PNM Integrated Resource Planning (IRP) Study

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Disclaimer

The study analysis provided in this presentation is based on the assumptions and data availability. The views expressed in this presentation are solely those of the presenters and do not necessarily represent those of New Mexico State University.

This study did not receive any grant from any funding agency in the public, commercial, or non-profit sectors.

Please contact the presenters for more information about the modeling, simulation, analysis, and conclusions.

Purposes

- Customized IRP engine to provide a computationally tractable way of performing IRP analysis
  - Eliminating binary variables
  - Decomposition methods such as Benders, Lagrangian relaxation, and progressive hedging cannot guarantee faster convergence
- Understand the marginal value of integrating new resources in PNM
  - A lot of moving targets for integrating new resources
    - Too many combinations of technologies and the cost of constructing and operating new resources are changing
  - Bottom line of integrating a new resource is that its marginal value> its marginal cost (e.g., levelized cost of energy*) or positive net benefit
- The marginal value of new resources are inter-dependent
  - Quantify the marginal values under different circumstances
  - Understand what could impact the optimal mix of new resources integration

*The levelized cost of electricity (LCOE) Measures lifetime costs divided by energy production.

$$\mathrm{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}}$$

Methodology

- Adding conceptual resources to understand the marginal values of following resources:(1) Solar (2) Wind (3) Energy storage (4-hour duration, 8-hour duration, 70-hour duration)
- 20 years (2023-2042) 8760 hours Cost minimization
- Monetize unserved energy with **Value of Lost Load (VOLL)** ($2,000/MWh, $5,000/MWh)
  - Imply costs associated with an interruption of electricity supply.

2018 comparison of scarcity pricing policy per ISO/RTO [1]

Market	Resource Adequacy Construct	Price Cap ($/MWh)	Generator Offer Cap ($/MWh)	Reserves Depletion Pricing	Relationship to VOLL
ISO-NE	Forward capacity market	Highest shortage price is $2,350	$1,000	Additive penalty factors by type	Price cap + capacity market performance incentives = VOLL
PJM	Forward capacity market	$3,700	$2,000	Additive penalty factors and step functions by type	Price cap + capacity market performance incentives = VOLL
NYISO	Prompt capacity market	None, but highest shortage price is $2,775	$1,000	Additive penalty factors and step functions by type	None
CAISO	Developed through regulatory process with ISO procurement backstop	None, but highest shortage price is $1,000	$1,000	Additive penalty factors and step functions by type	None
SPP	Reserve margin requirement for utilities	$50,000	$1,000	Additive penalty factors and step functions by type	None
MISO	Voluntary capacity market	$3,500	$1,000	Hybrid additive penalty factors and function of VOLLxLOLP	Price cap = residential VOLL
ERCOT	Energy only	Highest shortage price is $9,000	$9,000	Step function for regulation; economic demand curves for operating reserves	Price cap = VOLL

[1] CAISO, “Efficient Market Prices During Tight Supply Conditions: Scarcity Pricing Market Design”, available at /http://www.caiso.com/InitiativeDocuments/GDSAssociatesReport-EfficientMarketPricesDuringTightSupplyConditions-IssuesandRecommendations.pdf

Base Model

$$Min: \sum_{\forall g,t}(C_g+E_g)p_{g,t} + \sum_{\forall t} VOLL * s_t$$

Subject to:

$$\sum_{\forall g} p_{g,t} + \sum_{es} p_{es,t}^{discharge} - \sum_{es} p_{es,t}^{charge} + s_t = D_t \ \forall t$$

$$0 \le p_{g,t} \le P_{g,t}^{max} \ \forall g,t$$

$$0 \le p_{es,t}^{charge} \le P_{es}^{Charge} \ \forall \ es,t$$

$$0 \le p_{es,t}^{Discharge} \le P_{es}^{Discharge} \ \forall es,t$$

$$soc_{es,t} + p_{es,t}^{charge}\eta_c - p_{es,t}^{Discharge}/\eta_d = soc_{es,t+1} \ \forall es,t$$

$$\underline{SOC_{es}} \le soc_{es,t} \le \overline{SOC_{es}} \ \forall es,t$$

Nomenlature

Indices:

g	Index of generators.
t	Index of time intervals.
es	Index of energy storage
Parameters	
D_t	Electric demand at interval t
C_g, E_g	Energy cost and emission cost
$P_{g,t}^{max}$	Maximum capacity of generator g. (Renewable maximum outputs are updated by intervals.)
$P_{es}^{Charge}, P_{es}^{Discharge}$	Maximum Charge and discharge rate of energy storage es
$\underline{SOC_{es}}, \overline{SOC_{es}}$	Minimum and maximum state of charge limits
$\eta_{c,es}, \eta_{d,es}$	Charge and discharge efficiency of energy storage es
Decision variables	
$p_{g,t}$	Power output of generator g at interval t
$soc_{es,t}$	State of charge of energy storage es at interval t

Model with Conceptual Resources

$$Min: \sum_{\forall g,t}(C_g+E_g)p_{g,t} + \sum_{\forall t} VOLL * s_t$$

Subject to:

$$\sum_{\forall g} p_{g,t} + \sum_{es} p_{es,t}^{discharge} - \sum_{es} p_{es,t}^{charge} + p_t^{CS} + p_t^{CW} + p_t^{CES,discharge} - p_t^{CES,charge} + s_t = D_t \ \forall t$$

$$0 \le p_{g,t} \le P_{g,t}^{max} \ \forall g,t$$

$$0 \le p_{es,t}^{charge} \le P_{es}^{Charge} \ \forall\, es,t$$

$$0 \le p_{es,t}^{Discharge} \le P_{es}^{Discharge} \ \forall es,t$$

$$0 \le p_{es,t}^{charge} \le P_{es}^{Charge} \ \forall\, es,t$$

$$0 \le p_{es,t}^{Discharge} \le P_{es}^{Discharge} \ \forall es,t$$

$$soc_{es,t} + p_{es,t}^{charge}\eta_{c,es} - p_{es,t}^{Discharge}/\eta_{d,es} = soc_{es,t+1} \ \forall es,t$$

