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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

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

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

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- **Note:** This study is published in the spirit of a working paper for public dissemination prior to peer review. Final publications based on this report will be subject to further peer review and may be revised.
- **Correction:** This version, published March 26, 2022, corrects an error in the calculation of 2019 New Jersey bulk electricity supply costs used as a benchmark throughout this report. All depictions of 2019 costs and comparisons to this benchmark are updated and corrected in this version.

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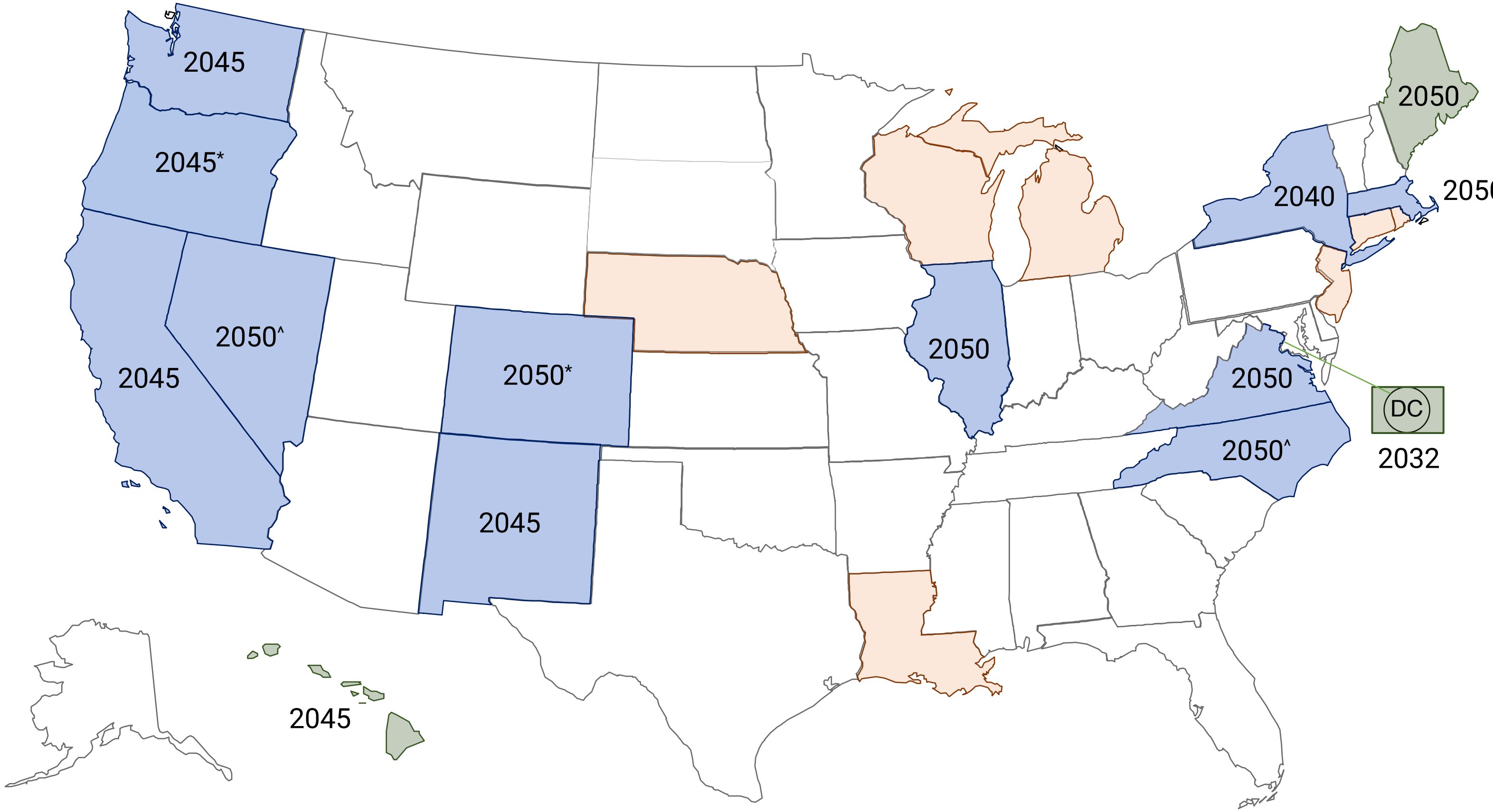
Introduction and Motivations

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



States with legislative requirements of 100% carbon-free electricity supply, carbon-neutral electricity, and/or economy-wide net-zero emissions

States with legislative requirements of 100% renewable electricity supply

States with executive orders or commitments from publicly-owned utilities to reach 100% carbon-free electricity or economy-wide net-zero emissions

* Applies to specific investor owned utilities

^ Non-binding statutory goal

Data source: Clean Energy States Alliance, https://www.cesa.org/projects/100-clean-energy-collaborative/guide/table-of-100-clean-energy-states/

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.

Summary of the New Jersey *Energy Master Plan*

Strategy 1: Reducing Energy Consumption and Emissions from the Transportation Sector, including encouraging electric vehicle adoption, electrifying transportation systems, and leveraging technology to reduce emissions and miles traveled.

Strategy 2: Accelerating Deployment of Renewable Energy and Distributed Energy Resources by developing offshore wind, community solar, a successor solar incentive program, solar thermal, and energy storage. It also involves adopting new market structures to embrace clean energy development and contain costs, opening electric distribution companies' circuits for distributed energy resources (DER), and developing low-cost loans or financing for DER.

Strategy 3: Maximizing Energy Efficiency and Conservation, and Reducing Peak Demand including enacting 0.75 percent and 2 percent utility energy efficiency standards for natural gas and electricity, respectively, improving energy efficiency programs in New Jersey, adopting new clean energy and energy efficiency financing mechanisms, and strengthening building and energy codes and appliance standards.

Strategy 4: Reducing Energy Consumption and Emissions from the Building Sector through decarbonization and electrification of new and existing buildings, including the expansion of statewide net zero carbon homes incentive programs, the development of EV-ready and Demand Response-ready building codes, and the establishment of a long-term building decarbonization roadmap.

Strategy 5: Decarbonizing and Modernizing New Jersey's Energy System through planning and establishment of Integrated Distribution Plans, investing in grid technology to enable increased communication, sophisticated rate design, and reducing our reliance on natural gas.

Strategy 6: Supporting Community Energy Planning and Action in Underserved Communities through incentivizing local, clean power generation, prioritizing clean transportation options in these communities, and supporting municipalities in establishing community energy plans.

Strategy 7: Expand the Clean Energy Innovation Economy by expanding upon New Jersey's existing 52,000 clean energy jobs and investing in developing clean energy knowledge, services, and products that can be exported to other regions around the country and around the world, thereby driving investments and growing jobs. New Jersey will attract supply chain businesses to create dynamic new clean energy industry clusters and bring cutting-edge clean energy research and development to the state.

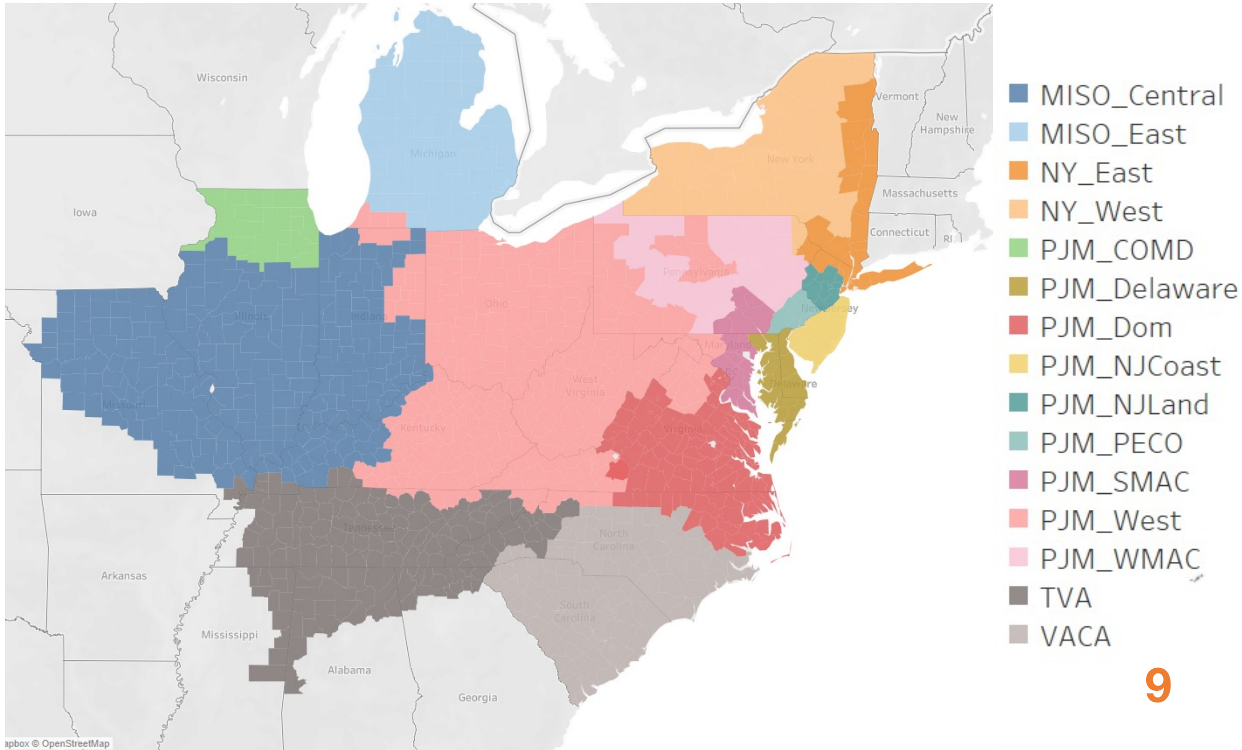
Source: https://www.nj.gov/governor/news/news/562020/approved/20200127a.shtml

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 for additional details.

Model regions/zones used in this study



Summary for Decision Makers

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 CO_2 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

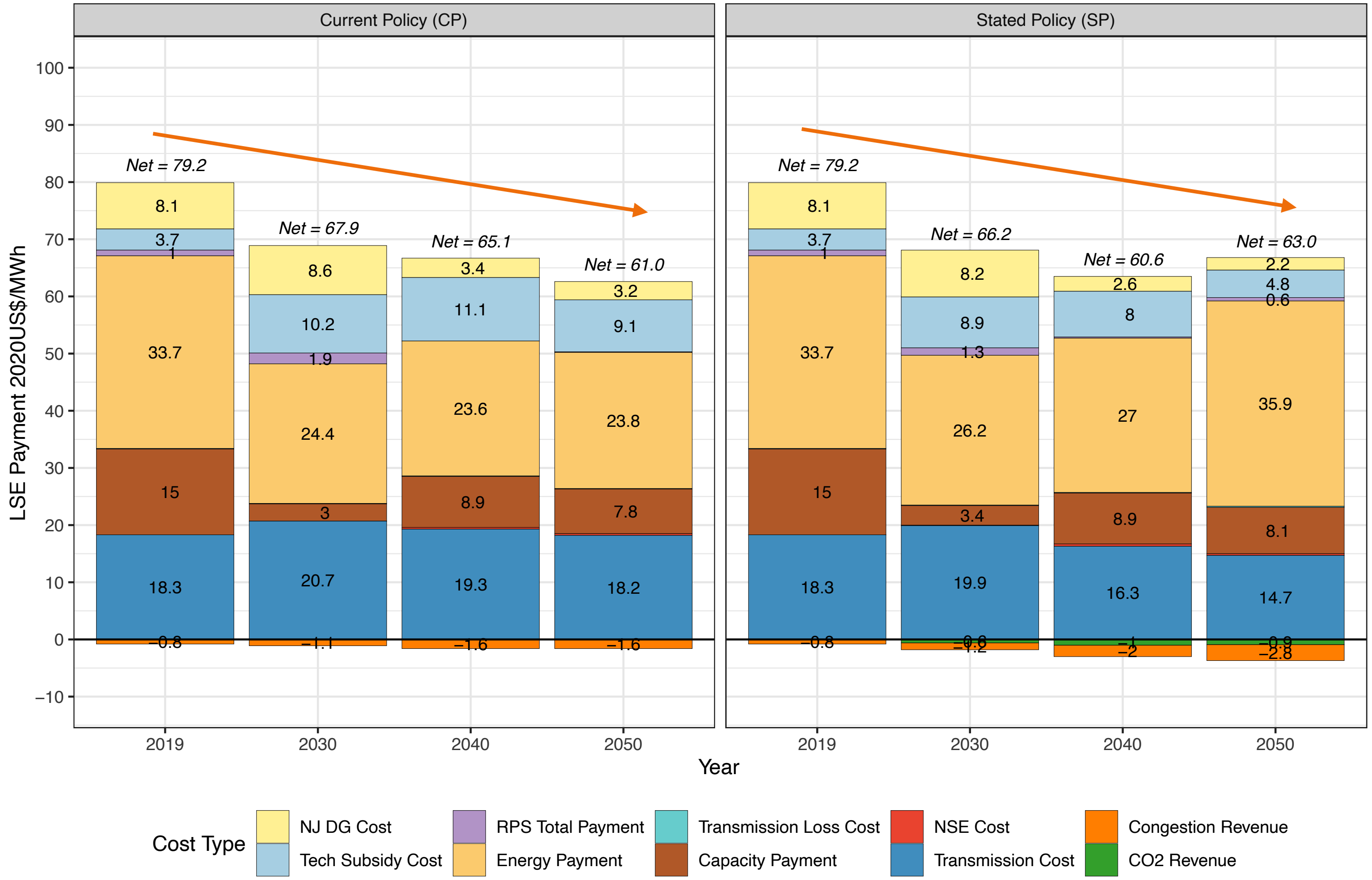
Three main scenarios modeled in this study:

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.

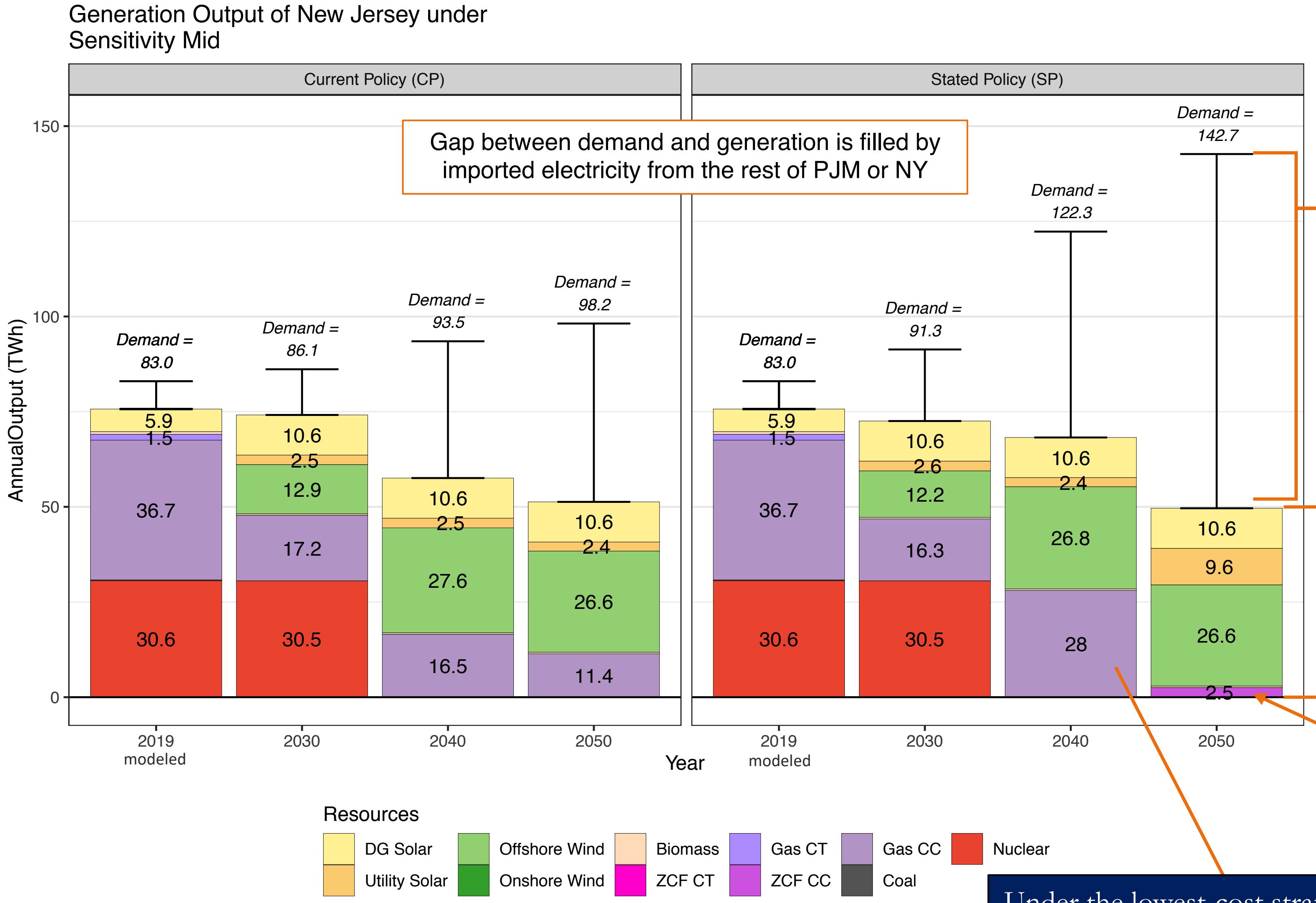
The costs of policy support for DG solar installation are estimated outside of GenX modeling and added to modeled system cost results.

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



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

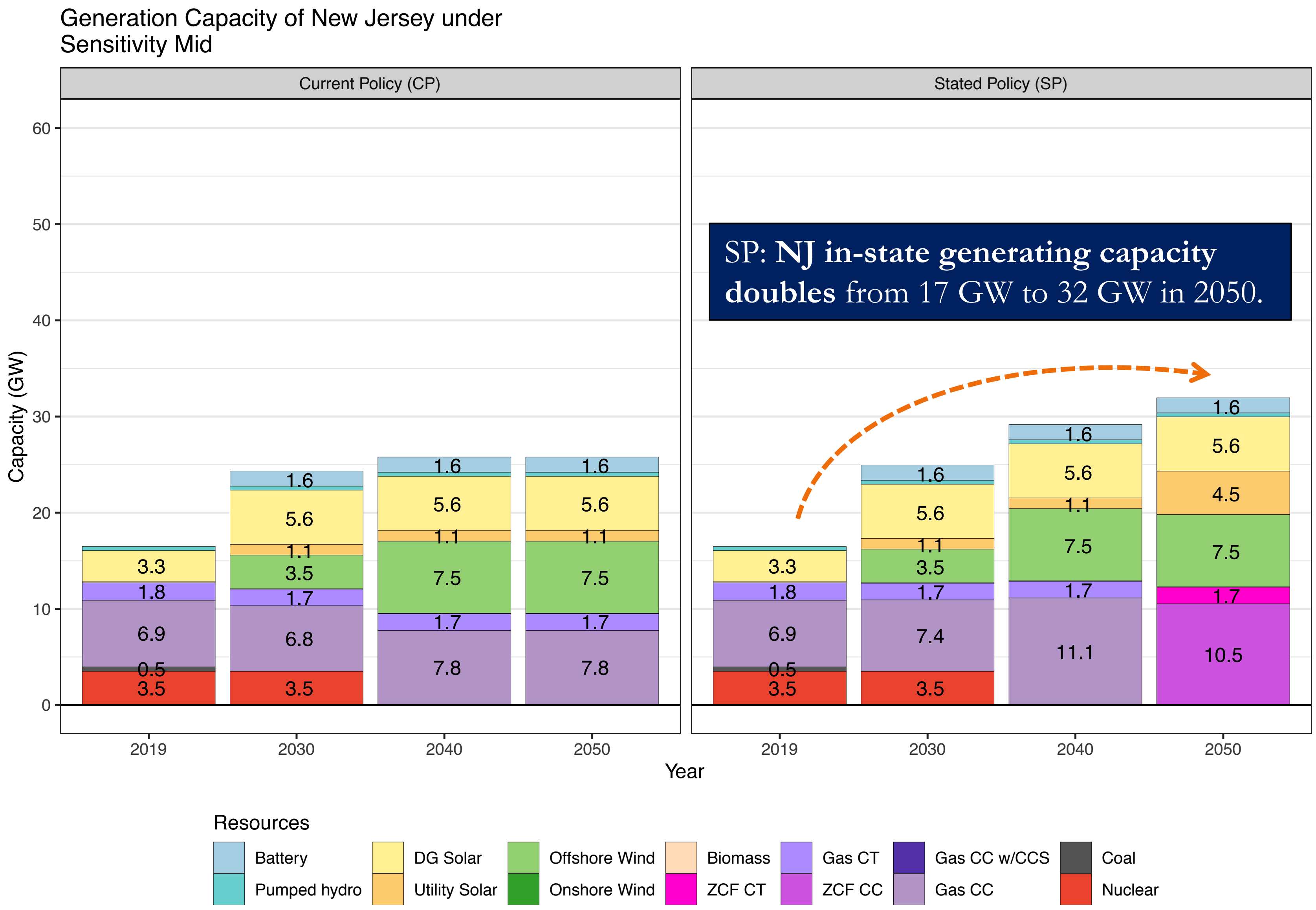
By 2050, in-state power generation is 100% CO_2 emission-free

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.

