



PRINCETON UNIVERSITY

ZERO LAB

Zero-carbon Energy Systems Research and Optimization Laboratory

New Jersey's Pathway to a 100% Carbon-Free Electricity Supply: Policy and Technology Choices Through 2050

Summary for Decision Makers

Qingyu Xu, Neha Patankar, Chuan Zhang, and Jesse D. Jenkins, March 14, 2022

New Jersey's Pathway to a 100% Carbon-Free Electricity Supply: Policy and Technology Choices Through 2050

Summary for Decision Makers

Qingyu Xu, Neha Patankar, Chuan Zhang, Jesse D. Jenkins

Zero-carbon Energy Systems Research and Optimization Laboratory (ZERO Lab)
Princeton University

March 14, 2022

(Corrected version published March 26, 2022)

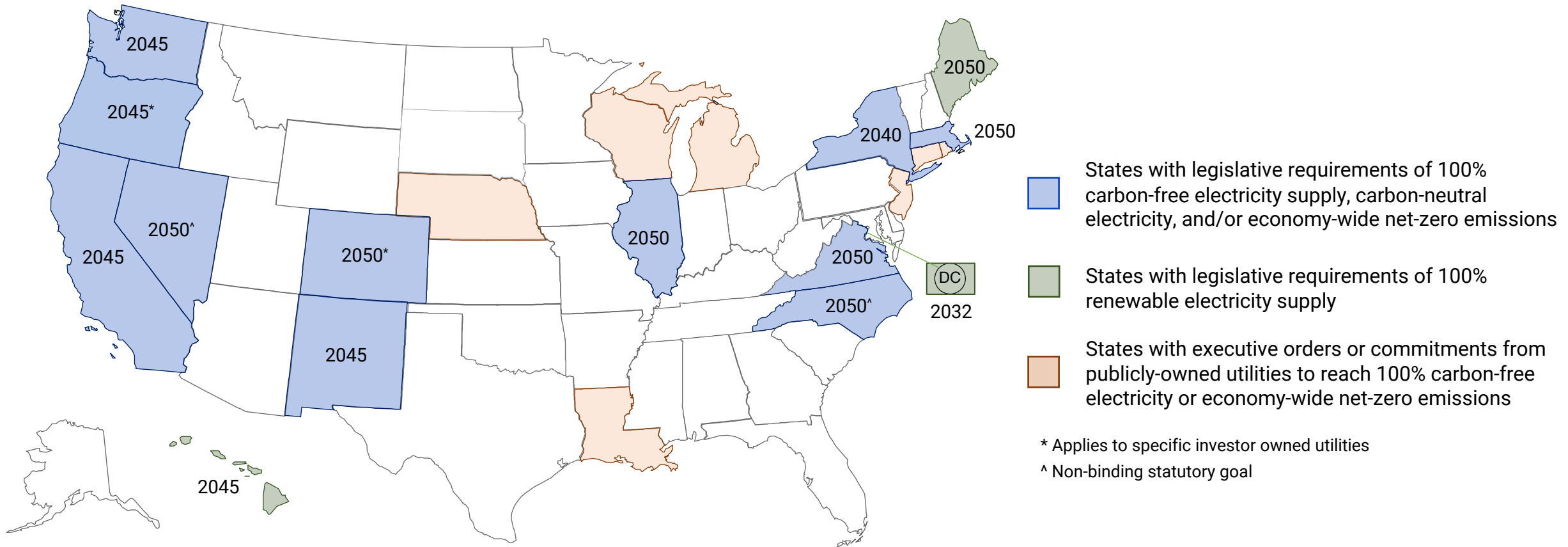
Suggested citation: Xu, Q., Patankar, N., Zhang, C., and Jenkins, J.D., 2022, "New Jersey's Pathway to a 100% Carbon-Free Electricity Supply," Zero-carbon Energy Systems Research and Optimization Laboratory (ZERO Lab), Princeton University, Princeton, NJ, March 14.

[doi:10.5281/zenodo.6345570](https://doi.org/10.5281/zenodo.6345570)

This project was supported by Public Service Enterprise Group (PSEG) through Princeton E-affiliates Partnership.

Access and download data and other resources at <https://zenodo.org/record/6345570>

New Jersey is among a vanguard of states pursuing a transition to a 100% carbon-free electricity system.



New Jersey's commitment to 100% clean electricity

In 2018, Governor Phil Murphy's [Executive Order 28](#) set a goal of 100% clean energy by 2050 and tasked the state's Board of Public Utilities, in consultation with other state agencies, to develop the **New Jersey Energy Master Plan** to provide a “comprehensive blueprint” for the state's conversion to a carbon-free electricity supply. Additionally, the state's [Global Warming Response Act of 2007](#) (P.L. 2007 c.112; P.L. 2018 c.197) directs state agencies to develop plans and policies to reduce statewide greenhouse gas emissions 80% by 2050.

The [Energy Master Plan](#) (*EMP*), released in January 2020, defines the goal of “100% clean energy” as 100% carbon-neutral electricity supply by 2050 and maximum electrification of transportation and buildings to meet or exceed the requirements of the Global Warming Response Act. The *EMP* includes comprehensive modeling of pathways to transform the state's energy system (the “Integrated Energy Plan”) and outlines a set of seven key strategies to reach New Jersey's clean energy goals. The *EMP* strategy rests centrally on electrification of vehicles and buildings, accelerated deployment of renewable and distributed energy resources, retention of existing nuclear power plants, and improved energy efficiency. Goals include (among other measures):

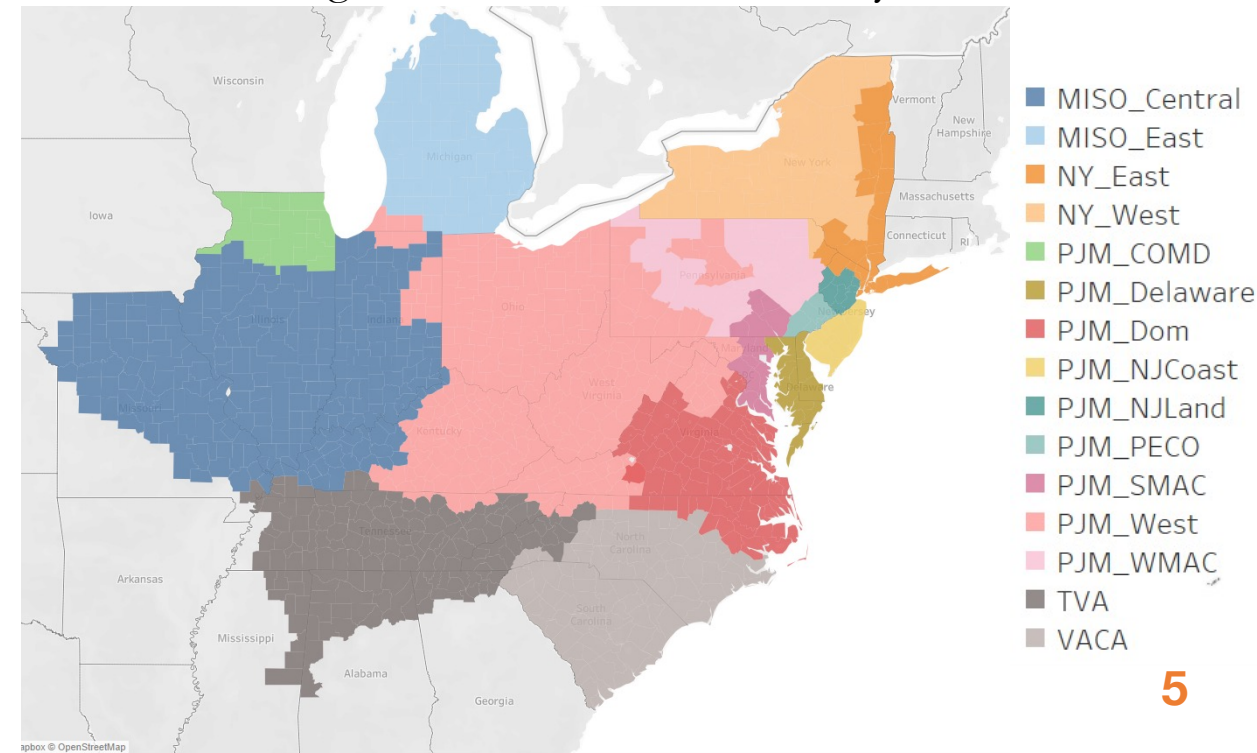
- **100% carbon-neutral electricity supply and 75% renewable electricity supply by 2050**, building on the state's current law requiring 50% renewable electricity by 2030 and zero-emissions certificates supporting the state's existing nuclear power plants through 2030.
- **7,500 megawatts of offshore wind by 2035.**
- **2,000 megawatts of energy storage by 2030.**
- Increased deployment of **distributed and community solar photovoltaics.**
- **330,000 light-duty electric vehicles on the road by 2025.**
- Incentives for electrified **heat pumps**, hot water heaters, and other appliances.
- Programs to **reduce overall energy consumption** and, in particular, peak electricity demand.

This study

The goal of this study is to provide a detailed assessment of key policy and technology options and choices and their implications for New Jersey's pathway to 100% carbon-free electricity. In particular, this study examines least-cost pathways to reach New Jersey's current laws and stated policy goals under a range of possible future conditions and explores the role of in-state solar PV, offshore wind, nuclear power, gas-fired power plants and imported electricity in the state's electricity future. Our goal is to provide an independent assessment of costs and trade-offs associated with different choices facing New Jersey stakeholders provide actionable insights for decision-makers.

For this study, we use a state-of-the-art open-source electricity system optimization model, [GenX](#), which plans investment and operational decisions to meet projected future electricity demand while meeting all relevant engineering, reliability, and policy constraints at the lowest cost. We create a detailed model of the electricity system of New Jersey, the PJM Interconnection, and neighboring grid regions (15 total zones including two in NJ and nine in PJM) and explore a range of policy, technology, and fuel price scenarios to assess options for New Jersey to reach a 100% carbon-free electricity supply by 2050. See the [Methods](#) section in the full report for details.

Model regions/zones used in this study



Key findings

1. A transition to **100% carbon-free electricity is feasible while maintaining reliability and with reductions in bulk electricity supply costs** (-29% to -10% vs. 2019 costs under a least-cost approach).
2. The lowest-cost strategy to reach 100% carbon-free electricity supply entails a significant increase in NJ's **dependence on imported electricity**. Imports of wind, solar and other carbon-free resources from out of state are generally more affordable than available in-state resources.
3. Electricity **demand could increase significantly** (up to +70% total sales and +85% peak demand), and **patterns of consumption shift** dramatically (from summer afternoon to winter overnight peak demand) due to electrification of vehicles and buildings consistent with NJ economy-wide climate goals.
4. The **lowest-cost pathway to 100% carbon-free electricity departs from NJ's current policy approach**, which prioritizes in-state and distributed generation (e.g., solar, offshore wind, nuclear).
5. Import dependence can be reduced by **requiring in-state renewable resources and preserving the state's existing nuclear reactors**; the most affordable strategy to prioritize in-state resources increases bulk electricity supply costs by 7-10% relative to the least-cost 100% carbon-free pathway, but still results in costs comparable to or lower than today (-24% to -1% vs 2019).
6. If **more states in the region pursue parallel deep decarbonization goals, the costs of reaching 100% carbon-free electricity in NJ increase** by 16-20% in 2050, as greater demand for clean electricity across the region drives up import costs and NJ relies more on in-state clean energy resources. Bulk electricity supply costs in 2050 range from -17% to +5% relative to 2019 costs if all states in the region pursue 100% carbon-free electricity and high electrification strategies.



