# The moonshot 100% clean electricity study

*Assessing the tradeoffs among clean portfolios with a PNM case study*

**TECHNICAL APPENDIX 2**

Regionally coordinated planning using SWITCH model

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# The SWITCH WECC model

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# SWITCH WECC review

## Capacity expansion deterministic linear program

### Minimizes total cost of the power system:

- Generation investment and operation
- Transmission investment and operation

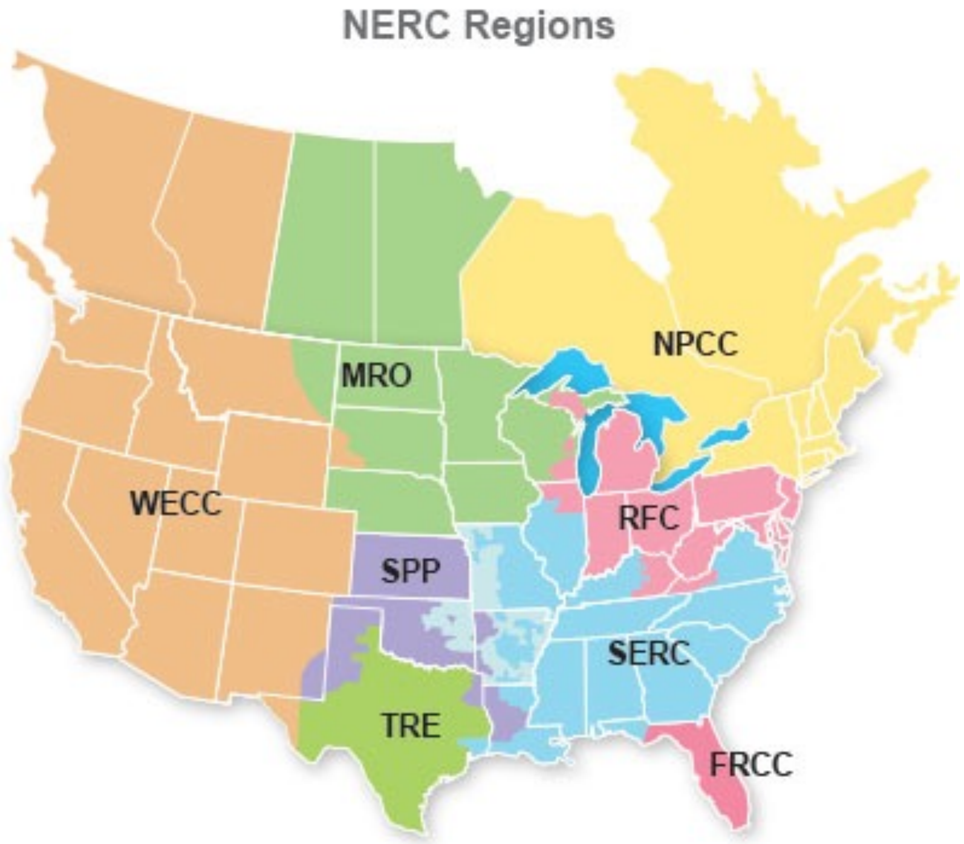
### Geographic:

- Western Electricity Coordinating Council
- 50 load areas

### Temporal:

- Investment periods: 2026-2035 (“2030”); 2036-2045 (“2040”); 2046-2055 (“2050”);
- Time resolution: sampling every 4 hours, for a subset of days or every day in a year
- Dispatch simulated simultaneously with investment decisions

*https://github.com/REAM-lab/switch/*



# SWITCH WECC review

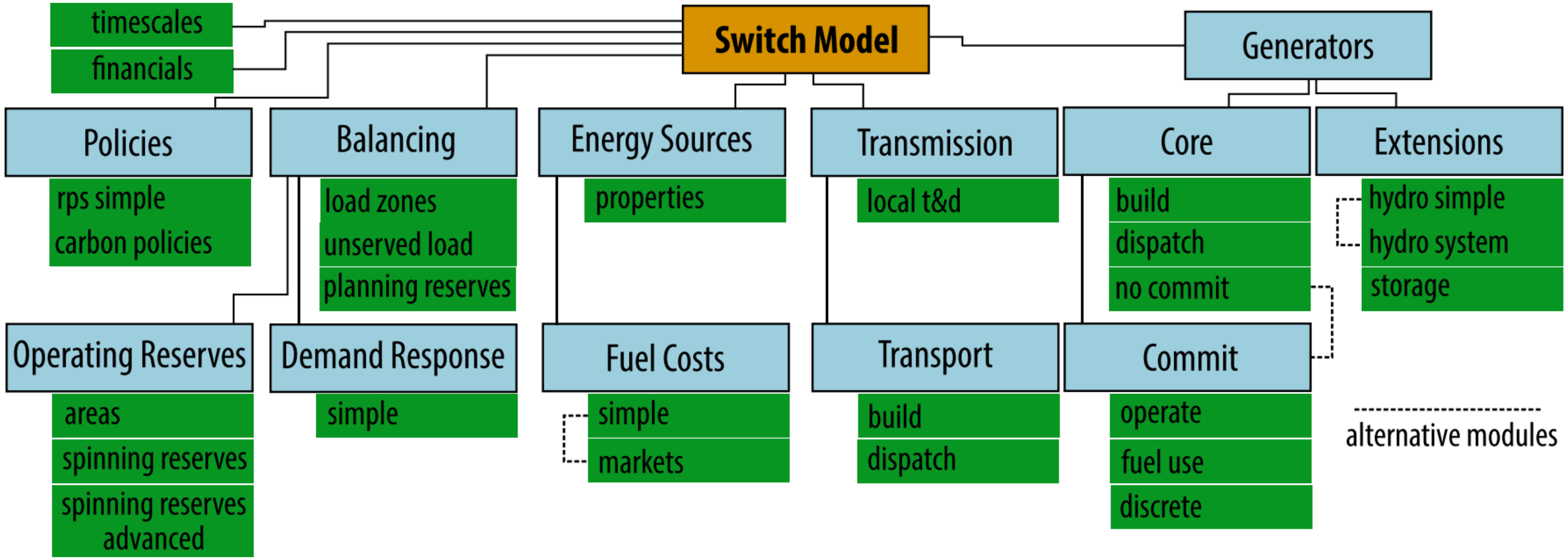



*Image source: J. Johnson et al., Switch 2.0: A modern platform for planning high-renewable power systems, 2019*
*https://github.com/REAM-lab/switch/*

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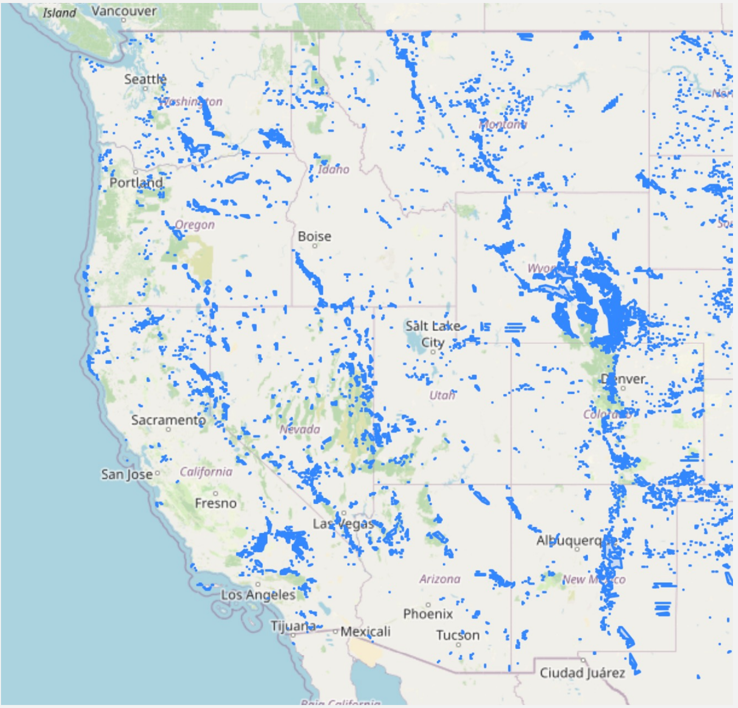
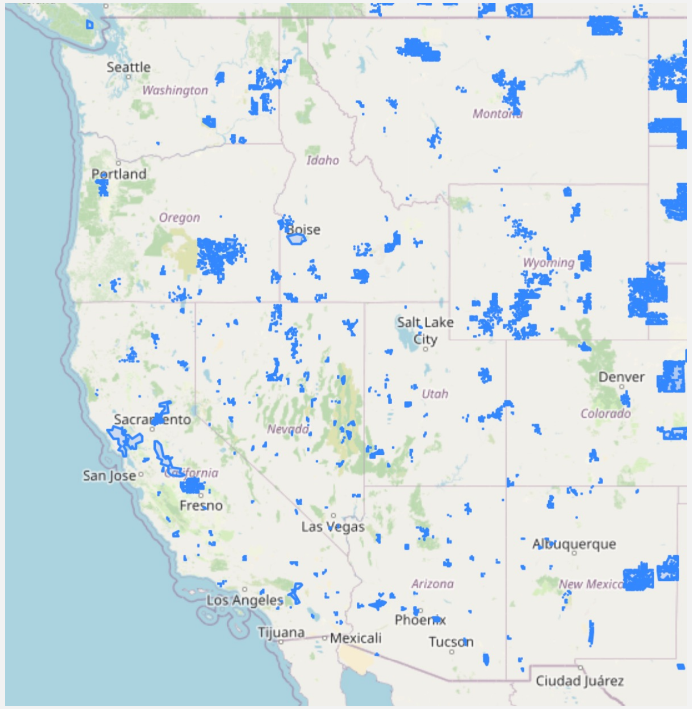
# SWITCH WECC review

## Highlights

- Understand interactions between PNM and the WECC
- Capacity expansion WECC model using 50 zones, 1 zone maps to PNM LSE
- All existing generators (3,000+) disaggregated
- 7,000+ potential new generators
- Hourly data for 50 load zones, solar/wind capacity factors
- Aggregated existing transmission between 50 zones
- Each zone modeled as copper plate
- Year 2035 modeled with 365 days, 6 time blocks/day (to facilitate modeling multiday storage/long duration energy storage (LDES))
- Representing imports and exports as physical electricity flows




Wind candidates




Solar candidates

# Methodology

# Customization of SWITCH WECC for PNM study

## Code development

### WECC

- Improved treatment of RPS modeling for non-zero emissions scenario (outside PNM)
- Time sampling for all 365 days of 2035
- Zonal carbon cap
- New hourly demand forecast from EnergyPATHWAYS mapped into SWITCH zones *

### PNM

- Imports/exports constraints on an annual and hourly basis
- Solar to wind ratio of deployment
- Constraint to force total installed capacity

## Overall Objectives

- Understand interactions between PNM and the WECC
- Understand role and value of multiday/long-duration energy storage (LDES) in PNM

** See Appendix 1 for a description of the demand forecasts developed by EnergyPATHWAYS*

# Scenarios and sensitivities development

- To further understand the interactions of PNM with the rest of the WECC, we conducted a range of scenarios and sensitivities:
- There are three main classes of scenarios:
  - Baseline demand scenarios in which PNM interacts with the WECC, under both conditions of a) WECC-wide net zero emissions reductions, and b) PNM achieves net zero emissions but the rest of the WECC achieves 50% GHG emissions reductions (relative to 2005)
  - High electrification demand scenarios in which PNM interacts with the WECC, under both conditions of a) WECC-wide net zero emissions reductions, and b) PNM achieves net zero emissions but the rest of the WECC achieves 80% GHG emissions reductions (relative to 2005)
  - PNM operates as an electrically islanded zone and does not have any imports or exports with the WECC
- We exercised SWITCH to understand the impact, independently, of a) imports and exports, b) relative build quantities of wind and solar in PNM, c) the cost of long duration storage
- The sensitivities were conducted as follows:
  - The imports/exports sensitivities were conducted by enforcing an annual imports/exports quantity
  - The wind/solar sensitivities were conducted by varying the ratio of wind to solar build in PNM
  - The long duration cost sensitivity was conducted by varying the energy ($/kWh) cost (note, SWITCH separately optimizes on storage capacity and energy, and applies different storage capacity and energy costs as inputs)
- Not all sensitivities were conducted for each scenario