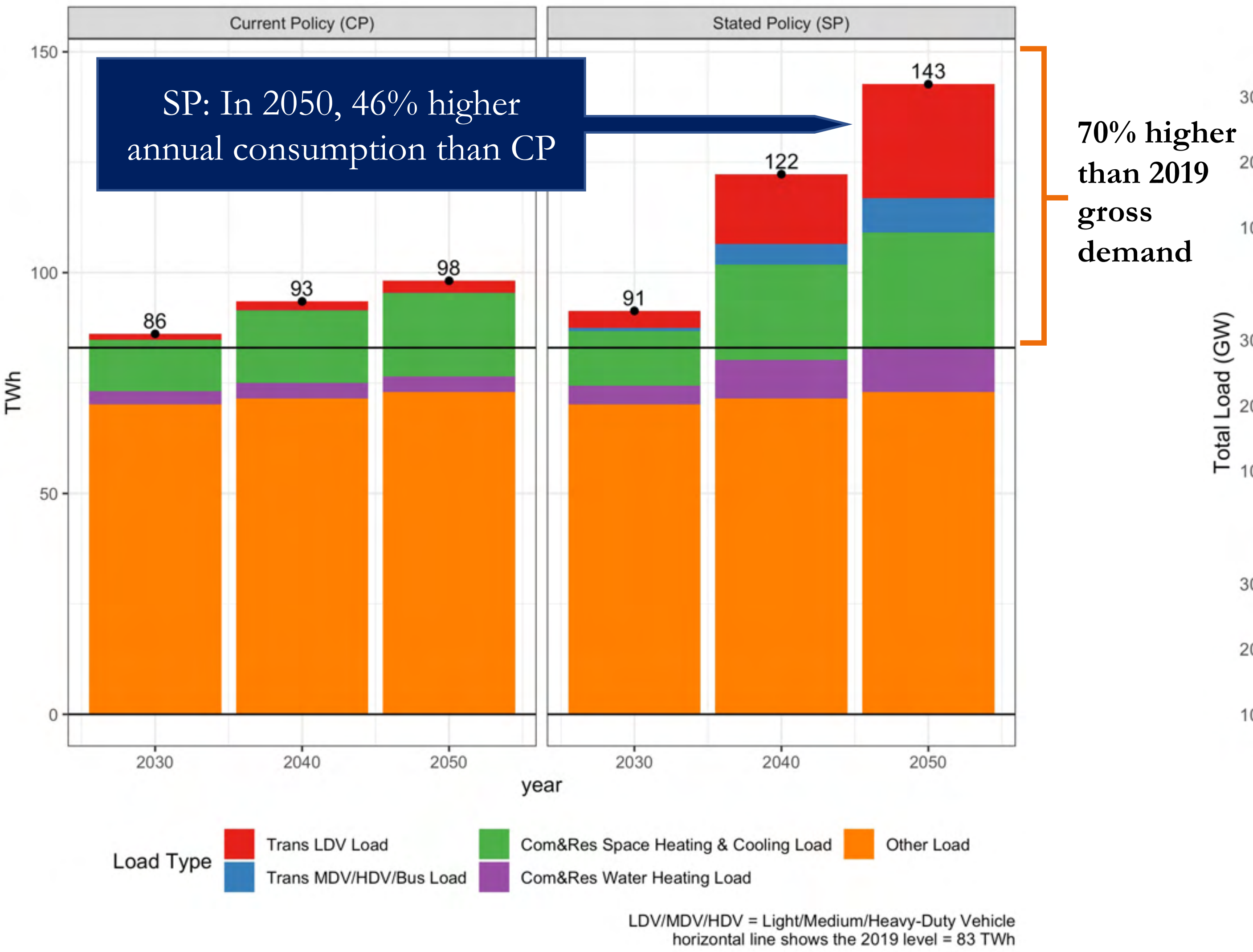


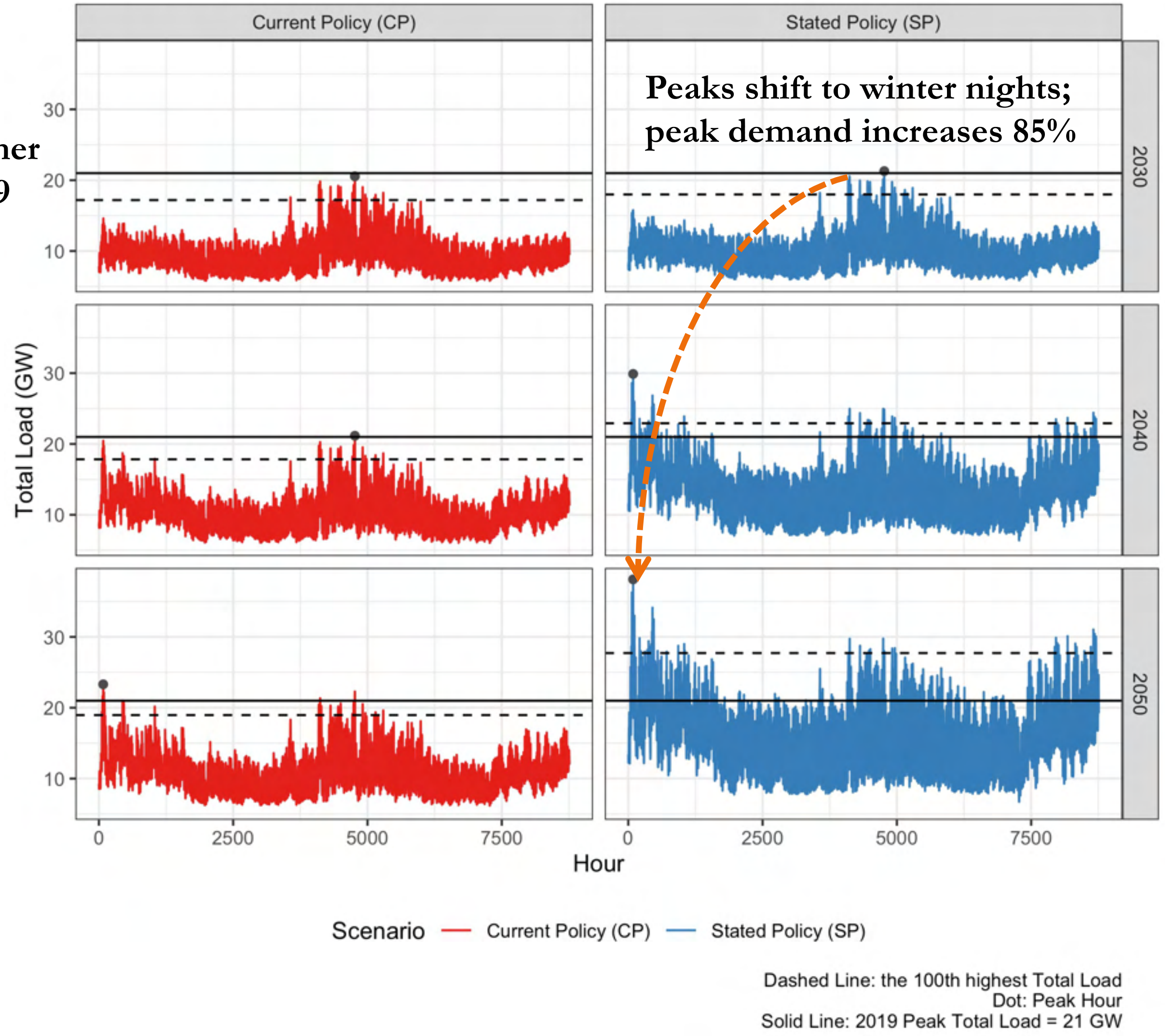
The least-cost pathway to 100% carbon-free electricity includes **expansion of utility-scale solar** and **new gas-fired combined cycle power plants,** with conversion of all gas-fired power plants to run on **zero-carbon fuels** (e.g., hydrogen, biomethane, synthetic methane) by 2050.

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.

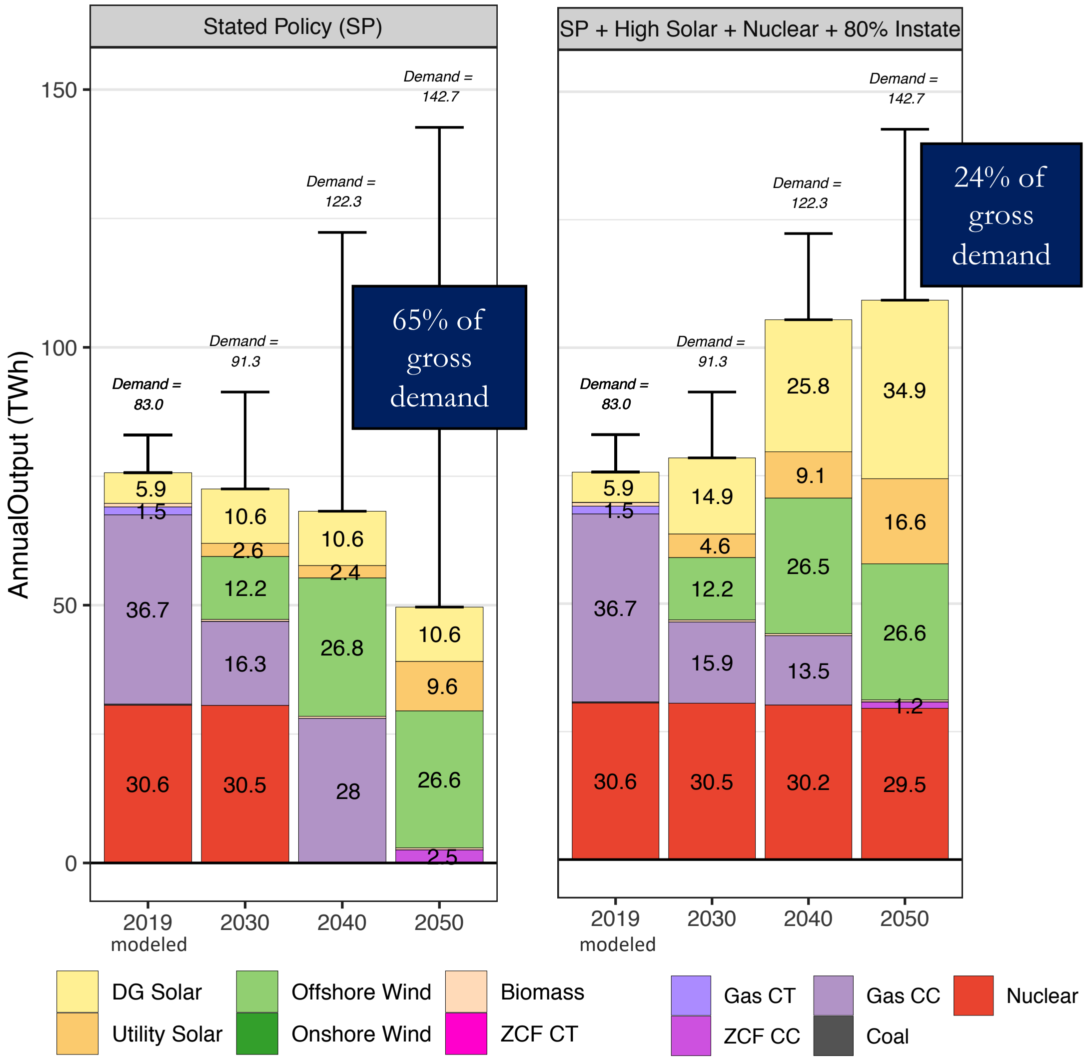
Electricity demand could increase significantly and patterns of consumption shift dramatically (from summer afternoon to winter overnight peak demand) due to electrification of vehicles and buildings

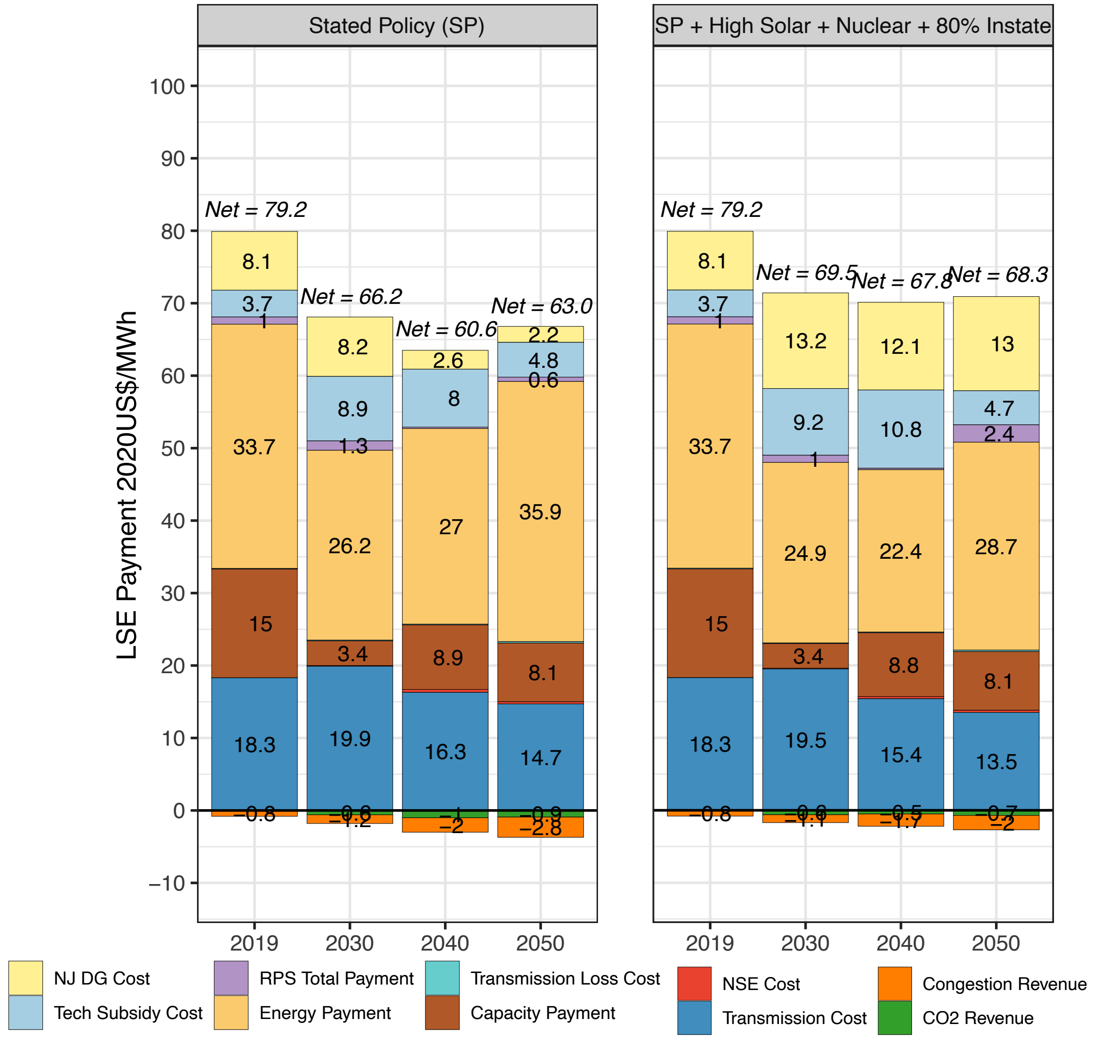




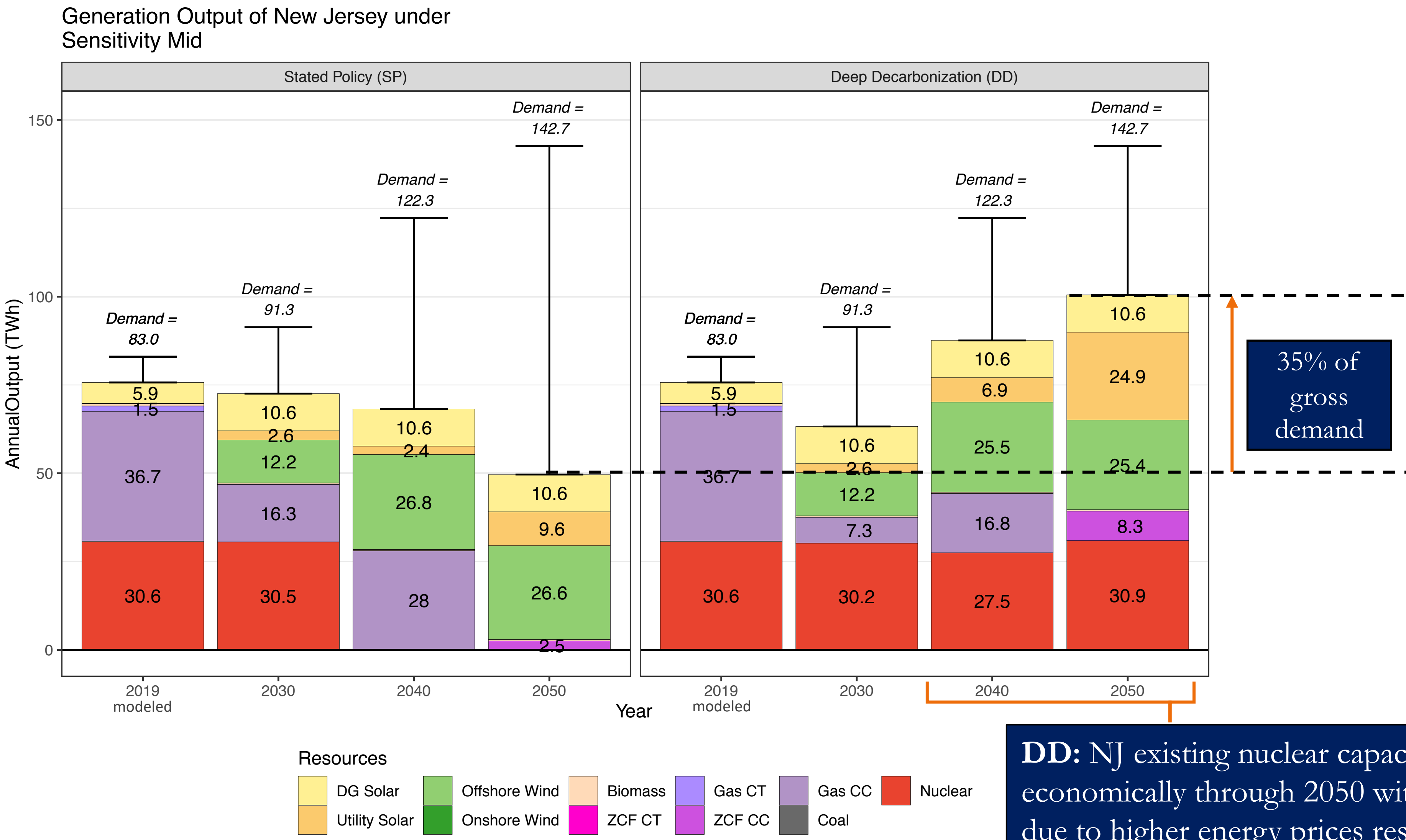
The lowest-cost pathways to 100% carbon-free electricity depart from NJ's current policy approach, which prioritizes in-state and distributed generation

Import dependance 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.

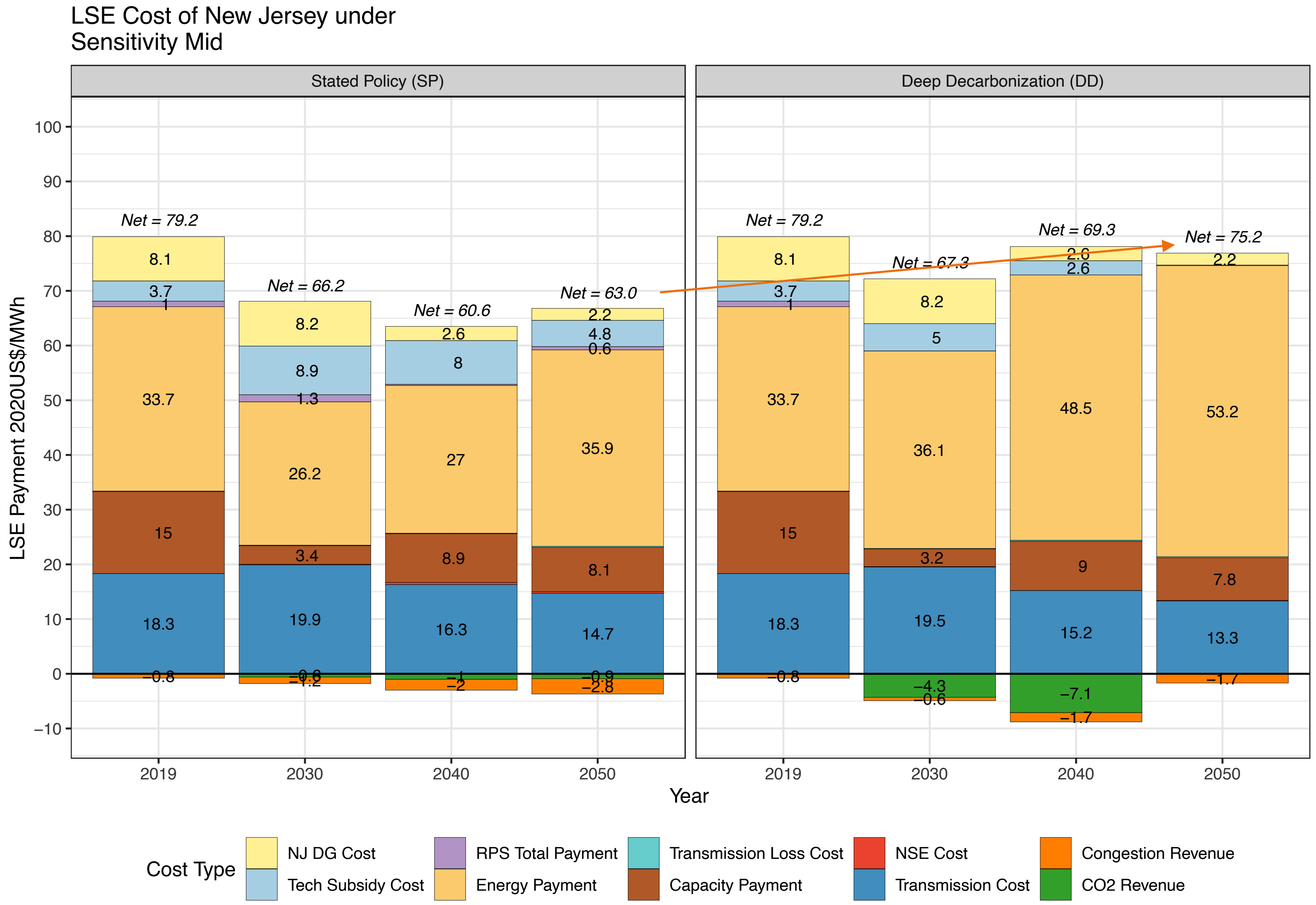


DD: As a result of more expensive imports, NJ builds higher-cost in-state resources, reducing reliance on imports relative to SP scenarios. (In-state generation doubles from SP.)

DD: NJ existing nuclear capacity can continue to run economically through 2050 without continued ZEC payments due to higher energy prices resulting from a CO_2 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.

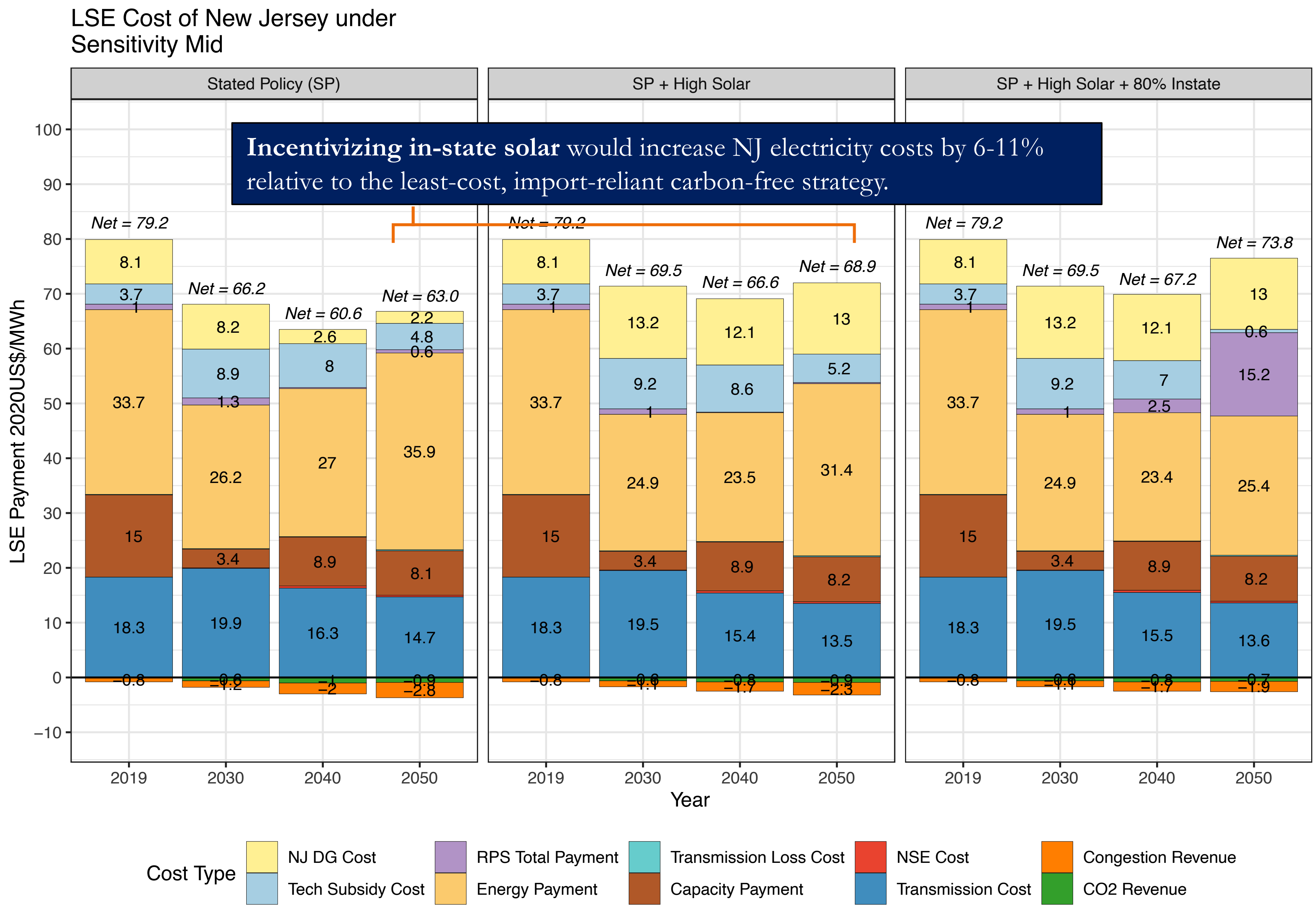


Expanding distributed solar is amongst the most expensive options for NJ and would require substantial policy support to continue growing beyond current state mandates

<u>Case descriptions</u>

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).