Key technology options

- The least-cost pathway to 100% carbon-free electricity supply for NJ includes substantial **expansion of utility-scale solar, new gas-fired generating capacity** (combined cycle power plants), conversion of all gas plants to run on **zero-carbon fuels** (e.g., hydrogen, biomethane, synthetic methane) by 2050, and **increased imports** of zero-carbon electricity from out of state, along with offshore wind, distributed solar, and storage capacity required by current policy.
- Preserving **NJ's nuclear generators** can reduce dependence on imports and avoid an increase in fossil gas generation and associated CO₂ emissions and air pollution in the 2030s. Supporting continued operation of NJ reactors after 2030 is consistently amongst the lowest-cost options for in-state carbon-free generation but would require ongoing policy support after 2030. If all states in the region pursue deep decarbonization and/or NJ prioritizes in-state generation, maintaining nuclear operation is a least cost strategy.
- **Utility-scale solar** is considerably lower cost than the distributed solar systems that have been historically prioritized by state policy. Expanding utility-scale solar is part of the least-cost portfolio in all scenarios, but deployment may be constrained in the long-run by available land for siting of large-scale solar farms.
- Expanding **distributed solar** will require substantial policy support but may become lower cost than offshore wind by the 2040s. Requiring 23 gigawatts of distributed solar by 2050 (similar to the NJ *Energy Master Plan* scenario) would increase 2050 bulk electricity supply costs 6-11% relative to the least-cost, import-dependent strategy, but growing distributed solar could lower costs if the state requires 80% of clean electricity is produced in NJ. Note this study is limited in scope to modeling of the wholesale electricity supply and transmission system. Distributed solar systems can result in significant distribution network costs or savings, depending on the pattern and scale of deployment, and these impacts are not assessed.

Key technology options

- **Offshore wind** is one of the more expensive options for NJ decarbonization and is rarely deployed beyond current mandated levels across scenarios modeled in this report. Exceptions are observed in futures where all states pursue deep decarbonization goals or if the state opts not to develop lower cost solar or preserve existing nuclear.
- **Flexible electricity demand** can reduce NJ's peak consumption and help compensate for increasing demand from electrification of vehicles and buildings. Unlocking flexible demand can substitute for poorly utilized battery energy storage and gas-fired generator capacity and eventually lead to cost savings for NJ consumers on the order of half a billion dollars annually.
- NJ **gas-fired generating capacity** expands until 2040 in all scenarios, while electricity generation, consumption of fossil gas, and related emissions from these units all decline. Gas-fired capacity would need to be converted to run on zero-carbon fuel (or any residual emissions would need to be offset by carbon removal technologies) by 2050 when 100% carbon-neutral electricity is required. By this time, gas generators are used very infrequently to provide firm power during periods when both wind and solar output are low.
- NJ will need to **expand transmission** to increase deliverability between the coastal and inland areas in the near term in order to integrate offshore wind as well as significantly strengthen ties to neighboring PJM & NY areas in the longer term to enable greater imports.

Implications for New Jersey decision makers

- **Electricity costs can remain affordable** (comparable to or lower than 2019 costs) even as New Jersey transitions to 100% carbon-free electricity by 2050, consistent with the goals outlined by Governor Murphy in 2018 and the 2020 *Energy Master Plan*.
- However, **New Jersey decision-makers and stakeholders face a key choice** as to whether to pursue a lower-cost pathway to 100% carbon-free supply that involves significantly increased dependence on imported electricity or to continue to prioritize in-state carbon-free resources such as solar PV and offshore wind at a higher cost. As the full range of implications extends far beyond electricity supply costs, further discussion and analysis should carefully explore these choices and the associated impacts on the state's economy, environment, and quality of life.
- In particular, **New Jersey should prepare for the possibility that other states in PJM and neighboring regions follow New Jersey on the path to deep decarbonization**, which we find would significantly increase the cost of imported clean electricity from elsewhere in the region and make further cultivation of in-state resources more desirable.
- Of all in-state carbon-free resources, **maintaining operations of the state's three existing nuclear reactors (at Salem and Hope Creek stations) is consistently amongst the cheapest available options, along with further development of utility-scale solar PV**. Smaller-scale distributed solar PV and offshore wind are costlier options.
- **Modest expansion of gas-fired generating capacity through 2040 appears to be a robust strategy** across all scenarios, providing additional firm capacity to meet increased peak demand from electrification, **but with declining utilization rates and associated emissions** of greenhouse gases and air pollutants over time. **By 2050, all gas-fired generators would need to convert to use zero-carbon fuels** (such as hydrogen, biomethane, synthetic methane or ammonia produced via zero- or negative-emissions processes) or offset residual emissions with carbon removal and would operate at low annual utilization rates (capacity factors).
- **Regulatory and policy incentives and market reforms to unlock flexible electricity demand are critical** to secure the most cost-effective route to 100% carbon-free electricity and accommodate significant increases in electricity demand associated with electrification of vehicles, buildings and industry consistent with the state's economy-wide decarbonization goals.

Overview of scenarios

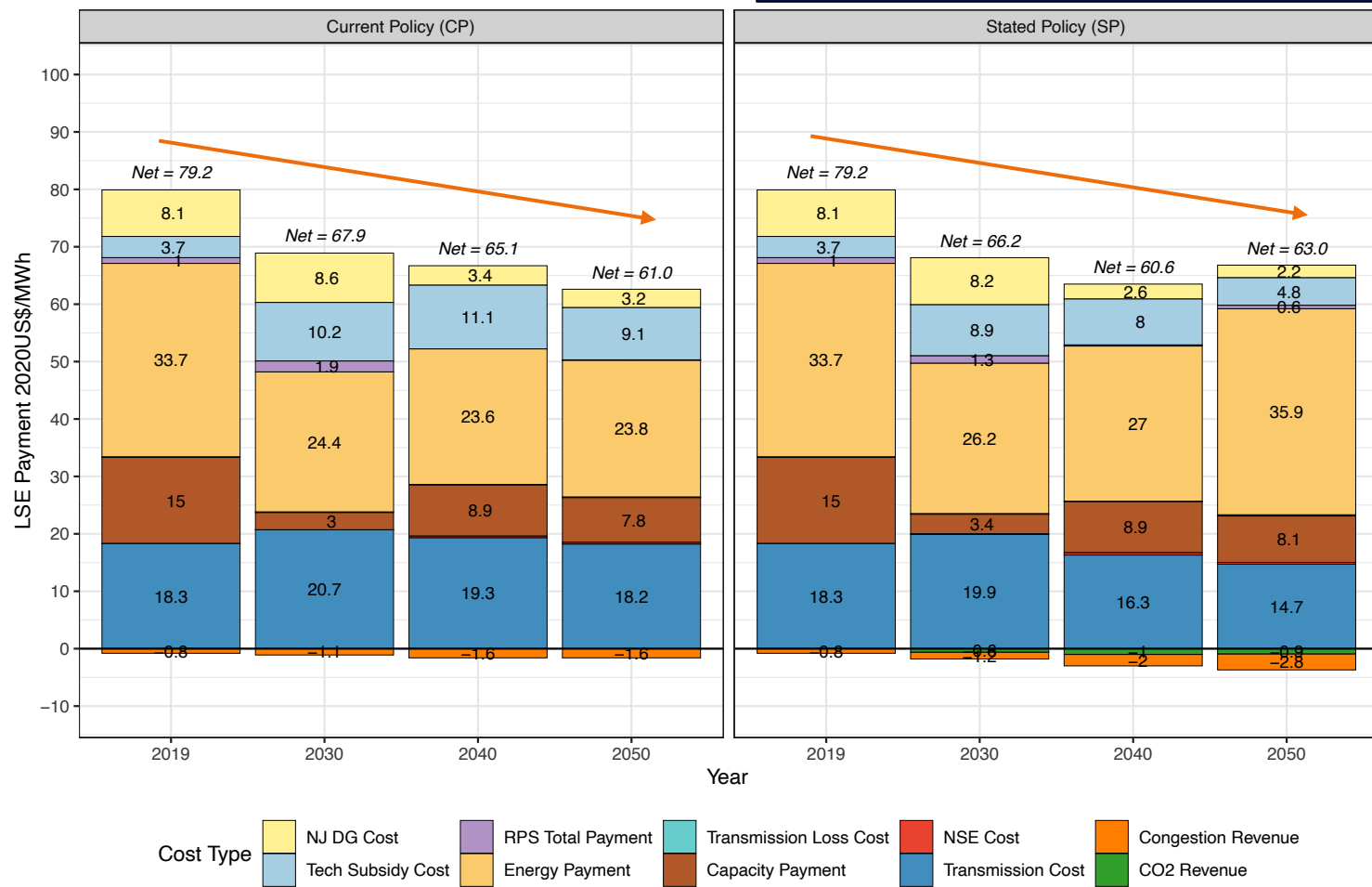
Three main scenarios modeled in this study:

- 1. Current Policies (CP):** a business-as-usual scenario, with all electricity sector-related legislation and regulation as codified as of the end of 2020. Policies include state renewable portfolio standard (RPS) and clean electricity standard (CES) policies, technology-specific RPS carve-outs (e.g., distributed solar), capacity deployment mandates (e.g., offshore wind), and state supports for existing nuclear power plants (e.g., NJ zero emissions certificates (ZEC) program). On the demand side, only states with codified electrification targets and state supports to reach these goals (e.g., NJ goal of 330,000 plug-in electric vehicles by 2025) are included.
- 2. Stated Policies (SP):** Includes all Current Policies as well as state-level goals enshrined in executive orders as of the end of 2020. For New Jersey, this includes a 75% RPS and 100% carbon-free electricity standard by 2050. Other state goals such as Pennsylvania joining the Regional Greenhouse Gas Initiative are also modeled. Any state (including NJ) with an economy-wide emissions goal is assumed to pursue a high electrification strategy, with new demand from heating electrification (heat pumps for space and water heating) and vehicle electrification (across light, medium and heavy duty segments) included.
- 3. Deep Decarbonization (DD):** All Current Policies plus all states in PJM and modeled surrounding areas pursue 100% carbon-free electricity by 2050, modeled as a declining emissions intensity limit with an interim requirement of 80% below 2005 by 2030, 90% by 2040, and 100% by 2050.

A transition to 100% carbon-free electricity is feasible while maintaining reliability and with reductions in bulk electricity supply costs for NJ electricity consumers

CP: without new policy, electricity supply costs for NJ load serving entities (LSE) fall 23% (in real \$ terms)

SP: Under Stated Policies, a 100% emission-free electricity supply will cost NJ electricity consumers 20% less than payments for bulk electricity supply* in 2019 (spanning 10%-29% cost decrease across the range of possible futures modeled)



* Note: The scope of this report is limited to modeling of the wholesale electricity supply and transmission level.

DG solar PV is modeled as a reduction in net demand at the transmission level.

We do not make an attempt to assess potential costs or savings related to impacts of distributed solar PV on distribution networks, which are out of scope for this study, but relevant for consideration of the full cost/benefit of distributed solar installation.

The costs of policy support for DG solar installation are estimated outside of GenX modeling and added to modeled system cost results.

