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An Analysis of PNM's Renewable Reserve Requirements to Meet New Mexico's Decarbonization Goals

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ABSTRACT

Over the next three years, the Public Service Company of New Mexico (PNM) plans to increase utility-scale solar photovoltaic (PV) capacity from today's roughly 330MW to about 1600MW. This massive increase in variable generation—from about 15% to 75% of peak load—will require changes in how PNM operates their system.

We characterize the 5 and 30-minute solar and wind forecast errors that the system is likely to experience in order to determine the level of reserves needed to counteract such events. Our focus in this study is on negative forecast error (in other words, shortfalls relative to forecast) – whereas excess variable generation can be curtailed if needed, a shortfall must be compensated for to avoid loss of load. Calculating forecast error requires the use of the same forecasting methods that PNM uses or a reasonable approximation thereof.

For wind, we use a persistence forecast on actual 5-minute 2019 wind output data (scaled up to reflect the amount of wind capacity planned for 2025). For solar, we use a formula incorporating the clear sky index (CSI) for the forecast. As the solar on the grid now is a small fraction of what is planned for 2025, we generated 5-minute solar data using 2019 weather inputs.

We find that to handle 99.9% of the 5-minute negative forecast errors, a maximum of 275MW of variable generation reserve during daylight hours, and a maximum of 75MW during non-daylight hours, should be sufficient. Note that this variable generation reserve is an additional reserve category that specifies reserves over and above what are currently carried for contingency reserve. This would require a significant increase in reserve relative to what PNM currently carries or can call upon from other utilities per reserve sharing agreements.

This variable generation reserve specification may overestimate the actual level needed to deal with PNM's planned variable generation in 2025. The forecasting methodologies used in this study likely underperform PNM's forecasting – and better forecasting allows for less reserve. To obtain more precise estimates, it is necessary to consider load and use the same forecasting inputs and methods used by PNM.

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CONTRIBUTOR ROLES

James F. Ellison generated the solar data used in this study, analyzed the data, and wrote the original draft. Cody J. Newlun reviewed the methodology used for data analysis and reviewed and edited the paper. Andrew G. Benson performed statistical analysis of the data, suggested an improvement in the solar forecasting methodology, wrote a section of the paper analyzing the correlation between solar and wind forecast error, and reviewed and edited the paper.

[1] All of the individuals listed in this paragraph are with Sandia National Laboratories.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

Power output from wind and solar photovoltaic (PV) generation is termed variable generation as it can vary based on short-term fluctuations in weather. Utilities forecast variable generation output to plan their system operations. However, perfectly forecasting wind and solar generation is not possible. Forecast errors arise when actual production deviates from what was forecast.

This study characterizes the distribution of forecast errors on time scales of five and thirty minutes attributable to the solar PV and wind plants that the Public Service Company of New Mexico (PNM) intends to have on its system in 2025. It uses this distribution to formulate a reserve requirement capable of compensating for all but the rarest, most extreme ramping events.

2025 was chosen as the system study date as about 1,600MW of utility-scale solar capacity should be online,[2] all coal plant capacity could potentially be retired, and PNM's contracted output from the Palo Verde Nuclear Plant will have decreased [1].

We simulated 5-minute solar output data using **pvlib python** [2], which in turn used 5-minute weather data from the National Solar Radiation Database (NSRDB) [3] as an input. The solar data was generated using state-of-the-art tools and inputs. Nevertheless, we acknowledge that it is not actual observed solar generation data.

The wind data is actual 5-minute wind plant output data for the three wind plants in existence in 2019.[3] However, only about half of the wind capacity planned for 2025 existed in 2019. We multiplied the hourly output from the existing wind plants by 1.87 to account for the additional wind capacity planned to come online by 2025. While we believe this treatment to be a good approximation, it may not capture the benefits of locational diversity in adding wind farms at two more locations.

During daylight hours, it makes sense to consider a reserve that is a function of combined solar and wind output. This combined reserve level, at both the 5-minute and 30-minute intervals, was found to be the same as what was required by solar variability alone. During non-daylight hours, the reserve should be defined as a function of wind output alone.

The 5-minute variable generation regulating reserve ruleset is illustrated in Figure 1-1. For daylight hours, it is shown as the gold curve, and is a function of both wind and solar output. For non-daylight hours, it is shown as the blue curve, and is a function of wind output only.

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[2] See *Table 3-1. Solar plants in study* for reference.

[3] The three plants the data is from (along with their net capacities) are: the New Mexico Wind Energy Center (200MW), Casa Mesa (50MW), and Red Mesa (102MW).

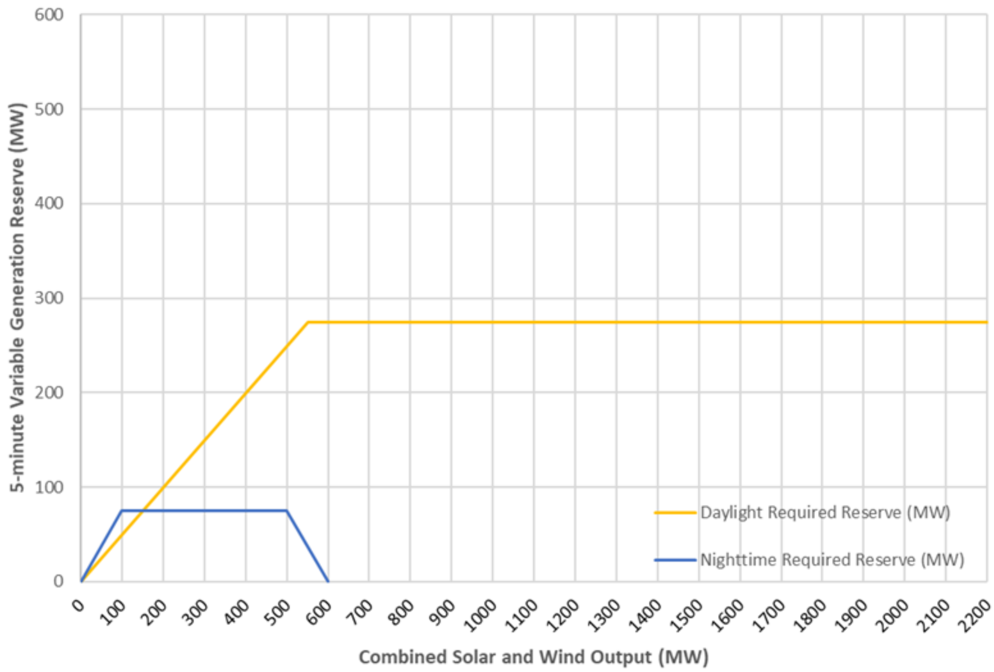

Figure 1-1. 5-minute variable generation reserve formula

In brief, we find that to handle 99.9% of the 5-minute negative forecast errors (shortfalls relative to forecast), a maximum of 275MW of reserve during daylight hours, and a maximum of 75MW during non-daylight hours, should be sufficient. This reserve should be in the form of spinning (or regulating) reserve, as it isn't possible to get a quick-start generator on-line within 5 minutes.

The 30-minute variable generation reserve ruleset is illustrated in Figure 1-2. For daylight hours, it is shown as the gold curve, and is a function of both wind and solar output. For non-daylight hours, it is shown as the blue curve, and is a function of wind output only.

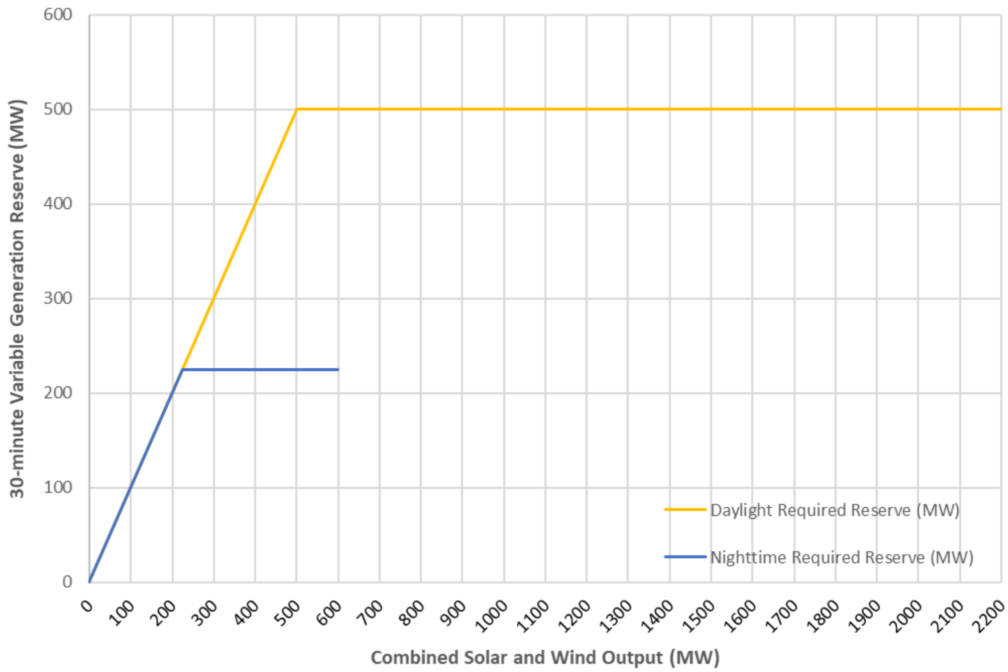

Figure 1-2. 30-minute variable generation reserve formula

In brief, we find that to handle 99.9% of the 30-minute negative forecast errors, a maximum of 500MW of reserve during daylight hours, and a maximum of 225MW during non-daylight hours, should be sufficient. This reserve can be partially provided by spinning (or regulating) reserve, and partially provided by quick-start reserve, as there is time to get the quick-start units on-line within the 30-minute time frame.

To be clear, we are not suggesting a separate variable generation reserve category for 5-minute and 30-minute forecast errors. Rather, we are suggesting what level of variable generation reserves may be needed to handle shorter duration (5-minute) and longer duration (30-minute) forecast errors within the hour. Some portion of this variable generation reserve may be provided by synchronized or storage resources, and some portion may be provided by quick start resources.

The variable renewable generation reserve specified here may overestimate the actual level needed to deal with PNM's planned variable generation in 2025. We did not have access to PNM's proprietary wind and solar forecasting software at the time of this study, and so used an approximation. It is likely that the forecasting methods employed in this study underperform PNM's forecasting -- and better forecasting allows for less reserve. To obtain more precise estimates, it is necessary to consider load and use the same forecasting inputs and methods used by PNM.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AC	Alternating current
AGC	Automatic Generation Control
BA	Balancing Authority
CSI	Clear Sky Index
DC	Direct current
MW	Megawatt
MWh	Megawatt-hour
NM PRC	New Mexico Public Regulatory Commission
NSRDB	National Solar Radiation Database
PNM	Public Service Company of New Mexico
PV	Photovoltaic
SRSG	Southwest Reserve Sharing Group

1. STUDY PURPOSE

The purpose of this study is to characterize the unexpected intra-hour forecast error resulting from having a large amount of variable generation -- both solar photovoltaic (PV) and wind -- on the system and based on that understanding to specify a prudent level of reserve dedicated to variable generation (or "variable generation reserve").

At the time of this study, installed utility-scale solar PV capacity is roughly 330 MW (or about 15% of the peak load).[4] However, this will change dramatically as another 1,240 MW in utility-scale solar PV capacity is likely to be added over the next two years. A solar PV capacity of around 1,600 MW will mean that the solar capacity is about 75% of the peak load in 2025, which will require changes to the way the system is operated.[5]

Given that around 500 MW / 2,000 MWh in battery capacity (lithium ion) has been approved or is under review by the New Mexico Public Regulatory Commission (NM PRC) [1], one might argue that it is not very important what the solar forecast errors are given that there will be enough battery ramping capability to smooth them out. However, one cannot make this argument without characterizing the variability that solar forecast errors impose on the system – this variability might be greater than the capability of the planned battery storage to compensate. We should understand that we are dealing with two separate issues – the variability that solar PV and wind generation impose on the system, and the resources the system requires to compensate for that variability.

The system can compensate for solar and wind generation variability in various ways, such as using battery storage or dispatchable generation, or by contracting for resources outside of the PNM balancing authority ("BA"). If battery storage is required to provide 300 MW of variable generation reserve, for example, then this puts a constraint on the other services the battery can provide.

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[4] Please see Table 3-1. 330MW is the summation of all utility-scale plants that have been installed (in other words, the entire table except for the plants highlighted in blue with no installation date noted).

[5] PNM 2020-2040 IRP, Appendices, Table H-7 has existing and planned solar PV resources at 1035MW. To this we add three other plants under consideration – Atrisco (300MW), Sky Ranch (190MW), and Encino North(50MW), for a total of 1575MW.

2. STUDY METHODOLOGY

The primary goal of this study is to be of use in specifying a variable generation reserve – which would be an additional reserve requirement – sufficient to compensate for the generation and load mismatch under the high penetration of variable generation resources.[6] To do this, it is first necessary to characterize forecast errors of the solar and wind generation.

In order to assess the amount of variable generation reserves required, we analyze the solar and wind forecast error, characterizing its amount and frequency. Since dispatch considers the forecasted levels of wind and solar, the forecast error will tell us the amount of generation shortfall (or surplus) that must quickly be compensated for.

However, to propose a rule set for variable generation reserves, we must also decide what percentage of forecast errors we want to have covered. We could decide to have reserves in place for 100% of the forecast errors, but it would probably be costly to set aside this much reserve. In this study, we assume 99.9% of all forecast errors must be covered by the variable generation reserve rule set. This means that the variable generation reserve would likely be inadequate to deal with 0.1% of the events. Since the PNM Balancing Authority (BA) is interconnected with the rest of the WECC, the imbalance in such an event would be drawn from the outside grid. If this is done too frequently, PNM could find itself in violation of NERC reliability rules.

