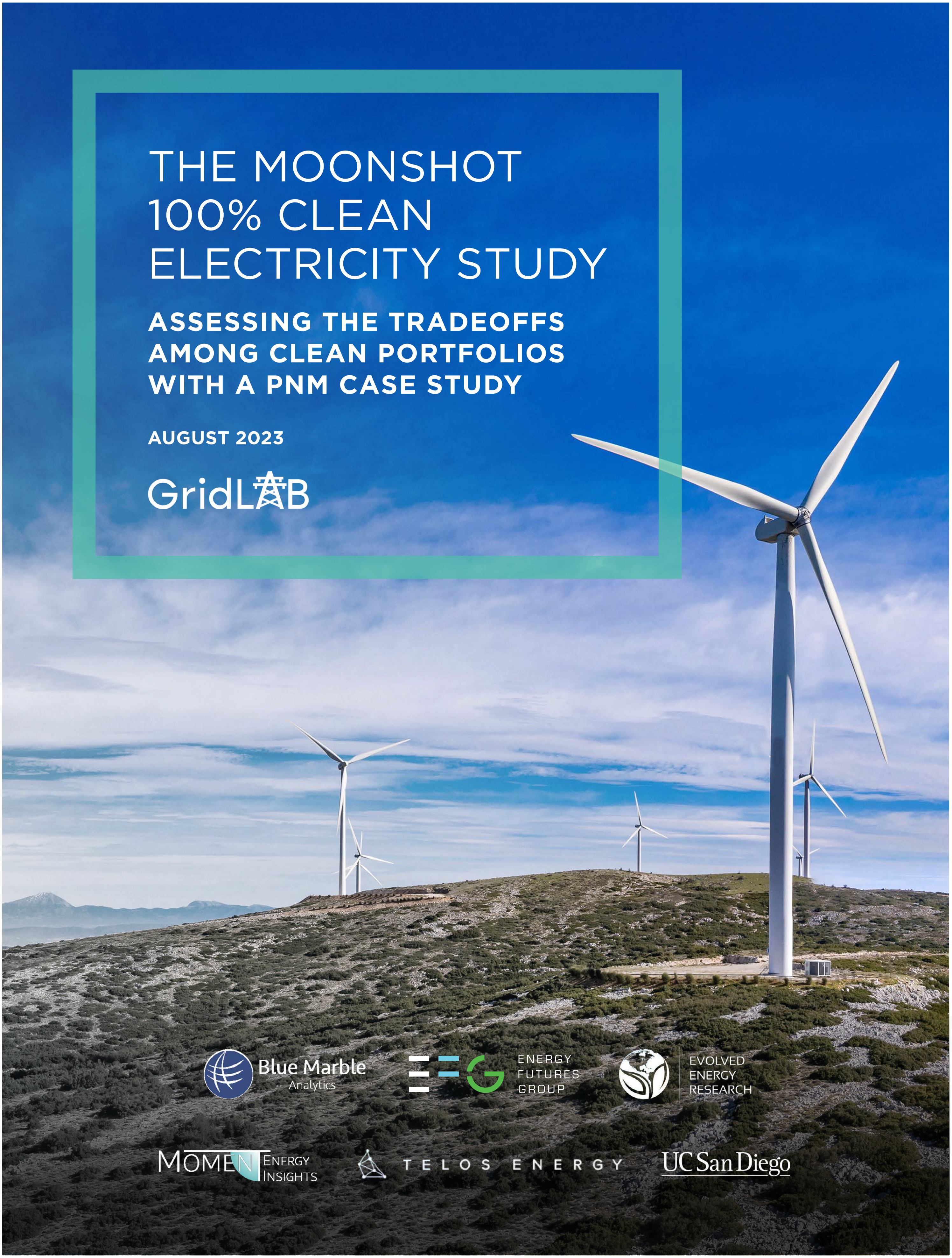


THE MOONSHOT 100% CLEAN ELECTRICITY STUDY

ASSESSING THE TRADEOFFS AMONG CLEAN PORTFOLIOS WITH A PNM CASE STUDY

AUGUST 2023

GridLAB

Blue Marble Analytics

ENERGY FUTURES GROUP

EVOLVED ENERGY RESEARCH

MOMENT ENERGY INSIGHTS

TELOS ENERGY

UC San Diego

CONTRIBUTORS

This project was completed through the collaboration of a diverse group of experts and organizations. (Listed alphabetically)

Ryan Deyoe, *Telos Energy*
Elaine Hart, *Moment Energy Insights*
Patricia Hidalgo-Gonzalez, *University of California San Diego*
Chelsea Hotaling, *Energy Futures Group*
Ryan Jones, *Evolved Energy Research*
Ana Mileva, *Blue Marble Analytics*
Paul Serna-Torre, *University of California San Diego*
Anna Sommer, *Energy Futures Group*
Priya Sreedharan, *GridLab*
Derek Stenclik, *Telos Energy*

PROJECT LEADERSHIP

Priya Sreedharan, *GridLab*
Derek Stenclik, *Telos Energy*

ACKNOWLEDGMENTS

We thank Alex Routhier of Western Resource Advocates, and Casey Baker and Ric O'Connell of GridLab for their thoughtful feedback throughout the study and on the report. We thank Annie Dore of BeeSpring Designs for the graphic design of this report.

TECHNICAL REVIEW COMMITTEE

Paul Denholm, *National Renewable Energy Laboratory*
Severiano DeSoto, *Western Resource Advocates*
Jessica Keetso, *Tó Nizhóní Ání*
Michael Milligan, *Milligan Grid Solutions*
Nicholas Phillips, *Public Service New Mexico*
Justin Sharp, *Sharply Focused*

DISCLAIMER

SUGGESTED CITATION

GridLab, 2023, The Moonshot 100% clean electricity study: Assessing the tradeoffs among clean portfolios with a PNM case study, www.gridlab.org/publications

EXECUTIVE SUMMARY

Decarbonizing the power system is a central component of economy-wide decarbonization and climate mitigation. New Mexico is among several states that have set goals to fully decarbonize their power systems, setting a 100% clean electricity target. This study, called the "Moonshot study," aimed to identify multiple technological pathways that would reliably and cost effectively achieve a 100% clean power system in the 2035-2040 time frame. In doing so, it identifies the tradeoffs among these pathways, and least regrets strategies common to all.

To ground the analysis, we selected the Public Service Company of New Mexico (PNM) as a case study. We used a suite of models that stepped through demand forecasting (using EnergyPATHWAYS), portfolio development (using EnCompass and SWITCH), and resource adequacy (using GridPath) analysis. The Inflation Reduction Act was explicitly incorporated into the modeling by incorporating electrification into our demand forecasts, and in considering the tax credits specific to New Mexico for renewable resources, green hydrogen, and storage technologies.

Our modeling included elements not typical in traditional planning, specifically, an economy-wide decarbonization lens that informed our demand projections, the inclusion of both a utility-focused planning tool (EnCompass) and a regional planning tool (SWITCH), an integrated west-wide resource adequacy analysis (GridPath), and an iterative approach between resource adequacy and portfolio design.

All our portfolios included large amounts of solar, wind and battery storage based on least-cost planning principles. Building these resources urgently and consistently is the most important step towards a clean portfolio, and with the Inflation Reduction Act, New Mexico has access to inexpensive clean resources that may offer economic development opportunities. The portfolios differed in terms of the quantities of clean firm resources (including peaking resources, such as hydrogen or other zero carbon combustion fuel); baseload resources, such as geothermal, thermal resources with carbon capture and sequestration (CCS), or nuclear; and multi-day storage (such as 100 hour battery storage). Collectively, these clean resources support reaching the "last mile" of a 100% clean power system and substitute for the services currently provided by natural gas and coal generation. Our modeling showed it is possible to reach 100% clean without these emerging firm resources, for example, by up-sizing solar and batteries, or adopting a regional planning approach.

While all portfolios performed reliably, our resource adequacy analysis showed that future constraints are driven by energy limitations (when there are sustained periods of low renewable output) and not only capacity shortfalls. We also showed that load flexibility from electric vehicles and electrified building end uses can offset significant battery storage needs. Choosing between battery storage and load flexibility is a policy decision that should consider costs, implementation feasibility, and technological maturity.

Ultimately, the pathway decisions for the last mile represents a tradeoff between cost and risk—one which does not need to be made today. Instead, planners should focus on the urgent priority of investment in clean resources and adoption of integrated planning approaches that can refine and inform these longer term choices as costs and planning decisions across the West become more clear.

TABLE OF CONTENTS

Executive Summary 1

Table of Contents 3

Introduction 4

Methodology 5

- Practitioner toolkit 6
- Regionally-coordinated planning 7

Key Findings 9

- **Finding 1.** There are multiple pathways towards achieving a 100% clean electricity target while maintaining a reliability and economical electricity system. 9
- **Finding 2.** Deploy, deploy, deploy: wind, solar, and battery storage are key components of any plan to decarbonize the PNM power system. 12
- **Finding 3.** The "last mile" to achieving 100% clean is uncertain in terms of the cost-optimal resource mix, but clean firm resources are beneficial for the last 5-10% of energy. 15
- **Finding 4.** Resource adequacy needs are increasingly driven by energy constraints, not just capacity. 17
- **Finding 5.** PNM should not go it alone—regional planning and coordination are critical for efficient reliability and cost mitigation. 20
- **Finding 6.** Electrification will require significantly more energy and capacity resources but does not fundamentally change the portfolio. However, weather dependent, future forecasts of end-use load are essential. 27
- **Finding 7.** Reliability risks are shifting—with high levels of electrification, summer peak demand will not remain the largest challenge. 30
- **Finding 8.** Cost, land use, and water requirements for PNM's energy transition are manageable. 35

Conclusions and Recommendations 41

INTRODUCTION

Several states across the West, including New Mexico, have set 100% clean electricity or net zero greenhouse gas emissions (GHG) targets within the next 20 years. However, few of these states have developed a clear path to achieve these targets or conducted analysis of future power systems that do. While recent research conducted across the country has shown that adoption of wind, solar, and battery technologies can enable very high renewable-based systems (exceeding 80-90% of load annually), there is limited research on the remaining resource mix to achieve 100% clean electricity without relying on the current thermal fleet. While the exact path towards 100% clean electricity does not need to be charted out today, it's important to begin to understand how these targets could be achieved in terms of potential resource mixes, while taking into consideration resource adequacy risk, environmental implications, and economic and regulatory uncertainties. This can help identify what policymakers should focus on in the near term as well as opportunities for further research.

> While the exact path towards 100% clean electricity does not need to be charted out today, it's important to begin to understand how these targets could be achieved in terms of potential resource mixes.

This study is called the Moonshot project, named after the Apollo project in which a man was safely landed and returned from the moon. This was an equally ambitious goal at the time—one which was proclaimed before we knew how to accomplish it. Much like the original moonshot project, it's important for our clean energy efforts to chart a path early on and improve it along the way. In the context of reaching a fully decarbonized power system, it's similarly important to think broadly, rather than incrementally, in order to pivot towards a 100% clean goal.

Grounded in state of the art utility resource planning approaches, this study illustrates how a 100% clean electricity target can be reached while highlighting important near term resource portfolio choices that align with the longer term commitment. In contrast with existing decarbonization studies, this study has a focus on resource adequacy—ensuring that load can be met across a wide range of weather-induced uncertainties. This affords policymakers the necessary information to develop a reliable roadmap to achieve clean electricity goals. In this study, we developed multiple clean portfolios, taking into account varying levels of electrification consistent with the Inflation Reduction Act (IRA). We then evaluated them for their ability to serve load across multiple conditions using a probabilistic resource adequacy modeling approach. We selected New Mexico and the Public Service Company of New Mexico (PNM) utility as a case study, but with the intention that the findings can bring value for other jurisdictions.

METHODOLOGY

The overall approach used in this study was to develop multiple resource mixes that achieved a 100% clean electricity target and to assess these portfolios and their respective tradeoffs in terms of resource adequacy, economics, environmental impacts and deployment feasibility. The approach follows the basic tenets of utility resource planning in that the modeling incorporates the steps of demand forecasting, capacity expansion modeling, production cost modeling, and resource adequacy analysis.

Two suites of modeling tools were used to develop portfolios and evaluate them for their resource adequacy—a “practitioner toolkit” that more closely resembles the methods currently used by individual utilities in integrated resource planning (EnCompass and GridPath)—and a modeling tool that takes a regionally-coordinated West-wide capacity expansion approach (SWITCH).