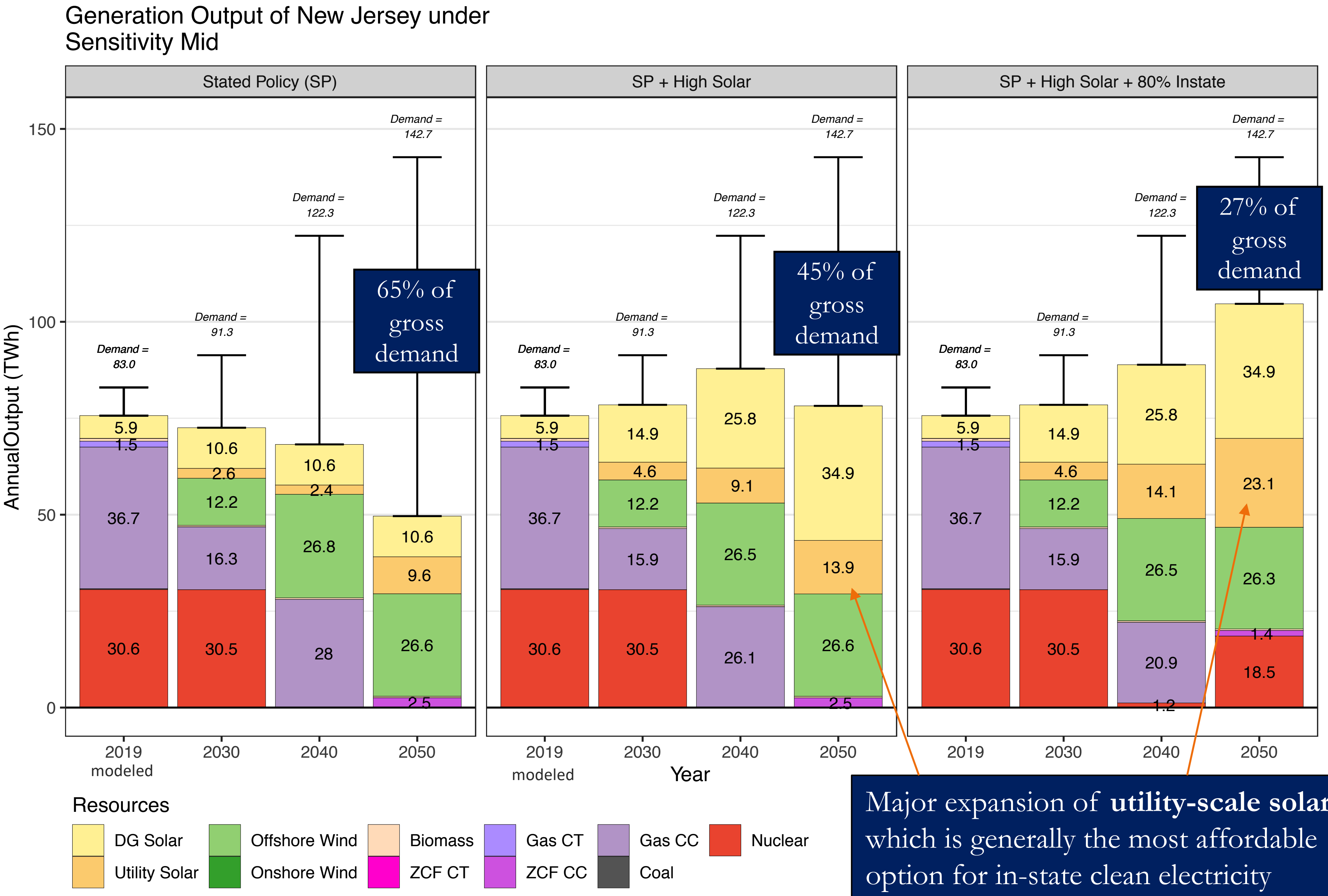


If NJ requires 80% of carbon-free electricity from in-state, distributed solar is expected to be lower cost than offshore wind by the 2040s and would expand after utility-scale solar reaches maximum potential

<u>Case descriptions</u>

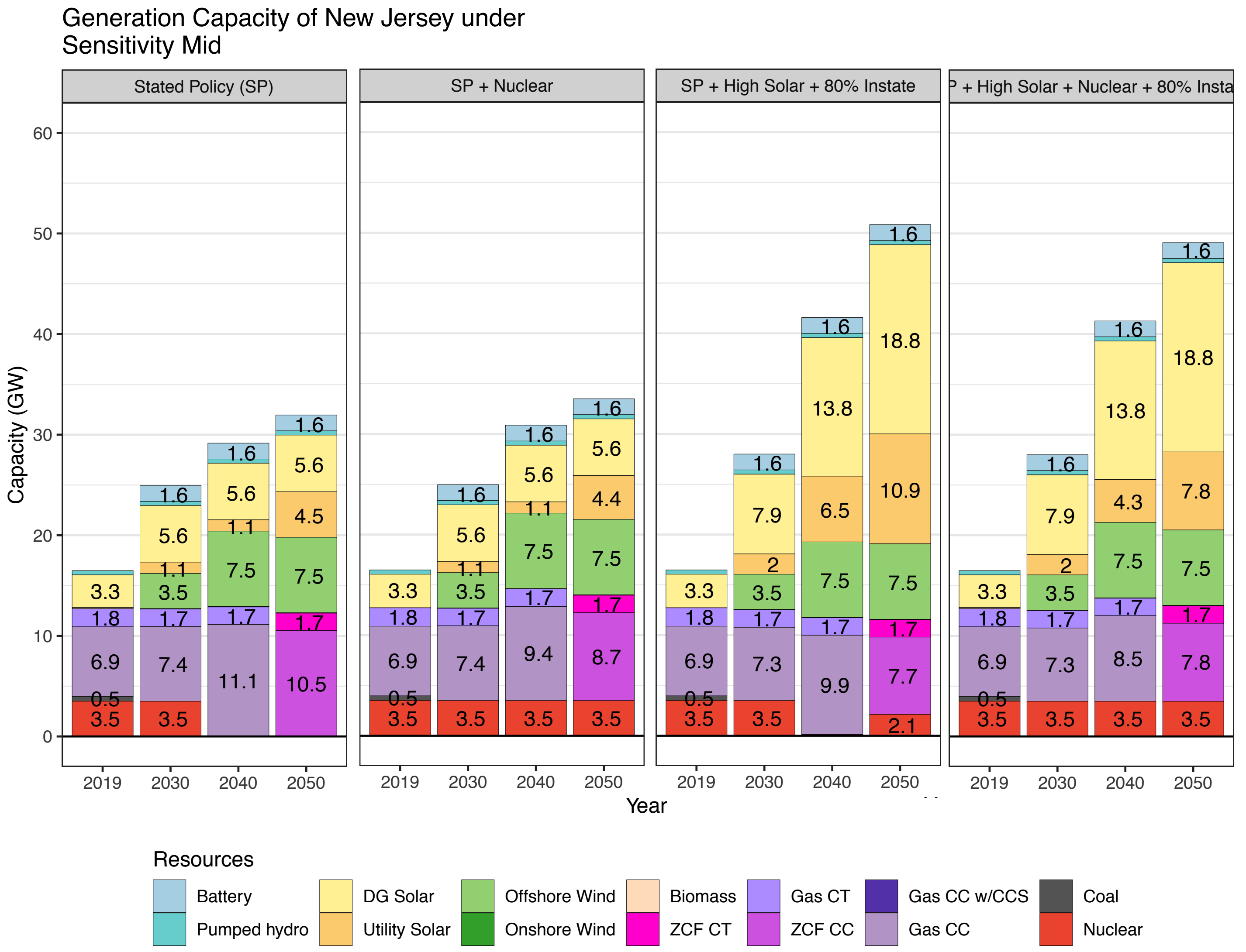
SP + High Solar: Requires 31 GW-dc solar PV capacity in NJ by 2050, including ~23 GWdc of distributed solar (similar to NJ *Energy Master Plan* scenario).

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).



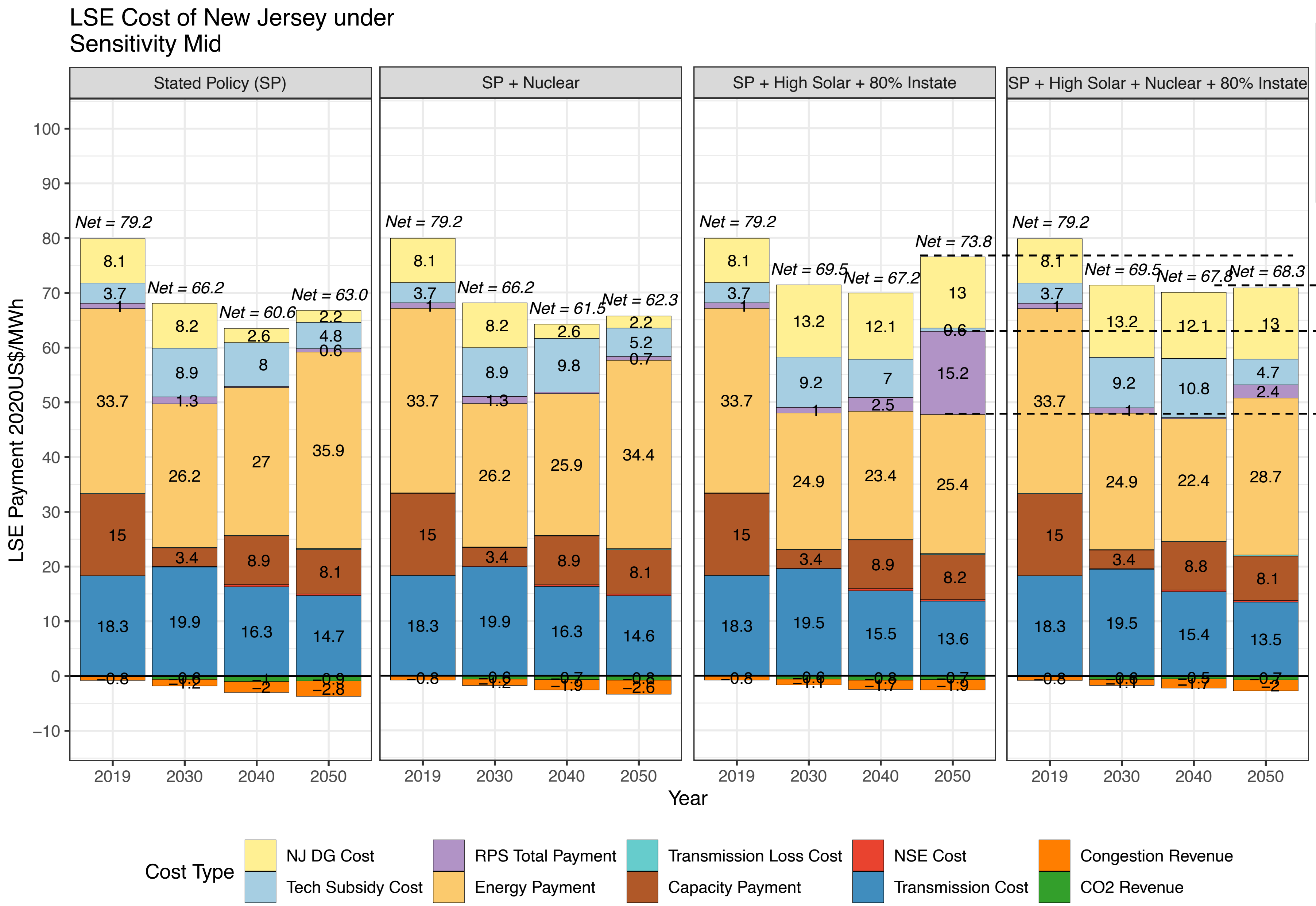
Major expansion of **utility-scale solar,** which is generally the most affordable option for in-state clean electricity

Preserving NJ's nuclear generators can reduce dependence on imports and avoid an increase in fossil gas fired generation and associated CO_2 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 NJ prioritizes in-state generation, maintaining nuclear operation is a least cost strategy.

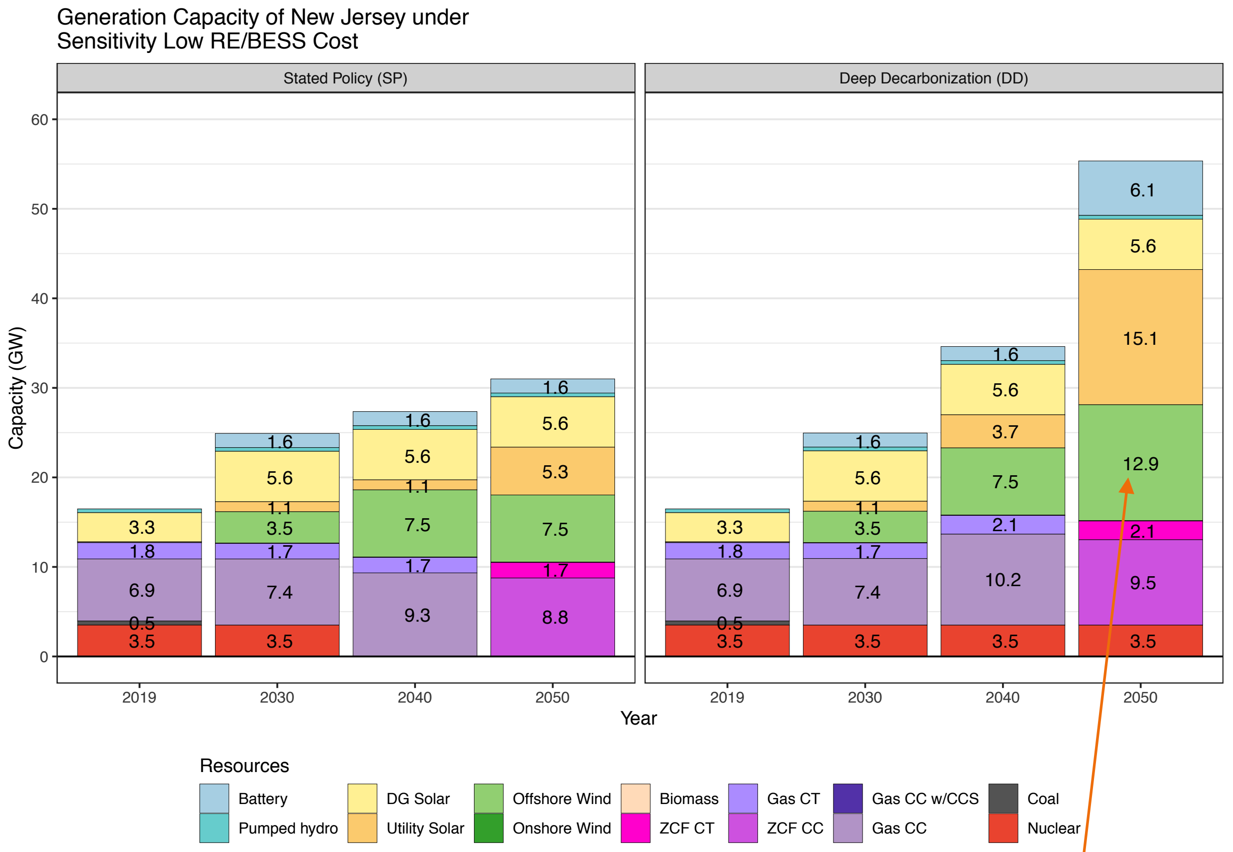
Supporting continued operation of NJ reactors after 2030 is consistently amongst the lowest-cost options for in-state carbon-free generation, but would require ongoing policy support after 2030



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

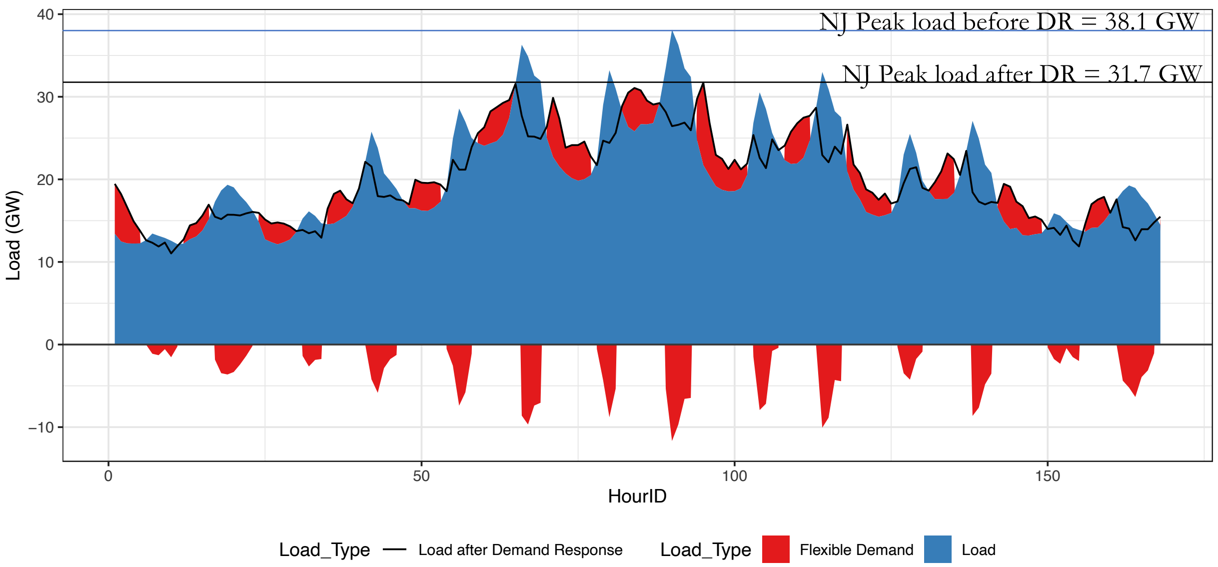


Offshore wind (OSW) is comparatively costly, so it is rarely developed beyond 7.5 GW as required by current state mandates. Exceptions are observed in futures where all states pursue deep decarbonization goals or if the state opts not to develop lower cost solar or preserve existing nuclear.

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

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

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



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.

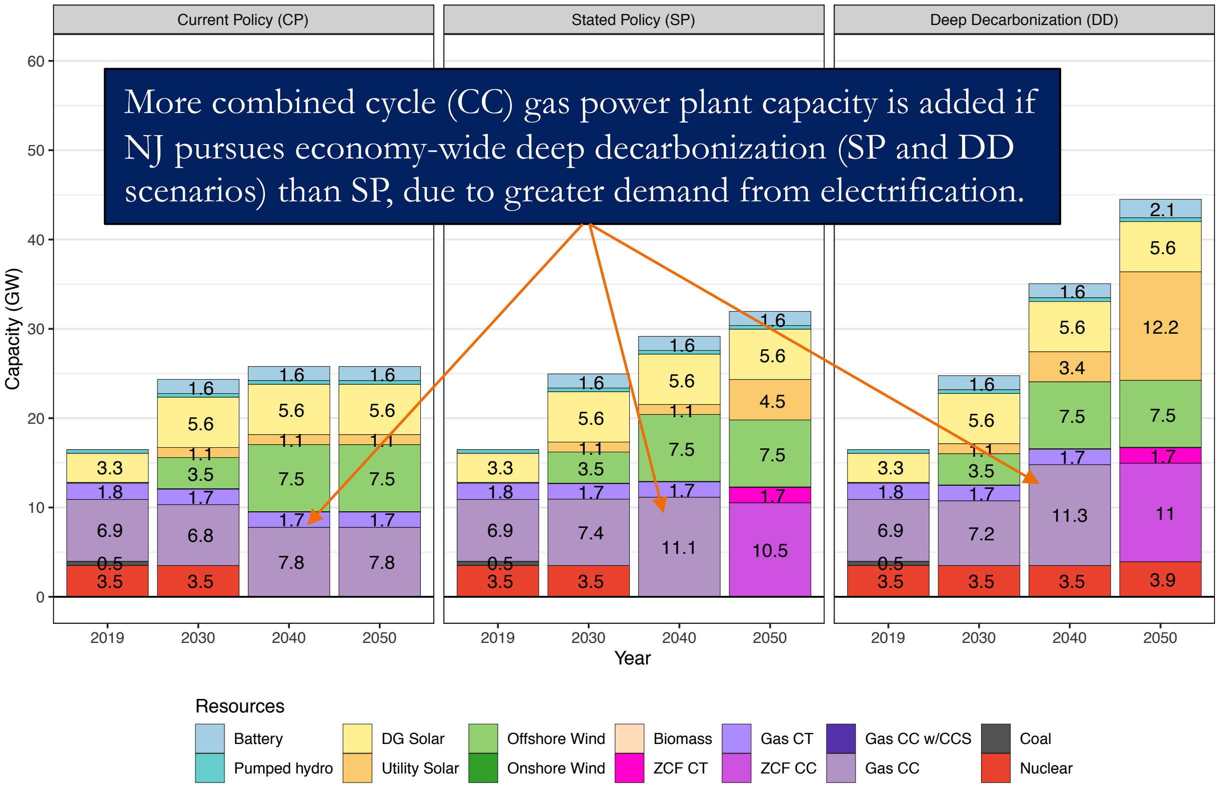
Impact of flexible load shifting on New Jersey electricity supply costs (SP scenario)

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.

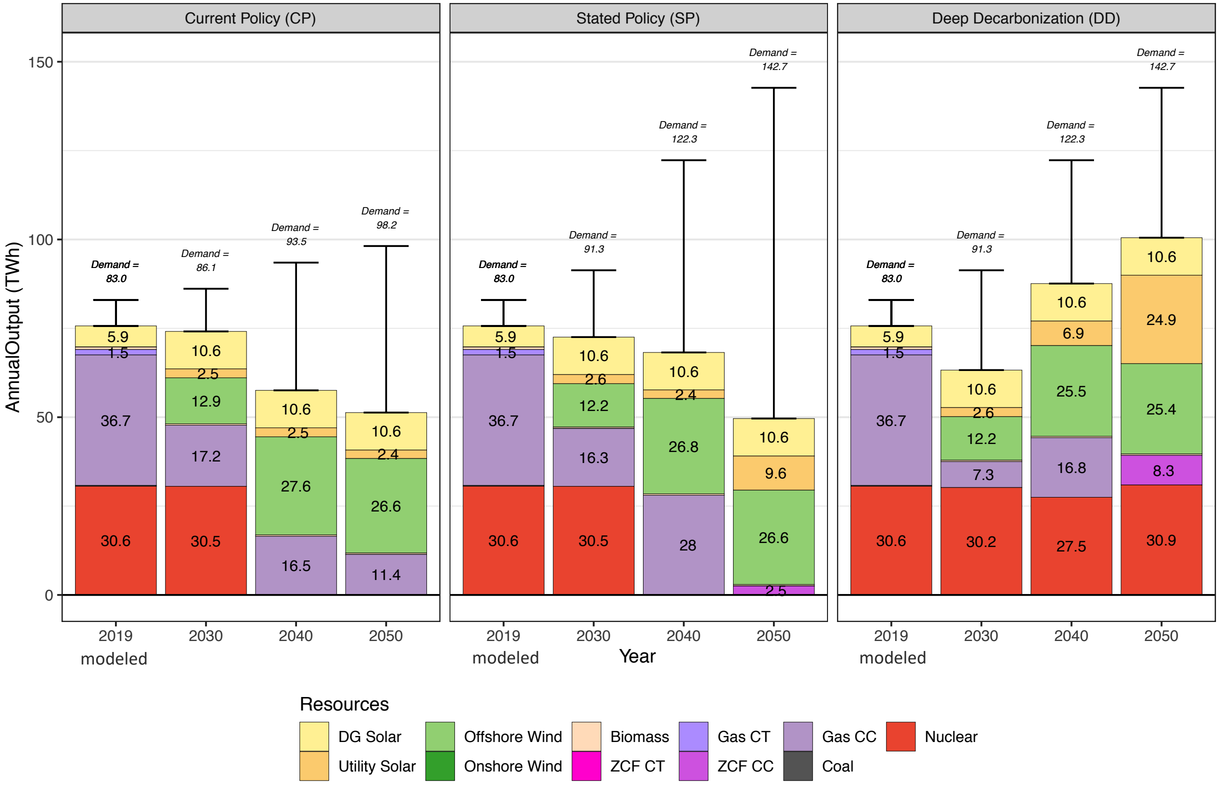
NJ gas-fired capacity expands until 2040 in all scenarios, while fossil gas-fired generation and related emissions decline; all gas-fired power plants are converted to run on zero-carbon fuels by 2050

Generation Capacity of New Jersey under Sensitivity Mid



More combined cycle (CC) gas power plant capacity is added if NJ pursues economy-wide deep decarbonization (SP and DD scenarios) than SP, due to greater demand from electrification.

