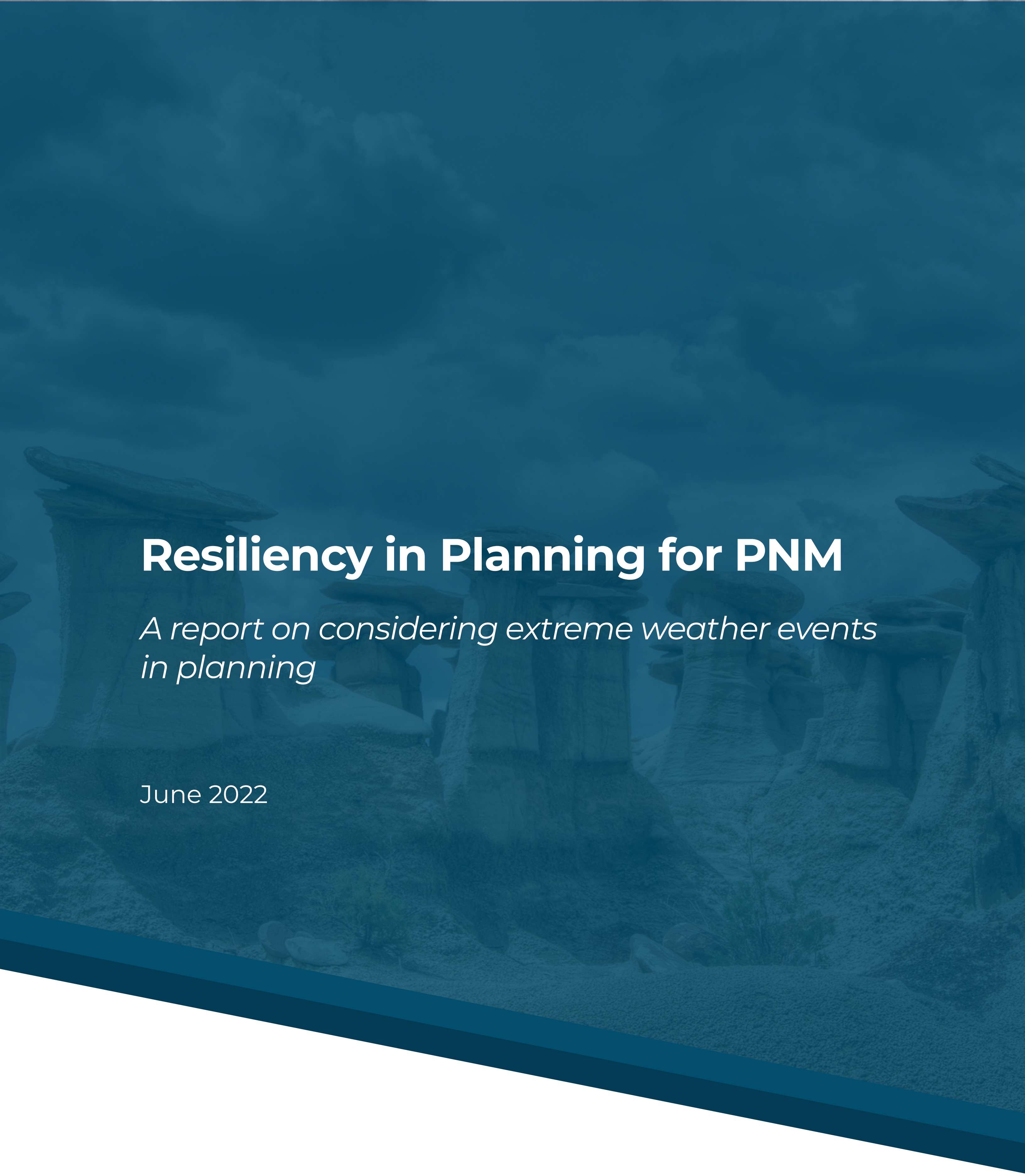


Resiliency in Planning for PNM

A report on considering extreme weather events in planning

June 2022

Energy+Environmental Economics

ASTRAPÉ CONSULTING
innovation in electric system planning

Project Team

This report was produced in a collaboration between Energy and Environmental Economics, Inc. (E3) and Astrapé Consulting and sponsored by the Public Service Company of New Mexico (PNM). While PNM provided input and perspectives regarding the study scope and analysis, all decisions regarding the analysis were made by E3 and Astrapé. Thus, this report solely reflects the research, analysis, and conclusions of the E3 and Astrapé study authors.

E3 is a leading economic consultancy focused on the clean energy transition. E3's analysis of clean energy issues and the electric power sector is utilized extensively by utilities, regulators, developers, and government agencies in leading-edge jurisdictions such as California, New York, Southwest, and Hawaii. E3 has offices in Boston, New York, San Francisco, Calgary, and Raleigh.

E3 Primary Authors: Saamrat Kasina, PhD; Manfei Wu; Ruoshui Li; and Nick Schlag

Astrapé Consulting provides expertise in generation and transmission planning and is the exclusive licensor of the SERVM model. Astrapé has provided electric system planning services and resource adequacy studies for many of the largest utilities and regulators in the US, Europe, and Asia. SERVM is the premier electric system risk model used for resource adequacy studies, capacity planning assessments, energy-limited resource analyses, renewable integration studies and more. Astrapé's consultants have decades of experience in a range of electric system planning functions.

Astrapé Primary Authors: Chase Winkler; Nick Wintermantel

Energy and Environmental Economics, Inc. (E3)
44 Montgomery Street, Suite 1500
San Francisco, CA 94104

Astrapé Consulting, LLC.
3000 Riverchase Galleria Suite 575
Hoover, Alabama 35244

Table of Contents

Table of Figures

Table of Tables

Abbreviations

AZPS	Arizona Public Service Company
EFOR	Equivalent Forced Outage Rate
ELCC	Effective Load Carrying Capability
ERCOT	Electric Reliability Council of Texas
ESIG	Energy Systems Integration Group
FCPP NNC	Four Corners Power Plant No New Combustion replacement
FCPP TN1	Four Corners Power Plant Technology Neutral replacement 1
FCPP TN2	Four Corners Power Plant Technology Neutral replacement 2
FCPP TN3	Four Corners Power Plant Technology Neutral replacement 3
GADS	Generating Availability Data System
GHG	Green House Gases
HILF	High Impact Low Frequency
IRP	Integrated Resource Planning
LOLE	Loss Of Load Expectation
PRM	Planning Reserve Margin
PV NNC	Palo Verde No New Combustion replacement
PVNGS	Palo Verde Nuclear Generating Station
RA	Resource Adequacy
RFP	Request For Proposals
SERVM	Strategic Energy and Risk Valuation Model
SME	Subject Matter Experts
TECO	Tampa Electric Company
TVA	Tennessee Valley Authority
UCAP	Unforced Capacity
VRE	Variable Renewable Energy

Executive Summary

Resource Adequacy planning ensures that adequate capacity is available to meet a utility's peak demand. This is especially important as electric grids throughout the US face changing demand patterns and increasing penetrations of variable energy. On the other hand, Resource Resilience, which is the focus of this study, focuses on ensuring the electric grid is prepared for and is able to minimize disruption during an extreme weather event.

Extreme weather events are expected to increase both in frequency and magnitude in the future. In the last decade, PNM experienced such occurrences at least three times – during ice storms in 2011 and 2021, and in the 2020 Western heat wave. These recent experiences have put the focus on resilience of the state's electric grid -- its ability to prepare for, withstand, respond to, and ultimately recover quickly from loss of function after a severe weather event. A crucial component of ensuring a resilient grid is to procure the correct types and quantities of resources that will enable it to avoid or minimize the impact of widespread blackouts. Procurement of resources is primarily driven by the needs identified in the IRP process, which identifies a cost-effective portfolio of resources to meet projected electricity demand over the next twenty years. Until now, data, modeling, and mathematical limitations have limited consideration of extreme weather events in PNM's modeling process. This report aims to fill the gap by clarifying what resilience in planning means for PNM and its relationship to traditional resource adequacy planning. Additionally, this report seeks to understand characteristics of resources that would help PNM withstand and possibly avoid the worst impacts of extreme events. Ultimately, the long-term intent of this report is to ensure PNM's procurement meets not only PNM's resource adequacy requirements, but also its resilience needs.

The analysis conducted in this study to understand the impacts of extreme weather on portfolio performance consisted of several steps. First, after consultation with PNM SMEs and after examining PNM's historical operations data, two types of extreme events were determined to pose the greatest threat – ice storms and heat waves. Sensitivities were then crafted where these events were parameterized using indicators like increased loads, renewable energy availability, weather-induced generator outages, and tighter market conditions. Simultaneously, a set of portfolios based on Four Corners Coal Plant replacement resources were assembled to be tested. A 'Base Case' portfolio was also tested that models the system as it exists today that retains Four Corners in the portfolio. To differentiate the performance of these portfolios in extreme weather and non-extreme conditions, the portfolios were all designed to meet the same resource adequacy standard of 0.2 LOLE.[1] The portfolios were then tested using the production costing software, SERVM (the same tool used in and holding many of the same assumptions as the 2020 PNM IRP). For each portfolio in each sensitivity, pre-determined resilience metrics such as average MWh lost, duration of the outage, probability of an outage were calculated.

Key findings from the study that provide insight into portfolio performance in extreme weather and how this might inform future resource procurements are found below.

---

[1] Expected load loss of 0.2 days per year (this is a measure of frequency)

- ***PNM's Resource Adequacy planning practices work as expected and allow PNM to maintain reliability under most summer conditions.*** PNM's resource planning framework is designed to meet a loss of load expectation (LOLE) standard of 0.2 days per year.[2] This standard allows for some probability of reliability events – typically in the summer peak – but also ensures that their occurrence is rare. The modeling in this study confirms that the RA process works as intended, illustrating that PNM's resource portfolios are able to meet loads reliably under most – but not all – summer conditions. In extreme circumstances – for instance, if summer loads reach 1-in-20 year levels, or if summer temperatures force large amounts of PNM generation or transmission to be offline -- PNM might experience loss of load events.

- ***PNM's system is designed for a summer peak but may still be vulnerable to extreme events in winter.*** PNM's system is designed to meet an RA standard that is based on summer peak. This study finds that in ice storms, if multiple generators are forced offline (as happened in PNM in 2011 and in Texas in 2021) either due to transmission failure or generator malfunction – or if the region as a whole experiences significant loss of generating capability – PNM may experience loss of load. These types of events are outside the envelope of PNM's traditional resource adequacy planning but do present a reliability risk to customers.

- ***Different resource portfolios that meet the same LOLE planning standard have varying performance during extreme events.*** All tested portfolios met the same LOLE standard of 0.2 days per year. This study shows that although the portfolios are all designed using the same resource adequacy standard, their performance varies widely in extreme weather simulations. In other words, the likelihood that an extreme event might result in an outage – and the size of its impact – may vary under different portfolios.

- ***Stress testing candidate portfolios for resilience can help identify differences in their performance.*** In the long-term, portfolios should be designed (and corresponding modeling frameworks developed) that successfully address both resource adequacy and resilience concerns. In the short-term, cost-effective candidate portfolios from the resource adequacy IRP process should be tested for resilience. The insights from such stress testing should be used to inform capacity investments that PNM makes.

- ***Weatherization of all generation resources to allow for performance under extreme conditions is an important resilience consideration.*** In the winter events studied, winterization measures for natural gas generators are demonstrated to have a large impact on the size, frequency, and duration of loss of load events. PNM has already invested in winterization of its own generation assets and has added criteria to PPAs to ensure wider temperature operating requirements. Similar to winter, engineering and operational measures to ensure resources are available under extreme summer temperatures – including natural gas and energy storage – can reduce the risk of loss of load events due to coincidence of high loads and widespread unit outages.

---

[2] PNM plans to move to a 0.1 LOLE standard in the next IRP cycle.

- ***Firm generation resources reduce the severity of extreme event impacts in both summer and winter.*** During severe weather events, firm resources – resources that are not energy-limited, help reduce both magnitude and duration of load outages and generally reduce the instantaneous power lost (peak MW). While winterization is one way to firm resources up, the operating characteristics of resources must also be considered. Firm resources need not be conventional fuel based, but instead could include hydrogen-fueled generators or long-duration storage.

- ***During ice storms, broader southwest dynamics will have significant impact on PNM's ability to avoid outages under winter extreme events.*** Historically, PNM has relied on neighbors' support during regional extreme winter weather. The notion of reliance on the external market for support during winter conditions is also built into PNM's resource adequacy planning practices, which allow for significant levels of imports in the winter season. This dynamic means that PNM's ability to maintain reliability under regional-scale extreme events may depend not only on the characteristics of its own loads and resources but on dynamics in the broader footprint of the Southwest region. Further, although not examined in this study, this points to the importance of PNM's transmission infrastructure (and the need to examine its vulnerability) during ice storms.

- ***As PNM increases its energy storage portfolio, its operational limits and utilization should be understood and considered in resource adequacy modeling.*** Conservative battery operations, where load shed is prioritized over economic arbitrage, helps mitigate the duration of outages during extreme operational stress. These considerations should be adequately reflected in resource adequacy modeling in addition to informing operator training and designing battery protocols.

PNM has committed to achieving a carbon-emissions free portfolio by 2040. It also has intermediate emission reduction goals to meet along the way. PNM's path to decarbonization should also adequately consider resilience in extreme weather situations along with other resource adequacy factors. This study demonstrates the effect of several factors on portfolio performance in extreme weather and is meant to lay the foundation necessary to quantify the impacts of extreme weather and support procurement considerations as the utility transitions to a carbon-emission free future.

1 Introduction

1.1 Study motivation

The state of New Mexico has been at the forefront of the renewable transition in the United States, especially in the southwest. The Energy Transition Act of 2019 (Senate Bill 489) set ambitious targets of 50% RPS and 100% carbon-free electricity by 2030 and 2045 respectively for the state.[3] As a requirement of and in support of this law, the Public Service Company of New Mexico (PNM) has established a goal of 100% carbon emission-free electricity for its customers by 2040.

Ensuring reliable electric service for end users is a cornerstone of electric sector planning in the developed world. The traditional definition of reliability as used in the planning community is closely linked to an expectation of lost load or the maximum number of hours PNM can afford to lose power over a period. In most places across the US, this Loss of Load Expectation (LOLE) standard is set to 0.1 or 0.2 days per year. PNM currently uses a 0.2 LOLE standard for its resource planning analyses.[4] This is reflected in the 2020 IRP report. While PNM uses this LOLE standard to ensure enough capacity is built to meet load under reasonably predictable conditions, High Intensity Low Frequency (HILF) or extreme weather events such as ice storms or heatwaves are still not fully considered in the planning paradigm due to data and modeling limitations.

HILF events are expected to increase in both frequency and magnitude in the future. PNM's own operational experience bears this out – in the past 10 years, PNM has experienced extreme events at least 3 times: the 2011 ice storm, 2020 heat wave, and 2021 ice storm. Simultaneously, PNM's conventional fleet of coal and gas-fired units is being replaced by Variable Renewable Energy (VRE) resources to meet Green House Gases ("GHG") goals. This can compound the problem of keeping lights on during severe weather events. For example, solar production might plummet during an ice storm.