Following prudent utility resource planning practice, we began the modeling process with an estimation of demand profiles. We developed time and weather synchronized, hourly demand profiles for all states in the West, including New Mexico, using publicly available information and the EnergyPATHWAYS model. EnergyPATHWAYS has been used in other economy-wide decarbonization studies and generates segmented, end-use demand profiles for electricity and other energy types. We developed demand profiles that incorporate baseline levels of electrification (“Baseline demand forecast”) and high levels of electrification and energy efficiency, as might be anticipated with the impact of the Inflation Reduction Act (IRA) (“High Electrification demand forecast”). These demand profiles were developed for weather years between 2007 and 2014, specifically capturing the response of end use loads (like cooling and heating demand and vehicle charging) to changing temperatures. We then adjusted these demand profiles based on PNM’s demand data from their 2020 IRP model to align with utility-specific data.

Two suites of modeling tools were used to develop portfolios and evaluate them for their resource adequacy—a “practitioner toolkit” that more closely resembles the methods currently used by individual utilities in integrated resource planning (EnCompass and GridPath)—and a modeling tool that takes a regionally-coordinated West-wide capacity expansion approach (SWITCH).

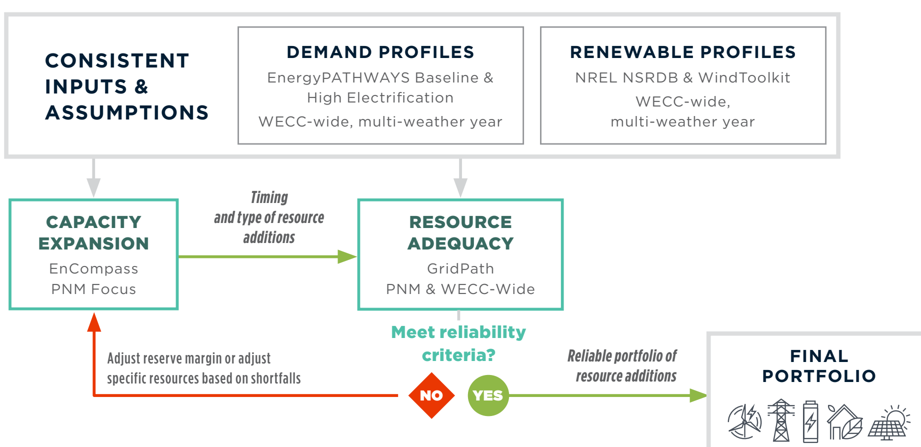
PRACTITIONER TOOLKIT

The practitioner toolkit utilized EnCompass for portfolio development (a capacity expansion and production cost modeling software tool commonly used by utilities in integrated resource planning) and GridPath for resource adequacy analysis (GridPath is an open source modeling tool with multiple capabilities; in this application, the resource adequacy features were leveraged, using the GridPath RA Toolkit as a starting point). EnCompass was used to develop portfolios for PNM, starting with PNM's 2020 IRP Encompass database. This application of EnCompass focused on the PNM region in isolation, with assumptions reflecting imports and exports, and was based on a "sample day" approach to characterize demand.

The resulting portfolios were evaluated in GridPath to understand their performance across all 8760 hours of the year across multiple weather years, and included a zonal treatment of the entire West to reflect interactions between PNM and the rest of the West. GridPath evaluated hour-to-hour variability in demand, available capacity (taking into account weather variability and generator outages), and scheduled storage and load flexibility resources in order to minimize unserved energy as determined by resource adequacy metrics. Where necessary, we iterated between GridPath and Encompass in order to ensure resources were able to meet a loss of load expectation (LOLE) standard of 1 day in 10 years (or 0.1 days per year)—this "round-trip" modeling approach is an effective method for ensuring designed portfolios are resource adequate. To accomplish this, the marginal resource adequacy resource was identified, and capacity was either added or removed from the model until the resource adequacy criterion (1-day-in 10 year LOLE) was met. While Encompass was used to develop resource builds for PNM, the resources across the West were developed based on utility IRP filings. A flow chart of the practitioner model approach is shown in Figure 1.

FIGURE 1.

Modeling methodology flow chart



Applying the practitioner toolkit, three portfolios were developed, each achieving 100% renewable energy, but with different amounts and types of firm renewables. The portfolios were specifically designed to provide insights on the potential technologies for serving the last 5-10% of annual energy. This "last-mile" of decarbonization is recognized as the hardest and most uncertain aspect of grid planning and deep decarbonization.

These three portfolios reflect sufficient diversity in resource mixes to enable us to assess the reliability and diversity value of different clean resources. While optimization was the starting point for developing the Optimized portfolio, two additional portfolios were developed by assuming specific quantities of emerging resources (rather than lowering the costs of these resources until they are selected). While this may not reflect cost-optimal builds based on today's projection of costs, this methodology is one way to bypass the uncertainties in projected costs of emerging technologies.

OPTIMIZED PORTFOLIO | The first portfolio was based on least-cost optimization in EnCompass. This resulted in hydrogen combustion turbines (CTs) being built to provide firm capacity and zero-carbon generation during sustained low wind and solar periods. In this example, hydrogen CTs are used as a proxy to represent generators that have a low capital cost and high fuel cost (alternatives may include biodiesel or other synthetic low carbon fuels).

DIVERSE CLEAN RESOURCES PORTFOLIO | The second portfolio added 300 MW of geothermal through a forced build, with the remainder of the portfolio determined by Encompass. Geothermal served as a proxy to represent a high capital cost, low fuel cost source of energy (alternatives may include fossil generation with CCS, and small modular nuclear reactors).

MULTI-DAY STORAGE PORTFOLIO | The third portfolio added 300 MW of long-duration, multi-day energy storage. It was assumed that the storage had a 100-hour duration. The remainder of the portfolio was determined by Encompass.

The entire design process was replicated for both the Baseline demand and High Electrification demand forecasts.

REGIONALLY-COORDINATED PLANNING

A second capacity expansion model, SWITCH, was leveraged to understand the benefits of a coordinated planning effort across the entire West, based on a West-wide capacity expansion optimization. SWITCH solves for an optimal portfolio based on minimizing the cost for the entire West subject to serving load across all 365 days sampling every 4 hours (i.e., 6 blocks per day), and subject to policy constraints (such as GHG emission reduction goals and renewable portfolio standards). An additional feature of SWITCH, relevant to this study, is the ability to optimize storage capacity and energy separately, rather than having to predefine selectable resources of fixed energy and capacity. Lastly, SWITCH includes over 7000 renewable generation hourly profiles across the west, and 280 profiles within PNM, which enables more optimized siting of renewables.

SWITCH was used to develop optimized portfolios for the entire West collectively, which consists of multiple zones including PNM, using consistent cost and demand profiles integrated in the practitioner toolkit. More than 40 sensitivities were conducted to better understand the importance of renewable resource selection, market interactions between PNM and the West, and the value of storage. These sensitivities were conducted by forcing different levels of solar-to-wind build in PNM, net annual export to self-generation ratios, and cost of storage energy. These sensitivities included cases in which PNM was electrically islanded from the rest of the West.

In addition, to understand the impact of asymmetric GHG emission reduction policies between PNM and across the rest of the West, SWITCH assumed both West-wide net zero GHG targets, and more modest GHG emission reduction targets across the remainder of the West (50%-80% reductions relative to 2005), all while maintaining a net-zero target in PNM.

Similar to the practitioner toolkit approach, the analysis was conducted using both the Baseline and High Electrification demand forecasts.

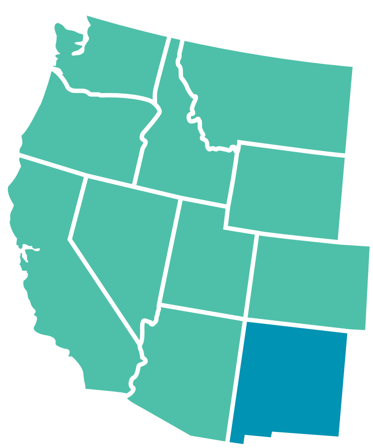
Figure 2 contrasts the topology for each modeling tool used in both the practitioner toolkit and regionally-coordinated planning approaches.

FIGURE 2.

Study Topology by Modeling Application

WEST-WIDE

Load Profiles,
Renewable Profiles
GridPath, SWITCH



PNM FOCUS

Disaggregated PNM Load
High resolution renewable profiles
GridPath (PNM isolated)
EnCompass (Capacity Expansion & Production Cost)

KEY FINDINGS

FINDING 1.

There are multiple pathways towards achieving a 100% clean electricity target while maintaining a reliability and economical electricity system.

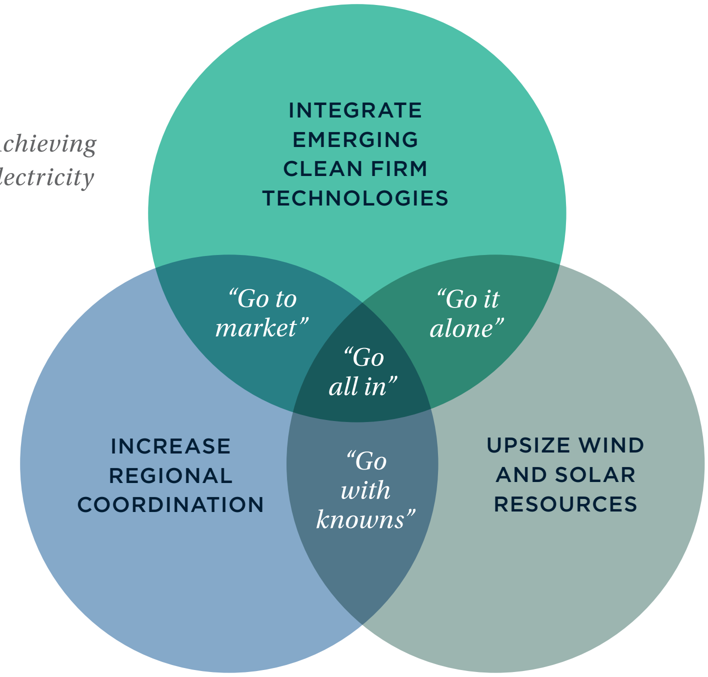
The objective of this study was not to develop a definitive plan to reach 100 percent clean electricity for PNM, nor was it intended to chart a specific course to get there. Instead, the study evaluated the reliability implications of a 100% clean energy powered system across a multitude of options. While there is no silver bullet and there is uncertainty in future technology costs, the study showed that there are multiple reliable and fiscally feasible portfolio pathways available to PNM to achieve 100% clean electricity. These options will differ in terms of the economics, ease of deployment, specific technologies required, and interregional electricity market conditions.

Broadly speaking there are three pathways to ensuring the power system remains reliable and efficient—integrate emerging clean firm technologies, increase interregional coordination and planning, and upsize the amount of wind and solar resources above what is needed most of the year. These three pathways are not intended to be mutually exclusive; different combinations of these pathways can achieve 100% clean electricity targets reliably, as our results show.

Broadly speaking there are three pathways, that are not mutually exclusive, to ensuring the power system remains reliable and efficient—integrate emerging clean firm technologies, increase interregional coordination and planning, and upsize the amount of wind and solar resources.

FIGURE 3.

Pathways to Achieving 100% Clean Electricity



INTEGRATE EMERGING CLEAN FIRM TECHNOLOGIES

While all the portfolios evaluated included large amounts of wind, solar, and battery storage, they differed with regards to the final resources required to reach 100% clean electricity. As reliance on regional coordination declines, some combination of clean firm resources, including hydrogen combustion turbines, geothermal, fossil fuels with CCS, or multi-day energy storage technologies are likely required in PNM for a fully decarbonized power system. These emerging clean firm resources provide much needed capacity and energy during low wind and solar events and ensure resources are available when needed for resource adequacy.

In this study, between 800 and 1600 MW of clean firm resource capacity was selected by 2035 to reliably meet load depending on the resource selected and the electrification level assumed. While their energy contribution is small, these additions represent approximately 30% of new installed capacity through 2035 and support resource adequacy during critical tight supply conditions.

EXPAND INTERREGIONAL COORDINATION

Like many utilities in the West, PNM is electrically interconnected with its neighboring utilities and balancing authorities. Although electricity flows across the network and economic transactions occur regularly, each utility plans to meet their load with their own resources. There is limited sharing of resources across the West for resource adequacy purposes. Geographic diversity in load and renewable resources provides a valuable opportunity for utilities to coordinate and share resources for resource adequacy and long-term planning. This can occur via bilateral contracts, regional resource adequacy programs,[1] and/or full participation in a regional transmission organization (RTO).[2] Each of these options would allow PNM to benefit from resources available in neighboring systems when it is calm and cloudy in New Mexico, and to sell surplus wind and solar energy during times of high production.

Both the SWITCH and GridPath results highlight the power of interregional coordination. Using a regional-capacity expansion approach, the SWITCH portfolios showed a maximum storage duration requirement of 8 hours across several cases and sensitivities. The GridPath resource adequacy simulations showed that if islanded—without imports and exports from neighboring regions—PNM's loss of load expectation (LOLE) would increase from 0.1 to 14 days per year (even when ensuring neighboring regions are not overbuilt *and* that weekly interchange is energy neutral).