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# PNM imports/exports constraints (1)

**Description of variables:**

- Injection is equivalent to generation in the PNM zone with the battery discharge
- Withdrawal is equivalent to the demand within the PNM zone with the battery charging
- Exports occur when injections exceed withdrawals

First, we define the zone injections and withdrawals:

$$\text{Zone\_Power\_Injections}_{(z,t)} = \text{Generation}_{(z,t)} + \text{Discharge BESS}_{(z,t)}$$
$$\text{Zone\_Power\_Withdrawals}_{(z,t)} = \text{Load}_{(z,t)} + \text{Charge BESS}_{(z,t)}$$

We define the PNM injections and PNM withdrawals as follows:

$$\text{PNM\_Injection}_{(tp)} = \sum_{z \in PNM} \text{Zone\_Power\_Injections}_{(z,t)}$$
$$\text{PNM\_Withdrawal}_{(tp)} = \sum_{z \in PNM} \text{Zone\_Power\_withdrawals}_{(z,t)}$$

***This describes the methodology implemented in the SWITCH code to conduct the import/export sensitivities.***

# PNM imports/exports constraints (2)

The constraints are:

$$(\text{ratio\_lowerbound}) \leq \frac{\sum_{tp} \text{PNM\_Injection}_{(tp)} \Delta tp}{\sum_{tp} \text{PNM\_Withdrawal}_{(tp)} \Delta tp} \leq (\text{ratio\_upperbound})$$

Where:

- PNM_Injection $_{(tp)}$ : Decision variable that represents zone power injections.
- PNM_Withdrawal$_{(tp)}$ : Decision variable that represents zone power withdrawals.
- ratio_upperbound and ratio_lowerbound : Input parameters.

**RESULTS**

# Baseline demand scenario sensitivities

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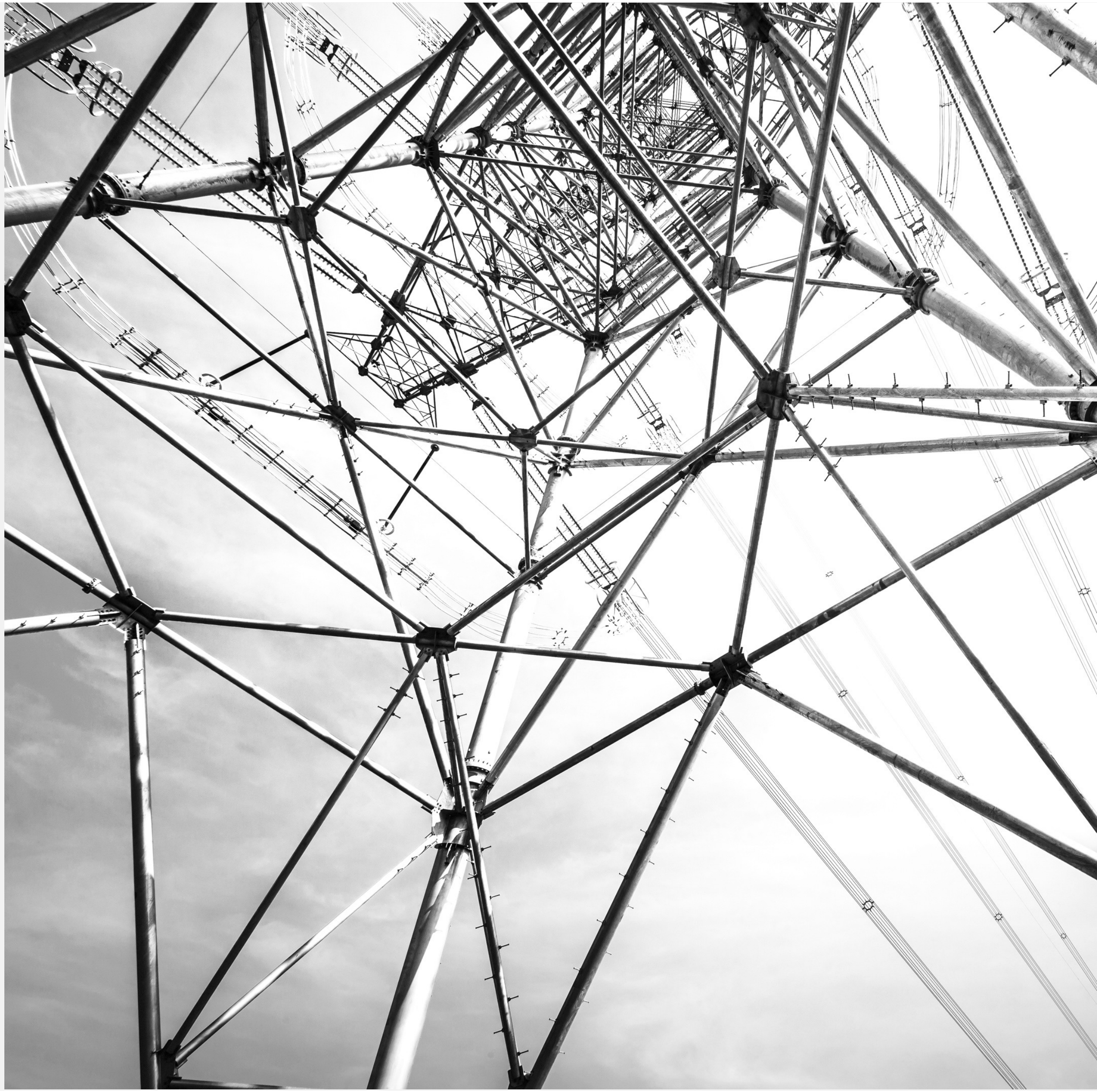
# Scenarios and PNM results from baseline

## Scenarios and sensitivities

- Zero emissions WECC wide
- 2035 using all 365 days, 6 hours/day
- PNM Sensitivities:
    - imports/exports,
    - wind/solar installed capacity,
    - forced total installed capacity

## PNM baseline

- 6.6 GW installed capacity, 5.9 h of storage duration
- Annual net exporter: 10% of its demand
- Heavily relies on imports during the summer (more than 40% in imports)

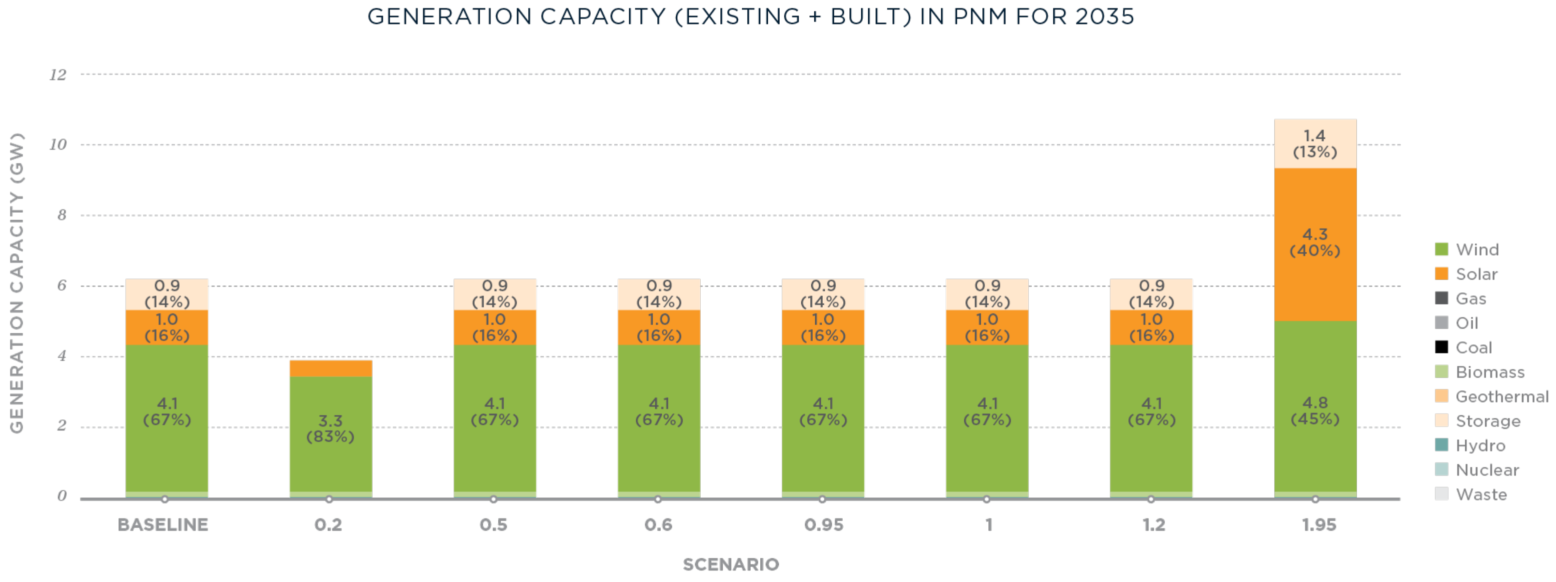


# PNM annual imports/exports sensitivity

## Scenarios

- Baseline: The baseline scenario is the solution in which SWITCH imposes no constraints on the imports or exports
- Injection/withdrawal ratios: 0.2 (net importer), …, 1 (break-even),…, 1.95 (net exporter)
- For example, an annual injection/withdrawal ratio of 0.2 implies that 80% of PNM's energy requirements over the year are met through net imports; an annual injection/withdrawal ratio of 1.95 implies that 95% of PNM's generation is exported