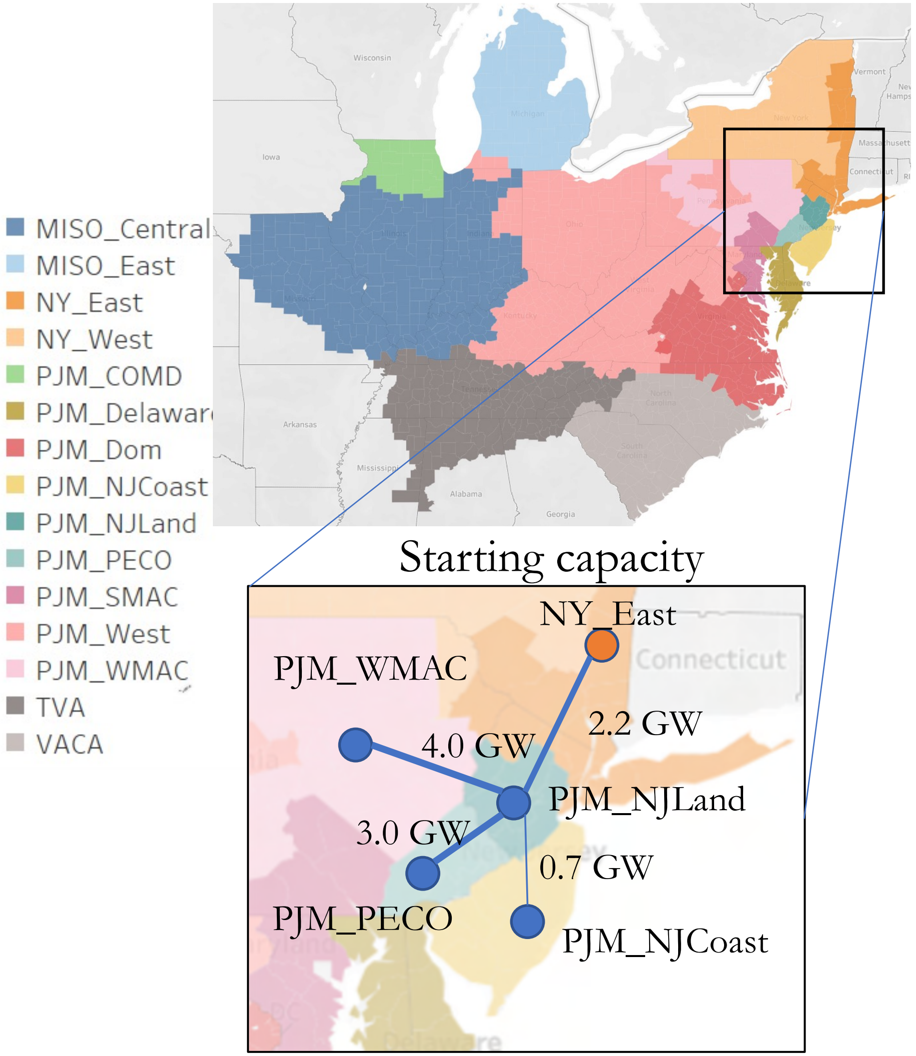
Generation Output of New Jersey under Sensitivity Mid

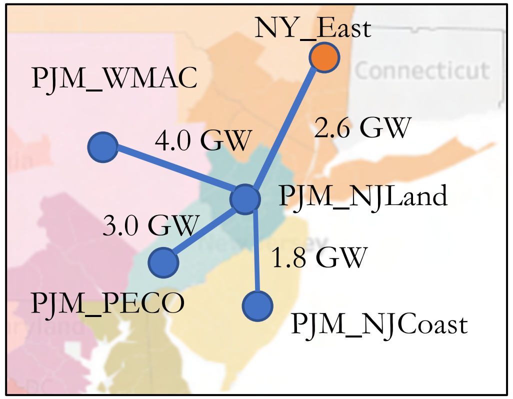


CC capacities expand from 2019 but gas-fired generation (and associated emissions) decrease, as CCs derive an increasing share of value from capacity payments and less frequent periods of higher energy market prices.

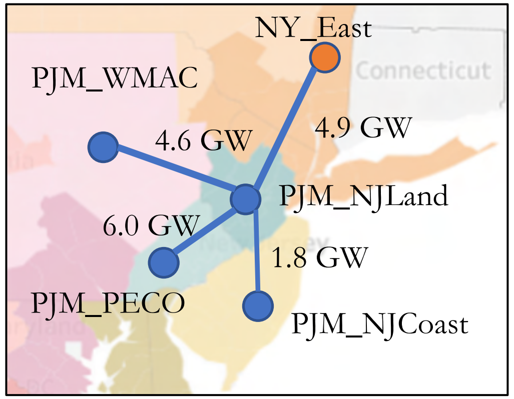
By 2050, gas-fired capacity converts to run on zero-carbon fuel (ZCF) to meet 100% carbon-free requirements in SP and DD scenarios.

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

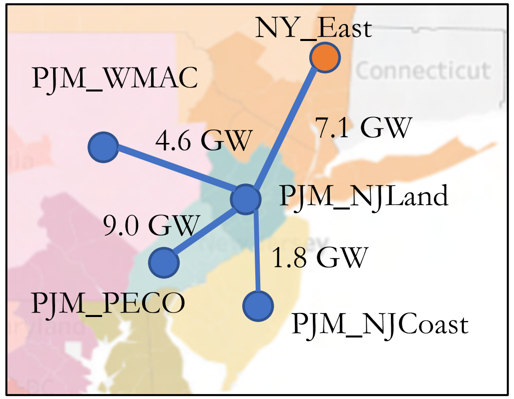




CP 2030

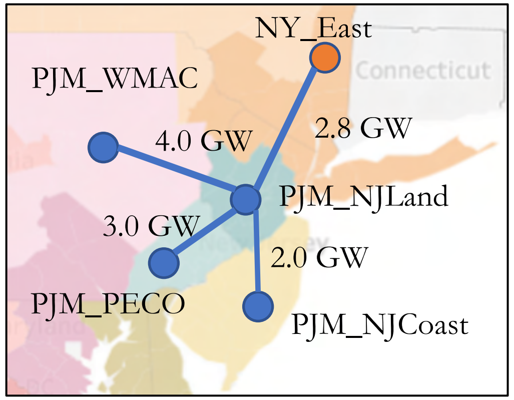


CP 2040

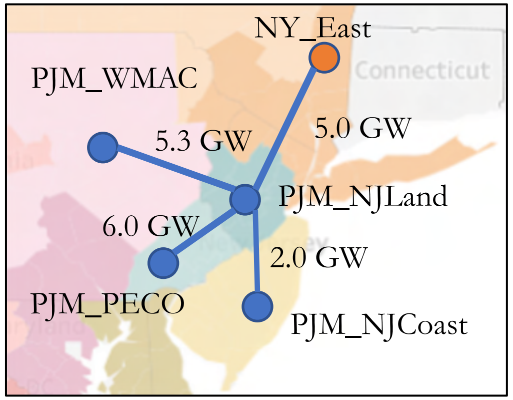


CP 2050 (+12.6 GW since 2021)

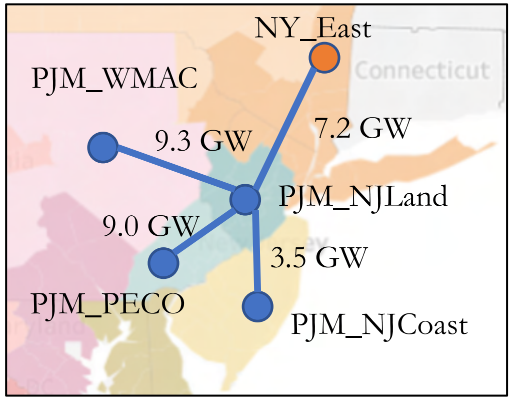
SP 2030



SP 2040



SP 2050 (+19.1 GW since 2021)



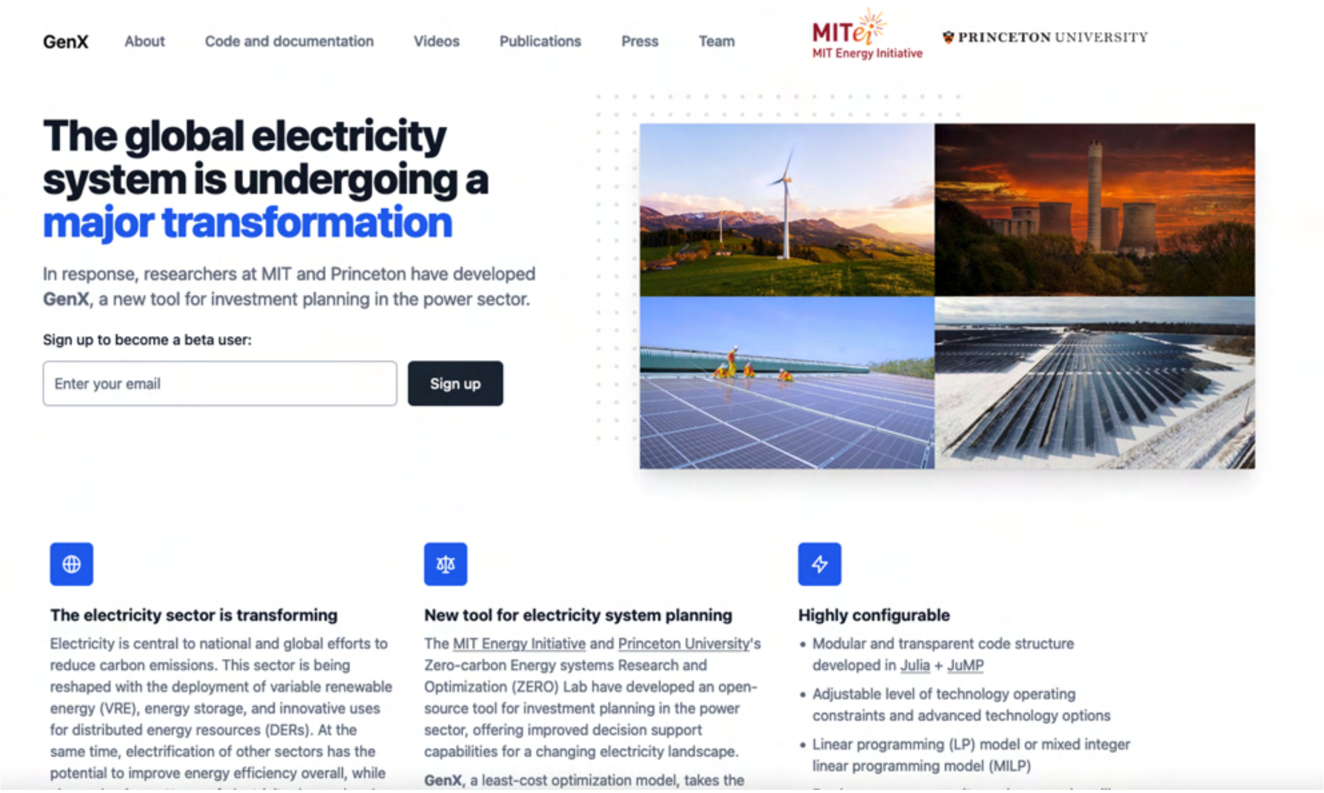
- **Before the end of 2030, the transmission capacity between coastal and inland NJ needs to be approximately tripled** to deliver planned offshore wind connected to the coastal area.
- **All transmission corridors between NJ & neighboring regions need to be expanded over time.**

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).

Summary of Methods

GenX: an electricity system planning model

- Open-source & highly configurable
- Optimization based (LP or MILP)
- Objective:
  - Minimize system cost (equivalent to maximizing welfare w/opportunity cost of price elastic demand curtailment)
- Decision variables:
  - Generation/transmission/storage expansion, retirement, and operations
- Subject to
  - Operation limits and unit commitment
  - Hourly resource availability (in this study: 12 representative 7 day periods)
  - Siting constraints
  - Policies including CO_2 cap, RPS, CES, technology-specific mandates
  - Resource adequacy requirements (capacity reserve margin/capacity market)
- Modular and transparent code structure developed in Julia + JuMP

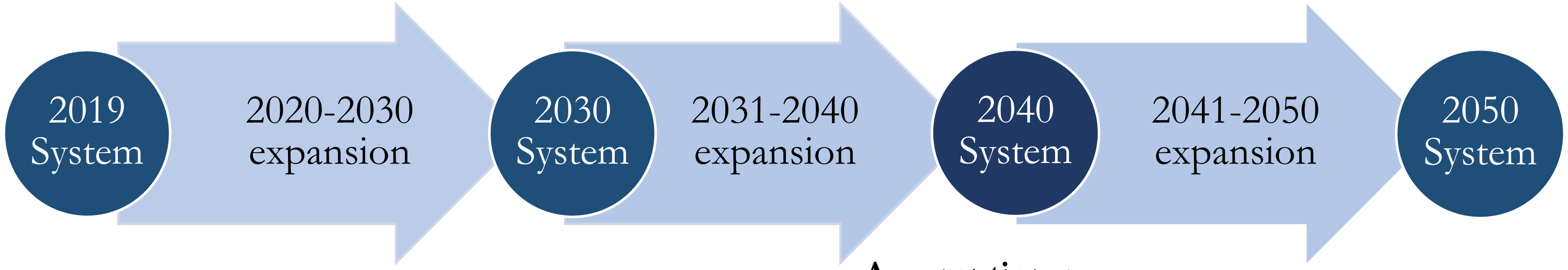


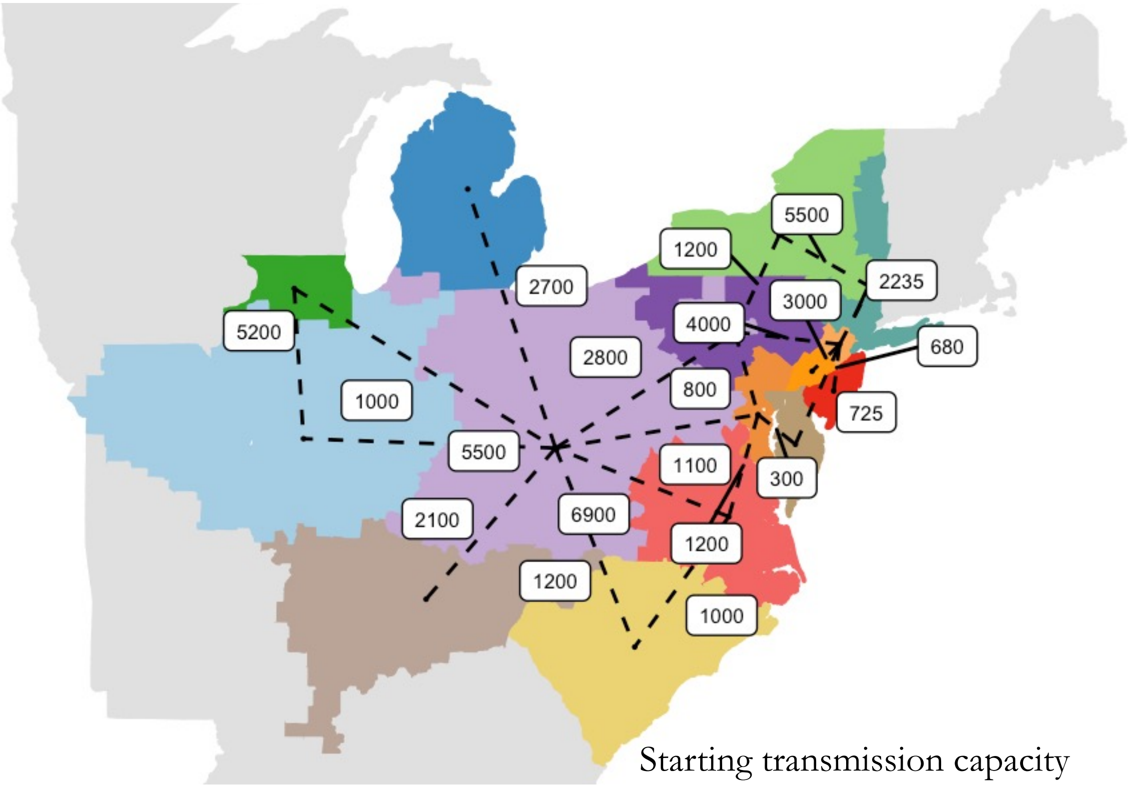
https://energy.mit.edu/genx/

https://github.com/GenXProject/GenX

Planning Framework and Data Sources

A myopic staged expansion





Starting transmission capacity (derived from EPA IPM and PJM Capacity Emergency Transfer Limit reports).

Assumptions:

- 15-zone network: 9 total zones in PJM + 6 neighboring zones in NYISO, MISO and SERC. Based on EPA IPM zones with further disaggregation of EMAAC zone into NJCoast, NJLand, PECO, and Delmarva zones;
- Existing Generation Data: EIA 860m @ Nov. 2020
- Wind and solar candidate project areas (4km x 4 km) grouped into 171 resource clusters in the study region from Princeton *Net-Zero America* study https://zenodo.org/record/4633707
- Climate year: 2012 (with impact of Hurricane Sandy on demand removed)
- Base capital cost and sensitivities: NREL ATB 2020; Regional capital cost multiplier: EIA AEO 2020; DG capital and fixed cost: Cadmus NJ SAM inputs.
- Base fuel cost assumption and sensitivities: EIA AEO 2020; 2019 monthly variation from EIA. High/low natural gas price sensitivity: AEO low/high resource scenarios.
- Load: demand flexibility and per unit time-series calculated from NREL's EFS study; stock values for EVs and heat pumps from Princeton *Net-Zero America* E+ scenario.
- Data populated by open-sourced power system data compiler *PowerGenome* https://github.com/PowerGenome/PowerGenome

Scenarios: Current Policies, Stated Policies, and Deep Decarbonization

Scenario and Sensitivity Summary (see following slides for details)

	1 **Current Policy (CP)** **(Legislated mandates)** Business-as-usual (BAU) with the power sector-related legislation as codified in 2020/21	2 **Stated Policy (SP)** **(e.g. NJ EMP stated goals)** CP + State-level 2050 de-carbonization policies announced yet not fully legislated	3 **PJM Deep Decarbonization (DD)** (Cross-industry de-carbonization across PJM, 100% clean electricity)	**4 Sensitivities**
3 Main Scenarios	**Modeled policy examples:** **Legislated RPS** (e.g. 50% RPS in NJ by 2030) **Mandated carve-outs** (e.g. in NJ 6.8 GW of solar DG by 2026 and 7.5 GW of offshore wind by 2035) **Mandated Energy Storage** (e.g. 2 GW by 2030 in NJ) **Nuclear support** (e.g. in NJ through 2030 only) **Announced electrification** (e.g. in 330,000 plug-in electric vehicles by 2025)	**Modeled policy examples:** **Stated RPS policy** (e.g. in NJ 75% RPS by 2050) **Stated Clean Energy Standard** (e.g. in NJ 100% clean electricity by 2050) **Mandated Energy Storage** (e.g. 2 GW by 2030 in NJ) **Nuclear support** (e.g. in NJ none after 2030) **Cross-industry de-carbonization** (e.g. NJ EMP, 80% below 2006 levels by 2050 via building and transportation electrification) **Expanded RGGI:** PA joins RGGI	**On top of SP:** **Whole study area (PJM and neighboring regions) moves to 100% clean electricity by 2050** - In 2030, PJM carbon intensity is 80% lower than in 2005. **High electrification of buildings and transportation in the whole study area**	1. Low cost renewables / battery energy storage systems (BESS) 2. High cost renewables / BESS 3. Low natural gas price 4. High natural gas price
8 Scenario Variants to SP		1) Keep NJ nuclear through 2050 with any required ZEC payments 2) "High in-state solar variant" - NJ support for in-state DG solar will continue beyond 2026 3) 80% of NJ's RPS and CES must be met by in-state resources 2041-2051 4) 2 x 2 x 2 = 8 variants		

Modeled federal tax credits:

- Solar ITC: 10% of capital expenditure (permanent tax code)
- Offshore Wind ITC: 30% of capital expenditure for resources online through 2030 (assuming “safe harbor” eligibility for projects that commence construction before the end of 2025 and complete construction by 2030)
- 45Q: $50/ton (real 2020$) captured CO_2 (available for projects built through 2030)

Current Policies (CP) Scenario

- **Current Policy (CP) scenario** serves as a business-as-usual case with no further legislation/regulations beyond those codified as of the end of 2020 (see following tables)
  - Specifically, no state in the study region will undergo accelerated demand electrification consistent with a deep decarbonization pathway.
  - For New Jersey, distributed (sub-transmission level) solar installation is 6.8 GWdc in 2030 and beyond, based on NJ BPU's reported data and requirements of the New Jersey Solar Act of 2021. New Jersey also requires 2.0 GW of storage by 2030, which we assume includes existing storage e.g. Yard's Creek pumped hydro. The remaining 1.6 GW is assumed to be met by battery storage (see table below.)

State-level RPS targets

State	Coverage	2030	2040	2050
District of Columbia	100%	87.0%	100.0%	100.0%
Delaware	100%	25.0%	25.0%	25.0%
Illinois	91%	25.0%	25.0%	25.0%
Maryland	100%	50.0%	50.0%	50.0%
Michigan	100%	14.3%	13.6%	12.7%
Missouri	74%	15.0%	15.0%	15.0%
North Carolina	100%	11.9%	11.9%	11.9%
New Jersey	98%	52.5%	52.5%	52.5%
New York	100%	70.0%	70.0%	70.0%
Pennsylvania	97%	8.0%	8.0%	8.0%
Virginia - Dominion	87%	46.3%	81.2%	100%
Virginia - APCO	63%	35.2%	67.6%	100%

State-level technology mandates (min. installed capacity, GW)

State	Technology	2030	2040	2050
New York	Offshore Wind	5.7	9.0	9.0
Maryland	Offshore Wind	1.2	1.2	1.2
New Jersey	Offshore Wind	3.5	7.5	7.5
Virginia	Offshore Wind	3.9	5.2	5.2
New York	Battery Storage	3.0	3.0	3.0
New Jersey	Battery Storage	1.6	1.6	1.6
Virginia	Battery Storage	1.4	2.3	2.3
New York	Utility Solar	6.0	6.0	6.0
New Jersey	Utility Solar	1.1	1.1	1.1
New York	Nuclear	3.3	0.0	0.0
Illinois (ComEd)	Nuclear	3.0	3.0	3.0
New Jersey	Nuclear	3.5	0.0	0.0

RGGI CO_2 emissions budget

State	Emission allowances (Million Metric Ton)
Delaware	1.60
Maryland	7.95
New Jersey	11.43
New York	13.92
Virginia	17.78

Note 1: Coverage modifies the stated RPS rule to consider that some state RPSs do not cover 100% of utility types. For example, Illinois's RPS only applies to utilities serving 91% of the total load. The coverage is calculated from the sales data reported by EIA (U.S. Energy Information Administration 2018);
Note 2: The state of New York accepts conventional hydro as renewable, while other states in the study region do not, In addition, for the New York State, a 100% Clean Energy Standard (CES) will be effective in 2040.
Note 3: DG solar carve-out: District of Columbia at 5% of the load in 2030, 9.5% in 2040, and 10% in 2050, and Maryland at 14.5% in years ending 2030, 2040, 2050. New Jersey DG start at nameplate of 6753 MW-dc in 2030. See details of how this number is arrived in Appendix – New Jersey DG & Utility-level solar mandate. This starting DG does not equate to the NJ EMP "least cost pathway" target of 12.GW in 2030, and > 30 GW in 2050. This study has a separate policy variant for modeling high solar in New Jersey.

Stated Policies (SP) Scenario

- **Stated Policy (SP)** scenario, the core focus for this report, is designed to evaluate the impact of the state-level decarbonization policies announced but not codified by the state government.
  - The focus is on the policy goals encapsulated in recent Executive Orders, the New Jersey *Energy Master Plan* and other BPU proposed rules.

Stated Policy scenario includes the following changes relative to CP:

- ✓ **High electrification in New Jersey, New York, and Virginia**: these three states have legislated economy-wide deep decarbonization goals but have not fully implemented policies required to achieve such goals. In SP, we assume more rapid electrification of commercial water heating, commercial space heating and cooling, residential water heating, residential space heating & cooling, and transportation. Stock values are consistent with Princeton *Net-Zero America* E+ scenario. For NJ stocks, check "Appendix - New Jersey Electrification" for more details.
- ✓ **100% CES in New Jersey by 2050:** a 100% clean electricity standard will be effective in New Jersey and New Jersey's RPS will rise to 75% in the year 2050 (as per Executive Orders accompanying the *EMP*).
- ✓ **Other policy modifications to CP:**
  - A 100% RPS will be effective in Virginia in 2050;
  - Pennsylvania will join RGGI with an emission budget of 52.71 Million Metric tons/year;
  - In the year 2040 and beyond, New York state is assumed to import Quebec hydropower from the Champlain-Hudson Power Express line.

Deep Decarbonization (DD) Scenario

❑ The **Deep Decarbonization (DD)** scenario is a modified SP scenario where the whole study region is moving towards economy-wide deep decarbonization.

Deep Decarbonization scenario includes the following changes relative to SP:

✓ **High Electrification in the whole study area:** Every state in the study region will see high electrification of commercial water heating, commercial space heating and cooling, residential water heating, residential space heating & cooling, and transportation. Stock values are consistent with Princeton *Net-Zero America* E+ scenario.

✓ **CO_2 emissions limits:** A cap-and-trade system will be implemented across all of PJM, with equally stringent caps applied in neighboring regions and no permit trading between PJM and neighboring regions.

- In 2030, the load-based emission rate of PJM will be 0.121 metric ton per MWh of load, 80% lower than the 2005 level of 0.607 metric ton/MWh.* This emission rate cap will decline linearly to zero in 2050, requiring a 90% reduction from 2005 levels by 2040 and 100% by 2050.
- NYISO and modeled MISO and southeast regions are each assumed to implement a similar emissions constraint that is no dirtier than the PJM one. No trading of emissions permits between these regions is permitted.

* In 2005, PJM's generation-based emission rate was about 1290 lb/MWh, the total generation of PJM was 710.4 TWh, and the total load of PJM was 684.6 TWh. Thus, the load-based emission rate is 1338 lb/MWh = 0.607 metric ton/MWh.

Policy Variants

Eight policies variants are considered, each a combination of one or more of the following options.*

❑ **High in-state solar variant** assumes NJ will continue policy support for in-state solar (distributed and utility-scale) beyond 2026, with the following installation schedule:

(GW-dc)	Distributed Solar**	Utility-level Solar***	Total
2030	9.5	> 2.7	> 12.2
2040	16.5	> 5.7	> 22.2
2050	22.6	> 8.7	> 31.3

❑ **In-state RPS/CES requirement variant** assumes New Jersey establishes a carve-out policy requiring 80% of NJ RPS and CES requirements must be met by in-state renewable/carbon-free generation in 2031-2050 (e.g. with a 75% RPS in 2050 in SP, this variant would require 60% of NJ load is met by in-state qualifying renewables).