UPSIZE THE WIND AND SOLAR DEPLOYMENT

Another option available to meet a 100% clean electricity system is to increase the buildout of solar, wind and battery storage resources beyond what is needed for local energy consumption within PNM. In this option, surplus wind and solar energy can either be sold to neighboring regions if it is economical to do so, used for electrolysis and hydrogen production, or ultimately curtailed. While curtailment is viewed negatively, it may be a preferred, lower cost alternative, than building additional clean firm resources. Currently, however, PNM as a regulated utility is unable to build resources or take on market risk associated with export revenues, limiting the portfolio options available for PNM to reach a 100% clean grid.

The SWITCH analysis conducted for this study showed that a large increase in wind and solar capacity could be sited in New Mexico, utilized when needed for PNM, and exported to meet neighboring clean energy and capacity requirements. This is especially true given the high resource quality of New Mexico's solar and wind resources. While it represents an extreme condition, the electrically islanded sensitivity conducted in SWITCH showed that a combination of upsized solar, wind and battery storage, with small amounts of biomass generation, could reach a 100% clean electricity goal.

It is important to note that these three pathways are not mutually exclusive. Some combination of these options is essential for PNM to reliably and economically reach a 100% clean electricity goal—that combination should be selected based on the pros and cons of each approach.

---

1 For example, the Western Resource Adequacy Program (WRAP) is an emerging coalition of western utilities to coordinate on resource adequacy planning and share capacity across the Western Interconnection. PNM is currently a participant in the WRAP.

2 Currently there are multiple prospective plans for a Western RTO that could coordinate operations, transmission, planning, and resource sharing across the region.

FINDING 2.

Deploy, deploy, deploy: wind, solar, and battery storage are key components of any plan to decarbonize the PNM power system.

Several potential portfolios were evaluated in the study, with a common finding across all portfolios: wind, solar, and battery storage are the lowest cost options for achieving the majority of decarbonization across the electric power system for PNM. While the scenarios differed in the total capacity build of each resource, all of them required a significant increase in deployment relative to historical rates.

Figure 4 illustrates the new build utility-scale capacity additions over time for PNM to achieve a 100% clean electricity grid.[3] Regardless of the quantities of clean firm technologies (represented as hydrogen CT or geothermal), or multi-day storage needed to reach 100% clean electricity, large deployment of wind, solar, and batteries are no regrets options that leave the door open for future resource options. And if costs continue to decline on wind, solar, and battery technologies, it might be more economical to rely on portfolios with upsized variable renewable resources and batteries. The figure illustrates early investments in battery storage and solar, followed by Hydrogen CTs in the latter years. These investments are being driven by IRA incentives, capacity requirements, and the 100% clean electricity target.

3 Our analysis assumes a 100% clean portfolio by 2035. Capacity additions represent values incremental to announced and under construction projects and continued rooftop PV growth.

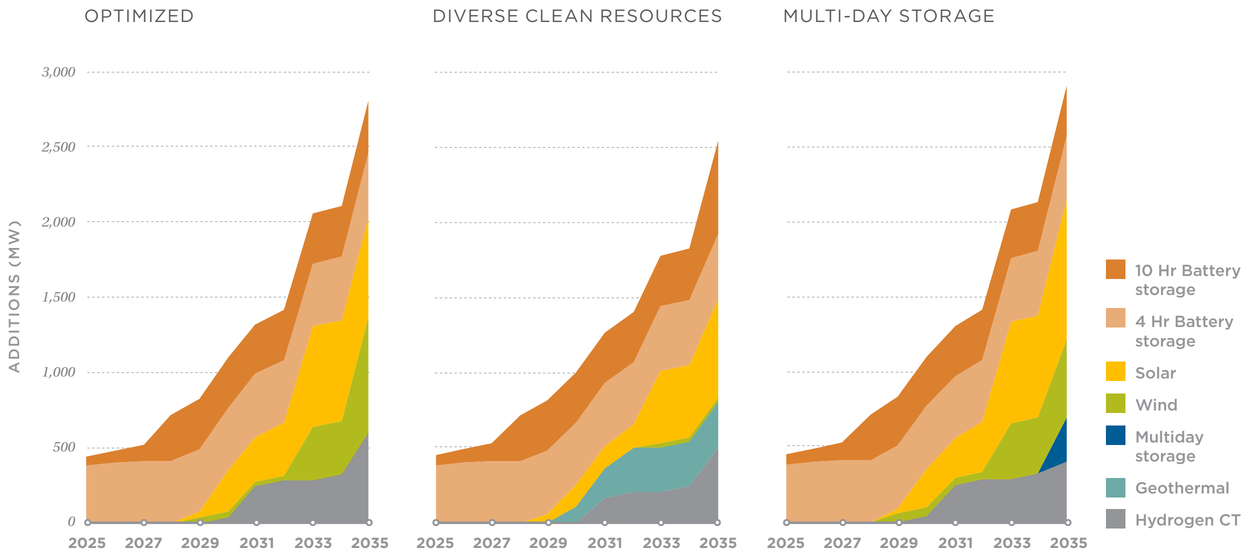


FIGURE 4.

Capacity additions to reach 100% clean, by portfolio, Baseline demand

Note: Hydrogen CT capacity need — or equivalent clean firm capacity characterized by low-capital cost, high fuel costs — is further reduced in each portfolio after running resource adequacy simulations.

While the relative cost comparison between these portfolios was not the primary intent of the study—given the high degree of cost uncertainty for each emerging clean firm resource—each portfolio shows similar total costs (within roughly 5% of net present value). The Multi-day Storage portfolio was at parity with the Optimized portfolio, while the Diverse Clean Resources portfolio cost was within 5%.

ACCELERATED INVESTMENT IS NEEDED

To achieve New Mexico's ambitious renewable energy and decarbonization goals, accelerated deployment and investment must start now. Even without making assumptions about high electrification rates, the pace of development will need to be significantly accelerated, and system planning and action plans today must take a 10-15 year view.

> Our findings suggest that accelerating the deployment of wind, solar, and battery storage resources is crucial for PNM to achieve a 100% renewable system in the 2035-2040 timeframe.

Our findings suggest that accelerating the deployment of wind, solar, and battery storage resources is crucial for PNM to achieve a 100% renewable system in the 2035-2040 timeframe. Early additions of battery storage resources are also critical for reliability, being added in early years to meet the planning reserve margin (PRM) and resource adequacy targets. Assuming a target date of 2035, the total annual capacity builds of wind, solar, and battery storage would have to increase by 130-250%, from approximately 100 MW per year seen from 2013-2022 up to 130-250 MW per year through 2035. With high electrification, these values would need to accelerate further, to 250 to 400% of historical build rates.

Figure 5 illustrates the pace of annual capacity additions of wind, solar and storage required to reach a fully decarbonized PNM power system by 2035. This would require significantly accelerating, on a consistent basis, the development of each of these resource types; in addition, starting investment in new clean firm renewable resources (i.e., hydrogen, biodiesel, thermal resources with carbon capture sequestration) or geothermal would be needed for which there is little industry experience. While this development pace is accelerated, new provisions in the IRA and other state policies can support this goal. Continued investment is not only needed for new resources, but also enabling transmission alongside streamlined land use and regulatory processes. While the study did not evaluate transmission needs explicitly, it did incorporate first-order transmission cost additions—developed by PNM—that would be necessary to add large amounts of new wind and solar resources.

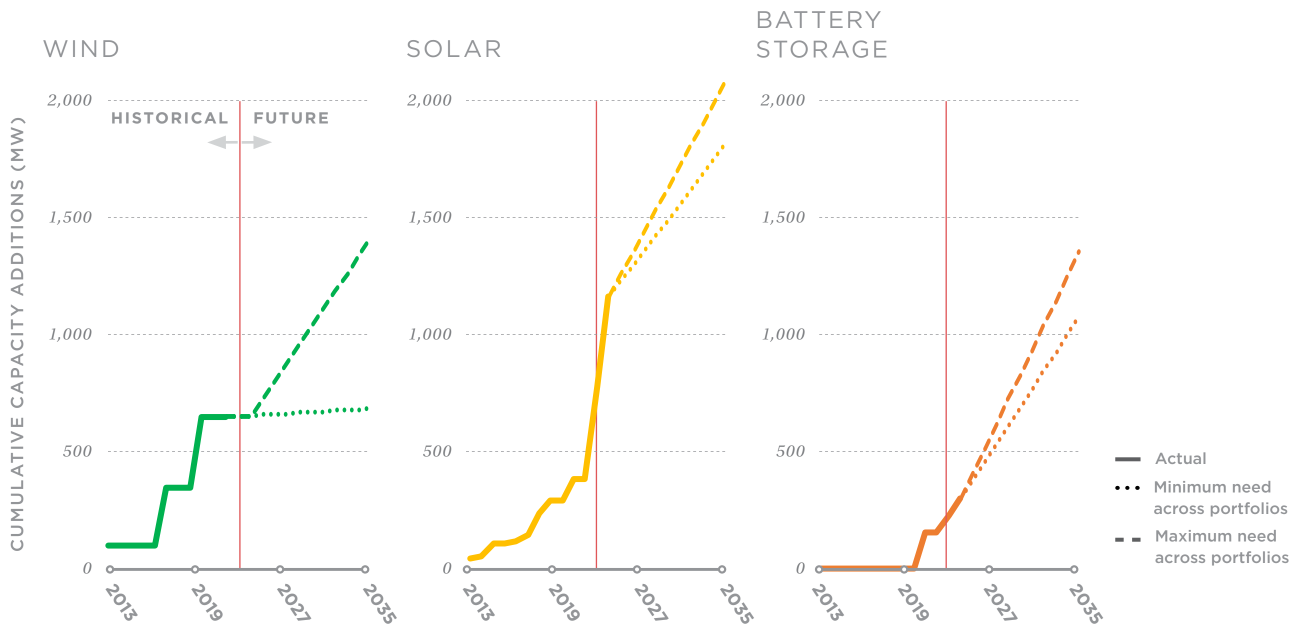


FIGURE 5.

PNM cumulative capacity additions by year and resource type, Baseline demand

FINDING 3.

The “last mile” to achieving 100% clean is uncertain in terms of the cost-optimal resource mix, but clean firm resources are beneficial for the last 5-10% of energy.

While renewable energy sources such wind, solar, and batteries offer the lowest cost energy resource options for meeting the 100% clean electricity target, they cannot provide all the reliability services required for the grid without significant upsizing or regionally optimized portfolio development. Both of these alternatives have drawbacks—portfolios with upsized wind and solar may result in higher levels of curtailment depending on the market opportunity for exporting surplus renewable generation; and regionally optimized portfolio development would require a paradigm shift in current utility planning practices, regulatory regimes, and/or the development of a western market.

> There may be long periods—potentially spanning multiple days—where solar and wind are unavailable, requiring other resources (such as hydrogen capacity) to be available in these times.

Short storage duration batteries (typically 4 to 10 hours) can provide a significant amount of capacity for reliability, but they cannot be the only capacity resource on the system (unless systems are upsized in terms of solar and wind resources, or capacity expansions are planned through a regional optimization approach). There may be long periods—potentially spanning multiple days—where solar and wind are unavailable, requiring other resources (such as hydrogen capacity) to be available in these times. During this time, even relatively long, 10-hour duration battery storage does not bridge the gap between periods of renewable production and demand, even when considering regional imports. This additional need was identified using both capacity expansion modeling, which assumed declining effective load carrying capability (ELCC) of battery storage resources, and resource adequacy simulations of specific events.

Figure 6 illustrates a challenging week in winter. Although winter demand is low relative to summer demand,[4] there are sustained multi-day periods where solar and wind resources cannot fully meet load, even with battery storage. During this period, low levels of wind and solar in neighboring regions limits clean imports, except during mid-day hours when solar is highest. In these conditions, hydrogen CTs or alternative clean firm resources are required to meet demand.

4 Results shown in this figure are prior to electrification impacts.

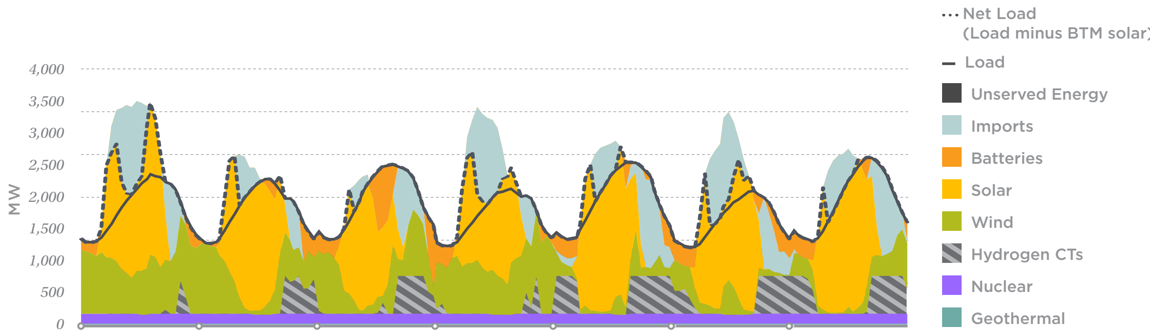


FIGURE 6.