The goal of this work then is to set the resilience context for planning in PNM, explore and characterize potential extreme weather events that affect PNM's territory, and understand PNM's resource mix's resilience to and performance under these conditions. Broadly, the goal of this study is to act as the foundation for bridging the gap between PNM's IRP process and planning for extreme conditions.

1.2 Report contents

The remainder of the report is organized as follows: Section 2 provides background and study context, including the historical motivation for PNM to look at resilience. It also defines resilience in the context of this study and gives an overview of the study setup. Section 3 provides an overview of the modeling approach, the software used, sensitivities that were simulated, and key assumptions utilized in the

---

[3] Not all RPS and Emissions requirements under the Energy Transition Act are enumerated.

[4] PNM plans to move to a 0.1 LOLE standard in the next IRP cycle.

analysis. Section 4 presents and discusses results from the modeling analysis and Section 5 is the conclusions section. In it, the implications of the results of the modeling in this study are discussed including limitations of this study and possible next steps.

2 Background and Context

One of the requests expressed by stakeholders leading up to the 2020 IRP was a desire to study a "climate change future." The IRP process was being conducted in the backdrop of California's rolling blackouts in Summer 2020 and many stakeholders noted concerns about the impact of extreme weather events such as long and geographically widespread heat waves on PNM's service territory. While PNM shares these concerns, such risks were not studied quantitatively in the IRP process due to limitations in the modeling framework – in particular, the lack of ability to adequately represent extreme weather events. Section 1.3 of the IRP acknowledged these limitations and committed to "developing methods to incorporate these considerations into future modeling." This study seeks to establish the foundation necessary to supplement PNM's IRP process with insights from extreme weather impacts on PNM's system and aims to understand generators' performance during such events.

HILF events are of particular concern to PNM as its system was operationally stressed at least three times in the last 10 years (2011, 2020, and 2021). Below is a brief overview of each of these events. The following is by no means meant to be a comprehensive review of these events. Rather, it is meant to illustrate the complex interactions between variables such as weather, load, market support, and outages. It is also meant to highlight the critical interdependency between the gas network and the electric grid, especially in winter.

February 2011 Freeze-Off

In the first week of February 2011, extreme cold weather in southern New Mexico and far west Texas resulted in a series of localized outages and natural gas curtailments affecting a total of 4.4 million people in the Southwest region. Several days of sub-freezing temperatures led to widespread wellhead freeze-offs in the Permian Basin, which left some communities in New Mexico without any gas for up to 6 days[5].

Gas supply curtailment induced low gas pressure, which in turn tripped several circuit breakers within PNM. To reduce gas usage, PNM attempted to switch from natural gas to distillate fuel oil at its Rio Bravo[6] combustion turbine.[7] The prolonged cold weather also caused failures of electric transmission infrastructures - a static wire, stretched by the extremely cold weather, snapped, and fell on one of the phases of the line, interrupting service to a town in Clayton for roughly two hours[8]. Additionally, PNM was forced to implement a localized outages in southern New Mexico as a transmission line locked out due to a failed conductor clamp. This led to the overload of a Tri-State transmission line and localized curtailment. In total, over the course of the event, a little over 21,000 PNM customers were affected.

February 2021 Cold Snap

More recently, a record-breaking cold snap hit much of the central United States during early to mid-February 2021. The cold snap was centered over Texas and the Electric Reliability Council of Texas (ERCOT)

---

[5] Microsoft Word - RISA cold snap report 9-7-11 v10.docx (nerc.com) (starting from p14)
[6] In 2011, this unit was called "Delta Person".
[7] A faulty valve prevented this attempted changeover.
[8] Report on outages and curtailments during the Southwest cold weather event (ferc.gov)

territory suffered a major power crisis, as millions throughout the state were left without power for up to six days.[9] PNM's utility services mostly continued as normal: power facilities were winterized post-2011 and well prepared for the cold weather; shifting natural gas supply away from Permian Basin and predominantly toward the San Juan Basin prevented customers from losing service due to supply disruptions in Texas.[10] PNM was also able to switch from gas to oil at its dual-fuel resource facilities to mitigate gas purchases.[11] PNM still experienced some pockets of disruption, for example, in the Valencia and Las Vegas counties where about 6,000-7,000 customers were without power at one point due to distribution system outages.[12]

August 2020 Western Heat Wave

In August 2020, a widespread heat wave caused a surge of electric demand across the Western Interconnection. While the most extreme effects of this event were in California, where the California Independent System Operator implemented rolling blackouts for the first time since the 2001 Energy Crisis, utilities throughout the West experienced a tightness of supply, and Energy Emergency Alerts were widespread.

Between August 14-17, when conditions in the rest of the West were extreme, PNM operators were able to balance the system without relying on the market for support. However, towards the end of August 17, PNM experienced a large thermal generator outage. Over the subsequent several days, PNM's remaining resources were stretched to their limits; during PNM's net peak periods, Western bilateral markets were illiquid, and PNM were unable to procure additional supplies from the wholesale market despite offering high prices (see Figure 1).[13]

---

[9] Busby, J. W., Baker, K., Bazilian, M. D., Gilbert, A. Q., Grubert, E., Rai, V., ... & Webber, M. E. (2021). Cascading risks: Understanding the 2021 winter blackout in Texas. Energy Research & Social Science, 77, 102106.

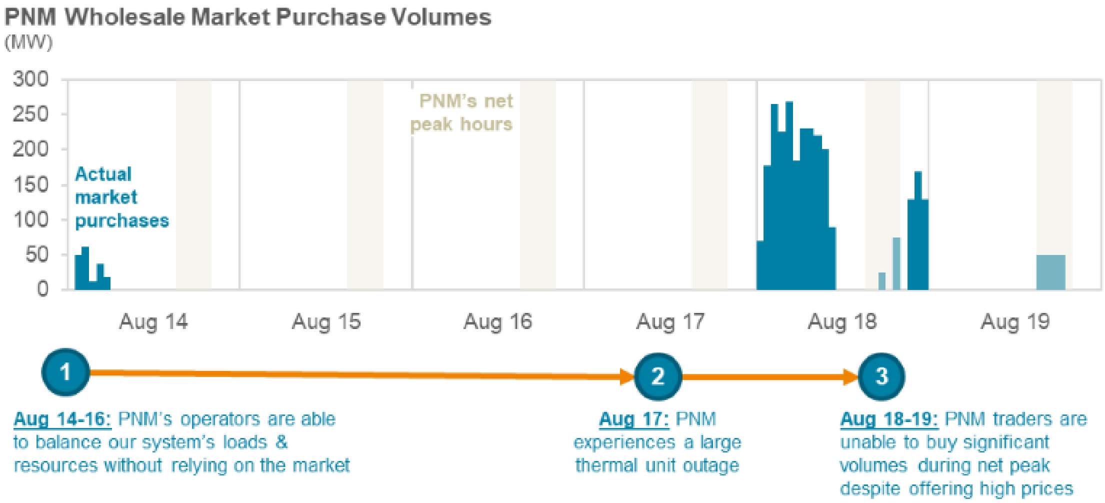
[10] San Juan Basin played key role in preventing outages in New Mexico (daily-times.com)

[11] Southwest Regulators Hear From Utilities in Aftermath of Texas Catastrophe | Southwest | newsdata.com

[12] https://www.koat.com/article/winter-storm-causes-power-outages-in-multiple-counties/35504077

[13] PNM-2020-IRP-FULL-PLAN-NEW-COVER.pdf (pnmforwardtogether.com)

Figure 1: PNM's hourly wholesale market purchases during the August 2020 heatwave[14]



It is clear from the overviews above that over the past decade, in extreme weather situations, PNM's system was operationally stressed. Generators and transmission lines experienced weather-induced outages, gas supply was constrained, and loads were high. In 2011, the utility experienced both forced and rotating blackouts. Post-2011 and winterization, while PNM was able to avoid widespread blackouts, in some cases, the system came perilously close to experiencing one (such as in 2021 and 2020). Anecdotally, PNM states that there were many near-misses, and the affected customers number would have been even higher if during these extreme events, more infrastructure had failed. Having a framework to characterize and simulate extreme events will help in understanding generator performance in extreme weather. This will in turn inform the types, amounts, and operational characteristics of generators needed to withstand such events.

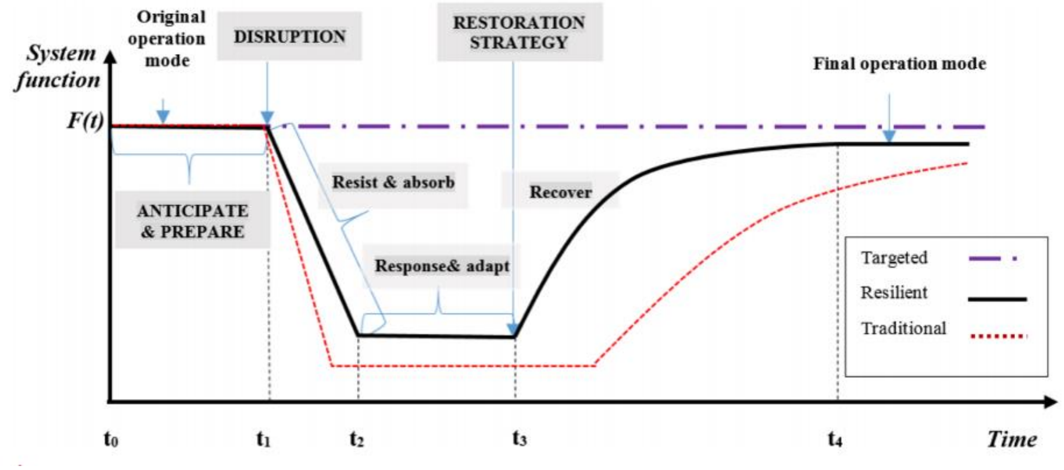
2.1 What is grid resilience and its meaning in this study?

There is no single definition of grid resilience that has widely adopted by the industry. Multiple agencies and research institutes have defined resilience in the context of policy proposals and research projects. FERC, for example, defines it as the "*the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.*" NARUC too defines resilience as *"Robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event."* Across most definitions, the focus is generally on a system's ability to withstand, reduce the impact, and rapidly recover from disruptive events.

---

[14] Reproduced from Page 49 of PNM IRP

Figure 2: Illustrative performance of a resilient grid[15]



Resilience is seen as evaluating a system's performance under different phases of a disruption that includes "prepare", "absorb", "adapt", and "recover", referred to as the "resilience trapezoid" in some reports.[15] The second commonality across most definitions is that resilience is typically evaluated against *specific* HILF events. The resilience characteristics needed to withstand an ice storm are very different than one required to withstand an earthquake.

2.1.1 Grid resilience in this study

A disruptive event could impact different components of an electricity grid. The resilience of a power system includes resilience of its generation supply, transmission and distribution infrastructures, and system communications. Different components of the grid might be prone to a specific set of resiliency threats and require different adaptation measures. For example, extreme weather events and natural disasters could affect generators. Adaptation and mitigation measures for generators in such situations include generator hardening, fuel supply hardening, resource overbuilds, or investing in distributed resources. Adapting the transmission and distribution system to such events, on the other hand, include line hardening, network redundancy, or underground builds, etc. Although resilience is usually discussed with a focus on extreme weather events, there are other threats the grid might face such as cyber-threats. A different set of investments in generators and transmission infrastructure are required to mitigate and manage such risks. More generally, resilience-focused actions and investments can be thought of being part of a matrix with specific identified threats (cyber, hurricanes, earthquakes, ice-storms) being one axis and the other being the targeted grid infrastructure component (generators, transmission, distribution, software). While resilience is an umbrella term that is used for the entire gamut of threat-component actions and investments, implementation studies such as this one generally focus only on one cell of this matrix. This study deals only with generator (or supply) resilience in the context of two identified threats to the PNM system – ice storms and heat waves (see section 3.4 on how these were chosen).

---

[15] Bie, Zhaohong, et al. "Battling the extreme: A study on the power system resilience." Proceedings of the IEEE 105.7 (2017): 1253-1266.

Resilience studies conducted by other utilities in the U.S. also have a narrow focus. For example, Tampa Electric Company (TECO) submitted a ten-year storm protection plan to the Florida Public Service Commission in April 2020 following the requirement set by the Florida legislature.[16] The plan focused specifically on transmission and distribution resilience and laid out a comprehensive framework to assess potential risks and impacts from storms and evaluate mitigation measures. Tennessee Valley Authority's (TVA) resilience study was a more expansive and focused on Transmission infrastructure and a wide variety of threats were evaluated systematically – from Cyber-attacks to Severe flooding.[17]

As mentioned above, in this study, the focus is only generator resilience. T&D resilience is equally important in the context of extreme events. But given the time and scope of this study and its eventual goal of informing the broader IRP process, the immediate focus is only on supply resilience.[18]

2.1.2 Resilience, Reliability, and Resource Adequacy

To further understand what resilience means in this study, it is important to characterize it with respect to other terms used in this space – Reliability and Resource Adequacy. Differentiating Resilience from Resource Adequacy (which is the primary focus of the IRP process) and understanding how together, they help make PNM's system more reliable will define the scope for supply resilience.

---

[16] https://www.burnsmcd.com/insightsnews/1898/case-studies/making-case-for-utility-infrastructure-hardening

[17] Clayton Clem, *Approaches to Resiliency at TVA*

[18] In the rest of the report, the term 'resilience' refers to supply resilience.

Figure 3: Relationship between Reliability, Resource Adequacy, and Resilience

Distribution System Reliability

Ensure distribution systems are planned to enable delivery of electricity to loads even under severe contingency conditions

Transmission System Reliability

Ensure transmission systems can deliver electricity from generators to distribution systems under steady state and dynamic contingency conditions

Resource Adequacy

Ensure sufficient generation resources are available to meet load with an acceptable level of reliability across a broad range of load conditions while accounting for generator outages , weather impacts on loads & resources, and other constraints on generator availability

Operational Reliability

Maintain system reliability in real-time operations by balancing loads with generation while maintaining sufficient operating reserves to meet flexibility needs and respond to contingencies

Resilience

Anticipate, respond to, and recover from extreme unexpected events and systemic shocks to any and allparts of the electricity system, including extreme weather events and cyber threats

‘Reliability’ is usually considered to be an umbrella term under which Resource Adequacy and Resilience are two components (See Figure 3). The other components of reliability are defined as Transmission Stability, Distribution reliability, and Operational reliability.

As efforts to define what it means to plan for a resilient supply of electricity continue, it will be critical to clarify the differences between utilities’ traditional efforts to plan for resource adequacy and emerging efforts to improve resilience. NERC defines resource adequacy as “the ability of the electric system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, *taking into account scheduled and reasonably expected unscheduled outages of system elements”* (emphasis added). Planners have relied on a range of methods and tools to plan for resource adequacy, but most approaches – like the ones used by PNM – are built upon a foundation of probabilistic analysis that relies on mathematical techniques to measure the likelihood of potential supply shortfalls based on known probabilities of extreme weather events, generator outages, and variable resource production patterns.