Our focus in this report will be negative forecast error (in other words, shortfall relative to forecast). Whereas positive forecast error (or surplus relative to forecast) can be dealt with through curtailment if needed, negative forecast error must be compensated for in order to prevent loss of load.

Analyzing the solar and wind forecast errors independently provides useful information. This analysis allows us to specify what level of regulating reserves may be required for wind alone at night.

However, the required reserves during the day may not be a simple addition of the solar and the wind forecast errors. The solar reserve requirements may dominate, given the large amount of solar capacity, or there could be a correlation between solar and wind forecast errors. We therefore need to analyze the combined solar and wind forecast errors and specify a regulating reserve as a function of the combined solar and wind output.

2.1. Solar

Since most of the solar that will be on the system in 2025 does not yet exist, solar PV output was modeled at a 5-minute scale for each existing and planned solar plant using 2019 data from the National Solar Radiation Database (NSRDB) [3] and the **pvlib python** [2] package in the python programming language.

Whether a solar plant is fixed-axis or single-axis tracking was taken into account. All yet-to-be-built solar plants are assumed to be single-axis tracking utility-scale PV plants. All solar plants (existing and future) are assumed to have an inverter load ratio (ILR) of 1.3, meaning that their solar panel capacity is 30% greater than the capacity of the inverter to transform the DC power from the panels into AC power for the grid. This means that in the middle of the day, the daily generation curve will be flatter than otherwise, and that rapid changes in generation due to cloud cover will be mitigated. Detailed information about how the solar output was modeled can be found in Appendix A.

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[6] Note – energy storage, such as battery storage, can provide an injection or absorption of power on a moment's notice, much like what a traditional generation unit offering spinning reserve can do.

Variable generation reserve is needed to compensate for forecast error. As diurnal ramps are predictable, we are not interested in them. We need to use a forecasting methodology that, at a minimum, takes these ramps into account.

The methodology we use here, therefore, takes into account the clear sky (or "CS") output. The clear sky output is a calculated value (based on a specific location) for what the solar output should be at each point in time on a clear day [4]. In addition, the clear sky index ("CSI") is the ratio of the actual solar output at a point in time divided by what the clear sky output at that same point in time should be [5]. If the CSI is 1, this means that the actual solar output is the same as the clear sky solar output. As the weather becomes more overcast or cloudy, the CSI decreases. As displayed in Equation (1), we calculate the CSI based on the actual solar output divided by the clear sky output of the current time step, t.

$$\boldsymbol{CSI_t = \frac{Solar\ Output_t}{Clear\ Sky\ Output_t}} \tag{1}$$

For the 5-minute time step, following the methodology in [6], we take the forecast output to be the current level of solar output plus the product of the clear sky 5-minute ramp and the clear sky index. This is provided via Equation (2).

$$\boldsymbol{P^f_{t+s} = P^a_t + \left(P^{CS}_{t+s} - P^{CS}_t\right) \times CSI_t} \tag{2}$$

Where P^f_{t+s} is the forecasted solar output, P^a_t is the actual solar output at time t, and P^{CS}_t is the calculated clear sky output at time t. The subscript t+s represents s intervals after t, i.e. either 5 minutes or 30 minutes in the future relative to the current time period.

As displayed in Equation (3), the actual solar generation at time t+s has the following relationship with the forecast made s time steps ago at time t:

$$\boldsymbol{P^a_{t+s} = P^f_{t+s} + \varepsilon_{t+s}} \tag{3}$$

We denote ε_{t+s} as the forecast error. We define a ramp in actual solar generation in Equation (4).

$$\boldsymbol{\Delta P^a_{t+s} = P^a_{t+s} - P^a_t} \tag{4}$$

By combining Equations (3) and (4), it can be seen that the actual ramp is composed of a forecasted ramp and an unexpected ramp that is identically equal to the forecast error via Equations (5)-(7)

$$\boldsymbol{\Delta P^a_{t+s} = (P^f_{t+s} + \varepsilon_{t+s}) - P^a_t} \tag{5}$$

$$\boldsymbol{\Delta P^a_{t+s} = (\ P^a_t + \left(P^{CS}_{t+s} - P^{CS}_t\right) \times CSI_t + \varepsilon_{t+s}) - P^a_t} \tag{6}$$

$$\boldsymbol{\Delta P^a_{t+s} = \left(P^{CS}_{t+s} - P^{CS}_t\right) \times CSI_t + \varepsilon_{t+s}} \tag{7}$$

Hereafter, we refer to the "ramp forecast error" and the "forecast error" interchangeably.

Once we have plotted the current solar output versus the 5-minute and 30-minute unexpected down ramps, we can then formulate a rule for the amount of variable generation reserve required as a function of the current level of solar output.

2.2. Wind

For wind, as with solar, we are interested in forecast error. Unlike solar, wind generation does not follow a predictable diurnal pattern.

We evaluated the performance of autoregressive moving-average (ARMA) models, which rely only on the time series of wind generation to predict future wind generation. Unfortunately, when compared to a naïve persistence forecast which assumes the future, the resulting improvement in the wind forecast is negligible. For lack of access to weather data and more sophisticated forecasting tools, and in the interests of simplicity, we adopt a persistence forecast for both time horizons. For the 5-minute forecast, the wind output in 5 minutes is assumed to be at the current level of wind output.

For the 30-minute ahead forecast, the wind output in 30 minutes is also assumed to be at the current level of wind output. Since we have 5-minute data, every five minutes we will have a new 30-minute ahead forecast. Table 2-1 illustrates how the 30-minute ahead wind persistence forecast was performed in this study. At timestamp 1:00, the wind output was 202.3MW. This becomes the forecast for timestamp 1:30. Similarly, the output at timestamp 1:05 was 200.6MW, which becomes the forecast for timestamp 1:35.

What using this forecasting methodology means is that we will simply analyze the 5-minute and 30-minute ramping events in wind generation. This is because we are forecasting the wind output to remain the same, so any deviation from the current level of output will be forecast error.

Table 2-1. Illustration of half-hourly persistence forecast for wind

Timestamp	Actual Output (MW)	Forecasted Output (MW)	Actual – Forecasted Output (MW)
1:00	202.3	201.5	0.8
1:05	200.6	201	-0.4
1:10	201.1	200.3	0.8
1:15	200.8	200.6	0.2
1:20	201.4	200.4	1
1:25	200	202.6	-2.6
1:30	200	202.3	-2.3
1:35	201.2	200.6	0.6
1:40	201.8	201.1	0.7
1:45	201.6	200.8	0.8
1:50	202.7	201.4	1.3
1:55	202.2	200	2.2
2:00	203.8	200	3.8

Note: matching colors indicate pairs of forecasted and actual wind output values

Since the data PNM provided was for 350MW of wind plant capacity (the amount present on PNM's system in 2019), and since we are studying a year in which 650MW of wind on the system is planned, we multiplied the actual output in each 5-minute period by 1.87 to scale it.

We realize that this may not fully take into account the benefits in locational diversity that would accrue from adding wind plants at two additional locations (La Joya 1 and 2). However, given that one of the wind plants existing in 2019 (Red Mesa) is geographically removed from the other two, simply scaling up the output may be a reasonable approximation.

2.3. Limitations of Methodology

While using wind persistence for the 5 and 30-minute ahead wind forecast (and the methodology specified for the 5-minute ahead solar forecast) should be a good approximation of what PNM uses for forecasting at these time intervals, they are not the same as PNM's forecasting methodology.

Applying the solar forecasting methodology outlined here to the 30-minute ahead solar forecast will likely have greater forecast error than PNM's forecasting at this time interval. In cases where the weather deteriorates rapidly, this underperformance is likely to be substantial. This is because the methodology used here does not use external weather forecasts – it assumes the weather at the next time step (30 minutes in this case) will be the same as it is now.

Load forecasting is not considered, therefore errors in load forecasting are not taken into account. These errors could magnify or reduce the unexpected variable generation ramping events and, in turn, affect the proposed rule for the regulating reserves presented in this work. In addition, distributed generation (rooftop solar PV) is likely to exacerbate solar ramping and increase the solar generation shortfall during weather events that impact solar generation, but is not considered here as the amount of utility-scale PV that will be on the PNM system in 2025 is uncertain -- the study team judged the amount of rooftop PV to be within that margin of error. An analysis of reserve that accounts for all sources of uncertainty in grid operations would require more information than is presently available.

3. PNM SYSTEM RESOURCES

This section highlights the generation and energy storage resources that are projected to be in place by 2025, the year this study focuses on.

Figure 3-1 depicts the existing and planned solar PV (50MW and above) and wind plants contracted for by PNM.

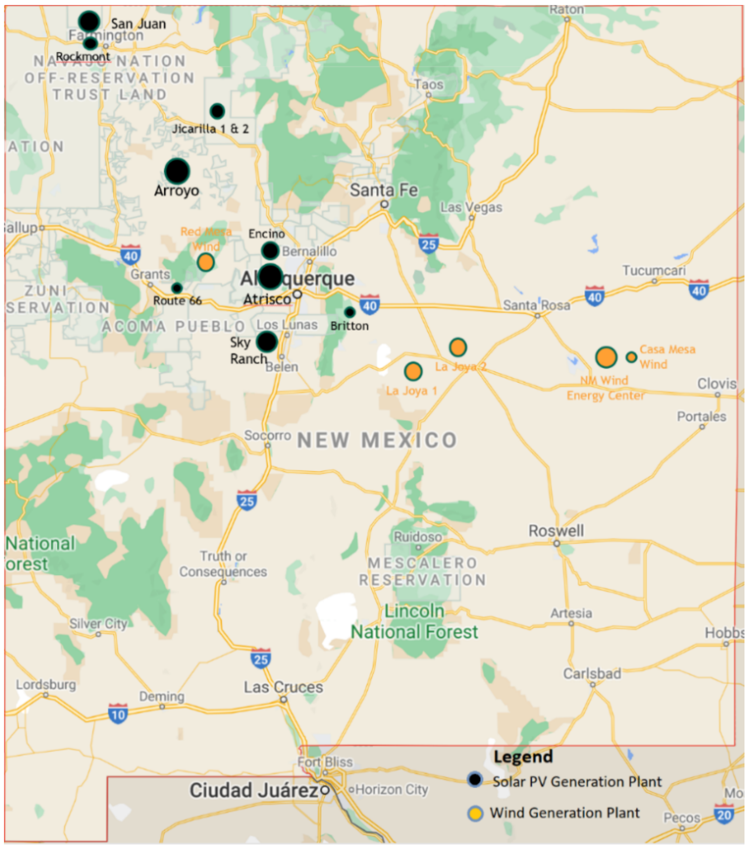

Figure 3-1. Existing and planned solar PV and wind generation contracted for by PNM

Source: authors, based on assembled data. Note: Solar plants 50 MW and above are shown. Larger circles indicate larger capacity plants.

3.1. Utility Solar

The utility-scale solar plants in Table 3-1 were considered in this study.

The plants highlighted in blue in the beginning of Table 3-1 have been either approved by the New Mexico PRC (Arroyo, Jicarilla, San Juan, Rockmont) or are in the approvals process (Atrisco, Sky Ranch, Encino North) and are estimated to be online within the next one to two years. While it now appears that Rockmont is unlikely to be built, we assume that by 2025 another solar PV plant of similar capacity is likely to be built. These plants will add about 1,240 MW of solar capacity to the PNM system.

The other plants in Table 3-1 are the existing solar PV resources. These plants amount to roughly 330 MW of solar capacity. Of note is that the older plants (prior to 2015) are fixed-axis PV, while those built in 2015 and later are single-axis tracing PV. The fixed-axis PV plants are shown in Table 3-1 in green, and total about 44 MW.

For this study, each individual plant in Table 3-1 was modeled in **pvlib python** [2]. Solar irradiation data was supplied in, and power output data was calculated for, five-minute intervals for a calendar year (2019). The power output for all plants in each five-minute period was summed for the analysis.

Clearly, going from about 330 MW to about 1,600 MW in solar PV capacity is a major change for PNM, which has historically relied on dispatchable resources: coal, natural gas, and nuclear. Given that the system's peak load is expected to be about 2,150 MW in 2025 (PNM IRP Appendix, p. J-3), the total solar capacity will go from about 15% to about 75% of peak load. This change requires careful consideration of how conventional plants will be dispatched as well as how the new battery storage will be used.

Table 3-1. Solar plants in study

Name	Lat	Long	Installation Year	Net AC Capacity (MW)
Arroyo	35.96	-107.63		300
Jicarilla 1 and 2	36.32	-107.33		100
San Juan	36.84	-108.35		200
Rockmont	36.78	-108.37		100
Atrisco	35.20	-106.93		300
Sky Ranch	34.78	-106.79		190
Encino North	35.36	-106.85		50
Alamogordo	32.86	-106.01	2011	5
Albuquerque	35.06	-106.53	2011	2
Deming	32.18	-107.77	2011	9
Las Vegas	35.64	-105.21	2011	5
Los Lunas	34.84	-106.77	2011	7
Manzano	34.74	-106.65	2013	8
Otero	32.98	-105.97	2013	7.5
Prosperity	35.00	-106.63	2011	0.5
Britton	35.02	-106.09	2019	50
Cibola	35.14	-107.83	2015	6.9
Encino	35.36	-106.85	2020	50
Facebook 1	34.84	-106.79	2017	10
Facebook 2+3	35.36	-106.87	2018	20
Meadow Lake	34.8	-106.51	2015	8.9
Rio Communities	34.74	-106.65	2015	9.9
Rio Del Oro	34.70	-106.69	2019	9.8
Rio Rancho	35.18	-106.81	2019	9.7
Route 66	35.08	-107.61	2021	49.5
San Miguel 1+2	35.62	-105.17	2019	20
Sandoval	35.28	-106.81	2014	6
Santa Fe	35.56	-106.09	2015	9.2
Santolina	35.02	-106.87	2015	10.5
South Valley	34.98	-106.73	2015	10
Vista	34.74	-106.65	2019	9.9
TOTAL				**1574.3**

Source: Name and capacity from Appendices, Table H-7 "Existing and Planned Solar PV Resources" [1], with the addition of the Atrisco, Sky Ranch, and Encino North plants. Location from public data sources and Google Maps search.

