Economic Planning for the Clean Energy Transition

Final Policy Scenario and Stakeholder-Requested Sensitivity Results

ECONOMIC STUDIES AND ENVIRONMENTAL OUTLOOK

ECONOMIC PLANNING FOR THE CLEAN ENERGY TRANSITION (EPCET)

EPCET Overview

- The Economic Planning for the Clean Energy Transition study piloted new tools and modeling methodologies for the new economic study process.
- Study was grounded in three main scenarios and one stakeholder-requested sensitivity:
  - Benchmark (2021, year prior to study, used to test model integrity)
  - Market Efficiency Needs (2032)
  - Policy (up to 2050)
  - Stakeholder-Requested
- EPCET modeled 33 scenarios and sensitivities and conducted 2,800 modeling runs.
- Work was performed from 2022 to April 2024. The report was published and a final presentation was given in August 2024.

EPCET Policy Scenario

- The EPCET Policy Scenario utilized a capacity expansion model and a production cost model to find the least-cost built out to meet a state policy compliant 2050 system.
- A variety of sensitivities were performed with new technology types, variations in emission goals/prices, modifications to demand, and other slight modifications to the base case.
- The ISO experimented with new modeling settings throughout EPCET, and the following results reflect a final set of results with consistent model settings.

EPCET Policy Scenario Sensitivity List

- Reference: “Base Case” model – only PV, LBW, OSW, 4 hour BESS, and 8 hour BESS available as expansion candidates
- SMR: Small modular nuclear reactors available as expansion candidates. Capital and operating cost data is from EIA AEO. Additional sensitivity where capital costs are doubled.
- Non-Constrained: No carbon constraint is applied to model
- Socialized Cost of Carbon: Expansion is performed without a carbon constraint, but with the carbon price set to the EPA social cost of carbon
- Nuke Retire: All New England nuclear units are retired over time
- SNG: New England natural gas is gradually replaced by carbon neutral synthetic gas
- 100 Hour BESS: 100 hour iron-air batteries available as expansion candidates
- No Electrified Load: No growth of heat pump or electric vehicle demand in load profile

EPCET Stakeholder-Requested Sensitivity

- A stakeholder-requested sensitivity utilized a capacity expansion model to build a 2045 decarbonized system on the way to meeting state goals.
- The sensitivity investigated the effect of two revenue adequacy mechanisms: continued use of power purchase agreements (PPAs) and PPAs with a reliability adder.
- The sensitivity also had a high-level resource adequacy constraint built into the model.
- A sensitivity to this scenario added price-responsive load to the system.

POLICY SCENARIO REFERENCE CASE

EPCET Policy Scenario Reference Case Overview

- Decarbonizing with only wind, PV, and energy storage becomes very inefficient. Some seasons will become decarbonized before others, and new additions will lead to significant amounts of curtailment.
- Energy storage will be drawn down quickly during subsequent low wind, low PV days. An energy-secure dispatchable resource will always be needed.
- In an electrified economy with lots of intermittent resources, both supply and demand will become increasingly variable. This was demonstrated by running the built out through 20 weather years of data.

EPCET Policy Scenario Reference Case Build

Technology	Capacity Built (MW)
PV	27,538
LBW	7,500
OSW	34,406
BESS 4	14,664
BESS 8	13,000
Total	97,108

- Base case model builds 97 GW of new resources by 2050
- Pace of new resource was observed to accelerate in mid-2030s

EPCET Policy Scenario Reference Case Cost Data

Metric	Data
2050 Capital Costs (Fixed + Annualized Build Cost) (Million $)	24,502
2050 Production Cost (Million $)	978
2050 Emissions (Tons)	826,862
2050 Curtailment (GWh)	61,834 (28%)
2050 Energy Export (GWh)	19,229 (9%)
2050 Renewable Utilization (GWh)	140,245 (63%)
Total Cost per MWh of Load ($/MWh)	139

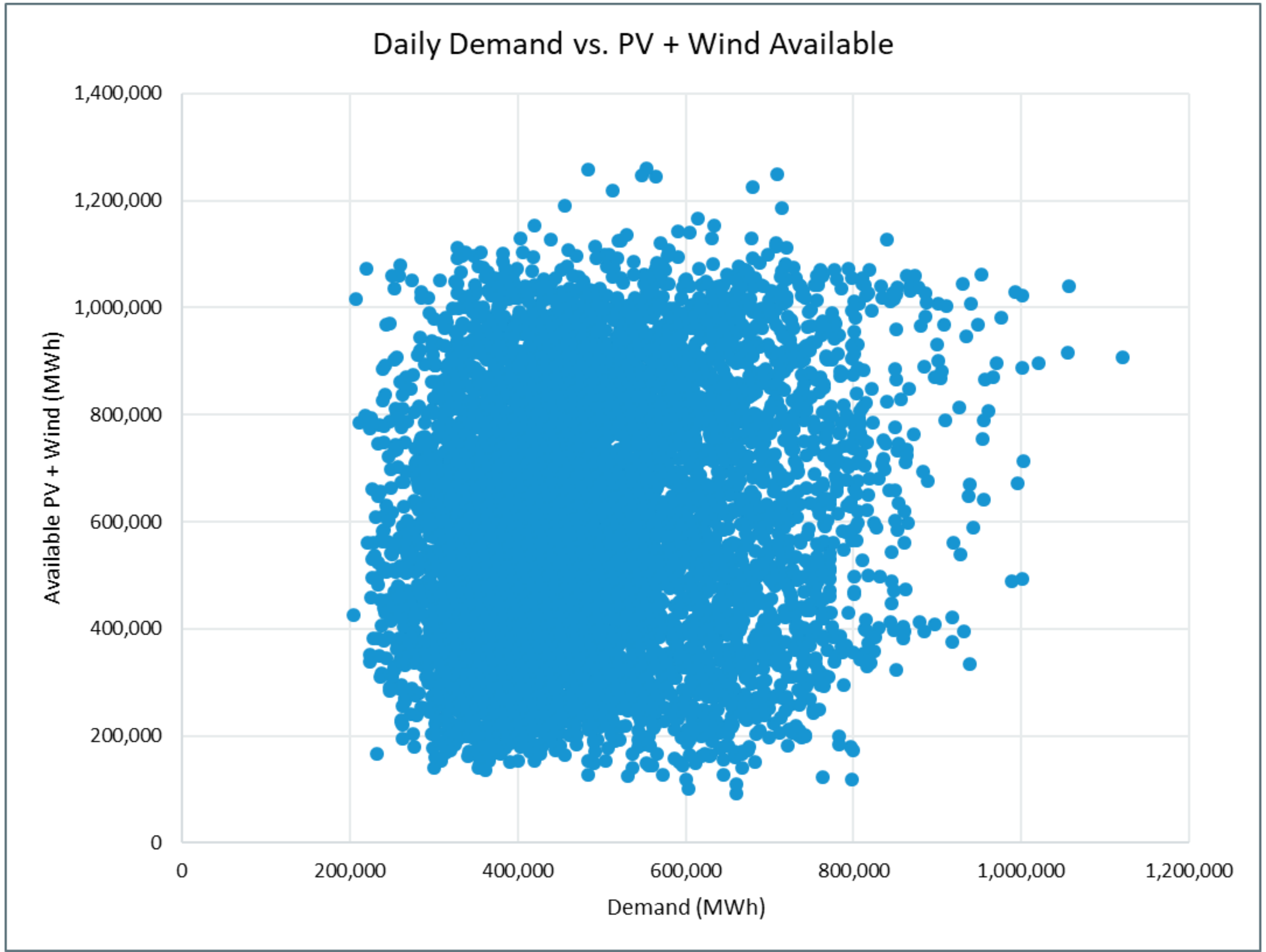
- Production costs are low due to low amounts of generation from thermal resources. Capital costs are very high due to significant addition of new generating resources.
- Of all PV and wind energy, approximately 9% is exported and 28% is curtailed. Only 63% is utilized internally.
- Total carbon emissions (from gas, oil, and coal) are under the target of 1 million tons.

EPCET Policy Scenario Reference Case Generation by Fuel Type

Fuel	Generation (GWh)
ADR	0
Coal	5
Oil	0
Gas	1,971
MSW/LFG/Wood	5,595
NUC	29,240
Hydro	3,458
Imports	5,947
PV	18,880
Wind	121,365

- Majority of system energy comes from native wind and PV resources.
- Fossil generation is still needed during low wind and PV production periods.

EPCET Policy Scenario Reference Case: 20 Weather Years



- In a 2050 system, most days will be fully supplied by zero-carbon resources, mainly wind and PV.
- However, there will always be some days with low wind and PV output.
- During subsequent days of low wind and PV generation, energy storage will be depleted.
- A fuel-secure resource is needed to fill the energy gaps and ensure reliability.

SMALL MODULAR NUCLEAR REACTORS (SMRS)

EPCET Policy Scenario – SMR Overview

- Results showed a persistent need for fuel secure dispatchable resources to serve load on low wind, low PV days.
- SMRs were modeled as expansion candidates to serve as a zero-carbon dispatchable resource.
- EIA figures were used for SMR capital costs. The capital costs start at ~$8,500/kW and fall to ~$5,500/kW in 2050.
- SMRs are a relatively new resource, and the utilized cost assumptions may be optimistic. To reflect the higher possible costs, an additional sensitivity doubled the SMR capital costs (SMR_2x).
- At the assumed cost, SMRs are able to lower total costs by displacing a significant amount of intermittent resources. Even at higher capital cost assumptions, SMRs still provide value to a deeply decarbonized system.

EPCET Policy Scenario SMR Build

Technology	Reference (MW)	SMR (MW)	SMR_2x (MW)
PV	27,538	10,783	27,538
LBW	7,500	6,250	6,700
OSW	34,406	5,015	13,464
BESS 4	14,664	12,913	13,642
BESS 8	13,000	6,460	9,047
SMR	0	15,119	10,547
Total	97,108	56,540	82,079

- The first SMR results build significantly less PV, wind, and energy storage while building ~15,000 MW of SMRs.
- The second SMR results still build approximately 10,500 MW of SMRs while building less OSW. Even at very high capital costs, SMRs have value for their dispatchability and fuel security.

EPCET Policy Scenario SMR Cost Data

Technology	Reference	SMR	SMR_2x
2050 Capital Costs (Fixed + Annualized Build Cost) (Million $)	24,502	16,595	22,841
2050 Production Cost (Million $)	978	1,724	1,156
2050 Emissions (Tons)	826,862	567,112	485,658
2050 Curtailment (GWh)	61,834 (28%)	15 (~0%)	8,277 (7%)
2050 Energy Export (GWh)	19,229 (9%)	55 (~0%)	4,634 (4%)
2050 Renewable Utilization (GWh)	140,245 (63%)	63,223 (~100%)	112,336 (89%)
Total Cost per MWh of Load ($/MWh)	139	100	131

- The first SMR case has significantly lower capital costs due to smaller amounts of new capacity needing to be build. Production costs are higher due to more fuel consumption, but total costs are still lower.
- Curtailment and exports are much lower in the SMR case. Because the system is much less overbuilt, almost all of the energy from intermittent resources is utilized.
- The second SMR case lies between the reference case and the first sensitivity. Capital costs are higher due to the much higher capital cost of SMRs. The system becomes more overbuilt, but curtailment and exports are much lower than in the reference case.

EPCET Policy Scenario SMR Generation by Fuel Type

Fuel	Reference (GWh)	SMR (GWh)	SMR_2x (GWh)
ADR	0	0	0
Coal	5	0	0
Oil	0	0	0
Gas	1,971	1,420	1,204
MSW/LFG/ Wood	5,595	5,603	5,594
NUC	29,240	82,624	44,919
Hydro	3,458	7,125	6,409
Imports	5,947	24,786	16,562
PV	18,880	14,167	28,859
Wind	121,365	49,057	83,477

- The first SMR case has significantly less PV and wind generation and significantly more nuclear generation. Imports are also higher.
- The second SMR case is again in the middle of the reference and the first SMR case.
- All three models still have a need for fossil generation during some hours.

NON-CARBON CONSTRAINED

EPCET Policy Scenario – Non-Carbon Constrained Overview

- The reference Policy Scenario had a carbon constraint to force the model to produce under 1 million tons of CO_2 by 2050.
- To see the effect of the carbon constraint, a non-carbon constrained (NCC) sensitivity was run without the constraint. The model only built new resources to serve load and avoid unserved energy.
- Without a carbon constraint, the model builds significantly less new generating resources. The only technology types that are built to a similar level are short duration storage and LBW.
- Carbon emissions from oil, coal, and gas are very high: over 28 million tons.

EPCET Policy Scenario Non-Carbon Constrained Build

Technology	Reference (MW)	NCC (MW)
PV	27,538	6,581
LBW	7,500	5,456
OSW	34,406	4,100
BESS 4	14,664	10,499
BESS 8	13,000	1,662
Total	97,108	28,298

- Significantly less PV and wind resources are built.
- Similar amounts of short duration storage are built, but much less medium duration storage (8 hour BESS) are built.
- Overall, only about 30% as much capacity is built without a carbon constraint.

EPCET Policy Scenario Non-Carbon Constrained Cost Data

Technology	Reference	NCC
2050 Capital Costs (Fixed + Annualized Build Cost) (Million $)	24,502	4,260
2050 Production Cost (Million $)	978	5,132
2050 Emissions (Tons)	826,862	28,635,005
2050 Curtailment (GWh)	61,834 (28%)	0 (0%)
2050 Energy Export (GWh)	19,229 (9%)	45 (~0%)
2050 Renewable Utilization (GWh)	140,245 (63%)	50,561 (~100%)
Total Cost per MWh of Load ($/MWh)	139	51

- The non-carbon constrained sensitivity had significantly lower capital costs due to much less new generating capacity being built. However, the production costs are significantly higher due to much more fuel being consumed. Overall, the total cost per MWh of load is 63% lower.
- Carbon emissions (from oil, coal, and gas only) are very high in the NCC case.
- There is no curtailment and very few exports in the NCC case. Almost all of the wind and PV generation is utilized internally.

EPCET Policy Scenario Non-Carbon Constrained Generation by Fuel Type

Fuel	Reference (GWh)	NCC (GWh)
ADR	0	18
Coal	5	358
Oil	0	198
Gas	1,971	65,212
MSW/LFG/ Wood	5,595	6,503
NUC	29,240	29,241
Hydro	3,458	7,166
Imports	5,947	25,474
PV	18,880	8,785
Wind	121,365	41,776

- In the non-carbon constrained case, generation from PV and wind are much lower.
- The additional load was mostly met by fossil generation.

SOCIAL COST OF CARBON

EPCET Policy Scenario – Social Cost of Carbon Overview

- The reference Policy Scenario had a carbon constraint to force the model to get under 1 million tons of CO_2 by 2050.
- In this sensitivity, the carbon constraint was replaced with a carbon price equal to the EPA social cost of carbon (SCOC). The cost per ton was interpolated from a 2020 value of $190/ton to a 2050 value of $310/ton.
- A cost on carbon is somewhat effective in encouraging decarbonization. However, an ultimate cost of $310/ton is not sufficient to reach state decarbonization goals.
- Production costs and LMPs are high with a large carbon adder in the market.

EPCET Policy Scenario Social Cost of Carbon Build

Technology	Reference (MW)	SCOC (MW)
PV	27,538	26,478
LBW	7,500	7,250
OSW	34,406	10,054
BESS 4	14,664	10,155
BESS 8	13,000	4,897
Total	97,108	58,834

- The SCOC sensitivity builds similar amounts of the cheaper generating sources (PV and LBW) but builds significantly less OSW and medium term storage.
- Overall, about 60% as much new capacity is built.

EPCET Policy Scenario Social Cost of Carbon Cost Data

Technology	Reference	SCOC
2050 Capital Costs (Fixed + Annualized Build Cost) (Million $)	24,502	10,813
2050 Production Cost (Million $)	978	5,527
2050 Emissions (Tons)	826,862	10,539,635
2050 Curtailment (GWh)	61,834 (28%)	5,269 (5%)
2050 Energy Export (GWh)	19,229 (9%)	3,440 (3%)
2050 Renewable Utilization (GWh)	140,245 (63%)	100,168 (92%)
Total Cost per MWh of Load ($/MWh)	139	89

- Because much less expensive capacity is built, the 2050 capital costs are much lower. Due to the large carbon price, production costs are much larger. Altogether, the total cost per MWh of load is 36% lower.
- 2050 carbon emissions are far above the 1 million ton constraint.
- Because the case capacity is more efficiently built, curtailments and exports are lower, and 92% of renewable energy is utilized internally.