Challenging winter week dispatch for PNM, Optimized portfolio Baseline demand

While the portfolio illustrated in this figure considers only hydrogen CTs as the clean firm resource, there are other potential resources that can provide resource adequacy in a highly decarbonized power system. Generally speaking, these include relatively low capital cost, high fuel cost resources (like hydrogen, or biofuel combustion turbines), high capital cost, low fuel cost resources (nuclear, geothermal, and carbon-capture sequestration plants), and multi-day energy storage resources.

Each of these options have a high degree of uncertainty in technical maturity, cost, and availability but may play a role for the 'last mile' of decarbonization. The exact type of dispatchable clean resource needed to bridge periods of low wind and solar energy does not need to be determined today. Each of the three portfolios, which leveraged a different combination of "last mile" clean resources, did not materially change in terms of the rest of the renewable portfolio or close the door on variable renewable and storage options. This underscores Finding 2 which emphasizes that our near term focus should be on deploying large quantities of wind, solar, and battery storage.

FINDING 4.

Resource adequacy needs are increasingly driven by energy constraints, not just capacity.

When considering clean firm needs of the power system, it is important to quantify both the energy and capacity needs for resource adequacy. This is especially important for high renewable systems which are more energy constrained than capacity limited. While resource adequacy in today's system can be characterized by short-duration events during the highest peak demand periods, future events will be driven more by sustained lulls in wind and solar availability, rather than outages of thermal units or a short term spike in demand. As a result, there may be sufficient capacity on the system, but storage constraints—due to both charging constraints and duration limitations—may limit their ability to mitigate energy shortages.

In an energy constrained system, clean firm resources are not only needed for capacity during an event, but also to provide energy to charge storage resources so that they can be fully utilized during high risk periods.

In an energy constrained system, clean firm resources are not only needed for capacity during an event, but also to provide energy to charge storage resources so that they can be fully utilized during high risk periods. This creates a double dividend for clean firm resources—they provide both capacity *during* the event, and the *energy* that enables other resources to provide additional capacity to the system. It is important to identify the duration of expected events and the amount of energy required to mitigate them. This is particularly true for hydrogen CT capacity, which has a fuel supply requirement, and long duration storage, which would require information on proper sizing.

To evaluate both the capacity and energy needs of clean firm resources, the study implemented an iterative approach to the capacity expansion and resource adequacy analysis. First, the three portfolios were designed with EnCompass, assuming an initial ELCC for wind, solar, and storage resources. As shown in Table 1, EnCompass identified an approximate need of 820-1,060 MW of additional clean firm resource need, depending on the fixed build assumption (i.e., when 300 MW of geothermal or multi-day storage was included).

Because hydrogen CTs were selected across all portfolios, the resource was determined to be the common marginal capacity resource selected by EnCompass to ensure the planning reserve margin requirement was met.[5] Each portfolio was analyzed using a probabilistic

5 The marginal capacity resource built by the model can be determined by incrementing the PRM requirement up or down and seeing the resulting capacity build.

resource adequacy analysis to identify the average energy need across many years of weather, load, outage, and hydro conditions.

TABLE 1. *EnCompass clean firm capacity builds by portfolio*

	OPTIMIZED	DIVERSE CLEAN RESOURCES	MULTI-DAY STORAGE
	ENCOMPASS PORTFOLIO (based on PRM)		
Total Clean Firm (MW)	1000	820	1060
Hydrogen CT Capacity (MW)	1000	520	760
Hydrogen H2 Generation (GWh)	511	410	371
Hydrogen Capacity Factor (%)	6%	9%	6%

ROUND-TRIP MODELING ALLOWS FOR REFINEMENT OF CAPACITY EXPANSION MODELING RESULTS

The resource adequacy analysis found that all of the portfolios developed by EnCompass outperformed the standard of 1 day-in-10 year loss of load expectation (Table 2). This result could be attributed to simplifications in capacity expansion modeling. First, ELCCs of wind, solar, and storage used in EnCompass did not reflect potential portfolio benefits that can arise when they are co-optimized with each other and with other resources in the portfolio, including hydrogen CTs. Second, PRM constraints in capacity expansion models may approximate the capacity needs that correspond to meeting a resource adequacy standard, but those approximations are system specific and difficult to extrapolate to different portfolios. Finally, our EnCompass capacity expansion modeling did not explicitly consider the opportunity to leverage West-wide load and resource diversity through imports and exports. Because ELCC and PRM approximations are *inputs* into the capacity expansion model, but actually vary based on the portfolio selected, it is difficult to properly anticipate the total portfolio effects of various resources.

This circularity challenge is increasingly problematic for long-term, high-renewable, capacity expansion planning studies, but can be overcome with iterative or "round-trip" capacity-expansion and resource adequacy modeling. While it is important to start with reasonable ELCC values of various resources, they do not need to be exact (and can't be known apriori). Instead of confirming reliability based on achieving a PRM, it is more robust to confirm reliability based on full probabilistic resource adequacy analysis. If a resource adequacy surplus (exceeding the reliability criteria) or deficit exists, the portfolio can be adjusted accordingly. This can be done using one of three ways:

1. By adjusting the PRM requirement in the capacity expansion plan and rerunning; or
2. By adjusting the ELCC of resources in the capacity expansion plan and rerunning; or
3. Adding or removing the marginal capacity resource.

For this study, each portfolio was adjusted by iterating the amount of the marginal capacity resource (hydrogen CTs, in this case) until the reliability criterion was achieved. More specifically, to refine the resource portfolios, the hydrogen CT capacity was adjusted incrementally until the loss of load expectation (LOLE) exceeded 1 day in 10 years (Table 2).[6]

TABLE 2. *Clean firm capacity builds by portfolio after adjusting to the reliability criterion*

	OPTIMIZED		DIVERSE CLEAN RESOURCES		MULTI-DAY STORAGE	
	ENCOMPASS PORTFOLIO (based on PRM)	**GRIDPATH ADJUSTED PORTFOLIO** (based on 0.1 days/year LOLE)	**ENCOMPASS PORTFOLIO** (based on PRM)	**GRIDPATH ADJUSTED PORTFOLIO** (based on 0.1 days/year LOLE)	**ENCOMPASS PORTFOLIO** (based on PRM)	**GRIDPATH ADJUSTED PORTFOLIO** (based on 0.1 days/year LOLE)
GridPath LOLE (days/year)	0.00	0.09	0.07	0.04	0.00	0.04
Total Clean Firm (MW)	1000	600	820	800	1060	700
Hydrogen CT Capacity (MW)	1000	600	520	500	760	400
Hydrogen Generation (GWh)	511	508	410	402	371	445
Hydrogen Capacity Factor (%)	6%	10%	9%	9%	6%	13%

These results show that while the capacity expansion portfolios offered a good initial starting point, the synergy between the existing resource mix and the marginal resources added to ensure reliability is underrepresented. By completing a round-trip analysis, the total capacity needed is refined and decreased, lowering the overall capital cost requirement to attain a reliable portfolio.

These results show that while the capacity expansion portfolios offered a good initial starting point, with round-trip analysis between capacity expansion and resource adequacy tools, the total capacity needed is refined and decreased, lowering the overall capital cost requirement to attain a reliable portfolio.

Another interesting finding is that while the overall capacity needs changed, the total *energy* required of the hydrogen CTs did not materially change as hydrogen CTs were removed. This highlights that the high renewable and storage system becomes predominantly *energy constrained,* rather than capacity limited, and that clean firm resources can provide dual benefits—providing capacity during a shortfall event, and

6 The hydrogen capacity was adjusted, initially, to the nearest 100 MW of capacity, and subsequent incremental adjustments were 100 MW each.

by providing energy preceding or immediately following an event, thus enabling other resources to provide additional capacity to ensure reliability.

One additional benefit from conducting a round-trip analysis is that the delivered energy required from the marginal capacity resource can be better quantified, and year-to-year variability of annual fuel requirements (facilitated by the multiple weather year analysis in resource adequacy modeling) is transparent to planners.

FINDING 5.

PNM should not go it alone—regional planning and coordination are critical for efficient reliability and cost mitigation.

Increased regional coordination is one of the three broad pathways to achieving PNM's renewable energy transition goals. While regulatory rules require that much of PNM's long term planning is focused on serving its load with its own resources, there are both reliability and economic benefits of increased resource sharing and coordination across the West.

There are two primary reasons for the benefits that result from regional coordination. First, PNM's service territory, and New Mexico more generally, has some of the best wind and solar resources across the West. The region is already a large exporter of electricity, but the state could become a generation hub for the rest of the region—and New Mexico's residents could access the cheap, renewable electricity commensurate with the scale of the projects required for in-state use.

The second reason is that regional coordination and resource sharing would capture diversity in *both* the load and renewable generation patterns. While regional weather can influence a large part of the West simultaneously, there is still diversity in loads across the region. For example, the Northwest region is winter peaking while the Southwest is summer peaking. Time zone variation also contributes to load diversity, as well as the timing of solar generation. Most weather patterns (like heat waves and cold snaps) are regional, rather than continental, in scale. Renewable generation is often diversified across the region as wind speeds and cloud cover are not uniform across the West. When it is cloudy in California, it may be sunny in New Mexico and vice-versa.

The modeling that assessed regional coordination benefits is described below.

ASSESSING CURTAILMENT BENEFITS AND EXPORT OPPORTUNITIES OF REGIONAL COORDINATION

To evaluate this opportunity, a West-wide regional planning capacity expansion model, SWITCH, was used to develop portfolios for two broad classes of operating assumptions:

- one that considered long-term, least-cost, economic capacity expansion for the entire Western Interconnect in which PNM was one of many balancing authorities in the region.[7] This class of portfolios included a number of sensitivities that considered constraints of varying levels of annual net exports, wind to solar ratios, and storage costs.[8]
- a second type of portfolio was developed assuming PNM was an electrical island and could not benefit from imports or exports.

Both classes of portfolios were developed for the following combinations of demand forecasts and West-wide GHG policy hypothetical conditions: (1) Baseline demand and zero GHG emissions West wide; (2) High Electrification demand and zero emissions West wide; (3) and High Electrification demand and 80% GHG emissions reductions West-wide compared to 2005 emissions.

All regionally-coordinated cases found that it was optimal for PNM to be an annual net exporter (exporting 11% to 18% compared to its demand), but nevertheless was a net importer during summer months. In contrast, when PNM was electrically islanded, investment and operational costs (as defined by resources located within PNM's zone) increased by 30% to 104%.[9] In terms of total installed capacity, the electrically islanded cases resulted in 11 GW to 13 GW of solar, wind and batteries, while the regionally connected cases built 6 GW to 10 GW of solar, wind and batteries. The amount of storage duration was higher for the electrically islanded cases compared to cases with regional coordination by a few hours. Curtailment increased 37% to 42% when PNM was electrically islanded compared to 5% to 14% when regional coordination was possible.

7 This included full interconnection modeling and developed a regionally-coordinated resource plan for the entire interconnection with more than 7,000 potential locations to choose from for new wind and solar power in the West.

8 The results of all the SWITCH cases are reported in the technical appendix.

9 To approximate the impact of market interactions (imports and exports to and from the PNM zone as it was defined in SWITCH), we approximated a net cost to PNM based on applying LMPs to PNM's consumption, exports and imports. This calculation showed that the islanded case was ~ 3% to 50% more costly compared to the non-islanded cases, depending on the sensitivity.

To further understand the impact of different levels of annual exports or imports, we conducted additional sensitivities in which we forced different relative quantities of annual imports and exports into SWITCH. This was done by varying an input parameter termed the "annual generation-to-demand ratio" in PNM's zone (which we hereafter refer to as the "ratio").[10] Subtracting 1 and multiplying by 100 gives the percent of exports (or imports if negative) over an annual basis (e.g., a ratio of 1.3 means that 30% of the annual generation is exported on a net basis). Absent forcing any particular annual import or export level, SWITCH developed a portfolio in which 13% of PNM generation is exported over the course of a year—meaning it was cost optimal for the entire West for resources to be located in the PNM zone and exported to the rest of the region at an annual net export rate of 13%. We then ran 3 different import sensitivities: forcing PNM to become a net importer (0.95 ratio), forcing PNM to break even (ratio equal to 1), and as a net exporter by 30% (ratio equal to 1.3). Changing from being a net importer (0.95) to a net exporter (1.3) only increased total investment and operational costs by 3% (though net benefits to ratepayers will depend on market revenues, which are uncertain). However, all our import/export sensitivities—even those reflecting annual net export from PNM—showed that PNM heavily relies on imports during the summer (Figure 7). In terms of curtailment, when PNM was forced to become a net exporter (1.3 ratio), we observed curtailment dropping to the lowest value across all sensitivities to a value of 1%.