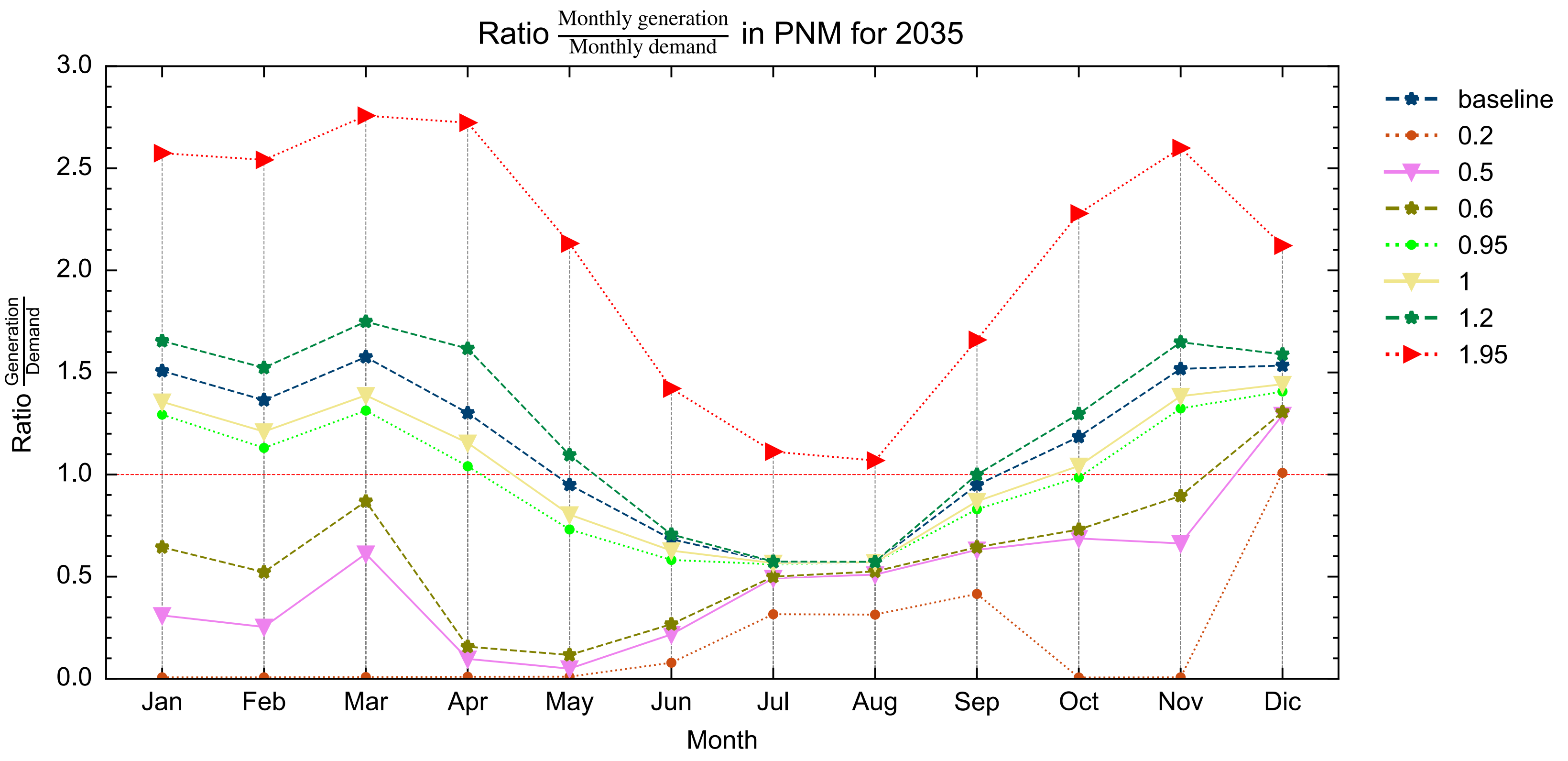
## Installed capacity




- Constant installed capacity despite ranging from 50% net importer to 20% net exporter
- Mostly wind deployed
- Increased generation (active constraint for imports/exports)

# PNM annual imports/exports sensitivity

## Monthly average injection/withdrawal




- In most scenarios, **PNM requires 50% of imports or more during summer months.**
- Only when PNM is forced to export 95% of its generation it can become self sufficient on every month.
- This showcases the value of a coordinated market between PNM and its neighbors.

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# PNM annual imports/exports sensitivity

## Lessons learned

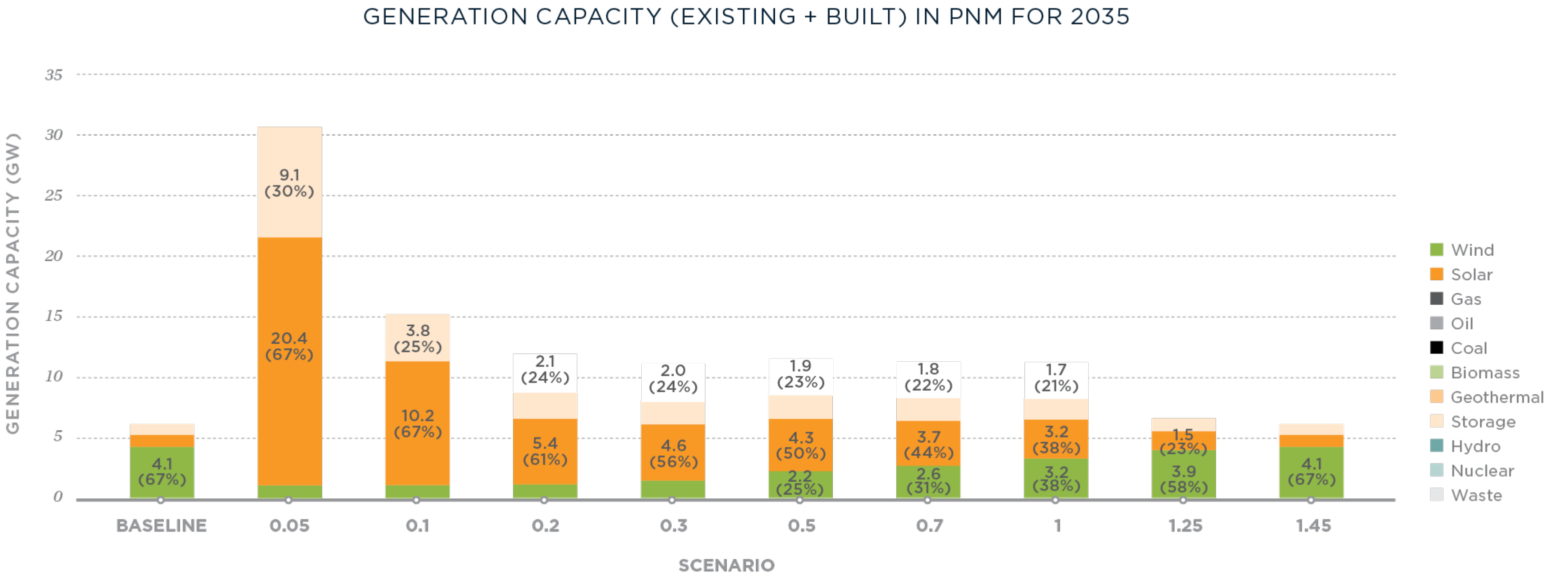
- When PNM is forced to produce 95% more than its demand, it can serve its own electricity demand in all months. Otherwise, it depends on imports during the summer
- Forcing PNM to range from 50% net importer to 20% net exporter does not change its installed capacity
- Wind dominates the mix except in the 95% net exporter case
- All scenarios, except 80% net importer, show a storage duration of 5.9h

# GridLAB PNM installed wind/solar ratio sensitivity

## Scenarios

- Baseline (wind/solar = ~4)
- Wind/solar ratios: 0.05 (solar dominant), …, 4 (wind dominant)
- No imports/exports constraint

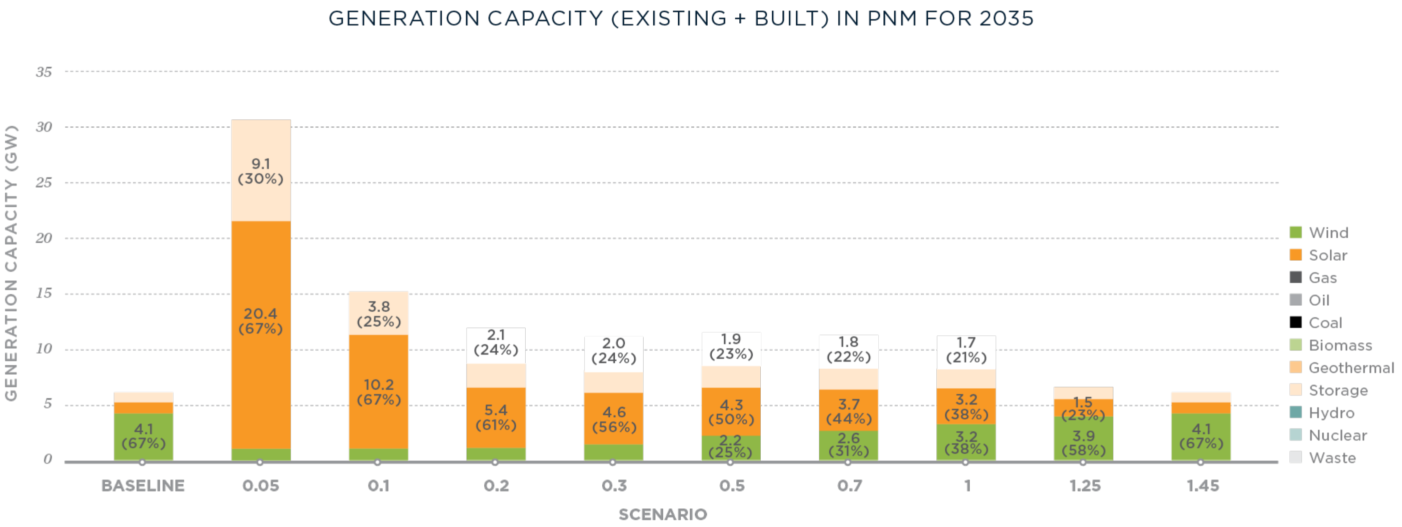
## Installed capacity




- Installed capacity increases 1.3x between baseline (wind dominant) and equal solar/wind deployment, and 2.4x when 90% solar
- **Note: to be solar dominant, PNM requires ~16 GW instead of 6.6 GW.**
- Storage duration increases with solar share: 5.9 to 6.9 h

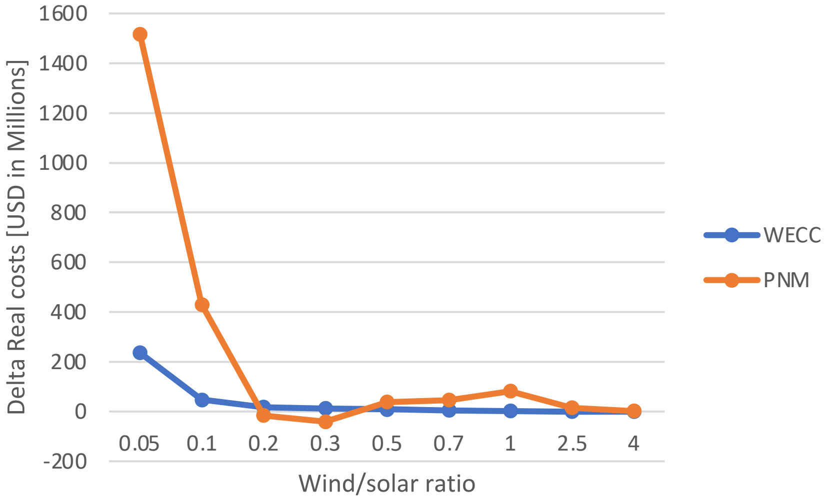
# PNM installed wind/solar ratio sensitivity

## Generation




- Generation capacity is relatively unaffected, except in extreme solar dominant scenarios.