❑ **Nuclear support variant** assumes New Jersey continues its Zero Emissions Certificate (ZEC) subsidy program to support continued operation of in-state nuclear power plants.

*Note: A combination of the first two variants will be similar to the "least-cost pathway" proposed in NJ *Energy Master Plan*.

**Distributed Solar: solar facilities that are connected to the distribution grid, including both front-of-the-meter solar (such as grid supply and community solar) and behind-the-meter solar.

***Utility-level solar: solar facilities that are connected to the transmission grid.

New Jersey Fuel Price (2020$/MMBTU)

Natural Gas Price (Low Level)

Month	2030	2040	2050
Jan.	4.13	4.00	3.97
Feb.	3.59	3.49	3.46
Mar.	3.34	3.24	3.22
Apr.	2.34	2.27	2.26
Ma	2.35	2.28	2.26
Jun.	2.23	2.17	2.15
Jul.	2.32	2.26	2.24
Aug.	2.25	2.19	2.17
Sep.	2.22	2.15	2.13
Oct.	2.17	2.11	2.09
Nov.	2.48	2.4	2.39
Dec.	2.40	2.33	2.31

Natural Gas Price (Medium Level)

Month	2030	2040	2050
Jan.	4.97	5.11	5.49
Feb.	4.33	4.45	4.78
Mar.	4.03	4.14	4.45
Apr.	2.82	2.90	3.12
Ma	2.83	2.91	3.13
Jun.	2.69	2.77	2.97
Jul.	2.80	2.88	3.09
Aug.	2.72	2.79	3.00
Sep.	2.67	2.75	2.95
Oct.	2.62	2.69	2.89
Nov.	2.99	3.07	3.3
Dec.	2.89	2.97	3.19

Natural Gas Price (High Level)

Month	2030	2040	2050
Jan.	7.04	8.01	9.33
Feb.	6.13	6.98	8.13
Mar.	5.70	6.49	7.56
Apr.	4.00	4.55	5.30
Ma	4.01	4.56	5.32
Jun.	3.81	4.34	5.05
Jul.	3.96	4.51	5.25
Aug.	3.84	4.37	5.09
Sep.	3.78	4.30	5.01
Oct.	3.70	4.21	4.91
Nov.	4.23	4.81	5.60
Dec.	4.09	4.65	5.42

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

	2030	2040	2050
Uranium	0.70	0.72	0.74
Zero-carbon Fuel	14.00	14.00	14.00

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference. Natural gas prices variations are based on monthly variation from annual mean price in EIA 2019 state-level Natural Gas price report. Zero-carbon Fuel (ZCF) price reflects approximate modeled hydrogen supply cost from Princeton *Net-Zero America* study. All other fuel data (for each modeling region, and each fuel type) can be obtained from the Appendix – Fuel Prices

New Jersey Candidate Resources (Thermal & Battery)

Resource	2030 CAPEX ($/kW)	2040 CAPEX ($/kW)	2050 CAPEX ($/kW)	FOM ($/MW-year)	VOM ($/MWh)	Heat Rate (MMBTU/MWh)
NGCC Candidate	932	883	856	12,595	1.63	6.27
NGCT Candidate	730	688	667	7,046	4.54	9.90
Nuclear Candidate	7,138	6,676	6,201	122,638	2.39	10.46

	Year	Level	Capacity CAPEX ($/kW)	Capacity FOM ($/MW-year)	Energy CAPEX ($/kWh)	Energy FOM ($/MWh-year)	Round Trip Efficiency
Battery	2030	Low	154	3,855	177	4,427	84.6%
	2040	Low	93	2,332	107	2,678	84.6%
	2050	Low	73	1,820	84	2,091	84.6%
	2030	Medium	198	4,956	228	5,692	84.6%
	2040	Medium	140	3,505	161	4,026	84.6%
	2050	Medium	121	3,034	139	3,485	84.6%
	2030	High	242	6,056	278	6,956	84.6%
	2040	High	197	4,929	227	5,662	84.6%
	2050	High	171	4,268	196	4,902	84.6%

All $ in this report is 2020 US real dollars.

New Jersey Offshore Wind Cost/Limit

	Year	Level	CAPEX ($/kW)	FOM ($/MW-year)	Interconnection Annuity ($/MW-year)	Capacity Factor	Total Developable Capacity
Offshore Wind	2030	Low	2,074	82,513	25,262 - 55,950	44.8% - 46.4%	33.4 GW
	2040	Low	1,931	49,009			
	2050	Low	1,676	43,175			
	2030	Medium	2,295	92,679			
	2040	Medium	2,506	66,530			
	2050	Medium	2,229	60,000			
	2030	High	2,733	115,303			
	2040	High	3,557	106,378			
	2050	High	3,377	102,108			

Offshore wind receives 30% federal investment tax credit (ITC) for projects coming online before 2030 (assuming "safe harbor" eligibility for projects that commence construction before the end of 2025 and complete construction by 2030), and thus modeled after-subsidy CAPEX in 2030 can be lower than 2040/2050

New Jersey Utility Solar Cost/Limit

	Year	Level	CAPEX ($/kW)	FOM ($/MW-year)	Interconnection Annuity ($/MW-year)	Capacity Factor (AC with Inverter Loading Ratio = 1.34)	Total Developable Capacity
Utility Solar	2030	Low	1,023	12,238	9,177 – 9,412	25.6% - 26.0% (AC) 19.1% - 19.4% (DC)	15.1 GW
	2040	Low	647	7,737			
	2050	Low	561	6,709			
	2030	Medium	1,105	13,216			
	2040	Medium	803	9,602			
	2050	Medium	728	8,705			
	2030	High	1,318	15,764			
	2040	High	1,127	13,482			
	2050	High	932	11,146			

Utility solar receives 10% permanent federal investment tax credit (ITC) in all scenarios

New Jersey Distributed Solar Cost

DG solar is assumed to have 25 years of economical life with WACC being ~4.7% real. The inverter loading ratio of NJ DG solar is assumed to be 1.2, and the capacity factor is about 20.4% AC in NJ. The residential and commercial DG solar is assumed to be 40% non-third party owned, 60% third party owned.

Medium RE/BESS Case

	CAPEX Cost ($/kWdc)			FOM ($/MWdc-year)		
	2030	2040	2050	2030	2040	2050
Residential	2,260	1,372	1,197	24,324	14,759	12,885
Commercial	1,411	1,038	909	34,327	25,264	22,122
Grid	1,318	1,005	911	20,958	15,981	14,489
Community	1,422	1,084	983	45,585	34,760	31,514

Low RE/BESS Case

	CAPEX Cost ($/kWdc)			FOM ($/MWdc-year)		
	2030	2040	2050	2030	2040	2050
Residential	2,057	1,037	869	22,142	11,158	9,350
Commercial	1,262	800	686	30,715	19,454	16,694
Grid	1,211	818	709	19,250	13,006	11,279
Community	1,306	883	765	41,871	28,290	24,534

High RE/BESS Case

	CAPEX Cost ($/kWdc)			FOM ($/MWdc-year)		
	2030	2040	2050	2030	2040	2050
Residential	3,201	2,586	1,771	34,442	27,829	19,058
Commercial	1,749	1,509	1,211	42,553	36,716	29,469
Grid	1,588	1,375	1,137	25,248	21,870	18,081
Community	1,713	1,484	1,227	54,918	47,569	39,328

Installation Schedule in non-High Solar Scenario variants

Unit: MWdc	2022-2030	2031-2040	2041-2050
Residential	650	-	-
Commercial	850	-	-
Grid	-	-	-
Community	750	-	-
Total	2250	-	-

Installation Schedule in High Solar Scenario variants

Unit: MWdc	2022-2030	2031-2040	2041-2050
Residential	1,713	2,320	1,865
Commercial	2,243	2,688	1,920
Grid	300	500	750
Community	1,050	1,500	1,500
Total	5,305	7,008	6,035

All distributed solar except residential DG solar PV receives 10% ITC in 2030, 2040 and 2050 because current residential solar ITC expires in 2024.

Other Cost/Capacity Assumptions

- Existing capacities are obtained from EIA 860 and 860m (Nov. 2020 version).
  - Heat rates are calculated from the annual fuel usage and annual production.
  - See "Appendix - New Jersey Starting Resources"
- Costs for new generation/storage candidates are obtained from NREL ATB 2020.
  - Wind/solar maximum capacity and capacity factors are based on the Candidate Project Area of Princeton *Net-Zero America* study, and mapped on to this study's 15-zone topology.
  - Low/High/Medium cost scenarios correspond to NREL's three levels of Wind/Solar/Battery costs.
- For cost assumptions for other New Jersey resources, please refer to "Appendix - Other Cost Assumption."
- Note: reported costs in this study do not include any policy support or private purchasing costs associated with demand electrification (e.g., EV or heat pump adoption).

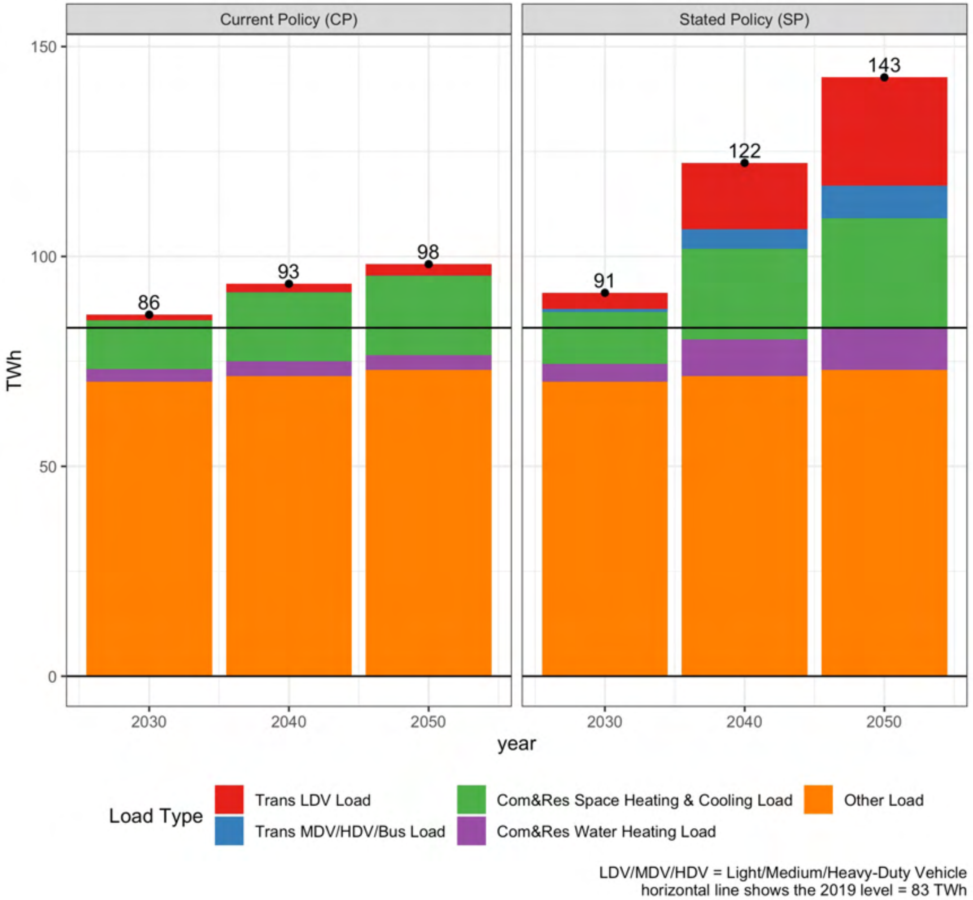
Treatment of Distributed Solar PV

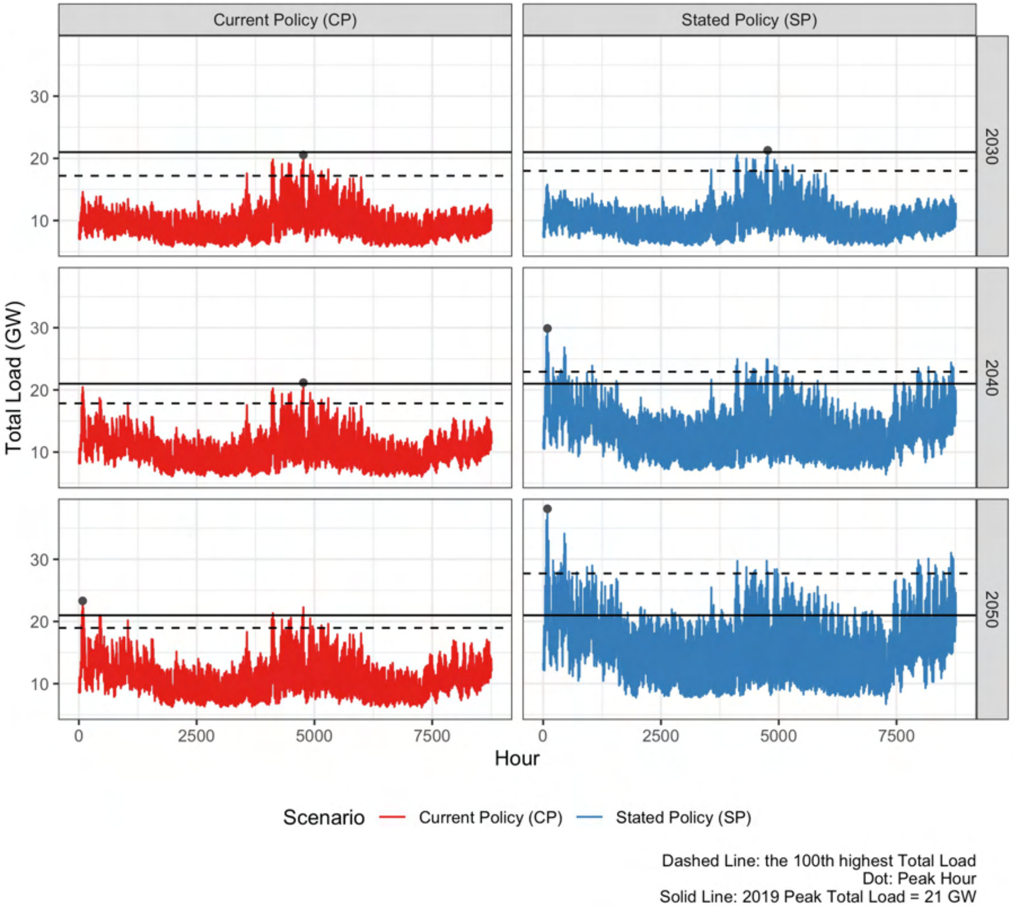
- **The report scope is limited to modeling of the wholesale electricity supply and transmission level.**
- DG solar PV is modeled as a reduction in net demand at the transmission level, with facility-level generation increased to reflect an assumed 4.5% average distribution network loss factor.
- We 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. See "Appendix – Distributed Solar Cost" for details on these calculations.
- 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.

Main Results

Note: The report scope is limited to modeling of the wholesale electricity supply and transmission level. See "Treatment of Distributed Solar PV" on slide 45 for more.

Demand electrification consistent with NJ's stated economy-wide deep decarbonization policies could cause significant changes in the magnitude and pattern of electricity consumption





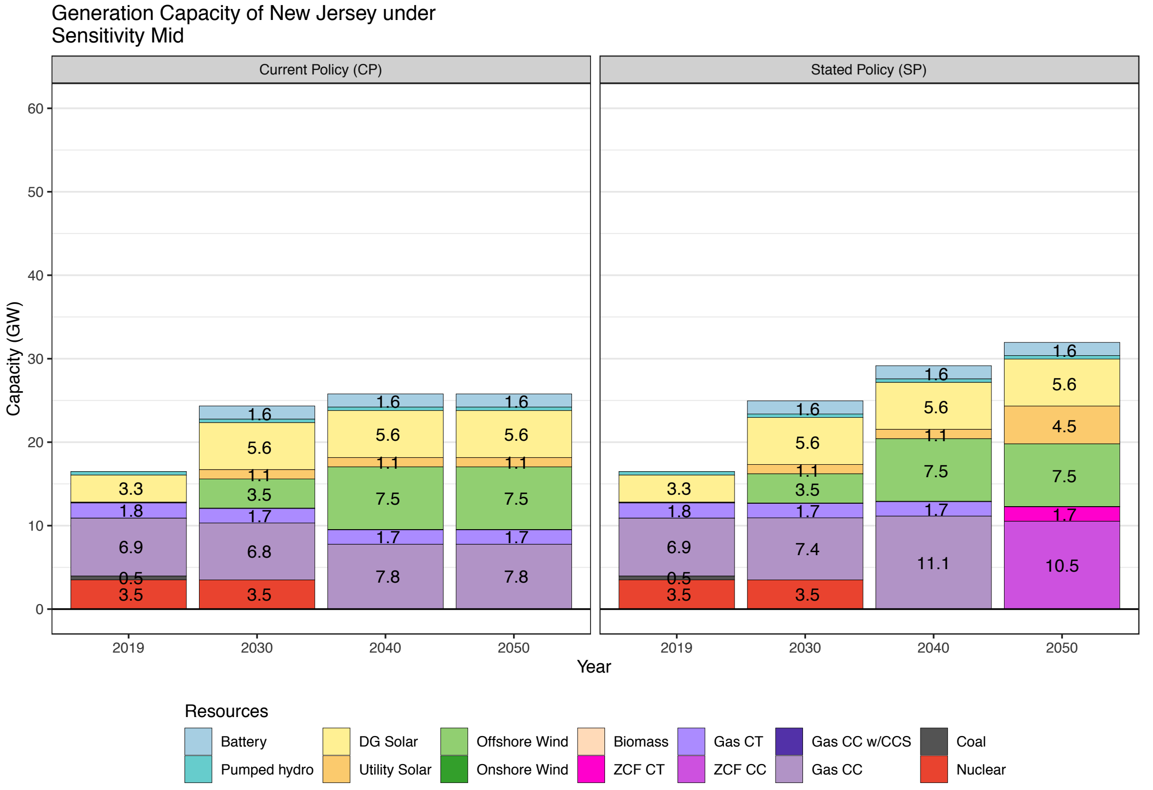
- **Accelerated electrification increases NJ gross electricity demand by 70%,** from 2019's 83 TWh to 143 TWh in 2050 (46% higher than the Current Policy scenario without accelerated electrification).

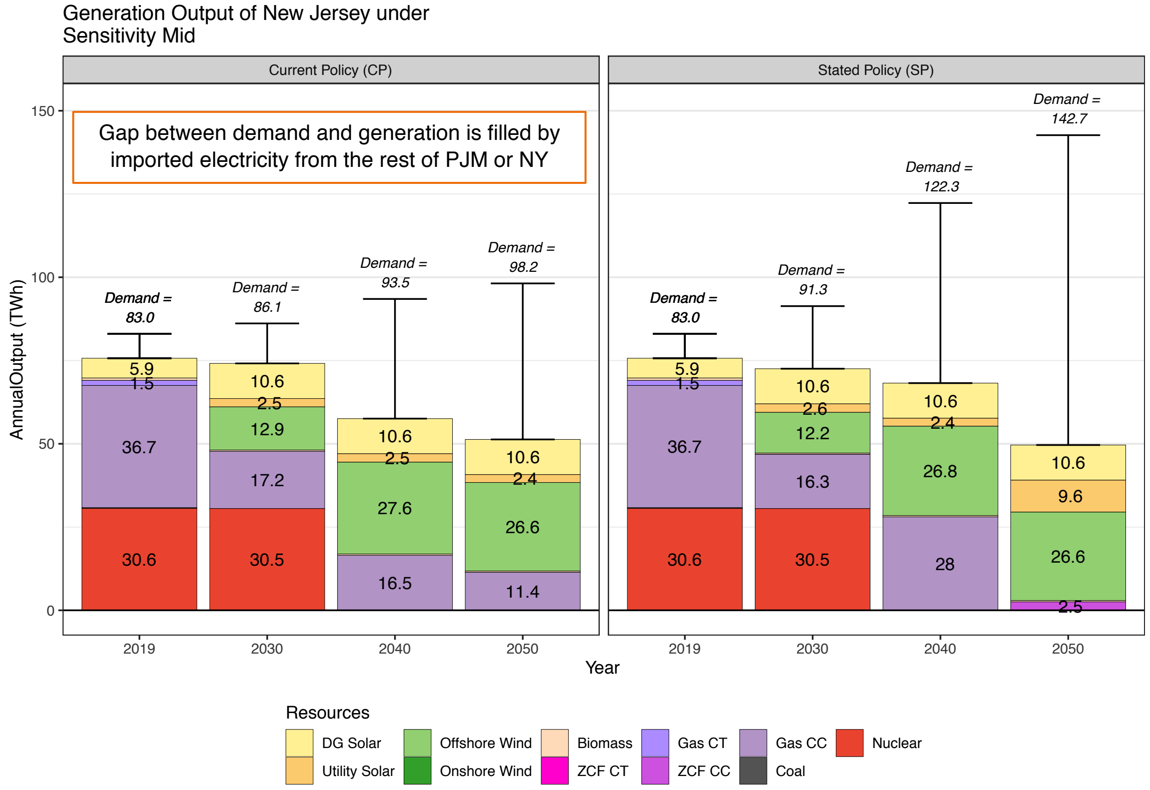
For stock values of electrified sectors, please check Appendix- "New Jersey Electrification Assumptions"
For decomposition of the aggregate load time series into sectors/devices, refer to Appendix- "Decomposition of New Jersey Load Time-Series."

- Heating **demand electrification moves the NJ peak demand periods from summer days to winter nights**, an important shift with implications for the value of different resources (e.g., daytime solar).
- **Peak demand increases 85%** from 21 GW to 38 GW in 2050 in SP.

Load (aka demand) in this slide is **total load** (or **gross load**) before subtracting distributed generation. In contrast, the **metered load** that will appear later in this report is the total load subtracting self-supplied demand or distributed generation. Metered load is what **load serving entities** (**LSEs**) need to serve by procuring energy from the PJM energy market or signing power purchase agreement (PPA).

With a diverse mix of NJ generating capacity and increased reliance on imported electricity, it is feasible for NJ to reach a 100% carbon-free electricity supply in 2050 while maintaining reliability and affordability.