This definition of resource adequacy focuses on meeting customer loads under “reasonably expected” outages of system elements – and yet, instances when outages and conditions have clearly exceeded “reasonable expectation” have led to some of the most notable and impactful reliability events in recent memory. Most recently, during Winter Storm Uri in 2021, widespread unplanned outages due to extreme cold temperatures and cascading failures of gas supply infrastructure left millions in Texas without power for days; at points, the amount of expected capacity unavailable due to unplanned outages reached 34,000 MW, nearly half the system's all time winter peak.[19] Four years earlier, Hurricane Maria destroyed generation, transmission, and distribution electric infrastructure across the island of Puerto Rico, leaving millions without power for months; restoration of electric service for some required nearly a year.[20] The risks posed by these HILF events – which are difficult to account for directly in resource adequacy because of their complexity and their uncertainty – underscore the importance of complementary efforts to consider possibilities beyond the bounds of "reasonable expectation." Such extreme events are the focus of the emerging field of "resilience."

Simply put, resource adequacy takes into consideration system operation under "normal" conditions including reasonable assumptions around load uncertainty, generator failures, and weather variability. Resilience on the other hand deals with "abnormal" conditions – extreme weather events or hard-to-predict cyber and human attacks on the system. In this study, as mentioned above, the focus is only on the impact of extreme weather events on PNM generators.

2.2 Study setup

An easy way to visualize this study's setup is to consider Figure 4. This is a schematic that shows that severe weather conditions or related conditions are relatively rare compared to the body of "normal" events. Borrowing terminology from Gholami et al., 2018,[21] the weather conditions that make up this distribution can be thought of as falling into three categories as indicated in the schematic:

1. **Known events:** Conditions for enough historic data is available that it is possible to reasonably estimate the odds of these conditions occurring. There is also enough historic data of grid performance during these conditions that these can be considered "normal" operating conditions. These are already directly captured in Resource Adequacy studies such as that completed in PNM's IRP process.
2. **Gray swan events:** The second category are weather conditions whose nature can be predicted based on some indications or occurrences from the past or future projections, but the data is too sparse to reasonably estimate their odds. In this study, these are referred to as gray swan events.
3. **Black swan events:** The third category are the black swan conditions which by definition cannot be predicted. These are conditions that for which neither odds nor nature can be predicted.

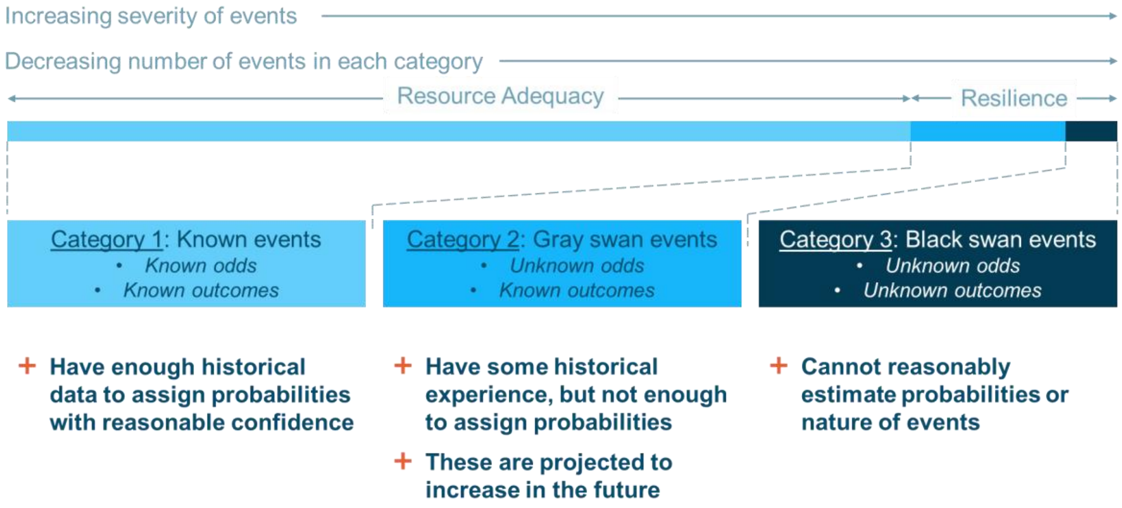
---

[19] https://www.ferc.gov/media/february-2021-cold-weather-outages-texas-and-south-central-united-states-ferc-nerc-and

[20] Robles, Frances. "Puerto Rico Spent 11 Months Turning the Power Back On. They Finally Got to Her." *New York Times*. https://www.nytimes.com/2018/08/14/us/puerto-rico-electricity-power.html

[21] Gholami A, Shekari T, Amirioun MH, Aminifar F, Amini MH, Sargolzaei A. *Toward a Consensus on the Definition and Taxonomy of Power System Resilience*. IEEE Access. 2018;6:32035-32053. doi:10.1109/ACCESS.2018.2845378

Figure 4: The three categories of events faced by power systems

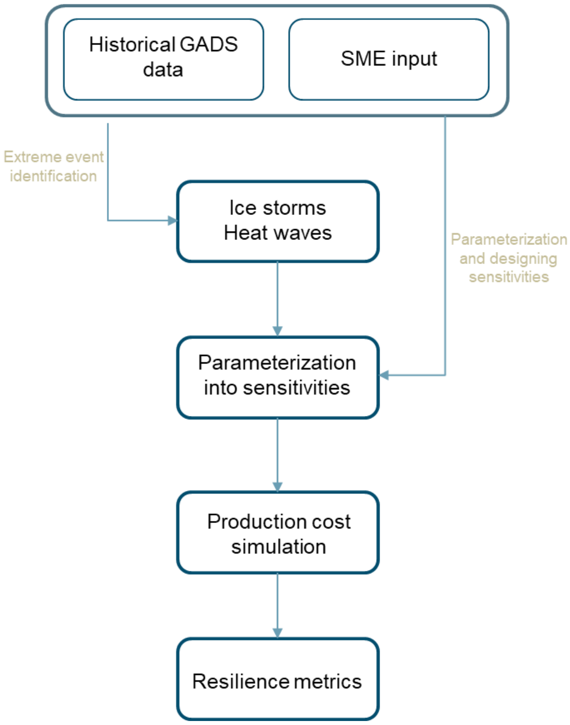


Building on the foundation of PNM’s existing resource adequacy analysis developed in its IRP, this study’s objective is to investigate a range of the Gray swan events in category 2. Category 1 events are already being analyzed and included in decision-making (along-with some estimates of category 2) in the IRP. This study aims to formalize the process of studying category 2 events with the long-term goal of informing the IRP process with learnings from future resilience/gray swan events studies.

3 Modeling and Sensitivity Analysis Approach

The previous section already established that estimating reliable odds for gray swan events is not possible (if it were possible, these conditions should be incorporated directly into resource adequacy analysis in the planning process). In the absence of robust data to characterize probabilities of these events in a manner that would allow them to be incorporated into traditional statistical assessments of resource adequacy, event-based sensitivity analysis to assess performance provides a complementary view as to how different portfolios might perform under specific extreme events. An overview of its implementation in this study is shown in Figure 5.

Figure 5: Schematic of analysis approach



- First, an identification exercise was carried out to detail the type and nature of extreme events of greatest concern to PNM based on the specific geography and meteorology of the state of New Mexico. For PNM, this was determined to be ice storms and heat waves; each of these events serves as the basis for a "case study" in this analysis.
- Next, these events were parameterized into simulation sensitivities. For example, ice storms were defined by different levels of extreme temperatures, increased loads, weather-correlated generator outages, and reduced external market support.
- Multiple sensitivities of ice storms and heat waves were put together after consultation with the PNM team. The sparsity of historical data on gray swan events meant this exercise was necessarily informed by inputs from both historical data and PNM subject matter experts.
- Multiple PNM resource portfolios were designed for analysis, all of which met the same LOLE standard of 0.2 days per year. Consequently, any differences in portfolio performance across

sensitivities can be attributed to differences in portfolios' performance during the extreme event being simulated.
- The identified sensitivities were then simulated using production cost simulation software, SERVM, and from simulation results, pre-determined resilience metrics were calculated for all portfolios.

The following sections describe the above steps in greater detail and present the tested portfolios and other study assumptions.

3.1 Modeling methodology and connection to PNM 2020 IRP

In the 2020 IRP, PNM used SERVM (Strategic Energy and Risk Valuation Model), a production cost and loss of load probability model, as the basis for its resource adequacy planning. Using an approach consistent with industry best practices and followed by many utilities, PNM used an annual loss-of-load-probability modeling framework to assess and characterize its resource adequacy needs. Specifically, SERVM was used to develop two key inputs into the IRP planning process:

- The planning reserve margin requirement for the PNM system needed to meet an LOLE standard of 0.2 days per year; and
- The effective load carrying capability (ELCC) of renewables, demand response, and storage resources, which measures their contribution towards that PRM requirement.

Additionally, PNM also used SERVM to validate that the portfolios produced by its long-term capacity expansion model (EnCompass) met or exceeded the desired standard for resource adequacy (an LOLE of 0.2 days per year).

This study uses the same model and datasets to study the aforementioned questions relating to resiliency, but the use of the model is necessarily different given the scope of the questions. Whereas the analysis conducted in the IRP focused on characterizing the probability of insufficient supply based on known probability distributions for load, renewable availability, generator outages, and storage dispatch, this study uses SERVM to examine specific case studies of extreme events to assess their impact. Each case study represents a plausible extreme weather event lasting up to one week in duration. To understand the possible range of different outcomes in each event, stochastics and sensitivities are applied in each case study:

- Each week-long case study is simulated multiple times using a Monte Carlo approach to capture the impact of the randomness of unit forced outages;
- Key assumptions in each case study are varied under sensitivities to explore their impacts.

The resulting output from these simulations is a realization of thousands of possible reliability outcomes under a specific extreme event that allow this study to characterize the potential distribution of risks.

3.2 Measured metrics

Currently, there is no widely agreed upon standard for measuring resilience of a system. For this study, the following metrics were measured and used to quantify portfolio performance during HILF events:

- Probability of shedding load
- Expected Value of MWh shed (MWh)
- Expected Value of worst hour of shedding (MW)
- Number of unique hours where loss of load was observed to occur (Hours)

Probability of load shed is the fraction of iterations that see any load shed. Generator outages were modeled as stochastic in each iteration (while hewing to an annual outage distribution) and each iteration is different in the type and amount of outage it samples. So, for the same portfolio, one simulation run might see no loss of load during the critical week while another run might experience loss of load. This is because in some cases, the system will be able to withstand the magnitude and nature of the specific randomly drawn generator outages while in others, even after accounting for imports, load shed might be necessary. Expected Value of MWh shed is the average of the load shed over the critical week across all Monte Carlo runs. And the expected value of worst hour of shedding is the average of the peak MW shed in each run. Lastly, the number of unique hours where loss of load was observed is the count of distinct hours within each sensitivity where load was shed.[22]

3.3 Generation portfolios

This study analyzes four different generation portfolios. The four portfolios reflect different combinations of resources that could meet PNM's 2025 needs. Below, the Base Portfolio is described first, and then alternative portfolios are presented. The alternative portfolios contain the same resources as the Base Portfolio except for Four Corner Power Plant (FCPP). Each alternative portfolio explores a replacement of FCPP. SERVM was used to assess the reliability of the portfolios and adjustments were made to ensure all portfolios met the 0.2 LOLE standard.

3.3.1 Base portfolio

The Base Portfolio that represents the PNM's 2025 mix is based on a Palo Verde Replacement portfolio where a portion of the Palo Verde Nuclear Generating Station (PVNGS) is replaced with 190 MW of 4 hour battery-paired-solar, 100 MW of standalone 2 hour batteries, and 450 MW of solar units. This portfolio was selected by the Encompass capacity expansion tool using ELCCs developed from SERVM while targeting a 18% UCAP Reserve Margin target.

Conventional thermal resources owned by the company and controlled via Purchase Power Agreements were modeled consistent with the 2025 study year. These resources were economically committed and dispatched to load on a 5-minute basis respecting all unit constraints including startup times, ramp rates, minimum up times, minimum down times, and shutdown times. All thermal resources were allowed to serve regulation (if AGC capable), spinning, and load following reserves as long as the minimum capacity level is less than the maximum capacity.

---

[22] These distinct hours could be contiguous or not. This metric gives the combined duration of all outages in the critical week. In the rest of the report, this is referred to simply as duration or length of the outage.

The PNM system resource mix as studied is provided in Table 1.

Table 1: Tested resources characteristics

Type	Capacity (MW)	EFOR (%)
Solar PV	1,523	0
Wind	607	0
Combined Cycle	425	4
Combustion Turbine	416	3
Solar-Battery Hybrid	300	1
Steam Turbine Coal	200	20
Geothermal	12	24
Nuclear	298	2
Demand Response	48	0
Steam Turbine Gas	146	3

The modeled Equivalent Forced Outage Rates were based on historical performance or expected future performance provided by PNM. Unlike typical production cost models, SERVM does not use an Equivalent Forced Outage Rate (EFOR) for each unit as an input. Instead, historical (GADS) data events are used to create an outage probability distribution for each unit and SERVM randomly draws from this distribution for each unit to simulate outages.[23]

3.3.2 Alternative portfolios

To gain insight into how different types of resources would perform under severe weather stress, alternative portfolios were tested and compared to the base case. The alternative portfolios considered various replacements of the Four Corners Power Plant (shown earlier in this report as 200 MW of "Steam Turbine Coal"). The replacement portfolios were selected based on either a technology neutral or no new combustion strategy and were tested in SERVM to meet a 0.2 summer LOLE reliability standard.[24] Any differences between portfolios' performance in this study is inferred to be due to resiliency differences between each, as well as events specific to the 2011 and 2020 weather events.

The alternative portfolios tested are summarized in Table 1. PV NNC is the base case (Palo Verde No New Combustion replacement). One of the FCPP units is assumed to be on maintenance in winter. The second portfolio is PV NNC Change which is the Base Portfolio except both FCPP units are available to PNM. FCPP NNC, TN1, TN2, and TN3 are sensitivities in which the 200 MW Four Corners plant is replaced. The FCPP NNC (No New Combustion replacement) replaces FCPP with a mix of Solar, Stand-alone batteries (4hr), and Paired batteries (2hr). TN1-3 replace FCPP with Technology Neutral. FCPP TN1 uses a combination of

---

[23] Units without historical data use data from similar units. See appendix for more details on outage modeling

[24] The portfolios were tested in the same environment as the IRP and PV replacement studies (i.e., all weather years were used)

new gas, wind, and batteries. TN2 is a combination of new gas, solar, and batteries and TN3 consists of all new gas. Another modeling assumption was that all new gas resources were assumed to be aeroderivative turbines with winterization.

Table 2: Portfolio mixes tested in 2025.

Resource	Sensitivity-Specific Resources (MW)					
	PV NNC (Base)	PV NNC Change (Only in winter)	FCPP NNC	FCPP TN1	FCPP TN2	FCPP TN3 (Gas Only)
Palo Verde	288	-	-	-	-	-
Demand Response	48	-	-	-	-	-
Geothermal	11	-	-	-	-	-
Four Corners	200 (summer)/100 (winter)[25]	+100 (only in winter)	-200	-200	-200	-200
Gas	987	-	-	+39	+39	+152
Wind	607	-	-	+180	-	-
Solar	1523	-	+96	-	+96	-
Batteries (4hr)	490	-	+108	+90	+108	-
Batteries (2hr)	100	-	+48	-	-	-

In the Ice storm case study, Four Corners Unit 4 (100 MW) was modeled as being on maintenance. This refers to the weather-normal maintenance modeling performed (maintenance is scheduled during normal weather). For the Ice storm assessment an additional portfolio was created where both Four Corners units were available, subject to random forced outages. This portfolio is referred to as ‘PV NNC Change’.