## Costs




- WECC costs monotonically increase as more solar is forced in PNM
- PNM costs marginally decrease as solar goes from 50% to 80%

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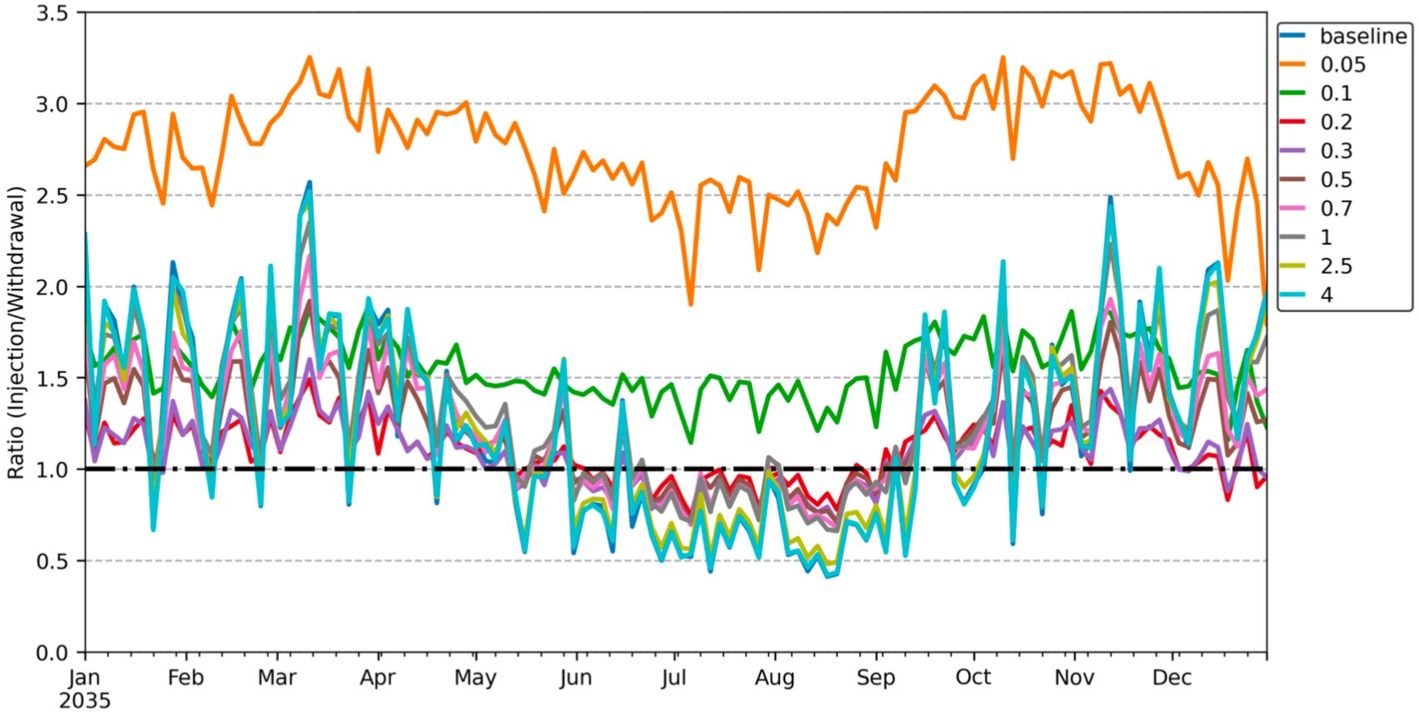
# PNM installed wind/solar ratio sensitivity

- Annually, PNM is a net exporter in all scenarios
- **PNM becomes net exporter in all months** only when **solar power is 90% or more** of the total installed capacity
- When solar power is 80% or less of the installed capacity, PNM relies on imports during the summer

## Sampled injection/withdrawal



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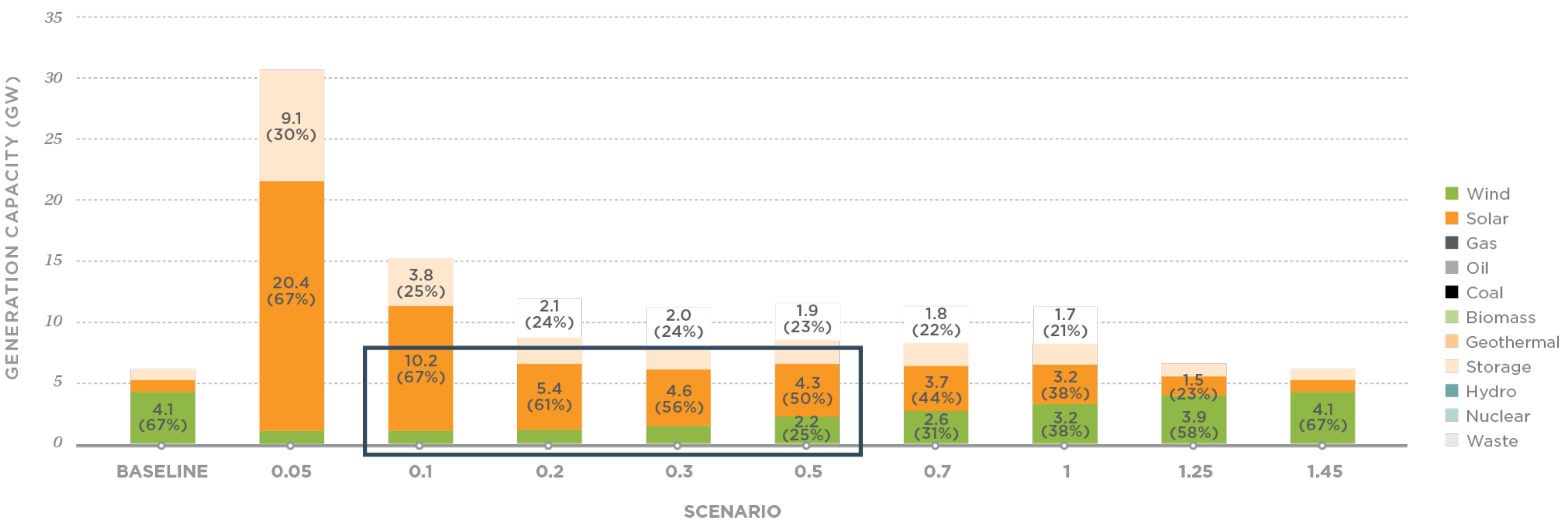
# PNM installed wind/solar ratio sensitivity

## Lessons learned

- Installed capacity increases 1.3x between baseline (wind dominant) and equal solar/wind deployment, and 2.4x when 90% solar
- PNM costs marginally decrease as solar goes from 50% to 80%
- Annually, PNM is a net exporter in all scenarios
- **PNM becomes net exporter in all months only when solar power is 90% or more** of the total installed capacity

GENERATION CAPACITY (EXISTING + BUILT) IN PNM FOR 2035



# PNM total installed capacity sensitivity

## Question

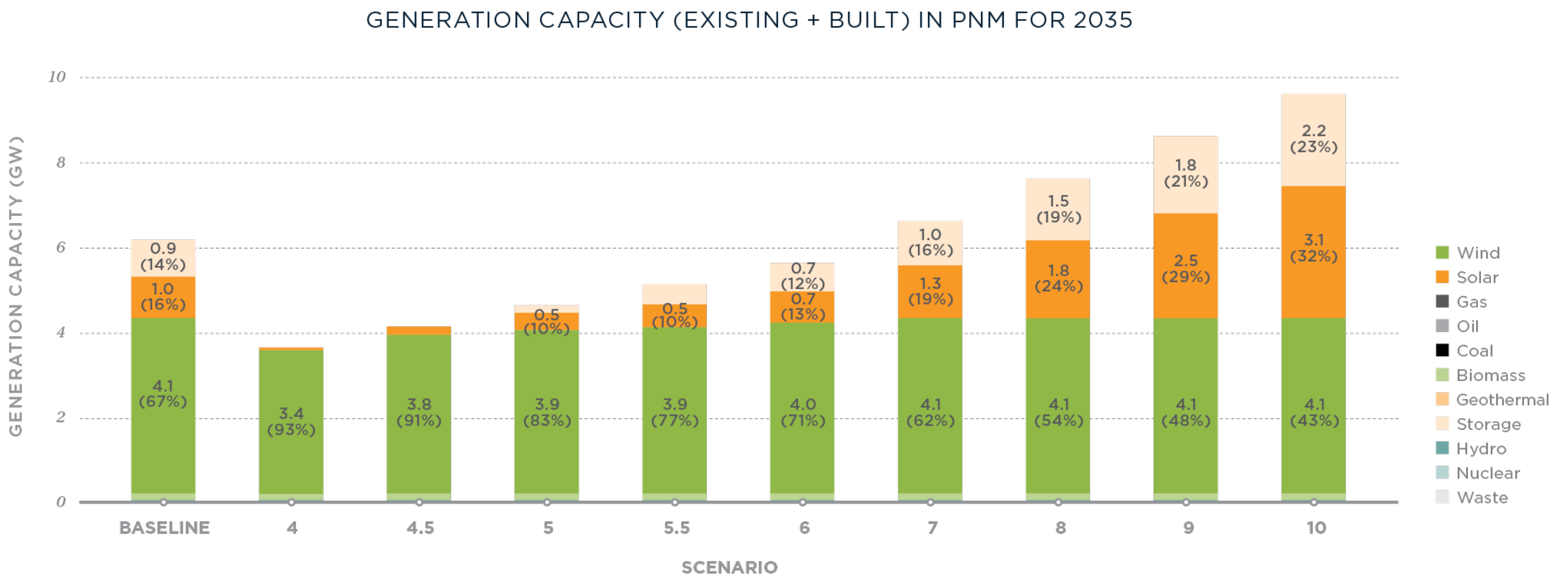
If no wind/solar ratio is enforced, what installed capacity is required for self-sufficiency? How does the capacity mix change?

## Scenarios

- Baseline (6.6 GW, no enforcement)
- Installed capacity sensitivity: 4 – 10 GW
- No imports/exports or wind/solar constraints
- Installed capacity

## Insights

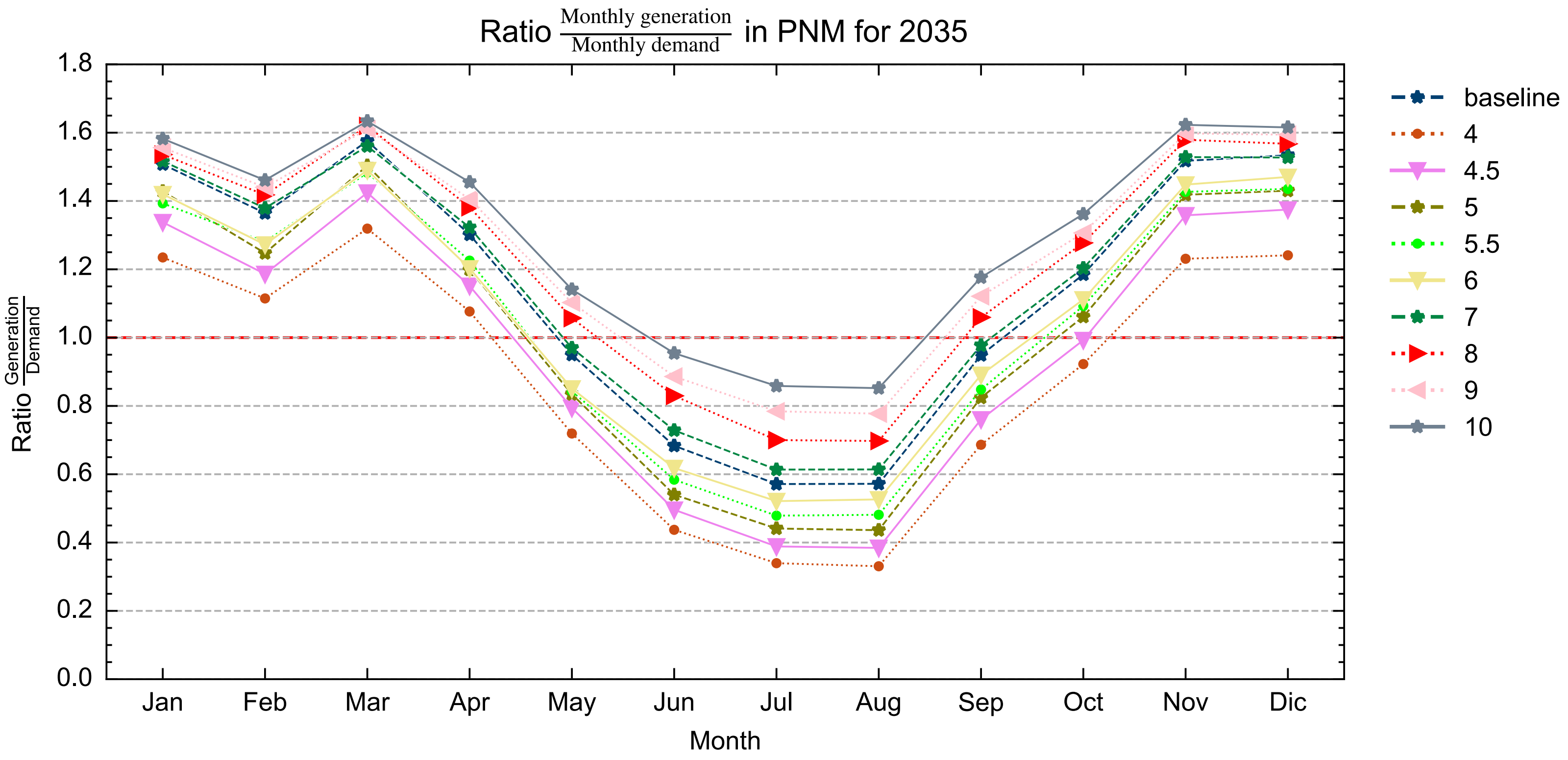
- Stable optimal wind deployment
- Solar power and storage correlated increase
- Same storage 5.9 h duration across scenarios with storage