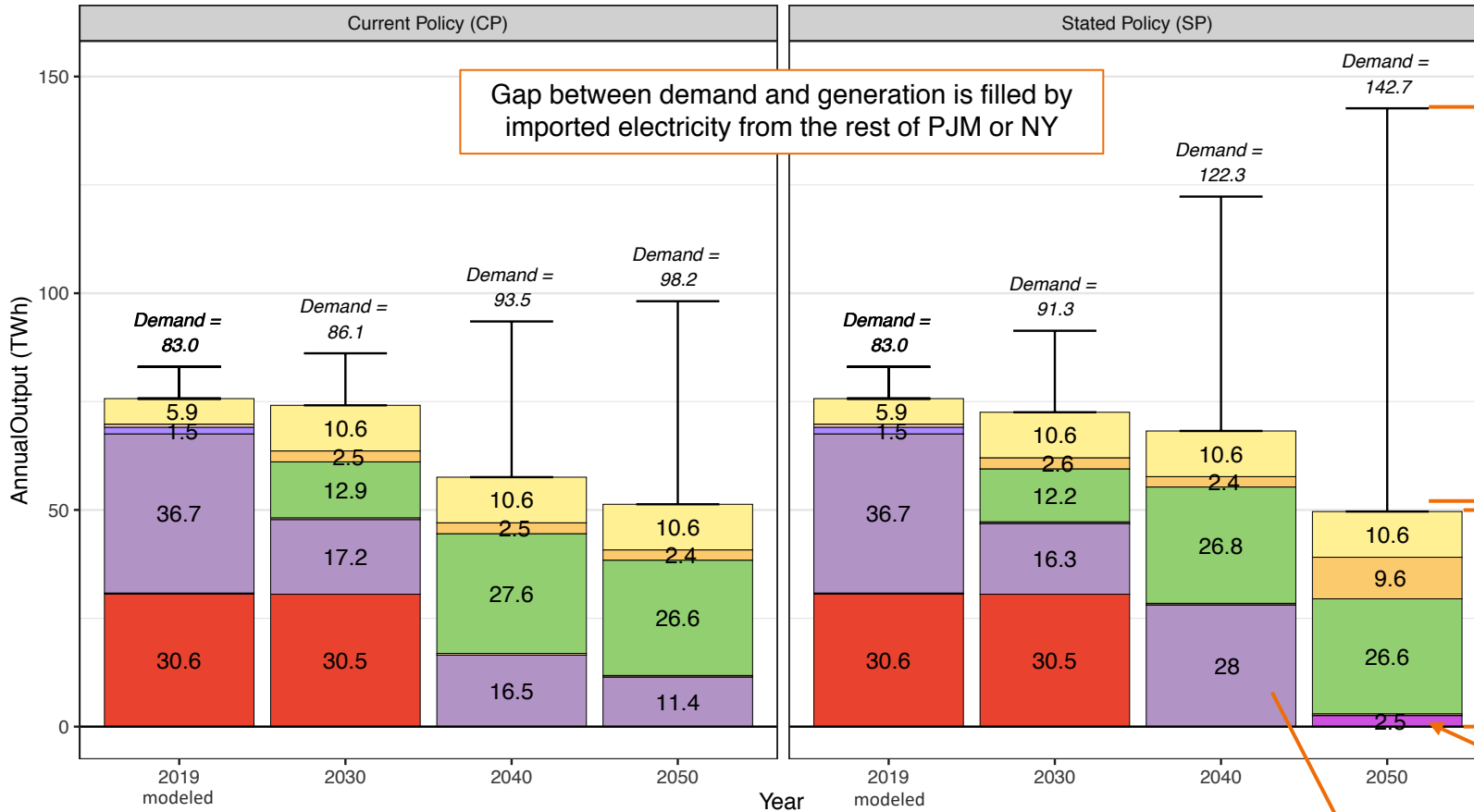
Relatedly, all battery capacity modeled in this report is assumed to operate at transmission voltage levels and does not include battery storage paired with distributed solar devices.

All reported \$ values are in real 2020 dollars.

Legend clarification: LSE = load serving entity (suppliers of end-use electricity); NJ DG Cost = subsidy for distributed solar PV; RPS Total Payment = subsidy for Class I RPS and CES eligible resources; Tech Subsidy Cost = subsidy for specifically mandated resources (offshore wind, storage, existing nuclear); NSE Cost = cost of involuntary non-served energy (\$0 in all cases due to capacity reserve requirement).

The lowest-cost strategy to reach 100% carbon-free electricity supply entails a significant increase in NJ's dependence on imported electricity

Generation Output of New Jersey under Sensitivity Mid



Gap between demand and generation is filled by imported electricity from the rest of PJM or NY

65% of 2050 load is supported by imports, with each MWh of demand in NJ matched with clean energy certificates from the rest of PJM

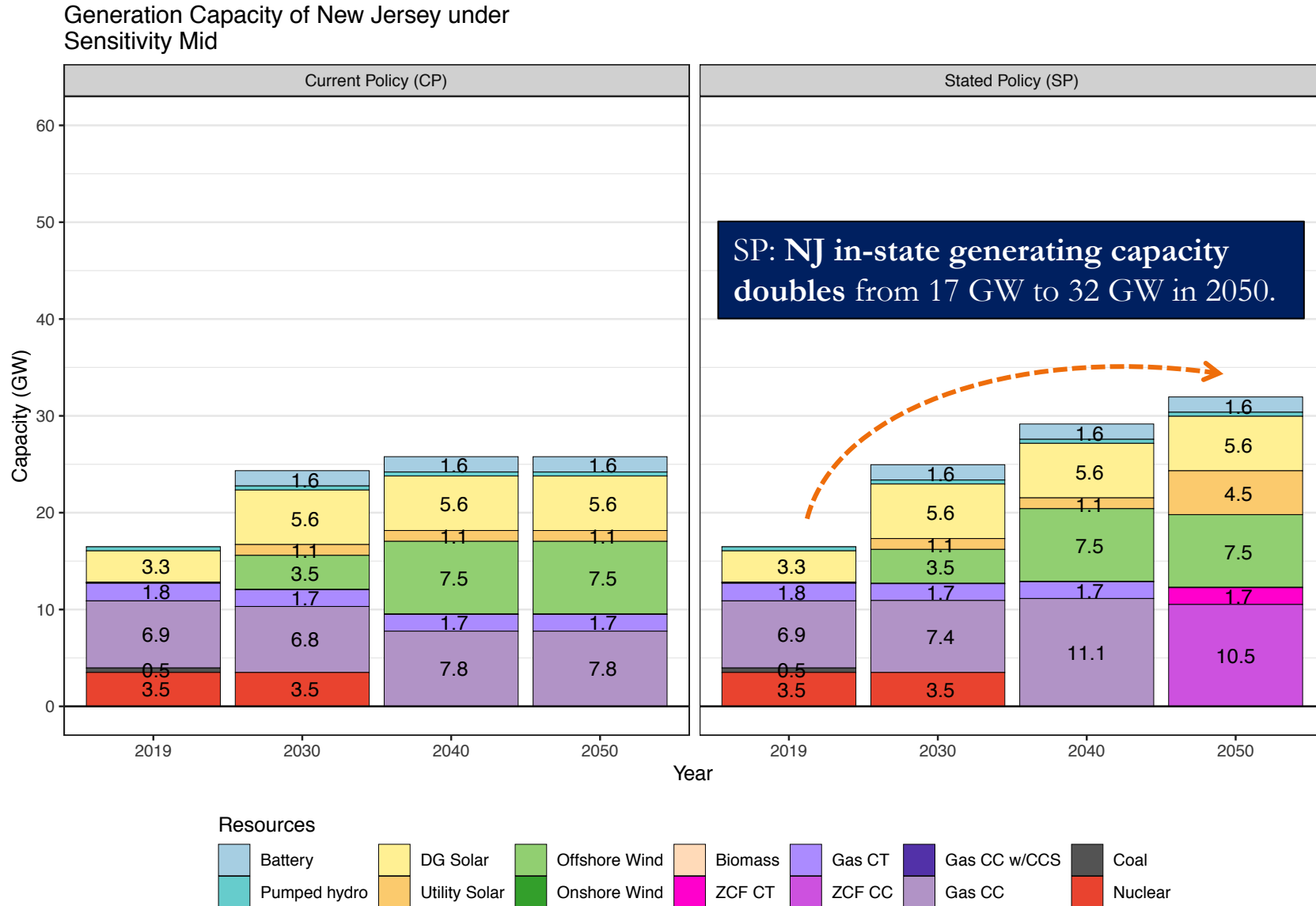
By 2050, in-state power generation is 100% CO₂ emission-free

By 2050, gas-fired combustion turbine & combined cycle power plants convert to use zero-carbon fuels, providing firm capacity but limited generation (2-3% annual utilization rate).

Under the lowest-cost strategy, natural gas capacity & generation increase in 2040 to meet growing demand from electrification and fill the supply gap left by retiring nuclear. **This can be avoided by retaining existing nuclear.**

Legend clarification: CC = combined cycle; CT = combustion turbine; Gas = fossil gas; ZCF = zero-carbon fuel; DG solar = solar PV capacity connected to the distribution system (both behind-the-meter and front-of-the-meter systems); Utility Solar is solar PV connected to the transmission system.

The lowest-cost strategy to reach 100% carbon-free electricity sees NJ's installed generating capacity double by 2050, formed by a diverse and clean resource mix.

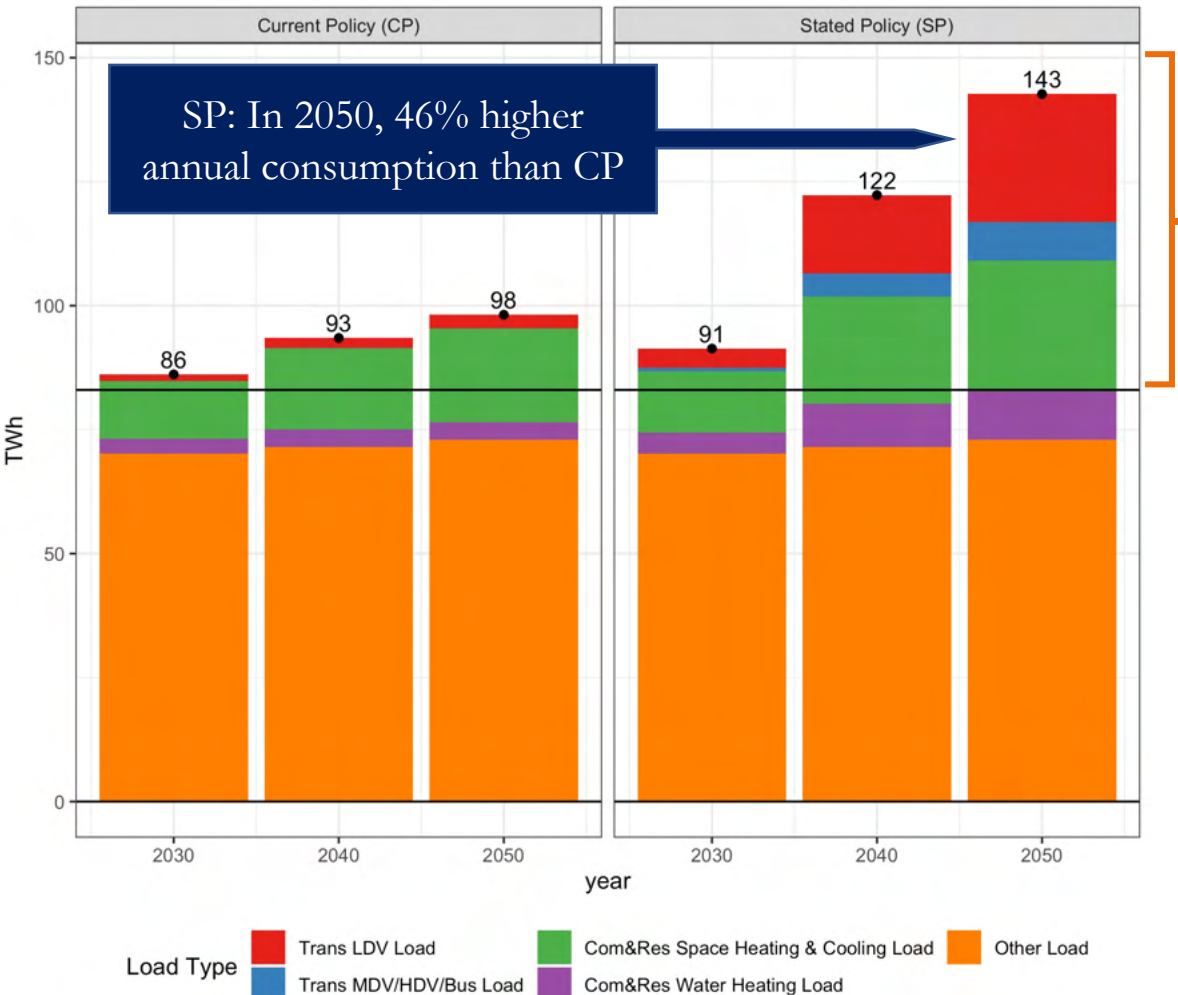


The least-cost pathway to 100% carbon-free electricity includes **expansion of utility-scale solar** and **new gas-fired combined cycle power plants**, with conversion of all gas-fired power plants to run on **zero-carbon fuels** (e.g., hydrogen, biomethane, synthetic methane) by 2050.