3.4 Extreme event identification and simulated sensitivities

Plausible extreme events for analysis were identified based on a survey of historic events and in consultation with SMEs from the PNM IRP team. The framework took into consideration PNM’s operational and weather conditions to determine the extreme events to be simulated. Broadly, this study

---

[25] An additional 100 MW is assumed to be on maintenance in winter. The PV NNC Change portfolio assumes the full 200 MW is available to PNM.

examines two case studies – an extreme winter case study and an extreme summer case study. This was based on PNM's historical experiences of facing extreme summer and winter events, for example, the 2020 heat wave and 2021 ice storm. Multiple sensitivities were simulated for a critical week within each case study (Ice storm case study and Heat wave case study) where sensitivities were defined by a combination of different levels of weather conditions, levels of market support, and generator outages. Each category (Ice storm or Heat wave) starts with a base case followed by sensitivities reflecting increasing stress on PNM. The parameters and assumptions used in each category are discussed in the upcoming sections.

3.4.1 Parameters for summer extreme event: Heat wave

The Summer 2020 heat wave gave way to sustained temperatures across the western interconnect for several days. During this event, PNM observed decreased market depth for imports. This year was selected as a starting point to define potential heat waves PNM could face in the future. This was deemed appropriate given the severity and recentness of the event.

Given the event occurred only a year prior to this analysis, actual loads and renewable performance was directly utilized for this analysis. Generator outages were simulated as random Monte Carlo draws to reflect uncertainty surrounding them. Random forced outages were modeled to capture the risk of a generator having failed (even if it didn't necessarily fail during the actual event). This provides a wider distribution of outcomes to understand the impact of this uncertainty on results. For neighbor assistance, the assumptions and constraints used in the IRP were enforced.[26] These constraints were initially informed by the summer 2020 events, and simulating neighbors allows for the full interaction of PNM with neighboring entities for commitment and dispatch decisions. Table 3 summarizes data and assumptions used to define the heat wave in the simulations.

Table 3: Summary of variable values for Heat wave case study

Input	Summer
Weather Year	2020
Solar Data	Actual Capacity Factor
Wind Data	Actual Capacity Factor
Load Data	Actual
Generator Outages	Monte Carlo
Planned Outages	Weather-Normal
Neighbor Assistance	IRP Assumptions

3.4.1.1 Heat wave case study

In addition to simulating each portfolio in the base case, several sensitivities were identified, and the portfolios were cross tested across all of them. These sensitivities focus on several themes of heightening

---

[26] 200-300 MW during high load conditions, and 50 MW cap during net demand periods

[27] Actual capacity factors were applied to the installed capacity of the modeled portfolio

risk conditions to PNM and neighboring areas. The theme of each sensitivity, as well as a description are in Table 4.

Table 4: Heat wave case study sensitivities

Season	Sensitivity	Description
Summer	Base	Base case heat wave
	Island	PNM is simulated as an island (no neighbors, imports, and exports = 0)
	1 in 20	PNM's peak load is consistent with a 1 in 20 load forecast
	G1	The largest battery contingency occurs for the week (150 MW)
	G2	The two largest battery contingencies occur for the week (150 MW + 150 MW = 300 MW)
	G2 + 1 in 20	Sensitivity G2 + Sensitivity 1 in 20

One of the most significant aspects of the changes in the region's projected portfolio of resources as represented by the IRP portfolios is the dramatic increase on battery storage over the analysis horizon. Recent technological advances and continued cost reductions provide cause for optimism, and yet: the projected quantities of installed capacity of battery storage – 590 MW by 2025 and 1535-2306 MW[28] by 2040 – are profoundly large for a technology that is, as yet, largely untested at grid scale. In these early years, unexpected events may result in extended outages as utilities and regulators seek to understand the cause of performance failure. Such has been the case for APS' McMicken facility, where, after a 2019 fire, APS took the plant offline during an extended root cause assessment;[29] as well as for the 300 MW Vistra Energy Storage Phase I facility at Moss Landing, which overheated during high summer temperatures in 2021 and the 100 MW Moss Landing Phase 2, which has also been forced offline due to a sprinkler event.[30] Both units had not returned to service as of the publication of this report. More recently, a 10 MW battery unit, installed in 2019, inside a Salt River Project (SRP) substation caught fire.[31,32]

These types of events naturally raise questions of how reliably storage facilities will be available to supply the grid when it needs power most – and what the resulting impacts on overall resource adequacy and

---

[28] Technology Neutral and No New Combustion 2040 portfolios from PNM IRP.

[29] https://www.aps.com/-/media/APS/APSCOM-PDFs/About/Our-Company/Newsroom/McMickenFinalTechnicalReport.ashx?la=en&hash=50335FB5098D9858BFD276C40FA54FCE

[30] https://www.ksbw.com/article/second-battery-malfunction-in-less-than-6-months-reported-at-moss-landing-power-plant/39083568#

[31] https://www.12news.com/article/news/local/valley/incident-srp-battery-storage-facility-chandler-arizona/75-45b96a5e-14b5-4799-b777-e1195e24199f

[32] https://pv-magazine-usa.com/2022/04/26/battery-fire-at-salt-river-project-in-arizona/

resilience may be if they cannot. A number of uncertainties – particularly acute in the early years of new technology commercialization – may impact the effectiveness of energy storage as a capacity resource:

- **Outage rates:** one of the uncertainties associated with battery storage performance is the relative risk of experiencing plant outages; while manufacturer specifications indicate a low risk of plant outages, newly commercialized technologies can often experience unexpected outages for multiple reasons.
- **Performance under extreme heat:** the extreme summer temperatures of the Southwest create a difficult operating environment for electrochemical processes. In addition to potentially contributing to increased risk of outages, high temperatures could lead to degradation of output.
- **Dispatch uncertainties:** the dispatch of energy storage in the "Base Case" is an idealized representation of storage intended to maximize the economic arbitrage opportunities; however, real-world operations of energy storage may deviate from this ideal dispatch. A missed opportunity to charge or a discharge that precedes the timing in which it is most needed could inherently limit the effectiveness of storage.

Because there is little empirical data to inform precise estimates of these impacts, this study explores a broad range of sensitivities that vary both the outage rates and the amount of duration available from battery storage devices. The impacts of these uncertainties on resilience is tested by adjusting specific storage-related inputs:

(1) In the Heat wave case study, three sensitivities simulate combinations of forced outages of two large storage units and extremely high loads at the same time.
(2) In the Ice storm case study, one sensitivity simulates conservative battery operations. This is to understand system impacts in a winter extreme event of operating batteries for capacity rather than economic arbitrage.

As has occurred for other new technologies in their early stages of commercialization, experience and a longer operational history should help mitigate the risks surrounding these uncertainties. As engineering and construction firms, plant operators, and maintenance crews gain experience and build collective knowledge of how to manage grid-scale storage assets effectively, potential high outage rates in initial years of implementation are likely to decrease over time. What this means is that the questions around performance and the risk of outages are most uncertain in the next five years while the industry achieves its initial phase of commercial development.

3.4.2 Parameters for winter extreme event: Ice storm

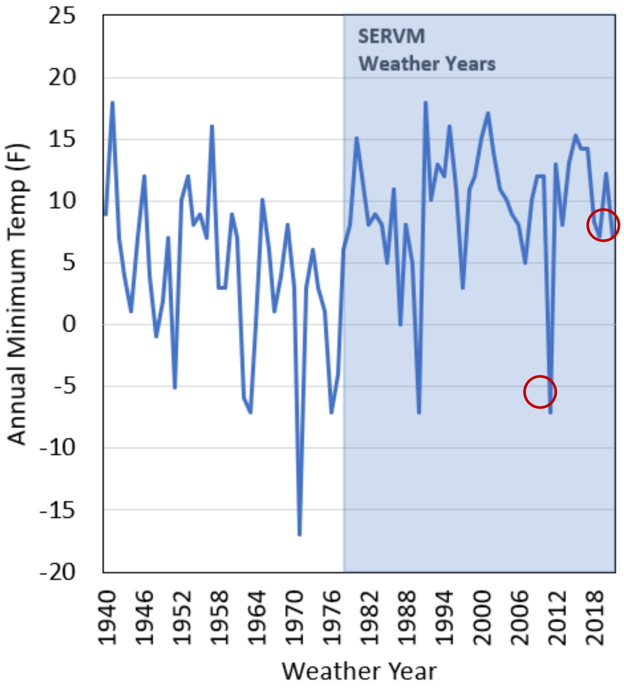
There were several candidate ice storms to use as a starting point for the winter analysis. One possibility was to perform a similar assessment to summer and assess and analyze the most recent event - the 2021 cold snap. Alternatively, synthetic data could be created for the 2011 cold weather event, and this could be utilized.[33] It was determined to use the 2011 data as, for PNM, this event was a much more severe

---

[33] It is worth noting that colder events have occurred than the 2011 event (see 1971). However, these data were not readily available for modeling purposes (Synthetic data was created back to 1980), and climate change could reduce the confidence in the likelihood of older weather years

weather event than 2021. The difference in severity between the two weather years is visualized in Figure 6: 2021 experienced a minimum temperature of 7 degrees, while 2011 saw temperatures down to -7. Though 2021 could have been simulated with more recent data, the risk of additional outages and load response caused by the colder temperatures was explored by simulating the more severe 2011 event.

Figure 6: Weather years and minimum temperatures. Compare minimum temperatures in 2011 and 2021 for PNM.



Similar methodologies to Heat wave simulations were used to model Ice storm generator outages and planned. The difference is that for the Ice storm case study, synthetic wind, renewable, and load data was used instead of actual data based on data availability as well as reasonableness of inputs (for example, customer use patterns have changed resulting in different demand shapes and loads have grown considerably). Table 5 summarizes the assumptions used for both case studies.

Table 5: Assumptions for both Heat wave and Ice storm case studies

Input	Heat wave	Ice storm
Weather Year	2020	2011
Solar Data	Actual Capacity Factor	Synthetic
Wind Data	Actual Capacity Factor	Synthetic
Load Data	Actual	Synthetic
Generator Outages	Monte Carlo	Monte Carlo
Planned Outages	Weather-Normal	Weather-Normal
Neighbor Assistance	IRP Assumptions	IRP Assumptions

---

[34] Actual capacity factors were applied to the installed capacity of the modeled portfolio

[35] Synthetic refers to the weather year modeling as described previously

3.4.2.1 Ice storm case study

For the Ice storm case study, a similar process was followed as for the Heat wave. 2011 weather conditions were used as the starting point for analysis (reflected as the base case). Other sensitivities reflect a progressively increasing risk to PNM. A description of all sensitivities in the Ice storm case study is provided in Table 6. The risk factors investigated through these sensitivities are further discussed below.

Table 6: Ice storm case study sensitivities

Ice storm Sensitivity #	Sensitivity Name	Description
1	Base	Base cold snap sensitivity
2	Island	PNM is simulated as an island (no neighbors, imports, or exports)
3	Island, Conservative Battery Operation	Island sensitivity, but batteries are operated as capacity only resources (no energy arbitrage).
4	Localized Plant Outages	2020 Ice storm ERCOT level of forced outages simulated for PNM. PNM is connected to neighbors
5	Regional Plant Outages	PNM and neighboring entities experience ERCOT level of outages
6	Outages + Island	ERCOT level of forced outages simulated for PNM. No support available from neighboring markets
7	Island + PNM South Generation Out	PNM loses access to south region generation for the week (simulating a major transmission fault, or fuel supply issues). For a loss of 500 MW of generation

Natural Gas Unit Outage Risks

One of the key risks investigated through sensitivity analysis of the Ice Storm case study is the impact of natural gas generator outages. A growing body of literature has highlighted the potential impact of correlated outages of natural gas generators on system reliability, a risk that may be present due to either the increased likelihood of generators to fail under extreme weather conditions or the chance that natural gas supplies may not be available for delivery to plants when needed. The blackouts experienced in Texas during 2021 Winter Storm Uri, which have been attributed to the systemic failure of natural gas supply, delivery, and generation infrastructure in the state, provide a stark real-world example of this risk.[36]

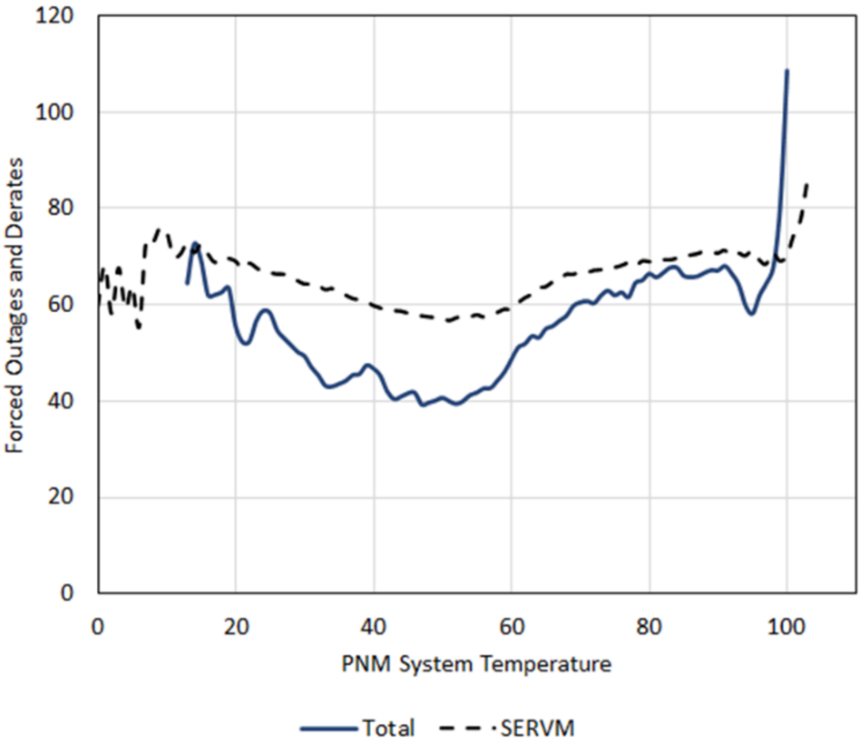
SERVM uses Monte Carlo simulation to model plant outages and derates. As part of the process of developing case studies for this analysis, historical outage data gathered from GADS was compared against outages simulated in SERVM under a range of temperatures. Monte Carlo samples are drawn from a historical seasonal distribution to ensure seasonal outage patterns are captured. Figure 7 shows a comparison of simulated and actual historical outages in PNM, illustrating that the frequency and

---

[36] PNM’s winterization efforts post-2011 have addressed this risk as mentioned on Page 8.

likelihood of outages modeled for natural gas plants under extreme temperature conditions (i.e., at very low and very high temperatures) aligns well with the historical record.