EPCET Policy Scenario Social Cost of Carbon Generation by Fuel Type

Fuel	Reference (GWh)	SCOC (GWh)
ADR	0	6
Coal	5	68
Oil	0	48
Gas	1,971	24,623
MSW/LFG/ Wood	5,595	7,008
NUC	29,240	29,240
Hydro	3,458	7,035
Imports	5,947	19,034
PV	18,880	29,067
Wind	121,365	71,101

- In the SCOC case, lower generation from wind resources leads to higher PV generation, higher imports, and much higher gas generation.

NUCLEAR RETIREMENT

EPCET Policy Scenario – Nuclear Retirement Overview

- The nuclear retirement sensitivity assumed gradual retirement of the New England nuclear generators by 2050.
- By 2050, the system becomes somewhat overbuilt due to the spring, summer, and fall months being decarbonized earlier than the winter. As a result, the retirement of nuclear generation mostly leads to decreased curtailments.
- The carbon emission goal is slightly missed, as emissions are at 1.6 million tons.
- However, the model does build significantly more energy storage to provide the same amount of dispatchable zero-carbon energy during low renewable periods.

EPCET Policy Scenario Nuclear Retirement Build

Technology	Reference (MW)	Nuke Retire (MW)
PV	27,538	27,538
LBW	7,500	7,500
OSW	34,406	34,406
BESS 4	14,664	20,647
BESS 8	13,000	13,000
Total	97,108	104,885

- No additional generating capacity is built in the nuclear retirement sensitivity, as there is already plenty of system energy.
- Additional energy storage capacity is built to provide the same stored energy as the nuclear units.

EPCET Policy Scenario Nuclear Retirement Cost Data

Technology	Reference	Nuke Retire
2050 Capital Costs (Fixed + Annualized Build Cost) (Million $)	24,502	26,147
2050 Production Cost (Million $)	978	662
2050 Emissions (Tons)	826,862	1,626,133
2050 Curtailment (GWh)	61,834 (28%)	47,802 (21%)
2050 Energy Export (GWh)	19,229 (9%)	15,811 (7%)
2050 Renewable Utilization (GWh)	140,245 (63%)	165,818 (72%)
Total Cost per MWh of Load ($/MWh)	139	146

- Because more energy storage capacity is built, capital costs are higher in the nuclear retirement sensitivity. The total cost per MWh of load is 5% higher.
- The emission target is missed by 600,000 tons in the nuclear retirement case.
- Curtailments are lower because the case has more energy storage capability and more opportunity for intermittent generation to run. More wind and PV generation is utilized internally.

EPCET Policy Scenario Nuclear Retirement Generation by Fuel Type

Fuel	Reference (GWh)	Nuke Retire (GWh)
ADR	0	1
Coal	5	28
Oil	0	24
Gas	1,971	3,696
MSW/LFG/ Wood	5,595	5,612
NUC	29,240	0
Hydro	3,458	4,247
Imports	5,947	7,838
PV	18,880	23,378
Wind	121,365	142,439

- With the nuclear units retired, more PV and wind generation is able to run.
- However, gas generation is also higher to replace some of the nuclear generation that ran during low wind, low PV periods.

SYNTHETIC NATURAL GAS

EPCET Policy Scenario – SNG Overview

- The synthetic natural gas (SNG) sensitivity assumed that over time, the New England natural gas supply was gradually replaced with carbon neutral SNG sourced from electrolysis and direct air carbon capture. This would be chemically identical to methane but would have zero net emissions .
- The natural gas supply was assumed to gradually have 0 lbs/MMBtu of carbon but would reach a cost of $40/MMBtu by 2050.
- The SNG sensitivity built less generating and energy storage capacity to reach the emission goal.
- Because fuel secure dispatchable generation was always needed, it may be worthwhile to make that dispatchable generation carbon neutral.

EPCET Policy Scenario SNG Build

Technology	Reference (MW)	SNG (MW)
PV	27,538	25,329
LBW	7,500	7,000
OSW	34,406	13,645
BESS 4	14,664	11,124
BESS 8	13,000	3,978
CC	0	2,105
Total	97,108	63,181

- Approximately 35% less capacity is built in the SNG sensitivity.
- Most of the reduced capacity is in offshore wind and 8 hour batteries. The offshore wind is generally the most expensive source of generation while the medium duration batteries are needed to store the additional energy.
- The SNG sensitivity also builds ~2,000 MW of new combined cycles running on SNG.

EPCET Policy Scenario SNG Cost Data

Technology	Reference	SNG
2050 Capital Costs (Fixed + Annualized Build Cost) (Million $)	24,502	12,568
2050 Production Cost (Million $)	978	5,850
2050 Emissions (Tons)	826,862	65,732
2050 Curtailment (GWh)	61,834 (28%)	13,791 (8%)
2050 Energy Export (GWh)	19,229 (9%)	7,496 (4%)
2050 Renewable Utilization (GWh)	140,245 (63%)	111,689 (88%)
Total Cost per MWh of Load ($/MWh)	139	101

- Capital costs are significantly lower because much less expensive generation is built. Production cost are much higher due to the relatively high cost of SNG. However, total cost per MWh of load is 27% lower.
- Curtailment is much lower because the system is much less overbuilt. About 88% of PV and wind energy is utilized internally.

EPCET Policy Scenario SNG Generation by Fuel Type

Fuel	Reference (GWh)	SNG (GWh)
ADR	0	17
Coal	5	18
Oil	0	50
Gas	1,971	16,654
MSW/LFG/ Wood	5,595	6,623
NUC	29,240	29,240
Hydro	3,458	6,460
Imports	5,947	16,347
PV	18,880	27,810
Wind	121,365	83,878

- With much less OSW built, total wind generation is lower.
- With a less overbuilt system, more PV and import energy is utilized.
- 16,600 GWh of synthetic gas runs. Small amounts of non-SNG fossil generation does also run during low PV and wind periods.

100 HOUR BESS

EPCET Policy Scenario – 100 Hour BESS Overview

- In this sensitivity, 100 hour iron air batteries were modeled as expansion candidates. These batteries have an extremely long duration, but have approximately 50% of the round trip efficiency of lithium-ion batteries.
- The long duration storage was found to eventually become the most cost-effective technology for decarbonization.
- With long duration storage, less generation capacity and energy storage capacity was needed to reach the emission goal. However, fossil generation was still needed during hours when the storage was drawn down.

EPCET Policy Scenario 100 Hour BESS Build

Technology	Reference (MW)	100 HR (MW)
PV	27,538	23,092
LBW	7,500	7,100
OSW	34,406	26,177
BESS 4	14,664	12,979
BESS 8	13,000	0
BESS 100	0	12,168
Total	97,108	81,516

- Approximately 17% less capacity was built in the 100 hour BESS sensitivity.
- The long duration storage displaced 8 hour batteries, some offshore wind, and some PV.

EPCET Policy Scenario 100 Hour BESS Cost Data

Technology	Reference	100 HR
2050 Capital Costs (Fixed + Annualized Build Cost) (Million $)	24,502	20,890
2050 Production Cost (Million $)	978	960
2050 Emissions (Tons)	826,862	710,333
2050 Curtailment (GWh)	61,834 (28%)	13,791 (8%)
2050 Energy Export (GWh)	19,229 (9%)	7,496 (4%)
2050 Renewable Utilization (GWh)	140,245 (63%)	158,113 (88%)
Total Cost per MWh of Load ($/MWh)	139	119

- Capital costs are lower due to less generating and storage capacity needing to be built. Total costs per MWh are reduced by about 15%.
- Curtailments and exports are much lower due to the system being less overbuilt and the energy from intermittent resources being better utilized.

EPCET Policy Scenario 100 Hour BESS Generation by Fuel Type

Fuel	Reference (GWh)	100 HR (GWh)
ADR	0	0
Coal	5	5
Oil	0	8
Gas	1,971	1,681
MSW/LFG/ Wood	5,595	5,586
NUC	29,240	29,241
Hydro	3,458	4,230
Imports	5,947	9,048
PV	18,880	24,398
Wind	121,365	133,715

- Even though the 100 hour BESS Scenario had less PV and wind capacity, the energy was better utilized due to the long duration storage, so total generation was higher.

NO ELECTRIFIED LOAD

EPCET Policy Scenario – No Electrified Load Overview

- In the no electrified load (NEL) Scenario, load growth from expected heat pump and electric vehicle demand was removed from the load profiles. This is meant to measure what it would take to decarbonize a system with a load similar to the current New England system.
- This is a bookend case – state policies and consumer decisions will cause load growth to happen. However, this sensitivity shows that directionally, some costs from meeting a highly electrified load may be avoidable.
- With a lower peak load, a smaller amount of new generating and energy storage resources are needed to decarbonize the electric sector.

EPCET Policy Scenario No Electrified Load Build

Technology	Reference (MW)	NEL (MW)
PV	27,538	22,539
LBW	7,500	4,900
OSW	34,406	3,200
BESS 4	14,664	8,016
BESS 8	13,000	6,460
Total	97,108	41,525

- Approximately 58% less capacity was built in the NEL sensitivity.
- The model builds similar amounts of cheaper generation (PV and LBW) and a moderate amount of energy storage, but builds significantly less expensive generation.

EPCET Policy Scenario No Electrified Load Cost Data

Technology	Reference	NEL
2050 Capital Costs (Fixed + Annualized Build Cost) (Million $)	24,502	5,970
2050 Production Cost (Million $)	978	940
2050 Emissions (Tons)	826,862	593,730
2050 Curtailment (GWh)	61,834 (28%)	3,312 (5%)
2050 Energy Export (GWh)	19,229 (9%)	3,279 (5%)
2050 Renewable Utilization (GWh)	140,245 (63%)	58,772 (90%)
Total Cost per MWh of Load ($/MWh)	139	61

- Capital costs are lower due to less generating and storage capacity needing to be built and the model only building cheaper generating resources.
- Utilization of the renewable resources is better due to a less significant overbuild being needed to reach decarbonization.
- The cost per MWh is lower by about 56% (note that the demand is significantly lower in the NEL case).

EPCET Policy Scenario No Electrified Load Generation by Fuel Type

Fuel	Reference (GWh)	NEL (GWh)
ADR	0	0
Coal	5	0
Oil	0	1
Gas	1,971	1,524
MSW/LFG/ Wood	5,595	5,589
NUC	29,240	29,241
Hydro	3,458	5,286
Imports	5,947	14,911
PV	18,880	24,468
Wind	121,365	34,304

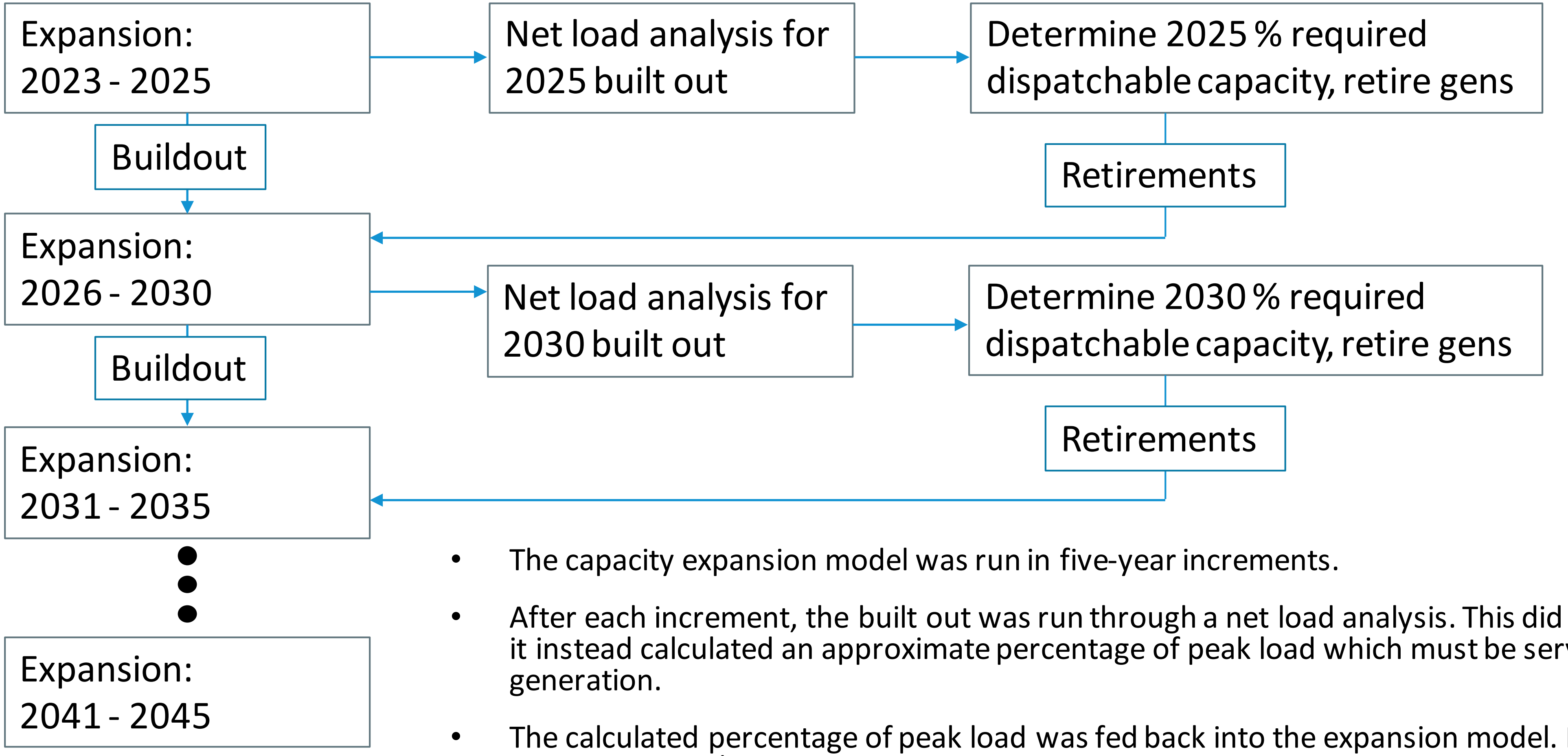
- The NEL sensitivity has significantly less wind generation than the reference case due to significantly less OSW being built.
- However, the total load is much lower.
- More imports and hydro generation are utilized.

STAKEHOLDER-REQUESTED SENSITIVITY METHODOLOGY

Overview of Methodology

- While the ISO cannot perform a full resource adequacy analysis on the system, this methodology created an approximate need for dispatchable resources as a percentage of peak load.
- With this methodology, generator retirement decisions were made during the capacity expansion model.
- Different compensation mechanisms were be examined with the new methodology.
- Disclaimer: None of these methodologies are used in real ISO markets or systems. These were only utilized to give an approximate future representation of current ISO practices.

Expansion Reliability Methodology

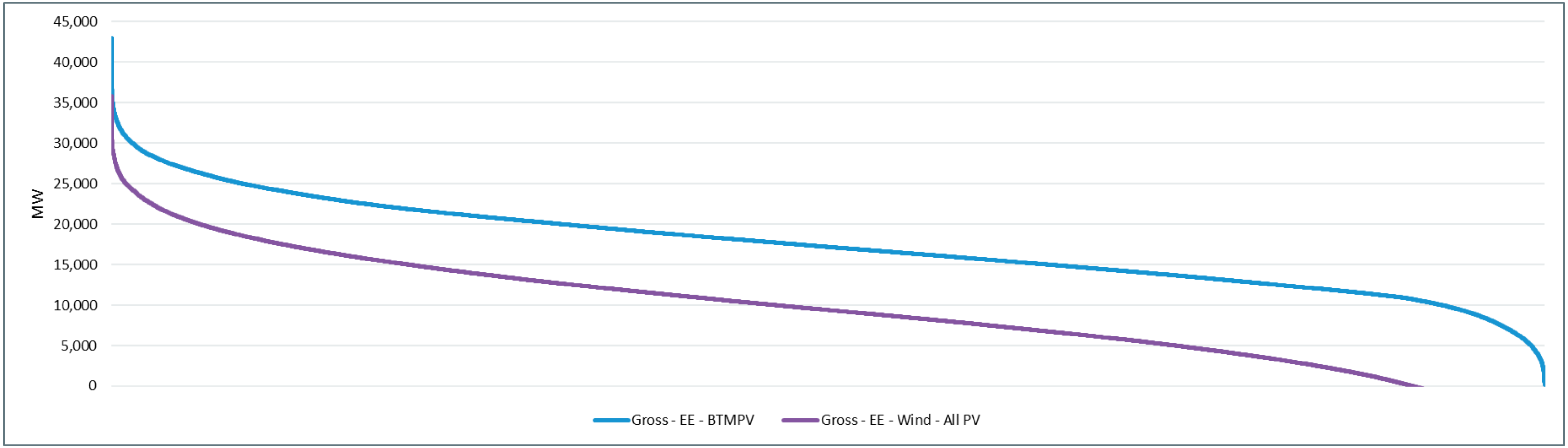


- The capacity expansion model was run in five-year increments.
- After each increment, the built out was run through a net load analysis. This did not calculate a LOLE, but it instead calculated an approximate percentage of peak load which must be served by dispatchable generation.
- The calculated percentage of peak load was fed back into the expansion model. For the next five year step, the model built/retained dispatchable capacity to meet the constraint.
- Retirement decisions were made based on the calculated percentage of peak load – if the model had more dispatchable capacity than was needed, resources were retired based on age.