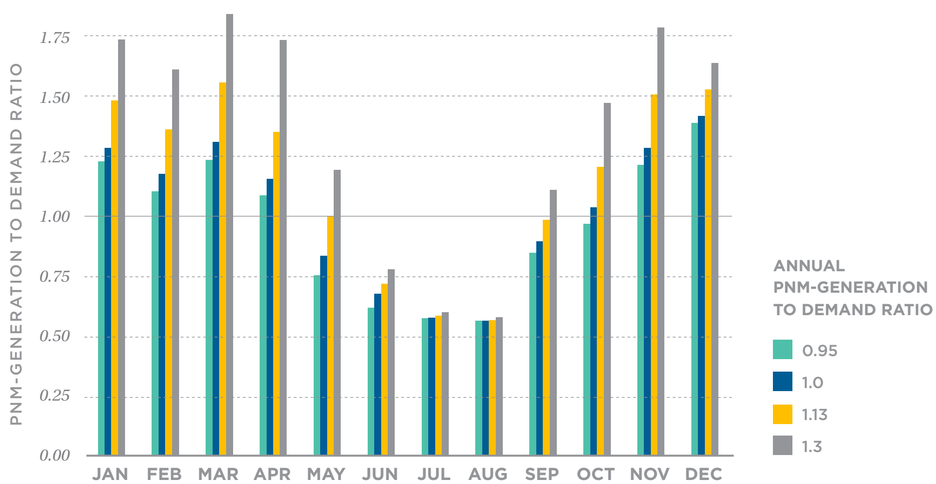


FIGURE 7.

Sensitivities on PNM-Generation to demand ratio, High Electrification demand. (Each color reflects a particular annual ratio; ratio values exceeding 1 reflect net exports, less than 1 reflect net imports)

10 The generation to demand ratio reflects how much generation within PNM is produced to serve PNM's load. A ratio exceeding one implies PNM is a net exporter, when less than one, PNM is a net importer. The ratio was implemented as an annual ratio.

Several sensitivities on the installed wind-to-solar ratio were conducted. For reference, when the wind-to-solar ratio was unconstrained, the model built more wind than solar in the PNM zone (ranging from 4 to 10 times wind over solar). Across the wind-to-solar ratio sensitivities, PNM maintained its net annual exporting position with imports in the summer except in solar dominated cases—in the Baseline demand case, once solar capacity was forced to be 10 times more than wind capacity, PNM became a net exporter. However, this increased the total required capacity build by more than 2.4 times and increased curtailment from ~15 to 25%. Storage duration remained relatively constant across all wind-to-solar sensitivities and at most increased by 0.6 hours. It is worth noting that the required storage duration across all SWITCH cases and sensitivities was relatively low, ranging from 4 to 8 hours for most cases.

Overall, these results show that regionally-coordinated planning can result in lower capacity requirements of resources in PNM, lower curtailment, and lower storage duration.

Overall, these results show that regionally-coordinated planning can result in lower capacity requirements of resources in PNM, lower curtailment, and lower storage duration. However, these findings stem from co-optimized capacity expansion and dispatch and don't reflect market operations or contractual arrangements.

REGIONAL COORDINATION CAPTURES RELIABILITY BENEFITS OF LOAD AND RESOURCE DIVERSITY

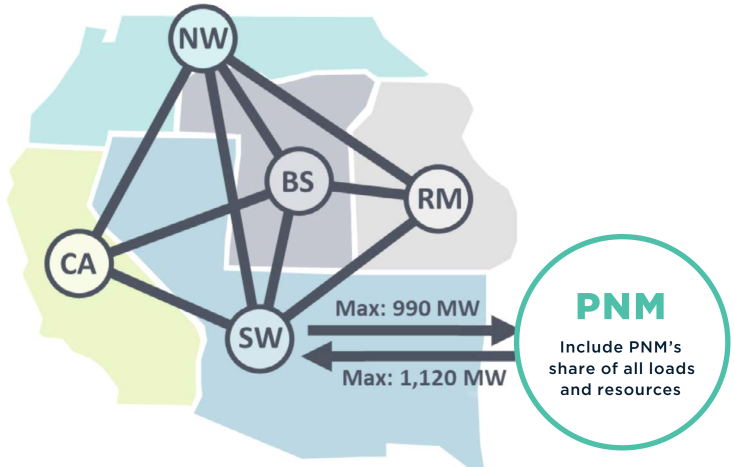
Broadening PNM's planning to include a regional view is critical, especially for resource adequacy analysis. But this requires careful implementation—the analysis should enable *sharing, but not leaning.* We developed a resource adequacy analysis approach, using the practitioner toolkit, that allows PNM to benefit from the resource and geographic diversity across the West, while avoiding leaning on neighbors for assistance.

Following the practitioner planning approach, we developed a PNM-only portfolio (using EnCompass), rather than solving for a full West-wide expansion plan. In this process, PNM is required to have sufficient capacity available to serve its own load with its own resources. However, when analyzing resource adequacy, it is important to recognize that PNM is part of the region. The resource adequacy analysis, using GridPath, included a representation of expected resources across the full Western Interconnection, excluding Canada and Mexico (Figure 8); this representation was based on analysis of recent utility Integrated Resource Plans (IRPs).[11] Imports into and exports from PNM were constrained by transmission limits consistent with PNM's IRP assumptions. A resource adequacy modeling sensitivity was conducted using the assumption that these import and export limits were zero to avoid all interactions with the rest of the West.

11 The study team reviewed the latest IRPs from each utility or planning entity at the beginning of the study and assumed each region achieved its plans for 2030, including both new installations and planned retirements of coal, gas and nuclear generators. Note that IRPs used to create future West-wide portfolios did not include the Inflation Reduction Act at the time of this study.

FIGURE 8.

Study topology and import/export assumptions for PNM



One challenging aspect of modeling PNM subject to a GHG emissions constraint within the broader West was ensuring that GHG emitting resource generation outside of PNM was not supporting resource adequacy within PNM. To prevent leaning on emitting generation outside of PNM within the resource adequacy analysis, we developed a novel approach to constrain regional interactions. In this approach, all GHG-emitting resources were removed from the Western footprint and the resource adequacy analysis was first conducted on the Western footprint *without* PNM. Energy-limited technology agnostic resources were then added to each region to exactly meet all energy and capacity needs in each week. PNM loads and resources were then added back into the 100% reliable system and any observed unserved energy in the final simulation was attributed to PNM.[12]

By doing this, the modeling allowed for PNM to import energy from neighboring regions but did so in a way that it could not lean heavily on neighbors for reliability. The approach also required PNM to provide energy back to neighbors to ensure they meet their reliability obligations.

This process ensured net-zero GHG emissions because for each MWh of imports from a neighbor, PNM was required to replace that with an equivalent zero-carbon MWh export. This approach not only ensures that PNM is meeting its net-zero GHG emissions goals but also ensures that it is not over-relying on any single resource type, thus reducing its risk exposure.

12 The model strictly disallowed unserved energy elsewhere in the West in the final runs to ensure this outcome.

The results of this analysis (Table 3) show that the resource adequacy of the PNM system is highly affected by coordination and resource sharing with the West. Without imports from the West, PNM's loss of load expectation (LOLE), expected unserved energy, and hydrogen fuel requirements would increase. Without considering imports in long-term planning, PNM would need to supplement its capacity portfolio with additional clean firm resources to achieve reliability, which would increase costs.

Without considering imports in long-term planning, PNM would need to supplement its capacity portfolio with additional clean firm resources to achieve reliability, which would increase costs.

TABLE 3.

Resource adequacy results with and without regional coordination

	OPTIMIZED PORTFOLIO			
	ENCOMPASS PORTFOLIO (based on PRM)	GRIDPATH ADJUSTED PORTFOLIO (based on 0.1 days/year LOLE)	ENCOMPASS PORTFOLIO No Imports	GRIDPATH ADJUSTED PORTFOLIO No Imports
LOLE (days/year)	0.00	0.09	0.07	13.3
EUE (MWh/year)	0.00	29	31	11,282
Hydrogen CT Capacity (MW)	1000	600	1,000	600
Hydrogen Generation (GWh)	511	508	889	884
Hydrogen Capacity Factor (%)	6%	10%	10%	17%

Figure 9 shows the timing and magnitude of clean firm needs with and without import availability. The left frame of Figure 9 shows average hydrogen utilization with imports available. The hydrogen resource need is most pronounced in the morning and evening periods in peak summer months and winter periods when wind and solar droughts may occur. The right frame of Figure 9 shows an increase in utilization if imports are unavailable. Without imports, the need for hydrogen CTs is more pronounced in these periods and in general across all hours, including shoulder seasons when their use is minimal due to imports being available.

WITH IMPORTS

HOUR OF DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	6%	2%	0%	0%	0%	5%	46%	43%	7%	0%	2%	12%
1	6%	2%	0%	0%	0%	5%	43%	41%	7%	0%	2%	12%
2	7%	2%	0%	0%	0%	5%	43%	41%	7%	0%	2%	12%
3	8%	3%	0%	0%	0%	6%	44%	46%	8%	0%	3%	14%
4	11%	3%	0%	0%	0%	3%	40%	49%	9%	1%	4%	19%
5	15%	5%	0%	0%	0%	0%	13%	23%	5%	1%	6%	27%
6	17%	4%	0%	0%	0%	0%	5%	7%	1%	0%	2%	27%
7	3%	1%	0%		0%	0%	2%	3%	0%	0%	0%	4%
8	1%	0%				0%	1%	1%	0%	0%	0%	1%
9	0%	0%					1%	1%	0%	0%	0%	0%
10	0%	0%					1%	1%	0%		0%	0%
11	0%	0%				0%	1%	1%	0%		0%	0%
12	0%	0%				0%	4%	4%	0%		0%	0%
13	0%	0%		0%		0%	9%	10%	1%	0%	0%	1%
14	0%	0%	0%		0%	1%	19%	19%	2%	0%	0%	1%
15	2%	0%	0%	0%	0%	2%	31%	30%	5%	0%	1%	10%
16	14%	2%	0%	0%	0%	6%	47%	55%	19%	1%	6%	32%
17	16%	4%	0%	0%	0%	14%	77%	82%	28%	2%	6%	33%
18	16%	4%	0%	0%	1%	18%	85%	86%	28%	2%	6%	33%
19	16%	4%	0%	0%	0%	17%	85%	84%	27%	2%	6%	33%
20	15%	4%	0%	0%	0%	16%	80%	76%	22%	1%	6%	32%
21	14%	4%	0%	0%	1%	14%	68%	63%	16%	1%	5%	30%
22	10%	3%	0%	0%	1%	10%	56%	53%	10%	1%	4%	23%
23	7%	3%	0%	0%	1%	7%	50%	47%	8%	1%	3%	17%

WITHOUT IMPORTS

HOUR OF DAY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0	20%	13%	3%	1%	5%	22%	62%	59%	26%	10%	16%	34%
1	22%	14%	5%	1%	6%	23%	59%	56%	28%	12%	18%	35%
2	25%	16%	6%	2%	8%	26%	59%	57%	31%	14%	21%	38%
3	28%	19%	8%	4%	11%	30%	61%	63%	35%	17%	24%	40%
4	33%	22%	10%	5%	11%	23%	57%	67%	41%	20%	27%	43%
5	37%	26%	11%	1%	1%	2%	19%	35%	28%	21%	31%	47%
6	41%	20%	3%	0%	0%	1%	6%	9%	3%	3%	13%	47%
7	11%	4%	1%	0%	0%	1%	5%	8%	2%	1%	2%	13%
8	5%	2%	0%	0%	0%	1%	6%	8%	2%	1%	1%	7%
9	3%	1%	0%	0%	0%	1%	7%	9%	2%	1%	1%	6%
10	2%	1%	0%		0%	1%	9%	11%	2%	1%	1%	5%
11	2%	1%	0%		0%	2%	11%	13%	3%	1%	1%	6%
12	3%	1%	0%	0%	0%	2%	14%	16%	4%	1%	1%	7%
13	4%	1%	0%	0%	0%	4%	20%	22%	5%	2%	1%	8%
14	5%	2%	0%	0%	0%	6%	28%	31%	8%	2%	2%	11%
15	11%	4%	1%	0%	1%	9%	37%	38%	11%	4%	7%	26%
16	17%	7%	2%	0%	1%	12%	47%	52%	19%	6%	9%	31%
17	19%	8%	2%	0%	2%	17%	60%	62%	25%	7%	10%	35%
18	21%	9%	2%	1%	3%	26%	66%	67%	27%	7%	12%	37%
19	24%	10%	2%	1%	3%	25%	69%	68%	28%	8%	14%	39%
20	26%	12%	3%	1%	3%	25%	71%	71%	33%	10%	17%	42%
21	27%	14%	3%	1%	4%	29%	72%	71%	35%	12%	21%	43%
22	28%	16%	4%	1%	6%	33%	71%	69%	36%	14%	22%	42%
23	28%	18%	6%	2%	8%	31%	69%	66%	35%	15%	23%	42%

FIGURE 9.