# PNM total installed capacity sensitivity

## Monthly average injection/withdrawal

- All scenarios (4 – 10 GW) **heavily rely on imports during the summer months**



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# PNM total installed capacity sensitivity

## Lessons learned

- Fixed optimal wind deployment as total installed capacity increases
- Solar power and storage correlated increase
- Same storage 5.9 h duration across scenarios with storage
- All scenarios (4 – 10 GW) **heavily rely on imports during the summer months**

# Overarching finds for PNM's self-sufficiency

**PNM net exporter in all months requires:**

- At least 90% solar deployed (resulting in 15.6 GW of total capacity vs 6.6 GW) or
- Forcing PNM to generate 95% more of its demand annually

# RESULTS

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**RESULTS**

# PNM islanded versus connected to the WECC

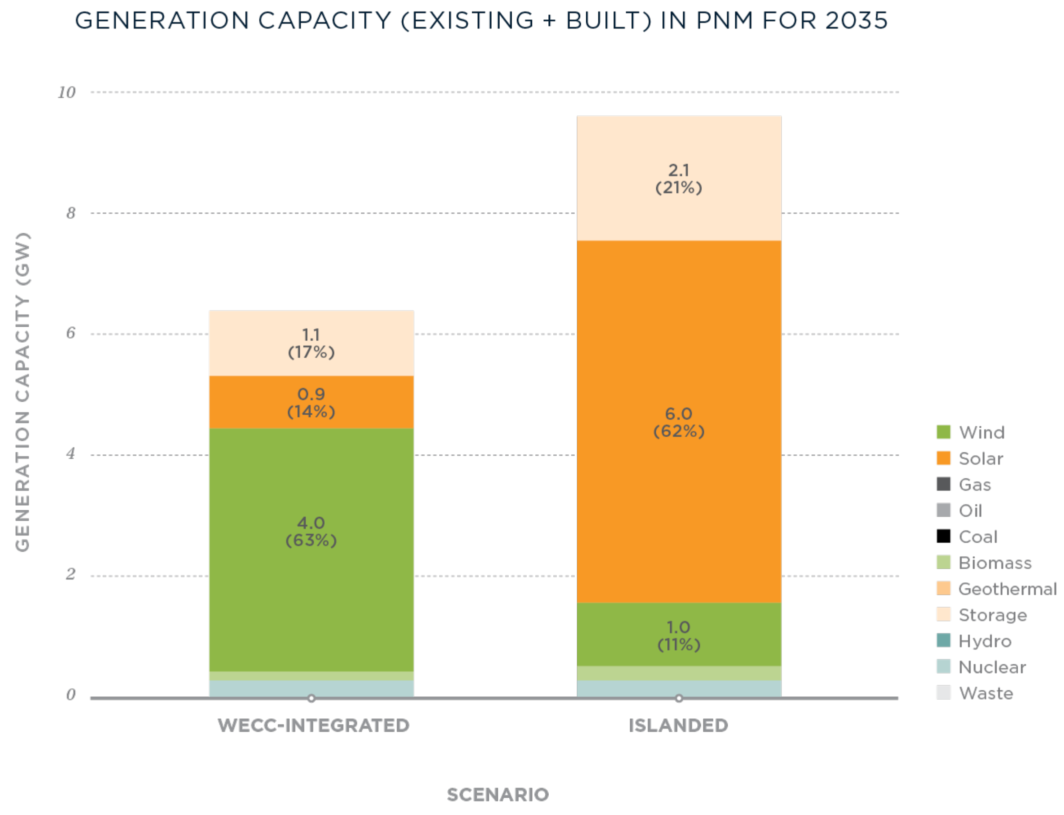
# PNM islanded versus connected to the WECC

## Scenarios

- Zero emissions WECC-wide (and in PNM)
- PNM islanded versus connected

## Key findings

- Costs ($/kWh): 220 (islanded) vs 125 (connected)
- **Islanded case is solar dominant (60%)**
- Curtailment: 43 – 14 %
- **Storage duration: 6.5 vs 6 hours**
- SWITCH islanded case is reliable under weather
- variability (as tested using GridPath)



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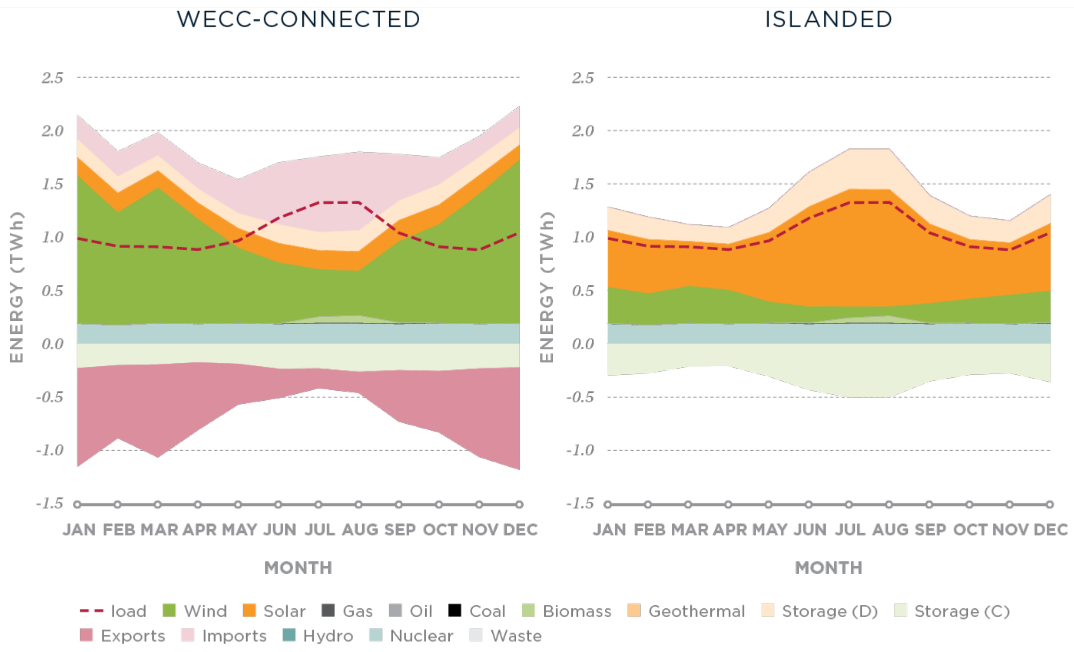
# PNM islanded versus connected to the WECC

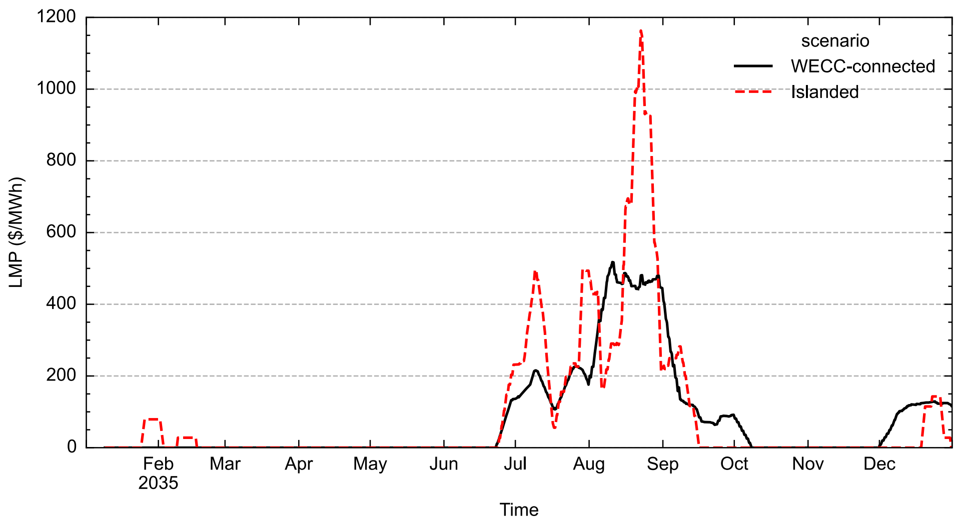
## Key findings

- High variability in seasonal dispatch
- LMPs vary widely during the summer
- SWITCH islanded case is reliable when tested in GridPath and robust to interannual weather variability (tested in GridPath

## Policy implications

- SWITCH Islanded case does not rely on hydrogen or other uncertain technologies
- Curtailment results from GridPath are 62% and under no imports/exports allowed and 42% when imports/exports are allowed (market for excess renewables)



**RESULTS**

# Long-duration energy storage cost sensitivity for PNM electrically islanded versus connected to the WECC

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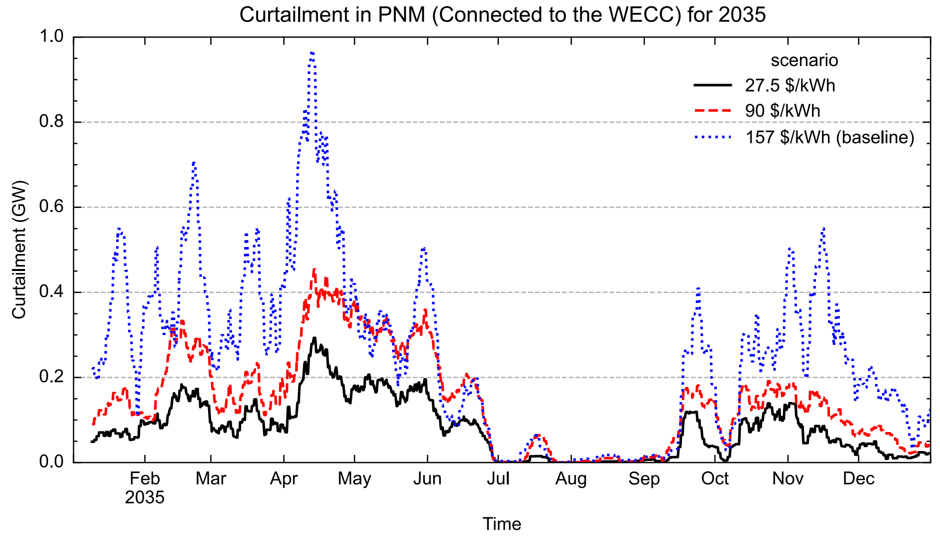
# Long-duration Energy Storage (LDES) cost sensitivities, **PNM connected to the WECC**