Additional Detail – Net Load Analysis & Dispatchable Ratio

- The net load analysis included 20 weather years of wind, PV, and load data.
- From the 20 weather years, the ISO identified the hours with the highest net loads.
  - Net loads = gross load – energy efficiency – wind generation – PV generation (BTM + Utility)
  - This is the load that had to be served by dispatchable generation.
- For the highest remaining net load hours, the necessary amount of dispatchable resources was calculated to reflect a reasonable margin.
  - The net load peak was increased by 10% to account for forced outages of dispatchable resources.
  - The net load peak increased by 20% set an upper limit on capacity (with excess being retired).
- The calculated ratio was compared with the total nameplate of dispatchable resources.
  - If the model had more dispatchable capacity than the maximum ratio, resources were retired based on age.
  - If the model was found to be deficient in dispatchable capacity, the next expansion phase would build additional dispatchable capacity to satisfy the ratio.
  - Energy storage was assumed to have 100% firm capacity regardless of duration. This assumption may be revised based on feedback and discussion.

Expansion Reliability Methodology Example – 2040 Net Load Analysis



- Across 20 weather years of data, peak load (gross after EE – BTM-PV) is 43,031 MW.
  - With the capacity expansion created built out, peak net load (gross after EE – all PV – wind) was 35,784 MW. This was the load that must be met by dispatchable generation.
- The model will try to maintain 110% - 120% of the calculated need for dispatchable resources (39,362 MW – 42,941 MW).
  - If the model had more than 42,941 MW of dispatchable capacity, resources were retired based on age. If the model had less than 39,362 MW of dispatchable capacity, resources would be added.

Overview of Compensation Mechanisms

- Having established a reliability methodology to ensure a continued balance of supply and demand, the ISO can model compensation mechanisms.
- Two methods of compensation were modeled:
  - Power Purchase Agreements (PPA) only
  - PPAs + reliability adder (PPA + RA)
- PPA :
  - PPA modeling mimics existing state policies.
  - New zero-carbon generating resources were paid a credit for each MWh of energy produced.
  - The price for this credit was determined via the marginal cost of zero-carbon energy in each time block.
  - All resources were assumed to have a 25-year economic life. A new generator received a locked in PPA price calculated for the time block when it came into service.
  - Energy storage resources did not receive a PPA, but they benefited from arbitrage with negative prices from new resources.
- PPA + Reliability Adder
  - In each five year-block, a PPA price and a reliability adder were calculated together. The reliability adder is a charge to carbon emitting resources which improves energy market revenues for units needed for system reliability.
  - These prices were determined such that the time weighted annual average LMP ensures revenue adequacy for the largest zero-carbon resource on the system.

Formulation of Compensation Mechanisms

- After a capacity expansion block, two versions of hourly production cost models were run: one with all built resources, and one with the last resource built removed.
- The marginal resource has an annualized build cost B_1 and fixed O&M costs F_1.
- The two production cost models will have zero-carbon energy Z_1 and Z_2.
- The PPA price was calculated as $PPA\left(\frac{\$}{MWh}\right) = \frac{B_1 + F_1}{Z_1 - Z_2}$.
- For the PPA + Reliability Adder Scenario, the PPA methodology was first applied, then the reliability adder price was calculated such that average time weighted LMPs = $41/MWh.
- Existing wind and PV resources were assumed to have a PPA of $10/MWh. While this is not representative of true existing PPAs, it was meant to demonstrate how the entry of new zero-carbon resources with larger PPAs could impact their revenue streams.

Compensation Mechanisms, cont.

- All zero-carbon energy resources were assumed to have their PPA over a 25-year economic life.
- This PPA was implemented as a negative VO&M charge. The zero-carbon energy resource revenue was from their PPA revenues.
  - In hours with positive LMPs, the total revenue per MWh was be equal to the PPA price.
  - In hours with negative LMPs, the total revenue was reduced.
    - For example, if the PPA is \$50/MWh and the LMP is -\$30/MWh, the resource revenue will be equal to \$20/MWh.
- When calculating total cost to load, the load was assumed to incur costs by buying the energy from the generator at the PPA price when LMPs are positive.
  - For example, if the PPA is \$50/MWh and the LMP is \$30/MWh, load will pay \$50/MWh for the energy from the generator.
  - If the PPA is \$50/MWh and the LMP is -\$30/MWh, load will pay \$20/MWh for the energy from the generator.

Overview of PPA vs. PPA + Reliability Adder Analysis

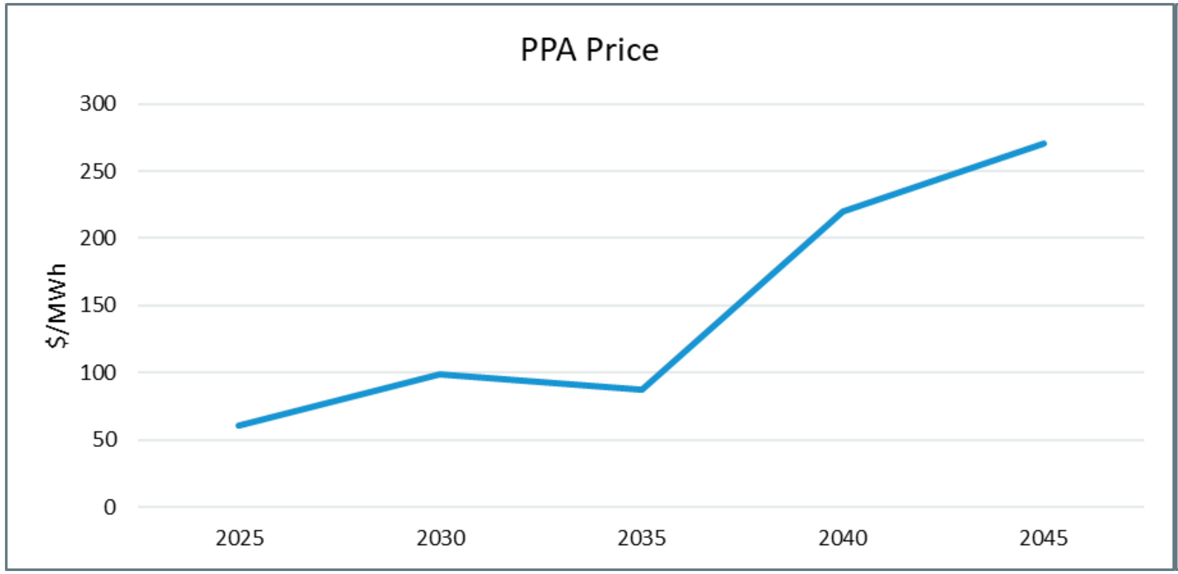
- The aforementioned methodologies have been applied to two capacity expansion models running from 2023 to 2045.
- These results are assumption driven, but directional trends can be observed from the prescribed policy.
- Both models build out a system that reduces CO_2 emissions to ~6 million tons by 2045.
- LMPs, resource adequacy built out metrics, and generator profits will be examined at five-year intervals.

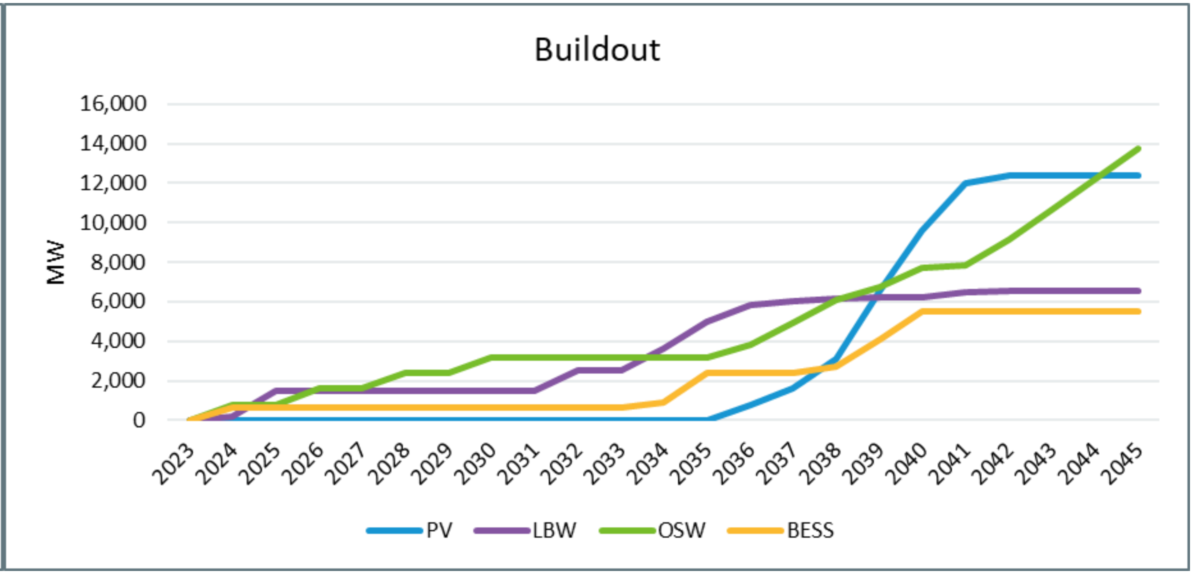
STAKEHOLDER-REQUESTED SENSITIVITY – PPA ONLY RESULTS

Takeaways of PPA Only Sensitivity

- PPAs get larger over time, as new resource additions later in the model horizon are curtailed for increasing percentages of the time.
- New zero-carbon energy resources are able to bid more negatively than existing resources, allowing for revenue adequacy for new resources.
- Existing zero-carbon energy resources are underbid by new zero-carbon energy resources, leading to lower generation and less revenue over time. Some of the resources built in the first years of expansion experience that same effect.
- Baseload resources see decreased profits over time as they are exposed to increased frequency of low and negative LMPs.
- Though resources were able to retire, no additional resources were retired beyond announced retirements. Large amounts of dispatchable energy storage (4-hour BESS) are also added for resource adequacy.

PPA Only: Buildout & PPA Prices





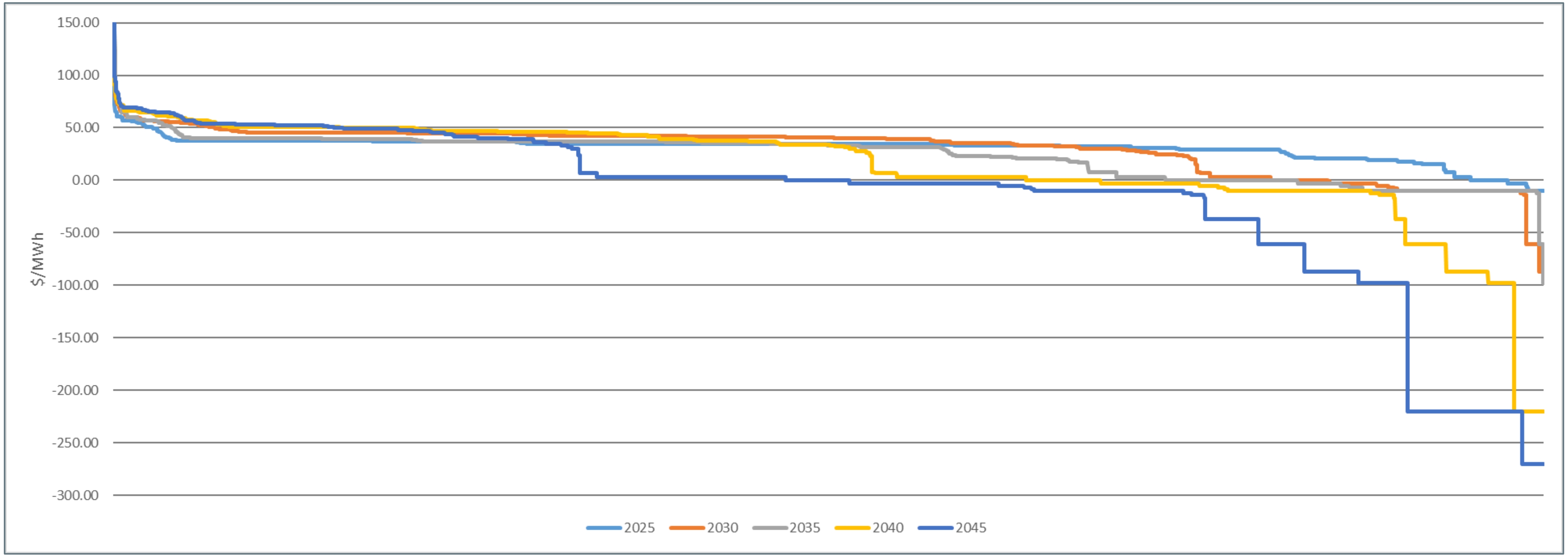
- Model builds 38 GW of new generating resources for decarbonization (this does not include 10 GW of energy storage resources added for resource adequacy).
- PPA prices are relatively steady initially, but begin to increase after 2035. New resources added in 2040 and 2045 lower the capacity factor of existing and previously added resources, increasing marginal costs of new zero-carbon energy.

PPA Only: Buildout Adequacy

	2025	2030	2035	2040	2045
Peak Gross Load (MW) (Gross – EE – BTM-PV)	25,591	27,403	33,551	43,031	50,789
Peak Net Load (MW) (Gross – EE – All PV – Wind)	25,004	25,469	28,674	35,784	40,927
Min RM (10%) (MW) (110% of Peak Net)	27,504	28,016	31,541	39,362	45,020
Max RM (20%) (MW) (120% of Peak Net)	30,005	30,563	34,409	42,941	49,112
Dispatchable Requirement as a % of Peak Gross	107.5	102.2	93.5	91.5	89.5
Dispatchable Nameplate (MW)	29,988	29,988	31,700	34,830	39,362
Capacity Added for Adequacy (MW)	0	0	0	4,532	5,657

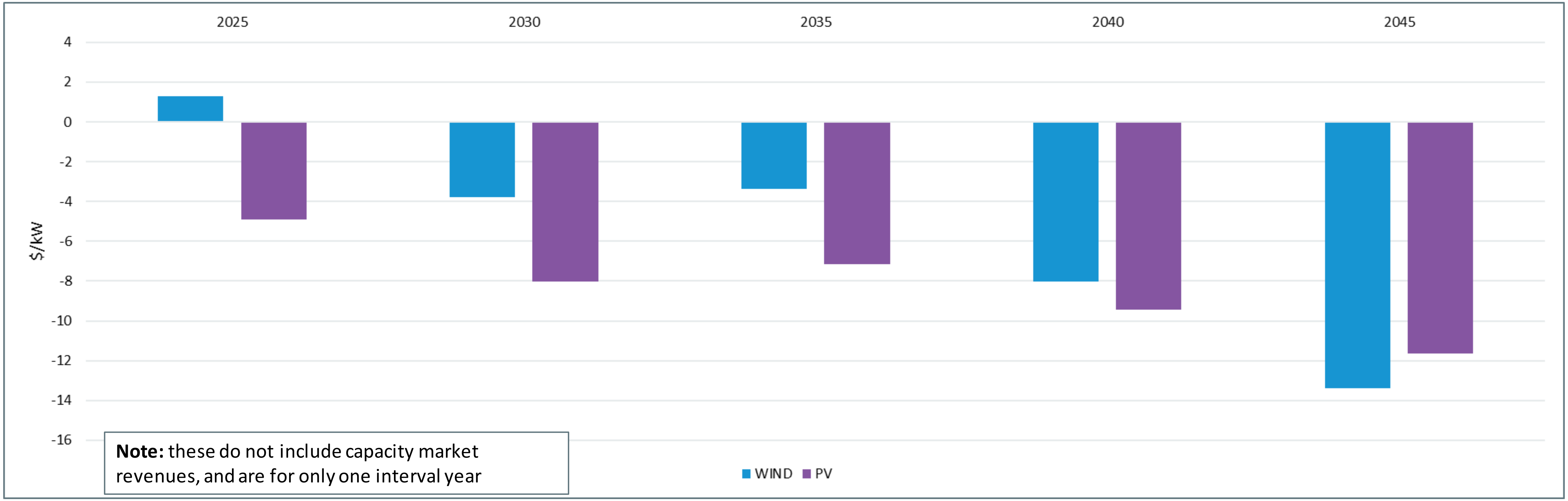
- No additional resources are retired in early years, as the 120% maximum reserve margin is never exceeded.
- The resource adequacy constraint becomes binding in 2040/2045, ultimately adding ~10,000 MW of energy storage. If additional resources were retired earlier, they would likely have to be replaced with more dispatchable generation later.
- In 2045, a 50,800 MW peak load is reduced to 40,900 MW by intermittent resources. To maintain the 110% of the peak net load, the model needs 45,000 MW of dispatchable resources. This results in needing to be able to cover 90% of the peak gross load with dispatchable resources.