3.2. Wind Generation

Table 3-2 contains information on the wind resources PNM will have on their system. Except for La Joya 1 and 2, which are under construction as of the release of this report, these plants are currently on-line. Additional wind resources are not projected to be on-line in 2025.

Table 3-2. PNM wind resources

Existing Wind PPA Resources	County	Net Capacity (MW)	Lat.	Lon.	Turbine Capacity (MW)	Turbine Model	Hub Height (m)
NM Wind Energy Center	Quay	200	34.63	-104.05	1.5	GE1.5-87	80
Casa Mesa Wind	Quay	50	34.60	-103.99	2.5	GE2.5-127	89
La Joya 1	Torrance	166	34.62	-105.65	2.5	GE2.5-127	89
La Joya 2	Torrance	140	34.69	-105.34	2.5	GE2.5-127	89
Red Mesa Wind	Sandoval	102	35.26	-107.38	1.6	GE1.6-82.5	80
TOTAL		658					

Source: Appendices, Table H-5 "Resource Data – Existing Wind PPA Resources" [1]; information from the US Wind Turbine Database (https://eerscmap.usgs.gov/uswtdb/, accessed 12 October 2021).

Figure 3-1 depicts existing and planned (by 2025) solar photovoltaic (50MW and above) and wind plants contracted for by PNM.

In addition to wind and solar, PNM has one geothermal power plant – the 11-MW Dale Burgett Geothermal Plant in Hidalgo County, NM.

3.3. Energy Storage

All the storage in Table 3-3 has either been approved or is being reviewed by the NM PRC. As this study focuses on solar ramp rates and the resulting reserve requirements, information about planned battery energy storage is not directly used. However, it is included here because it provides useful information about what resources the PNM system will have available to provide reserve.

Table 3-3. Projected energy storage resources

Resource Name	Power Capacity (MW)	Storage Capacity (MWh)
Arroyo	150	600
Atrisco	150	600
San Juan	100	400
Jicarilla	40	160
Rockmont	30	120
Sandia Peak	100	200
TOTAL	***570***	***2080***

Source: Compilation of Table 17 [1] and other public sources

3.4. Dispatchable Generation

PNM has two combined-cycle plants, five gas turbine units, and three steam turbine units at its disposal. All of these units are natural gas-fired, and are listed in Table 3-4.

Table 3-4. Dispatchable generation

Name	County	Net Capacity (MW)	Plant Type
La Luz Gas Turbine	Valencia	41	Gas Turbine
Lordsburg Unit 1	Hidalgo	43	Gas Turbine
Lordsburg Unit 2	Hidalgo	43	Gas Turbine
Rio Bravo (Delta) GT	Bernalillo	141	Gas Turbine
Valencia Energy Facility	Valencia	149	Gas Turbine
Afton Generating Station	Dona Ana	235	Combined Cycle
Luna Energy Facility	Luna	190	Combined Cycle
Reeves Unit 1	Bernalillo	41	Steam Turbine
Reeves Unit 2	Bernalillo	42	Steam Turbine
Reeves Unit 3	Bernalillo	63	Steam Turbine
TOTAL		*988*	

Source: Extract from Table 17 [1]

The Rio Bravo gas turbine can be operated on fuel oil, however it is restricted to about 1,000 hours a year of operation on fuel oil due to its air emissions permit.

Only the single-cycle gas turbine plants (highlighted in yellow in Table 3-4) can be synchronized within 10 minutes, and therefore can be considered quick start units. The total quick start capacity of the PNM system, therefore, is roughly 400 MW.

As they are steam turbine units, the Reeves units take around three hours to go from a cold state to grid-synchronized.

While PNM currently has a share of the capacity of the Four Corners coal-fired generating station, PNM has filed to abandon this capacity as of December 2024. If this filing is approved, PNM will no longer have and owned or contracted coal-fired capacity as of January 1, 2025. This plant is therefore not included in the list of PNM resources in this study.

3.5. Nuclear

PNM currently has 402MW of baseload power contracted from the Palo Verde Nuclear Power Plant in Arizona. This drops to 298MW in 2023, and to 288MW in 2024 as the leases for this capacity are returned.

4. RESERVES

In characterizing the variability of solar and wind forecast error, our intent is to be able to suggest reserve levels that are appropriate for dealing with this variability. It is helpful to distinguish between *reserve categories* and *reserve products*.

One reserve category is frequency response reserve, whereby a generation unit reacts autonomously to changes in the system frequency. This response must be instantaneous in order to avoid unacceptable drops in system frequency. Another reserve category is contingency reserve, which is designed to deal with a system contingency, such as a generation unit forced outage or a transmission line fault.

Reserve products must be called upon to provide the required reserve. Frequency response reserve has typically been provided by rotating generators on droop control.[7] Contingency reserve is typically provided both by units that are synchronized and can increase their level of generation (called 'spinning reserve'), as well as units that are off-line but can be started quickly (called 'quick-start reserve'). 50% of PNM's contingency reserve is from spinning reserve, and 50% is from quick-start reserve [1].

Figure 4-1 illustrates PNM's quick-start reserve. Assuming that the quick-start units are off-line, that they are activated five minutes following an event, and that they are activated sequentially (with the smaller units being dispatched first), about 45MW in quick-start reserve can be on-line in 15 minutes, 115MW in 30 minutes, and 400MW in 50 minutes.

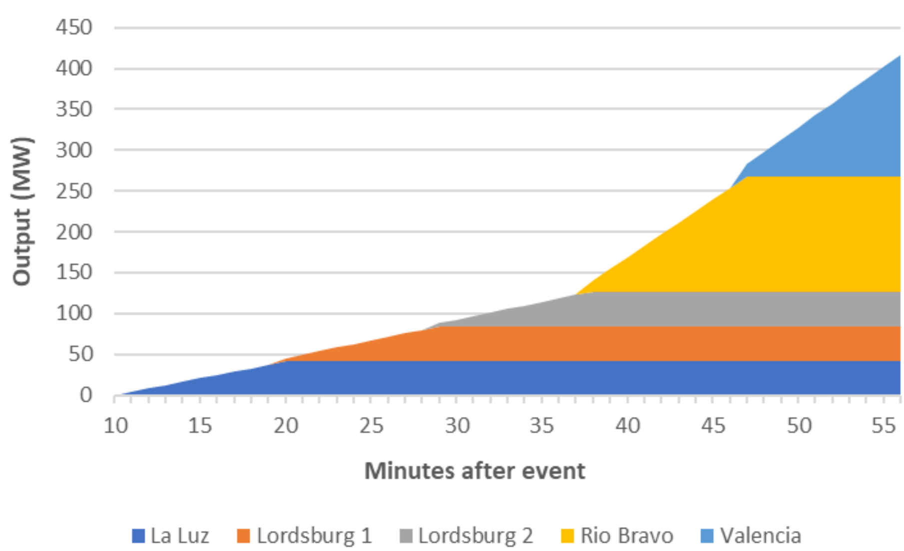

Figure 4-1. PNM quick start reserve

Per the terms of reliability requirement BAL-002-1 ("Disturbance Control Performance Standard"), PNM must restore the balance between supply and demand within a period of fifteen minutes [1, p. D1]. The first five minutes are allocated for PNM to identify the problem and call on its own reserves and reserve sharing agreements with other utilities. The next ten minutes are allocated for

[7] Generators on an AC power grid are typically placed in droop mode. In this mode, a generator adjusts its output based on changes in the grid frequency. When grid frequency declines, the generator's governor calls for an increase in power output. When frequency increases, the governor calls for a decrease in power output.

generators held in reserve to synchronize to the grid (if non-spinning) and ramp up to the requested level of output. This standard may not be adequate to address the most extreme ramps in variable generation on a five-minute time horizon.

Adding further complexity, we must consider that the PNM balancing authority (or 'BA') is not an island, but instead is interconnected with the Western Interconnection. PNM is part of the Southwest Reserve Sharing Group (SRSG), which is comprised of 15 southwestern utilities and is registered with NERC. This agreement results in PNM's needing to carry a minimum of 40 to 125MW of contingency reserve, which is split evenly between spinning and quick-start reserve [1]. This is a much lower level of contingency reserve than if PNM were required to cover its largest contingency (which currently is the San Juan Generating Station's Unit 4, a 392-MW unit). Carrying a lower contingency reserve can result in lower operational costs.

At the same time, it should be taken into account that PNM can receive assistance from SRSG for up to one hour. For example, if PNM were to lose large resources, such as SJGS Unit 4 or Afton, at the time of summer peak, the SRSG can provide up to 160 MW in the first hour [1]. Within that hour, PNM must restore balance to the PNM BA, as well as restoring its reserves (including its contribution to the SRSG). It is also worth clarifying that the amount of assistance provided from the SRSG will vary depending on the size of the PNM contingency and the availability of other SRSG members' resources. Additionally, PNM has a 100 MW hazard share agreement with Tri-State Generation and Transmission Association. However, this agreement is to be terminated once SJGS Unit 4 is retired. Additional details about PNM's balancing area reliability requirements are discussed PNM IRP Appendix D [7].

Our concern in this report is not the frequency response reserve or the contingency reserve. Rather, it is with an additional category of reserves required to accommodate the variability of wind and solar anticipated to be on PNM's system in 2025. In this report, we term this additional category a "variable generation reserve."

What type of reserve product would be used to satisfy this variable generation reserve requirement? To deal with short-term (up to 10-minute) variable generation forecast errors, regulating reserve would typically be used. Regulating reserve is a type of spinning reserve used to make short-term corrections in order to match generation to load. Regulating reserve is traditionally provided by units that take an automatic generation control (AGC) signal, which is sent centrally to all units that provide regulating reserve. Every few seconds, the AGC signal directs the units to adjust their output to a new setpoint. Regulating reserve has typically been used to compensate for unexpected changes in load. However, as the penetration of variable generation (solar and wind) on the grid increases, it becomes necessary to deal with this additional source of variability.

Regulating reserves can either increase or decrease generation. For this study, we focus on the aspect of regulating reserve that can increase generation to make up for unexpected drops (or "negative forecast error") in wind and solar generation. Unexpected increases in wind and solar generation can be curtailed as a last resort, whereas shortfalls in generation must be compensated for in order to prevent loss of load. Analyzing the 5-minute solar and wind forecast error will allow us to propose a variable generation reserve rule set to deal with down ramps.

We also analyzed the 30-minute solar and wind forecast error. The 30-minute forecast error is larger than the 5-minute forecast error. However, a reserve to cover 30-minute forecast error need not be entirely composed of regulating reserve. Quick-start units, as discussed earlier, are also able to contribute.

5. SOLAR FORECAST ERROR ANALYSIS

We examine the solar forecasting error at the 5-minute and 30-minute periods for the 2019 study year. If solar output could be perfectly predicted, there would be no need to allocate a variable generation reserve for it, because the changes in solar output would be foreseen and taken into account for unit commitment and dispatch.

5.1. 5-minute Solar Forecast Error

The 5-minute period is of interest because there is insufficient time to get a quick-start unit online – therefore, the power compensating for down-ramps at these time intervals must come from the outside grid or from regulating reserve within the PNM BA. Since unscheduled draws from (or output to) the wider grid can violate NERC reliability standards, our focus is on providing for the reserve from within the PNM BA.

Figure 5-1 shows a histogram for the 5-minute solar forecast error for solar PV alone for 2019. About 2.5% of all periods (with solar output) have forecast errors more extreme than -120MW, and about 3% of all periods have forecast errors greater than +120MW.

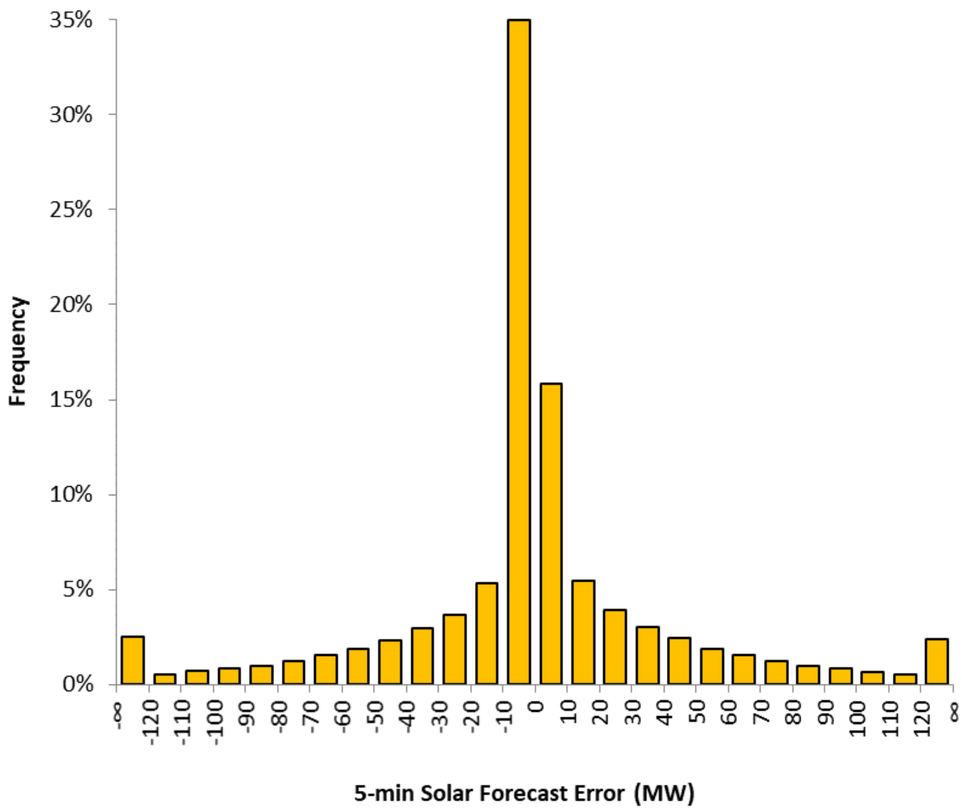

Figure 5-1. 5-minute solar forecast error histogram

We are more interested in negative forecast error (or shortfall relative to forecast), as the shortfall in power production must be replaced using regulation reserves. Whereas excess generation relative to forecast can be curtailed if needed, a shortfall in generation must be replaced in order to prevent a loss of load.