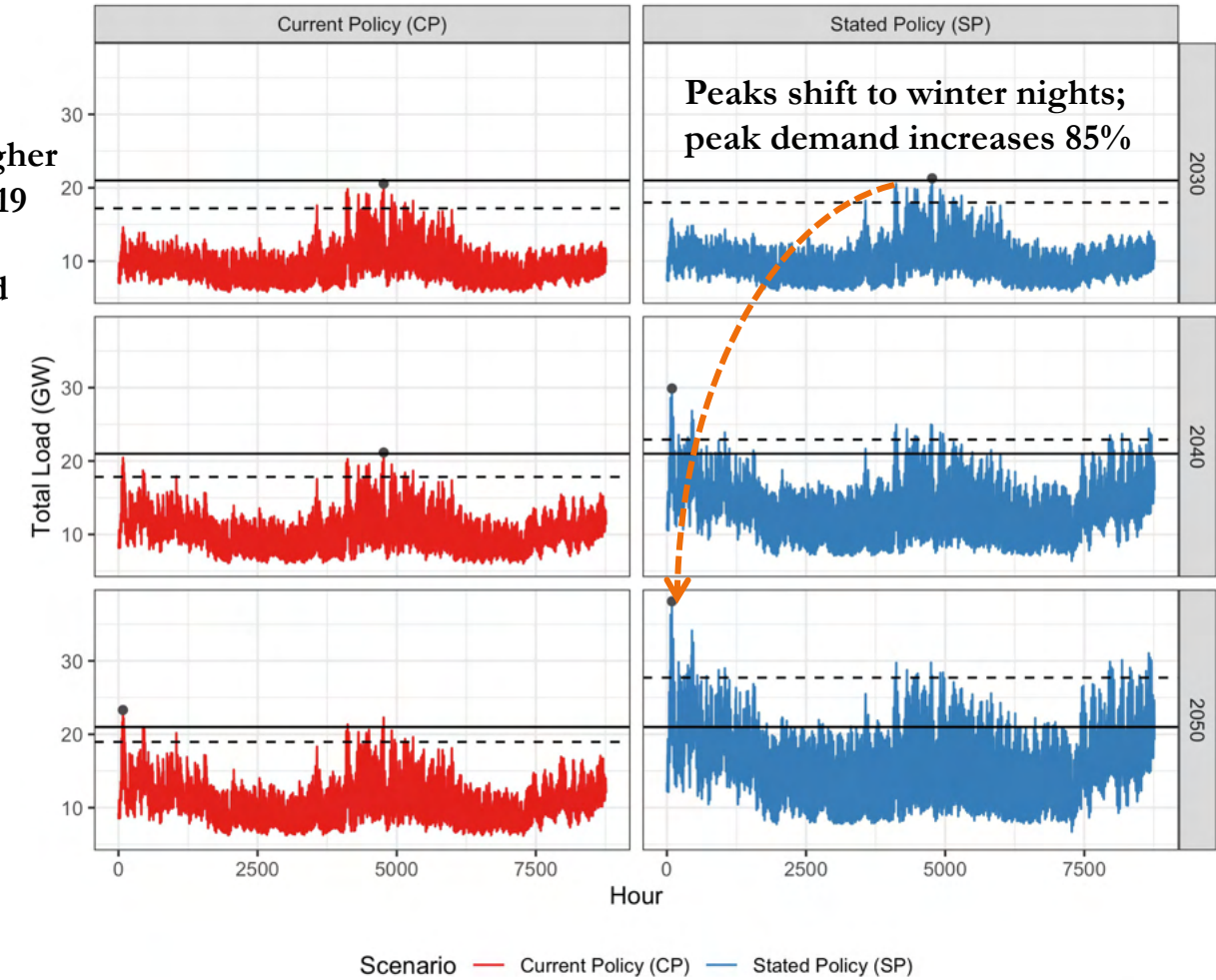
Offshore wind, distributed solar and battery storage do not expand beyond current NJ mandates in least-cost scenarios.

Nuclear capacity will also retire without further policy support beyond 2030.

Electricity demand could increase significantly and patterns of consumption shift dramatically (from summer afternoon to winter overnight peak demand) due to electrification of vehicles and buildings



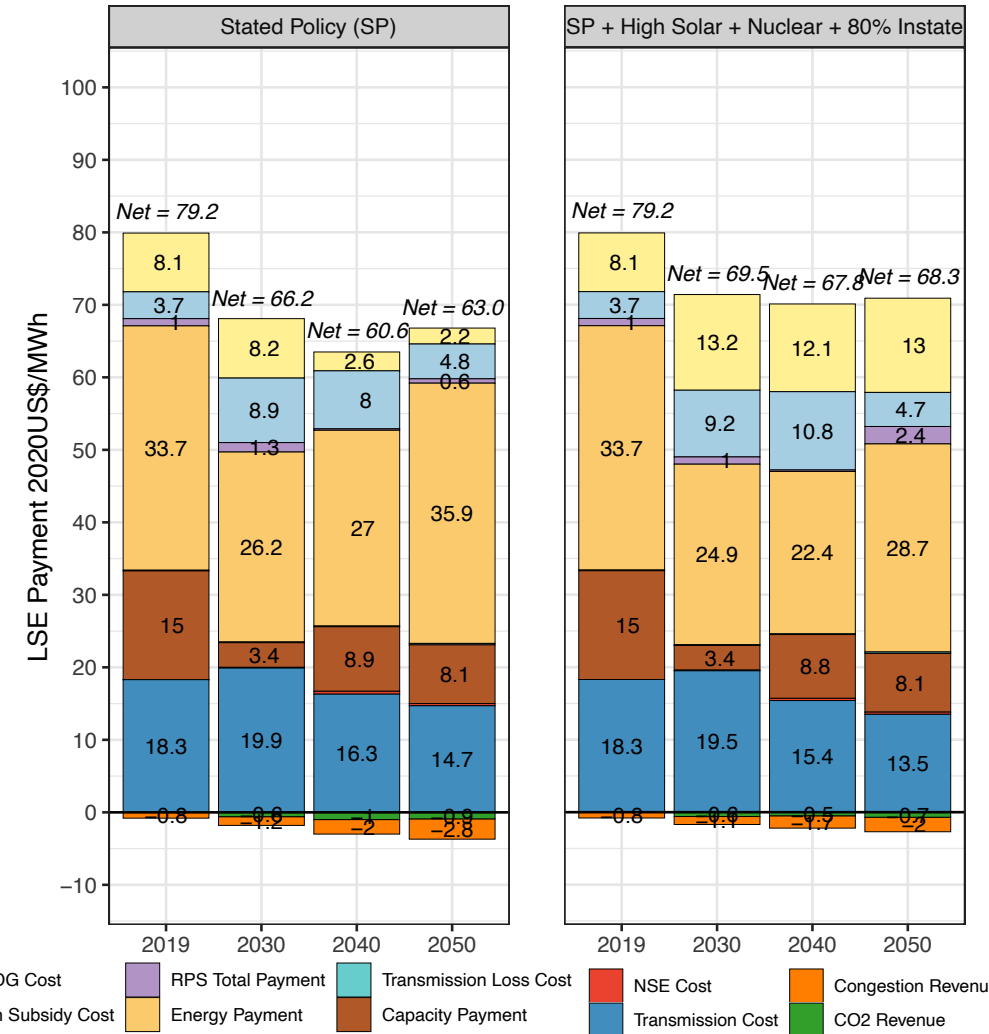
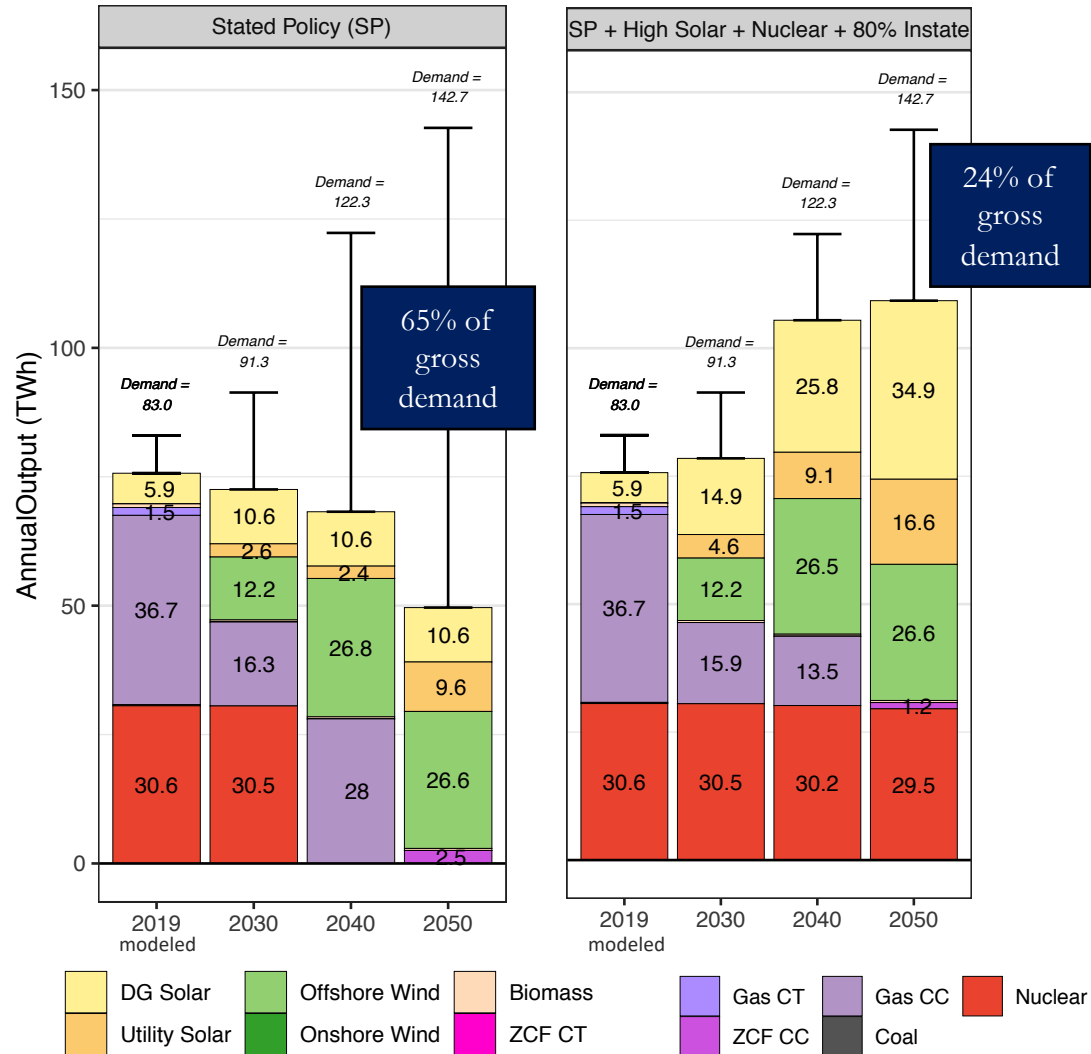
LDV/MDV/HDV = Light/Medium/Heavy-Duty Vehicle
horizontal line shows the 2019 level = 83 TWh



