is, letting P = total customer population plus infrastructure population equivalents,

$$\begin{aligned} &Expected\ risk\ reduction \\ &\qquad = [p(flooding\ failure\ without\ measure) \times P \times 96] \\ &\qquad - [p(flooding\ failure\ with\ measure) \times P \times 96] \\ &= [p(flooding\ failure\ without\ measure) - p(flooding\ failure\ with\ measure)] \times P \times 96 \end{aligned}$$

Con Edison storm hardening Cost-Benefit Analysis[25]

The overall structure of Con Edison's storm hardening cost-benefit analysis for substations was broadly similar to the Risk Prioritization analysis. The estimated 20-year flooding failure probabilities without and with measures were the same, as was the assumption of a 96-hour outage duration. Impacts were estimated for residential, commercial (now divided into Large and Small), residential high-rise buildings, hospitals and public health facilities, critical infrastructure, and public safety facilities served by a particular substation. However, the basis for calculations for impact estimation was the numbers of accounts in each of these classes or categories that were served by each substation (rather than numbers of customers or equivalents). For residential and commercial, the number of accounts was used to generate annual kWh consumption levels for each substation (presumably from billing data). Annual kWh "equivalents" for the other categories were again estimated using undocumented conversion formulae. Finally, impacts were in monetary units, as we now describe.

As noted in the text, Con Edison retained a consulting firm to extrapolate Berkeley Lab's 16-hour customer avoided cost estimates to durations up to 290 hours (12 days). This took the form of functions fitted to the Lab's short-duration estimates of costs per annual kWh for each of the Small Commercial & Industrial, Large Commercial & Industrial and Residential customer classes, respectively.[26] For the other categories (residential high-rise, etc.) one of the customer class functions was used.

Each of these extrapolation functions was of the form:

$$Outage\ cost = a \times (D^b)$$

[25] Con Edison. 2014. *Appendix S - Amended Storm Hardening and Resiliency Collaborative Phase Two Report.* November 14. https://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={2137E970-DC34-4630-839C-DD2F08357F2C}

[26] Con Edison Phase Two report, *ibid.*, Appendix T.

where D is duration in hours and a, b are constants depending on the customer class. The correspondence is shown in the following table:

Table A1. Con Edison's customer/facility category and the data sources of the avoided costs

Con Edison customer or facility category	Extrapolated avoided cost function based on…
Small commercial	LBNL small commercial & industrial (C&I)
Large commercial	LBNL medium and large C&I
Residential	LBNL residential
Hospitals and Public Health	LBNL residential
Critical infrastructure	LBNL medium and large C&I
Residential high-rise and public safety	Function based on weighted average of LBNL short-duration estimates across classes

To calculate expected costs, Con Edison applied a definition from Berkeley Lab's work: For a given customer class or category, the "cost per annual kWh" of an outage of duration *D* is the total cost of the outage divided by the annual consumption in kWh of the affected class or category.[27] This definition was applied assuming *D* = 96 hours. For each substation, Con Edison calculated expected costs for each class and category as:

$$Expected\ cost\ without\ measure = (cost\ per\ annual\ kWh\ of\ 96\ hour\ long\ outage) \times annual\ kWh \times p(flooding\ failure\ without\ measure)$$

$$Expected\ cost\ with\ measure = (cost\ per\ annual\ kWh\ of\ 96\ hour\ long\ outage) \times annual\ kWh \times p(flooding\ failure\ with\ measure)$$

These estimates were summed across the customer classes and categories. Using these totals, the expected benefits of a measure for a substation were calculated as:

$$\Delta Expected\ cost = (cost\ per\ annual\ kWh\ of\ 96\ hour\ long\ outage) \times annual\ kWh \times [p(flooding\ failure\ without\ measure) - p(flooding\ failure\ with\ measure)]$$

Con Edison developed capital cost estimates of the various measures under consideration, and to each added a 20% "carrying cost." Finally, they calculated both benefit-cost differences and ratios to evaluate each project, in total current dollars as well as in terms of Net-Present Value (with expenditures and expected benefits estimated annually across the 20-year asset life).

[27] Sullivan, Michael J., and Matthew Mercurio, Josh Schellenberg. 2009. *Estimated Value of Service Reliability for Electric Utility Customers in the United States.* Lawrence Berkeley National Laboratory Report LBNL-2132E, June. https://emp.lbl.gov/publications/estimated-value-service-reliability

Background on GDO

The U.S. Department of Energy’s Grid Deployment Office (GDO) works to provide electricity to everyone, everywhere by maintaining and investing in critical generation facilities to ensure resource adequacy and improving and expanding transmission and distribution systems. Working in strong partnership with energy sector stakeholders on a variety of grid initiatives, GDO supports the resilience of our Nation’s electric system and deployment of transmission and distribution infrastructure. GDO’s priority is to develop and deploy innovative grid modernization solutions to achieve the Administration’s clean energy goals and mitigate climate change impacts while ensuring the availability of clean, firm generation capacity, like hydropower and nuclear energy.

GDO’s works to make sure all communities have access to reliable, affordable electricity by leveraging unique authorities to:

- Improve resource adequacy by maintaining and investing in critical generation facilities
- Support the development of nationally significant transmission lines
- Drive transmission investment

Background on Lawrence Berkeley National Laboratory (Berkeley Lab)

Berkeley Lab is a multi-program science lab in the national laboratory system supported by the U.S. Department of Energy through its Office of Science. Berkeley Lab is managed by the University of California and is charged with conducting unclassified research across a wide range of scientific disciplines. Berkeley Lab’s Energy Markets & Policy (EMP) department strives to inspire and inform impactful solutions to existing and emerging global energy challenges through objective and timely research and technical assistance. We employ a range of interdisciplinary methods and tools appropriate to the topic at hand, including primary data, economic, and statistical analyses; modeling; and survey and interview-based research. We provide insight and information to public and private decision makers through direct technical assistance, publications, and presentations, and we make our work publicly-available to aid and inform all interested stakeholders.

Contact Us

U.S. Department of Energy Grid Deployment Office

GridDeploymentOffice@hq.doe.gov

www.energy.gov/gdo

Lawrence Berkeley National Laboratory

Resilience@lbl.gov

www.emp.lbl.gov

Get more information on how to join the Grid Deployment Office by scanning the QR code or visiting **www.energy.gov/gdo/join-our-team**

Increasing Manhattan's Energy Resilience through Storm Hardening

Consolidated Edison's East 13th Street Substation Storm Hardening Project, New York

JUNE 2024

BERKELEY LAB

GRID DEPLOYMENT OFFICE