Figure 5-2 shows the cumulative frequency of 5-minute negative solar forecast error equal to or more extreme than -220MW. (This histogram is a subset of the bar showing -120MW forecast error and below in Figure 5-1.) The frequency is calculated based on the total number of 5-minute periods with negative forecast error (as opposed to being based on all periods with solar output, as is the case in Figure 5-1). We see that about 1% of the largest 5-minute negative forecast errors are equal to or more extreme than 220MW.

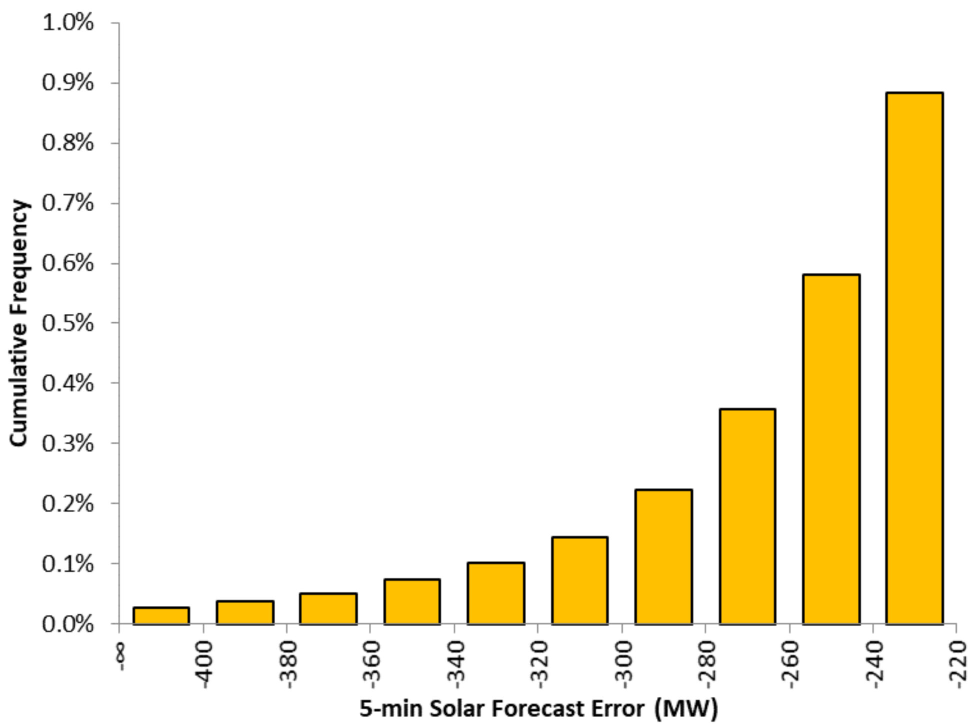

Figure 5-2. Cumulative 5-minute solar forecast error histogram with errors equal to and more extreme than -220MW

However, this histogram does not tell us the correlation between the current level of solar output and the magnitude of the negative forecast error over the next five minutes. For this, we need to do a scatter plot comparing current solar output and the negative forecast error over the next five-minute period. This relationship is shown in Figure 5-3.

We see a clear correlation between the current level of solar output and the negative forecast error over the next five-minute period in Figure 5-3. *Specifically, the absolute value of the negative forecast error over the next five minutes is always less than the current level of solar output.* This means that at low levels of solar output (say, below 600MW), the negative forecast error will also be low. However, we also see that above roughly 600MW of solar output, the negative forecast error does not become more extreme.

One reason for this is that individual solar facilities have solar panel capacities (which produce DC power) that are 30% higher than the inverters (which convert the DC to AC power for the grid) are rated for. At high levels of output, the inverter is the limiting factor. If the solar panel power production is at maximum, even a 30% drop in solar panel output would have no impact on the AC output of the facility.

The gold line labeled "Reserve Requirement" in Figure 5-3 delineates the negative forecast error events that a solar variable generation reserve might be required to cover over a 5-minute timeframe. As aggregate solar output increases to 550MW, the reserve would need to increase linearly to 275MW. As solar output continues to increase, however, the reserve would remain at 275MW.

This rule set would cover over 99.90% of all 5-minute forecast errors in the year, or if considering only shortfalls, it would cover 99.74% of all 5-minute negative forecast errors.

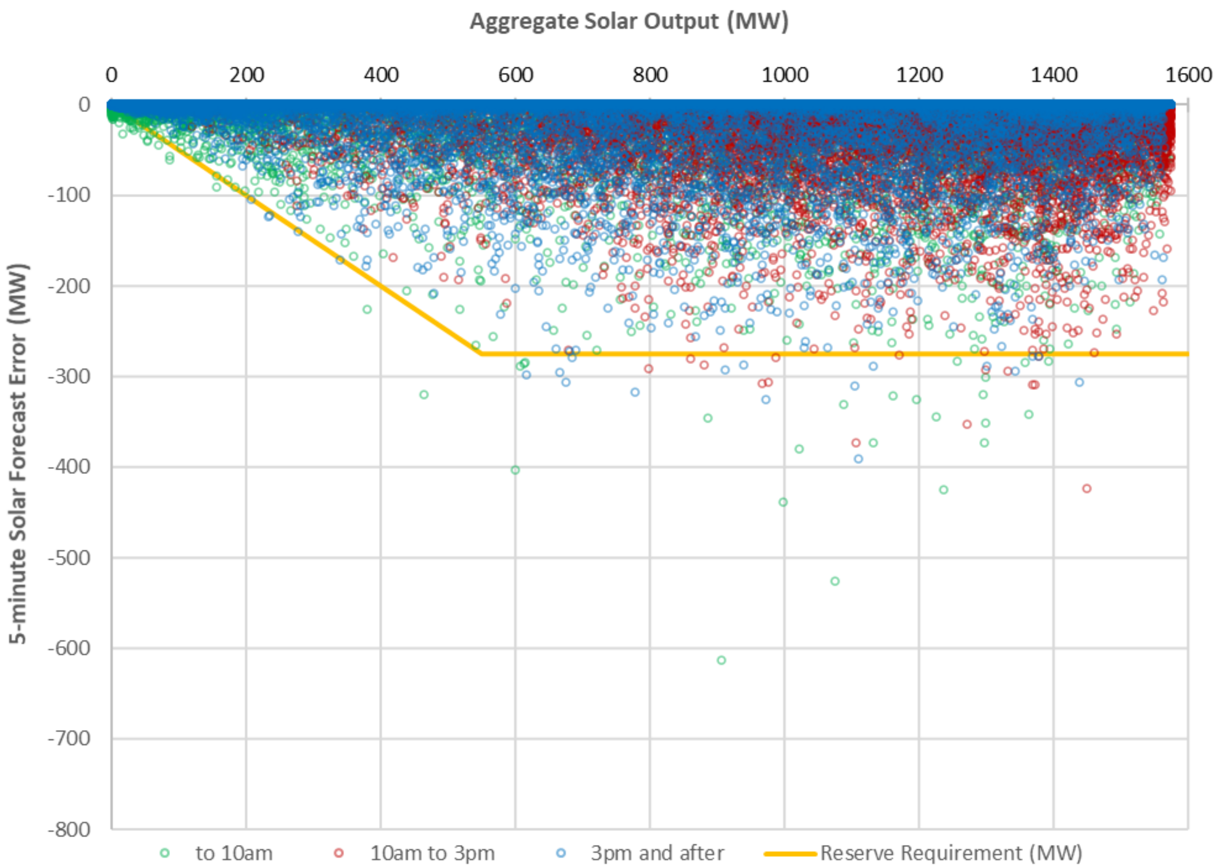

Figure 5-3. Solar output vs. 5-minute forecast error

We also separate the ramping events into time of day in Figure 5-3. The green circles are for ramps prior to 10am, the red circles are for ramps from 10am to 3pm, and the blue circles are for ramps after 3pm.

Table 5-1 shows the frequency and percentage of negative forecast errors equal to or more extreme than 100MW by time-of-day. The percent shown here is the number of negative forecast errors equal to or more extreme than 100MW in the time period divided by the total number of 5-minute intervals in that time period. We see that a higher percentage of these large negative forecast errors are in the afternoon.

Table 5-1. 5-min negative forecast errors equal to or more extreme than 100MW

Time Period	Frequency	Percent of all 5-min intervals in time period
Prior to 10am	503	2.9%
10am to 3pm	801	3.7%
3pm and later	688	4.8%

5.2. 30-minute Solar Forecast Error

The 30-minute period is of interest as we would like to understand the magnitude of forecast error over a longer time period than the 5-minute interval analyzed in the previous section. At the same time, the system has more at its disposal than regulating reserve to address generation shortfalls over the 30-minute period.

We assume that a quick-start unit can go from being offline to being synchronized to the grid at full output in 10 minutes, but also that it takes an operator 5 minutes to recognize a potential shortfall and trigger the quick-start unit. This means that PNM would need to rely on some combination of regulating or spinning reserve and assistance from outside its balancing authority for the first 15 minutes, but then would be able to bring its quick start reserve on-line to assist. We are not focusing on the exact nature and composition of reserves to deal with 30-minute solar variability here. Rather, we concentrate on characterizing the unexpected solar ramps over the 30-minute period with a view to specifying what level of reserve would be necessary to deal with them.

Figure 5-4 shows a histogram for the 30-minute solar forecast error. About 2.5% of all periods (with solar output) have a negative forecast error more extreme than 225MW, and about 3.4% of all periods have a positive forecast error greater than 225MW.

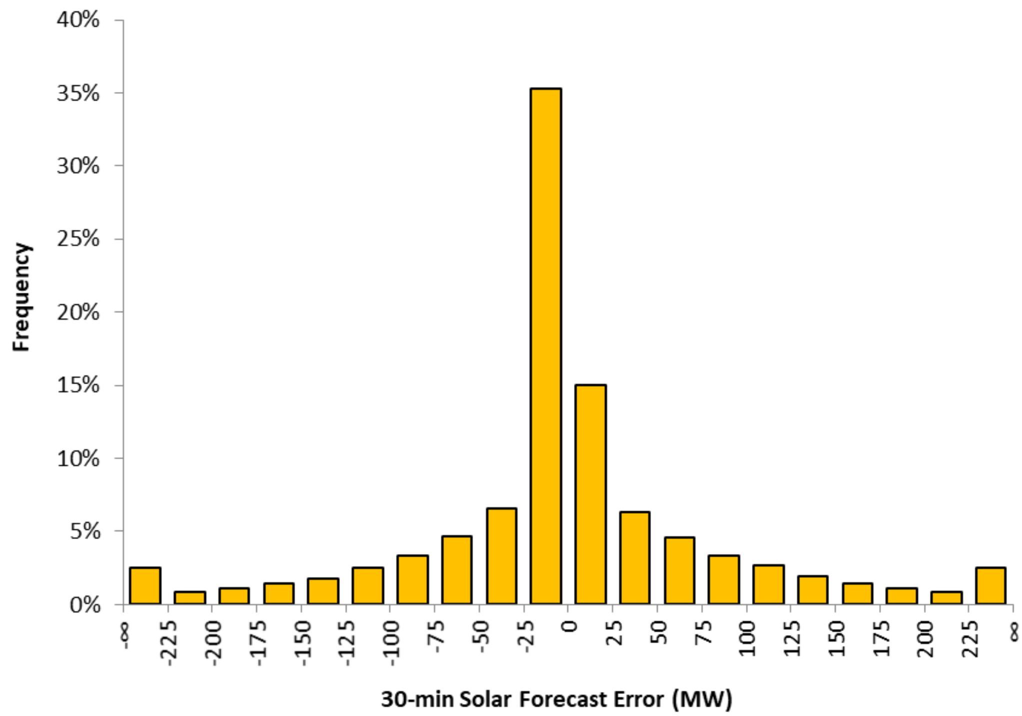

Figure 5-4. 30-minute solar forecast error histogram

We are more interested in negative forecast error (or shortfall relative to forecast), as the shortfall in power production must be replaced. In the case of positive forecast error (or surplus relative to forecast), the excess power output may be curtailed if there is no other option for dealing with it.

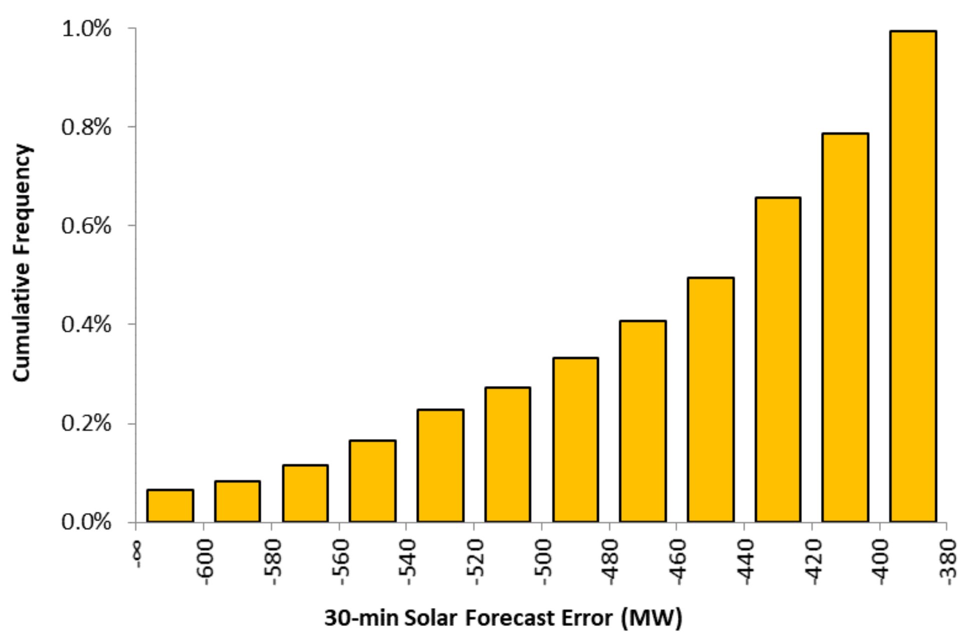

Figure 5-5. Cumulative 30-minute solar forecast error histogram with errors equal to or more extreme than -380MW

Figure 5-5 shows the cumulative frequency of 30-minute solar negative forecast errors equal to or more extreme than 380MW. The frequency is calculated based on the total number of 30-minute periods with negative forecast errors (as opposed to using all periods with positive solar output, as is the case in Figure 5-1). We see that 1% of the largest 30-minute negative forecast errors are equal to or more extreme than 380MW.