PPA Only: LMPs



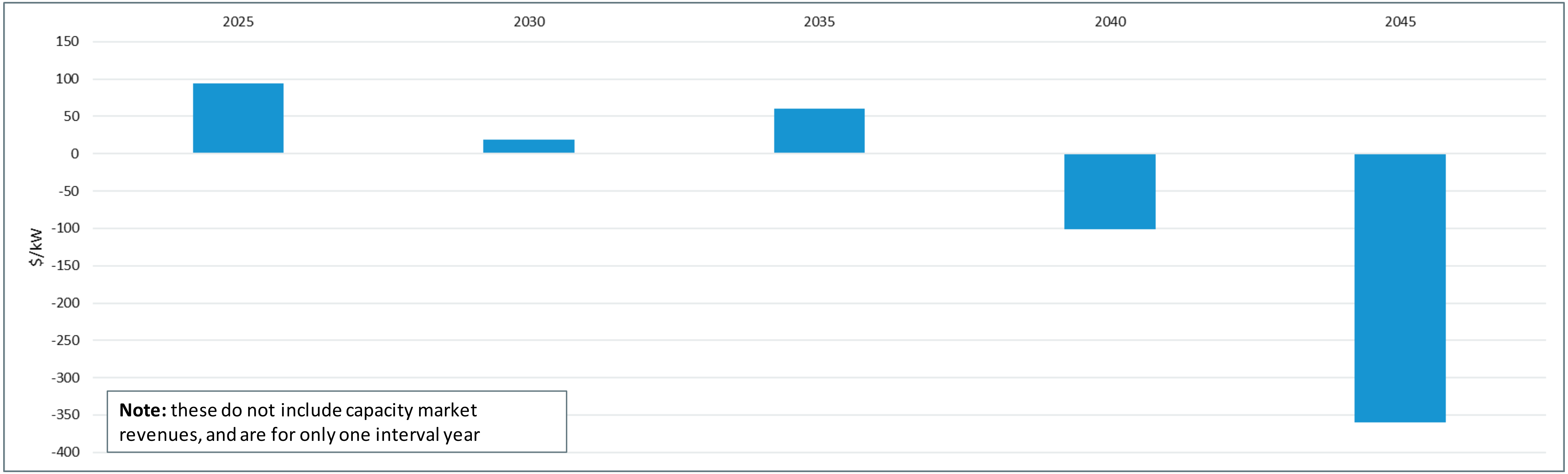
- LMPs become increasingly negative over time, reaching a time weighted value of $-15.83/MWh by 2045. 2045 has negative LMPs for 53% of hours and LMPs less than $41/MWh for 75% of hours.
- There are some hours with very low LMPs in 2040 and 2045, indicating significant periods when new and existing zero-carbon resources did not run for economic reasons.
  - This includes resources built from 2036-2045.

Average Annual Net Profit by Resource Type: Existing Wind and PV Energy Resources



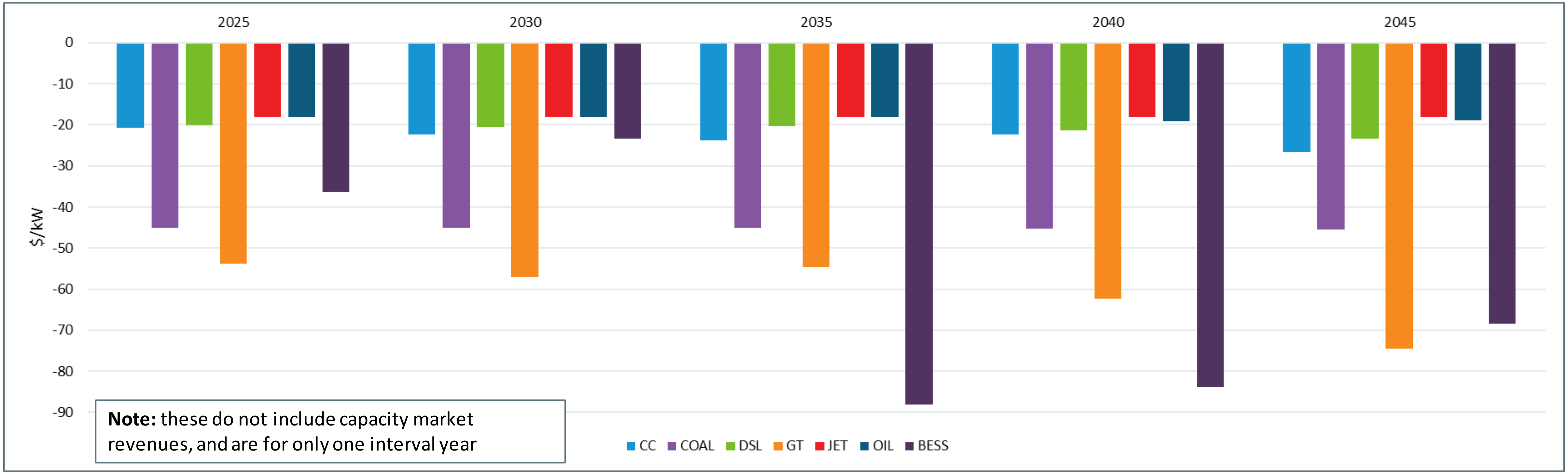
- Note: profits shown do not include revenue from the capacity market. Profit = revenue – production costs – fixed costs – annualized build costs.
- Net profits for existing zero-carbon energy resources decline over time. Existing PV and wind resources are increasingly underbid by new resources with higher priced PPAs.
- Some of the new zero-carbon energy resources built in the earlier blocks are also frequently curtailed as they are underbid by resources built later in the horizon.

Average Annual Net Profit by resource Type: Nuclear Generators



- Nuclear resource net profitability (absent capacity payments) decline over the study period as energy prices decrease.
- These profits are significantly impacted by fixed cost assumptions. The ISO is using generic assumptions from the EIA for nuclear resources rather than resource specific cost assumptions. These results can be used to identify trends over time. However, profitability isn't guaranteed through 2040.

Average Annual Net Profit by Resource Type: Dispatchable Resources



Note: these do not include capacity market revenues, and are for only one interval year

- Most dispatchable resources are operating in the negative. Revenues made in the energy market are small compared to their fixed costs.
- Large amounts of energy storage is added starting in 2035. With significant penetration of energy storage, the profit each resource can make is decreased due to the smoothing effect on LMPs.
  - With large amounts of storage, high LMPs are reduced and low LMPs are increased.

2035 - 2045 Single Resource Analysis: New LBW

Metric	Unit	2035	2040	2045
Generation	GWh	198.15	184.80	163.58
Energy Curtailed	GWh	0.04	12.92	34.61
Percent Curtailed	%	0.02	6.53	17.46
FO&M Cost	Thousand $	1,500.00	1,500.00	1,500.00
Annualized Build Cost	Thousand $	14,570.95	14,570.95	14,570.95
Total Costs	Thousand $	16,070.95	16,070.95	16,070.95
PPA Revenue	Thousand $	16,739.56	14,830.22	12,678.54
Net Profit	$/kW-yr	13.37	-24.81	-67.85

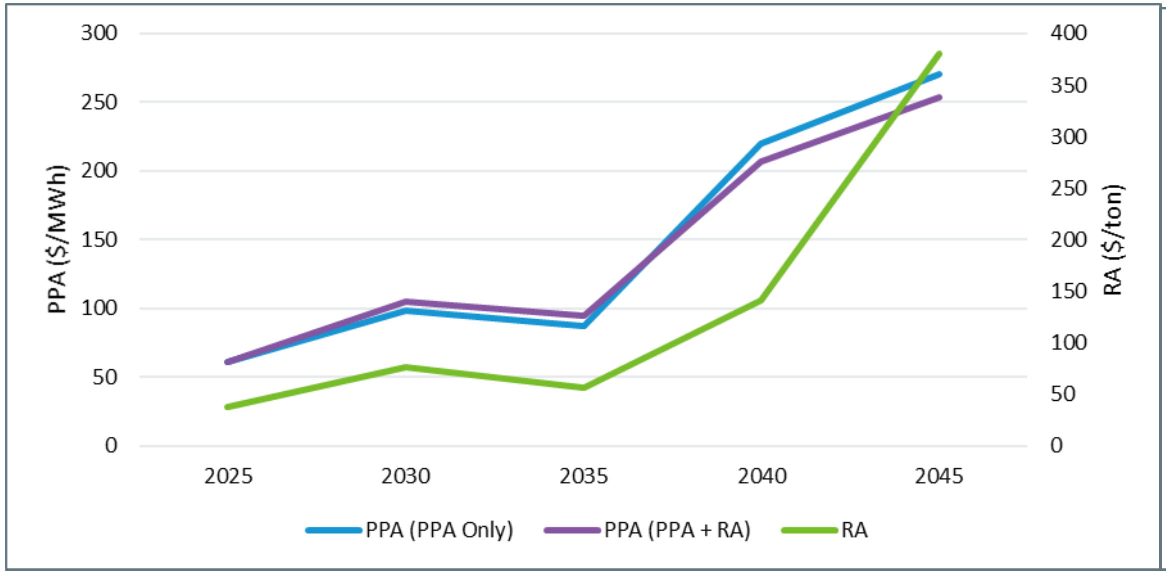
- This is a 50 MW new LBW resource built in 2035 receiving a PPA of $87/MWh.
- As load starts to grow rapidly at the horizon of the CELT load growth (after 2033), curtailment of new resources and PPA prices drop.
- While the PPA price ensures revenue adequacy in 2035, new additions in 2040 and 2045 are given higher priced PPAs and are able to underbid this resource. Within five years of entry, this resource is no longer profitable at the original PPA price.
- Many existing and new clean energy resources may require escalations of PPAs.

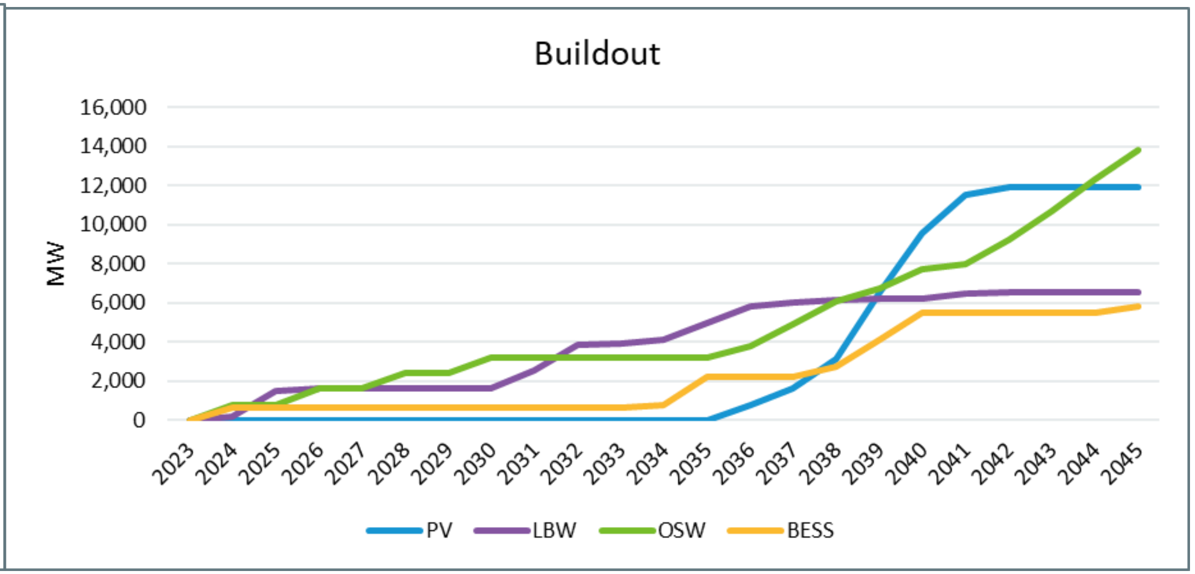
STAKEHOLDER-REQUESTED SENSITIVITY – PPA + RELIABILITY ADDER RESULTS

Takeaways of PPA + Reliability Adder Sensitivity

- PPA prices are similar in both sensitivities because PPA resources see no additional revenue from the reliability adder.
- Nuclear profits remain steady over time in the PPA + Reliability Adder sensitivity.
  - Whereas, in the PPA-only sensitivity, nuclear profits fall significantly over time.
- Because most resources are receiving more revenue in the energy market, capacity payments or other compensation streams are expected be lower for resources needed for resource adequacy or reliability.
- With a shrinking number of hours with positive LMPs, the reliability adder will increase significantly in price in later years. This will drive price volatility.
- Adding significant amounts of energy storage for reliability creates a smoothing effect on LMPs.
  - Negative LMPs are raised, high LMPs are reduced.

PPA + Reliability Adder: Buildout & PPA/Reliability Adder Prices





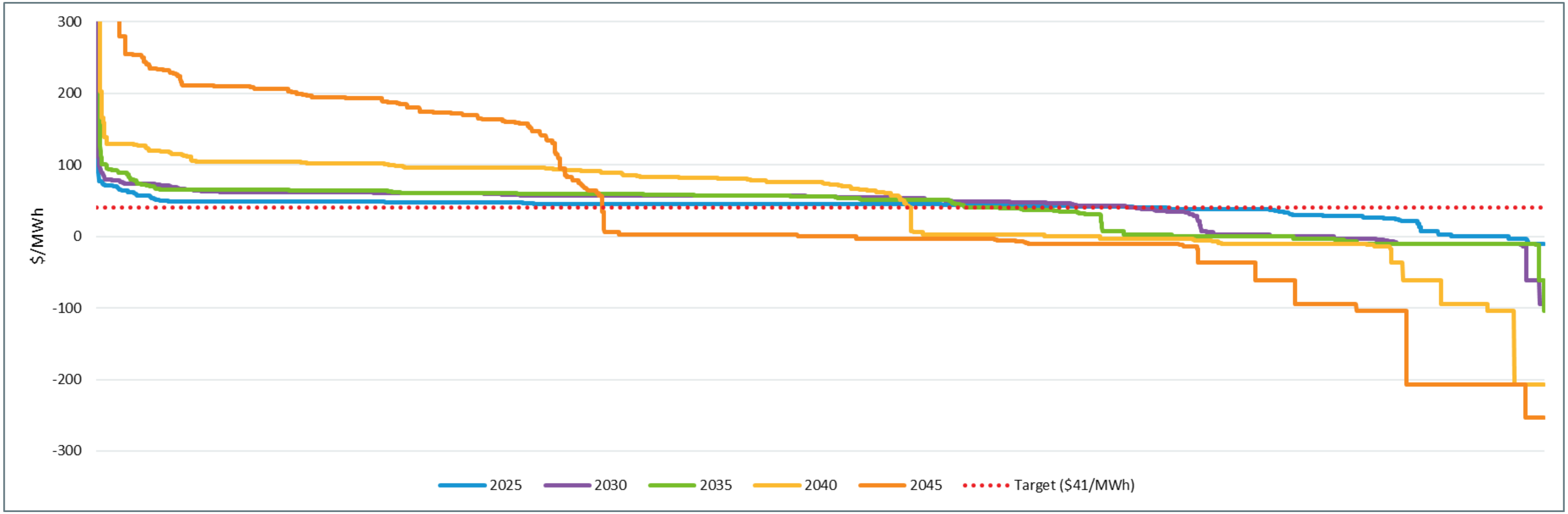
- Buildout is similar to the PPA-only sensitivity. An identical carbon constraint leads to a similar built out.
- With the reliability adder, PPA prices are very similar to the PPA-only sensitivity. This is because PPA resource revenues are unaffected by the reliability adder.
- There is a growth in the reliability adder value in the later years of the model due to there being fewer and fewer hours with positive LMPs.