Dashed Line: the 100th highest Total Load
Dot: Peak Hour
Solid Line: 2019 Peak Total Load = 21 GW

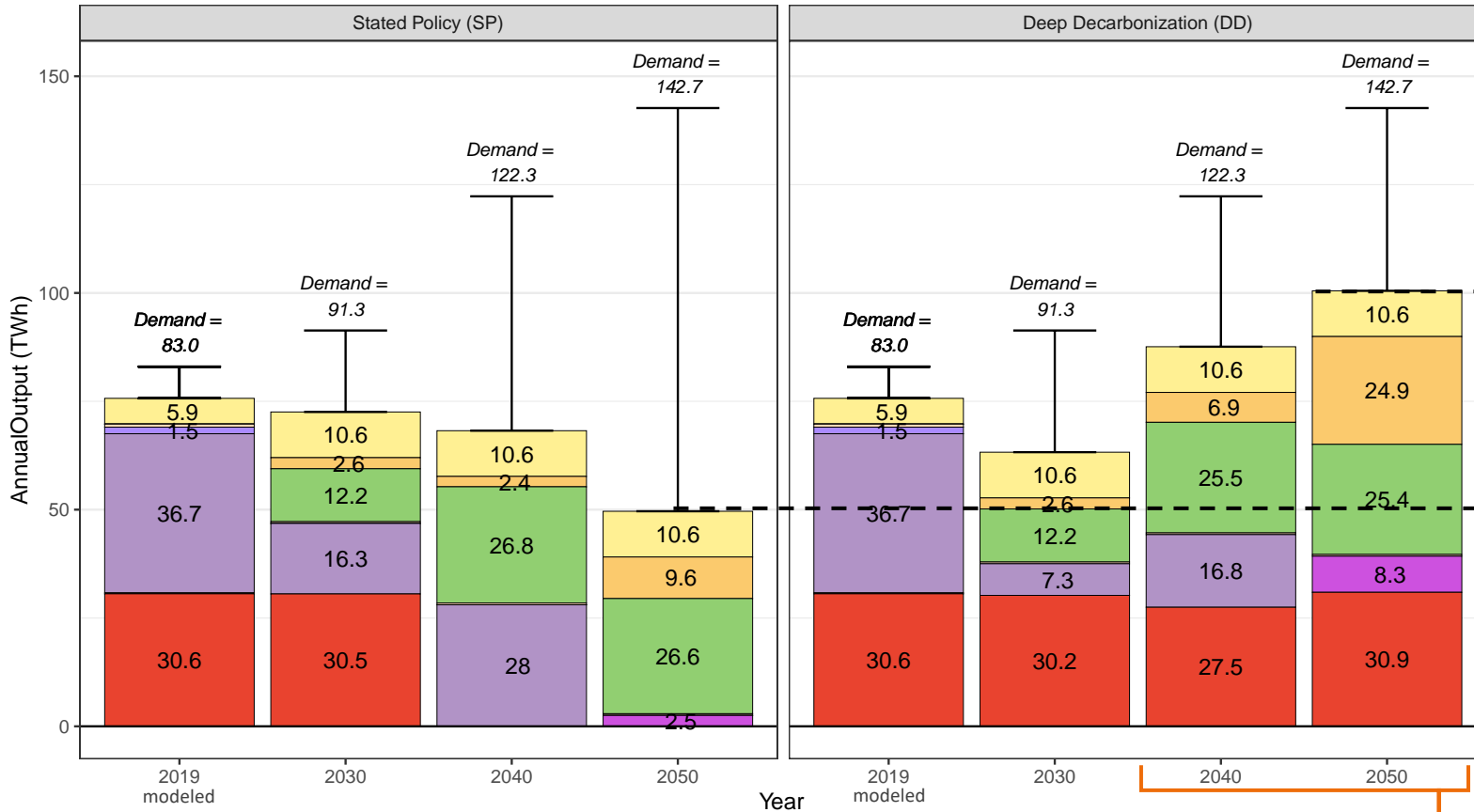
The lowest-cost pathways to 100% carbon-free electricity depart from NJ's current policy approach, which prioritizes in-state and distributed generation

Import dependence can be reduced by requiring in-state carbon-free resources and preserving the state's existing nuclear reactors; this increases bulk electricity supply costs by 7-10% relative to SP, but still results in costs comparable to or lower than today.



If all states in the region follow NJ on the path to deep decarbonization, greater demand for clean electricity across the region drives up import costs and NJ relies more on in-state clean energy resources.

Generation Output of New Jersey under Sensitivity Mid



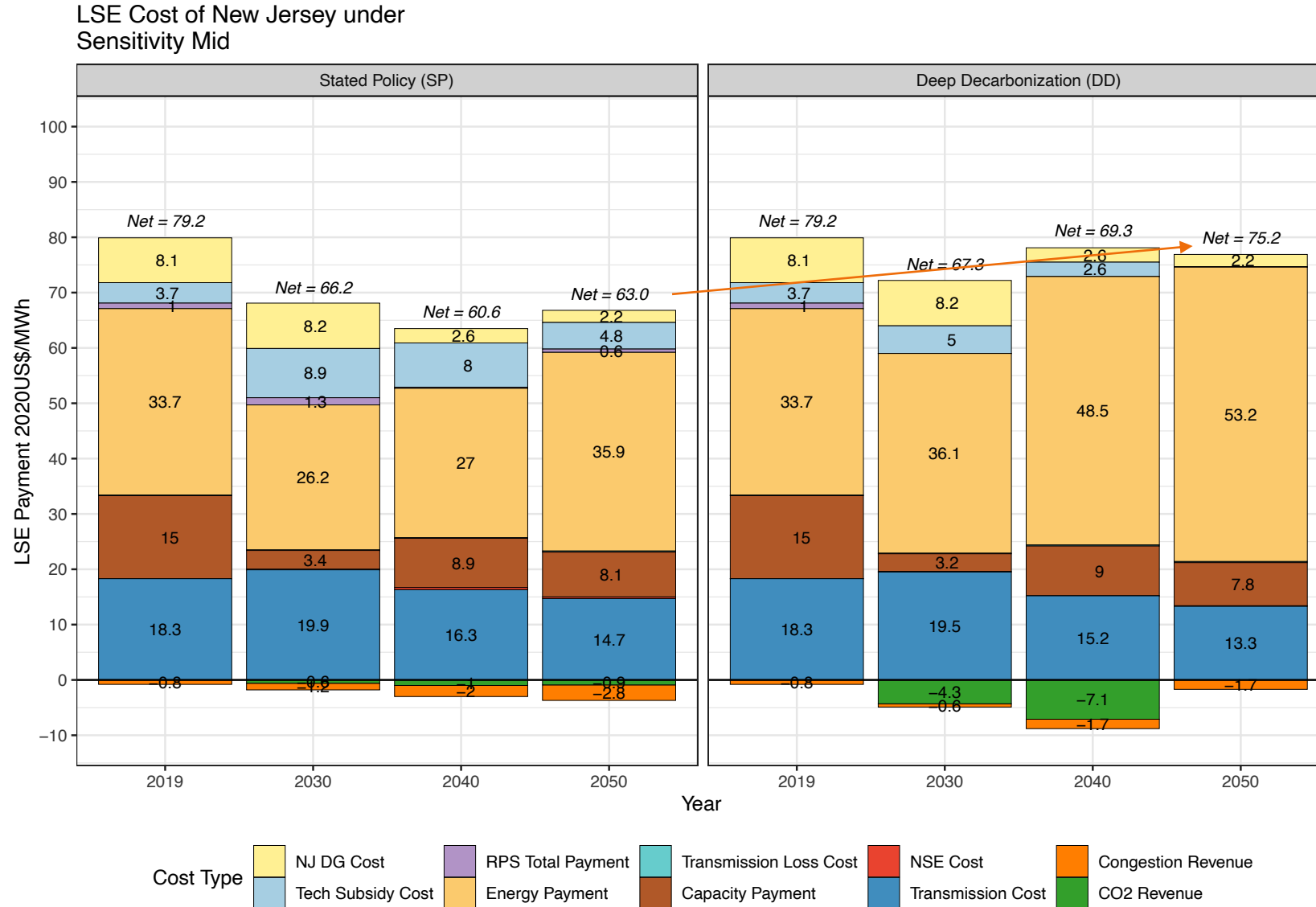
DD: As a result of more expensive imports, NJ builds higher-cost in-state resources, reducing reliance on imports relative to SP scenarios. (In-state generation doubles from SP.)

35% of gross demand

DD: NJ existing nuclear capacity can continue to run economically through 2050 without continued ZEC payments due to higher energy prices resulting from a CO₂ emissions limit.

Note: Deep Decarbonization is modeled through emission caps (carbon pricing) on PJM and neighboring regions separately (with no emissions permit trading between regions). In 2050, emission caps are zero, and gas-burning CC/CT are given the options to either retire or switch to zero-carbon-fuel; existing CC/CT that is built before 2020 and survives until 2050 are assumed to incur a capital expenditure equal to 50% of normal CC/CT CAPEX to retrofit for zero-carbon fuel combustion. (The same retrofit cost is applied for NJ CC/CT capacity in Stated Policies when 100% carbon-free electricity is required).

If all states in the region pursue parallel deep decarbonization goals, the costs of reaching 100% carbon-free electricity in NJ increase by 16-20% in 2050 and range from -17% to +5% relative to 2019 costs.



Expanding distributed solar is amongst the most expensive options for NJ and would require substantial policy support to continue growing beyond current state mandates