However, this histogram does not tell us the correlation between the current level of solar output and the magnitude of the negative forecast error over the next 30 minutes. For this, we need to do a scatter plot comparing current solar output and the 30-minute negative forecast error. This relationship is shown in Figure 5-6.

We also separate the forecast error periods into time of day. The green circles are for forecast error periods prior to 10am, the red circles are for forecast error periods from 10am to 3pm, and the blue circles are for forecast error periods after 3pm.

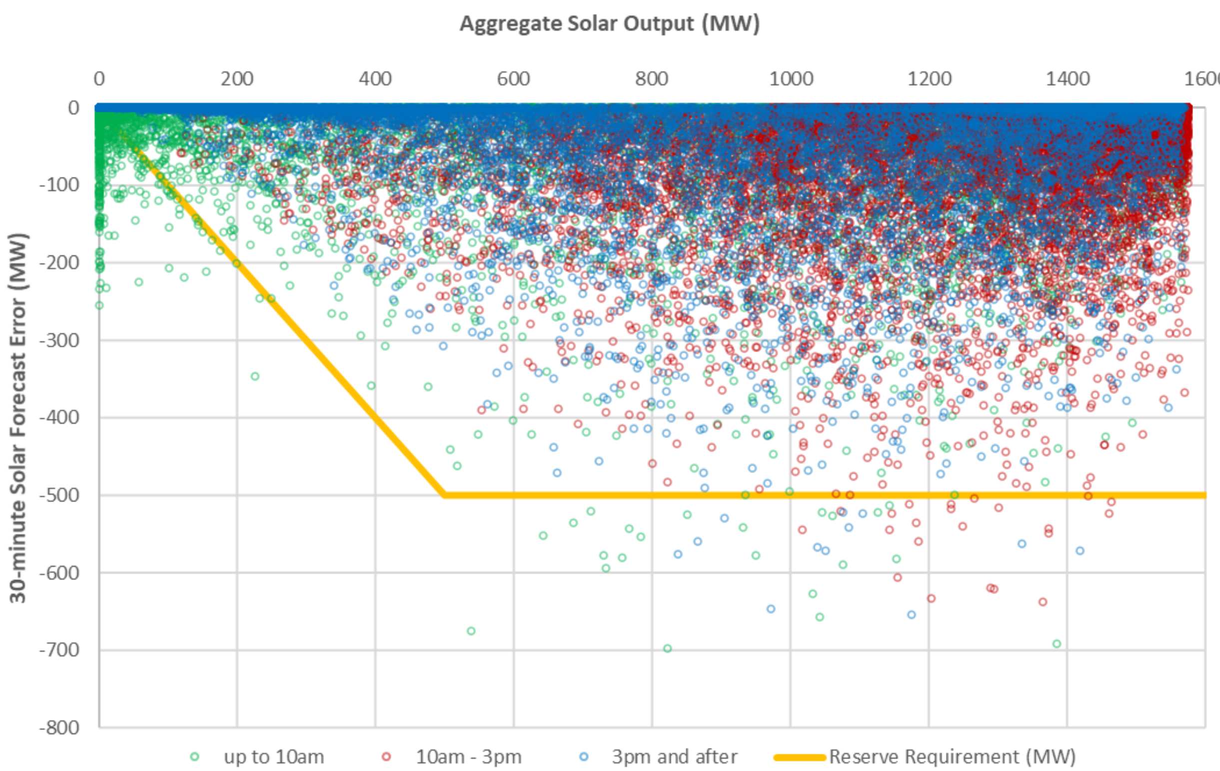

Figure 5-6. Solar output vs. 30-minute forecast error

At the 30-minute level, we also see a correlation between the current level of solar output and the negative forecast error. Generally, the absolute value of the negative forecast error is less than the current level of solar output (just as is the case at the 5-minute level).

However, there are a number of points at output levels below 200MW where this is not the case. These points occur primarily before 10AM. The output in thirty minutes is forecasted to be the current level plus the clear sky ramp over the next thirty minutes times the clear sky index. If the weather is at first clear, then rapidly deteriorates, then the clear sky index for the next 30-minute forecast will be 1, which will cause the forecast to be significantly higher than the actual output.

At the 5-minute time scale, we do not see this behavior. This is because the forecast is for a small time increment, which means that it is updated frequently, taking current weather conditions into account.

This highlights the fact that this forecasting method does not use weather forecasting data. We assume here that it is likely that PNM would use weather information to anticipate an overcast day, in which case these ramping events would not be a surprise. We construct our reserve rule set here not considering these points.

The gold line labeled "Reserve Requirement" in Figure 5-6 delineates the negative forecast error events that a solar variable generation reserve might be required to cover over a 30-minute timeframe. As aggregate solar output increases to 500MW, the reserve would need to increase linearly to 500MW. As solar output continues to increase, however, the reserve would remain at 500MW.

This rule set would cover 99.89% of all 30-minute forecast errors in the year, or if considering only shortfalls, it would cover 99.73% of all 30-minute negative forecast errors. (Note that these calculations ignore the points below 200MW solar output that lie outside of the curve).

Table 5-2 shows the frequency and percentage of 30-min solar negative forecast errors equal to or greater than 200MW by time-of-day. The percent shown here is the number of 30-min periods with negative forecast errors equal to or more extreme than 200MW in the time period divided by the total number of 30-minute intervals in that time period. We see that negative forecast errors equal to or more extreme than 200MW are about twice as likely to occur after 10am than they are prior to 10am.

Table 5-2. 30-min negative forecast error equal to or more extreme than 200MW

Time Period	Frequency	Percent of all 30-min intervals in time period
Prior to 10am	346	2.0%
10am to 3pm	876	4.0%
3pm and later	570	4.0%

6. WIND FORECAST ERROR ANALYSIS

Since the data PNM provided was for 352MW of wind plant capacity (the amount present on PNM's system in 2019), and since we are studying a year in which there will be 658MW of wind on the system, we multiplied the actual output in each 5-minute period by 1.87 to scale it.[8]

6.1. 5-minute Wind Ramp Rate

If the wind output in the next five-minute period were perfectly forecasted, then there would be no need to maintain a variable generation reserve for it (there would still be the need for a reserve to deal with load forecast errors between changes in dispatch – but this is different from having a 5-minute variable generation reserve).

We further assume that at the 5-minute scale a persistence forecast is the best forecast available. Using this 5-minute persistence forecast gives us the distribution of 5-minute forecast errors in Figure 6-1. About 2.6% of forecast errors are shortfalls greater than 25MW, and about 4.9% of forecast errors are surpluses greater than 25MW.

Since we are using a 5-minute persistence forecast, we are interested in simply the ramp from one time interval to the next, since by definition this will be the forecast error.

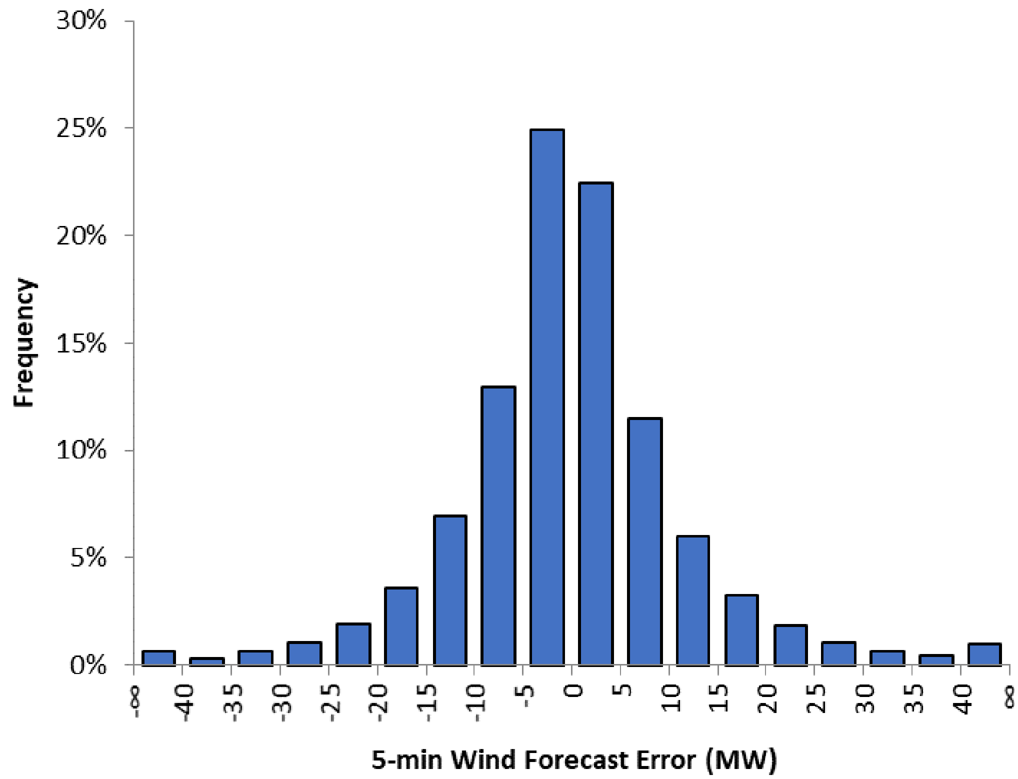

Figure 6-1. 5-minute wind forecast error histogram

[8] PNM's system had 352MW of installed wind capacity contracted for in 2019 – NM Wind Energy Center at 200MW, Casa Mesa at 50MW, and Red Mesa at 102MW. With La Joya 1 and 2, the installed capacity will rise to 658MW. 658MW / 352MW = 1.87

While both forecast error surpluses and shortfalls are shown, we are mainly concerned with the shortfalls.

Figure 6-2 shows the most extreme negative forecast errors, this time as a cumulative frequency up to about 1%. The percentage given is a percentage of all negative forecast error periods – not of all data points. We see that about 1% of the most extreme 5-minute negative forecast errors are 40MW or greater.

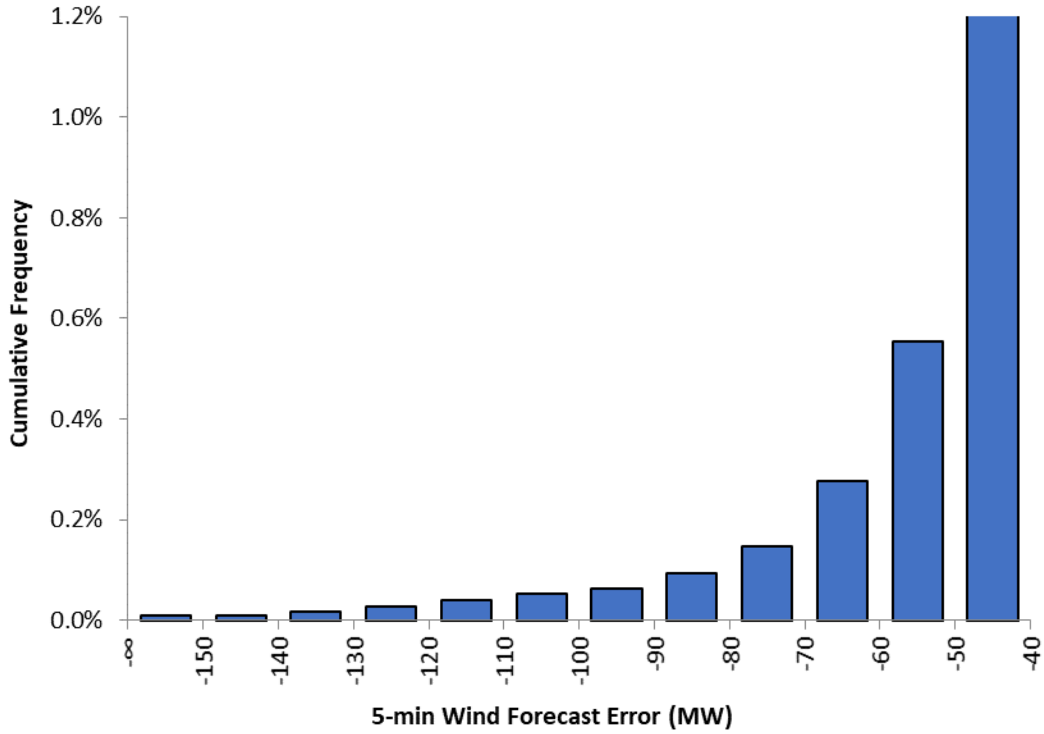

Figure 6-2. Cumulative 5-minute wind forecast error histogram with errors equal to or more extreme than -40MW

Figure 6-2 helps to characterize the forecast errors. However, it does not tell us the correlation between the current wind output and the 5-minute negative forecast error that will follow. For this, we need to make a scatter plot of current wind output versus the 5-minute negative forecast error. This plot is shown in Figure 6-3.

We see that the most extreme negative forecast errors tend to occur above 100MW and below 500MW of wind output. This is probably because when generation is low there isn't much room to fall, and when it is very high a sharp decrease in generation over the next five minutes is unlikely.