$$\underline{SOC_{es}} \le soc_{es,t} \le \overline{SOC_{es}} \ \forall es,t$$

$$0 \le p_t^{CS} \le dummy_p{}^{CS,max} * \pi_t^{CS} \forall t$$

$$0 \le p_t^{CW} \le dummy_p{}^{CW,max} * \pi_t^{CW} \ \forall t$$

$$0 \le p_t^{CES,discharge} \le dummy\_p^{CES,discahrge\_max} \ \forall\, t$$

$$0 \le p_t^{CES,charge} \le P^{CES,charge} \ \forall\, t$$

$$soc_t^{CES} + p_t^{CES,charge}\eta_{c,CES} - p_t^{CES,discharge}/\eta_{d,CES} = soc_{t+1}^{CES} \ \forall t$$

$$\underline{SOC_{CES}} \le soc_t^{CES} \le P^{CES,discahrge} * Duration \ \forall\, t$$

$$dummy\_p^{CES,discahrge\_max} \le P^{CES,discahrge\_max} \ (\lambda^{CES})$$

$$dummy\_p^{CS,max} \le P^{CS,max} \ \ (\lambda^{CS})$$

$$dummy\_p^{CW,max} \le P^{CW,max} \ \ (\lambda^{CW})$$

Nomenlature

Indices:

g	Index of generators.
t	Index of time intervals.
es	Index of energy storage
ces	Conceptual energy storage
cs	Conceptual solar
cw	Conceptual wind

Parameters

D_t	Electric demand at interval t
$P_{g,t}^{max}$	Maximum capacity of generator *g*. (Renewable maximum outputs are updated by intervals.)
P_{es}^{Charge}, $P_{es}^{Discharge}$	Maximum Charge and discharge rate of energy storage *es*
$\underline{SOC_{es}}, \overline{SOC_{es}}$	Minimum and maximum state of charge limits
$\eta_{c,es}, \eta_{d,es}$	Charge and discharge efficiency of energy storage *es*
π_t^{CS}, π_t^{CS}	Scaled average solar and wind outputs of existing solar and wind per MW capacity

Decision variables

$p_{g,t}$	Power output of generator *g* at interval *t*
$soc_{es,t}$	State of charge of energy storage *es* at interval *t*

Shadow prices/dual variables

λ^{CES}	Marginal value of conceptual energy storage, in \$/MW
λ^{CS}	Marginal value of conceptual solar, in \$/MW
λ^{CW}	Marginal value of conceptual wind, in \$/MW

Simulation results

Simulation Environment

Simulation engine: customized IRP analysis engine
Software platform: AIMMS 4.96
Operating system: Windows 10 Pro
Solver: CPLEX 20.1
CPU: Intel i7- 10700K
RAM: 64 GB
Average size of the problem (requires ~16-32GB RAM):
- # of variables: ~10,000,000
- # of non-zeros: ~26,400,000
- # of constraints: ~11,000,000

Simulation computational performance:~2,000s average

Existing Generation and ES Portfolio

- Coal: 200 MW (retire 2024*)
- Nuclear: 288 MW
- Natural Gas: 1,002 MW (146MW retires by 2030)
- Solar: 1,477 MW
- Wind: 658 MW
- Geothermal: 11MW
- Storage: 620MW (4-hour duration)

* Prior to NM Supreme Court decision

Assumptions

- Renewable outputs
  - Normal scenarios: based on PNM provided data
  - Extreme scenarios:
    - Input is the original 20-year data set (Normal Scenarios)
    - Step a 10-day window through 365 days
    - From each window, use exact data from the year with the lowest renewables production
    - Each site is sampled independently.
    - Mean energy production is 23% lower than in the original.
    - NM Wind Center experiences three droughts in this one-year data set vs. 0.8 per year in the original data.
    - Its longest drought is 70 hours vs 46 hours in the original data.
    - Threshold for defining a drought is hourly capacity factor < 0.1 of nameplate.
    - This data used in simulation with original load data.

Assumptions

- Fuel Cost, emission cost: based on the reference price or costs provided by PNM
- Energy storage: perfect foresight vs imperfect foresight
- The output scenarios of conceptual wind/solar depend on the average output scenario of existing wind/solar units outputs
- Energy storage round trip efficiency: 86%
- Network constraints are not considered

Wind and Solar Marginal Value-No New Storage

New Solar Capacity

Wind Marginal Benefit
$/MWh

New Wind

	0	400	800	1200	1600	2000	2400	2800	3200	3600	4000
0	192.2	186.9	183.3	181.0	178.9	177.4	176.0	174.8	173.8	173.1	172.4
200	155.3	151.0	148.2	146.1	144.5	142.9	141.9	140.9	140.2	139.5	139.0
400	127.3	123.8	121.4	119.7	118.2	117.0	116.1	115.3	114.8	114.1	113.7
600	103.1	100.1	98.1	96.5	95.4	94.5	93.7	93.2	92.8	92.3	91.9
800	83.0	80.5	78.9	77.8	76.9	76.2	75.6	75.1	74.8	74.4	74.1
1000	66.5	64.4	63.1	62.1	61.4	60.7	60.2	59.8	59.5	59.2	58.9
1200	54.0	52.2	51.0	50.2	49.5	48.9	48.5	48.2	47.9	47.6	47.4
1400	43.7	42.1	41.1	40.4	39.8	39.4	39.1	38.8	38.5	38.3	38.1
1600	35.7	34.5	33.6	33.0	32.5	32.2	31.9	31.7	31.4	31.3	31.1
1800	29.4	28.2	27.6	27.1	26.7	26.4	26.1	25.8	25.6	25.5	25.3
2000	24.3	23.4	22.7	22.3	21.9	21.7	21.4	21.2	21.1	21.0	20.9