LSE Cost of New Jersey under Sensitivity Mid

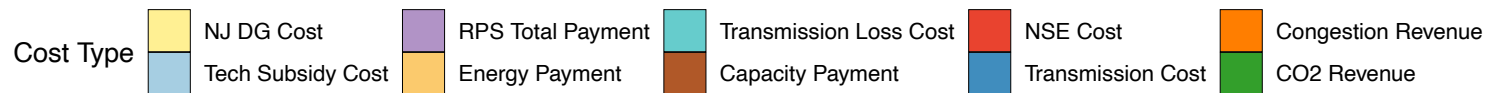
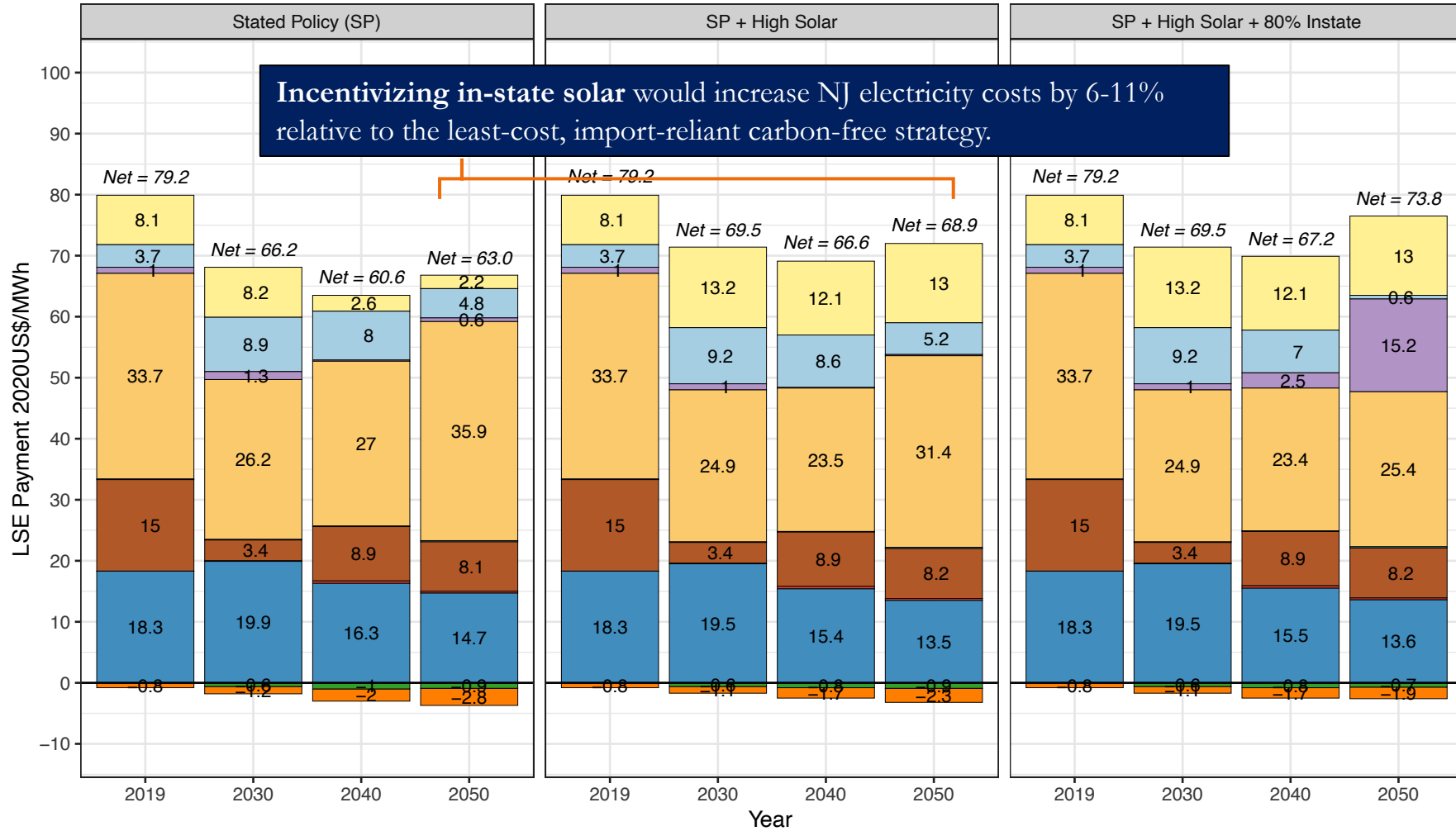
Case descriptions

SP + High Solar:

Requires 31 GW-dc solar PV capacity in NJ by 2050, including ~23 GW-dc of distributed solar (similar to NJ Energy Master Plan scenario).

SP + High Solar + 80% Instate:

Combines above requirements with additional requirement that 80% of clean energy supply for NJ (as required by RPS and CES obligations from 2031-2050) are met by in-state generation (including DG solar).



If NJ requires 80% of carbon-free electricity from in-state, distributed solar is expected to be lower cost than offshore wind by the 2040s and would expand after utility-scale solar reaches maximum potential

Generation Output of New Jersey under Sensitivity Mid

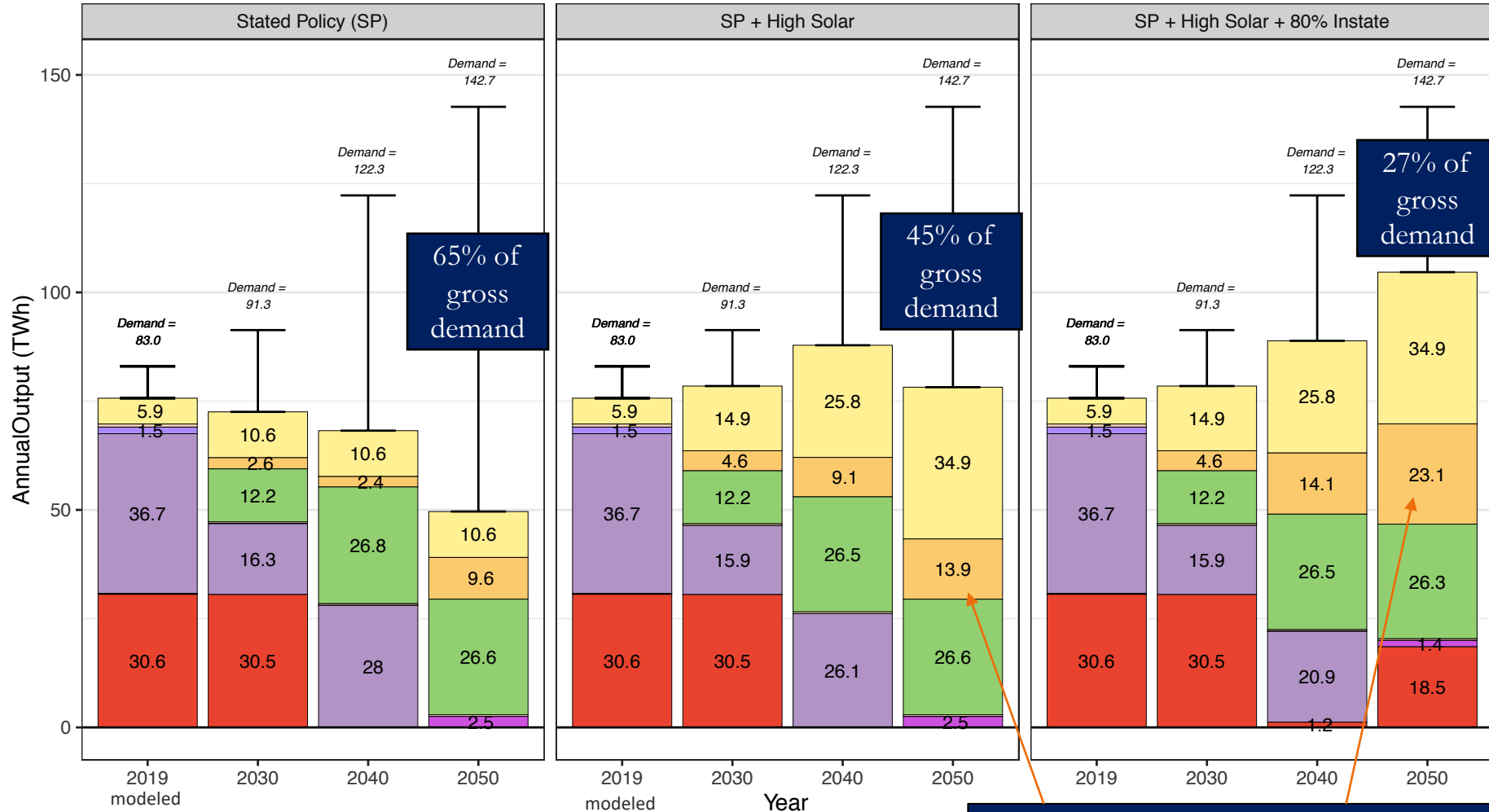
Case descriptions

SP + High Solar:

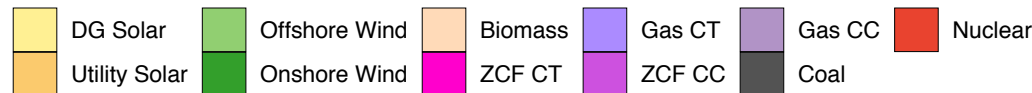
Requires 31 GW-dc solar PV capacity in NJ by 2050, including ~23 GWdc of distributed solar (similar to NJ Energy Master Plan scenario).

SP + High Solar + 80% Instate:

Combines above requirements with additional requirement that 80% of clean energy supply for NJ (as required by RPS and CES obligations from 2031-2050) are met by in-state generation (including DG solar).



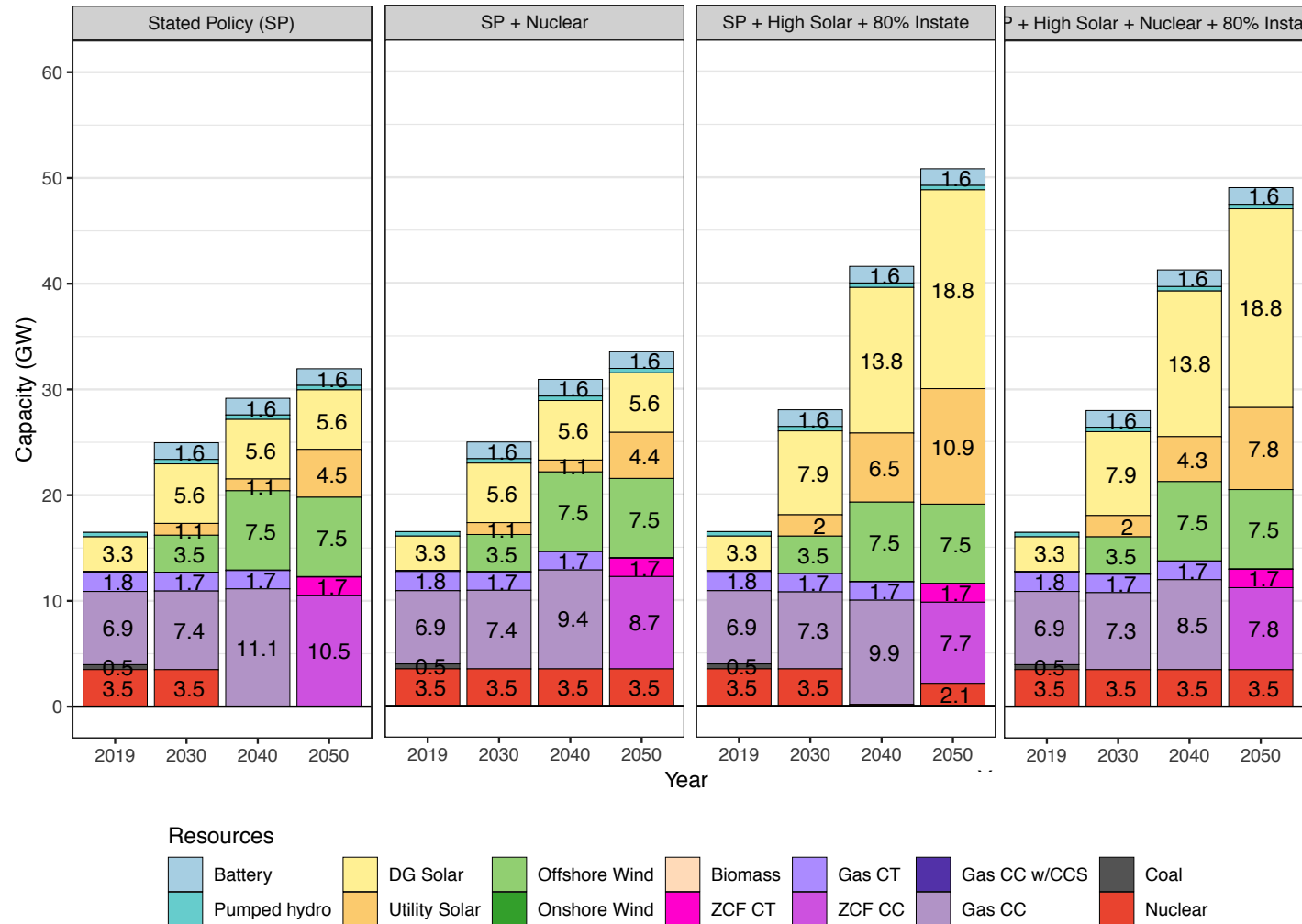
Resources



Major expansion of utility-scale solar, which is generally the most affordable option for in-state clean electricity

Preserving NJ's nuclear generators can reduce dependence on imports and avoid an increase in fossil gas fired generation and associated CO₂ emissions and air pollution in the 2030s