PPA + Reliability Adder: Buildout Adequacy

	2025	2030	2035	2040	2045
Peak Gross Load (MW) (Gross – EE – BTM-PV)	25,591	27,403	33,551	43,031	50,789
Peak Net Load (MW) (Gross – EE – All PV – Wind)	25,004	25,456	28,674	35,784	40,929
Min RM (10%) (MW) (110% of Peak Net)	27,504	28,002	31,541	39,362	45,022
Max RM (20%) (MW) (120% of Peak Net)	30,005	30,547	34,409	42,941	49,115
Dispatchable Requirement as a % of Peak Gross	107.5	102.2	94.0	91.5	88.6
Dispatchable Nameplate (MW)	29,988	29,988	31,578	34,829	39,689
Capacity Added for Adequacy (MW)	0	0	0	4,533	5,333

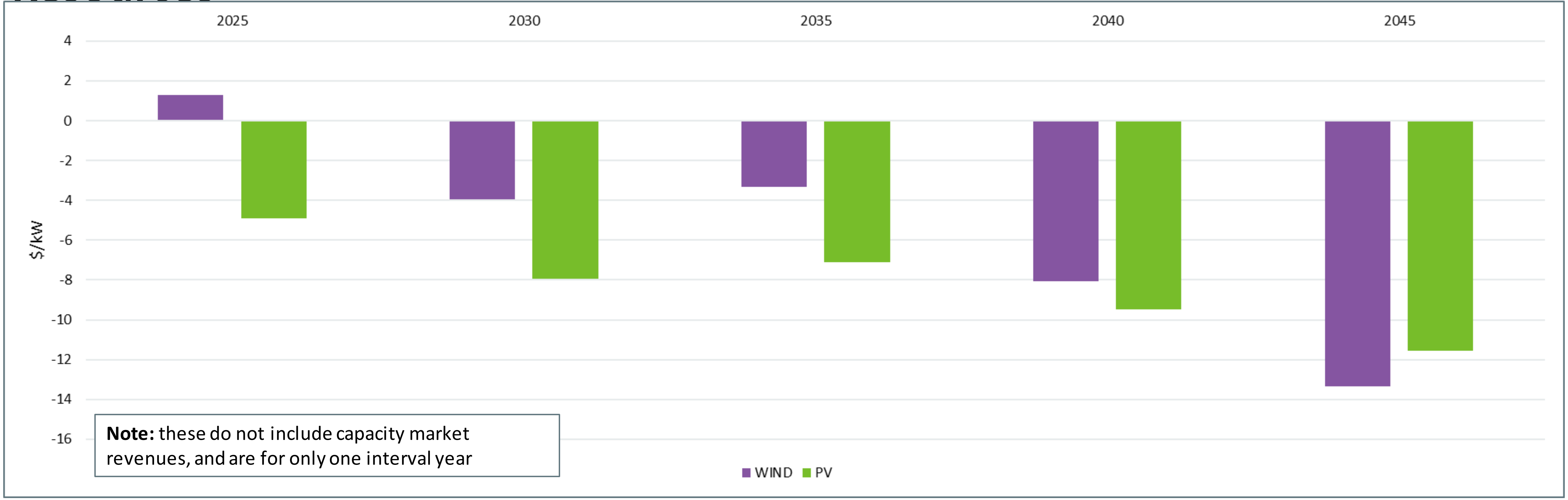
- Resource adequacy takeaways are similar to the PPA-only sensitivity due to similar built outs.
- Approximately 10,000 MW of dispatchable energy storage was added for resource adequacy. 89% of the peak load still needs to be covered by dispatchable capacity.

PPA + Reliability Adder: LMPs



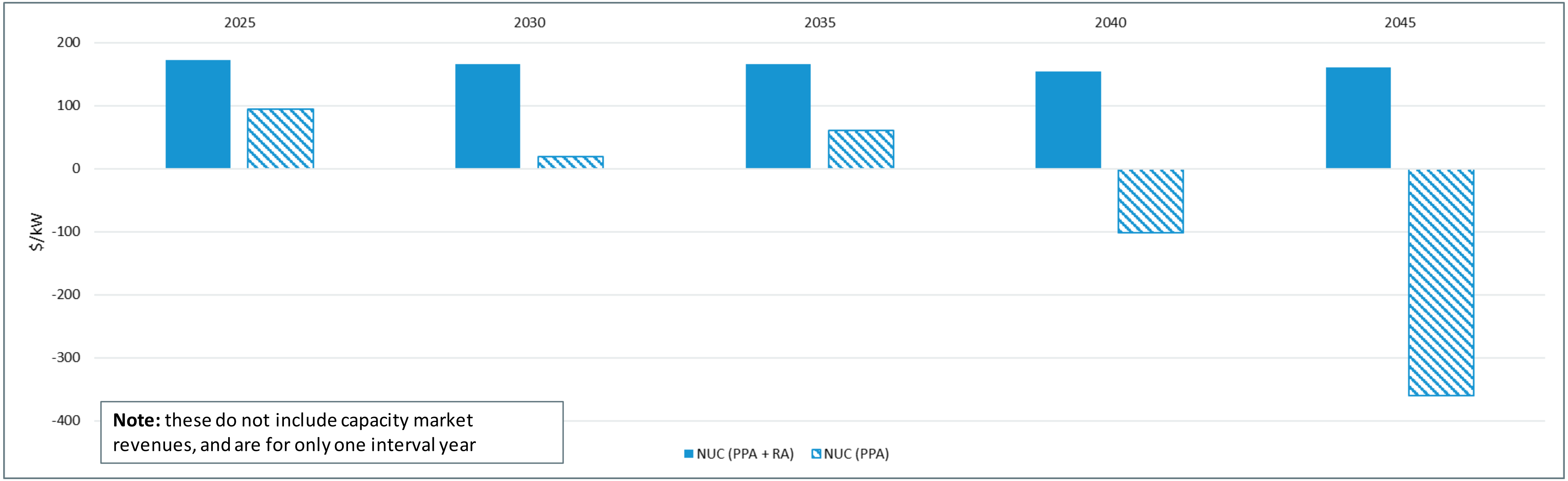
- Average LMPs are maintained at $41/MWh.
- Over time, more hours have negative LMPs, and hours with negative LMPs become more negative due to larger PPA prices.
- As a result, the declining number of hours with positive LMPs have higher and higher LMPs.

Average Annual Net Profit by Resource Type: Existing PV and Wind Resources



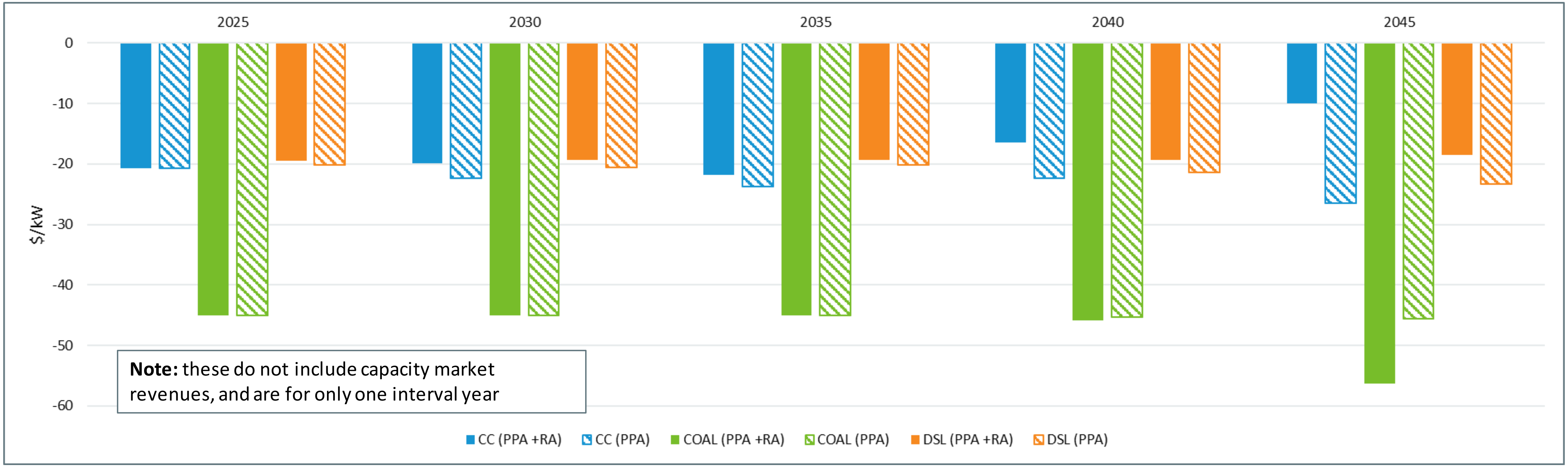
- Profits for existing wind and PV resources still decrease over time as they are underbid by new resources with higher priced PPAs.
- The reliability adder has no impact on existing wind and PV resource profits.

Average Annual Net Profit by Resource Type: Nuclear Generators



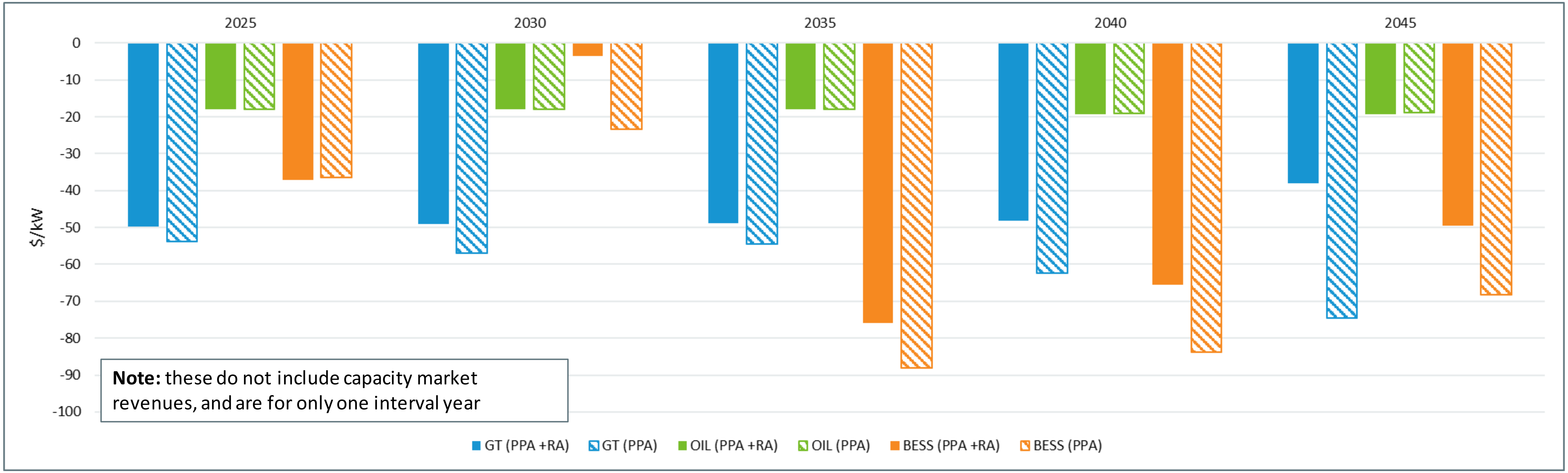
- With every year having a time weighted LMP of $41/MWh in the PPA + Relability Adder sensitivity, the nuclear resource profits are steady. In the PPA-only sensitivity, profits decline over time
  - There are slight variations due to time weighted LMPs being approximately (but not exactly) equal to $41/MWh.

Average Annual Net Profit by Resource Type: Dispatchable Resources



- Most dispatchable resources are still operating in the negative, but the majority are earning more revenue than they did in the PPA-only sensitivity.
- With a high reliability adder, lower emitting resources (CCs) are in the best position to earn more revenue, while higher emitting resources (coal STs) are earning less revenue.

Average Annual Net Profit by Resource Type: Dispatchable Resources, cont.



Note: these do not include capacity market revenues, and are for only one interval year

- The energy market is still saturated with storage, but storage resources are earning more revenue on average under the PPA + Reliability Adder sensitivity.
- Energy storage stands to earn more from arbitrage with higher annual average LMPs.

STAKEHOLDER-REQUESTED SENSITIVITY – TOTAL COST RESULTS

Takeaways of PPA vs. PPA + Reliability Adder Costs

- Specific resource profits can be very assumption driven.
  - For example, this model does not have a unique fixed O&M cost for each resource. A generic EIA $/kW value is used for each resource type (which may be very different from the current & future actual fixed costs).
- In earlier years, the additional LSEEE expense from the reliability adder tends to be more expensive than the higher capacity costs in the PPA-only sensitivity.
- However, there is a clear trend that most resources will need increasing amounts of non-energy market compensation as energy market revenues shrink. The PPA + Reliability Adder sensitivity reduces the amount of non-energy market compensation because more money is kept in the energy market.
- The PPA + Reliability Adder Scenario generally does a better job of securing resource revenue adequacy. Providing greater revenues to baseload resources may reduce the likelihood of retirement.

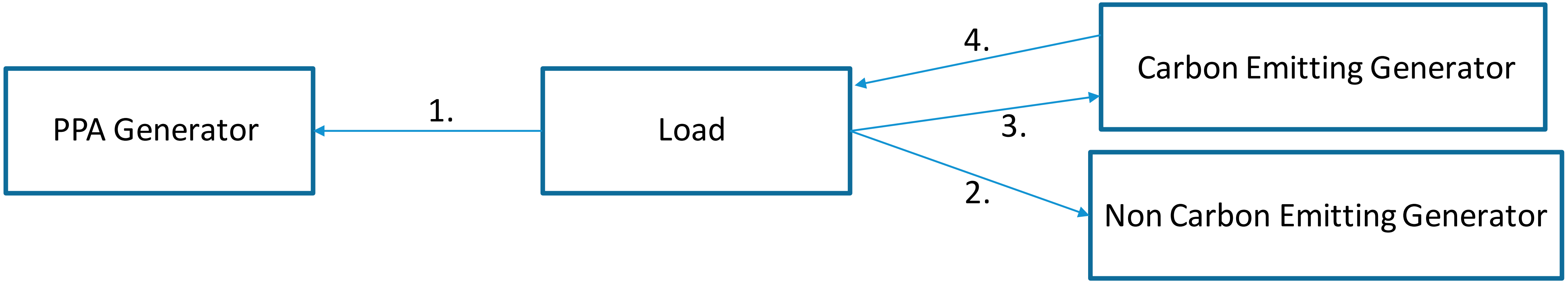
Stakeholder-Requested Sensitivity Total Cost Overview

- *Results are highly driven by assumptions. None of these values are certain, and are meant to only provide directional results.*
- Total costs to load are broken down into three categories:
  - Load serving entity energy expense (LSEEE): sum of hourly (positive) LMP ($/MWh) x Load (MWh)
  - PPA costs: for each resource with a PPA, sum of generated MWh x PPA price ($/MWh)
  - Capacity costs: most negative profit ($/kW) x (peak renewable reduction + firm capacity requirement) (MW)
    - Example: 2040 has a 43,031 MW peak load reduced down to a 35,784 MW net load. Peak renewable reduction = 43,031 – 35,784 = 7,247 MW. Firm capacity requirement = 1.1 x 35,784 = 39,362 MW. Total MW for capacity cost calculation = 7,247 + 39,362 = 46,609 MW
  - There are also rebates associated with the reliability adder.
- This analysis was done with an unconstrained transmission model. Transmission/distribution upgrades and their associated costs are excluded from this cost analysis. There will be additional cost when those are considered.
- The modeled sensitivities include reserve requirements (120% of largest contingency as 10 minute, 50% second largest contingency as 30 minute). With energy storage being allowed to provide reserves and a lack of retirements of fast start resources, reserve requirement violations are infrequent and total reserve revenue is small.
  - It is important to note that this model has perfect dispatch foresight and does not model the intricacies of DA vs. RT dynamics or outages. There is the potential for DA vs. RT uncertainty to create more revenue opportunities for flexible resources that is not captured here.