Solar Marginal Benefit
$/MWh

New Wind

0	22.7	14.1	9.7	7.4	5.8	4.7	3.8	3.2	2.7	2.3	2.0
200	19.5	12.1	8.5	6.4	5.0	4.0	3.2	2.7	2.3	2.0	1.7
400	17.0	10.5	7.3	5.5	4.3	3.4	2.8	2.3	2.0	1.7	1.4
600	15.0	9.2	6.4	4.8	3.7	3.0	2.4	2.0	1.7	1.5	1.2
800	13.3	8.1	5.6	4.2	3.3	2.6	2.1	1.8	1.5	1.3	1.1
1000	12.0	7.3	5.0	3.8	2.9	2.3	1.9	1.6	1.3	1.1	1.0
1200	10.8	6.6	4.5	3.3	2.6	2.1	1.7	1.4	1.2	1.0	0.8
1400	9.8	5.9	4.1	3.0	2.3	1.8	1.5	1.3	1.0	0.9	0.7
1600	8.9	5.3	3.7	2.7	2.1	1.7	1.4	1.1	0.9	0.8	0.7
1800	8.2	4.8	3.4	2.4	1.9	1.5	1.2	1.0	0.8	0.7	0.6
2000	7.5	4.4	3.0	2.2	1.7	1.4	1.1	0.9	0.8	0.7	0.5

Assumptions

(1) VOLL=$2,000/MWh

(2) Only with existing generation and energy storage portfolio. No newly added storage

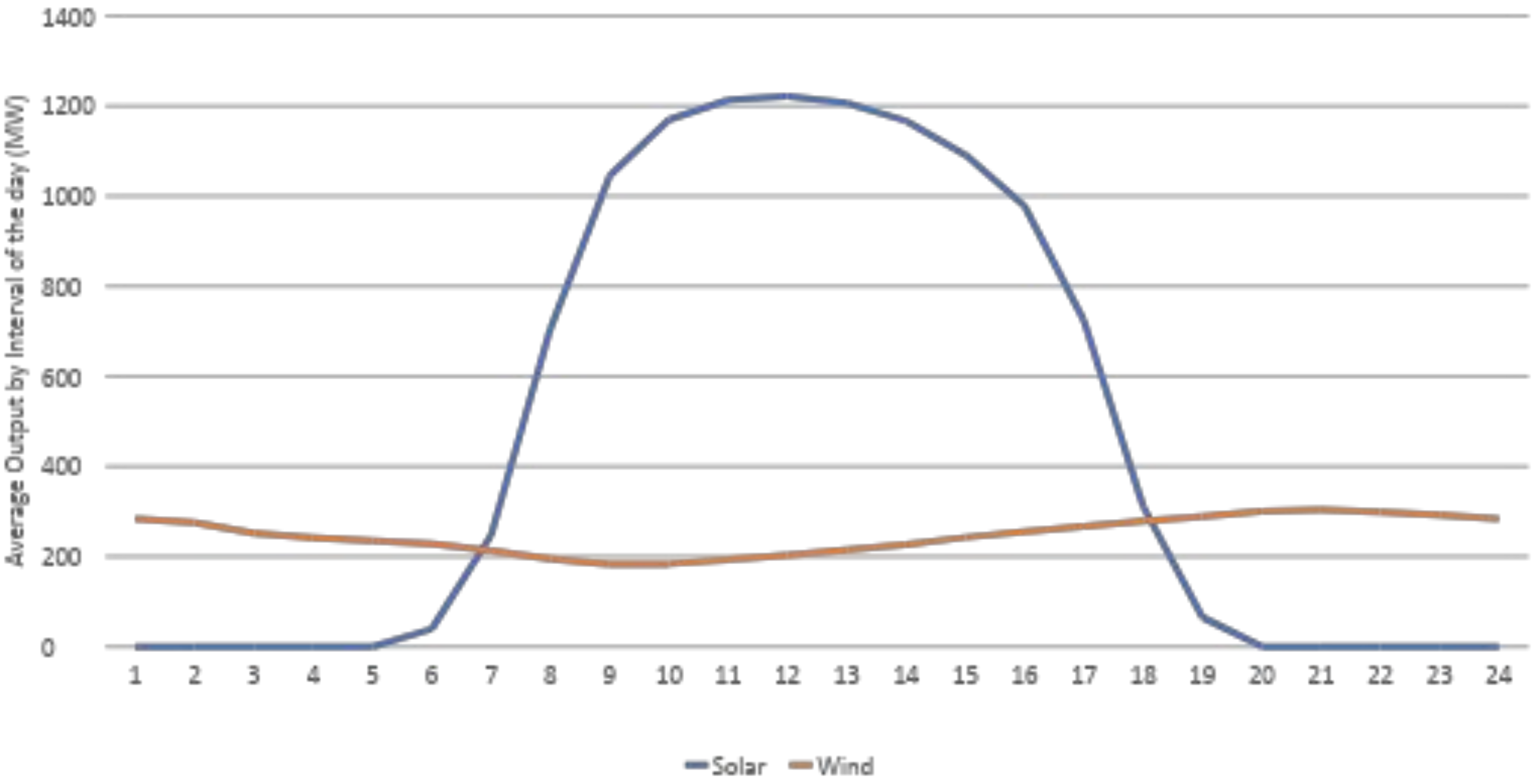
Takeaways

(1) Without newly added storage, wind capacity has much higher marginal value than solar capacity.