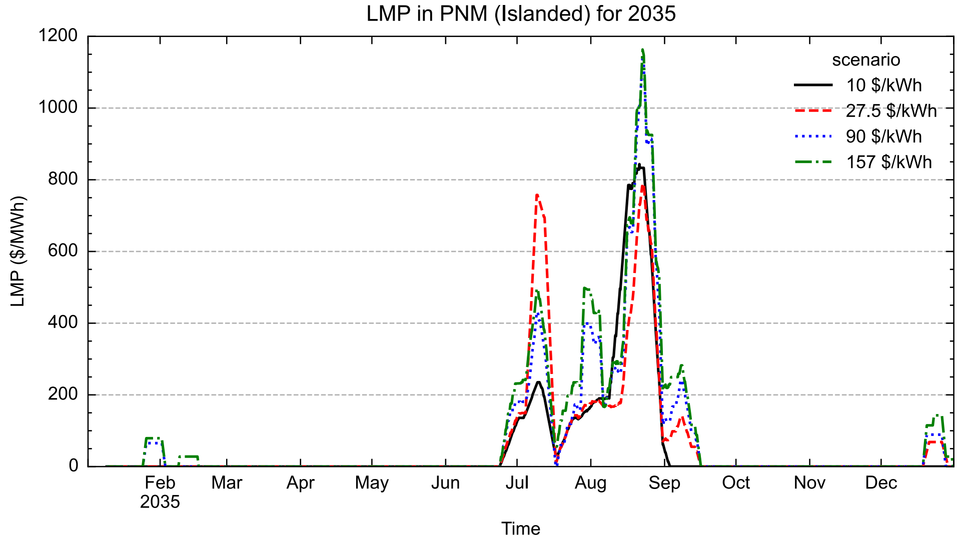
## Scenarios

- Zero emissions WECC-wide (and in PNM)
- Sensitivity on storage energy capacity capital costs:
  - 27.5 USD/kWh (DOE storage shot)
  - 90 USD/kWh
  - 157 USD/kWh (NREL ATB)

## Key findings

- Cost range: $31/kWh to $111/kWh
- Installed capacity range: 4.4 – 6.6 GW
- Curtailment: 7 – 13 %
- **Storage duration remains constant at 6h**
- Imports/Exports: **0.75 (importer)** to 1.1 (exporter)
- LMPs vary widely during the summer



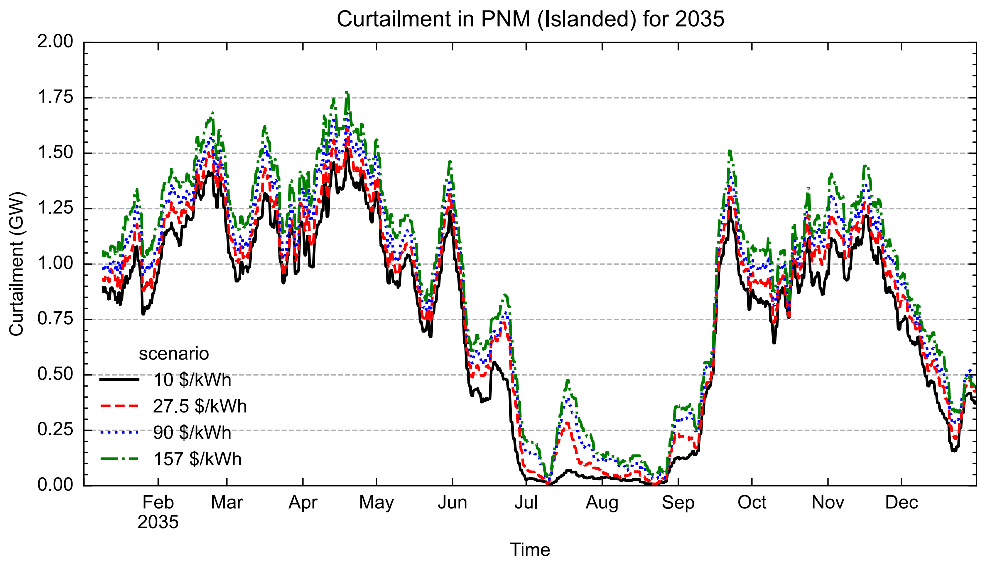
# Long-duration Energy Storage (LDES) cost sensitivities, **PNM islanded**

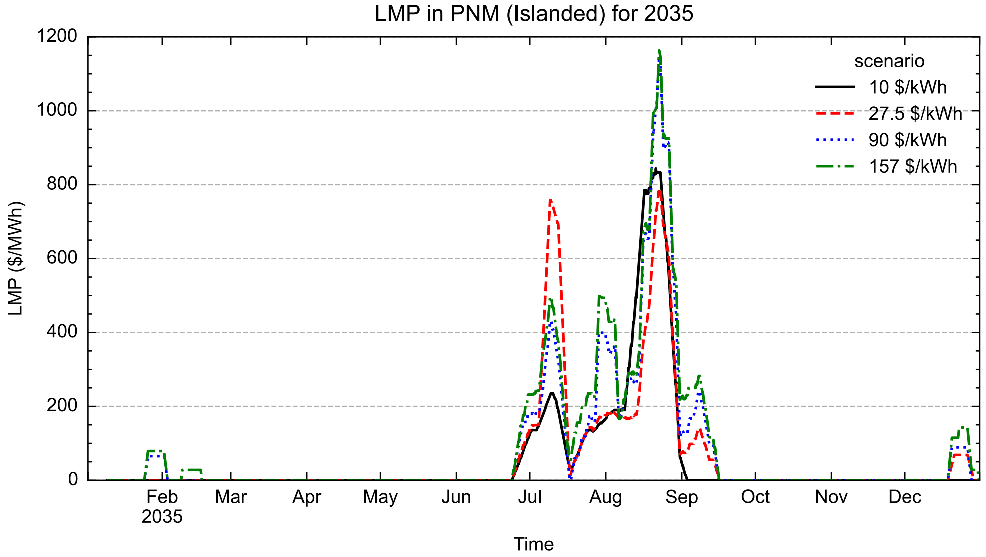
## Storage cost sensitivities

- Energy capacity capital costs:
  - 10, 27.5, 90,157 USD/kWh

## Key findings

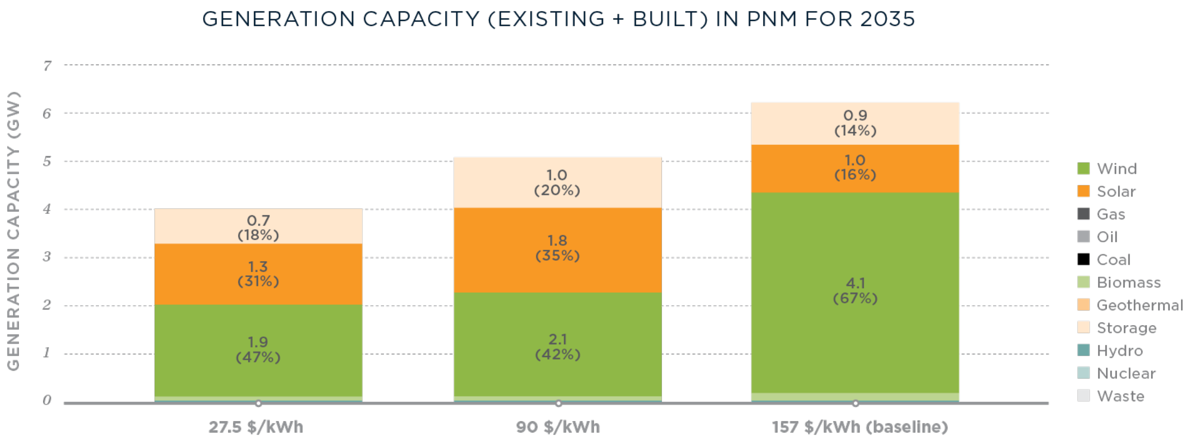
- Cost range ($/kWh): 75 - 219
- Installed capacity range: 9.2 – 10 GW
- **Solar power: 5.2, 5.5, 5.8, 6 GW**
- Curtailment: 37 – 43 %
- **Storage duration: 17.2, 9, 7, 6.5 hours**
- LMPs vary widely during the summer



# Long-duration Energy Storage (LDES) cost sensitivity, **PNM connected**

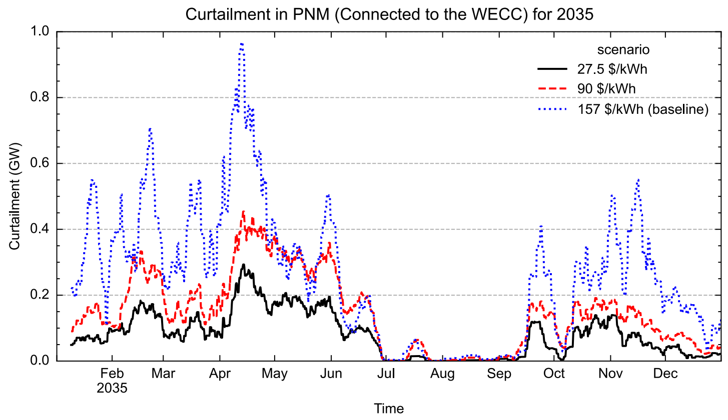
## Generation




- As the storage energy capacity cost declines, the installed generation decreases

## Curtailment

- Curtailment decreases with cost declines



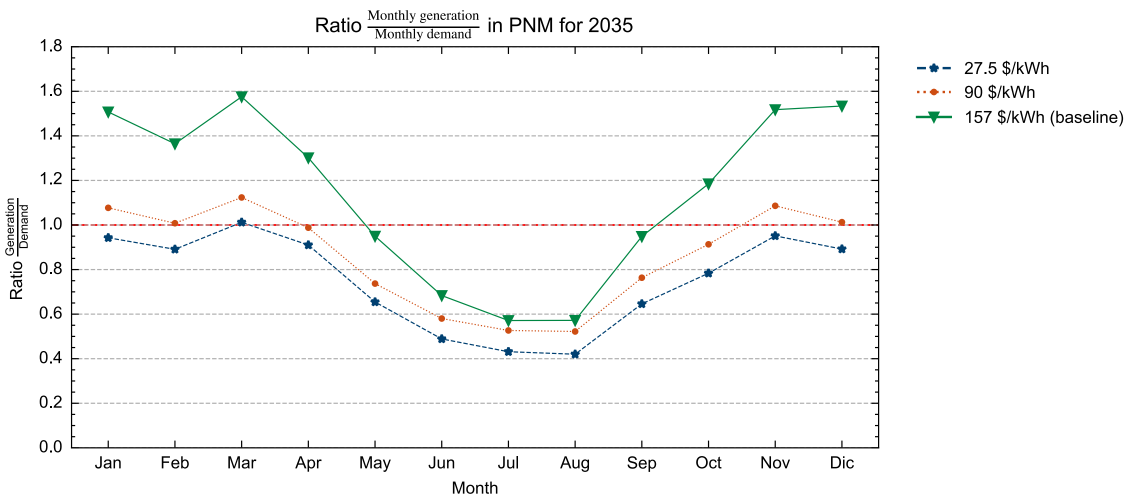

### Storage power, energy and duration in PNM

| Scenario | 27.5 USD/kWh | 90 USD/kWh | 157 USD/kWh (baseline) |
|---|---|---|---|
| Storage energy capacity (MWh) | 4239 | 6081 | 5100 |
| Storage power capacity (MW) | 721 | 1034 | 867 |
| Storage duration (hr) | 5.9 | 5.9 | 5.9 |

- Storage duration remains constant at 6h

# Long-duration Energy Storage (LDES) cost sensitivity, **PNM connected**

- Lower storage costs corresponds with less exports across the year
- In the lowest cost sensitivity, PNM is a net importer across the entire year including winter months
- These results result that the rest of the West has less need for resources located in PNM as storage becomes more economical