Discussion of Nuclear Profits in the PPA sensitivity

- When estimating capacity prices, the ISO has made an assumption that negative $/kW profits will roughly correspond with a resource's capacity bid.
- As resources start to be added for resource adequacy, the capacity price is equal to the new energy storage resources coming online.
- However, in the PPA sensitivity, nuclear net profits are so low in 2040/2045 that their capacity bid would be higher than the bid of an equivalent amount of new energy storage capacity coming online.
- What would likely happen would be nuclear retirement and replacement with dispatchable energy storage. However, because the 2045 system is still rapidly adding new resources for resource adequacy and the removal of all nuclear resources would have significant resource adequacy impacts, it is assumed here that the nuclear resources remain and the market clears at the high nuclear capacity bid.

Discussion of RA Rebates – Money Flow Example



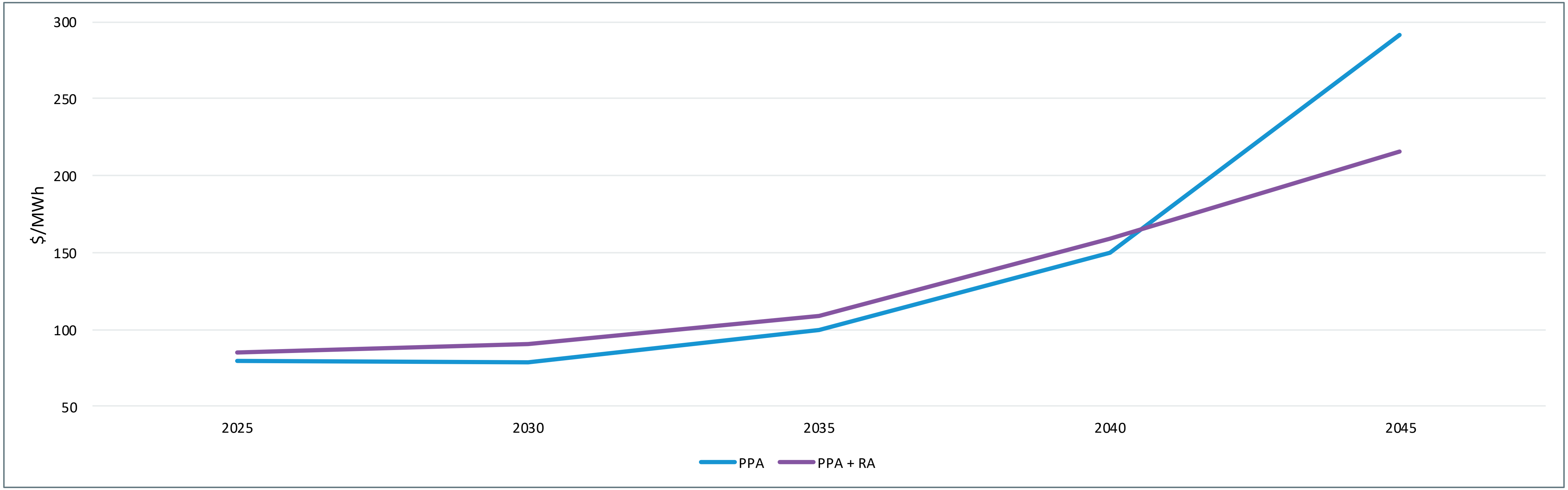
- Under the PPA + Reliability Adder framework, emitting generators must purchase allowances. As a result of the adder, their bids (and LMPs) are larger, driving up LSEEE costs.
- However, the original purchase of allowances are rebated back to load.
- The above diagram visualizes the flow of money.
  – 1. Load pays the PPA generator at the PPA price when LMPs are positive. When LMPs are negative, the generator is paid the difference between the LMP and the negative of the PPA price.
  – 2. Load pays the non-carbon emitting generator at the LMP.
  – 3. Load pays the carbon emitting generator at the LMP.
  – 4. However, there is a reliability adder rebated from the emitting generator back to the load.

PPA vs. PPA + Reliability Adder Capacity Costs ($/kW-month)

	2025	2030	2035	2040	2045
PPA + RA	6.53	6.30	7.83	7.30	6.13
PPA	6.61	6.66	7.84	8.68	30.15

- The PPA + Reliability Adder mechanism will keep capacity prices slightly lower due to most resources making more money in the energy market.
- Under the PPA-only sensitivity, capacity prices may need to increase further to support continued operation of certain baseload resources.

PPA vs. PPA + Reliability Adder Costs ($/Zero Carbon MWh)



- The presence of the reliability adder in the capacity expansion phase encourages the model to build more zero-carbon generation. This leads to lower carbon emissions but somewhat higher costs.
- The PPA + Reliability Adder sensitivity exhibits slightly higher costs until the last block. However, the PPA + Reliability Adder Sensitivity guarantees nuclear revenue sufficiency without needing large capacity payments, which ultimately drives the PPA-only cost spike in 2045.

PPA vs. PPA + Reliability Adder Costs (Million $)

	PPA				PPA + RA				
	LSEEE	PPA	Capacity	**Total**	LSEEE	PPA	Capacity	Rebates	**Total**
2025	3,264	846	2,227	**6,337**	4,208	849	2,200	-454	**6,803**
2030	2,616	1,933	2,394	**6,944**	4,350	2,045	2,265	-608	**8,052**
2035	3,578	3,062	3,421	**10,061**	4,957	3,222	3,426	-662	**10,944**
2040	3,004	11,763	4,853	**19,620**	6,443	11,448	4,086	-1,221	**20,756**
2045	2,267	22,485	19,856	**44,609**	9,770	21,365	4,037	-2,230	**32,942**

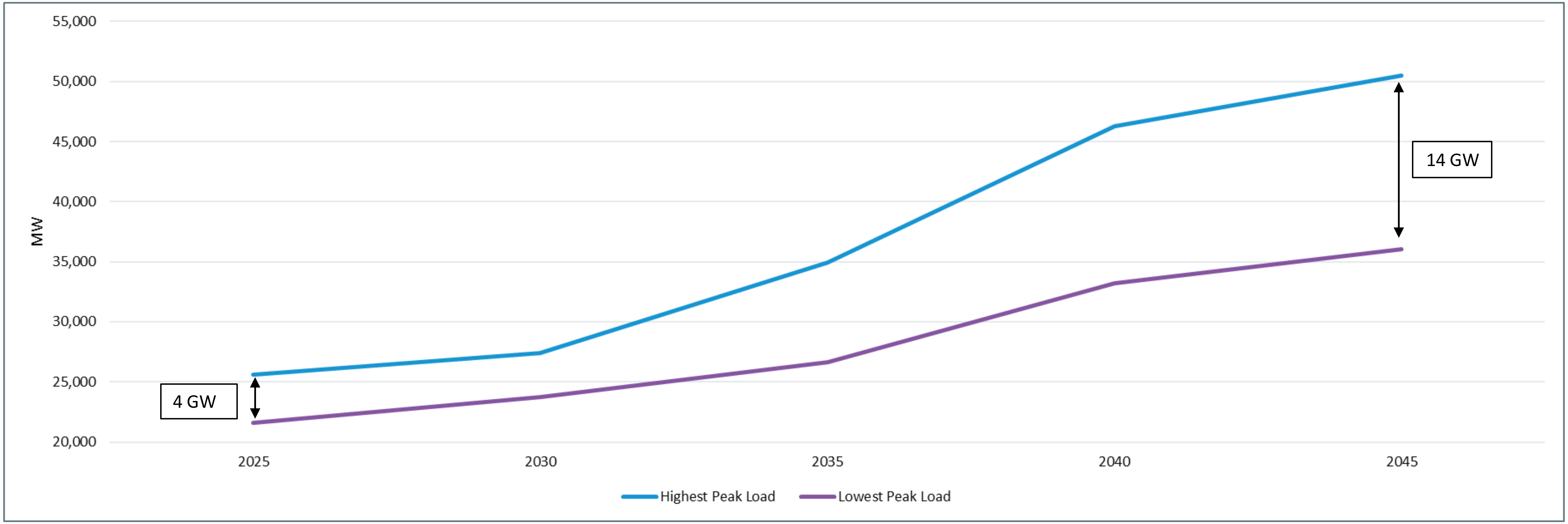
- Both sensitivities have significant cost escalation from large PPA payments. The reliability adder does nothing to directly reduce this because PPA resources are being compensated outside of the energy market.
- The PPA + RA sensitivity has large energy market payments. Though a significant amount of these payments are rebated back to load, the energy market still stays smaller in the PPA-only sensitivity.
- Capacity payments are larger in the PPA-only sensitivity, as resources unable to make money in the energy market or from PPAs must make money elsewhere. This is escalated in 2045 as nuclear revenues are very negative.

STAKEHOLDER-REQUESTED SENSITIVITY – THE IMPACT OF WEATHER ON A RELIABILITY ADDER

Overview of Weather Year Uncertainty

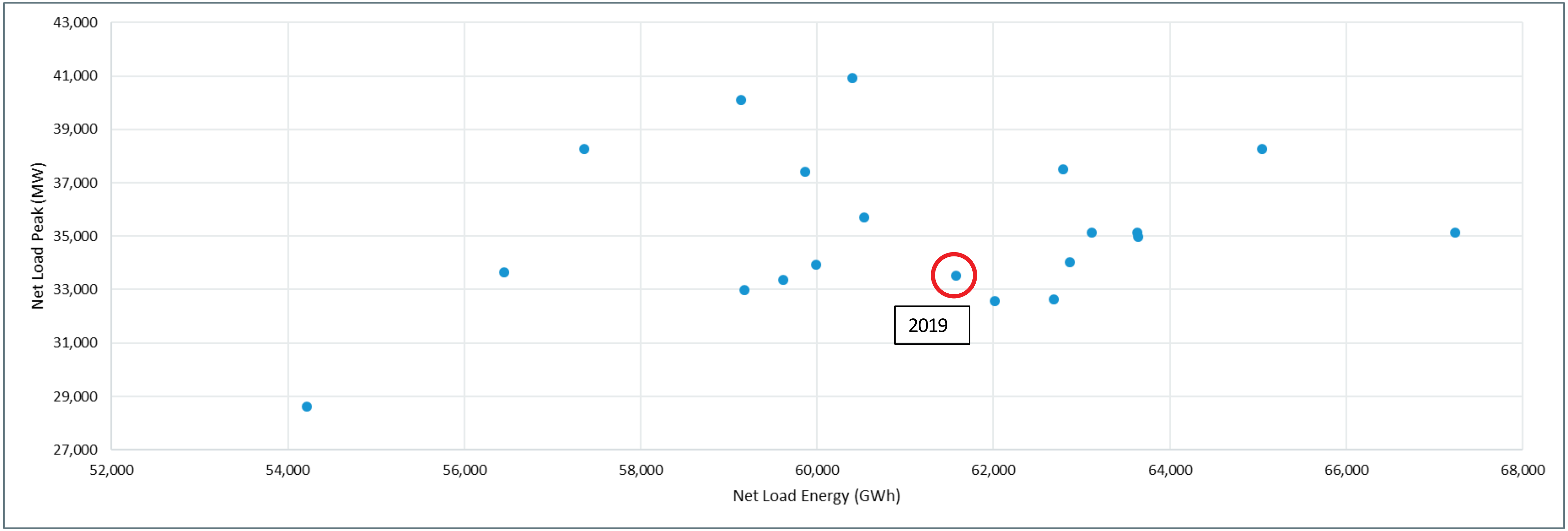
- As electrification loads increase and renewable energy penetration increases, both supply and demand will become increasingly sensitive to weather.
- This has a significant impact on energy demand from resources besides wind and solar. Between different weather years, the peak energy demand and variability in net load will drive revenue adequacy.
- Resource adequacy constraints have been implemented to ensure that sufficient dispatchable resources are included to cover the peak net load of multiple weather years.
- However, the planned reliability adder price shown so far was calculated for a single weather year (2019). In alternate weather years, the reliability adder price may be more than needed or not enough to ensure revenue adequacy.
- It is impossible to know with much accuracy what weather patterns may be more than a few days in advance. Extreme uncertainty regarding weather patterns will have significant impacts on revenue adequacy.

Peak Load Distributions



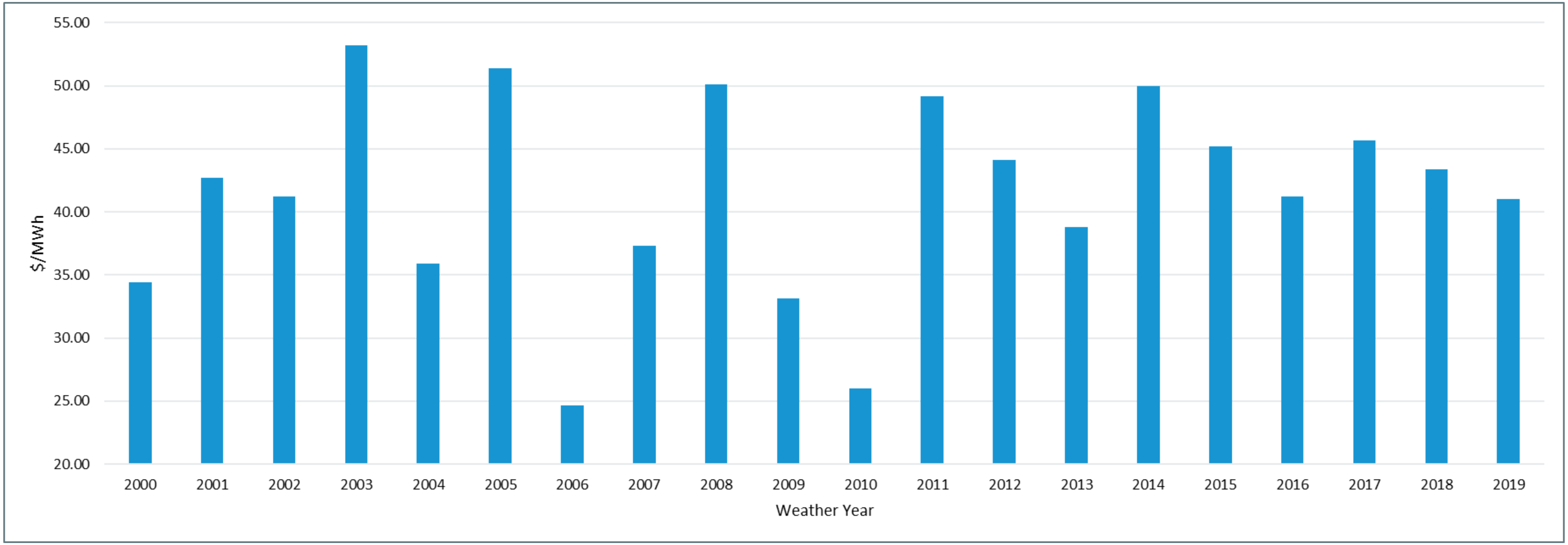
- Note: These loads are gross load after EE – BTM PV.
- The possible range of peak loads is expected to increase over time. As loads become increasingly sensitive to weather and temperature, the difference between a mild winter and a cold winter will have significantly more impact in 2045 than in 2025.
  - In 2025, the gap between the maximum and minimum peak load weather years is 4 GW. In 2045, this gap is 14 GW.
- This has implications for resource and revenue adequacy. The system will be built for resource adequacy for the worst case weather year, but a mild weather year may have many resources sitting unused which still must be compensated.