The 5-minute wind renewable generation reserve, based on the yellow curve in Figure 6-3, would increase from 0MW at no wind generation to 75MW at 100MW of wind generation – where it would remain constant until reaching 500MW of wind generation. From 500MW to 600MW of wind generation, the reserve would linearly decline from 75MW to 0MW. 99.94% of all forecast error periods, and 99.88% of all forecast error periods with shortfalls, are within the bounds of the yellow curve.

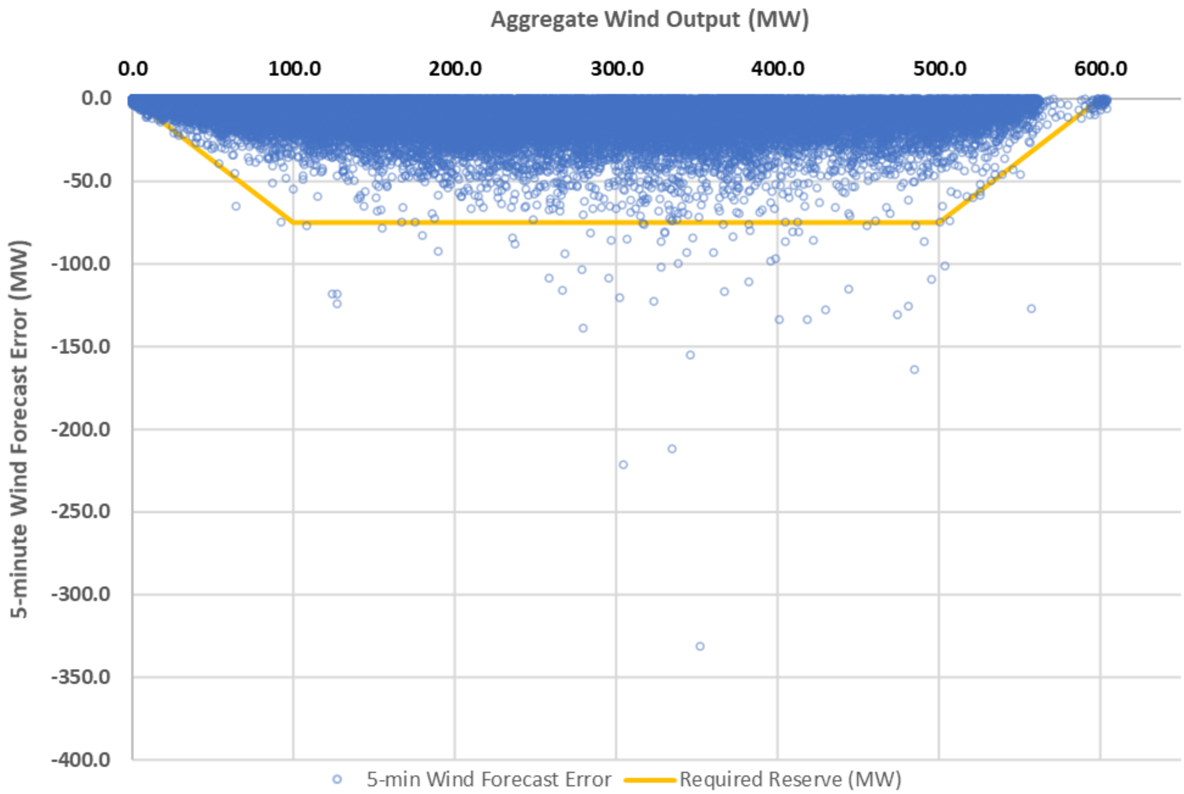

Figure 6-3. Wind output vs. 5-minute wind forecast error

6.2. 30-minute Wind Forecast Error

We are interested in how wind forecast error at the 30-minute interval informs our variable generation reserve requirement. However, not all of this reserve need be regulating reserve or even synchronized. The 30-minute time frame allows sufficient time to get quick-start reserves on-line.

We assume that at the 30-minute scale a persistence forecast is the best forecast available. This means that we are actually analyzing 30-minute ramping events, since by definition any change from the current level of output will be forecast error.

Using this 30-minute persistence forecast gives us the distribution of 30-minute forecast error in Figure 6-4. About 2.3% of all forecast error periods are shortfalls greater than 90MW, and about 3% of all forecast error periods are surpluses greater than 90MW.

While both forecast error shortfalls and surpluses are shown, we are mainly concerned with the shortfalls. Whereas surpluses can be dealt with by curtailment if needed, replacement generation must come online to cover the shortfalls.

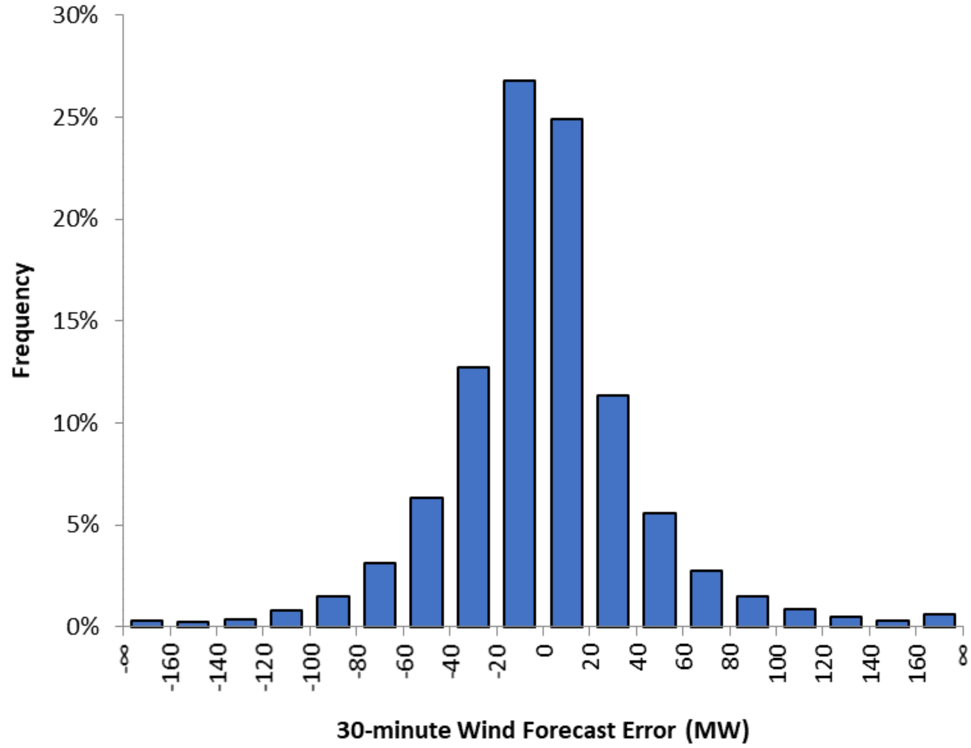

Figure 6-4. 30-minute wind forecast error histogram

Figure 6-5 shows the largest negative forecast errors, this time as a cumulative frequency up to 1%. The percentage given is a percentage of all periods with negative forecast error. We see that 1% of the most extreme 5-minute negative forecast errors are equal to or more extreme than 140MW.

Figure 6-4 and Figure 6-5 help to characterize the forecast errors. However, they do not tell us the correlation between the current wind output and the 30-minute negative forecast error that will follow. For this, we need to make a scatter plot of current wind output versus the 30-minute negative forecast error. This plot is shown in Figure 6-6.

The yellow line in Figure 6-6 delineates the negative forecast error events that a wind variable generation reserve might be required to cover over a 30-minute timeframe. The reserve would need to increase from 0MW at no wind generation to 225MW of reserve at 225MW of wind generation. As wind generation increases from 225MW, the reserve requirement would remain the same. 99.94% of all forecast errors, and 99.88% of all forecast error shortfalls, are bounded by this curve.

As previously discussed, some of this reserve requirement may supplied by regulating reserve, and some may be supplied by quick-start reserve.

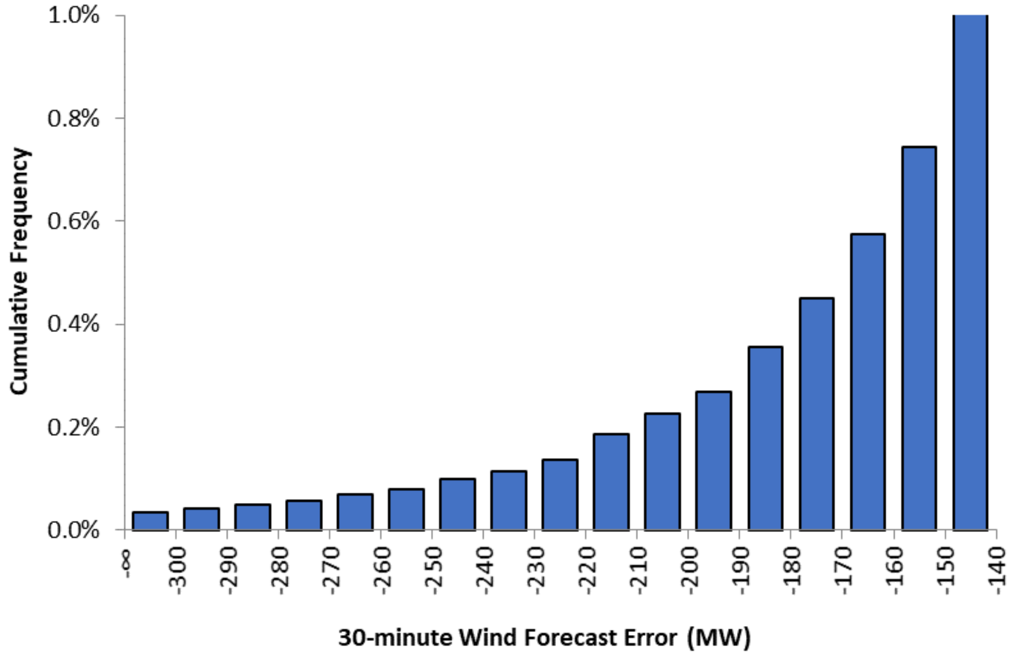

Figure 6-5. Cumulative 30-minute wind forecast error histogram with errors equal to or more extreme than -140MW

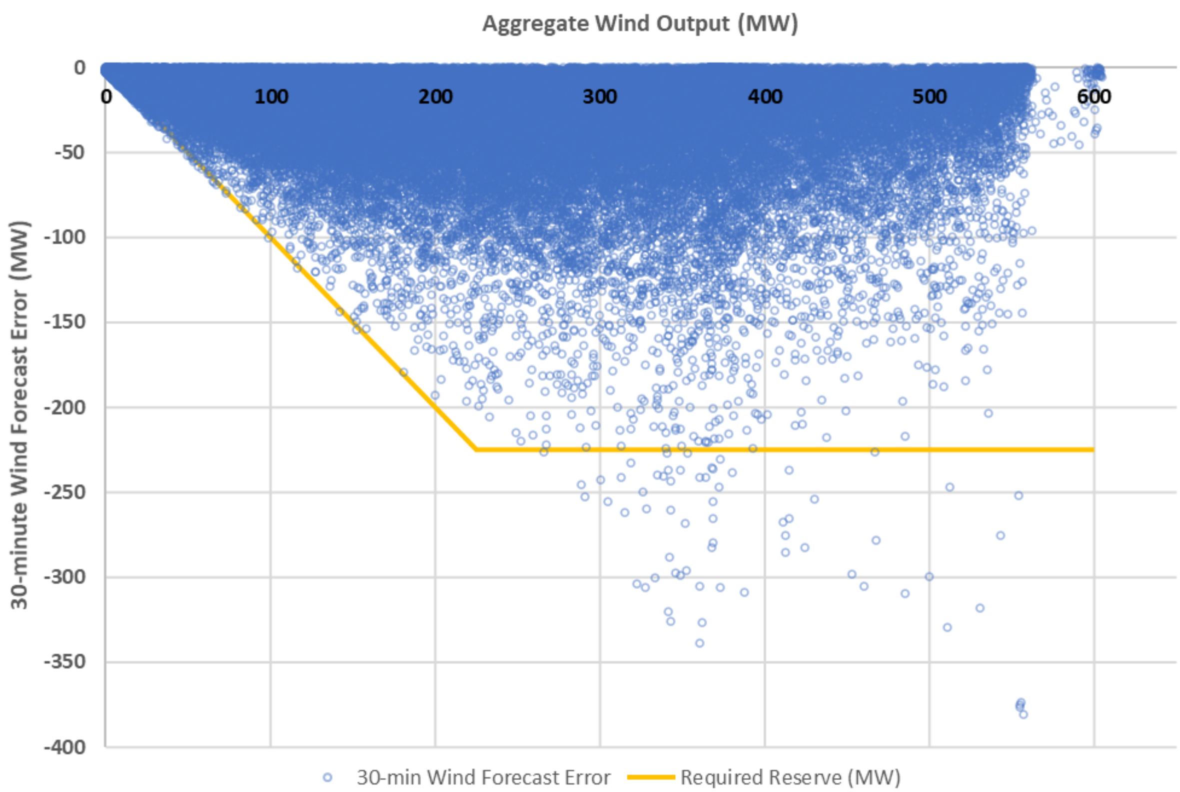

Figure 6-6. Wind output vs. 30-minute wind forecast error

7. COMBINED SOLAR AND WIND RAMP RATE ANALYSIS

Since wind and solar output can be correlated, it is important to examine solar and wind forecast error added together. This was done to take into account resource diversity.

Figure 7-1 illustrates the 5-minute solar and wind forecast error for a representative day (in this case, August 20). This helps give a sense of the timing, magnitude, and correlation of the solar and wind forecast errors.