Figure 7: Simulated (SERVM) vs PNM historic outages



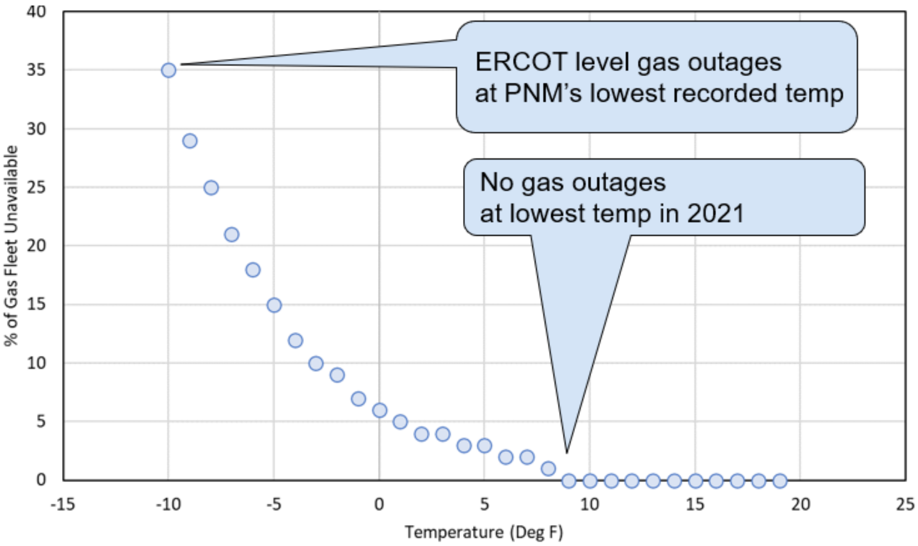
Due to limited availability and data quality, historical GADS data was not useful for analysis of correlated outages among PNM's natural gas generators. Nevertheless, this is a known risk[37] and this study examines the potential impacts of a higher level of natural gas generator outages as an upper bound on risk. For Ice storm sensitivities 3-6, depending on the sensitivity in question, simulations assume either PNM or PNM and its neighbors experience 2021 "ERCOT levels" of forced outages.[38] This is meant to represent the phenomenon where generators have an increased probability of experiencing a forced outage event as temperature decreases. For the Ice storm case study, a potential outage curve as a function of temperature was developed based on historic events. This hypothetical curve for PNM is shown below.

---

[37] Such a risk clearly existed in 2011 when several PNM generators were forced out either due to cold weather induced issues or lack of available gas. PNM's winterization efforts post-2011 have addressed this risk.

[38] Although ERCOT and PNM have very different regulatory market designs, this study uses ERCOT outages to derive a hypothetical gas unavailability curve with temperature. These are extreme events and very little geography specific data is available and this study uses the limited data available. This is not meant to represent actual correlations between PNM gas outages and temperatures.

Figure 8: Hypothetical gas unavailability based on ERCOT 2021 outages

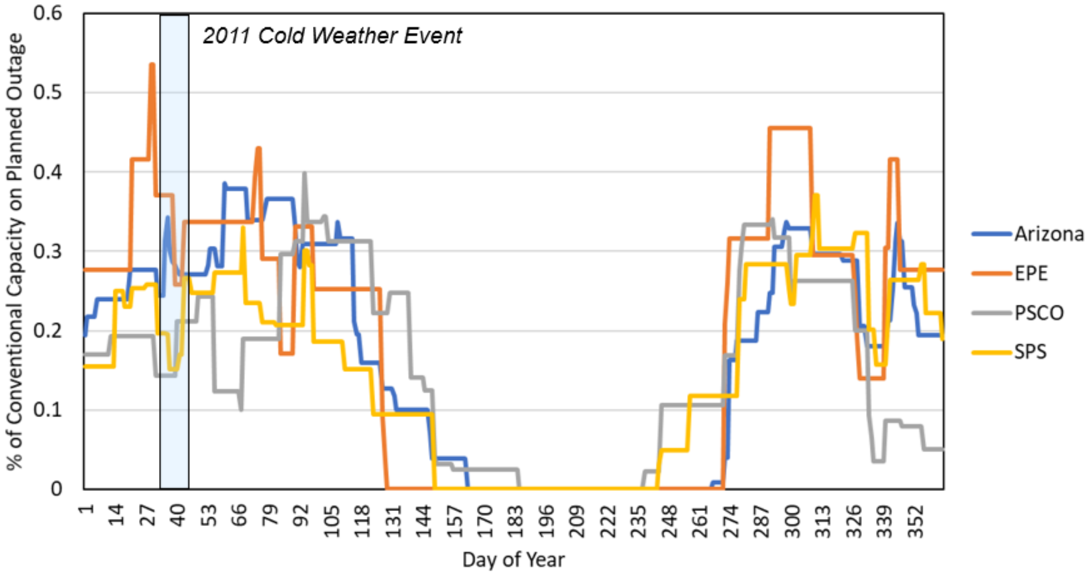


The curve in Figure 8 is meant to reflect hypothetical PNM outages. Since this study aims to consider conditions representative of an ice storm centered over PNM, it is assumed that neighbors would face this phenomenon too, but to a lesser degree. To reflect this, in sensitivities where PNM's neighbors experience cold weather-correlated forced outages, they experience half the outages that PNM does.

Market Assistance Risks

Additionally, neighboring entities for the "Southwest Outages" sensitivity were assumed to have planned maintenance which could not be recalled for the event. A 15% planned + maintenance outage rate was assumed and scheduled to minimize maintenance during high load days. This creates the time series of maintenance events shown in Figure 9.

Figure 9: Maintenance events in southwest outages sensitivities



3.4.3 A note on PNM’s ability to import from neighbors

PNM has roughly 800 MW of transmission connectivity to Arizona Public Service Company (AZPS) but the ability to deliver to the load centers is dependent upon several complicating factors based on real-time operations of the system. PNM also has transmission connectivity with other neighboring regions as well, albeit with less transfer capability (e.g., EPE, Tri State, SPS). This means, technically it can import large amounts of power from its neighbors. Historically, in summer, actual imports were quite limited (averaging 50 MW during high net peak loads) as this is also the time when the entire region needs power. For example, during the 2020 heat wave, PNM found it difficult to procure power even when they offered high prices. In contrast, winter-time imports were relatively unconstrained due to the lack of an event that simultaneously stressed both PNM an its neighbors. For example, during the Feb 2021 ice storm, PNM was able to rely on west-wide imports because there was excess power available west-wide and importantly, there was no transmission outage on PNM’s connections to its neighbors. To isolate PNM’s system performance under extreme conditions, in some sensitivities PNM was simulated as an island i.e., it has zero ability to import from neighbors. In such sensitivities, if the results show lost load within PNM, it does not mean that load will necessarily have to be shed. Rather, this is meant to demonstrate the level of PNM’s dependance on its neighbors after fully utilizing its own resources. If actual market support ends up being less than the “load shed” in a particular island sensitivity, then PNM will actually have to shed load.

4 Sensitivity Analysis Results

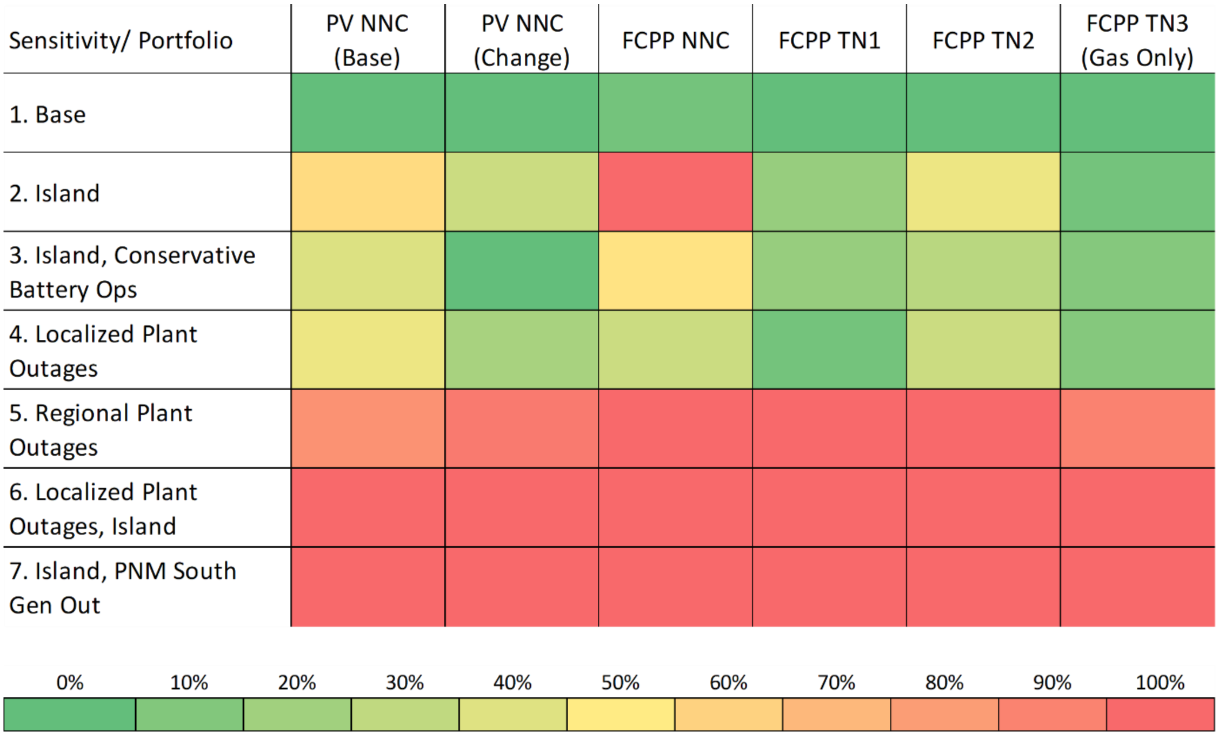
In Section 3, the modeling framework used, the portfolios tested, and the data and assumptions for each case study was presented. In this section, the metrics used in this study to measure portfolio performance during resilience events are presented followed by modeling results for all the sensitivities simulated.

4.1 Ice storm case study results

All metrics used to measure and compare portfolio performances during an ice storm are presented in this section. Figure 10 shows the probability of load shed during the event as a heat map where red indicates 80-100% chance of load shedding. Table 7-11 show the expected MWh lost, expected peak MW shed, and number of load shed hours (duration of load shed).

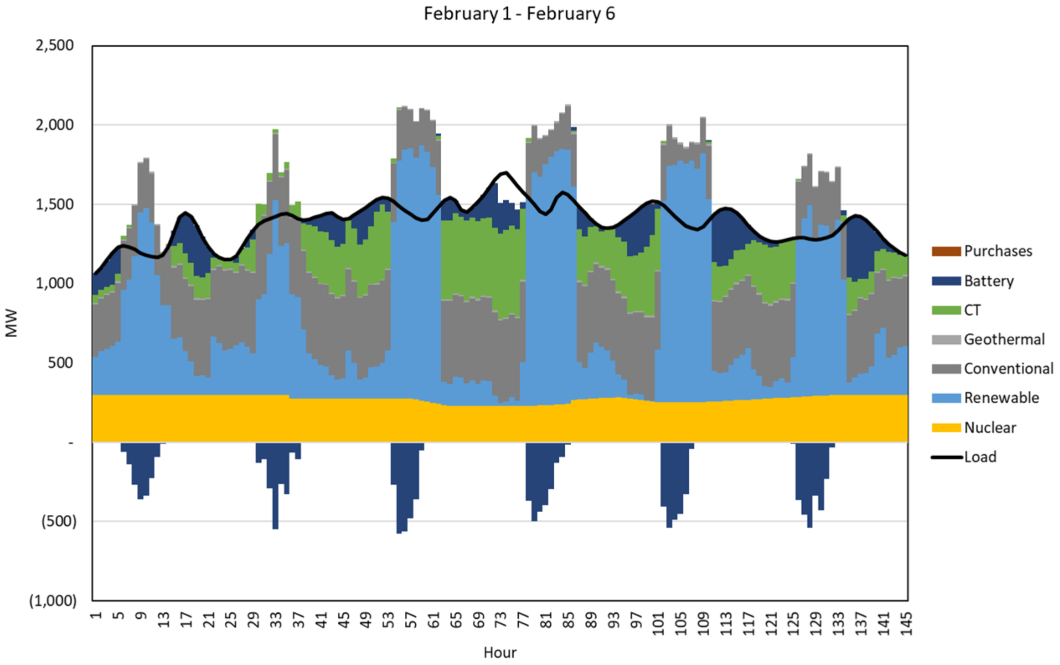
Figure 10 shows that in the base case i.e., in a situation where temperatures are low in PNM, but PNM has ample access to its neighbors and experiences no extraordinary unforeseen generator outages, the odds of blackouts are very low. A critical factor is market support – in Island mode, the odds of blackouts in PNM greatly increase. Weather-correlated generator outages in PNM, those affecting PNM's neighbors, and losing market support either due to transmission faults (which are to be expected in ice storms) are all factors that compound with each other to drastically increase the chances of lost load. If PNM's neighbors too experience generator outages during the Ice storm, PNM will most certainly face blackouts as well.

Figure 10: Probability of load shed during ice storm



'Base', 'Island', and' Island with Conservative Battery Operations'. The results show that PNM will be able to get through an ice storm in the base case if it can rely on its neighbors for imports (i.e., in the base case, when temperatures are low, but there are no weather-correlated generator outages in PNM or across the southwest). Comparing results in Table 7 for the base sensitivity and the Island case, depending on the portfolio being tested, the Island case shows 181-702 MWh of lost load if PNM is unable to import power during the storm (See Figure 11). The implication here is not that PNM will inevitably have to shed load during an ice storm; rather, it demonstrates the level of market support required after PNM uses all its internal resources fully.[39]

Figure 11: Island Sensitivity dispatch plot during critical week



The next sensitivity, Island with conservative battery operations, from Tables 9, 10, and 11 shows that the impact of islanding can be lessened to a degree by conservative battery operations (compare Island to Island with conservative battery ops). Notably, just operating existing batteries conservatively[40] ensures that PNM's system is better able to withstand the event when measured using a variety of metrics – the probability of load shed is lower, the peak MW shed is generally lower, and the duration of loss of load is also shorter.

---

[39] In this study, for winter, PNM's import capability is limited by each neighbor interface (990 MW total).

[40] See Section 4.1.1 for an explanation of conservative battery operations.

Table 7: Average lost load for tested portfolios across Ice storm case study

Sensitivity	Study Assumptions			Average Load Shed (MWh)					
	PNM as an Island	Cold Weather Outages	Battery Economic Arbitrage	PV NNC (Base)	FCPP NNC	FCPP TN1	FCPP TN2	FCPP TN3 (Gas Only)	PV NNC (Change)
Base	No	No	Yes	-	6	-	-	-	-
Island	Yes	No	Yes	461	702	310	494	176	181
Island, Conservative Battery Ops	Yes	No	No	342	412	213	452	103	127
PNM outages	No	Yes	Yes	18	20	3	15	4	11
Southwest Outages	No	Yes	Yes	385	812	572	674	218	196
Outages + Island	Yes	Yes	Yes	4,345	6,227	4,701	5,156	3,218	3,260
Island + PNM South Gen Out	Yes	Yes	Yes	21,253	26,157	17,284	22,958	15,400	15,111

‘PNM outages’ and ‘Southwest outages’. The ‘PNM outages’ sensitivity shows that if PNM experiences cold weather correlated generator outages (as detailed in Section 0), similar to ERCOT during the 2021 winter, some load is shed, but mostly it can reply on neighbors to minimize lost load. However, when both PNM and neighbors experience cold weather correlated outages (‘Southwest outages’), although PNM can import from its neighbors, because supply conditions are tight across the southwest, lost load becomes worse in PNM. Figure 12 shows an example of dispatch within PNM during such conditions (FCPP NNC portfolio) – note that owing to reduced firm generation within PNM and tight conditions across the southwest, despite relying on purchases from the external market, PNM sheds load.