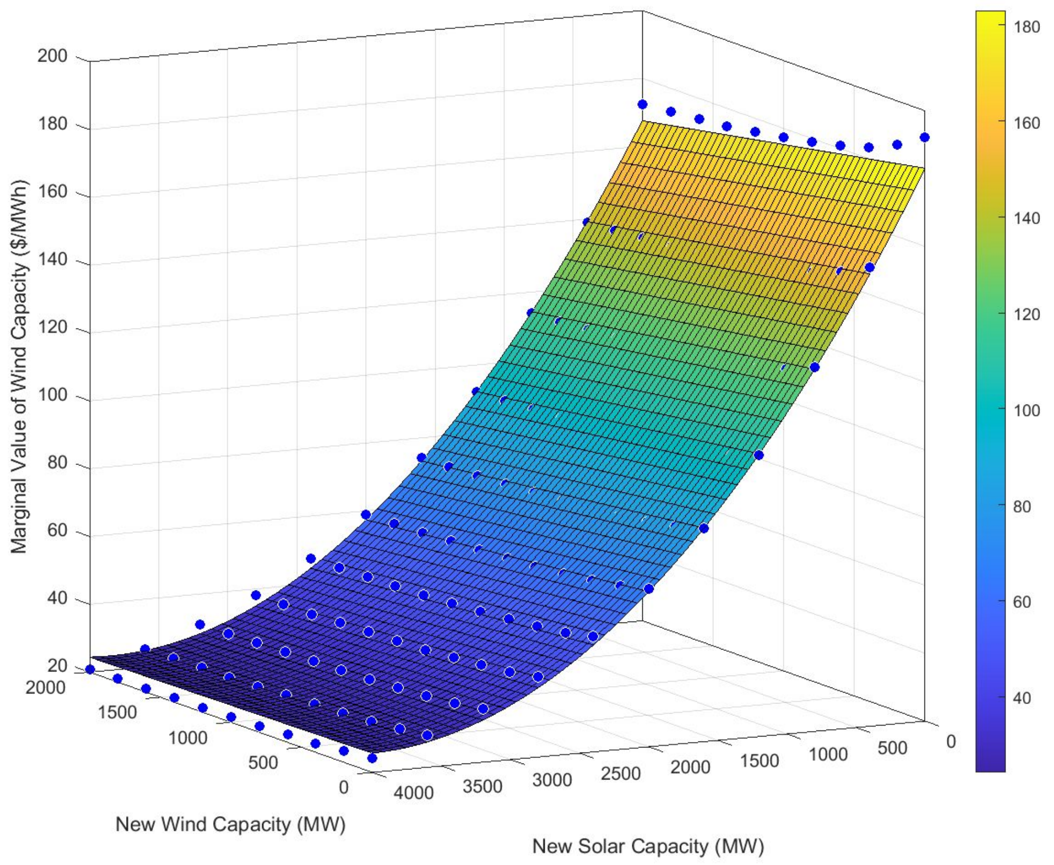
(2) As the wind capacity increases, the marginal value of wind capacity goes down.

(3) Adding solar capacity only slightly decreases the marginal value of wind.

Average System-wide Solar/Wind Outputs



Surface plot and Fit Function



sf(x,y) = p00 + p10*x + p01*y + p11*x*y + p02*y^2

Coefficients (with 95% confidence bounds):

p00 = 183 (181.3, 184.7)

p10 = -0.007767 (-0.009076, -0.006457)

p01 = -0.07795 (-0.07937, -0.07654)

p11 = 1.785e-06 (1.232e-06, 2.339e-06)

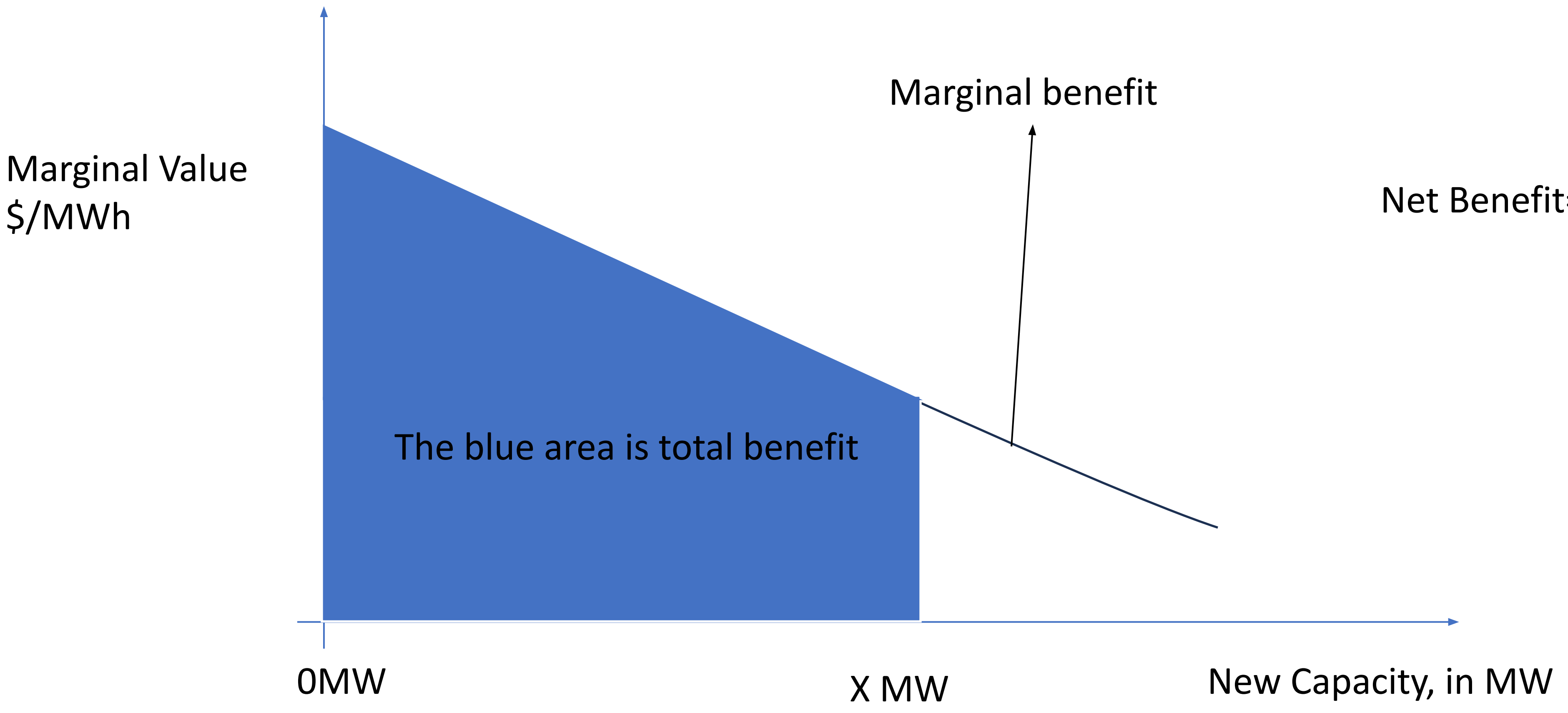
p02 = 9.653e-06 (9.34e-06, 9.966e-06)