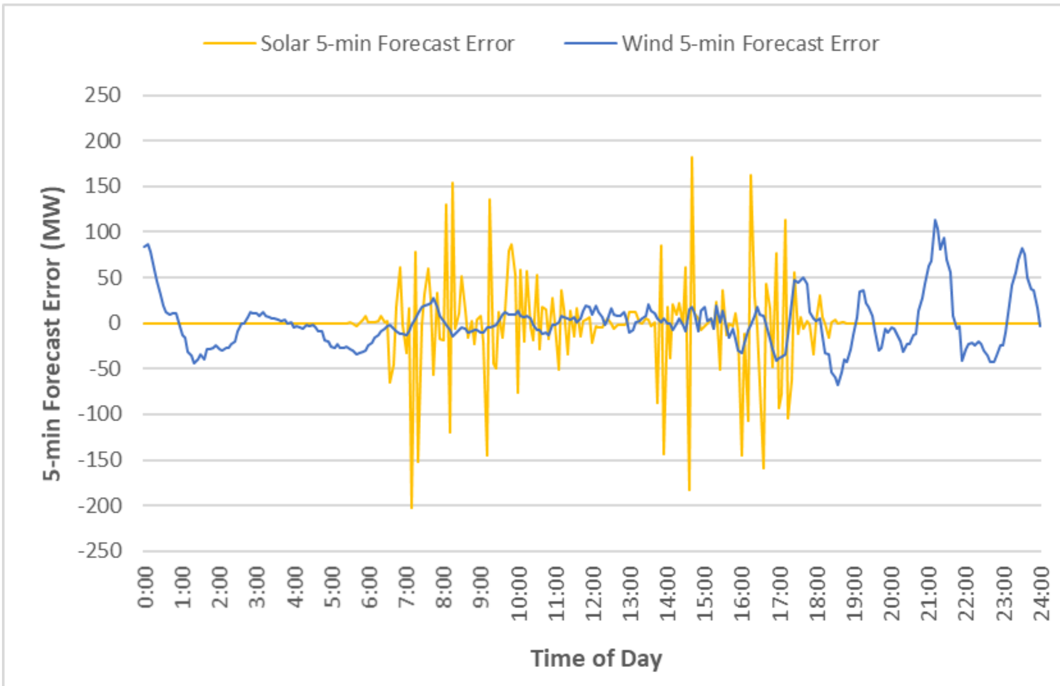

Figure 7-1: 5-minute solar and wind forecast error for a representative day

We will now examine combined 5-minute and 30-minute wind and solar forecast errors over the entire year.

7.1. 5-minute Combined Forecast Error

Figure 7-2 illustrates the relationship between the combined solar and wind output during daylight hours and the subsequent 5-minute combined solar and wind negative forecast error.[9]

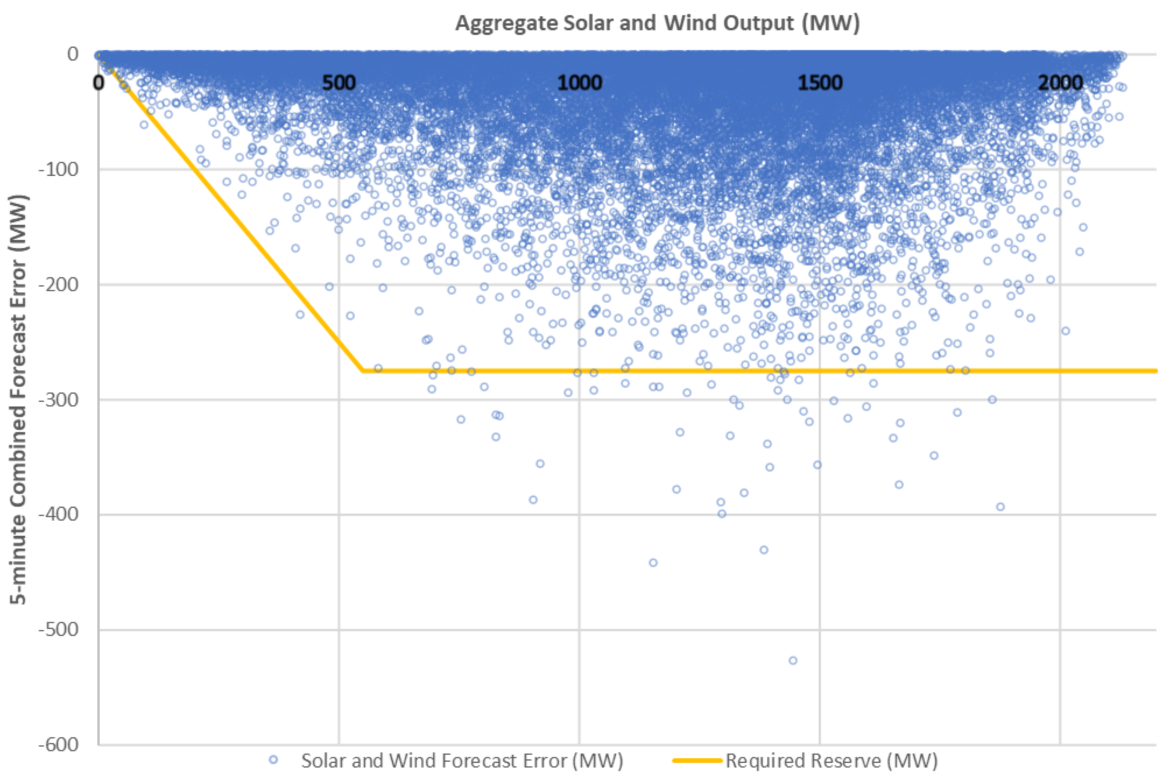

Figure 7-2. 5-min forecast error for aggregate solar and wind output (daylight hours only)

The yellow curve drawn here suggests a rule set for variable generation reserve during daylight hours. From 0MW to 550MW of renewable generation, the reserve would need to increase linearly from 0MW to 275MW. This rule set would cover 99.9% of all daylight forecast error periods, and 99.8% of all daylight forecast error periods with shortfalls. It can be argued that the points falling outside that this reserve rule can be partially or fully met by the assistance of the SRSG, as discussed in Section 4.

We note that the 5-minute variable generation reserve requirement for solar alone was found to be 275MW at its greatest (at solar output equal to and greater than 600MW), and the 5-minute reserve requirement for wind alone was found to be 75MW (at wind output equal to and greater than 100MW). We conclude that the level of variable generation reserves required for wind and solar combined are at the same as that required for solar alone.

[9] Only hours with solar output were examined here. The reason for this is that we are interested in the ramping of solar and wind output combined. In hours with no solar output, there can only be wind output. This is sufficiently described by wind output alone.

7.2. 30-minute Combined Forecast Error

Figure 7-3 illustrates the relationship between the combined solar and wind output during daylight hours and the subsequent 30-minute combined solar and wind negative forecast error.[10]

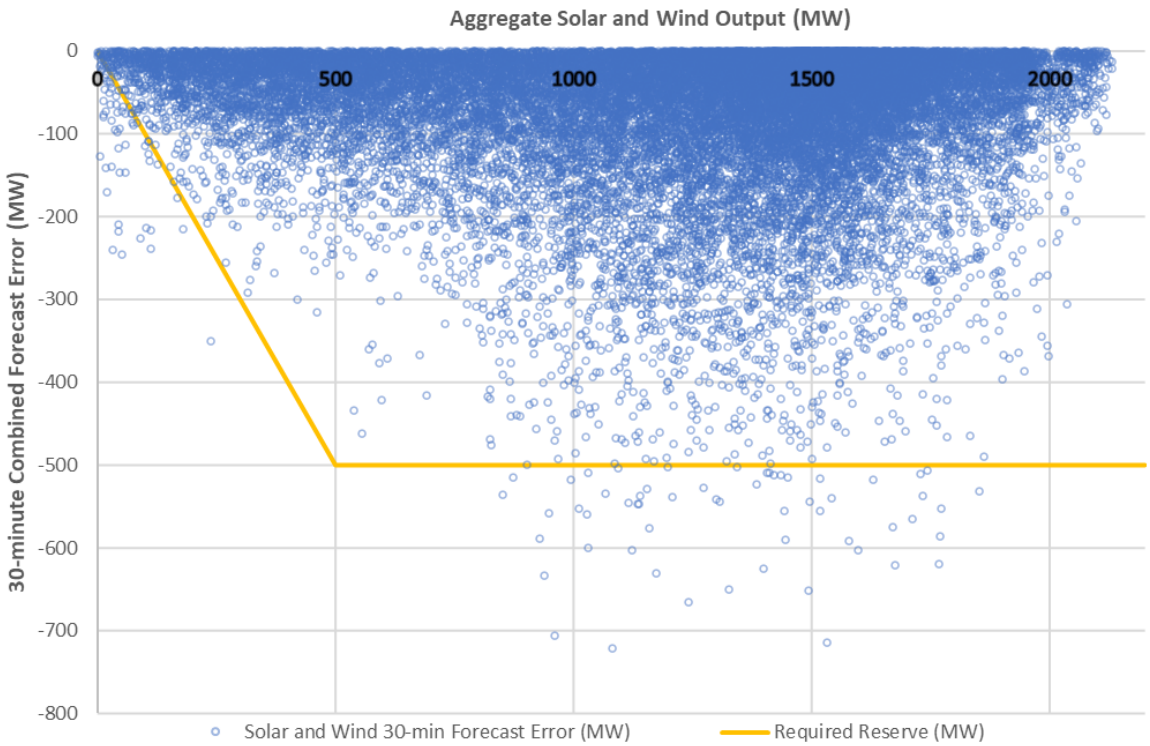

Figure 7-3. 30-min forecast error for aggregate solar and wind output (daylight hours only)

The yellow curve drawn here suggests a rule set for variable generation reserve over a 30-minute timeframe during daylight hours. As variable generation increases from 0MW to 500MW, the required reserve would increase from 0MW to 500MW (in other words, there would be a 1:1 ratio). This rule set would cover 99.9% of all daylight forecast error periods, and 99.75% of all daylight forecast error periods with shortfalls.[11]

We note that the 30-minute reserve requirement for solar alone was found to be 500MW at its greatest (at solar output equal to and greater than 500MW), and the 30-minute reserve requirement for wind alone was found to be 225MW (at wind output equal to and greater than 225MW). When the solar and wind 30-minute forecast errors are considered together, the total level of required reserves is the same as what is specified for the 30-minute solar reserve alone.

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[10] Only hours with solar output were examined here. The reason for this is that we are interested in the ramping of solar and wind output combined. In hours with no solar output, there can only be wind output. This is sufficiently described by wind output alone.

[11] This calculation excludes the points outside of the curve below about 200MW, which are a result of using a 30-minute solar forecasting methodology that doesn't take weather into account. We assume that PNM would avoid these events by incorporating weather forecasting into its 30-minute solar forecasting methodology.

7.3. Correlation Between Solar and Wind Forecast Error

We have found that the reserve requirement to handle 99.9% of five-minute forecast errors in the combination of wind and solar generation is less than the sum of the separate requirements for wind and solar. Mathematically, such a result is termed "subadditivity"—the whole is less than the sum of its parts. Indeed, the combined requirement is equivalent to the requirement for solar alone; wind does not increase the recommended reserve. To explain this finding, we examine the correlation between wind and solar ramps.

During daylight hours, five-minute forecast errors in wind and five-minute forecast errors in solar exhibit a coefficient of correlation of -0.01. While this correlation is statistically significant (p=0.02) as a result of the large number of observations, the correlation is practically zero. This absence of a correlation is illustrated by the scatter plot in Figure 7-4.

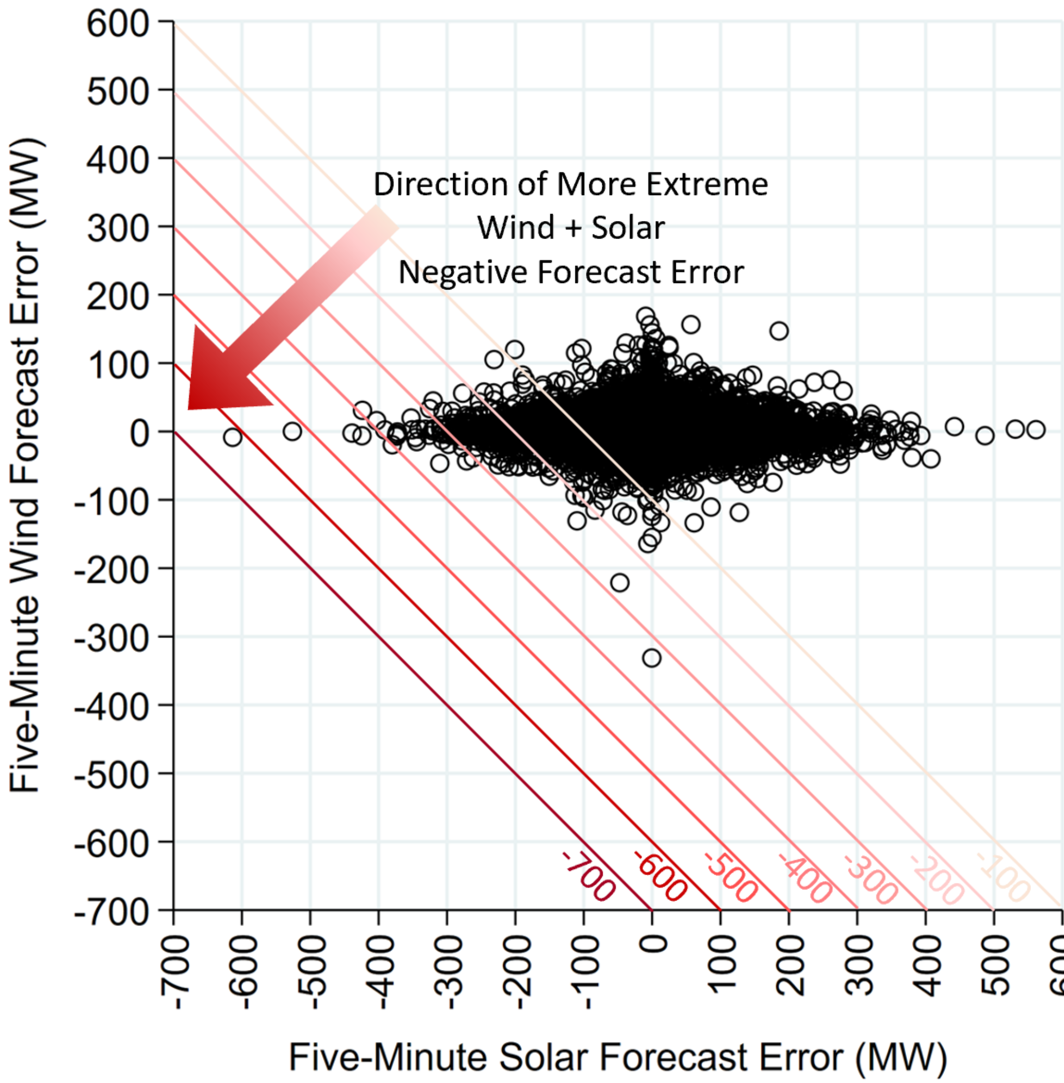

Figure 7-4. Scatter plot of wind vs. solar forecast errors

Each circle represents a single five-minute interval during daylight hours; the x-coordinate corresponds to the solar forecast error at a given point in time while the y-coordinate corresponds to the wind forecast error at that same point in time. The pattern of black circles exhibits visible no tendency towards a positive or negative slope, which is consistent with the lack of a meaningful correlation in the forecast errors.