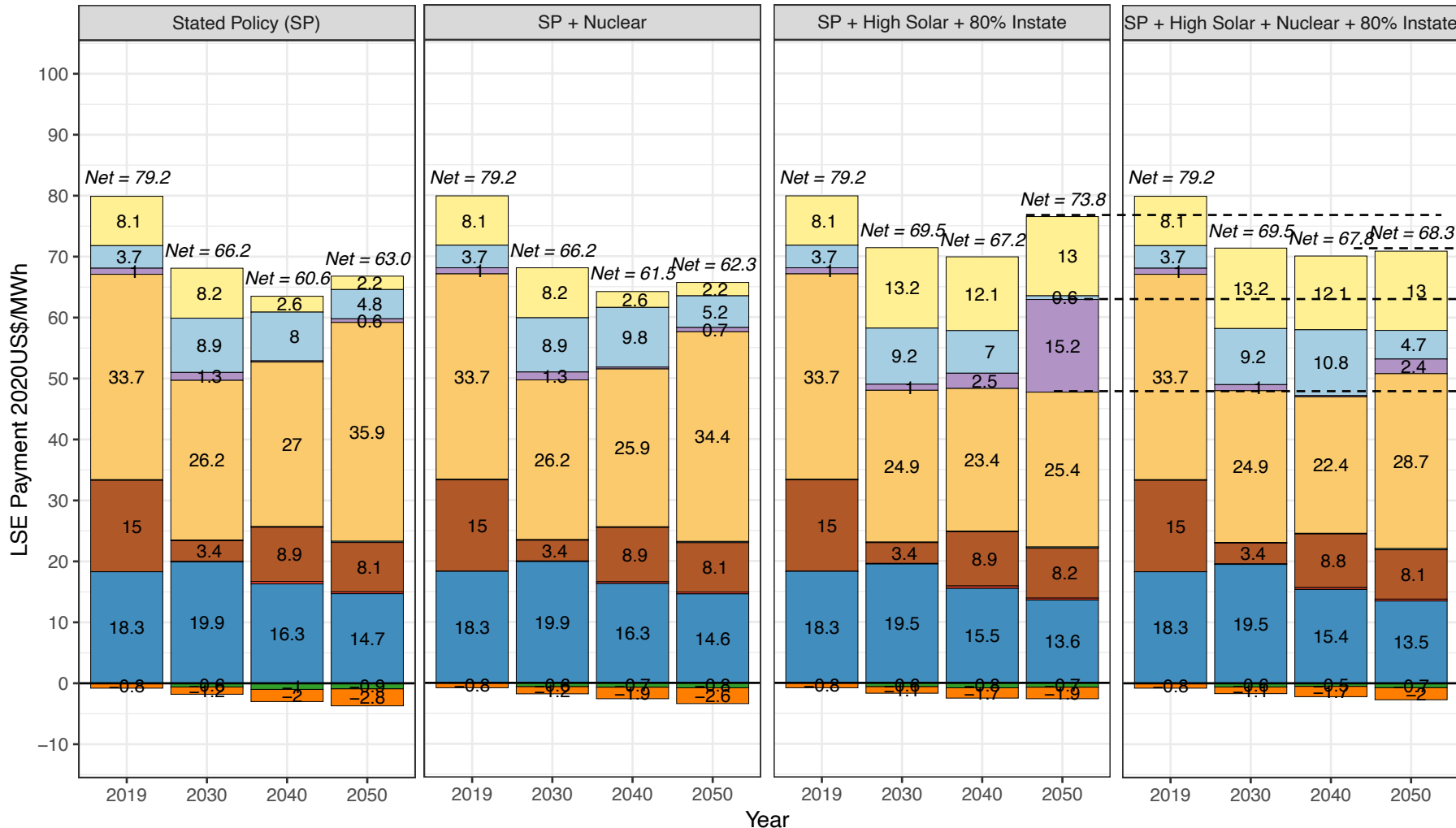
Generation Capacity of New Jersey under Sensitivity Mid



- Supporting continued operation of NJ reactors after 2030 is consistently amongst the lowest-cost options for in-state carbon-free generation, but would require ongoing policy support after 2030.
- If NJ prioritizes in-state generation, maintaining nuclear operation is a least cost strategy.

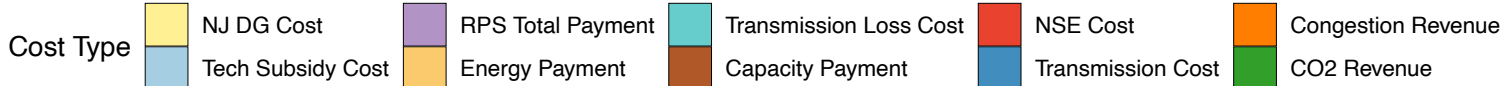
Supporting continued operation of NJ reactors after 2030 is consistently amongst the lowest-cost options for in-state carbon-free generation, but would require ongoing policy support after 2030

LSE Cost of New Jersey under Sensitivity Mid



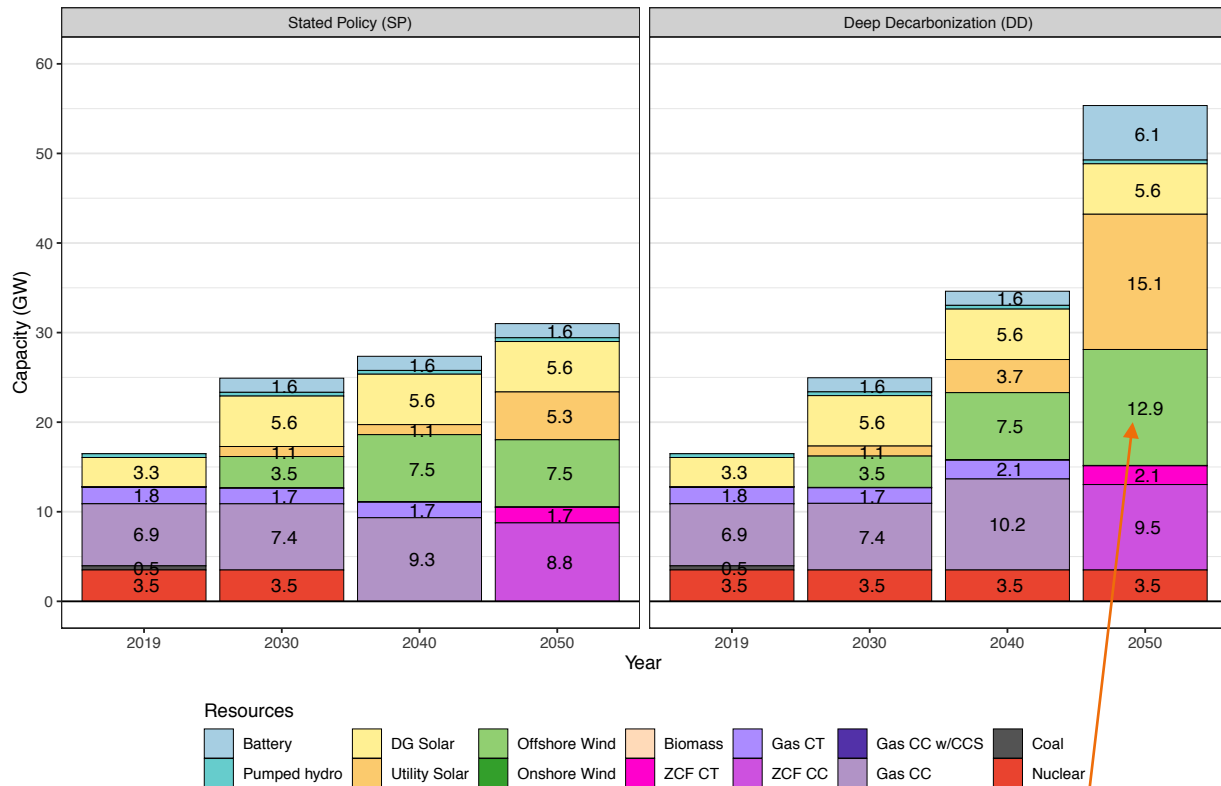
If NJ prioritizes in-state clean generation while meeting the 100% carbon-free supply goal, retaining existing nuclear capacity will reduce NJ electricity supply costs by \$5.5/MWh (7%) in 2050.

Cost-savings are achieved by reducing RPS/CES payment that is otherwise needed for supporting new utility-scale solar and new nuclear built in 2050 to reach 100% carbon-free supply with 80% of generation from in-state.



Offshore wind is one of the more expensive options for NJ decarbonization and is rarely deployed beyond current mandated levels across scenarios modeled in this report

Generation Capacity of New Jersey under Sensitivity Low RE/BESS Cost



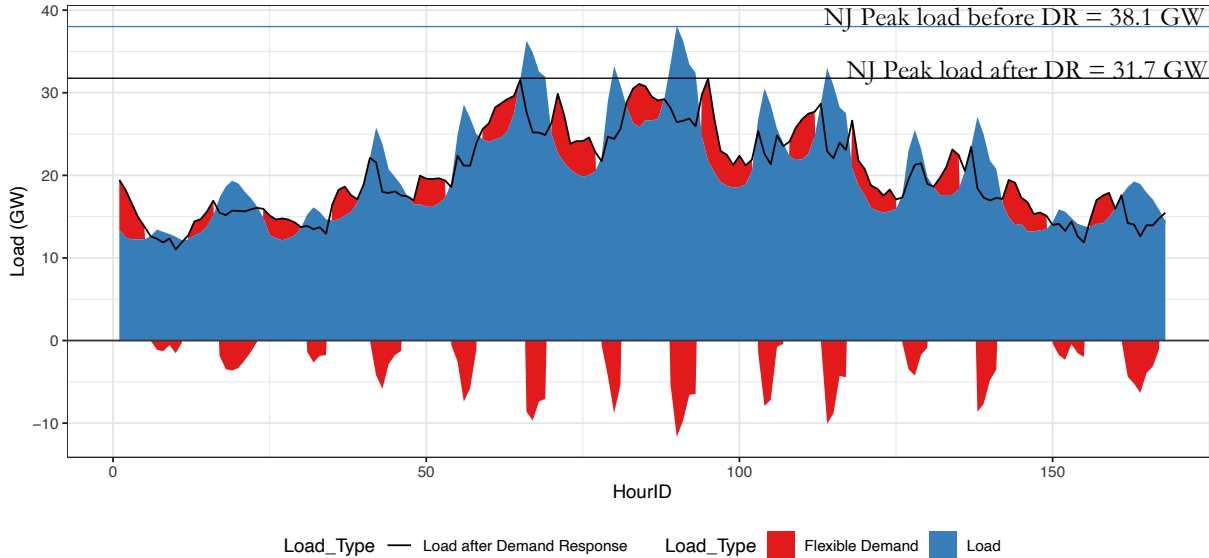
Deep Decarbonization scenario (DD): If more states in the region pursue deep decarbonization goals and low capital cost projections for OSW, other renewables, and storage are realized (*Low RE/BESS* cost sensitivity), OSW expands beyond the current state mandate to 12.9 GW in the year 2050

Offshore wind (OSW) is comparatively costly, so it is rarely developed beyond 7.5 GW as required by current state mandates. Exceptions are observed in futures where all states pursue deep decarbonization goals or if the state opts not to develop lower cost solar or preserve existing nuclear.

Additional NJ OSW selected beyond 7.5 GW by 2050 (GW)	Mid	Low RE/BE SS Cost	Low Nat. Gas Price	High RE/BE SS Cost	High Nat. Gas Price
Current Policy	-	-	-	-	-
Stated Policy	-	-	-	-	-
SP + 80% Instate	+4.1	+5.7	+4.1	+4.2	+4.0
SP + High Solar	-	-	-	-	-
SP + 80% Instate + High Solar	-	+5.2	-	-	+0.1
SP + Nuclear	-	-	-	-	-
SP + Nuclear + 80% Instate	+4.1	+3.9	+4.1	+4.0	+3.9
SP + Nuclear + High Solar	-	-	-	-	-
SP + Nuclear + 80% Instate + High Solar	-	-	-	-	-
Deep Decarbonization	-	+5.4	-	-	+0.8

Flexible electricity demand can reduce NJ's peak electricity demand and save NJ consumers half a billion dollars annually by 2050.