x: new solar capacity

y: new wind capacity

sf(x,y): wind marginal value as a function of new solar and wind capacity

Marginal Benefit, Total Benefit, Net Benefit



Net Benefit=Total benefit-X*LCOE

Wind and Solar Marginal Value-No Added Storage

New Solar Capacity

New Wind

Wind Marginal Benefit $/MWh

	0	400	800	1200	1600	2000	2400	2800	3200	3600	4000
0	466.3	453.9	445.3	439.6	434.8	430.9	427.7	424.9	422.5	420.6	419.0
200	374.0	363.7	357.1	352.2	348.3	344.5	342.0	339.8	338.0	336.4	335.1
400	304.5	296.2	290.4	286.3	282.8	280.0	277.8	276.0	274.6	273.1	272.1
600	244.9	237.9	233.2	229.6	227.0	224.9	223.0	221.7	220.6	219.6	218.7
800	196.5	190.7	186.9	184.3	182.2	180.5	179.1	178.1	177.2	176.3	175.6
1000	156.9	152.1	148.9	146.7	144.9	143.3	142.2	141.2	140.4	139.7	139.1
1200	127.1	123.0	120.2	118.3	116.6	115.2	114.3	113.5	112.8	112.2	111.6
1400	102.6	99.1	96.8	94.9	93.6	92.7	91.9	91.2	90.5	90.0	89.6
1600	84.0	81.0	78.9	77.6	76.5	75.7	75.0	74.4	73.9	73.5	73.1
1800	69.0	66.3	64.8	63.5	62.7	61.9	61.1	60.6	60.1	59.8	59.5
2000	56.9	54.8	53.2	52.2	51.4	50.8	50.2	49.7	49.5	49.2	48.9

Solar Marginal Benefit $/MWh

New Wind

	0	400	800	1200	1600	2000	2400	2800	3200	3600	4000
0	52.9	33.1	22.8	17.5	13.7	11.0	9.1	7.5	6.3	5.5	4.7
200	45.5	28.3	19.9	15.0	11.8	9.3	7.7	6.4	5.5	4.7	4.0
400	39.6	24.6	17.2	13.0	10.1	8.1	6.5	5.5	4.7	4.0	3.4
600	34.8	21.5	15.0	11.2	8.8	7.1	5.7	4.8	4.1	3.5	2.9
800	30.9	19.0	13.1	9.8	7.7	6.1	5.0	4.3	3.6	3.0	2.6
1000	27.9	17.0	11.7	8.8	6.8	5.4	4.4	3.8	3.1	2.7	2.2
1200	25.2	15.3	10.5	7.9	6.1	4.8	4.0	3.3	2.7	2.3	2.0
1400	22.8	13.7	9.5	7.0	5.4	4.3	3.6	3.0	2.4	2.1	1.7
1600	20.7	12.4	8.6	6.3	4.9	3.9	3.2	2.7	2.2	1.9	1.5
1800	19.0	11.2	7.8	5.7	4.5	3.6	2.9	2.3	2.0	1.7	1.4
2000	17.4	10.3	7.1	5.3	4.1	3.2	2.6	2.1	1.8	1.5	1.3

Assumptions

(1) VOLL=$5,000/MWh

(2) Only with existing generation portfolio. No newly added storage

Takeaways

(1) Marginal value is primarily driven by unserved energy and VOLL.

Wind and Solar Marginal Value- 1500MW 70 Hours Energy Storage

New Solar Capacity

New Wind

Wind Marginal Benefit $/MWh

	0	200	400	600	800	1000
0	66.1	49.5	17.0	10.2	7.6	1.5
100	45.9	29.4	10.3	8.2	5.8	0.8
200	31.1	11.3	8.6	6.2	0.7	0.6
300	23.6	8.9	7.0	5.7	0.6	0.5
400	14.1	7.5	6.1	5.0	0.5	0.3
500	7.7	6.8	5.6	0.5	0.4	0.2
600	7.3	6.1	5.0	0.4	0.4	0.2
700	6.8	5.6	0.5	0.4	0.2	0.1
800	6.2	5.1	0.4	0.3	0.1	0.1
900	5.7	3.3	0.3	0.1	0.1	0.0

Solar Marginal Benefit $/MWh

	0	200	400	600	800	1000
0	48.8	37.2	13.0	9.5	7.5	0.8
100	37.4	26.1	9.8	8.3	6.3	0.5
200	28.2	10.8	9.0	7.0	0.6	0.4
300	23.8	9.3	7.9	6.5	0.4	0.4
400	15.2	8.5	7.0	5.9	0.4	0.2
500	8.8	7.8	6.6	0.4	0.3	0.2
600	8.5	7.2	5.9	0.4	0.3	0.1
700	8.0	6.7	0.6	0.3	0.1	0.1
800	7.4	6.1	0.4	0.3	0.1	0.0
900	6.9	4.0	0.3	0.1	0.1	0.0