Figure 12: Southwest outages scenario with FCPP NNC portfolio.

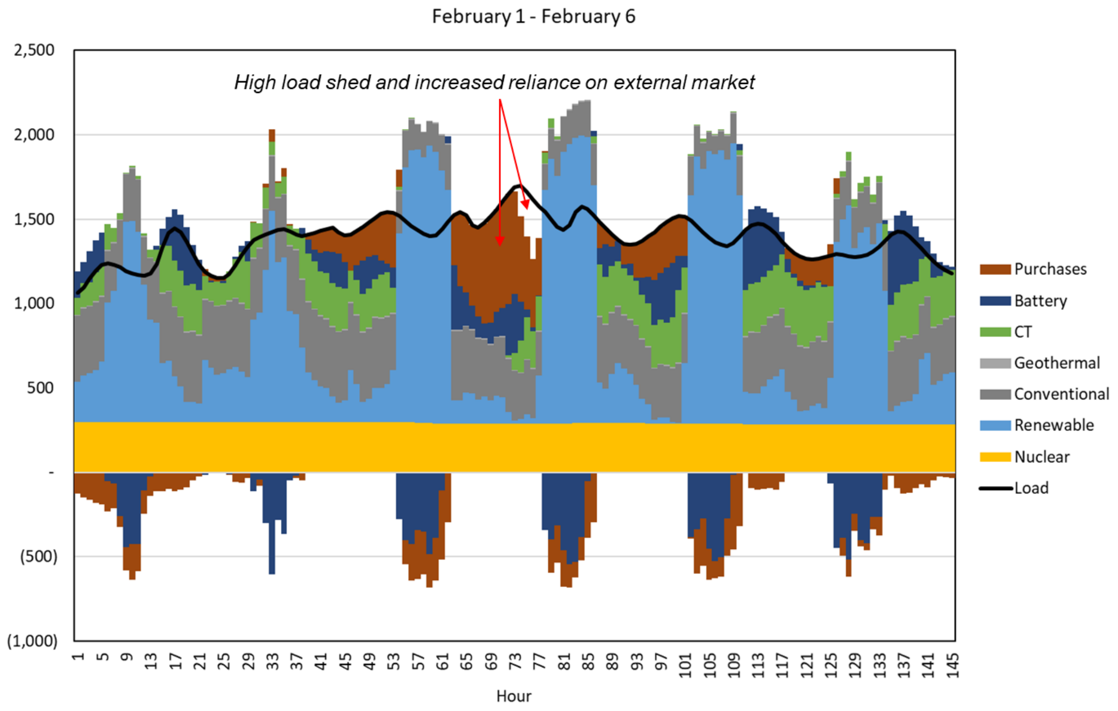


Table 8: Peak MW shed across Ice storm sensitivities

Sensitivity	Study Assumptions			Maximum Load Shed (MW)					
	PNM as an Island	Cold Weather Outages	Battery Economic Arbitrage	PV NNC (Base)	FCPP NNC	FCPP TN1	FCPP TN2	FCPP TN3 (Gas Only)	PV NNC (Change)
Base	No	No	Yes	-	28	-	-	-	
Island	Yes	No	Yes	513	606	530	565	315	335
Island, Conservative Battery Ops	Yes	No	No	517	596	521	550	379	379
PNM outages	No	Yes	Yes	31	79	26	44	33	81
Southwest Outages	No	Yes	Yes	83	140	116	121	78	81
Outages + Island	Yes	Yes	Yes	942	1,164	1,151	1,050	845	889
Island + PNM South Gen Out	Yes	Yes	Yes	959	1,063	936	1,020	911	922

'Outages+Island'. The situation is further worsened if PNM is completely cut off from its neighbors while facing weather-related forced outages. Again, this sensitivity is only meant to showcase PNM's potential dependence on its neighbors. The load shed dramatically increases by at least two orders of magnitude (compared to the 'PNM outages' case') if PNM's access to its neighbors is cut off. This points to the joint impact of weather-correlated outages and limited market support.

'Island+PNM South Gen Out'. On top of facing heightened gas outages and no market support, this sensitivity assumes that 500 MW of generation in PNM-South is lost. This is meant to be a proxy for either a major transmission fault or fuel-supply issues during the ice storm. As expected, this sensitivity sees the worst performance mainly due to a significant portion of PNM's generation being out.

Table 9: Duration of outage

Sensitivity	Study Assumptions			Duration of Outage (hrs)					
	PNM as an Island	Cold Weather Outages	Battery Economic Arbitrage	PV NNC (Base)	FCPP NNC	FCPP TN1	FCPP TN2	FCPP TN3 (Gas Only)	PV NNC (Change)
Base	No	No	Yes	-	2	-	-	-	-
Island	Yes	No	Yes	14	21	7	17	6	7
Island, Conservative Battery Ops	Yes	No	No	8	11	7	10	5	5
PNM outages	No	Yes	Yes	5	4	1	5	1	4
Southwest Outages	No	Yes	Yes	9	8	8	8	6	5
Outages + Island	Yes	Yes	Yes	33	35	31	32	24	23
Island + PNM South Gen Out	Yes	Yes	Yes	78	79	58	74	63	72

Winterization and conservative battery operations help mitigate the impacts of the ice storm. The only difference between the 'Island' and 'Outages+Island' sensitivities is whether PNM's own generators are winterized or not. Comparing results from these sensitivities, during resilience events, winterization helps reduce load shed by an order of magnitude. Furthermore, the odds of having a blackout are reduced with winterization. A similar mitigation pattern, albeit to a smaller degree, can be observed with operating batteries conservatively i.e., being dispatched only to avoid load shed. Winterization and conservative battery operations are actions that are portfolio agnostic i.e., irrespective of what portfolio is tested, these actions deliver benefits.

Portfolio comparison. To understand differences in portfolio performance, columns in Tables 9, 10, and 11 should be compared. Figure 13 demonstrates key insights from portfolio comparisons in an easy-to-understand format. To create these portfolio-bubbles, results for each portfolio from all Ice storm sensitivities were sized according to expected MW shed in the most binding hour.[41]

---

[41] See Appendix for the exact weights used. It should be noted that this is just one way of assigning weights to sensitivities. They can be weighed differently.

Figure 13: Ice storm simulation results. Sensitivity metrics were weighted using an inversely proportional scale.

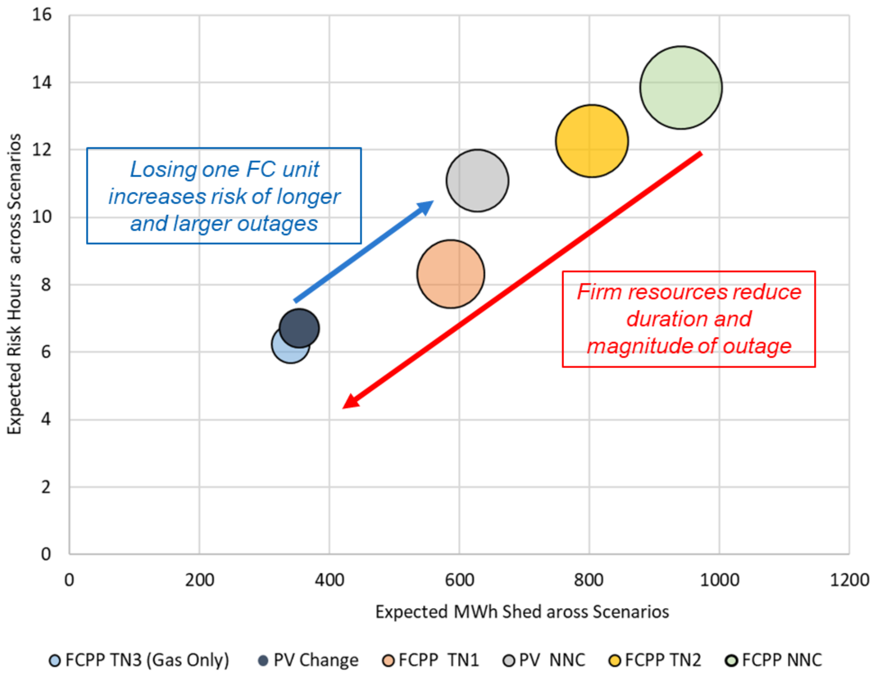
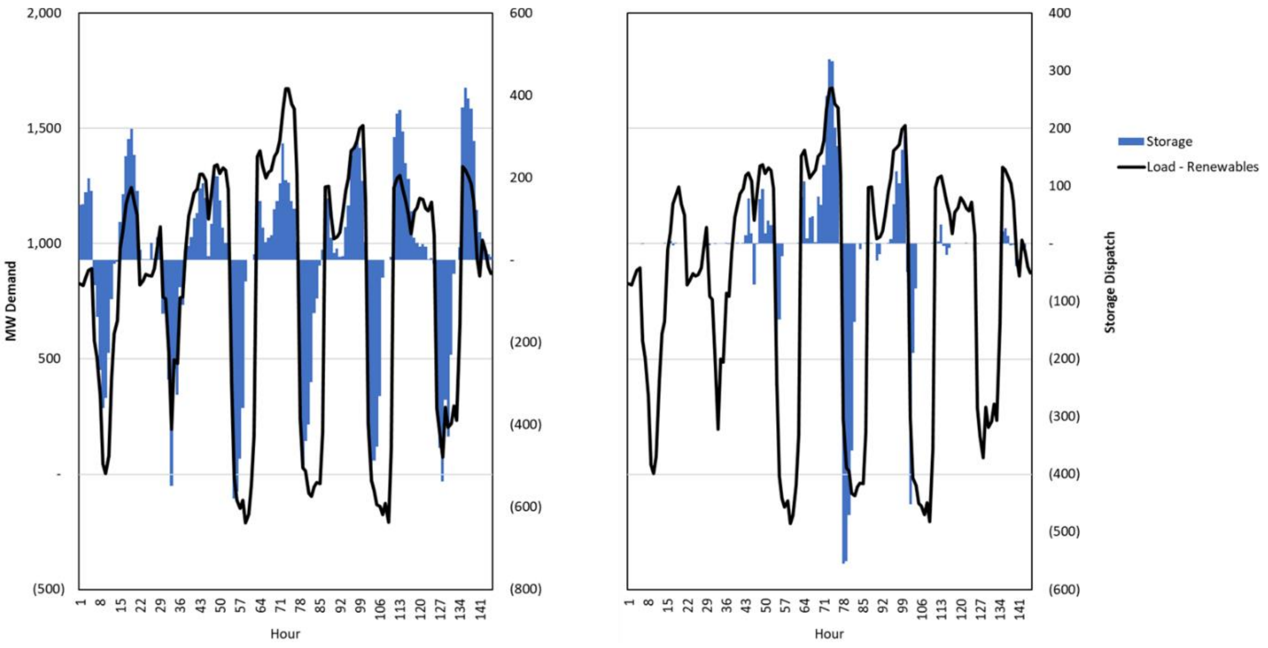


Figure 13 shows three metrics in the same chart, expected MWh shed across the sensitivities (on x-axis), duration of outage (y-axis) and worst MW shed (bubble size). Portfolio-bubbles that score well on all three metrics are those that are closer to the left bottom of the chart and are relatively small. Figure 13 shows that firm resources reduce both the duration and magnitude of the outage. Similarly, when one of the Four Corners unit is forced to go on maintenance, the duration and magnitude of outages increase. A portfolio that includes 39 MW of additional gas (FCPP TN2) instead of 48 MW of 2hour batteries (FCPP NNC) performs better when measured on these metrics. The system is severely energy constrained during resilience events and even if short-duration batteries are used in capacity mode, they are less reliable than firm generation such as gas. The general inference is that firm generation (whether it is gas-based, hydrogen-based, or long-duration storage) will help PNM weather ice storms better.

4.1.1 Conservative battery operation

The 'Island and Conservative Battery Operations' sensitivity showed that storage, operated conservatively, helps in reducing the total load shed, duration of the outage, and generally reduces the peak MW shed. In conservative operation mode, production cost savings from storage (through daily cycling) are sacrificed for enhanced reliability value. In this mode, storage will only discharge to avoid load shed. Figure 14 shows battery operations in the same dispatch week in economic arbitrage mode (regular) and capacity mode (conservative). On days 1 and 2, in the regular mode, the battery charges and discharges reacting to prices – charging when there is an excess of renewables and discharging when energy prices are higher. Conversely, in conservative operation mode, storage does not discharge at all on days 1 and 2, but on days 3-5, it discharges to mostly meet peak net demand and these are the days with the most extreme weather conditions and load is being shed.

Figure 14: Battery cycling in regular mode (left) driven by economic arbitrage opportunities and conservative mode (right). Note that the second axes are of different scales in both charts



4.2 Heat wave case study results

This section summarizes the performance of portfolios under different heat wave sensitivities that were examined. Table 10 shows the expected MWh of load shed under each pre-defined event across 25 simulations. Table 11 shows the expected value of worst-hour load shed in MW across 25 simulations and

Table 12 shows the total number of hours in which loss of load was observed.

The modeling generally indicates that PNM is better positioned to withstand a heat wave than an ice storm. In both the base and Island sensitivities, PNM sees no load shed for any tested portfolio. This is not surprising as all portfolios were designed to meet 0.2 LOLE in the RA planning, and this confirms that portfolio performs as expected. Furthermore, it is no surprise that the island case behaves similarly to the base case as only 50 MW of maximum market support was allowed in the Heat wave case study (as opposed to the Ice storm case study, which did not limit market depth). Simply put, the portfolios behave as expected in these two sensitivities.

When load was increased to a 1-in-20 year load, the model reports shedding anywhere between 37 – 162 MWh depending on the sensitivity. A similar effect was observed (loss of load of 18 – 196 MWh) when simulating outage of the largest storage facility (G1 sensitivity, loss of 150 MW). As expected, the loss of the largest two storage units (G2 sensitivity, 300 MW total lost) results in even more load shed. The worst simulated case here combines the loss of the two largest storage units with the 1-in-20 year load which results in shed load in the range of 540-989 MWh. Peak MW shed and duration of the outage also follow similar overall patterns: outages become worse when very high loads occur simultaneously with the loss of one, or two large generating units. Figure 15 shows an example of lost load in summer in the 'G2+1-in-20' year load scenario. Although not shown in the report, dispatch is similar across the tested portfolios for this scenario. Loss of large generators combined with high loads leads to lost load in the evenings. Even after fully discharging, the remaining storage falls short of meeting evening loads.