2045 Net Load Peak & Energy (After Wind + PV)



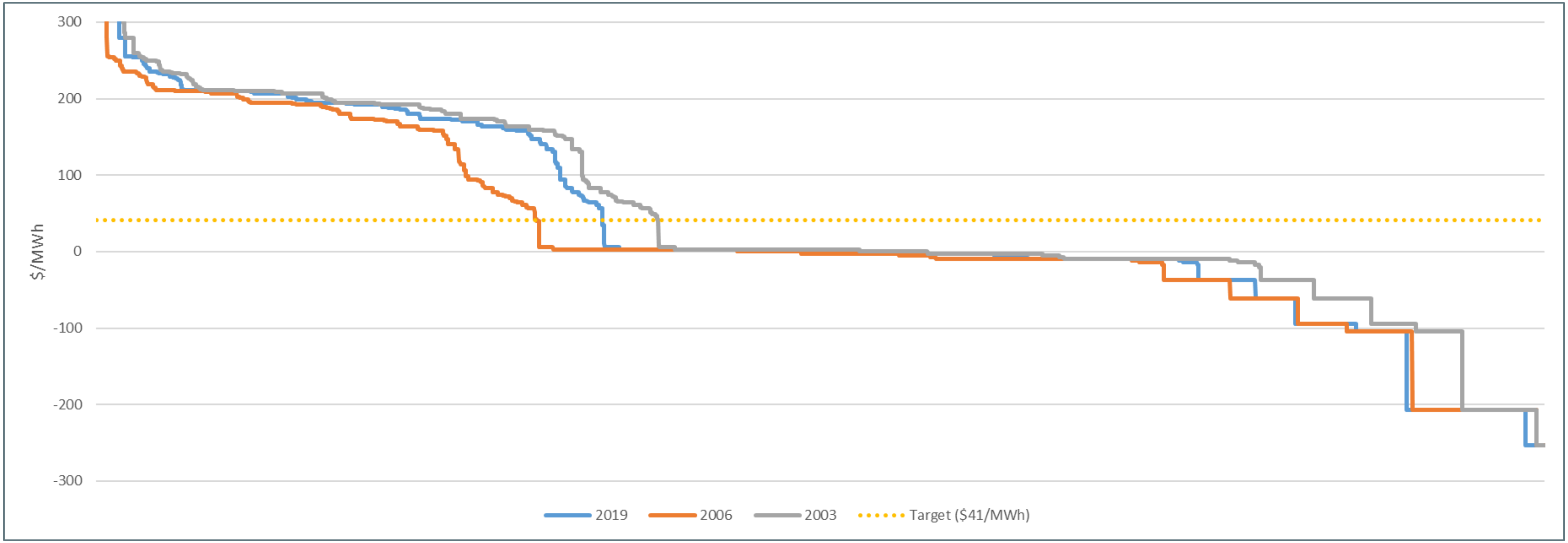
- Note: these loads are gross – EE – all PV – all wind (the amount of load which needs to be met by dispatchable capacity).
- The graph above shows the possible variation in net peak load and energy between weather years. This is the peak load and energy that must be met by dispatchable resources.
- The 2019 weather year (which was used for PPA and Reliability Adder calculations) is a relatively average year. A year with higher or lower demands for dispatchable generation will have different revenue adequacy outcomes with the calculated prices.

2045 Multiple Weather Year Time-Weighted LMPs



- These average LMPs are from a 2045 system with the PPA + Reliability Adder build out, PPA prices, and RA prices. Depending on the weather year, time-weighted LMPs can be far above or below the target of $41/MWh.
  – Time-weighted LMPs vary between $24/MWh with the 2006 weather year and $53/MWh with the 2003 weather year.

2045 LMPs for 2019, 2006, and 2003 Weather Years



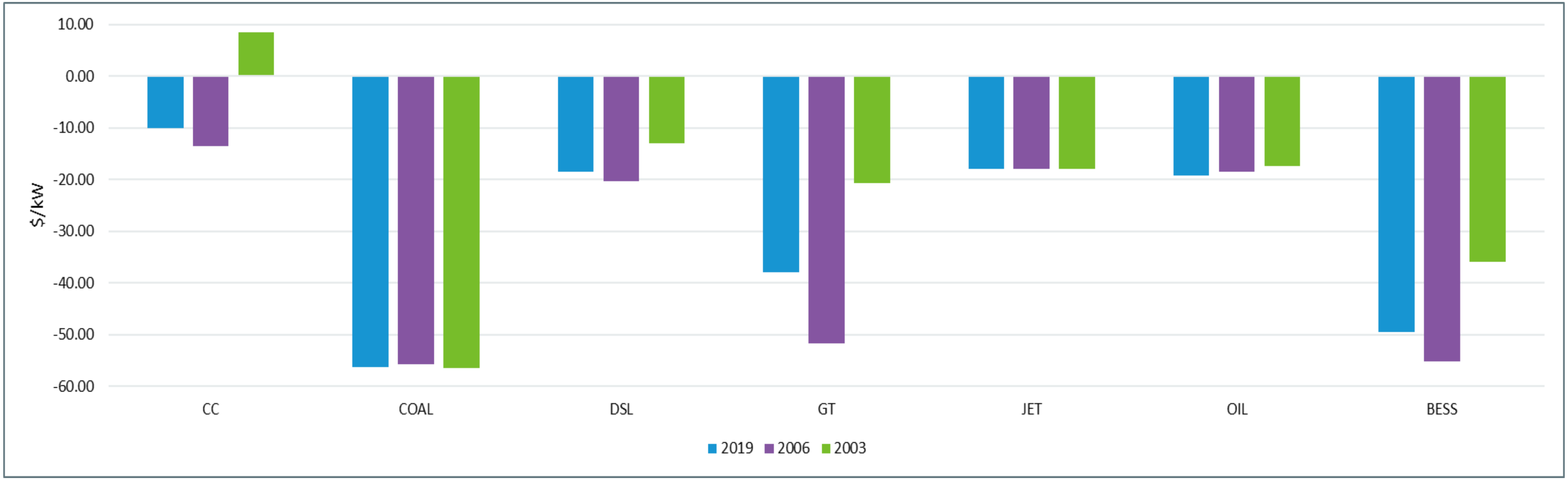
- A year with more need for dispatchable resources (2003) will have higher time-weighted LMPs, while a year with a lower need for dispatchable resources (2006) will have lower time weighted LMPs.
  - The 2003 weather year had 17 TWh of generation from emitting resources (6.9 million tons of carbon emissions) while the 2006 weather year had 10 TWh (4.3 million tons of carbon emissions).

2045 Average Capacity Factors for 2019, 2006, and 2003 Weather Years

	CC	COAL	DSL	GT	OIL	WIND	PV	New PV	New LBW	New OSW
2019	9.45	0.26	2.06	4.75	0.10	23.21	7.60	13.52	32.83	47.57
2006	7.52	0.17	2.00	4.56	0.02	20.95	7.83	13.12	32.55	48.88
2003	10.87	0.32	2.18	5.46	0.38	23.81	9.21	12.66	32.94	50.04

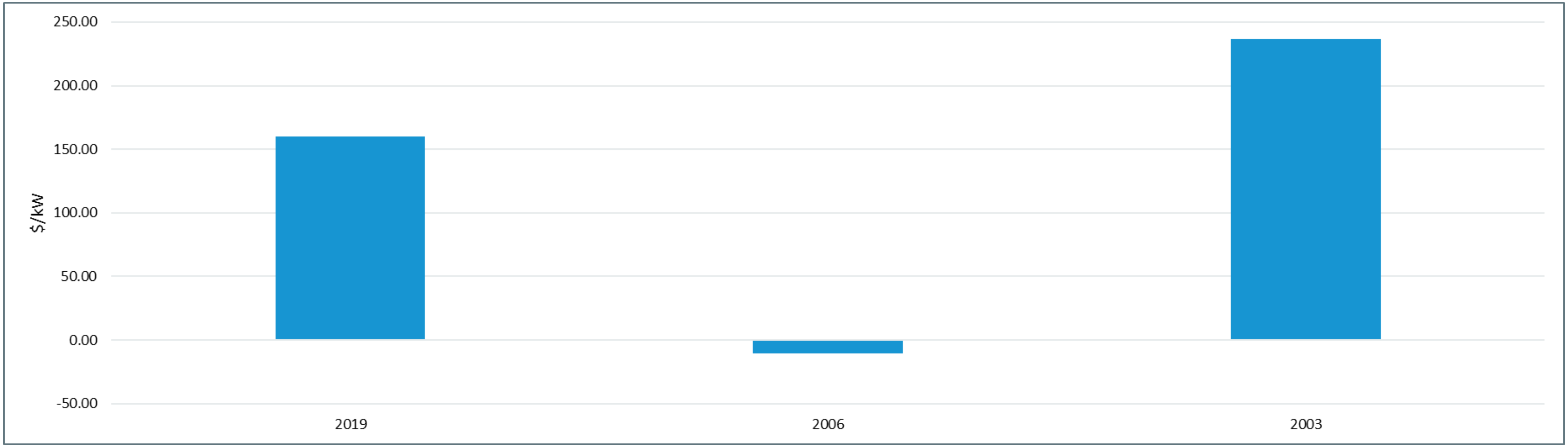
- Some years are slightly sunnier/windier than others. Newer clean energy resources always have larger capacity factors as they can underbid existing resources
- Capacity factors of dispatchable resources differ year to year depending on the hourly net load

2045 Multiple Weather Year Dispatchable Net Profits



- Higher LMPs (2003 weather year) mean that most dispatchable resources are earning more revenue. Lower LMPs (2006 weather year) mean that most dispatchable resources are earning less revenue.

2045 Multiple Weather Year Nuclear Net Profits



- While the calculated reliability adder guaranteed constant nuclear profit for the 2019 weather year, it was likely too low for the 2006 weather year and too high for the 2003 weather year.

2045 Multiple Weather Year Costs (Million $)

	LSEEE	PPA	Capacity	Rebates	Total
2019	9,770	21,365	4,037	-2,230	**32,942**
2006	7,247	20,947	5,304	-1,700	**31,798**
2003	10,484	21,513	3,359	-2,634	**32,722**

- Total costs did not change significantly between bookend weather years, but the allocation of costs did change somewhat:
  - Weather years with *less* need for dispatchable generation had *more* money in the capacity market and *less* money in the energy market.
  - Weather years with *more* need for dispatchable generation had *less* money in the capacity market and *more* money in the energy market.
- The region will not know ahead of time how much dispatchable generation will be needed. Capacity bids may reflect this uncertainty.

2045 Multiple Weather Year Discussion

- For a resource adequate and revenue adequate system, the New England region may have to build and maintain a large fleet of dispatchable resources which may only run occasionally.
  - To ensure resource adequacy, the region will have to plan for the year with the highest need for dispatchable resources.
  - To ensure revenue adequacy, the region will have to plan for the year with the lowest need for dispatchable resources.
- The hours with the most need for dispatchable resources will likely be in harsh winter conditions which may not be suitable for demand response.
- For a forward compensatory market, there will be extreme uncertainty year to year surrounding how often dispatchable resources will be needed.

Stakeholder-Requested Sensitivity Takeaways

- In the PPA-only sensitivity, nuclear resources experience declining revenues which could decrease their financial viability. Assuming that their missing money will be made up in the capacity market will lead to an increase in capacity prices.
- The PPA + Reliability Adder sensitivity prevents larger capacity payments by enabling most resources to continue making money in the energy market. However, this also results in higher energy market costs
  - The reliability adder does nothing to reduce PPA payments, which becomes one of the larger costs to the region in the later years.
- Both PPA prices and reliability adder prices escalate as the region decarbonizes. If there are fewer and fewer hours with carbon emissions to decarbonize, the marginal cost of abatement/new zero-carbon energy will rise.
- Uncertainty surrounding how often dispatchable resources will actually be needed may lead to a need for higher capacity payments. The region may end up paying for a pool of resources which are only needed once every few years.
- Despite significant addition of intermittent resources, most of the expected peak load (~90%) will need to be covered by dispatchable resources. Significant amounts of dispatchable resources were added starting in the 2030s, and any resources retired in the short term may have to be replaced in the future.

Stakeholder-Requested Sensitivity Analysis Limitations

- Both sensitivities see significant amounts of negative LMPs. New load-side resources could find a way to benefit from utilizing excess renewable energy at low/negative LMPs.
- Significant development of demand response resources could help alleviate the uncertainty surrounding multiple weather years. However, it may prove difficult to curtail some load (such as heating, cooling, or transportation) during periods of extreme weather.
- The resource adequacy process is making a significant simplification by assuming all dispatchable resources are equal. If energy storage is being added for dispatchable capacity, either larger amounts or longer duration storage may be needed for adequacy.
- No fuel constraints were modeled due to uncertainty regarding what the future of the gas pipeline and LNG facilities will be. However, if constraints continued to exist in some form:
  - Average LMPs would likely be higher due to expensive stored fuel generation running more frequently.
  - Additional resources would likely be needed for winter peaking resource adequacy.

STAKEHOLDER-REQUESTED SENSITIVITY
SENSITIVITY: PRICE RESPONSIVE LOAD

Stakeholder Scenario Sensitivity: Price Responsive Load

- The previous section showed Stakeholder-Requested Sensitivity results which examined two compensation mechanisms for a future decarbonized system: PPAs only, and PPAs with a reliability adder.
- One of the modeling caveats was that the ISO had not modeled any development of load side resources.
  - Besides energy storage charging, there was no discretionary load despite frequent negative LMPs.
- This sensitivity explores changes to the load side and its impacts.
- The ISO has run a version of the PPA-only sensitivity where hydrogen electrolyzers were added to the build out. These load side resources allow for more of the zero-carbon energy to be utilized to produce a marketable commodity.
  - This sensitivity did not include the cost to store or transport the commodity.
  - This sensitivity did not specify how this commodity would be used.

Price Responsive Load: Electrolyzer Assumptions

- These assumptions are from internal research done by the ISO, and are meant for a high-level directional analysis.
- Electrolyzer:
  - Build cost: $500/kW
  - Efficiency: 80%
  - 3.412 MMBtu H_2 / MWh
  - Approximately 9 kg H_2 / MMBtu
- Hydrogen:
  - Inflation reduction act (IRA) tax credits range from $0.6/kg to $3/kg H_2
  - Calculations assume $2/kg
  - Electrolyzers will only buy energy when LMPs are 0 or lower (only consume energy that would otherwise be curtailed).
  - The value of these credits were held constant through the entire study period (2024-2045).
- Important note: the ISO is only calculating the costs associated with the electrolyzer and the consumption of electricity. There is no consideration for hydrogen transportation, pipelines, etc.

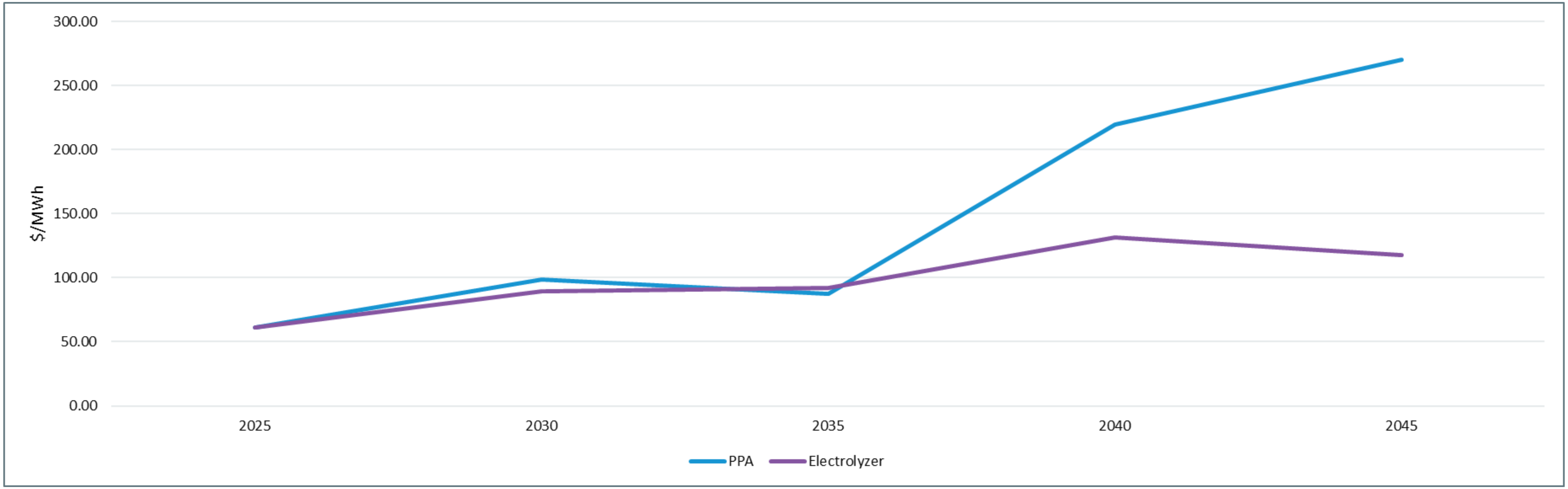
Price Responsive Load: Electrolyzer Quantity

- Given the previously stated assumptions:
  - Each MWh of electrolyzer load creates 24.57 kg of H_2 (3.412 MMBtu/MWh * 9 kg/MMBtu * 0.80).
  - Each kg of H_2 is worth $2 from production tax credits.
  - Each MW of electrolyzer added has an annualized build cost of $44,503/MW.
  - To make enough money from tax credits to cover the build cost, the electrolyzer fleet must have a capacity factor of 10.3%.
- To estimate how many MWs of price responsive load would be added due to ISO electrolyzer cost assumptions, the ISO analyzed curtailment data from the PPA-only sensitivity and determined an appropriate electrolyzer capacity for each five-year increment (such that the capacity factor would equal 10%).
  - 2025: 0 MW
  - 2030/2035: 500 MW (Annualized build costs = $22 million/year)
  - 2040: 8,000 MW (Annualized build costs = $335 million/year)
  - 2045: 23,000 MW (Annualized build costs = $1,021 million/year)
- The electrolyzers have been added to the build outs from the previous PPA only sensitivity and constrained to only consume energy when LMPs are less than or equal to 0.