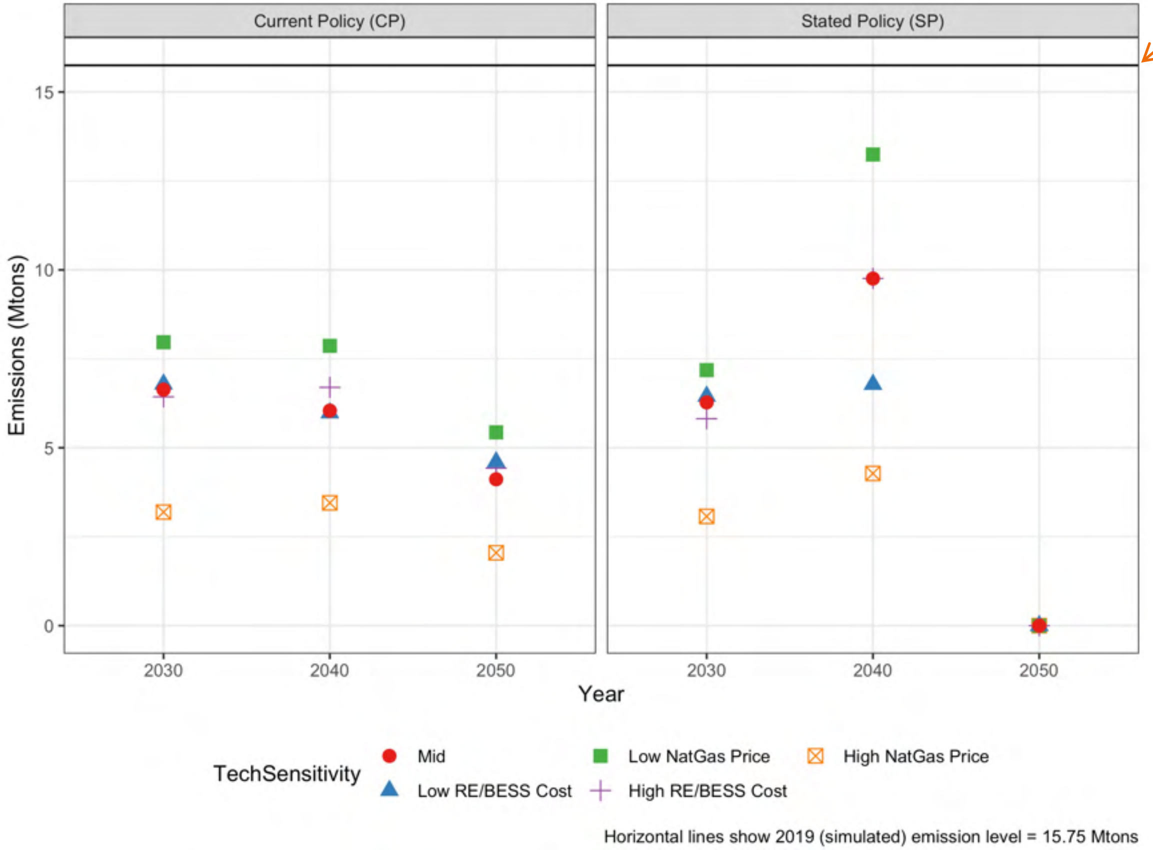


- SP: **NJ in-state generating capacity doubles** from 17 GW to 32 GW in 2050, **formed by a diverse mix** of solar PV (distributed and utility-scale), offshore wind, battery energy storage, and conversion of gas-fired capacity to run on zero-carbon fuel (e.g., clean hydrogen, synthetic methane, biomethane).
- CP/SP: **Offshore wind/storage does not expand** beyond NJ's mandate of 7.5 GW/2 GW; **Nuclear capacity will retire w/out further policy support.**

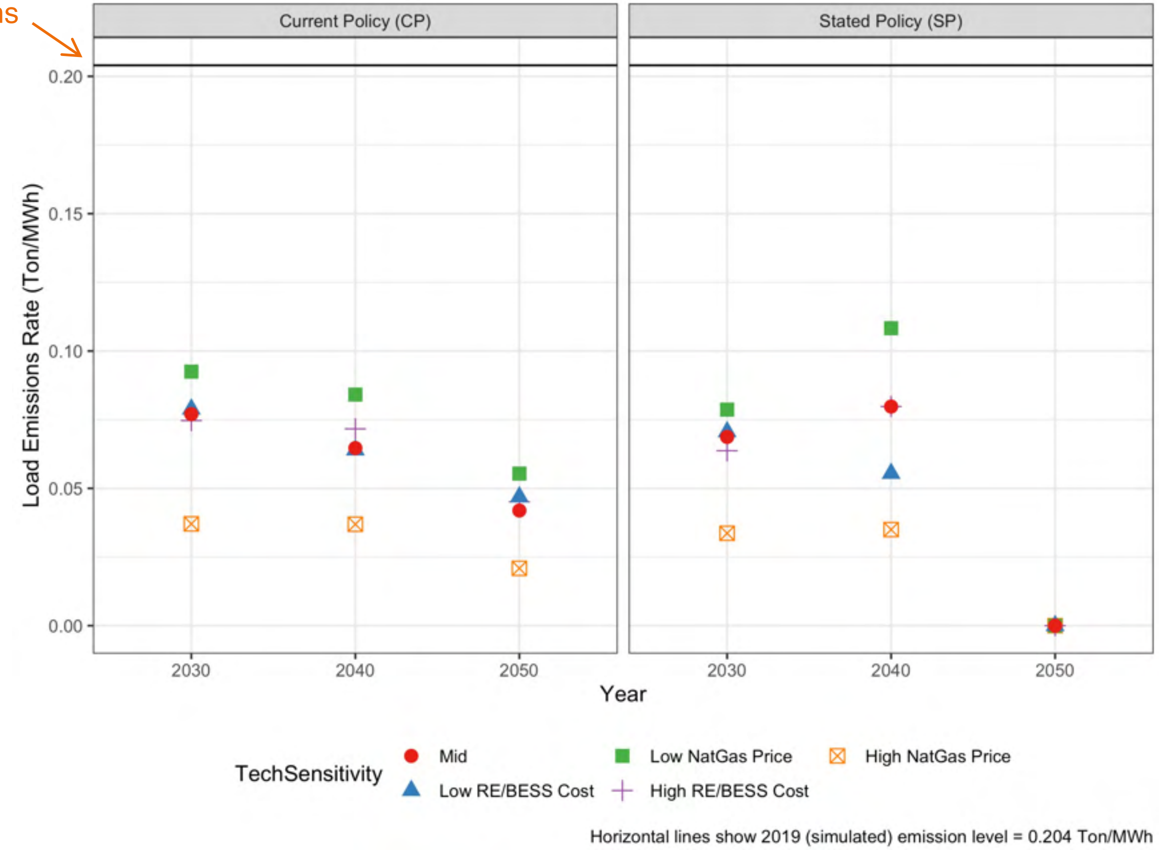
Legend clarification: *CC* = combined cycle; *CT* = combustion turbine; *Gas* = fossil gas; *ZCF* = zero-carbon fuel; *DG solar* = solar PV capacity connected to the distribution system (both behind-the-meter and front-of-the-meter systems); *Utility Solar* is solar PV connected to the transmission system.

- SP: In 2050, **in-state generation is 100% carbon-free** with 27 TWh offshore wind, 11 TWh distributed solar, 10 TWh utility-level solar, and small contributions from zero-carbon fuel combustion and biomass.
- SP: **NJ becomes a net importer of ~65% of total annual demand** by 2050, 100% matched with clean energy certificate purchases from the rest of PJM.
- SP: **Gas power plant capacity & fossil gas-fired generation increase in 2040** to replace nuclear and help meet increasing demand. **By 2050, all gas plants convert to use zero-carbon fuels, providing firm capacity but limited generation** (2-3% capacity factor).

If existing nuclear units retire after 2030, NJ CO_2 emissions from electricity supply can temporally increase in the 2030s due to increasing demand from electrification and greater use of fossil gas to replace nuclear.

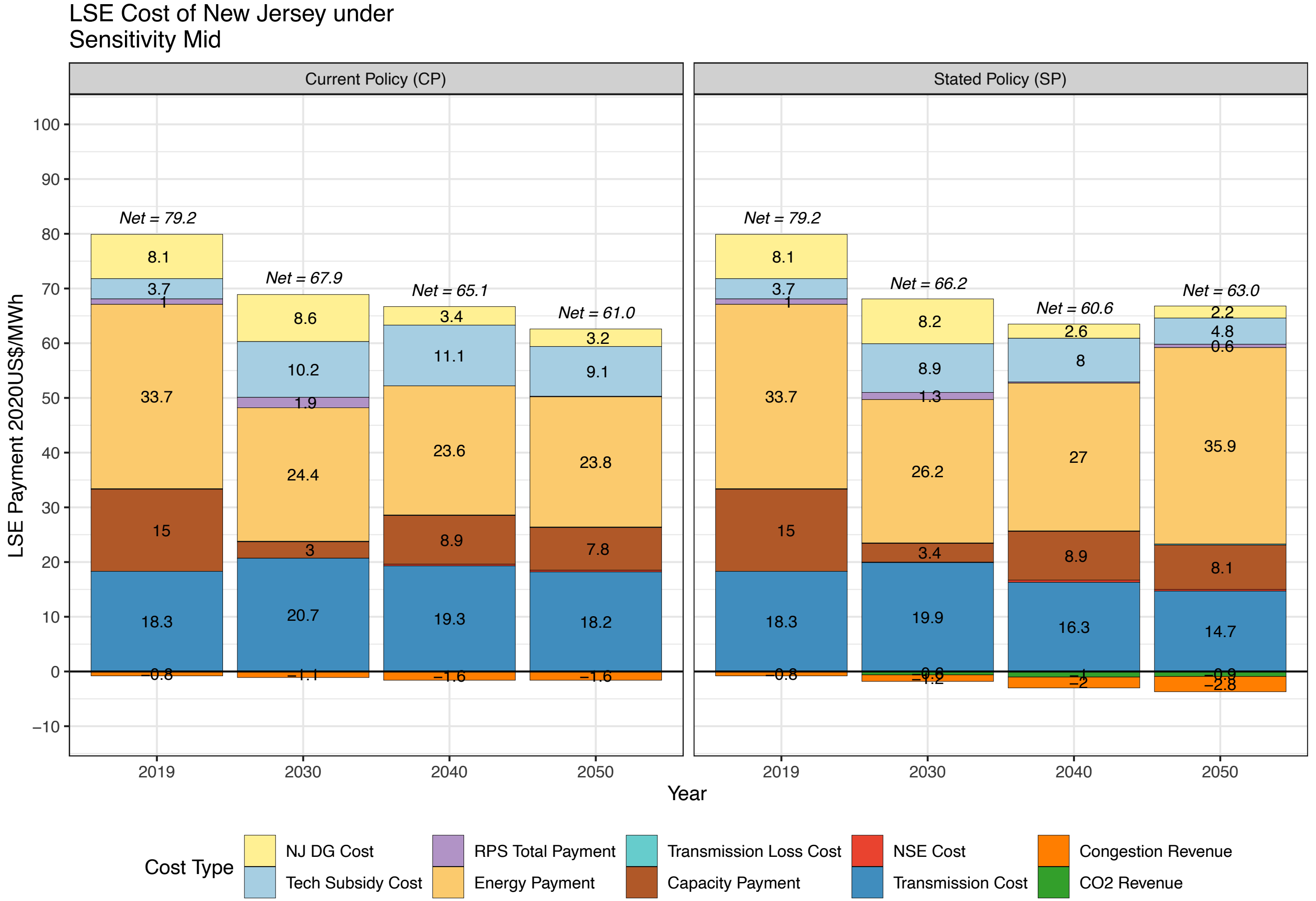


2019 emissions level



- CP: NJ CO_2 emissions (in tons) almost holds constant from 2020-2040 because fossil gas (aka natural gas) generation, the only emitting resource in NJ, does not significantly change. In 2050, in-state emissions decline because cheap imports substitute for the gas power, but not completely.
- SP: **In Stated Policies, NJ CO_2 emissions from power generation increase through 2040**, as a result of increased fossil gas-fired generation to meet increased demand from electrification and replace nuclear units, which retire after expiration of ZECs in 2030, **before falling to zero in 2050.**

Under Mid-range assumptions, electricity supply costs for NJ load serving entities decrease ~20% to $63/MWh by 2050 as the state transitions to 100% carbon-free supply; LSE supply costs fall 23% under Current Policies.

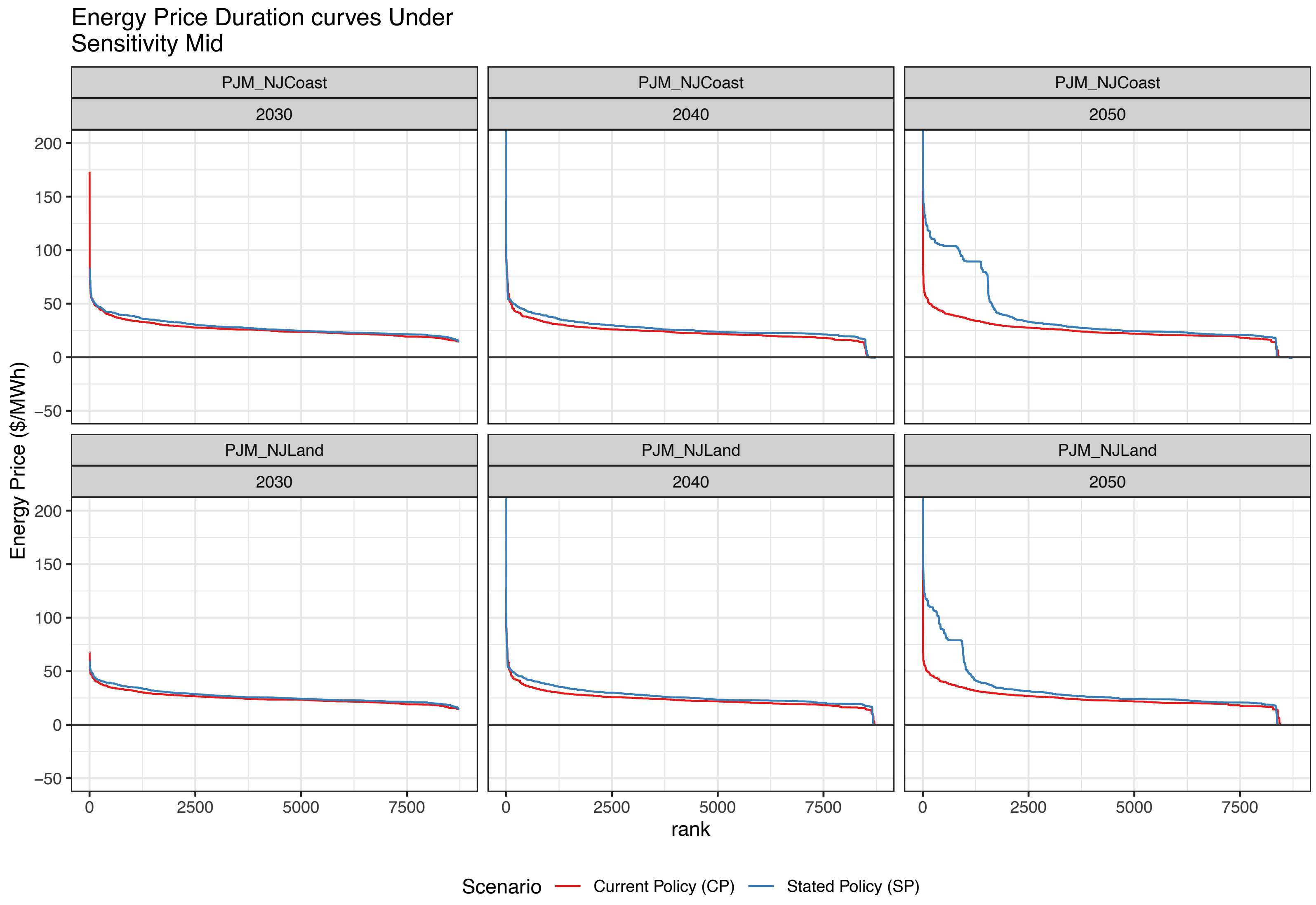


- Under both CP and SP scenarios: **bulk electricity supply costs decline** due to expiration of current DG solar incentives, no additional DG solar or offshore wind requirements beyond current law, lower modeled capacity payments, and greater demand (from electrification) over which to spread fixed costs. Projected continuation of cost declines for new utility-scale solar and wind also contribute to downward supply cost trends.
- CP: **Without new policy, electricity supply costs for NJ load serving entities (LSEs) fall 23%** to $61.0/MWh in 2050 (from $79.2/MWh in 2019) under Mid-range assumptions.
- SP: **Under Stated Policies, a 100% emission-free electricity supply will cost NJ electricity consumers 20% less than payments in 2019** ($63.0/MWh) assuming Mid-range cost assumptions (a savings of $16.2/MWh).
- SP: **Across the full range of sensitivities (aka possible futures) considered**, costs for NJ consumers in 2050 span a decline of 10-29% relative to 2019 costs, meaning **reaching 100% carbon-free electricity is feasible with reductions in bulk electricity supply costs** (see "Sensitivity Results: NJ Load Serving Entity Cost").

Note: for 2019 LSE cost benchmark calculation, check the Appendix – "2019 LSE Cost Benchmark." For costs calculation in 2030, 2040, 2050, check Appendix – "Other assumptions of LSE cost calculation." Every cost or benefit is evaluated at the transmission level, and thus, the potential cost impacts on the distribution system are not considered in this report. Note that total electricity bills may increase with electrification as total volume of electricity consumption increases, while total expenditures on energy (including fuels and heating) will likely decline. However, this report does not make any attempt to quantify total bill impacts or distribution of costs across customer classes or usage patterns.

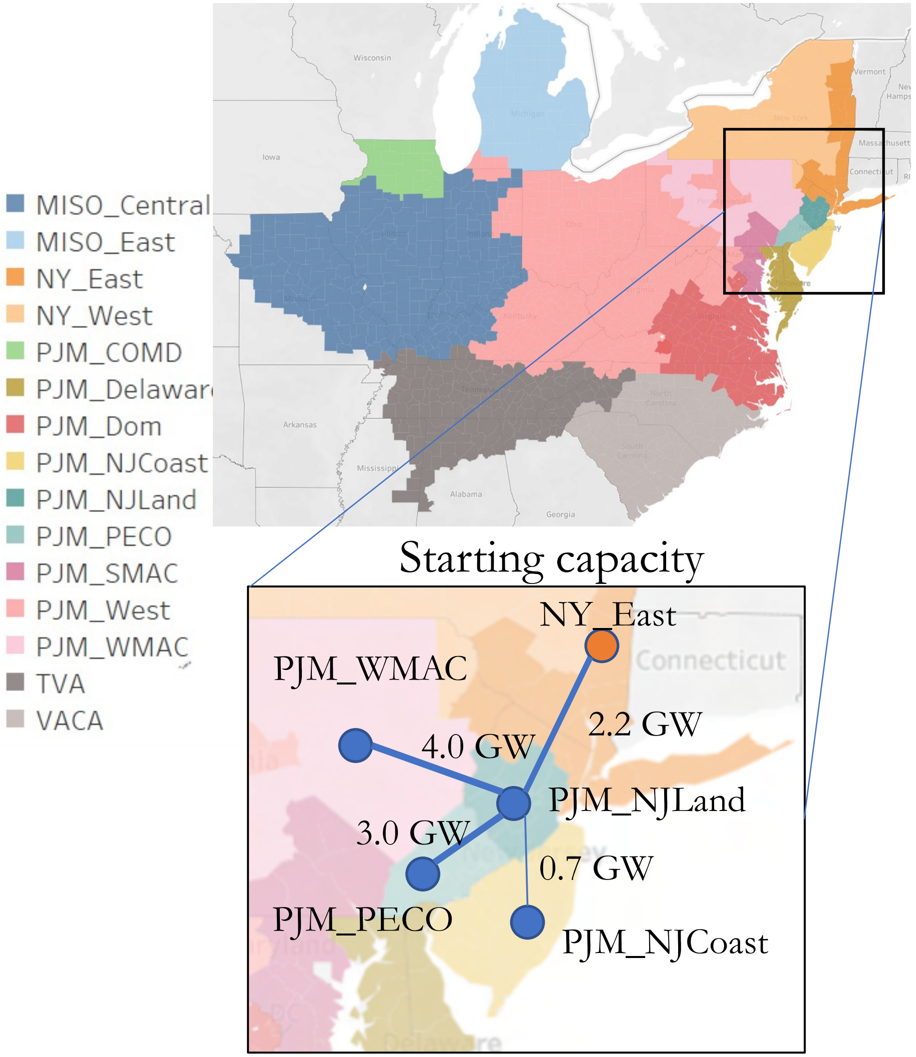
Legend clarification: *NJ DG Cost* is the total payment of current incentives for distributed solar, including SREC, TREC, and payments to cover the annualized fixed cost of incremental DG solar required by policy. See Appendix – "Distributed Solar Cost" for more details; *RPS total payment* includes payment to purchase both general renewable energy credits and clean energy credits for state class I RPS and CES policies. *Tech Subsidy Cost* is the subsidy payment (e.g., zero carbon emission credit for nuclear, offshore wind incentives) for specific technologies as specified in current or stated policies. *NSE cost* is the payment from LSE to end consumers for voluntary demand response (no involuntary demand shedding events occur in these scenarios given required installed capacity reserve margins).

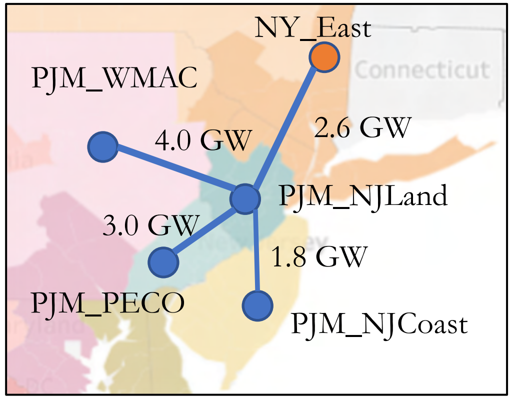
Shifting to 100% carbon-free electricity by 2050 entails an increase in prices during ~20% of the year when zero-carbon fuel burning plants set marginal prices, while average prices fall & prices are $0 ~10% of hours.

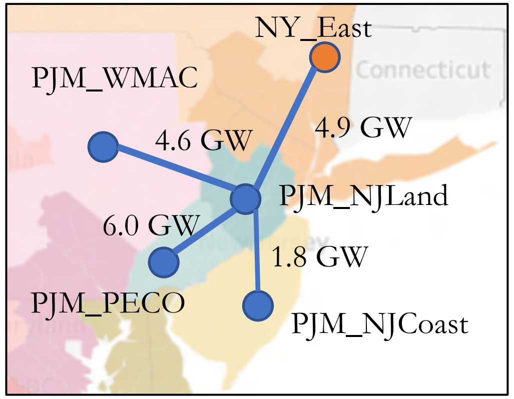


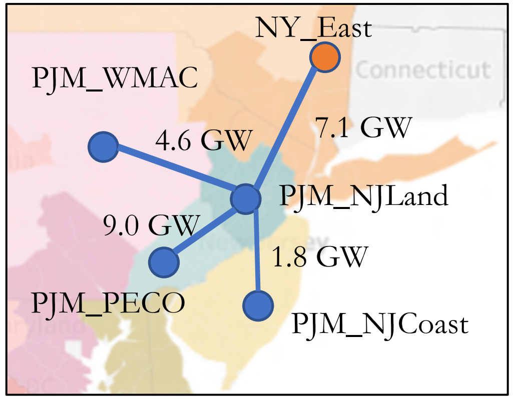
- CP/SP: **Average energy prices fall through 2050 (relative to 2019 levels) in both scenarios.**
- SP**: In 2050, higher price periods occur about 20% of hours** (increasing the "shoulder" of the price duration curves at left) **when plants burning zero-carbon fuel (ZCF) set the locational marginal price** (ZCF fuel assumed to be $14/MMBtu). This occurs more frequently in coastal NJ (*PJM_NJCoast* zone) than the interior of the state (*PJM_NJLand*).
- SP: **During more than two thirds of the year, NJ Prices in SP are only slightly higher than CP** because both scenarios rely heavily on imports from PJM or New York, which frequently set marginal prices in NJ.
- CP/SP: **Prices are $0/MWh about 10% of hours in both scenarios**, when wind or solar curtailments set marginal prices.
- See "Sensitivities: Electricity Price Duration Curves of NJ Zones" for variation across modeled Sensitivity scenarios.

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





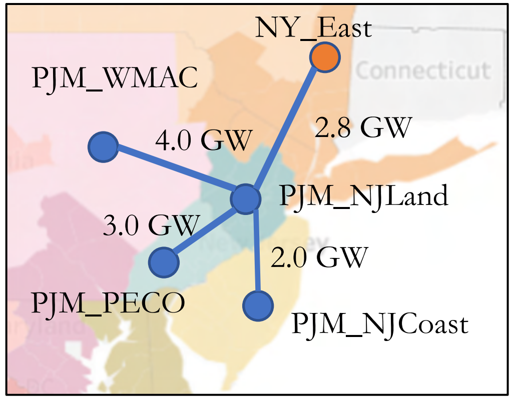


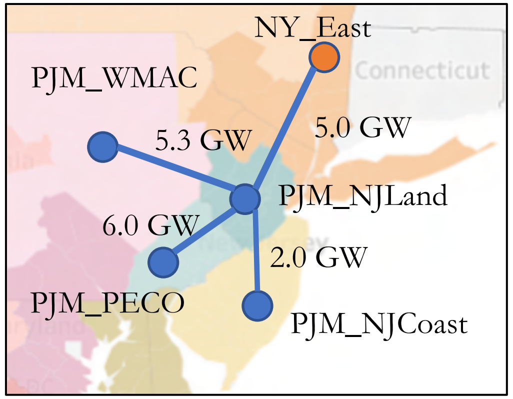


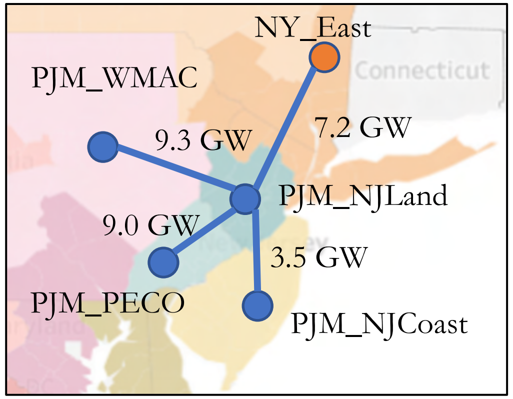
CP 2030
SP 2030

CP 2040
SP 2040

CP 2050 (+12.6 GW since 2021)
SP 2050 (+19.1 GW since 2021)







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).