Table 10: Average load lost across Heat wave case study

Sensitivity	MWh				
	PV NNC	FCPP NNC	FCPP TN1	FCPP TN2	FCPP TN3 (Gas Only)
Base	~0	*Not Assessed*			
Island	~0	*Not Assessed*			
1 in 20	74	162	45	50	37
G1	81	196	141	82	18
G2	198	408	316	298	210
G2 + 1 in 20	720	989	786	804	540

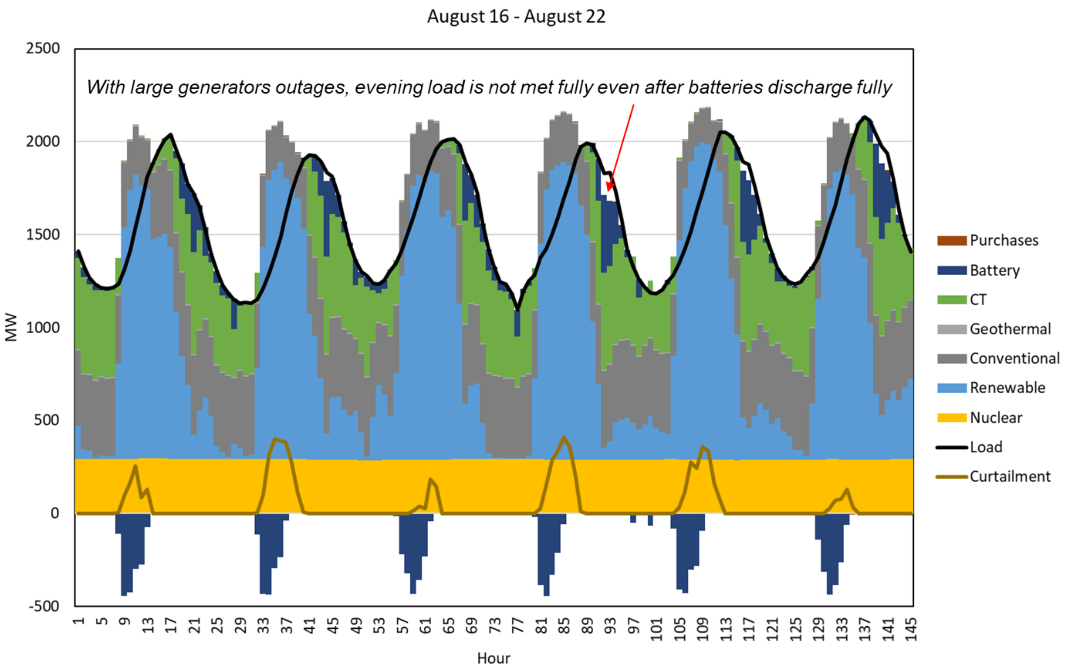
Table 11: Peak MW load lost across Heat wave sensitivities

Sensitivity	MW				
	PV NNC	FCPP NNC	FCPP TN1	FCPP TN2	FCPP TN3 (Gas Only)
Base	~0	*Not Assessed*			
Island	~0	*Not Assessed*			
1 in 20	29	28	13	27	13
G1	23	31	34	18	14
G2	64	63	76	70	54
G2 + 1 in 20	151	160	164	137	118

Table 12: Duration of the load outage

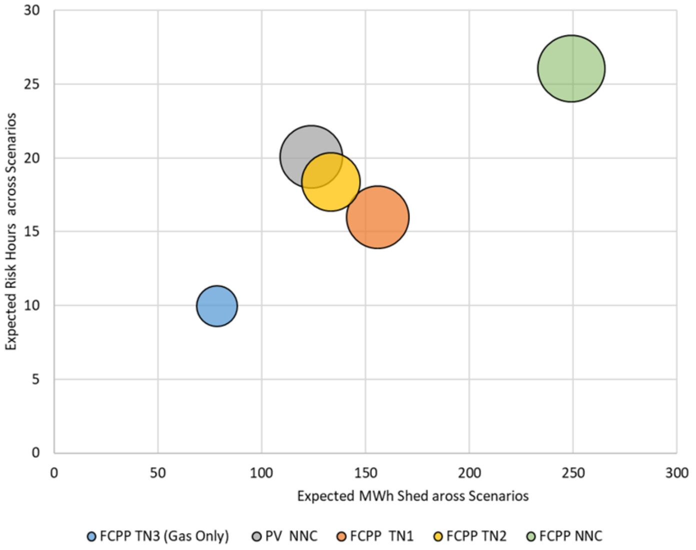
Sensitivity	Hours				
	PV NNC	FCPP NNC	FCPP TN1	FCPP TN2	FCPP TN3 (Gas Only)
Base	~0	*Not Assessed*			
Island	~0	*Not Assessed*			
1 in 20	19	20	9	12	9
G1	19	24	17	21	6
G2	21	41	28	27	18
G2 + 1 in 20	37	49	31	26	25

Figure 15: G2+1 in 20 scenario dispatch with FCPP NNC portfolio



Portfolio comparison. Similar to Ice storm case study, the performance of the portfolios was aggregated across sensitivities to produce a simple representation of the performance of a specific portfolio in the three metrics. Figure 16 below shows the aggregated results. In this chart, each dot represents a portfolio. The horizontal axis shows the expected load shed in MWh across sensitivities, and the vertical axis shows the expected hours with load shed across sensitivities. The size of the dots shows the expected worst load shed in MW across sensitivities.

Figure 16: Heat wave simulation results. Sensitivity metrics were weighted using an inversely proportional scale.



Similar to winter, during heat waves too, firm resources improve the generators’ performance. The more firm resources there are in the system, the less load shed (measured in all three metrics) there will be during extreme summer events like an unexpected load spike during heat waves or loss of battery storage due to high temperatures. Figure 16 shows that PNM’s system has the least load shed on average with the FCPP TN3 portfolio, and has highest load shed on average with the FPCC NNC portfolio. The performance of the PV NNC portfolio, the FCPP TN1, and the FCPP TN2 portfolio lie in between with limited amount of coal or gas resources in the resource mix. This is an indication that energy-limited resources like battery may provide limited support during heat waves and that thermal resources have more flexibility and can provide better support to the system during summer weather events when fuel supply is not interrupted. This may also indicate the length of storage pursued in these portfolios may meet LOLE standards but may expose PNM to increased risk of larger MWh shed events. Longer duration storage would likely mitigate the severity of such extreme events.

5 Conclusions and Next Steps

New Mexico is pursuing ambitious emission reduction goals and the electric sector is poised to play a key role. PNM has committed to play its part by setting itself a goal of emission-free electricity by 2040. The IRP process through its focus on Resource Adequacy ensures that the cost-effective capacity investments are being made that reduce emissions adequately while maintaining a reliable grid. Still, one of the limitations of the RA modeling is that extreme weather events cannot be adequately represented. The core of the problem is that while extreme weather events are predicted to increase, there is still very little or no data to assign probabilities to specific types of extreme events. This study takes first steps to address this problem by presenting a framework that contextualizes extreme weather event resilience with resource adequacy. This framework recognizes that resource adequacy and resilience are related but different.

The first step was to understand and characterize extreme weather events of interest to PNM. Based on discussions with PNM SMEs, and mining historical weather and load data, two types of events were decided – ice storms and heat waves. PNM's recent experiences with the 2011, 2021 ice storms and the 2020 heat wave supports this. Next, several hypothetical sensitivities of these events were parameterized. Working with PNM SMEs and based on historical weather and operational data, this was done by combining different levels of variables such as temperature, loads, outages, and market support. In parallel, a suite of portfolios based on a hypothetical Four Corners replacement were assembled to be tested, to evaluate their performance during extreme weather events.

The following conclusions, drawn from the analysis conducted in this study, provide insight into the nature, and mix of resources necessary to mitigate the impact of extreme weather events on PNM system:

- ***PNM's Resource Adequacy planning practices work as expected and allow PNM to maintain reliability under most summer conditions.*** PNM's resource planning framework is designed to meet a loss of load expectation (LOLE) standard of 0.2 days per year.[42] This standard allows for some probability of reliability events – typically in the summer peak – but also ensures that their occurrence is rare. The modeling in this study confirms that the RA process works as intended, illustrating that PNM's resource portfolios are able to meet loads reliably under most – but not all – summer conditions. In extreme circumstances – for instance, if summer loads reach 1-in-20 year levels, or if summer temperatures force large amounts of PNM generation or transmission to be offline -- PNM might experience loss of load events.

- ***PNM's system is designed for a summer peak but may still be vulnerable to extreme events in winter.*** PNM's system is designed to meet an RA standard that is based on summer peak. This study finds that in ice storms, if multiple generators are forced offline (as happened in PNM in 2011 and in Texas in 2021) either due to transmission failure or generator malfunction – or if the region as a whole experiences significant loss of generating capability – PNM may experience loss

---

[42] PNM plans to move to a 0.1 LOLE standard in the next IRP cycle.

of load. These types of events are outside the envelope of PNM’s traditional resource adequacy planning but do present a reliability risk to customers.

- ***Different resource portfolios that meet the same LOLE planning standard have varying performance during extreme events.*** All tested portfolios met the same LOLE standard of 0.2 days per year. This study shows that although the portfolios are all designed using the same resource adequacy standard, their performance varies widely in extreme weather simulations. In other words, the likelihood that an extreme event might result in an outage – and the size of its impact – may vary under different portfolios.

- ***Stress testing candidate portfolios for resilience can help identify differences in their performance.*** In the long-term, portfolios should be designed (and corresponding modeling frameworks developed) that successfully address both resource adequacy and resilience concerns. In the short-term, cost-effective candidate portfolios from the resource adequacy IRP process should be tested for resilience. The insights from such stress testing should be used to inform capacity investments that PNM makes.

- ***Weatherization of all generation resources to allow for performance under extreme conditions is an important resilience consideration.*** In the winter events studied, winterization measures for natural gas generators are demonstrated to have a large impact on the size, frequency, and duration of loss of load events. PNM has already invested in winterization of its own generation assets and has added criteria to PPAs to ensure wider temperature operating requirements. Similar to winter, engineering and operational measures to ensure resources are available under extreme summer temperatures – including natural gas and energy storage – can reduce the risk of loss of load events due to coincidence of high loads and widespread unit outages.

- ***Firm generation resources reduce the severity of extreme event impacts in both summer and winter.*** During severe weather events, firm resources – resources that are not energy-limited, help reduce both magnitude and duration of load outages and generally reduce the instantaneous power lost (peak MW). While winterization is one way to firm resources up, the operating characteristics of resources must also be considered. Firm resources need not be conventional fuel based, but instead could include hydrogen-fueled generators or long-duration storage.

- ***During ice storms, broader southwest dynamics will have significant impact on PNM’s ability to avoid outages under winter extreme events.*** Historically, PNM has relied on neighbors’ support during regional extreme winter weather. The notion of reliance on the external market for support during winter conditions is also built into PNM’s resource adequacy planning practices, which allow for significant levels of imports in the winter season. This dynamic means that PNM’s ability to maintain reliability under regional-scale extreme events may depend not only on the characteristics of its own loads and resources but on dynamics in the broader footprint of the Southwest region. Further, although not examined in this study, this points to the importance of PNM’s transmission infrastructure (and the need to examine its vulnerability) during ice storms.

- ***As PNM increases its energy storage portfolio, its operational limits and utilization should be understood and considered in resource adequacy modeling.*** Conservative battery operations, where load shed is prioritized over economic arbitrage, helps mitigate the duration of outages during extreme operational stress. These considerations should be adequately reflected in resource adequacy modeling in addition to informing operator training and designing battery protocols.

5.1 Next steps

There are many questions this study raises that need to be explored in further studies and through stakeholder engagement. PNM, whose portfolio was historically mainly firm fossil generation is on track to meet its clean energy goals by incorporating more renewable variable generation into its portfolio. PNM's IRP process ensures that the resulting portfolio always meets the RA standard of 0.2 LOLE. In other words, replacing fossil-generation with renewables is being done in a manner in which grid reliability, as defined by the RA standard, is always maintained. The RA standard in turn is tied to system peak load (in summer) and this study shows that indeed, all portfolios designed to meet the RA standard perform as expected when PNM's load reaches 1-in-10 year levels.[43] They key difference though is that during extreme HILF weather events, both in winter and summer, portfolios with more firm generation generally perform better than their counterparts with less firm generation, even though all of them meet the same reliability standard.

5.1.1 Is a LOLE standard adequate for PNM?

The analysis in this study shows that PNM's current RA standard of 0.2 LOLE is not enough to withstand extreme summer or winter events. Follow-up studies can focus on asking if PNM should explore alternate or complementary standards to the RA standard.[44].

Since the nature of extreme events is different for different geographic areas, any metric that considers portfolio response during extreme events should be tailored to the specific threats PNM might face. For example, in an ice storm, since the duration of the outage is most important, a complementary metric designed around the number of hours of load shed seems appropriate. Designing such a metric also addresses the complication that the Value of Lost Load (VOLL) increases with every passing hour during an extreme weather event.

It should be noted that it is not necessary to have new metrics; metrics such as Unserved Energy or duration of outage can be merged with the resource adequacy LOLE standard. Defining metrics that are tailored to PNM's unique geography, weather conditions, and portfolio will ensure that portfolios are designed to fill in the gap between portfolio planning and performance.

---

[43] See results from Summer base case.

[44] PNM's move to 0.1 LOLE in the next IRP cycle will ensure that more capacity is built, and the summer metrics measured in this study are likely to improve.

5.1.1.1 Testing IRP candidate portfolios against HILF events

In the short term, while the question of expanding or appending planning metrics is being answered, an immediate next step would be to test candidate portfolios from the IRP or other PNM modeling and procurement processes against PNM-specific extreme events such as the ones this study considers. This will ensure that prior to procurement, PNM possesses at least a qualitative understanding of how each of the candidate portfolios might perform during summer or winter extreme events. Once the question of appropriate planning metrics for PNM has been clarified and adopted, the new standard(s) can be used to determine PNM's investments.

5.1.2 What is the role of firm generation during extreme events?

This study also highlights the importance of firm generation's role during extreme events. The analysis in this study indicates that firm, dispatchable, and weatherized generation is one way to cost-effectively meet resilience challenges. But answers to questions about the type of firm generation, the capacity required, and the operational constraints they are likely to face during extreme events will inform procurement decision-making. For example, consider Figure 17 and Figure 18. Figure 17 shows the FCPP NNC portfolio[45] performance during the winter critical week. Compare this figure with Figure 18, which shows the PV NNC portfolio (where Four Corners continues to operate). This comparison shows that having more firm generation in the mix results in reduced load shed and reliance on purchases even though that firm generation is subject to correlated outages due to extreme weather.