Heatmap of hydrogen CT capacity factor with and without imports

To summarize, resource adequacy was evaluated based on analysis of PNM and its interactions with the West. PNM's future portfolio was developed using EncCompass, while the future portfolio for the rest of the West was based on recent IRPs. A methodology for analyzing resource adequacy in GridPath was developed that ensures that PNM does not lean on its neighbors at the expense of reliability in the rest of the West. The methodology ensured net-zero GHG emissions in PNM—for each unit of energy imported from the West, PNM was required to export an equivalent amount of zero-carbon energy. The approach captured the benefits of resource sharing without over-reliance on imports and provided a robust framework for evaluating the Western interconnection in the context of PNM.

FINDING 6.

Electrification will require significantly more energy and capacity resources but does not fundamentally change the portfolio. However, weather dependent, future forecasts of end-use load are essential to understand the reliability impacts of electrification, behind the meter generation, and to identify load flexibility opportunities.

We developed a second demand forecast, the "High Electrification demand forecast", that incorporates increased adoption of electric vehicles, building space and water heating, and industrial electrification; this forecast reflects the importance of electrification towards economy-wide decarbonization. The left frame of Figure 10 shows the Baseline electricity demand forecast for PNM through 2040 by sector and end use; the middle frame of the figure shows the High Electrification demand forecast; the right frame compares consumption between these forecasts by sector and end use in the 2035 study year.

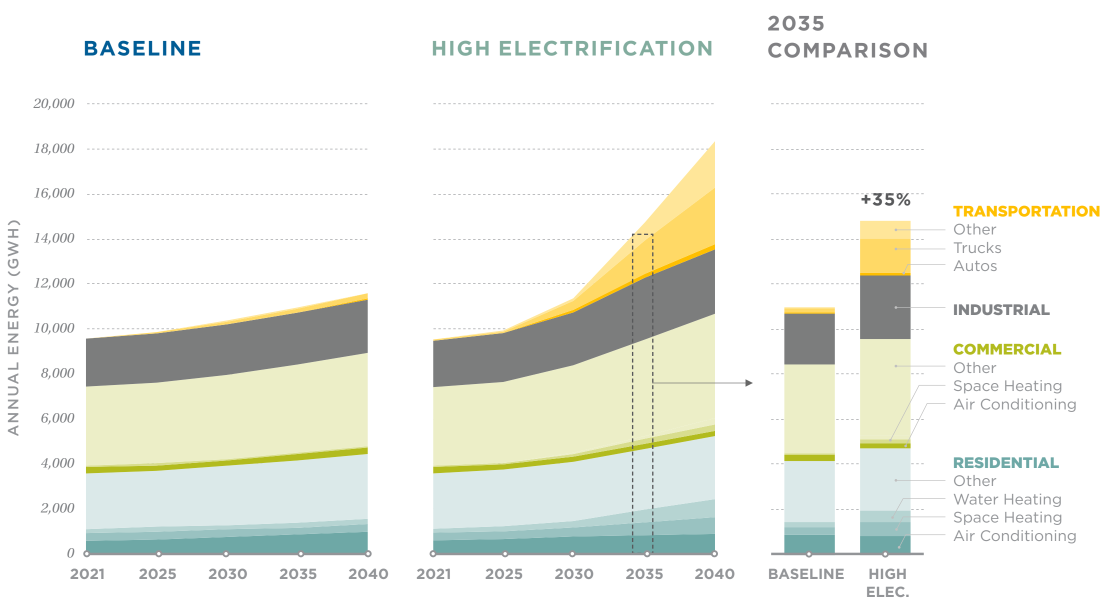


FIGURE 10.

Demand breakdown by sector and end use for the Baseline and High Electrification demand forecasts

The High Electrification demand forecast reflects a 35% increase in annual energy, relative to the Baseline demand forecast. The transportation sector experienced the largest load growth, accounting for over half (~60%) of the total annual energy increase in the High Electrification demand forecast, with most of the increase attributed to trucking and fleet vehicle electrification. Increases in load across the industrial, residential and commercial sectors are due to the electrification of space and water heating and are relatively comparable to one another.

Figure 11 compares the portfolios developed in EnCompass for the Baseline and High Electrification demand forecasts. Although annual energy consumption increased by 35% in the High Electrification demand forecast, this did not affect the general resource compositions of the generation portfolios but mainly increased the magnitude of resources needed (ranging from 1 to 2 GW additional resources). Under high electrification assumptions, wind, solar, and battery storage remained the primary types of capacity built across all three portfolios. This reaffirms the low regrets nature of these resources. Wind capacity experienced the largest increase in both the Diverse Clean Resources and Multi-day Storage portfolios.

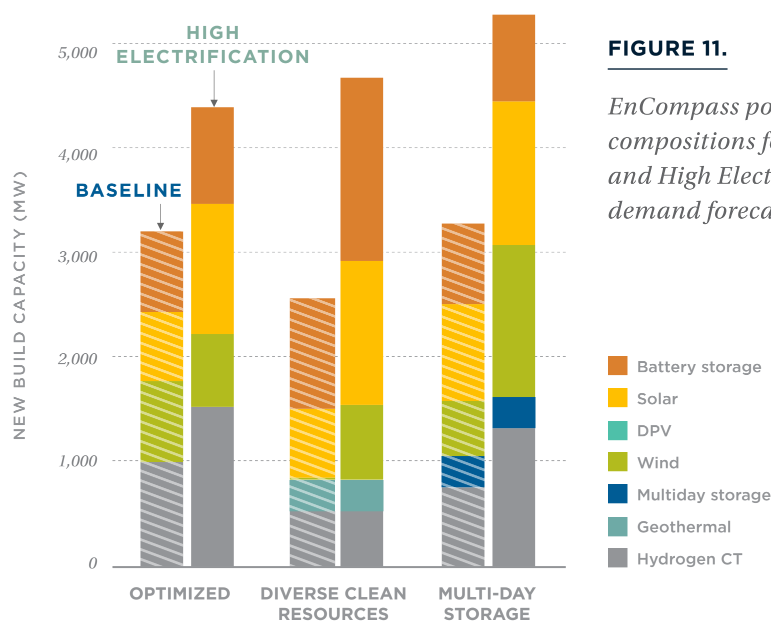


FIGURE 11.

EnCompass portfolio compositions for the Baseline and High Electrification demand forecasts

Similar to the Baseline demand results, geothermal and multi-day storage were not selected by EnCompass in the Optimized portfolio under high electrification. Hydrogen CTs remained the marginal capacity resource selected by EnCompass to meet the planning reserve margin requirement. Under high electrification, the Optimized and Multi-day Storage portfolios showed an increase in the amount of hydrogen CTs required for reliability. The Diverse Clean Resources portfolio did not require additional hydrogen CTs, highlighting the diversity benefit from geothermal and wind resources.

The portfolios developed by EnCompass for the High Electrification demand forecast were overbuilt from a loss of load expectation (LOLE) perspective (Table 4), similar to what we observed using the Baseline demand forecast.

TABLE 4.

Resource adequacy results and clean firm needs, High Electrification demand

	OPTIMIZED PORTFOLIO BASELINE DEMAND FORECAST		OPTIMIZED PORTFOLIO HIGH ELECTRIFICIATION FORECAST	
	ENCOMPASS PORTFOLIO (based on PRM)	GRIDPATH ADJUSTED PORTFOLIO (based on 0.1 days/year LOLE)	ENCOMPASS PORTFOLIO (based on PRM)	GRIDPATH ADJUSTED PORTFOLIO (based on 0.1 days/year LOLE)
LOLE (days/year)	0.00	0.09	0.00	0.05
LOLP (% of years)	0.0%	5.9%	0.0%	2.2%
LOLH (hrs/year)	0.0	0.3	0.0	0.4
EUE (MWh/year)	0	29	0	38
Hydrogen H2 CT Capacity (MW)	1,000	600	1,520	1,000
Hydrogen Generation (GWh)	511	508	927	922
Hydrogen Capacity Factor (%)	6%	10%	7%	11%

Using an iterative approach in GridPath, it was shown that a large portion of the hydrogen CT capacity for the Optimized portfolio (approximately 520 MW, or 35%, in the high electrification case) could be avoided while maintaining a reliable system.

FINDING 7.

Reliability risks are shifting—with high levels of electrification, summer peak demand will not remain the largest challenge.

An important finding of the High Electrification analysis was that although the portfolios did not change in terms of resource composition, we observed a shift in the periods of resource adequacy risk moving from summer-dominated risk to winter-dominated risk. This highlights the importance of modeling weather dependent, end-use load forecasts, especially when considering electrification impacts.

WINTER IS THE NEW SUMMER FOR RELIABILITY CONCERNS

Increased electrification had a large effect on the *seasonal* load profile, the timing of resource adequacy risk, and the opportunities for load flexibility. Electrification and particularly space heating, increased winter loads more than summer. This makes PNM a dual peaking system—by 2035, the winter peak demand is projected to almost rival the summer peak demand (Figure 12). While the peak demand remained highest in the summer months for most weather years, cold snaps and anomalous weather events could shift the peak demand to winter months.

While the peak demand remained highest in the summer months for most weather years, cold snaps and anomalous weather events could shift the peak demand to winter months.

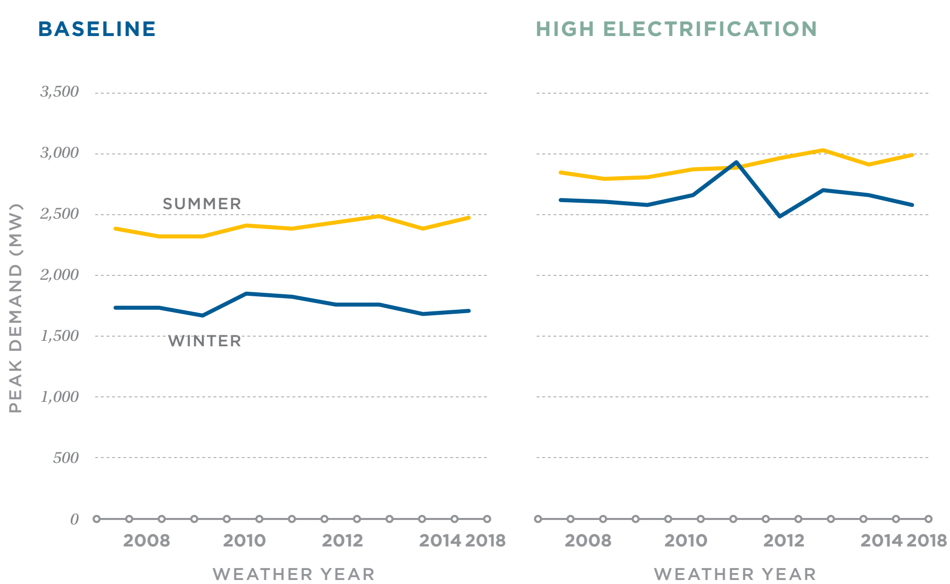


FIGURE 12.

Peak demand by weather year for Baseline and High Electrification demand forecasts

Figure 13 shows the hourly load across a full year (2011 weather) for the Baseline (blue) and High Electrification (green) demand forecasts; it shows the shift from summer peaking to winter and summer peaking with electrification. The red circle denotes an intense cold wave in New Mexico in mid February. While this event has a modest effect on load under Baseline demand assumptions, it has a considerable impact on load for the High Electrification demand forecast and results in the winter peak load exceeding summer peak load. Events such as these were incorporated in the development of the bottoms-up, end-use demand profiles and in the weather-dependent renewable generation profiles.