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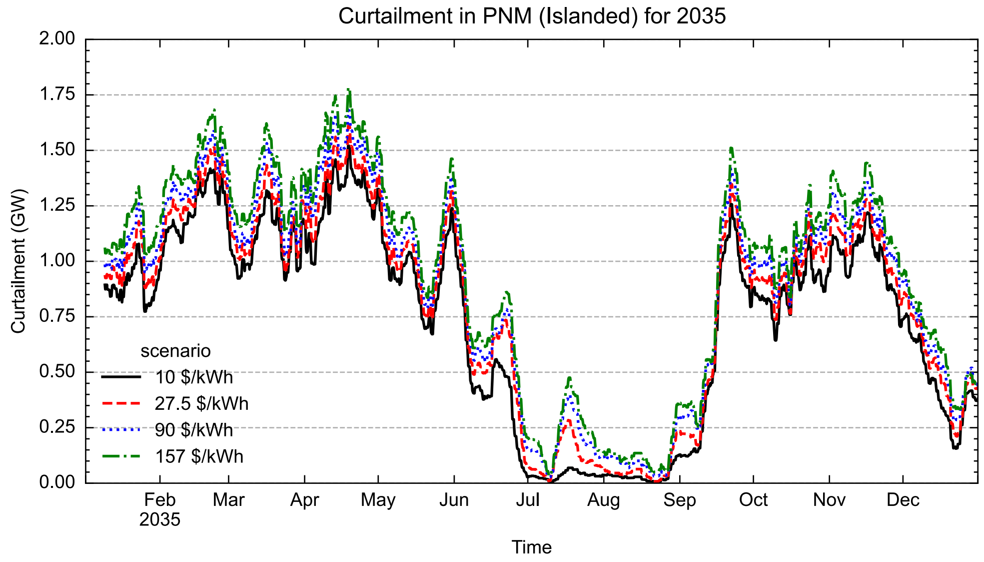
# Long-duration Energy Storage (LDES) cost sensitivities, **PNM islanded**

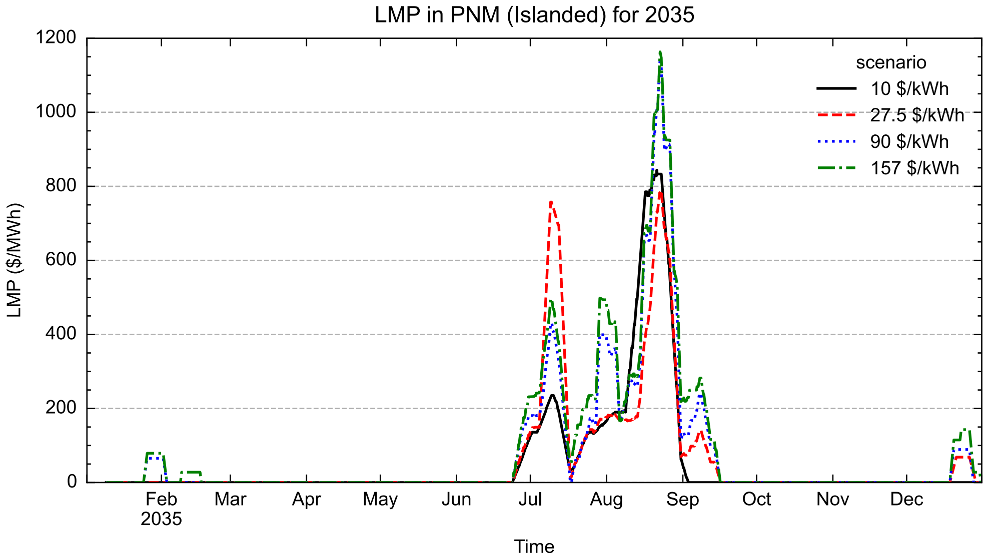
## Storage cost sensitivities

- Energy capacity capital costs:
  - 10, 27.5, 90,157 USD/kWh

## Key findings

- Cost range ($/kWh): 75 - 219
- Installed capacity range: 9.2 – 10 GW
- **Solar power: 5.2, 5.5, 5.8, 6 GW**
- Curtailment: 37 – 43 %
- **Storage duration: 17.2, 9, 7, 6.5 hours**
- LMPs vary widely during the summer



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**RESULTS**

50% $CO_2$ emissions reductions WECC-wide, net zero PNM

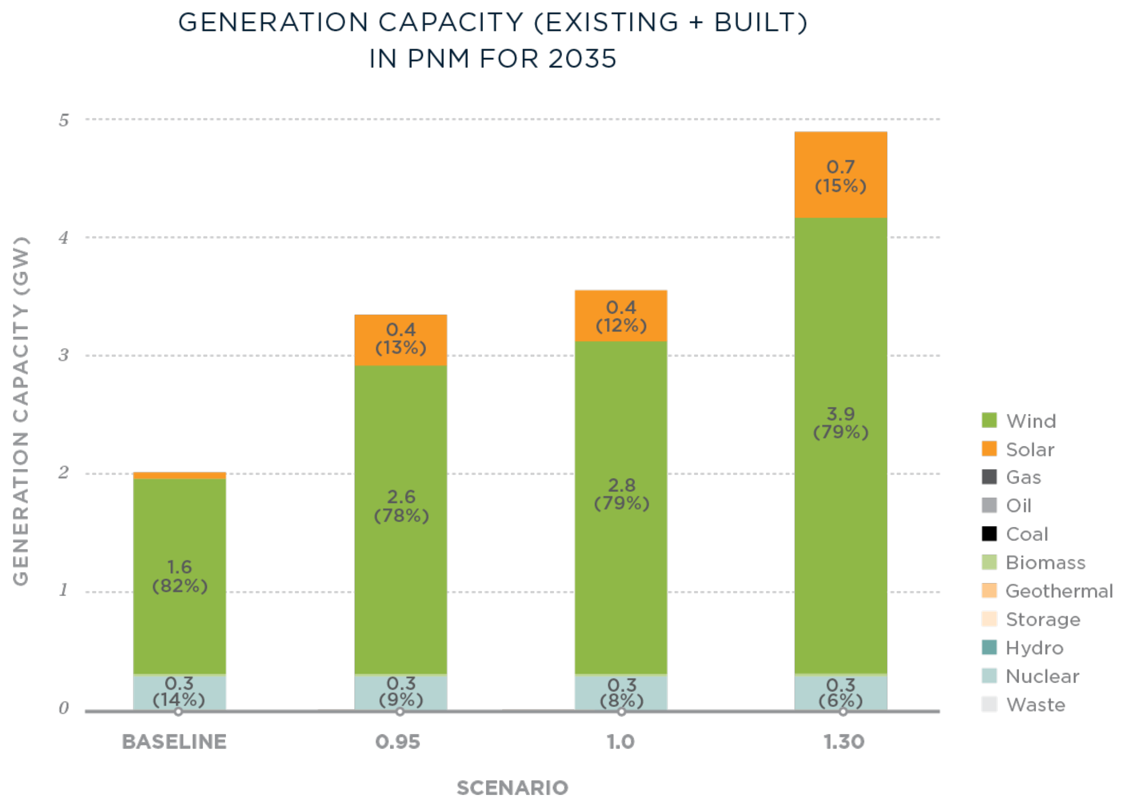
# $50\%$ $CO_2$ emissions reductions WECC-wide, net zero PNM

## Scenarios

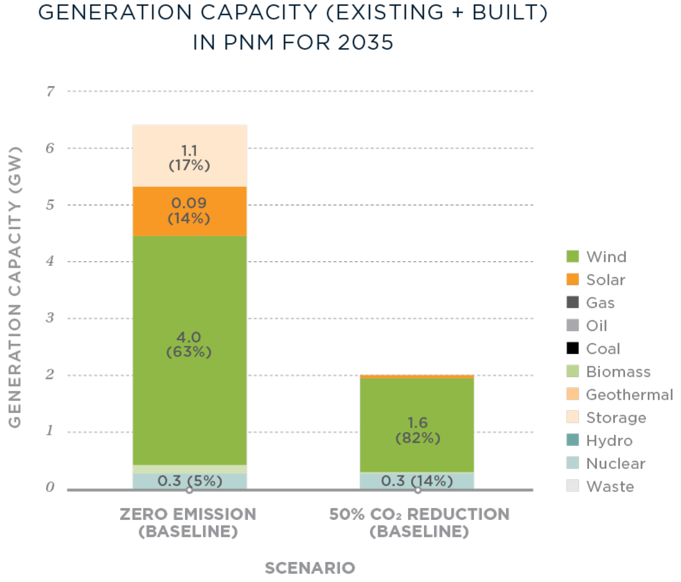
- 50% $CO_2$ emissions reductions emissions WECC wide
- PNM net zero, 90% RPS in CA
- Sensitivity on generation/load ratio in PNM
  - Baseline (.6, net importer)
  - 0.95, 1, 1.3 (net exporter)

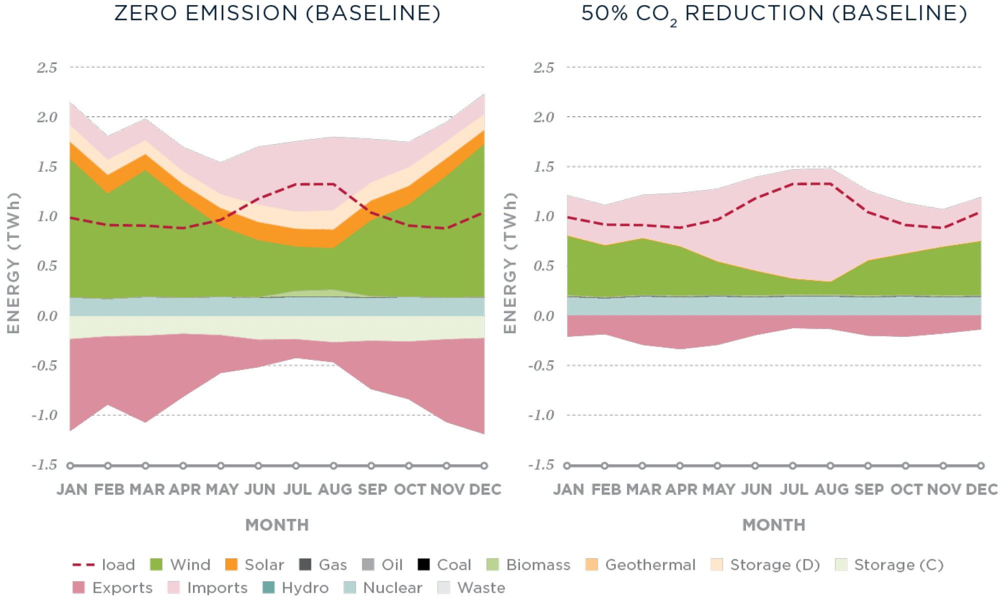
## Key findings

- Cost range ($/kWh): 8, 21, 23, 36
- Installed capacity range: 2.4 – 5.3 GW
- **Wind dominant (~70%)**
- **No exports market (baseline)**
- **No storage deployed**
- LMPs show roughly the same values across cases



# Comparison with the case in which the entire WECC emits zero GHGs




## Assumptions

Both scenarios consider a zero emissions policy in PNM. The "Zero emissions (baseline)" scenario considers a WECC-wide zero emissions policy, whereas the "50% $CO_2$ reduction (baseline)" considers 1.3 Gigatonness $CO_2$/year WECC-wide. Both have the baseline demand.

## Key findings

- PNM requires up to 225% less installed generation capacity with no solar and no storage in the "50% $CO_2$ reduction (baseline)"
- In the summer, the "50% $CO_2$ reduction" scenario visualizes PNM extremely reliant upon imports, especially in summer.
- In the "Zero emissions" scenario, the solar-storage and wind synergy diminish the needs for imports in the summer.