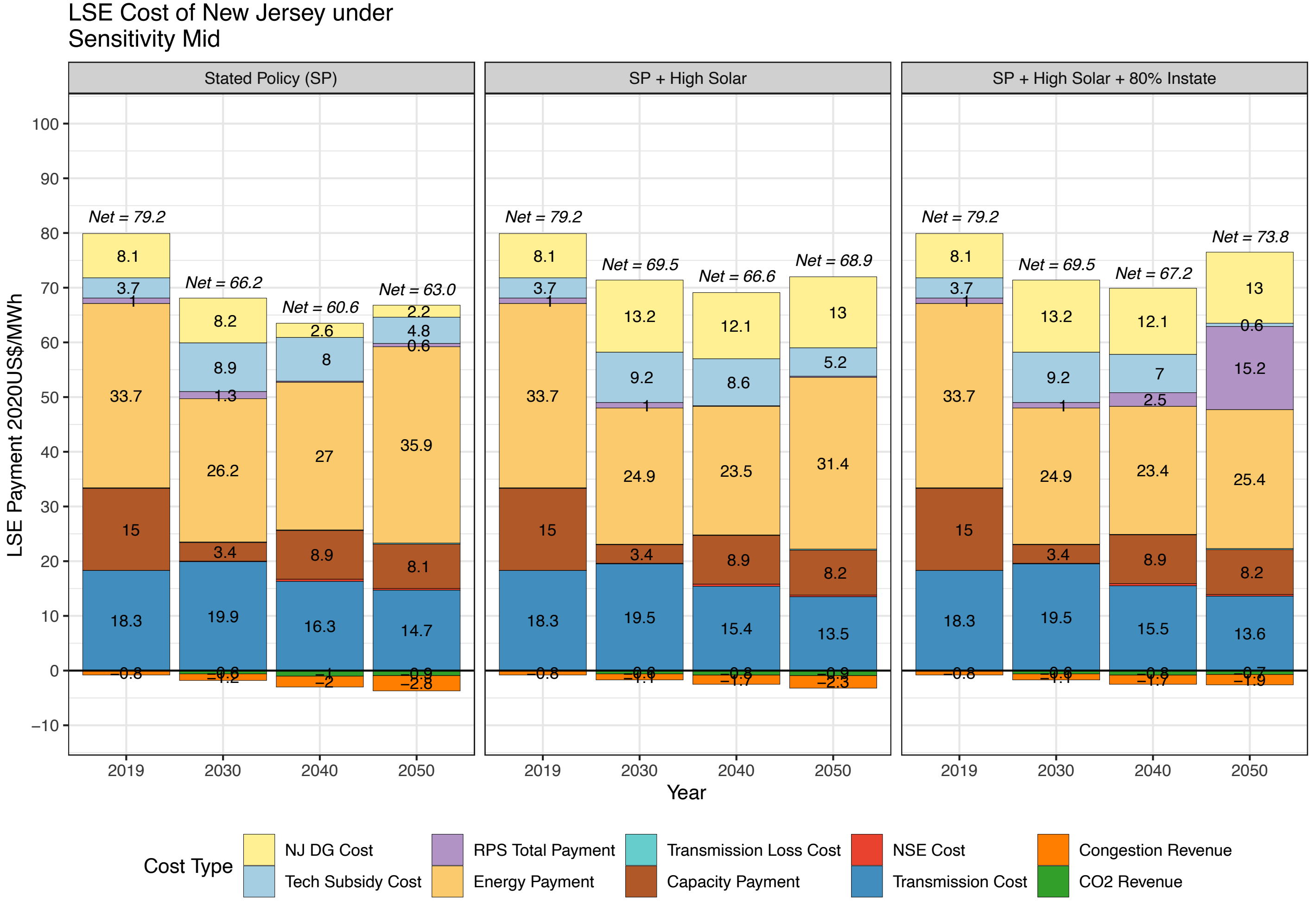
- **Before the end of 2030, the transmission capacity between coastal and inland New Jersey** (*PJM_NJLand* and *PJM_NJCoast* model zones) **needs to be approximately tripled** from the existing ~680 MW to ~1.8 GW to deliver planned offshore wind connected to the coastal area.
- Consistent with the high import-dependence of NJ in the Stated Policy scenario, **all transmission corridors between NJ and neighboring regions, including the rest of PJM and NYISO, also need to be expanded** (adding ~19 GW of capacity by 2050 in SP vs ~13 GW in Current Policies).

Continuing to prioritize in-state renewable/clean energy can increase costs of a 100% carbon-free electricity system for NJ but significantly reduces import dependence.

<u>Case descriptions</u>

SP + High Solar: Requires 31 GWdc 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).



Note: for the 2019 LSE cost benchmark calculation, check the Appendix – "2019 New Jersey LSE Cost Benchmark." For costs calculation in 2030, 2040, 2050, check Appendix – "Other assumptions of LSE cost calculation." Every cost or benefit is evaluated at the transmission level, and thus, the potential cost impacts on the distribution system are not considered in this report. Note that total electricity bills may increase with electrification as total volume of electricity consumption increases, while total expenditures on energy (including fuels and heating) will likely decline. However, this report does not make any attempt to quantify total bill impacts or distribution of costs across customer classes or usage patterns.

Legend clarification: *NJ DG Cost* is the total payment of current incentives for distributed solar, including SREC, TREC, and payments to cover the annualized fixed cost of incremental DG solar required by policy; *RPS total payment* includes payments to purchase both general renewable energy credits and clean energy credits for state class I RPS and CES policies. *Tech Subsidy Cost* is the subsidy payment (e.g., ZECs for nuclear, offshore wind incentives) for specific technologies as specified in current or stated policies. *NSE cost* is the payment from LSE to end consumers for voluntary demand response (no involuntary demand shedding events occur in these scenarios given required installed capacity reserve margins).

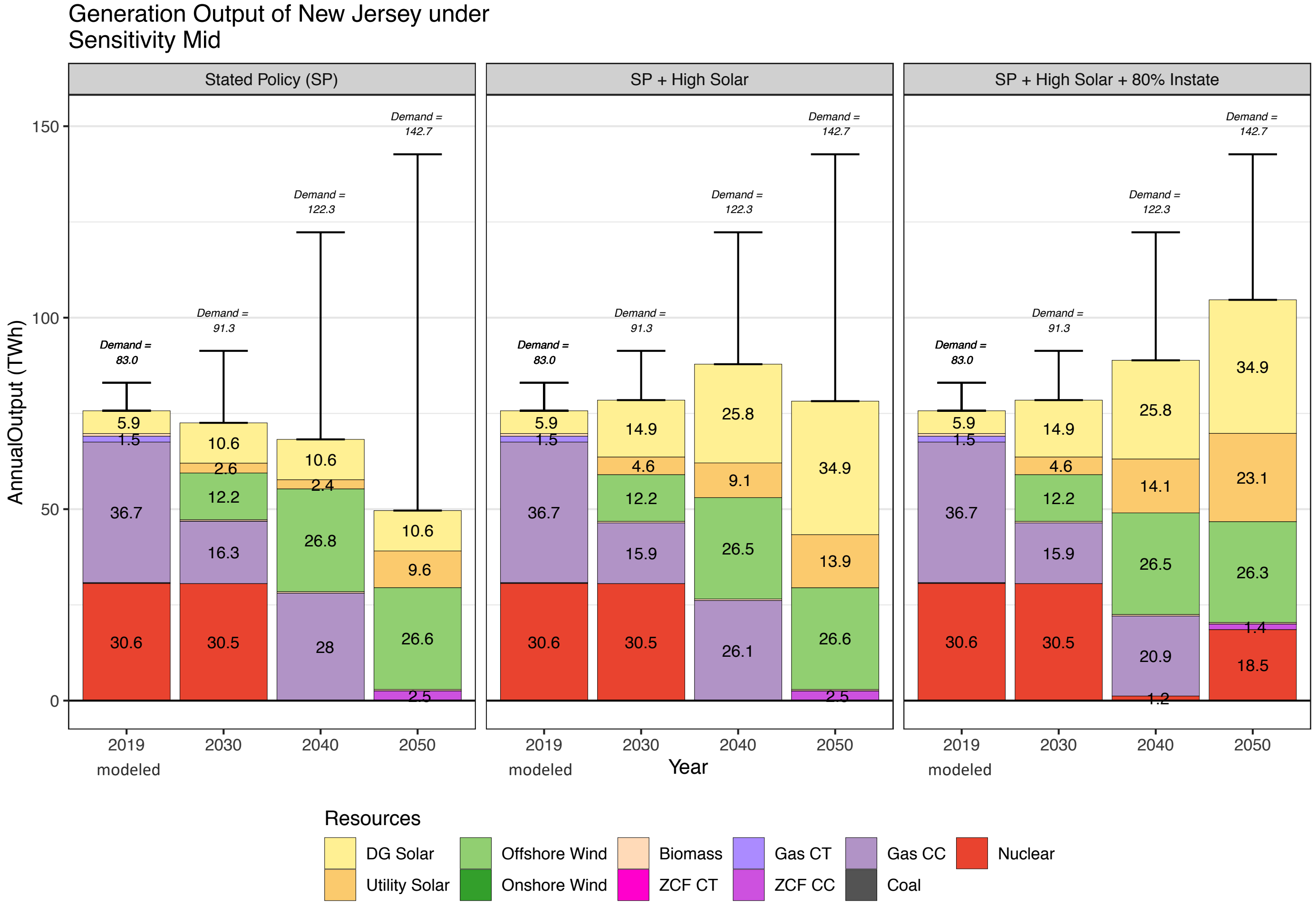
- **Incentivizing in-state solar** (requiring 31 GWdc solar PV by 2050 with >20 GWdc from distributed solar) **will increase NJ electricity costs compared to the least-cost Stated Policies pathway** by $3.3/MWh in 2030 and $5.9/MWh in 2050 (+9%). **However, costs in 2050 remain lower than 2019 levels** (~13% lower).
- **Prioritizing in-state renewable/clean generation** (requiring in-state solar as above as well as 80% of annual RPS/CES targets are met by in-state generation in 2031-2050) **will also increase NJ electricity costs** compared to the least-cost Stated Policies pathway by $10.8/MWh in 2050 (+17%). Across sensitivity cases, costs for this scenario range from 14% below to 6% above 2019 costs. Note this scenario is more costly than a scenario preserving existing nuclear plants.

Continuing to prioritize New Jersey in-state renewable/clean energy can increase costs of a 100% carbon-free electricity system, but significantly reduces New Jersey's import dependence.

Case descriptions

SP + High Solar: Requires 31 GWdc 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).



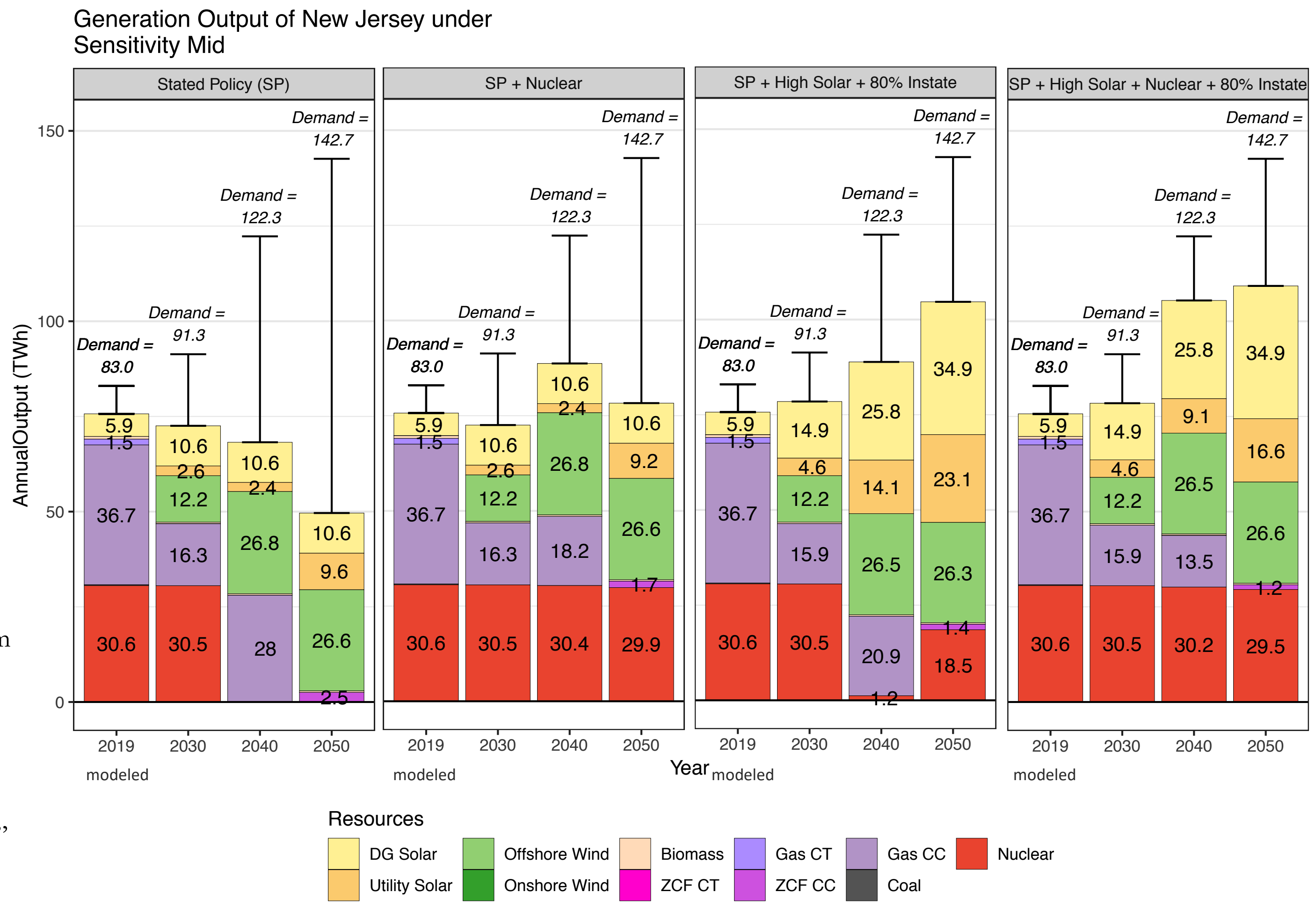
- ➢ **Imports supply about two-thirds of NJ electricity by 2050 under the lowest-cost Stated Policies pathway.**
- ➢ **Import reliance falls to 45% if in-state solar is prioritized (High Solar case) and is cut to 27% in the High Solar + 80% Instate scenario.**
- ➢ In addition to much greater deployment of in-state utility-scale & DG solar, prioritizing 80% in-state generation drives new nuclear capacity from 2041-2050 when 100% carbon-free electricity is required, despite seeing retirement of existing nuclear units during the 2031-2040 planning period. Retiring nuclear in the 2030s thus appears to be a result of the short-sighted or myopic nature of the staged expansion modeling in this study, indicating that nuclear retirements are not consistent with a portfolio ultimately prioritizing in-state resources by 2050. Offshore wind is also expanded beyond the current stated capacity target of 7.5 GW (3rd panel).

New Jersey nuclear will require continued subsidy to avoid retirement beyond 2030, when the current ZEC program ends. The required subsidy declines, and keeping nuclear can benefit NJ consumers in the long run.

Modeled Zero Emissions Certificate (ZEC) or equivalent subsidy required to keep nuclear from retiring by Stated Policies variant*

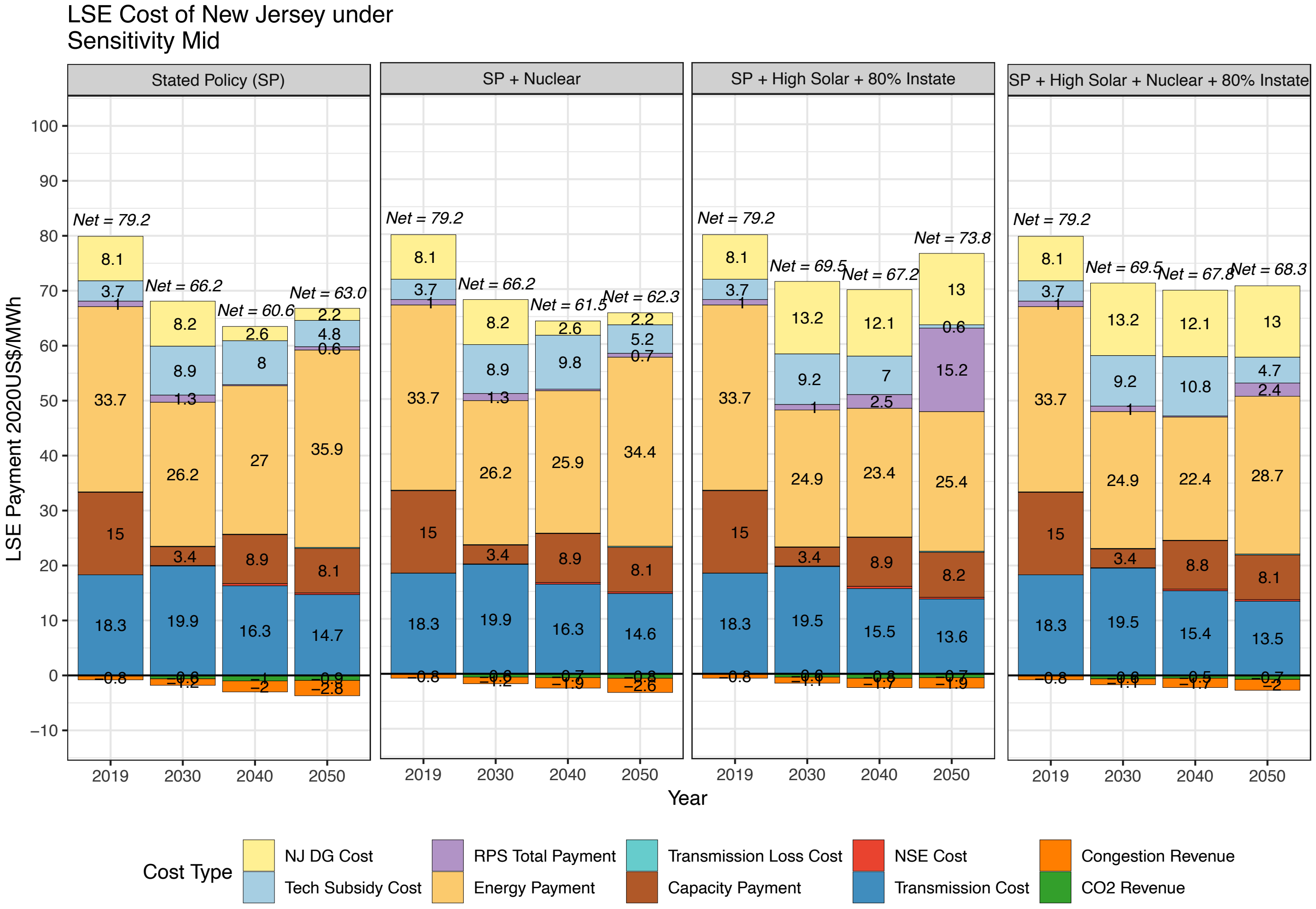
Unit: $/MWh generated by nuclear units	SP	SP + High Solar + 80% Instate RPS/CES
2019	11.5 (historical) / 10.1 (modeled)	
2030	8.6	8.8
2040	6.5	7.4
2050	1.4	3.0

*** Note: Estimated ZEC payments based on modeled results are approximate and likely underestimate actual required subsidy.** GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. In 2019, actual capacity factor was ~87% with refueling outages that year (source: IAEA Public Reactor Information System). Thus the modeled 2019 ZEC estimate above is ~12% less than actual historical subsidy. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures. For details on how nuclear and ZEC payments are modeled in GenX Appendix – Nuclear & Zero Emission Certificates.



- ➢ **Keeping existing NJ nuclear capacity requires a declining subsidy over time and will make NJ less dependent on imports from neighbors.**
- ➢ Prioritizing 80% in-state generation drives new nuclear capacity from 2041-2050 when 100% carbon-free electricity is required, despite seeing retirement of existing nuclear units during the 2031-2040 planning period (due to the myopic nature of staged expansion modeling in this study). **If in-state carbon-free generation is a priority, maintaining existing NJ nuclear capacity beyond 2030 would be a lower-cost, "no-regret" decision.**

New Jersey nuclear will require continued subsidy to avoid retirement beyond 2030, when the current ZEC program ends. The required subsidy declines, and keeping nuclear can benefit NJ consumers in the long run.



Note: for the 2019 LSE cost benchmark calculation, check the Appendix – "2019 New Jersey LSE Cost Benchmark." For costs calculation in 2030, 2040, 2050, check Appendix – "Other assumptions of LSE cost calculation." Every cost or benefit is evaluated at the transmission level, and thus, the potential cost impacts on the distribution system are not considered in this report. Note that total electricity bills may increase with electrification as total volume of electricity consumption increases, while total expenditures on energy (including fuels and heating) will likely decline. However, this report does not make any attempt to quantify total bill impacts or distribution of costs across customer classes or usage patterns.

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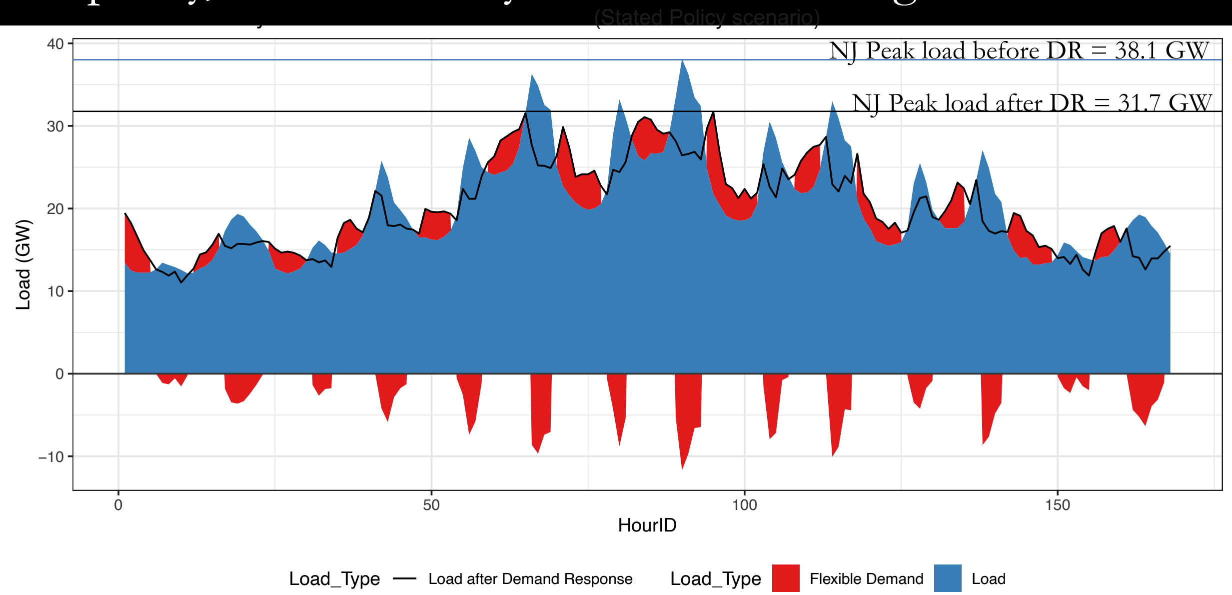
- **If NJ prioritizes in-state clean generation while meeting the 100% emission-free supply goal, retaining existing nuclear capacity will reduce New Jersey electricity supply costs** by $5.5/MWh in 2050, a 7% reduction. (Contrast panels: SP + High Solar + 80% Instate vs. SP + High Solar + Nuclear + 80% Instate.)
- Retaining existing nuclear reduces RPS/CES payment that is otherwise needed for supporting new-built offshore wind and new nuclear in 2050.

Note: For details on how nuclear and ZEC payments are modeled in GenX Appendix – Nuclear & Zero Emission Certificates. **Estimated ZEC payments calculated in this study are approximate and may underestimate subsidies required in reality.**

Flexible electricity demand can reduce NJ's peak demand, substitute for battery energy storage and combined-cycle capacity, and eventually lead to cost savings on the order of half a billion dollars annually for NJ consumers.



- Flexible load (modeled as time shiftable heating & EV charging, as an example) can help cut 2050 NJ peak demand by 17% (6.4 GW).
- Flexible load substitutes for battery energy storage and combined-cycle capacity and provides cost savings to NJ LSEs of $4.1/MWh in 2050 = $572M/year.
- Additional non-modeled distribution cost savings could also result.
- New market/rate design is needed to fully unleash the benefits of flexible load.