Load of New Jersey of the #1 week of the Year 2050 (Stated Policy scenario)



Impact of flexible load shifting on New Jersey peak electricity demand

Year Scenario	Original Peak	Peak after flexible load shifting	Diff.
2030	18.3	17.7	-0.6 GW
2040	29.9	25.1	-4.8 GW
2050	38.1	31.7	-6.4 GW

Flexible load can help cut 2050 NJ peak demand by 17% (6.4 GW), helping compensate for higher electricity usage from electrification of vehicles and heating.

Flexible load provides cost savings to NJ LSEs of \$4.1/MWh in 2050 = \$572M/year by substituting for infrequently utilized battery energy storage and gas-fired power plant capacity.

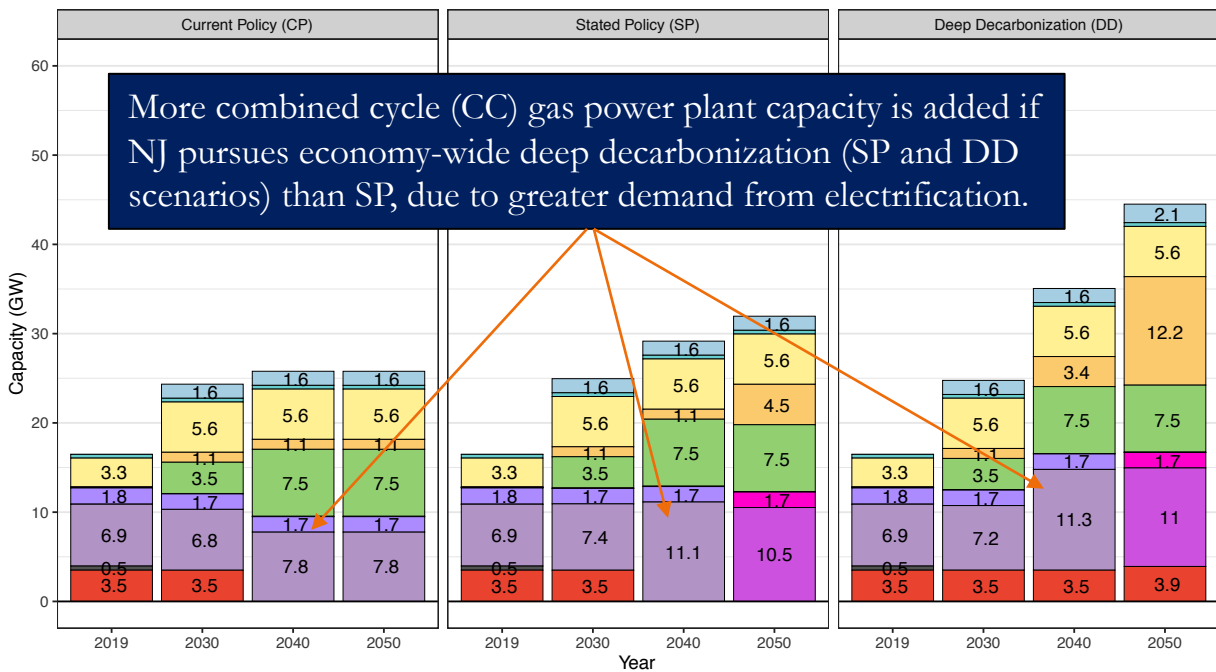
Impact of flexible load shifting on New Jersey electricity supply costs (SP scenario)

Year Scenario	SP & No Flexible Load	Stated Policy (SP)	Diff.
2030	67.1	66.2	-\$0.9/MWh
2040	62.9	60.6	-\$2.3/MWh
2050	67.1	63.0	-\$4.1/MWh

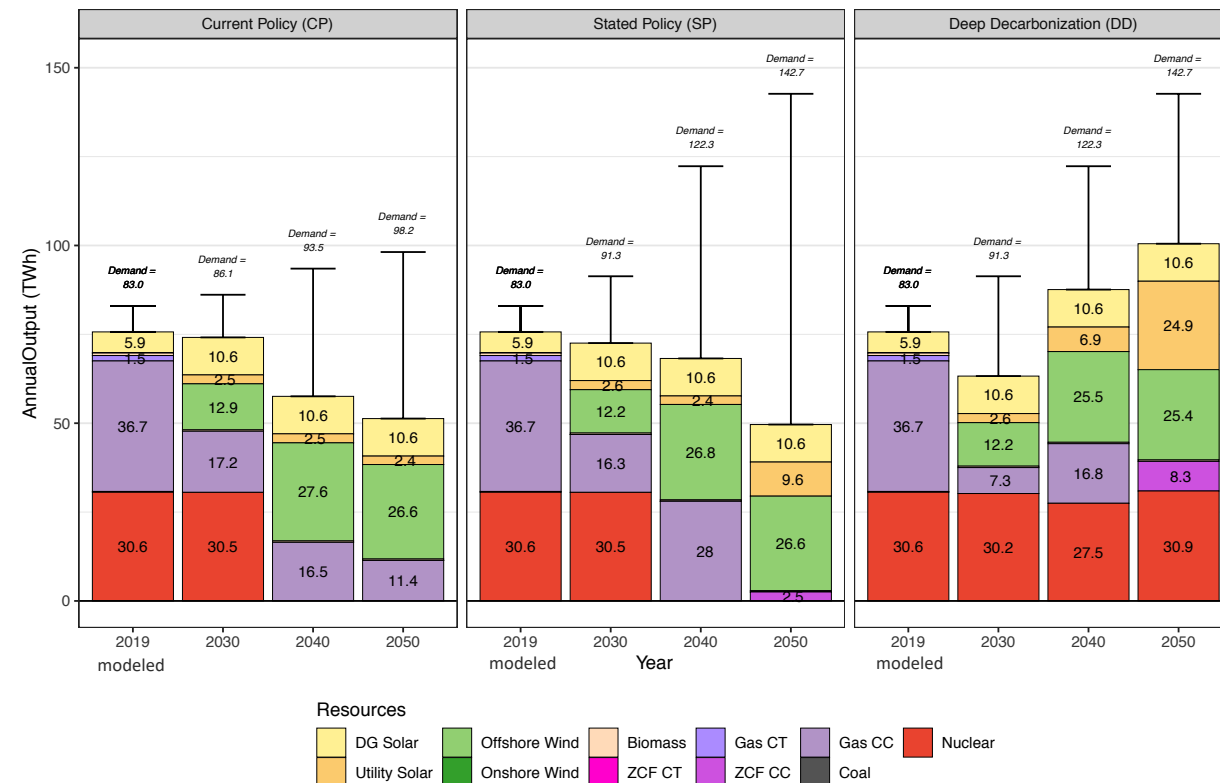
- Additional non-modeled distribution cost savings could also result.
- New market/rate design is needed to fully unleash the benefits of flexible load.

NJ gas-fired capacity expands until 2040 in all scenarios, while fossil gas-fired generation and related emissions decline; all gas-fired power plants are converted to run on zero-carbon fuels by 2050

Generation Capacity of New Jersey under Sensitivity Mid



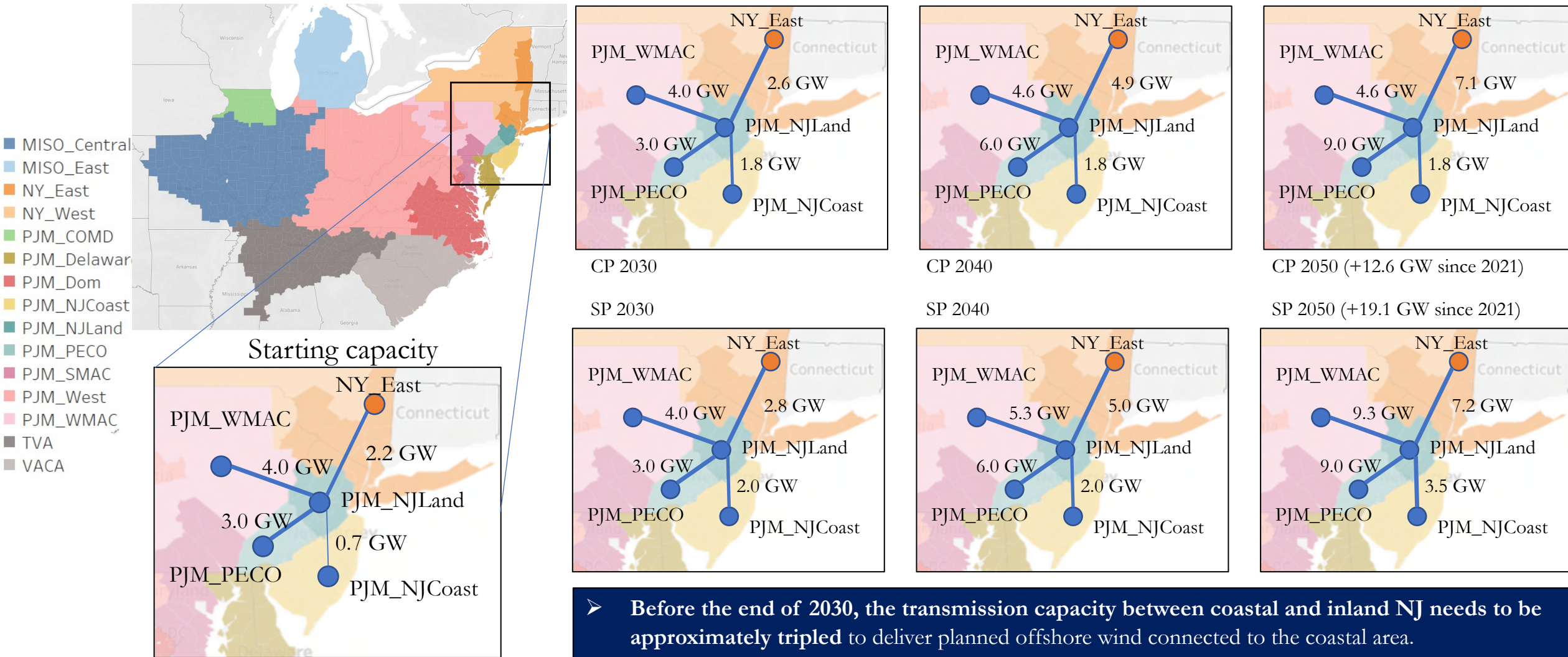
Generation Output of New Jersey under Sensitivity Mid



CC capacities expand from 2019 but gas-fired generation (and associated emissions) decrease, as CCs derive an increasing share of value from capacity payments and less frequent periods of higher energy market prices.

By 2050, gas-fired capacity converts to run on zero-carbon fuel (ZCF) to meet 100% carbon-free requirements in SP and DD scenarios.

NJ will need to expand transmission between coastal and inland areas in the near term to integrate offshore wind as well as significantly strengthen ties to neighboring PJM & NY areas in the longer term



- Before the end of 2030, the transmission capacity between coastal and inland NJ needs to be approximately tripled to deliver planned offshore wind connected to the coastal area.
- All transmission corridors between NJ & neighboring regions need to be expanded over time.

Note: the model topology is zonal and the location of nodes depicted here are for illustrative purposes only. Lengths of lines do not have physical meanings. Widths of lines are proportional to the inter-zonal transmission capability. Blue nodes represent PJM zones; orange are neighboring region zones (e.g. NYISO).

PRINCETON UNIVERSITY

ZERO LAB

Zero-carbon Energy Systems Research and Optimization Laboratory

For questions or inquiries related to this report, contact
Prof. Jesse D. Jenkins, jessejenkins@princeton.edu.

Access and download data and other resources at
<https://zenodo.org/record/6345570>