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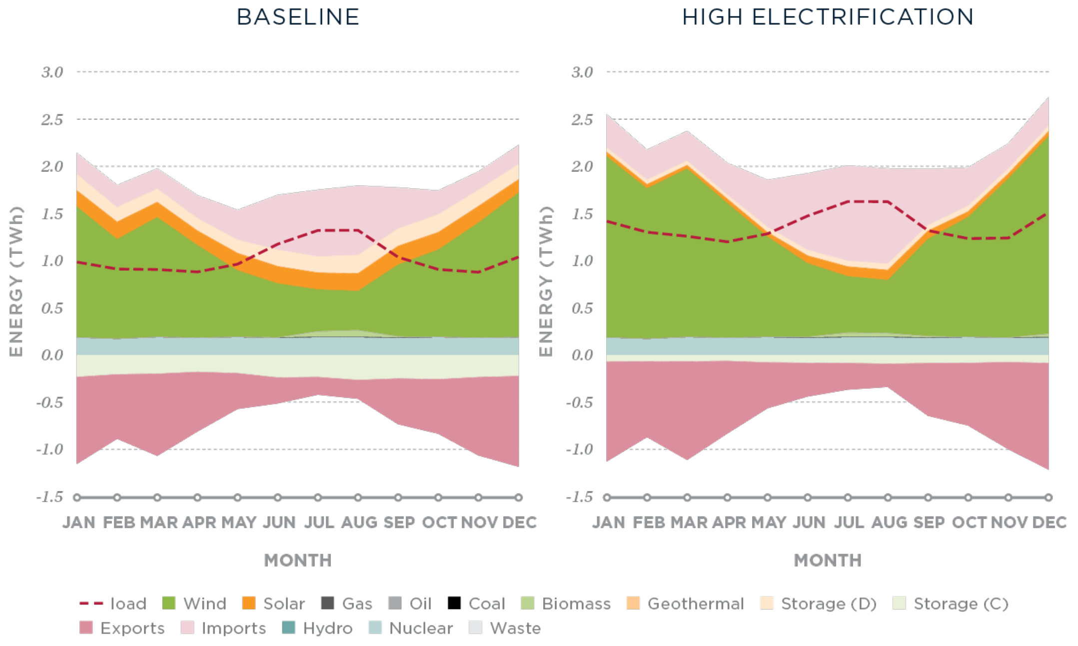
**RESULTS**

# High electrification with zero emissions for the WECC and PNM

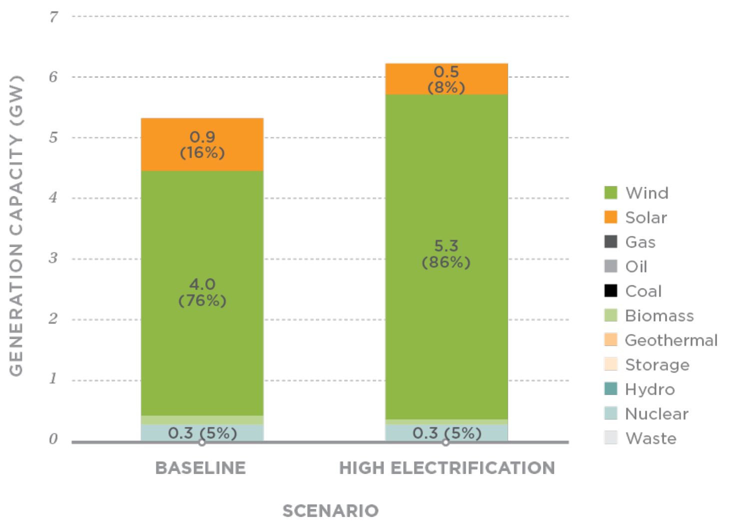
The impact of High Electrification on required resources compared with the Baseline demand

## Key finding

Significantly more wind capacity (5.3 GW) is required going from the baseline demand scenario to the high-electrification demand scenario. Storage and solar quantities are less affected.




GENERATION CAPACITY (EXISTING + BUILT) IN PNM FOR 2035



# Comparison of key attributes across scenarios

## (High electrification, net zero WECC wide)

### Description of scenarios in the table

- High electrification demand
- Zero emissions for the WECC and PNM
- Selected sensitivity cases (informed by the most interesting cases from prior results)

| Scenario | Payment to serve PNM's load * | WECC cost (billions USD) | Gen/demand | Curtailment | PNM cost (millions USD) | PNM cost as % | LDES duration |
|---|---|---|---|---|---|---|---|
| (base) WECC-connected | 100% | 68 | 1.13 | 13% | 1,514 | 100% | 6.2 |
| Islanded | 103% | 0 | 1 | 37% | 2,623 | 173% | 6.5 |
| LDES 10 USD/MWh | 56% | 50 | 1.11 | 12% | 1,443 | 95% | 13.3 |
| LDES 90 USD/MWh | 79% | 60 | 1.15 | 11% | 1,519 | 100% | 7.1 |
| Wind/solar = 0.46 (solar dominant) | 69% | 75 | 1.24 | 31% | 2,863 | 189% | 6.8 |
| Gen/demand = 0.95 | 100% | 68 | 0.95 | 30% | 1,514 | 100% | 6.2 |
| Gen/demand = 1 | 100% | 68 | 1 | 25% | 1,514 | 100% | 6.2 |
| Gen/demand = 1.3 | 99% | 68 | 1.3 | 1% | 1,553 | 103% | 6.6 |

### Key Highlights

- PNM would require at most 13.3 hours of storage duration (LDES $10/MWh scenario). Otherwise, the remaining scenarios show 6.2 – 7.1 hours of duration (almost double compared to the cases with 80% $CO_2$ reductions WECC-wide).
- Cost sensitivities on storage energy capacity ($10/MWh and $90/MWh) result in the highest cost savings for PNM (27% and 6% lower total costs with respect to the baseline).
- In terms of payments for electricity served in PNM (considering imports and exports payments), costs sensitivities on LDES as well as a solar dominant PNM (54% solar, 25% wind, 16% storage) results in electricity payment savings (44% - 21% in savings).

** "Payment to serve PNM's load" is an approximation of the net cost to PNM's load, accounting for imports and exports, and acknowledging that SWITCH is fundamentally a regional capacity expansion modeling tool.*

**RESULTS**

# High electrification with 80% $CO_2$ emissions reductions WECC-wide and PNM net zero emissions

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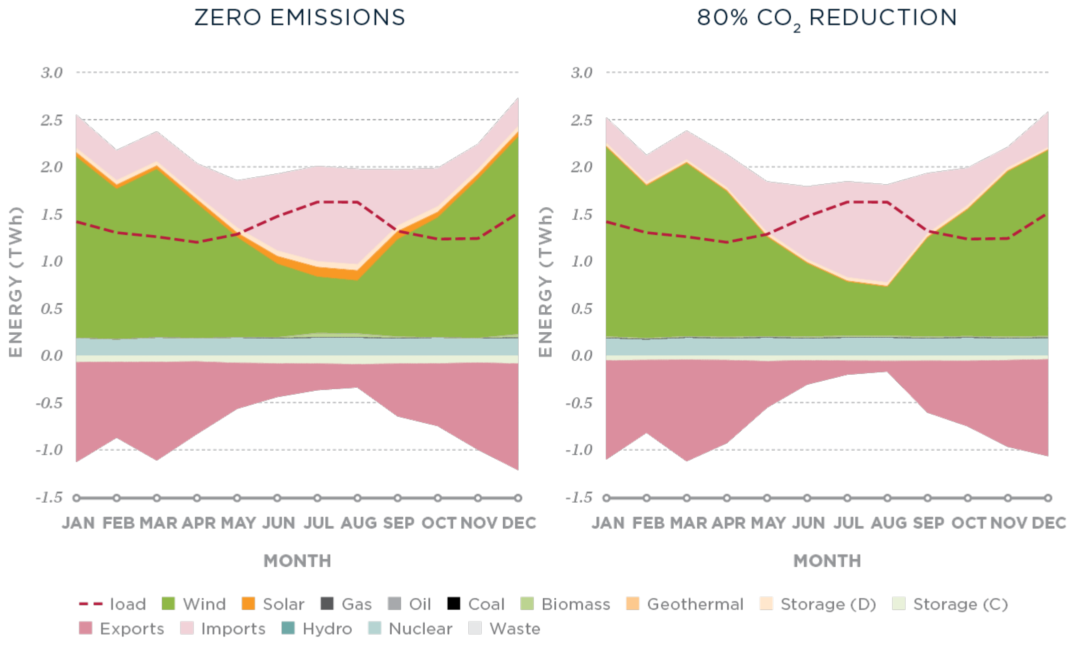
# Comparing the WECC wide zero GHG case with an 80% WECC wide GHG reductions case

## Assumptions

Both scenarios consider a zero emissions policy in PNM. The "Zero emissions" scenario considers a WECC-wide zero emissions policy, whereas the "80% $CO_2$ reduction" considers 80% GHG emissions reductions across the WECC (equivalent to 5.3 Gigatonnes $CO_2$/year). Both use the high electrification demand.

## Key findings

- Solar capacity is slightly required (0.5 GW) in the "Zero emissions" scenario as compared to almost zero solar capacity in the "80% $CO_2$ reduction scenario".
- PNM is wind-dominant (~85 %) in both scenarios.




GENERATION CAPACITY (EXISTING + BUILT) IN PNM FOR 2035

GridLAB

# Comparison of key attributes across scenarios

## (High electrification, 80% GHG reductions in WECC, PNM is net zero)

### Description of scenarios in the table

- High electrification
- 80% emissions reduction WECC-wide compared to 2005, coal retirement, allow gas to stay online
- Build new solar/wind/storage
- Net zero emissions for PNM
- Selected sensitivity cases (informed by the most interesting cases from prior results)

| Scenario | Payment to serve PNM's load | WECC cost (billions USD) | Gen/demand | Curtailment | PNM cost (millions USD) | PNM cost as % | LDES duration (hours) |
|---|---|---|---|---|---|---|---|
| (base) WECC-connected | 100% | 48 | 1.11 | 5% | 1,289 | 100% | 3.9 |
| PNM Islanded | 147% | 0 | 1 | 37% | 2,623 | 204% | 6.5 |
| LDES 10 USD/MW | 64% | 42 | 1.06 | 4% | 1,130 | 88% | 8.8 |
| LDES 90 USD/MWh | 88% | 46 | 1.11 | 5% | 1,230 | 95% | 3.9 |
| Wind/solar = 30 | 99% | 48 | 1.13 | 5% | 1,305 | 101% | 3.9 |
| Wind/solar = 50 | 100% | 48 | 1.13 | 5% | 1,295 | 100% | 3.9 |
| gen/demand = 0.95 | 101% | 48 | 0.95 | 19% | 1,247 | 97% | 3.9 |
| gen/demand = 1 | 100% | 48 | 1 | 17% | 1,289 | 100% | 3.9 |
| gen/demand = 1.3 | 93% | 48 | 1.3 | 1% | 1,447 | 112% | 3.9 |

### Highlights

- PNM requires at most 6.5 to 8.8 hours of storage duration (islanded and LDES $10/MWh scenarios). Otherwise, the rest of the scenarios show 3.9 hours of duration.
- Cost sensitivities on storage energy capacity ($10/MWh and $90/MWh) result in the highest cost savings for PNM (31% and 15% lower total costs with respect to the base).
- In terms of payments for electricity served in PNM (considering imports and exports payments), costs sensitivities on LDES as well as PNM becoming a net exporter (ratio of generation over withdrawals of 1.3) results in electricity payment savings (35% - 7% in savings respectively).
- Across most cases, the resources built in PNM are wind dominant. The exception is the islanded case in which it is optimal to deploy a solar dominant grid (60% solar, 22% storage, and 10% wind).