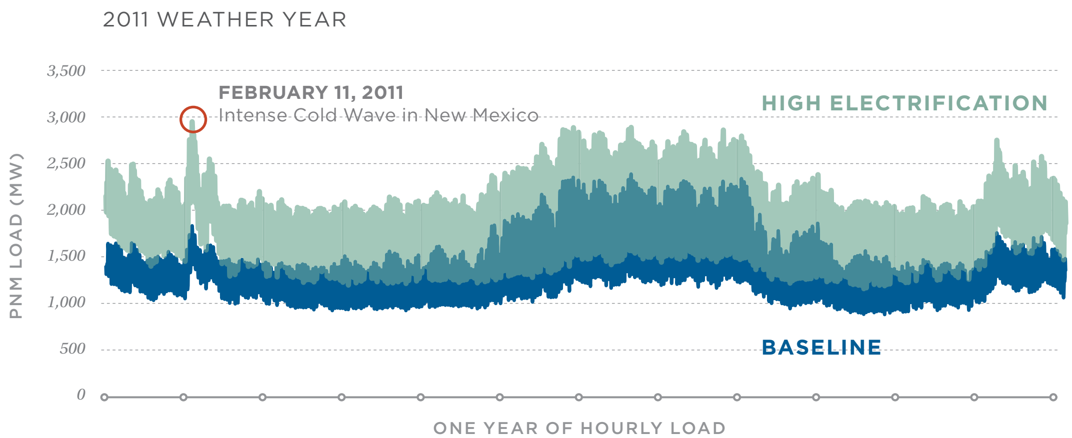


FIGURE 13.

Hourly demand for the Baseline and High Electrification forecasts for Weather Year 2011

Note: The high electrification line chart is transparent and overlaid on top of the Baseline demand. The shaded middle portion of the line chart represents the top of the Baseline Demand.

These types of weather phenomena, combined with electrification, can impact resource adequacy significantly. Not only can peak demand occur during the winter, but the demand can stay elevated for a longer period (relative to summer evening air conditioning peaks) and may occur during a sustained, multi-day low wind and solar period. The extended low wind periods are more likely in the winter when solar availability is also generally lower; winter storms may reduce availability further. As a result, peak risk, defined as the highest probability of load loss, begins to occur more often during the winter months under high electrification assumptions.

Figure 14 shows the expected unserved energy by month and hour of day for the Baseline and High Electrification demand cases. In both cases, the portfolio meets a 1 day in 10 year loss of load expectation requirement. The change in timing, both seasonally and by hour of day, illustrates the shifting nature of resource adequacy risk due to electrification. While summer evenings continue to experience some risk of shortfall, the majority of risk occurs in January and December and is spread across most hours of the day. The spread of risk over the entire day implies that the system is *energy* deficient rather than *capacity* limited. This is because heating demand load stays elevated for a longer period and because low wind and solar events can occur for longer periods in the winter.

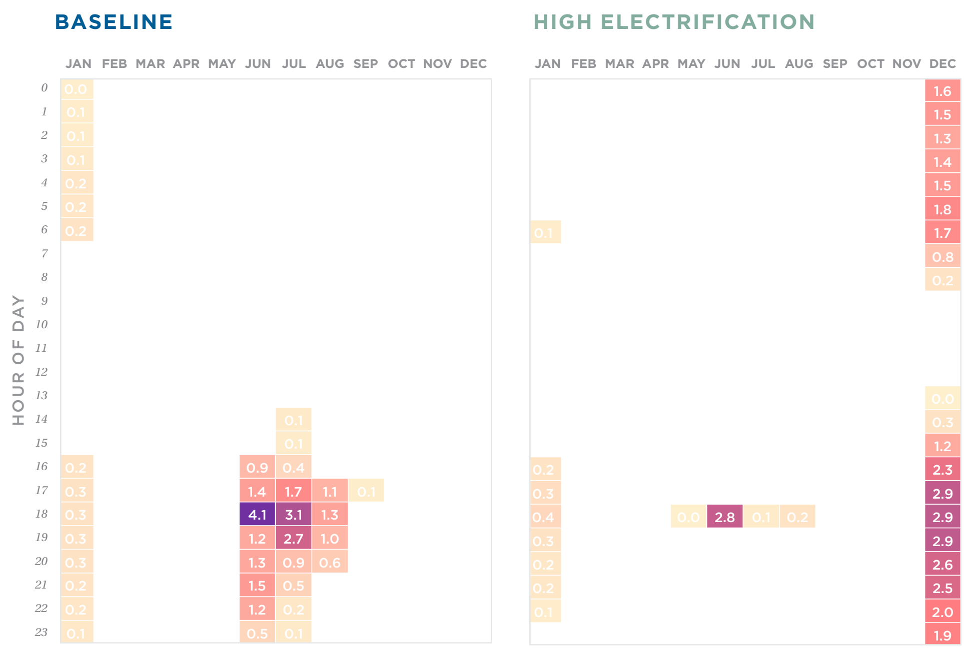


FIGURE 14.

Expected unserved energy by month and hour of day for the Baseline (left frame) and High Electrification (right frame) demand cases

Increased electrification, the shift towards elevated winter risk, and events that are spread across the entire day have important implications for the *duration* of resource adequacy events. The events analyzed using the High Electrification demand forecast were longer in duration compared with those using the Baseline Demand forecast. Energy constraints driven by low renewable output periods, which can span potentially multi-day periods, increase the likelihood of shortfalls exceeding 10 hours in duration.

Figure 15 shows the distribution of shortfall event durations and illustrates an increase in events that span 15-19 hours under high electrification conditions. While the total number of events is similar between the Baseline and High Electrification demand cases (1 day in 10-years loss of load expectation) the severity of the events are different. This is especially important given that events are occurring more often during winter cold

Increased electrification, the shift towards elevated winter risk, and events that are spread across the entire day have important implications for the *duration* of resource adequacy events.

snaps when consumers will be more reliant on electric heating. This risk becomes even more pronounced for heat pumps that rely on backup electric resistive heating in extremely low temperatures.

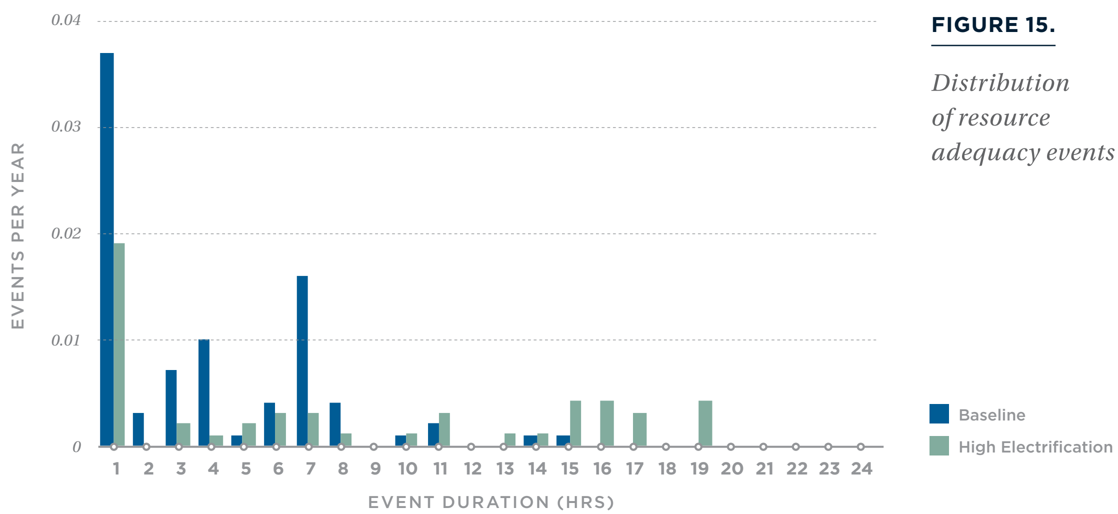


FIGURE 15.

Distribution of resource adequacy events

The impact of electrification on load composition and resource adequacy underscores the importance of developing weather dependent end-use load forecasts for long-term planning.

CHANGING OPPORTUNITIES FOR LOAD FLEXIBILITY

Weather dependent, end-use demand forecasts are important for analyzing opportunities for load flexibility. Increased electrification can facilitate load flexibility assuming that new end-use loads will be more technically advanced and include a higher level of control and communications. For example, the charging of EVs can be dynamically scheduled and new electrified building loads, such as heat pump water heaters, may come equipped with features that enable more sophisticated scheduling and control.

To evaluate this opportunity, we developed an end use load flexibility sensitivity in which we assumed roughly one-third of total residential and commercial HVAC, water heating demand and light-duty electric vehicles can be flexible. This translates to a load flexibility resource that ranges from one to eight hours in duration and can yield over 500 MW of available demand reduction (Table 5).

TABLE 5.

Load flexibility assumptions for HVAC, water heating, and light-duty vehicles

	% FLEXIBLE	DURATION (HRS)	HOURLY LOSSES	MAX LOAD (MW)
Res. HVAC	35%	1	20%	269
Res. Water Heating	35%	8	2.5%	78
Com. HVAC	34%	1	20%	80
Com. Water Heating	34%	4	2.5%	14
Light Duty Vehicles	38%	8	0%	169
		Maximum simultaneous flexible load (MW)		505

Our resource adequacy analysis found that, in the context of bulk system planning, load flexibility can avoid battery storage requirements. With load flexibility, we were able to significantly reduce the amount of battery storage (by 600 MW and 3,500 MWh) in the portfolio while maintaining similar levels of resource adequacy under a high load flexibility scenario (Table 6).

This shows that load flexibility can be a valuable substitute for other energy limited resources.

However, the use of flexible load *did not* reduce the need for clean firm resources, such as hydrogen CTs, which provide both capacity and energy to the system. This shows that load flexibility can be a valuable substitute for other energy limited resources—like battery storage—but may not reduce firm capacity needs in the future, which will be needed to mitigate risk occurring during winter cold-events and over long periods. This study did not address the potential benefits of load flexibility for distribution system planning under high electrification scenarios, nor did it investigate flexible industrial load that may offer longer duration flexibility.

TABLE 6.

Total hydrogen CT and storage capacity with and without load flexibility

	PORTFOLIO WITHOUT FLEXIBLE LOAD	PORTFOLIO WITH FLEXIBLE LOAD
Hydrogen CT Capacity (MW)	950	950
Storage MW	**1,565**	**950**
Storage MWh (MW x duration)	**9,155**	**5,626**
LOLE (days/year)	0.07	0.10
EUE (MWh/year)	17	15

In summary, weather dependent, end-use load forecasts are essential for long-term planning in the electricity sector, particularly in the context of electrification and load flexibility. The analysis shows that electrification increases the overall load of the system, making it a dual peaking system, and requires additional capacity to maintain resource adequacy, but does not significantly change the composition of resources needed to meet increased demand. While load flexibility can mitigate the need for additional storage capacity, it does not obviate the need for clean firm capacity in an energy constrained future.

FINDING 8.

Cost, land use, and water requirements for PNM's energy transition are manageable.

Although not a primary focus of the study, we developed approximations for the cost, land use, and water use across the different portfolios. Our results show that for each of these factors the impact on PNM ratepayers is manageable and reasonable relative to historical norms.

THE COST OF NEW RESOURCES IS SIMILAR TO EXISTING NATURAL GAS GENERATION

The study intentionally did not focus on the costs of achieving a 100% clean power system, but rather evaluated the technical feasibility and reliability of achieving this target. The reason for this is two fold. First, the enabling technologies associated with clean firm resources like hydrogen CTs, new geothermal, and thermal resources with carbon capture and sequestration, or multi-day energy storage are highly uncertain in terms of cost, and in some cases, performance and technical feasibility. These technologies, while proven to be feasible, have not been deployed at scale in the United States. Second, New Mexico's Energy Transition Act requires a net-zero PNM resource mix by 2045. As a result, only 100% decarbonized portfolios were evaluated and we did not evaluate the costs or savings attributed with lower decarbonization levels.

Despite the focus on feasibility and reliability, we estimated the *relative* costs of different portfolios to compare the total capital investment, fuel costs, and operations and maintenance costs of the final portfolios. This was computed for the total resource mix and levelized without making assumptions on the timing or trajectory of new investments.[13] The costs were then evaluated with and without subsidies related to the Inflation Reduction

13 The levelization of cost assumed that all investments occurred at the same time, and the analysis did not evaluate the net present value of different portfolios across a future planning horizon.

Act.[14] Figure 16 shows that the total system's levelized cost of energy from new resources (excluding existing PPAs) is between $35 and $40/MWh without considering IRA tax credits, and between $20 to $25/MWh when including IRA tax credits (well within the range of existing natural gas generation prices).