Price Responsive Load: Takeaways

- Most of the expensive aspects of the PPA only sensitivity came from the increased cost of deploying new zero-carbon resources.
  - As more of the year is decarbonized, new resources are not generating more energy for large portions of the year. To guarantee revenue for new resources, they had to be paid more than resources that already existed.
  - This led to higher PPA prices, higher curtailments, frequent negative LMPs, and higher capacity prices.
- With discretionary load, more energy from the new resources can be absorbed productively. This alleviates many of the issues related to continued deployment of PPAs.
  - Because more energy is used, curtailments are lower, there is less need to undercut existing resources, and negative LMPs are less frequent.
  - These results imply that load-side changes may be more impactful than resource mix changes at certain points in the build out of a low carbon grid.
- At the assumed production tax credit, electrolyzers are able to cover the cost of their build and operation. Additional costs and expenses that were not considered but would be very impactful to the economics of electrolyzer operation are:
  - Revenue from selling hydrogen
  - Cost of storing and transporting hydrogen

Price Responsive Load: PPA Prices



- The PPA only sensitivity saw a spike in PPA costs due to increasing amounts of curtailment past 2035.
- With additional electrolyzer load, more of the new resource energy can be used, leading to lower curtailments and lower PPA costs.

Price Responsive Load: Average Locational Marginal Prices

	2025	2030	2035	2040	2045
PPA Only ($/MWh)	31.37	29.95	23.88	12.50	-15.83
Price Responsive Load ($/MWh)	31.37	31.12	24.21	27.14	20.65

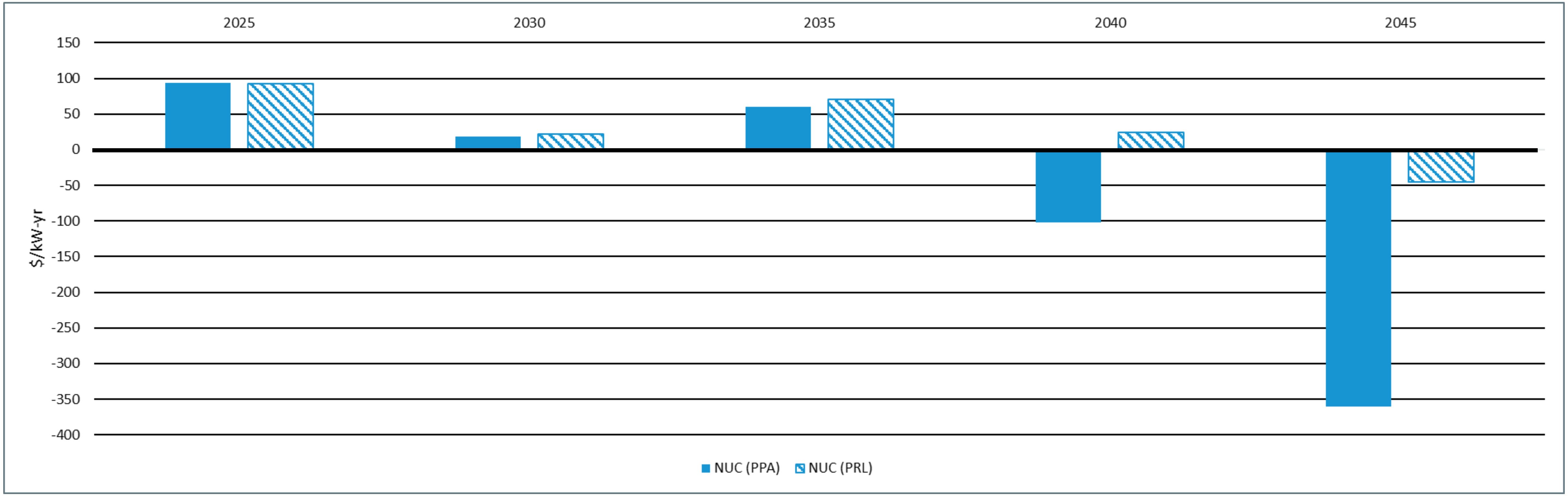
- In the PPA only sensitivity, LMPs dropped over time, with average LMPs being negative by 2045.
- In the price responsive load sensitivity, LMPs still decrease over time, but do not become as negative. The additional load raises average LMPs due to less frequent curtailments and associated negative LMPs.

Price Responsive Load: Generation by Fuel Type (GWh)

		Coal	Oil	MSW/LFG/ Wood	Gas	Nuclear	Hydro	PV	Wind	Imports
2025	PPA Only	0	0	5,584	29,903	29,241	10,030	385	13,140	27,227
	PRL	0	0	5,587	29,952	29,193	10,026	385	13,133	27,232
2030	PPA Only	0	0	5,608	20,929	29,124	9,129	324	23,533	26,193
	PRL	0	0	5,601	21,008	29,158	9,226	339	23,614	26,600
2035	PPA Only	0	0	5,607	29,462	29,158	9,422	337	36,072	26,002
	PRL	0	0	5,611	29,541	29,145	9,480	345	36,186	26,349
2040	PPA Only	3	0	5,651	22,382	29,206	8,221	12,546	57,905	22,800
	PRL	0	0	5,660	23,189	29,159	8,884	12,813	61,056	27,019
2045	PPA Only	38	0	5,658	14,836	29,211	7,093	15,440	81,830	19,198
	PRL	39	0	5,683	17,325	29,240	7,865	16,388	90,903	27,252

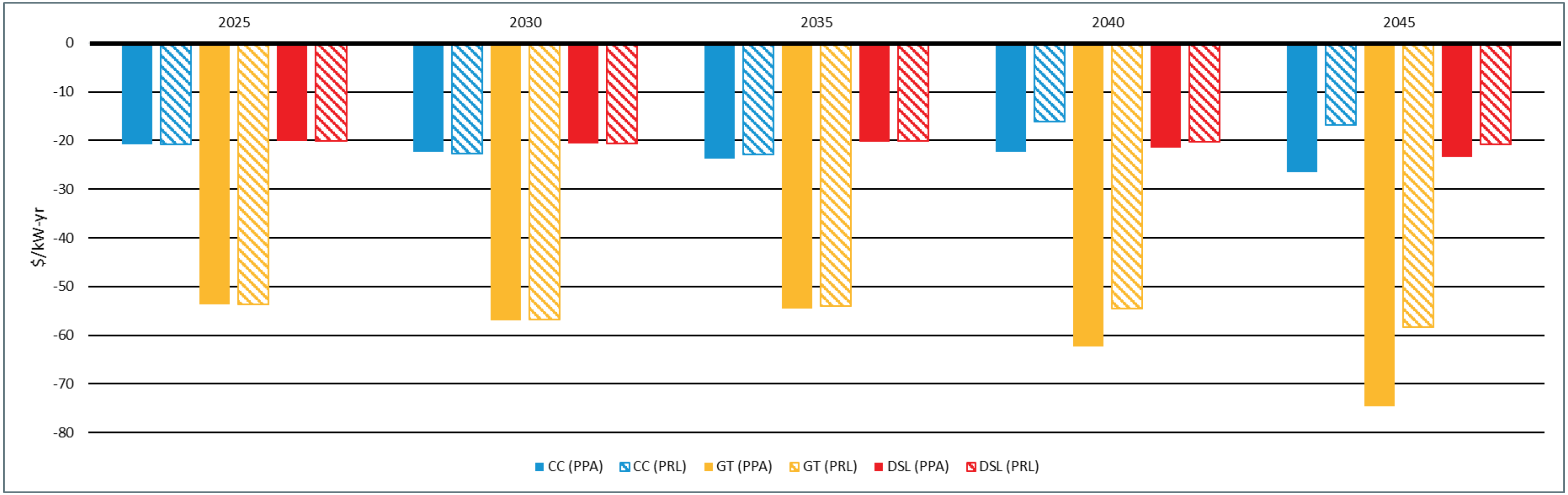
- The most significant difference is in utilization of zero-carbon resources and imports. In 2040 and 2045, the price responsive load sensitivity is able to utilize significantly more zero-carbon energy which would otherwise be curtailed.

Price Responsive Load: Effect on Nuclear Net Profits



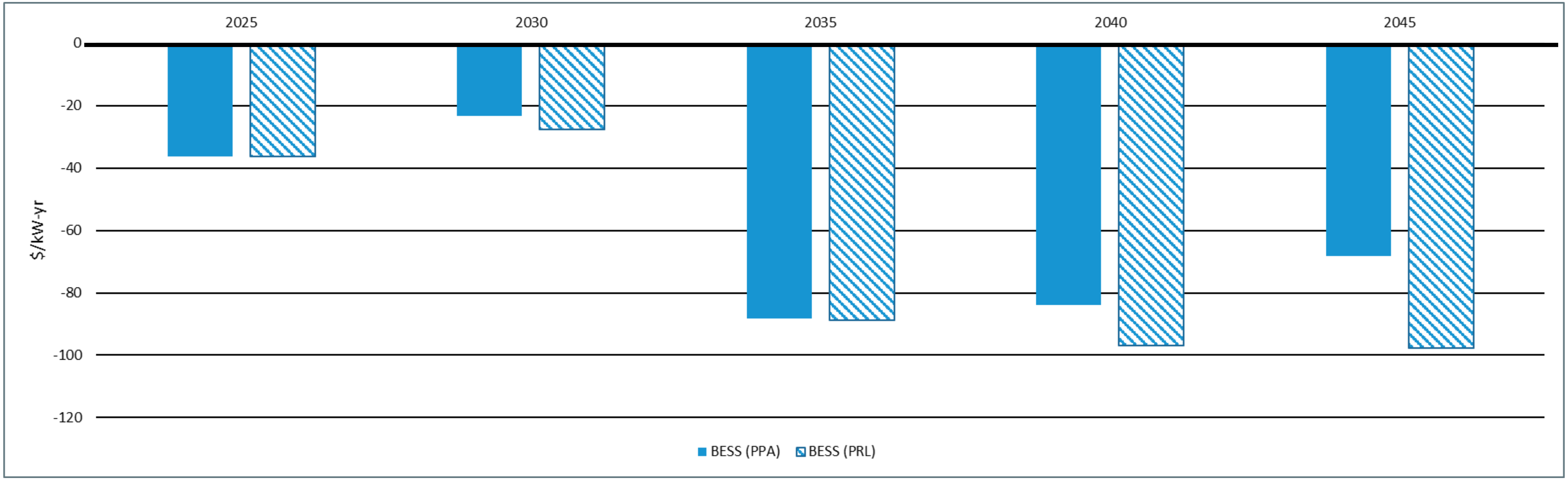
- Note: net profits = energy market revenues – fixed costs – production costs.
- The PPA saw decreased nuclear net profits due to frequent negative LMPs.
- With additional price responsive load, negative LMPs were less frequent and nuclear net profits did not drop as far.

Price Responsive Load: Fossil Unit Net Profits



- Note: net profits = energy market revenues – fixed costs – production costs
- Net profits for fossil units are similar in the two sensitivities.
- Differences in energy storage operation slightly impact the net profits of fossil units in later years.

Price Responsive Load: Energy Storage Net Profits



- Note: net profits = energy market revenues – fixed costs – production costs – build costs
- Negative LMPs increase energy storage net profits.
- With electrolyzers reducing the frequency of negative LMPs, energy storage units earn less profits than in the PPA-only sensitivity.

Price Responsive Load: Curtailment, Electrolyzer Load, and Energy Storage

	2025		2030		2035		2040		2045	
	PPA	PRL	PPA	PRL	PPA	PRL	PPA	Elec	PPA	PRL
Curtailed Energy (GWh)	49	49	1,444	804	1,730	1,274	7,883	309	17,940	0
ES net load (GWh)	211	211	544	519	657	628	2,476	1,430	4,947	1,481
Electrolyzer load (GWh)	0	0	0	704	0	609	0	9,923	0	24,612

- The addition of price responsive load greatly reduces the amount of curtailed energy.
- However, beginning in 2040 in the price responsive load sensitivity, batteries and pumped storage cycle significantly less energy and their net profits are lower as a result.

Price Responsive Load: Capacity Prices ($/kW-month)

	2025	2030	2035	2040	2045
PPA	6.61	6.66	7.84	8.68	30.15
PRL	6.61	6.94	7.82	8.54	8.66

- In the PPA sensitivity, the large negative profits of nuclear units materialized as a large capacity payment instead of unit retirement.
  - The marginal capacity bid is a fossil unit from 2025-2030, an energy storage unit in 2035, and the nuclear units in 2040-2045.
- In the price responsive load sensitivity, nuclear net profits do decrease over time, but nuclear units do not become the marginal capacity bid.
  - The marginal capacity bid is a fossil unit from 2025 to 2030, then an energy storage unit from 2035-2045.
- Total capacity payments to ensure revenue adequacy are much lower.

PPA vs. Price Responsive Load: Total Costs (Million $)

	PPA				Price Responsive Load			
	LSEEE	PPA	Capacity	**Total**	LSEEE	PPA	Capacity	**Total**
2025	3,264	846	2,227	**6,337**	3,264	846	2,227	**6,337**
2030	2,616	1,933	2,394	**6,944**	2,595	1,838	2,495	**6,928**
2035	3,578	3,062	3,421	**10,061**	3,645	3,026	3,419	**10,089**
2040	3,004	11,763	4,853	**19,620**	3,328	7,906	4,778	**16,012**
2045	2,267	22,485	19,856	**44,609**	2,557	11,687	5,702	**19,946**

- Total costs are lower in the price responsive load sensitivity for two reasons:
  - The additional load keeps PPA costs lower because more zero-carbon energy is being utilized. There is no need for new PPA contracts to have to be paid more to underbid existing contracts.
  - Without frequent very negative LMPs, nuclear revenues are not as low, and capacity prices never spike as they do in the PPA-only sensitivity.

Price Responsive Load: Electrolyzer Economics

	2025	2030	2035	2040	2045
Electrolyzer Nameplate (MW)	0	500	500	8,000	23,000
Annualized Build Cost (Thousand $)	0	22,207	22,207	355,309	1,021,515
Electrolyzer Load (GWh)	0	704	609	9,923	24,612
Load Revenue * (Thousand $)	0	4,803	6,136	21,778	4,347
H_2 Production (tons)	0	17,297	14,963	243,808	604,717
H_2 Tax Credit (Thousand $)	0	34,595	29,926	487,616	1,209,434
Electrolyzer Net Profit ($/kW)	0	34	28	19	8

- Note: these calculations do not include the cost of storage, transportation or any profits from selling the hydrogen.
- The electrolyzers return a net profit, though the profit decreases as more are deployed.

(*) Load Revenue is positive because energy is purchased only when less than zero (e.g., paid to take)