New Wind

Assumptions

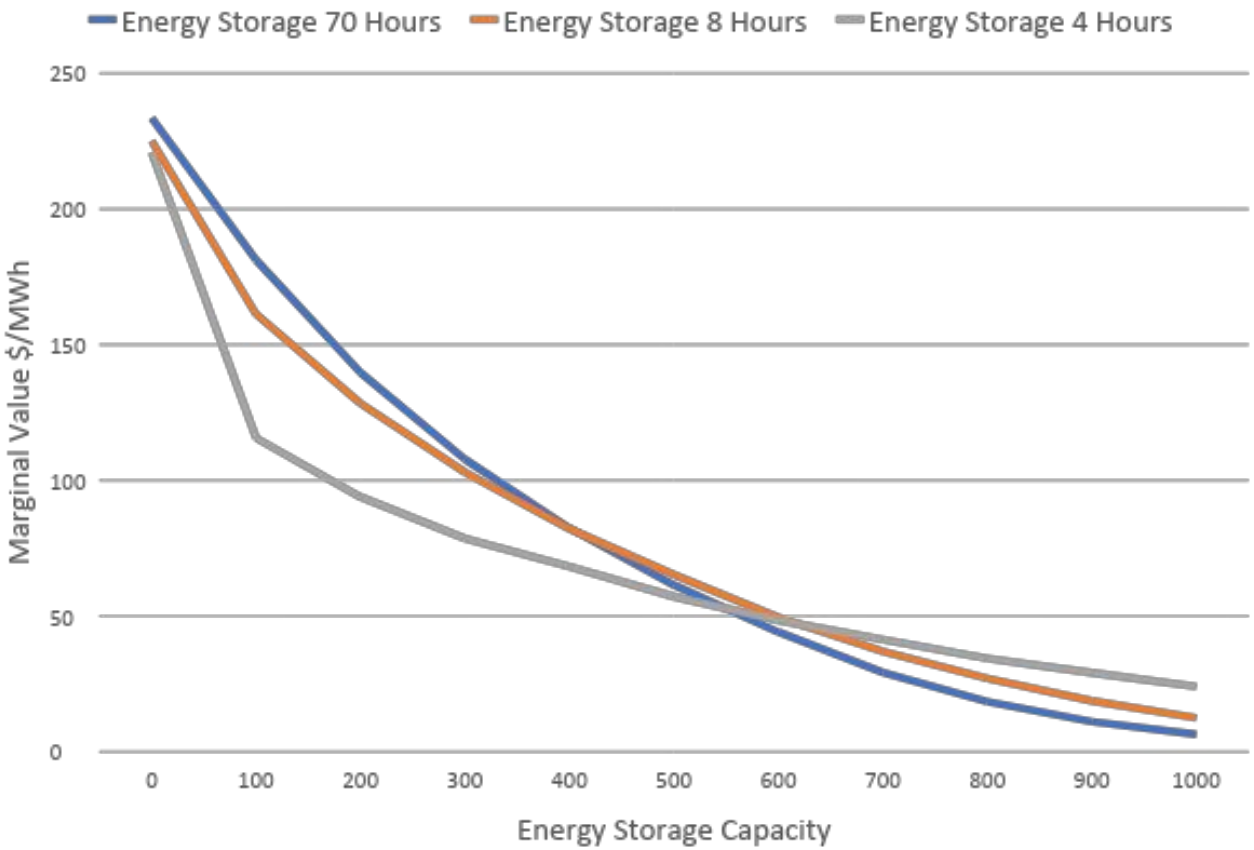
- VOLL=$2,000/MWh
- Energy storage: 1,500MW 70 Hours Duration

Takeaways

(1) Energy storage lowers the marginal value of wind and increase the marginal value of solar

(2) With adequate energy storage, adding solar capacity or wind capacity has similar effect in decreasing the marginal value of solar or wind capacity

Energy Storage Benefits-Normal Weather



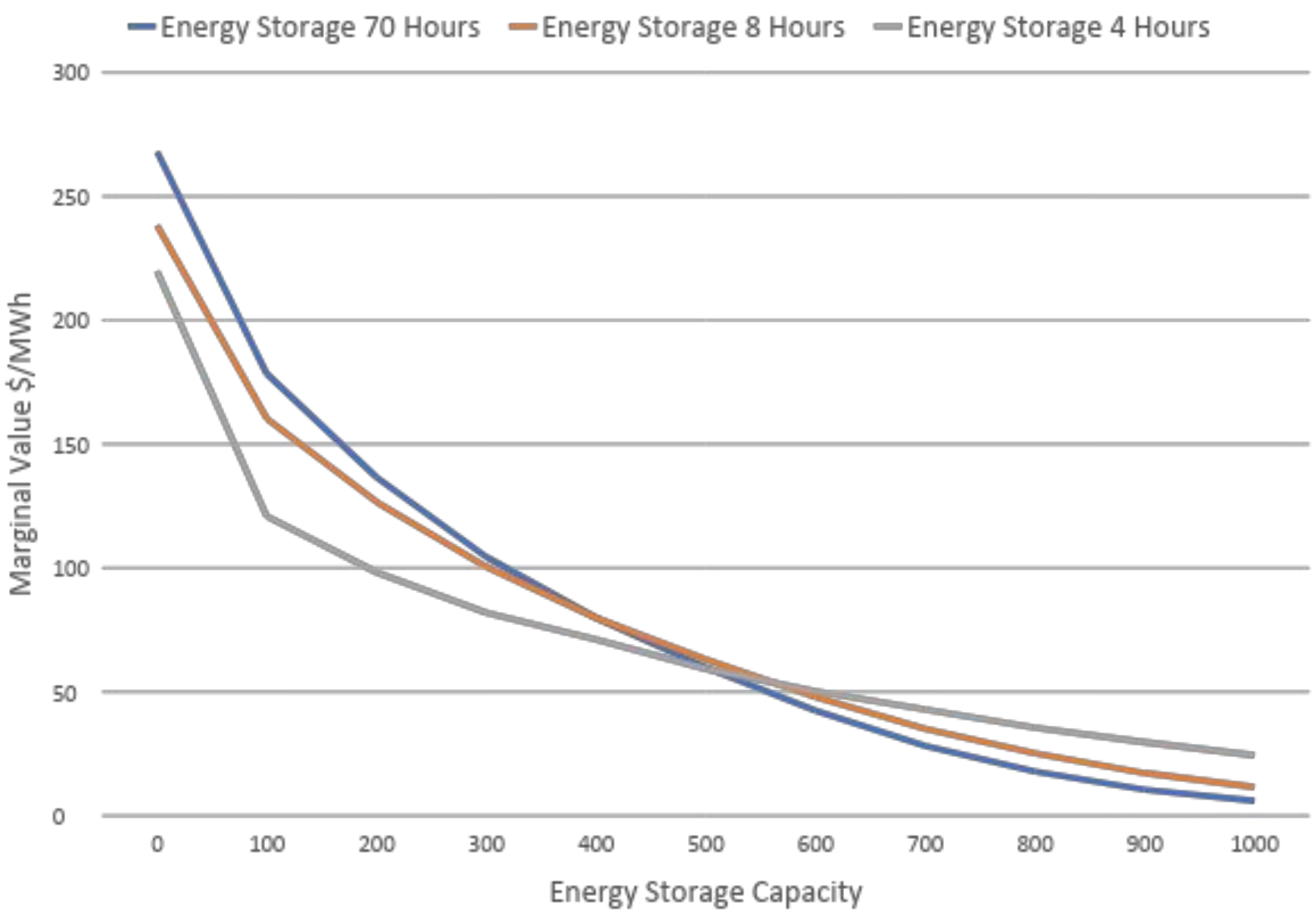
Assumptions

- VOLL=$2,000/MWh
- Newly added Wind 1,000MW
- Newly added Solar: 2,000MW
- Perfect foresight of operating energy storages

Takeaways

(1) With perfect foresight, long duration energy storage has much more benefit comparing with energy storage with shorter duration.