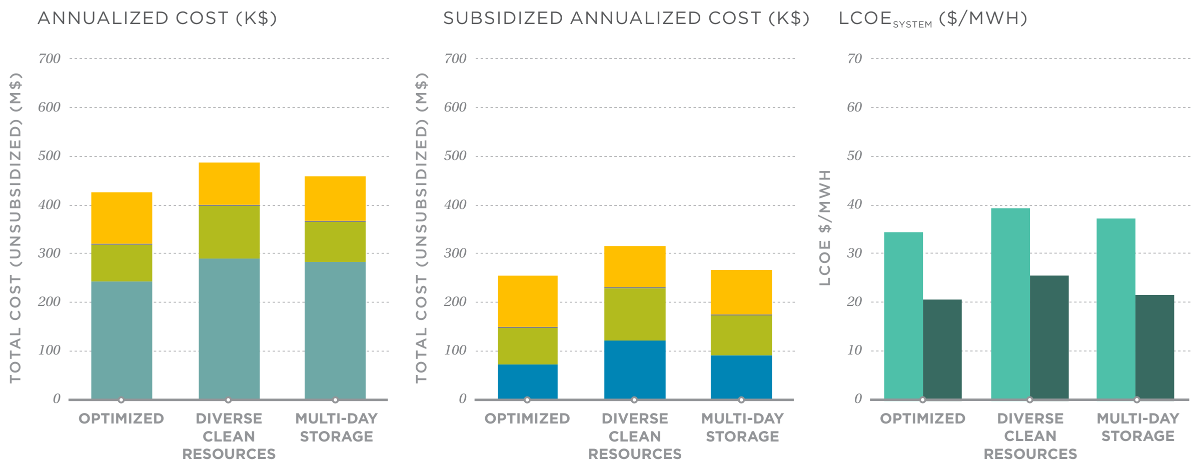


FIGURE 16.

Annualized cost and system LCOE for EnCompass derived 100% clean portfolios

While there is a high degree of uncertainty across the future capital cost assumptions for various resources and the costs of hydrogen fuel, the costs are reasonable relative to costs of existing portfolios that are not 100% clean. The analysis shows that the costs of hydrogen fuel (denoted as a yellow bar segment) show that this cost (assumed at $25/MMBtu or $3/kg in 2021$) becomes a large portion of the overall system cost in 2035. This highlights the rising incremental costs needed to achieve the final 5-10% of energy to achieve 100% clean electricity targets.

HYDROGEN PRODUCTION WILL REQUIRE ADDITIONAL RENEWABLE RESOURCES AND WATER, BUT IN MANAGEABLE QUANTITIES

This study did not evaluate full life-cycle green hydrogen production (i.e., renewable generation, electrolyzer operation, storage, and transportation). Instead, it took a simplifying assumption that hydrogen fuel would be available to PNM when needed, and provided via a third-party that self supplies renewable electricity (or purchases surplus on the market), stores, and delivers hydrogen as needed. The $25/MMBtu, or $3/kg, hydrogen fuel price was assumed to capture these costs after accounting for IRA subsidies.

14 For the purposes of this analysis, it was assumed that the production tax credit for all available wind and solar was captured and did not evaluate impacts of potential curtailment.

However, in order to compare portfolios in a consistent manner, it is important to calculate the additional variable renewable energy that would be required to power the hydrogen electrolyzers. In addition, given the scarcity of water resources across the West, it's important to understand the water requirements for hydrogen generation—the main feedstock required for hydrogen production via electrolyzers. We estimated the upstream renewable electricity and water requirements. Table 7 summarizes the hydrogen fuel requirements and operation, water consumption, and renewable energy required to produce PNM's hydrogen demand (exclusive of hydrogen storage and transportation considerations to ensure firm hydrogen delivery).

TABLE 7.

Hydrogen (H2) fuel and renewable needs by portfolio

	OPTIMIZED	DIVERSE CLEAN RESOURCES	MULTI-DAY STORAGE
GridPath LOLE (days/year)	0.09	0.04	0.04
H2 CT Capacity (MW)	600	500	400
H2 Generation (GWh)	508	402	445
H2 Capacity Factor (%)	10%	9%	13%
H2 Fuel Offtake (thousand metric tons H2/yr)[1]	36	29	29
H2 Renewable Capacity Need (MW)[2]	622	492	490
H2 Water Usage (million gallons)[3]	170	134	134
H2 Water Need (% of current PNM use)	6%	5%	5%

1 Hydrogen fuel offtake is based on it's lower heating value (33.33 kWh/kg H2) and a 42% efficient combustion turbine (lower heating value 8200 btu/kWh)

2 Renewable capacity needed is based on a 60% efficient PEM electrolyzer and a 50/50 split between wind (42% capacity factor) and solar (32% capacity factor)

3 Water usage for hydrogen electrolysis assumes 18 L H2O/kg H2 assuming that there are losses in providing proper water purity for the electrolyzer.

The buildout of additional wind and solar required to supply green hydrogen for PNM based on annual energy needs alone varies between an additional 30-40% for the Optimized and Multi-day Storage portfolios and an additional 75% for the Diverse Clean Resources portfolio. While the costs of these renewables are embedded in the hydrogen fuel cost assumption, the additional renewable capacity represents a substantial investment required by PNM or a third-party to provide green hydrogen for the electric power grid.

Lastly, it is important to note that while water needs for hydrogen production are substantial, these requirements must be calibrated against the water requirements of thermal generators in today's power system. The water required for hydrogen production in a 100% clean portfolio for PNM is estimated to be only 5% of the water consumed currently

by PNM's power system.[15] For additional context, this is less than 5% of New Mexico's water use for golf course irrigation.[16] The increase in water consumption for green hydrogen, which is important for the reliability of PNM's clean portfolio, will be more than offset by retiring existing thermal power plants.

TOTAL LAND USE REQUIREMENTS ARE SMALL

Land use requirements for new renewable generation are an important consideration. Assuming 120 acres/MW of indirect land use for wind resources[17] and 6 acres/MW_{dc} for solar resources[18], the total land use requirements for the Baseline demand portfolios are between 41,000 and 137,000 acres. The indirect land use assumption for wind is conservative; in reality much of the land use remains as open space and can be used for alternative uses like agriculture and grazing. These estimates include the renewable energy needed to produce green hydrogen (Table 8).

For comparison, this total land use represents less than 0.2% of New Mexico's total land area; when assuming high electrification, the total land use is less than 0.3%. While the total land needs for wind and solar projects are minimal, community acceptance, siting, and zoning rules will remain important considerations for future development. Given the small, relative acreage of potential renewable projects, it is more important to focus policy and zoning attention on avoiding important habitats and cultural sites, rather than focus on the total amount of land use required for new development.

15 PNM's fresh water withdrawals for 2021 was 2,793 million gallons, https://www.pnmresources.com/esg-commitment/environment/water-usage.aspx

16 USGS, Water Use Data for New Mexico, 2015, https://nwis.waterdata.usgs.gov/nm/nwis/water_use/

17 Assumes approximately 2 MW/km2 of indirect land use for the Southwest, based on https://www.nrel.gov/docs/fy22osti/75863.pdf

18 Assumes approximately 40 MWdc/km2 of land use. https://www.nrel.gov/docs/fy21osti/78195.pdf

TABLE 8.

Total land use requirements by portfolio[1]

	BASELINE LOAD			HIGH ELECTRIFICATION		
	OPTIMIZED	DIVERSE CLEAN RESOURCES	MULTI-DAY STORAGE	OPTIMIZED	DIVERSE CLEAN RESOURCES	MULTI-DAY STORAGE
New Wind Capacity Additions (MW)	765	32	521	709	720	1444
New Solar Capacity Additions (MW)	663	657	930	1238	1381	1369
Wind & Solar for Hydrogen Production (MW)	622	492	490	622	492	490
Wind Land Use (acres/MW)	120	120	120	120	120	120
Solar Land Use (acres/MWdc)	6	6	6	6	6	6
Total Land Use (thousand acres)	137	41	102	136	131	217
Total Land Use (% of total area)	0.18%	0.05%	0.13%	0.18%	0.17%	0.28%

1 Solar land use assumes 1.7 DC:AC inverter loading ratio for solar PV and single axis tracking systems; wind land use is intended to represent total indirect plant boundaries and representative of similar plants in the region

While this study included IRA credits as cost adjusters in the economic modeling, it's worth noting that up to 80% of New Mexico qualifies for credits that are available to energy communities,[19] with additional credits available for Native American land. We did not look at the economic development opportunities in this study, but follow-on efforts and policy actions should leverage the IRA and other programs to maximize economic and social development objectives for New Mexico.

Total land use and water requirements are reasonable and do not appear to be significant constraints for New Mexico. Instead, resource siting, community acceptance, transmission development, regulatory requirements, supply chains, and workforce development are likely to be the bigger challenges moving forward.

19 Approximately 30% of the state qualifies as a census tract or adjoining census tract with a coal closure, which qualifies for the 10% energy community bonus credit. Upwards of an additional 50% of the state may qualify because of 0.17% or greater direct employment related to extraction, processing, transport, or storage of coal, oil, or natural gas. Only a subset of these MSAs and non-MSAs will qualify as energy communities, depending on whether their unemployment rate for the previous year is equal to or greater than the national average unemployment rate. Based on the U.S. Department of Energy, National Energy Technology Laboratory website: https://energycommunities.gov/energy-community-tax-credit-bonus/

In addition, given the high quality wind and solar resource and the prevalence of energy communities that qualify for IRA bonus credits, New Mexico may see large demand for renewable projects sited within the state to support neighboring states and regional decarbonization plans. As a result, land use considerations may be small for PNM's local needs but could increase due to the larger regional need for clean electricity.

While the cost analysis did not evaluate the net present value of resource plans relative to a business as usual case, the results suggest that cost will not be the limiting factor in this transition. Continued cost declines in solar, wind, and battery technologies—combined with federal subsidies—should result in reasonable total portfolio costs. In addition, total land use and water requirements are reasonable and do not appear to be significant constraints for New Mexico. Instead, resource siting, community acceptance, transmission development, regulatory requirements, supply chains, and workforce development are likely to be the bigger challenges moving forward.

CONCLUSIONS AND RECOMMENDATIONS

This study evaluated multiple pathways to achieve a 100% clean electricity system using PNM as a case study. The project used a holistic modeling approach to develop different portfolios and evaluate these for resource adequacy. An economy-wide decarbonization approach, EnergyPATHWAYS, was used to develop two different sets of demand profiles for the PNM service territory and the rest of the West that reflect baseline and high electrification adoption.

Two broad suites of modeling tools were applied—a practitioner toolkit that included Encompass, a capacity expansion and production cost modeling tool commonly used by utilities (employing a sample day and PRM-ELCC approach) coupled with a modified version of the GridPath RA Toolkit—and a West-wide capacity expansion modeling tool, SWITCH, which solves across all hours of the year. The practitioner toolkit was exercised to develop three sufficiently different portfolios in terms of their dependence on clean firm resources, geothermal resources, and long duration storage. The regional coordination model was exercised in both West-connected and islanded modes and with varying assumptions of imports and exports and other sensitivities to understand the resource diversity benefits that the West brings. While a regionally-coordinated capacity expansion approach is idealistic, it provides insights into the value of a combined market and centralized planning approach.

SYNTHESIZING THE MODELING RESULTS, WE FIND THE FOLLOWING INSIGHTS.

- **FINDING 1.** There are multiple pathways towards achieving a 100% clean electricity target while maintaining a reliable and economical electricity system.
- **FINDING 2.** Deploy, deploy, deploy: wind, solar, and battery storage are key components of any plan to decarbonize the power system.
- **FINDING 3.** The "last mile" to achieving 100% clean is uncertain in terms of the cost-optimal resource mix, but clean firm resources are beneficial for the last 5-10% of energy.
- **FINDING 4.** Resource adequacy needs are increasingly driven by energy constraints, not just capacity.
- **FINDING 5.** PNM should not go it alone—regional planning and coordination are critical for efficient reliability.
- **FINDING 6.** Electrification will require significantly more resources but does not fundamentally change the portfolio. However, weather dependent, end-use load forecasts are essential to understand the reliability impacts of electrification, and also, to identify load flexibility opportunities.
- **FINDING 7.** Reliability risks are shifting—with high levels of electrification, summer peak demand will not remain the largest challenge.
- **FINDING 8.** Cost, land use, and water requirements for PNM's energy transition are manageable.

Ultimately, the choice between a specific set of resources will depend on economics, deployment challenges, reliability, and regulatory risk. Some of these may move in opposing directions. For example, increased regional coordination has benefits to reliability and economics (especially if resource and load diversity are maximized); however, regional coordination may pose some regulatory risk in the long term if imports contain GHG emissions. Each of the three broad pathways we identified—integrating emerging clean firm technologies, increasing regional coordination, and upsizing wind and solar resources—pose different factors to be weighed by regulators and policy makers. However, in the interim, the most important message from this report is that the focus in the near term must be on deployment of solar, wind and battery resources, and supporting regional coordination efforts, in order to preserve reliability in the long term, without being fixated on defining the cost-optimal pathway for the last "mile" of power system decarbonization.