---

[45] In this portfolio, Four Corners is replaced with a combination of solar, 2-hr, and 4-hr batteries

Figure 17: Portfolio comparison: FCPP NNC during winter extreme event

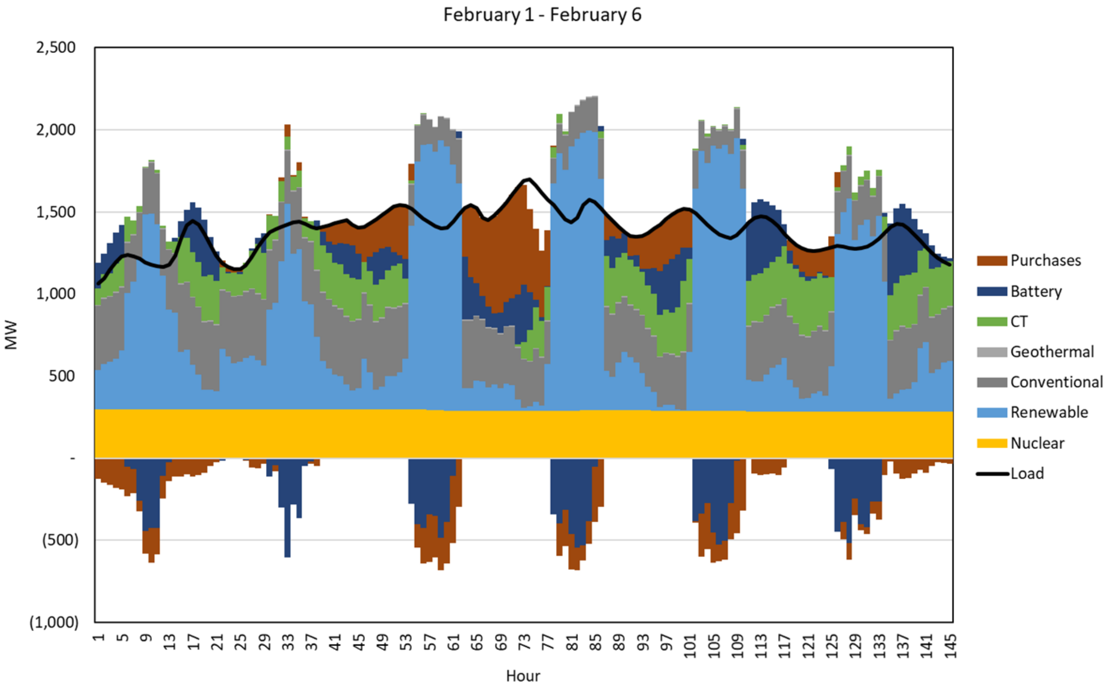
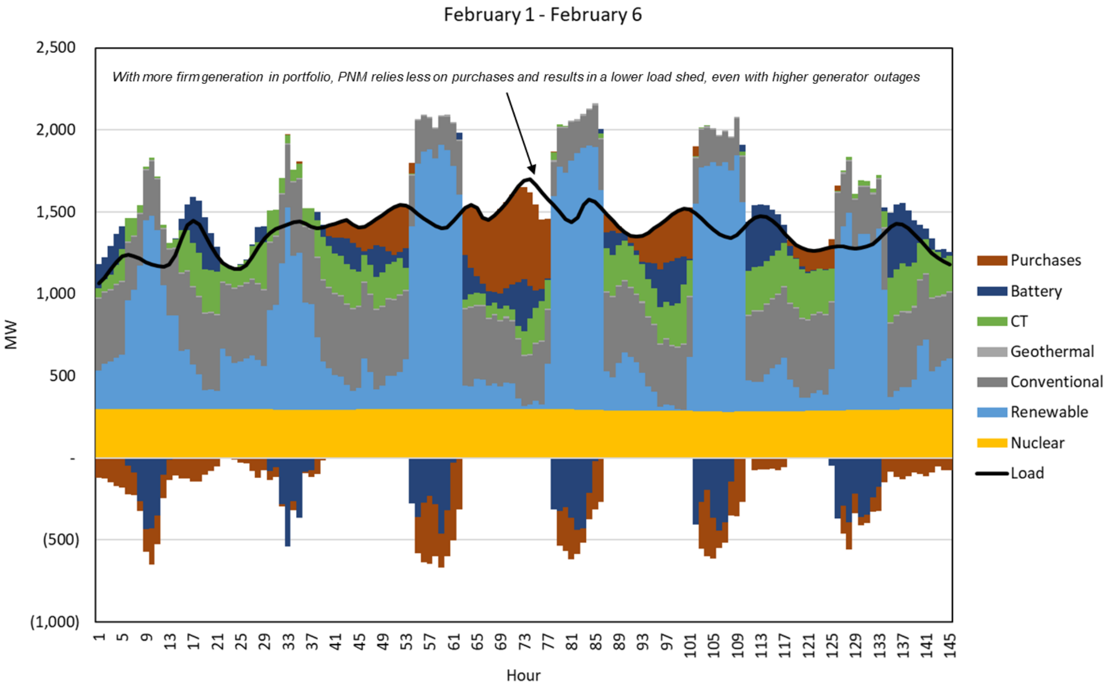


Figure 18: Portfolio comparison: PV NNC during winter extreme event

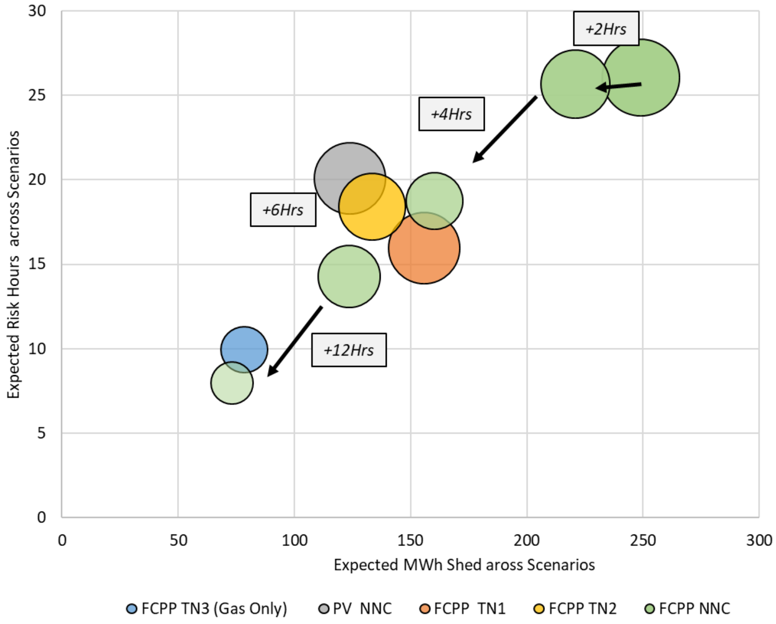


With more firm generation in portfolio, PNM relies less on purchases and results in a lower load shed, even with higher generator outages

In fact, firm generation need not be restricted to conventional generators alone. It could include gas generators with or without CCS, hydrogen or other zero-carbon fuels burned in CTs/CCGTs, advanced nuclear or long-duration storage. In the comparison example shown above, if the short-duration storage in the FCPP NNC portfolio is replaced by longer duration storage, its performance in extreme events becomes similar to portfolios with more firm generation.[46] This is shown in Figure 19, where increasing the duration of the 2-hour and 4-hour batteries in the FCPP NNC portfolio first by 2 hours each (making them 4-hr and 6-hr batteries respectively) improves all three metrics measured. This improvement continues as storage duration is progressively increased until the batteries are of 14-hours and 16-hours duration, at which point, the new portfolio's (with longer duration storage) performance becomes similar to the 'FCPP TN3 (gas only)' portfolio.

Figure 19 shows that long-duration generation can serve as one alternative to gas generation with comparable performance under extreme events. Additionally, it supports the argument made in Section 5.1.1 about the need for PNM to explore LOLE standard alternatives. Standards such as LOLE, that are driven by peak load alone will not incentivize investment in long-duration storage. Rather, a multi-hour need for energy, which is very likely to be the constraining factor during extreme events, must be captured in standards. Exploring the nature of firm generation that PNM needs and its relationship to planning standards is a topic of further study.

Figure 19: Increasing storage duration results in similar performance under Summer extreme events



Next, consider Figure 20, which shows operations during the winter critical week when PNM is treated as an island (winter sensitivity #2), and Figure 21, which shows the same situation but with batteries operating conservatively to minimize load shed (winter sensitivity #2). Batteries are usually thought of as a way to firm variable generation up, but these figures show that their duration and operational

---

[46] As measured by the three resilience metrics used in this study – Magnitude of load shed, Duration of load outage, and Peak MW shed.

characteristics are critical factors to consider while drafting procurement contracts. As shown in Figure 19, longer duration batteries improve grid resilience.

Figure 20: Winter ice storm. PNM as an island case.

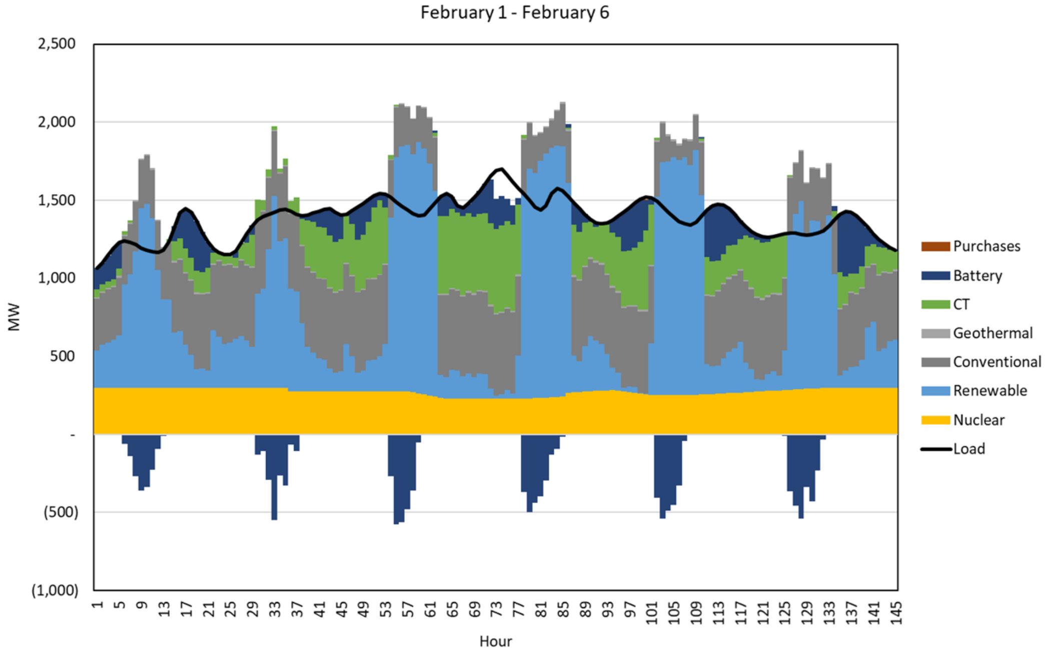
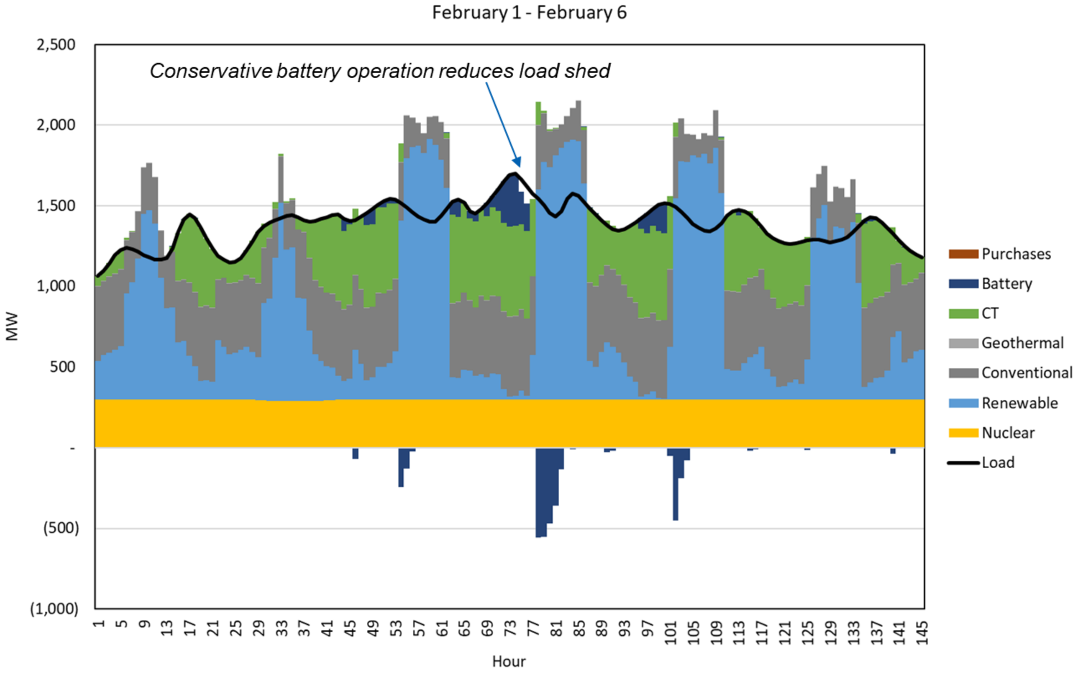


Figure 21: Winter ice storm. PNM as an island and batteries operated conservatively.



These figures show some of the challenges that PNM must confront during critical weeks of extreme weather. Next steps for this study should therefore explore the role of firm generation in PNM - specific firm resources options available to PNM, their quantities, and their operational characteristics whether they are hydrogen-based or long-duration storage, and their procurement process. It should also address questions related to emissions from firm resources during extreme events in the context of PNM's clean energy goals, and their costs.

5.1.3 What are the local or distribution-level impacts of severe weather events and their associated mitigation strategies?

In this study, the impact of severe weather events on PNM's system was examined through the narrow lens of high-level variables, for example, PNM-wide load or imports. This methodology was necessarily dictated by the study goal of supplementing and supporting the resource adequacy IRP process. But the question of resilience extends beyond just the questions of the type of resources to procure at the aggregate-PNM level. Local PNM transmission and distribution constraints, their vulnerabilities under severe weather-induced stress, or associated mitigation strategies, have not been examined. This is a subject of future research.

5.1.4 What are the response, adaptation, and recovery mechanisms, after loss of system function due to extreme weather?

Insights from this study about portfolio performance under severe stress will aid in procuring the appropriate type and quantity of resources that make the system resilient and capable of better withstanding extreme events. Once the ice storm or heat wave is underway though, PNM will face several operational challenges to minimize impact on customers. This study does not address these challenges or the operational changes and investments necessary to mitigate them. The resilience trapezoid in Figure 1 categorizes such efforts into two phases - 'Response & Adapt' and 'Recovery' – and this is a subject of future study at PNM. This study addresses only the first two phases of the trapezoid in Figure 1 – 'Anticipate and Prepare', and 'Resist and Absorb'.

6 Appendix

Weightings used to combine sensitivities to make Figure 13 and Figure 16. Given the large range of outcomes across sensitivities, metrics were weighted using an inverse proportional scaling (such that the extreme, low likelihood sensitivities did not dominate the weightings).

Table 13: Ice storm weights used

Sensitivity	Weighting		
	Included in Weighting	MWh Shed	% Weighting
Base	No	0	0%
Island	Yes	461	27%
Island, Conservative Battery Ops	Yes	342	37%
PNM outages	No	18	0%
Southwest Outages	Yes	385	33%
Outages + Island	Yes	4,345	3%
Island + PNM South Gen Out	Yes	21,253	1%

Table 14: Heat wave weights used

Sensitivity	Weighting		
	Included in Weighting	MWh Shed	% Weighting
Base	No	~0	0%
Island	No	~0	0%
1 in 20	Yes	74	42%
G1	Yes	81	38%
G2	Yes	198	16%
G2 + 1 in 20	Yes	720	4%

The formula used to calculate the weights of the sensitivities is:

$$Weighting_{Scenario} = \frac{\frac{1}{MWh_{Scenario}}}{\sum_{Scenario=1}^{\infty}\left(\frac{1}{MWh_{Scenario}}\right)}$$