Energy Storage Benefits Extreme Weather



Assumptions

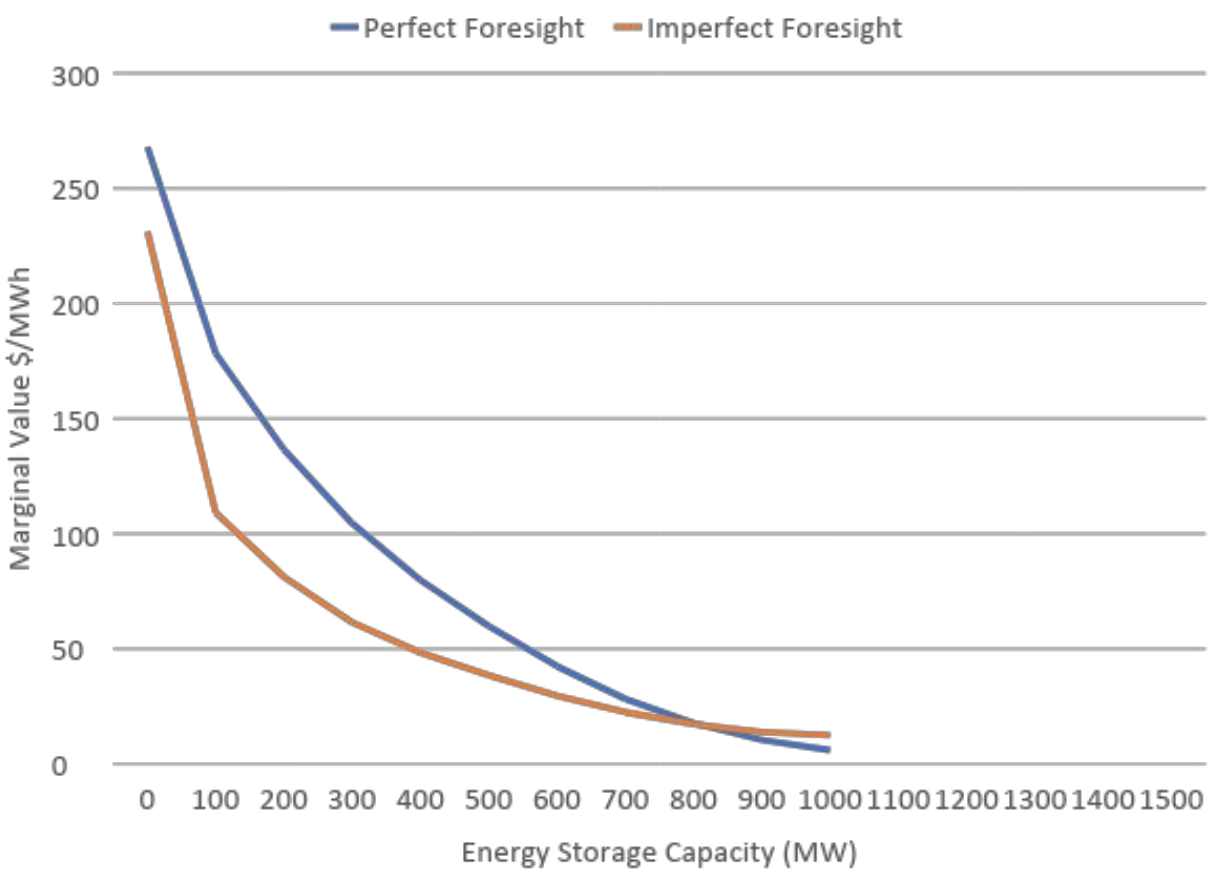
- VOLL=$2,000/MWh
- Newly added Wind 1,000MW
- Newly added Solar: 2,000MW
- Year 2039 has extreme weather that impacts the outputs of renewable

Takeaways

(1) All energy storages provide more value during extreme weather scenario than normal weather scenario.

(2) Long duration energy provides more benefit during extreme weather.

Energy Storage Benefits Imperfect Foresight



Assumptions

- VOLL=$2,000/MWh
- Newly added Wind 1,000MW
- Newly added Solar: 2,000MW
- Approximation of imperfect foresight by forcing energy storage to cycle every 6 hours.

Takeaways

(1) Imperfect foresight of operating energy storage can greatly decrease the value of energy storage.

Major Takeaways*

- Wind has higher marginal value in general comparison with solar.
- Energy storage has a better synergy with Solar energy due to solar output pattern.
- Value of long duration energy storage gets higher during extreme weather.
- The operation strategy of energy storage can greatly impact its value. Operation strategy should be carefully and realistically modeled in the IRP study.

* Note that the takeaways are based on the assumptions and data availability

Work that is important but needs to be done

- How to more realistically simulate the behavior of energy storage resources? How wind and solar capacity values are impacted by the modeling of imperfect foresight of energy storage operation?