Furthermore, Figure 7-4 helps illustrate why solar forecast errors are the sole driver of the combined reserve requirement. The colored diagonal lines -- ranging in shade from peach to dark red -- help visualize the magnitude of wind and solar combined negative forecast error. For example, a hypothetical observation located at (-300 MW solar, -200 MW wind) represents a combined forecast error of -500 MW. All other hypothetical or actual observations that might fall along the same bright red line would impact the PNM system through an equivalent -500 MW forecast error in variable renewable generation. In short, the closer an observation is to the bottom left of the graph, the more severe the combined forecast error. Observations along any given diagonal line are equally severe.

When considering the most severe combined forecast errors, we see that such observations tend to lie along the region of the graph where the wind forecast error is approximately zero and the solar forecast error is especially negative. There are very few severe forecast errors to which wind is a major contributor; for forecast errors with shortfalls greater than 300 MW, there is only one. Given that about 2.5 times more solar is planned for the system in 2025 as compared with wind, solar has the greater opportunity for larger forecast errors. Because wind and solar forecast errors are uncorrelated, sometimes wind makes an extreme solar forecast error slightly more severe; other times it makes it less severe. Thus, solar forecast error is the dominant consideration for the reserve requirement on the five-minute time horizon and wind forecast errors have a negligible effect.

8. CONCLUSIONS

This study characterizes the forecast error of the solar PV and wind plants that PNM intends to have on its system in 2025 and formulates a variable generation reserve requirement capable of compensating for those forecast errors.

2025 was chosen as the system study date as about 1,600MW of utility-scale solar capacity should be online, all coal plant capacity could potentially be retired, and PNM's contracted output from the Palo Verde Nuclear Plant will have decreased.

We simulated 5-minute solar output data using **pvlib python** [2], which in turn used 5-minute weather data from the National Solar Radiation Database (NSRDB) [3] as an input. The solar data was generated using state-of-the-art tools and inputs. Nevertheless, we acknowledge that it is not actual observed solar generation data.

The wind data is actual 5-minute wind plant output data for the three wind plants in existence in 2019.[12] However, only about half of the wind capacity planned for 2025 existed in 2019. We multiplied the hourly output from the existing wind plants by 1.87 to account for the additional wind capacity planned to come online by 2025. While we believe this treatment to be a good approximation, it may not capture the benefits of locational diversity in adding wind farms at two more locations.

During daylight hours, it makes sense to consider a reserve that is a function of combined solar and wind output. This combined reserve level, at both the 5-minute and 30-minute intervals, was found to be the same as what was required by solar variability alone. During non-daylight hours, the reserve should be defined as a function of wind output alone.

The 5-minute variable generation reserve specification is illustrated in Figure 8-1. For daylight hours, it is shown as the gold curve, and is a function of both wind and solar output. For non-daylight hours, it is shown as the blue curve, and is a function of wind output only.

[12] The three plants the data is from (along with their net capacities) are: the New Mexico Wind Energy Center (200MW), Casa Mesa (50MW), and Red Mesa (102MW).

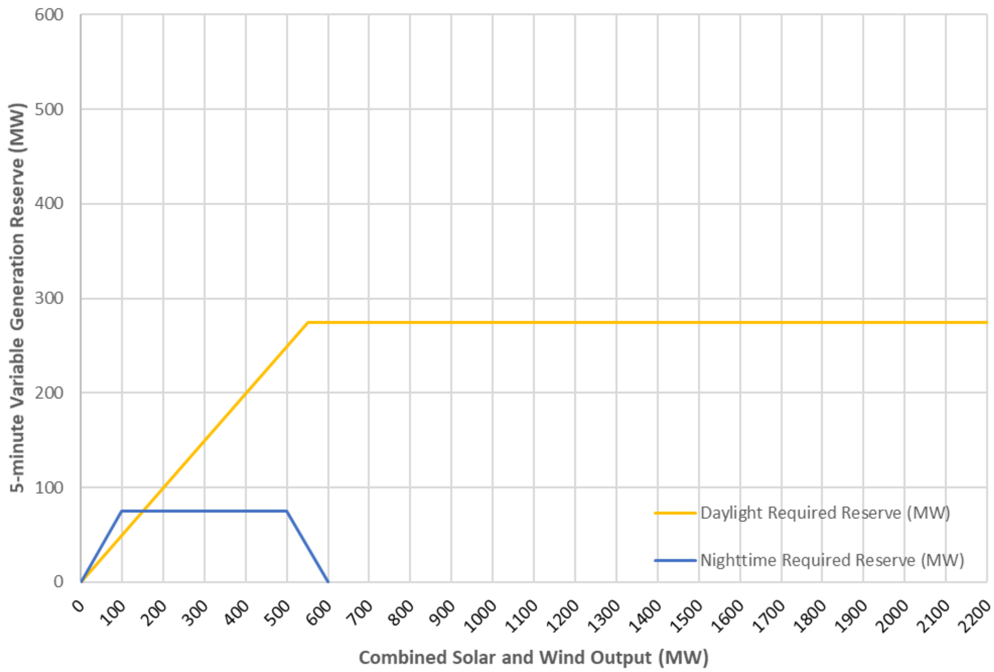

Figure 8-1. 5-minute variable generation reserve formula

In brief, we find that to handle 99.9% of the 5-minute negative forecast errors (shortfall relative to forecast), a maximum of 275MW of reserve during daylight hours, and a maximum of 75MW during non-daylight hours, should be sufficient. This reserve should be in the form of regulating reserve, as it isn't possible to get a quick-start generator on-line within 5 minutes.

The 30-minute variable generation reserve specification is illustrated in Figure 8-2. For daylight hours, it is shown as the gold curve, and is a function of both wind and solar output. For non-daylight hours, it is shown as the blue curve, and is a function of wind output only.

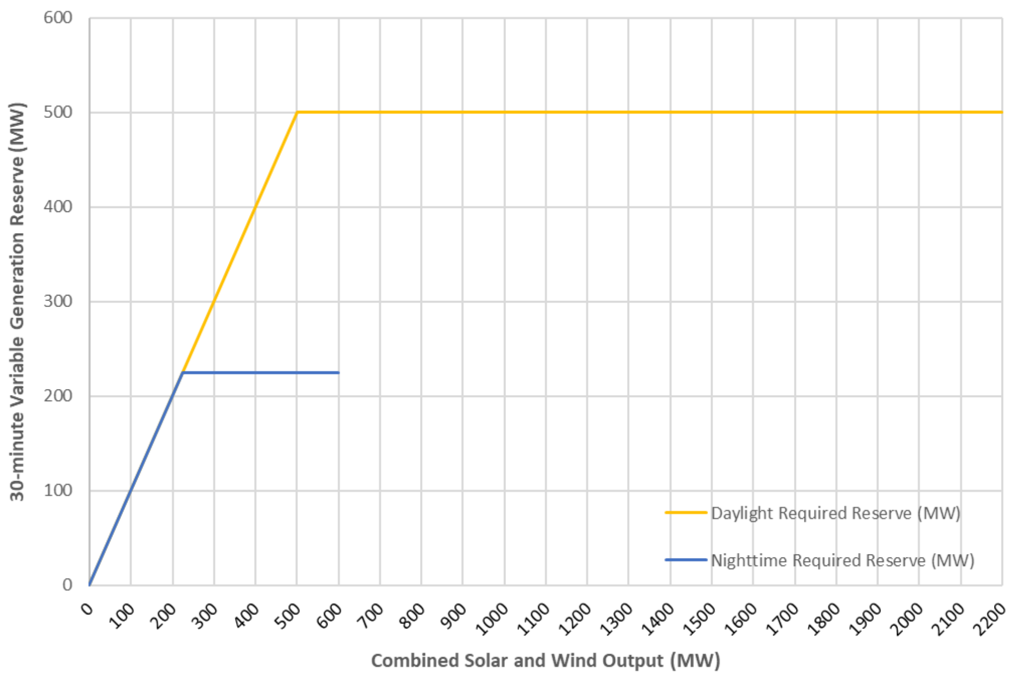

Figure 8-2. 30-minute variable generation reserve formula

In brief, we find that to handle 99.9% of the 30-minute negative forecast errors (shortfalls relative to forecast), a maximum of 500MW of reserve during daylight hours, and a maximum of 225MW during non-daylight hours, should be sufficient. This reserve can be partially provided by regulating reserve, and partially provided by quick-start reserve, as there is time to get the quick-start units on-line within the 30-minute time frame.

To be clear, we are not suggesting a separate variable generation reserve category for 5-minute and 30-minute forecast errors. Rather, we are suggesting what level of variable generation reserves may be needed to handle shorter duration (5-minute) and longer duration (30-minute) forecast errors within the hour. Some portion of this variable generation reserve may be provided by synchronized or storage resources, and some portion may be provided by quick start resources.

This variable generation reserve specification may overestimate the actual level needed to deal with PNM's planned variable generation in 2025. The forecasting methodologies used in this study likely underperform PNM's forecasting – and better forecasting allows for less reserve. To obtain more precise estimates, it is necessary to consider load and use the same forecasting inputs and methods used by PNM.

8.1. Possible future work

To more accurately specify the regulating reserve required by PNM in system year 2025, it is necessary to consider solar, wind, and load, along with taking into account precisely how PNM is doing short-term forecasting for each of those. In this way, the way solar, wind, and load interact would be considered, as would the accuracy of PNM's forecasting.

One way to do this would be to use the same commercial software package PNM uses for its solar, wind, and load forecasting, tune the model to the same inputs and sensitivities that PNM uses, and feed it the data it would have had available to make 5-minute ahead and 30-minute ahead forecasts.

To improve a future analysis of ramps in load, it would be helpful to be able to distinguish between ramping attributable to rooftop solar generation versus ramping due to electricity consumption. While the statistical distribution of consumption-related ramps is likely to remain similar over PNM's planning horizon, rooftop solar deployment has grown rapidly and is expected to continue to grow. Rooftop solar output is certain to be strongly correlated with utility-scale solar output, but the geographic diversity of rooftop solar implies that the rooftop solar forecast errors may be less severe than those for utility-scale solar.

PNM is not able to monitor behind-the-meter generation; rather, it observes a customer's net load at the meter. Therefore, statistical techniques could be applied to infer the relationship between clear sky solar generation, utility-scale solar generation, weather data (if available) and net demand. Such an analysis could produce an estimate of the magnitude of the most extreme ramps in net load given present levels of rooftop solar PV (about 120 MW to 150 MW as of the writing of this report) and enable an extrapolation to higher levels of rooftop solar deployment.

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APPENDIX A. SOLAR PV MODELING METHODOLOGY

Existing and planned solar PV plants were modeled using **pvlib python** [2]. **pvlib python** is a community-supported tool that allows for detailed simulation of the performance of photovoltaic energy systems. It was originally ported over from the PVLIB MATLAB toolbox developed at Sandia National Laboratories, and implements many of the models and methods developed there.

Solar irradiation (as well as ambient temperature and ground-height windspeed) data was downloaded from the National Solar Radiation Database (NSRDB) [3] at an 5-minute resolution each location. Each cell represents an area of 2 kilometers by 2 kilometers (4 km^2).

The solar irradiation data used in this model, specifically, are Direct Horizonal Irradiance (DHI), Direct Normal Irradiance (DNI), and Ground Horizontal Irradiance (GHI). The units for these measurements are in watts per square meter (W/m^2).

DHI is the amount of radiation received per square meter by a surface (not subject to any shade) that does not arrive on a direct path from the sun (in other words, light that's been scattered by molecules in the atmosphere).

DNI is the solar radiation per square meter by a surface that is always perpendicular to the light coming straight from the sun (given its current position in the sky).

GHI is the total amount of shortwave radiation received from above by a surface horizontal to the ground.

The relationship between these three measurements of solar irradiation is given by:
$GHI = DNI * \cos(\theta) + DHI$, where θ is the solar zenith angle (directly overhead would be $\theta = 0$) [7]

The PV system simulated in **pvlib python** was assumed to be a single-axis tracking plant with an inverter load ratio (ILR) of 1.3. In other words, the PV panel capacity for this plant was set at 1.3 times the capacity of the AC inverter. This is because it is not economical to size the inverter at the full output capacity of the PV panels, as this full capacity would be used only for a small fraction of time. In addition, setting the inverter at a smaller size than the PV panels allows for a more even power output profile in the middle of the day. When PV panel production is greater than the inverter can accept, cloud cover that reduces PV panel production down to the inverter's capacity has no impact on the actual AC power production from the plant.

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