Inputs
Weather data
Energy price
Load data
History of ES response

Train energy storage response models based on neural network

Profit Maximization

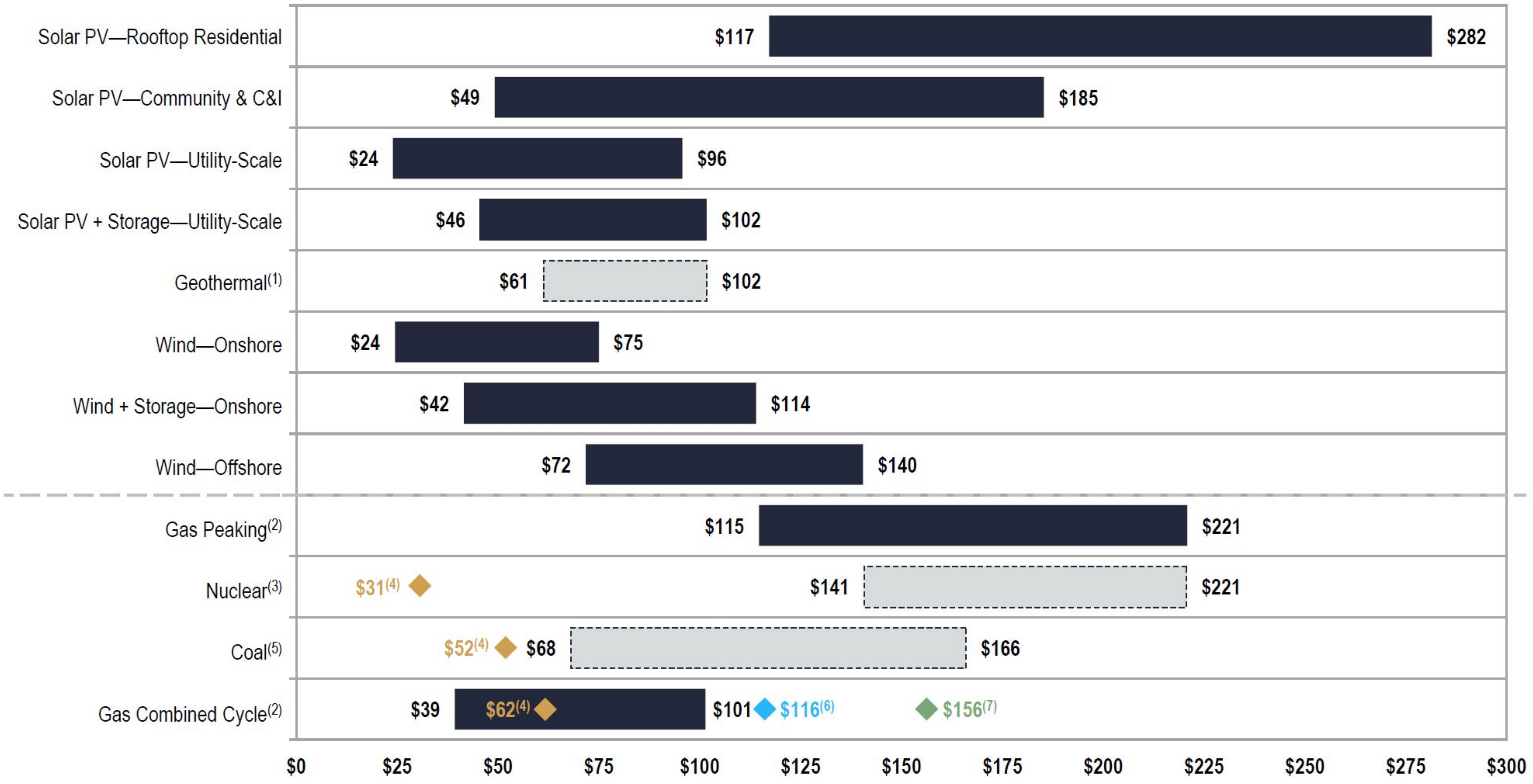
$$max\ \lambda^T y + \mu^T \mathrm{x}$$

s.t.: $$Ax = b$$

$$Gy + \mathrm{Dx} \leq \mathrm{h}$$

Agent-based energy storage response model

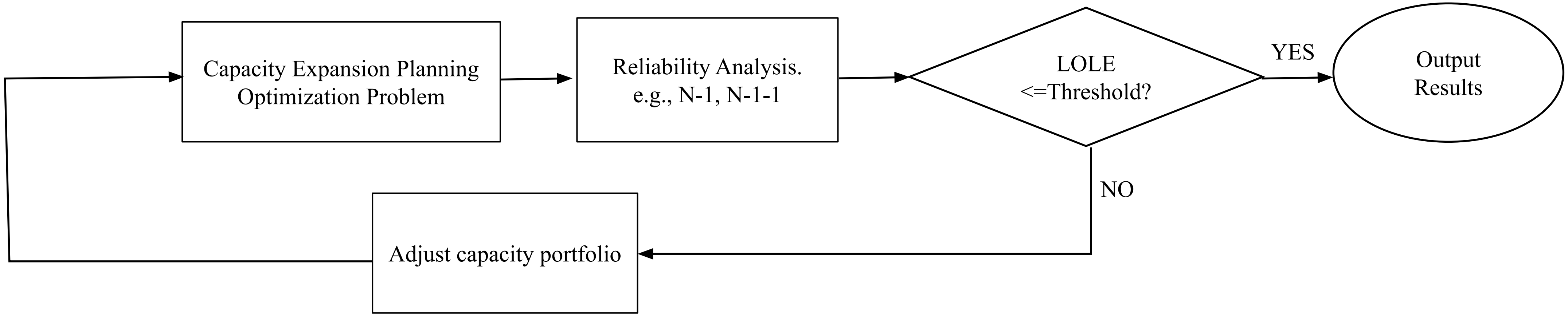
Unsubsidized LCOE by Technology[1]



[1] LAZARD,2023 Levelized Cost Of Energy+,
https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/

Final Notes

- Value of lost load should be identified.
  - LOLE and VOLL could be interchangeable. Maintaining low LOLE with high penetration of renewable energy without knowing the true cost could be an expensive illusion.
  - Promote demand response and economically incentivize demand side participation. Educate electricity consumers.
  - Survey should be done to understand the demand response potential in NM.



Final Notes

- Reserve requirements
  - Renewables can potentially provide ancillary services such as regulation reserve and contingency reserve, but it comes with significant opportunity cost and good renewable output forecasting technique.
- Supply chain risks
  - Tariffs on importing
  - Shortage in hardware
  - Retirement timeline

Final Notes

- Large-scale single energy storage vs stacked small scale energy storage
  - Economy of scale
  - Degradation cost
  - Environmental impact/water rights
  - Congestion
  - Who operates the ES?
- Operation of a decarbonized system
  - High penetration of inverter-based resources (IBRs). Coordination of IBRs may be challenging. Need electromagnetic transients simulators.

The end.
Thanks.