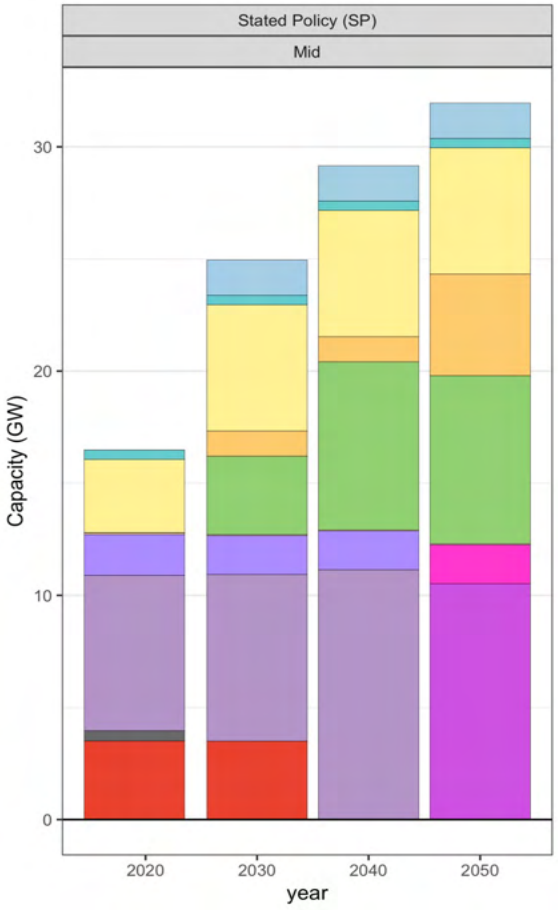
Impact of flexible load shifting on New Jersey peak electricity demand

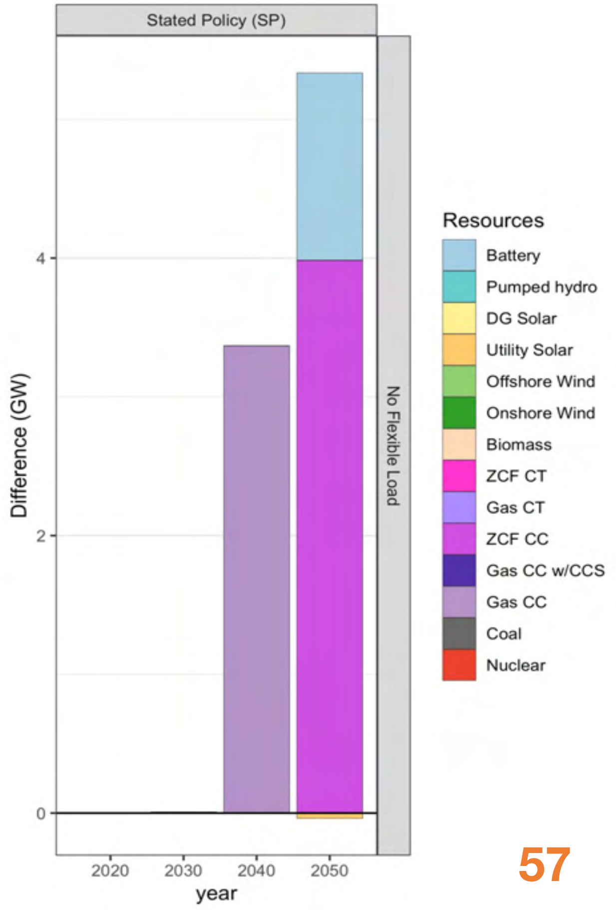
Year | Scenario	Original Peak	Peak after flexible load shifting	Diff.
2030	18.3	17.7	-0.6 GW
2040	29.9	25.1	-4.8 GW
2050	38.1	31.7	-6.4 GW

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

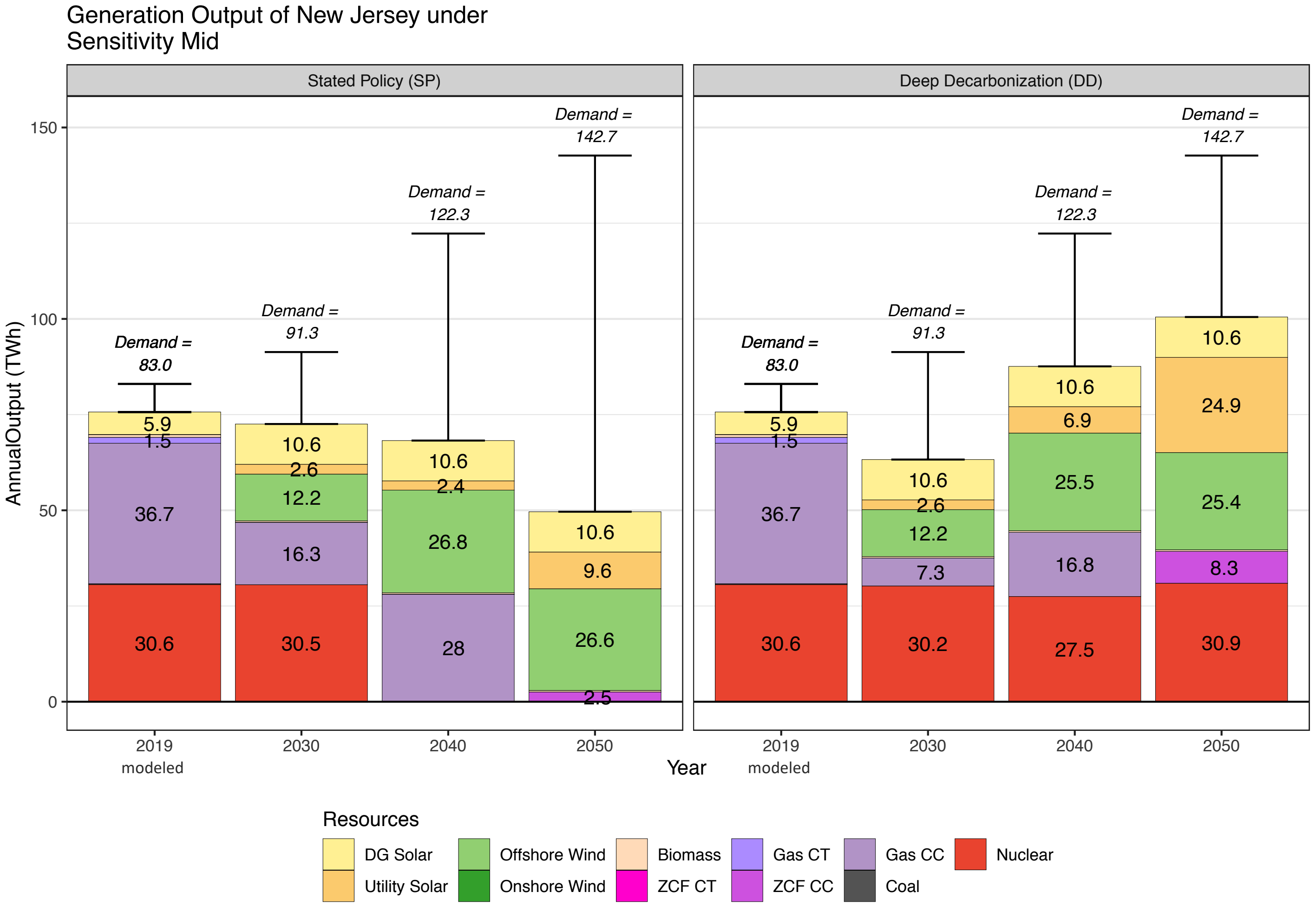
Year | Scenario	SP & No Flexible Load	Stated Policy (SP)	Diff.
2030	67.1	66.2	-$0.9/MWh
2040	62.9	60.6	-$2.3/MWh
2050	67.1	63.0	-$4.1/MWh

Note: for the availability and maximum delay time of flexible load, check Appendix – "Flexible demand"





If all PJM states pursue economy-wide deep decarbonization, greater competition for out-of-state clean energy resources drives greater use of costlier NJ resources.

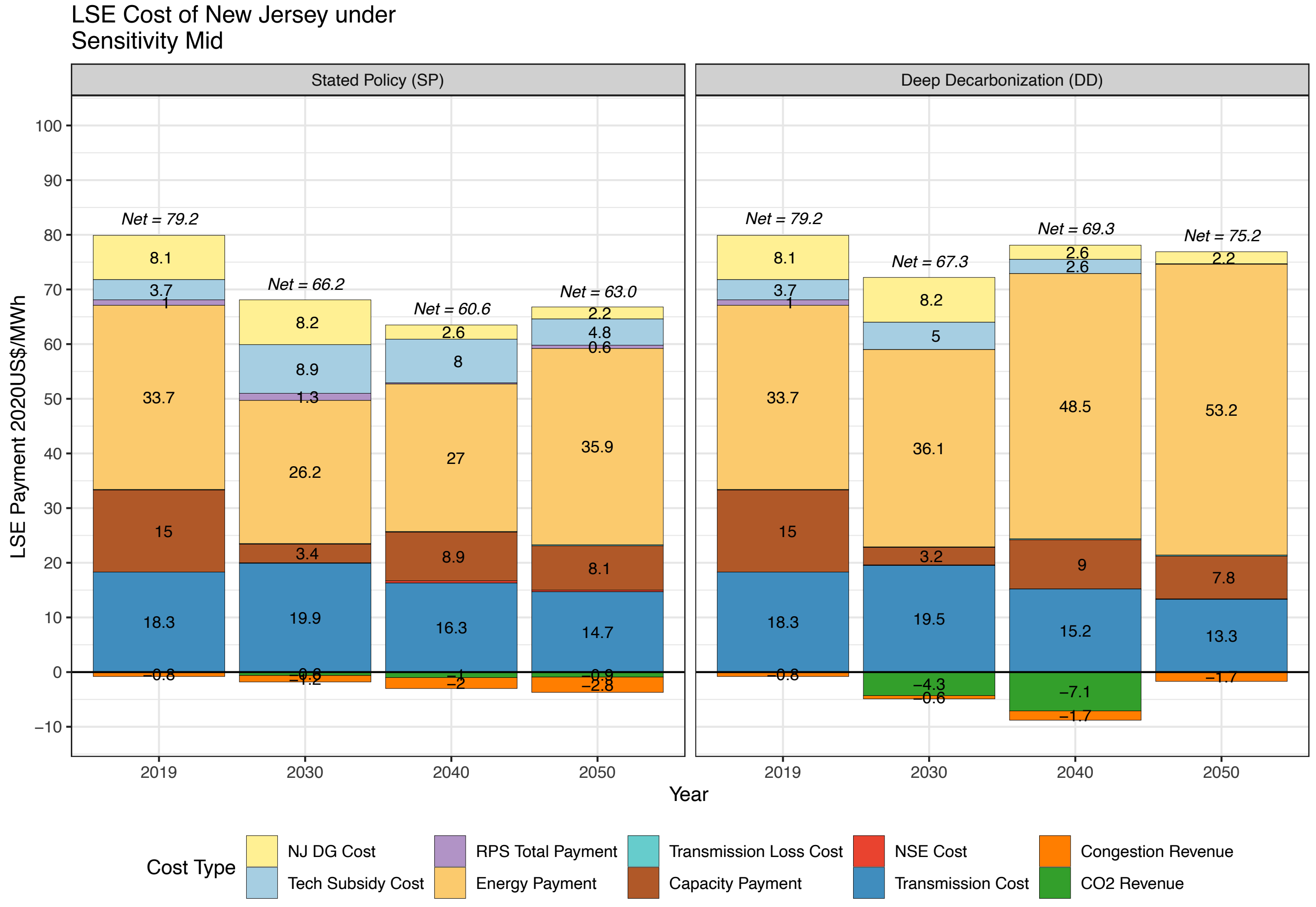


- **Under the Deep Decarbonization scenario (DD), all PJM states and neighboring regions require zero emissions from electricity generation by 2050 and undergo rapid electrification** of buildings and transportation consistent with economy-wide deep decarbonization goals.
- In DD scenarios, **greater competition for out-of-state clean electricity resources drives up import costs for NJ.**
- **As a result, NJ builds higher-cost in-state resources**, including in-state solar, retaining existing nuclear, and dispatching more zero-carbon-fuel, **reducing reliance on imports relative to SP scenarios**.
- In this scenario, **NJ existing nuclear capacity can continue to run economically through 2050 without continued ZEC payments after 2030.** Higher electricity prices across PJM due to emissions constraints provide sufficient revenue to retain existing nuclear without ongoing subsidy.

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).

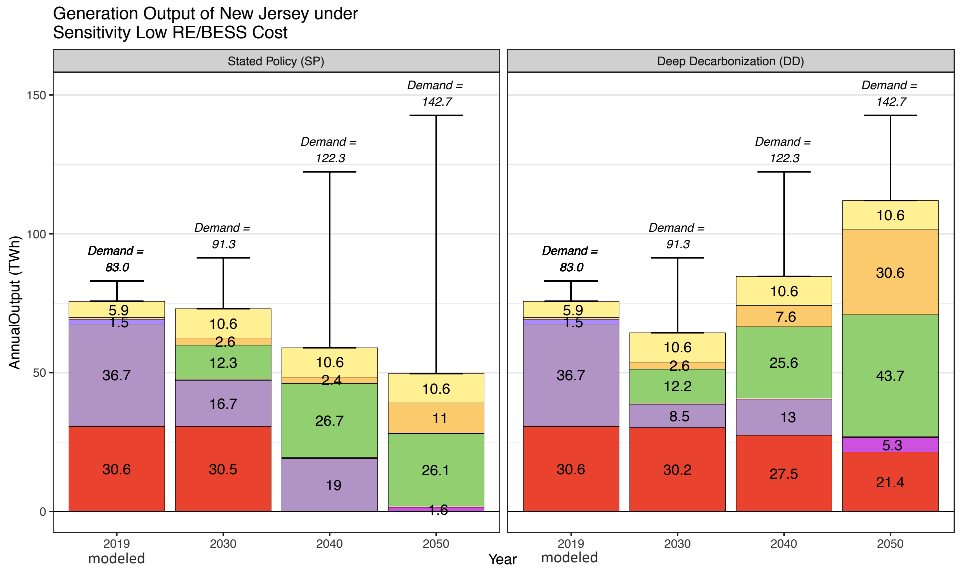
If all PJM states pursue economy-wide deep decarbonization, greater competition for out-of-state clean energy resources increases NJ electricity supply costs to $75/MWh in 2050 (19% higher than SP).

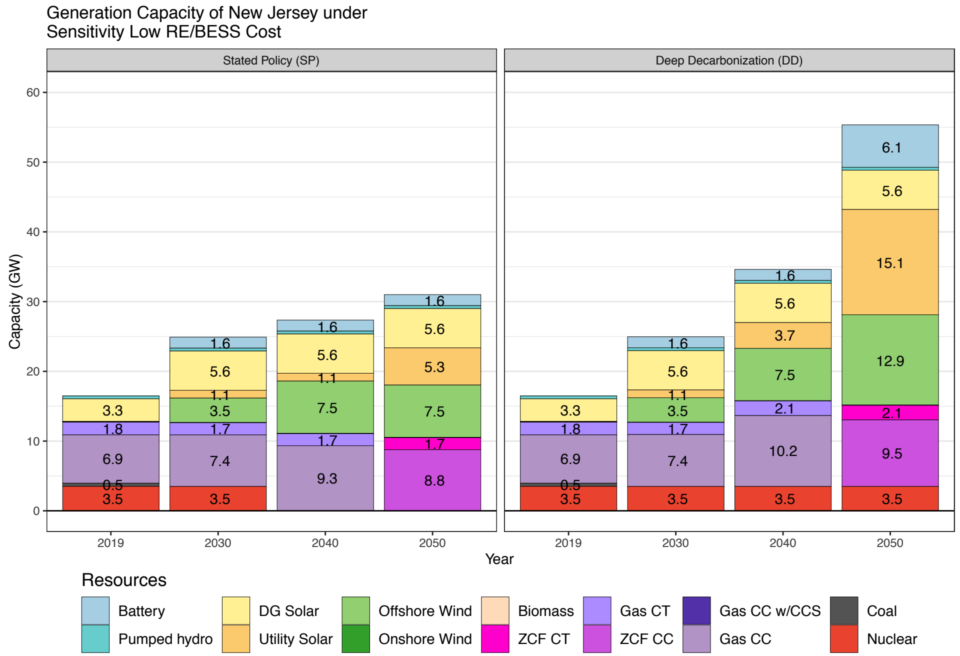
- **In DD, greater reliance on costlier in-state clean electricity resources and higher cost imports from the rest of PJM increase NJ electricity supply costs.**
- 2050 electricity supply costs for NJ LSEs are $75.2/MWh, or 19% higher than in SP, due to higher energy prices in NJ zones. However, these costs are still below 2019 levels.
- Under this study's cost allocation assumptions, NJ LSEs are allocated a share of carbon allowance revenues in the next decade and 2031-2041 in DD scenarios, offsetting some of the increase in electricity supply costs. However, this revenue stream will be gone by 2050 because there are no CO_2-emitting resources left in the system.



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).

Offshore wind is more costly than other NJ options but may expand if cost declines are rapid and in-state resources are needed (due to either state mandate or greater competition for out-of-state resources).

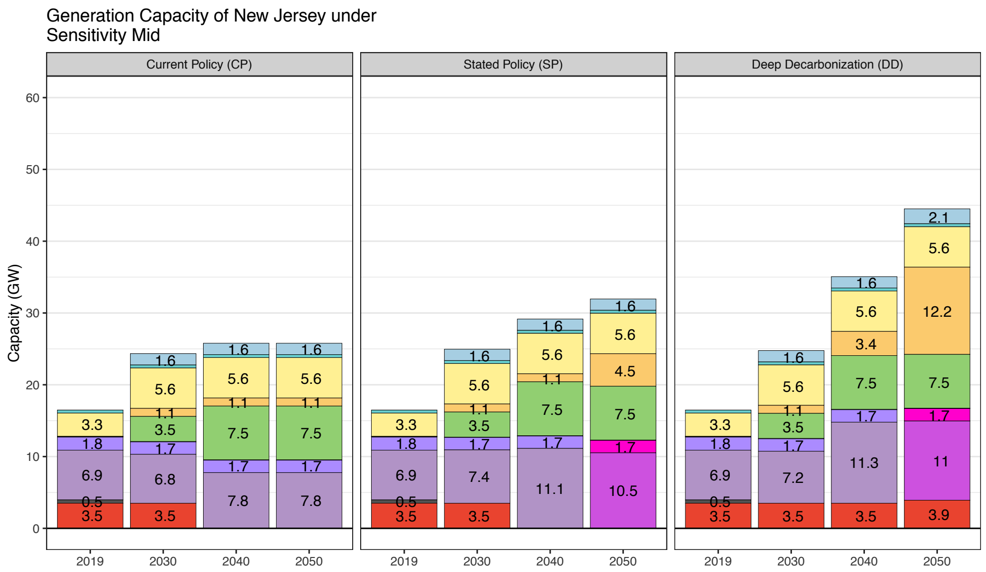




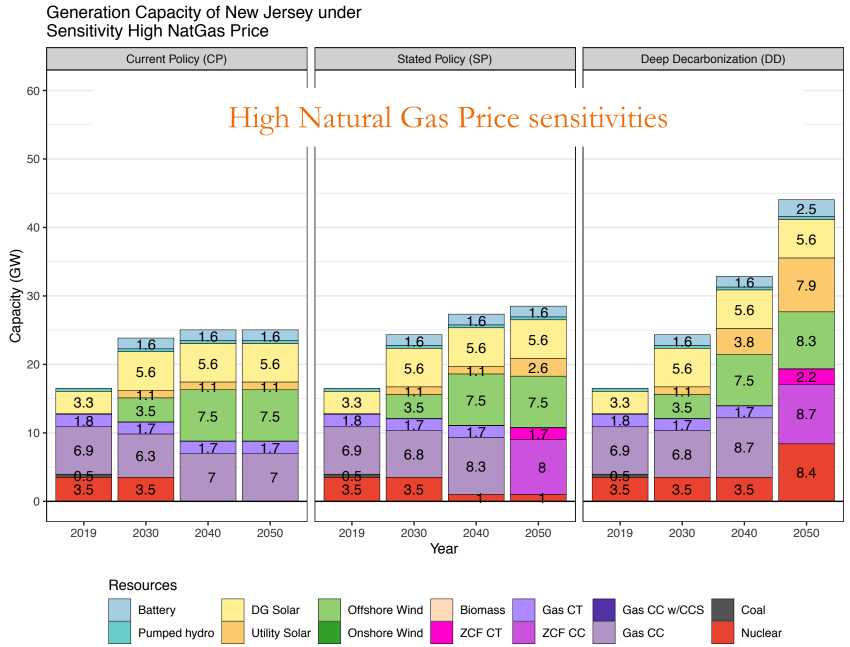
Additional NJ OSW selected beyond 7.5 GW by 2050 (GW)	Mid	Low RE/BESS Cost	Low Nat. Gas Price	High RE/BESS Cost	High Nat. Gas Price
Current Policy	-	-	-	-	-
Stated Policy	-	-	-	-	-
SP + 80% Instate	+4.1	+5.7	+4.1	+4.2	+4.0
SP + High Solar	-	-	-	-	-
SP + 80% Instate + High Solar	-	+5.2	-	-	+0.1
SP + Nuclear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

- **Offshore wind (OSW) is comparatively costly, so it is rarely developed beyond 7.5 GW in the cases explored 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.
- *SP, 80% Instate variants:* **OSW can be an economical choice if NJ continues to prioritize in-state clean power** (as in 80% Instate variants of Stated Policies)**.** However, if solar is prioritized by NJ policy-makers, the economic case for OSW is reduced (see *SP + 80% Instate + High Solar* scenarios).
- *Deep Decarbonization scenario*: If all PJM states (and neighboring regions) implement economy-wide deep decarbonization goals (as in the *Deep Decarbonization* scenario), electricity imports would be much more expensive for NJ. In this case, **OSW can help hedge NJ against the potential for higher import costs if more states follow NJ on a path to 100% carbon-free electricity.** Assuming low capital cost projections for OSW, other renewables, and storage (*Low RE/BESS* cost sensitivity), OSW expands beyond the current state mandate to 12.9 GW in the year 2050 in this scenario.

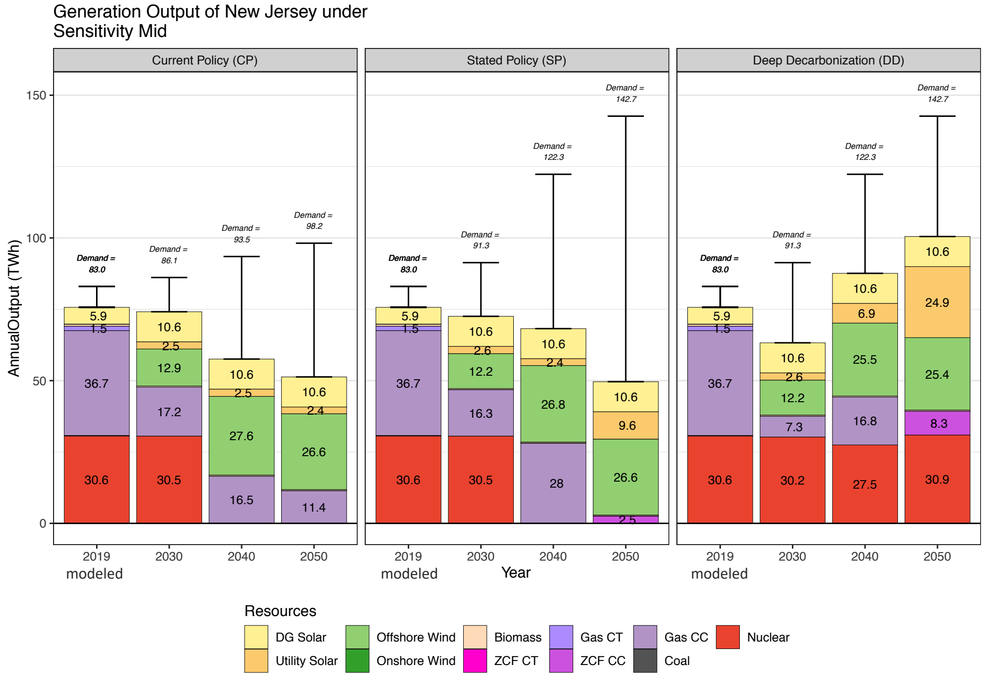
NJ combined cycle capacity expands until 2040 in all scenarios, while gas-fired generation declines. Gas-fired capacity is converted to run on zero-carbon fuel in 2050 when 100% carbon-free electricity is required.



Even if natural gas prices are high, CC capacities will be higher than the 2019 level.



CC capacities expand from 2019 but outputs decrease.



- **NJ gas-fired combined cycle (CC) capacity expands from 2019 levels until 2040 while total gas-fired generation declines in all scenarios and across all sensitivities.** Declining total generation also means lower overall NOx emissions from gas generators within New Jersey, although localized impacts of new gas capacity and down-wind impacts of generation out of state must be further assessed.
- **Capacity factors of NJ CCs steadily decline** from 60% (2019-level) to 24% in CP, 29% in SP and 17% in DD by 2040 (Mid-cost cases), indicating that CCs derive an increasing share of value from capacity payments and less frequent periods of higher energy market prices.
- **More CC capacity is added if NJ pursues economy-wide deep decarbonization** (SP / DD scenarios) **than under Current Policies, due to greater demand from electrification of buildings and transportation.**
- **By 2050, gas-fired capacity converts to run on zero-carbon fuel (ZCF) to meet 100% carbon-free requirements** in SP and DD scenarios.
- Note that we model conversion of any starting CC/CT capacity to ZCF as requiring a capital expenditure equal to 50% of the CAPEX of a new CC/CT. All existing gas-fired CC capacity (6.9 GW) and CT capacity (1.5 GW) opts to incur this cost and convert to ZCF by 2050 rather than retire, indicating the robust value of this firm low-carbon generating capacity.

Sensitivity Results

This study explores the following sensitivity cases, with variation of key results summarized in the following sections:

1. Medium case
2. Low cost of renewables / battery energy storage systems (BESS)
3. High cost of renewables / BESS
4. Low natural gas price
5. High natural gas price

NJ Generation Capacity

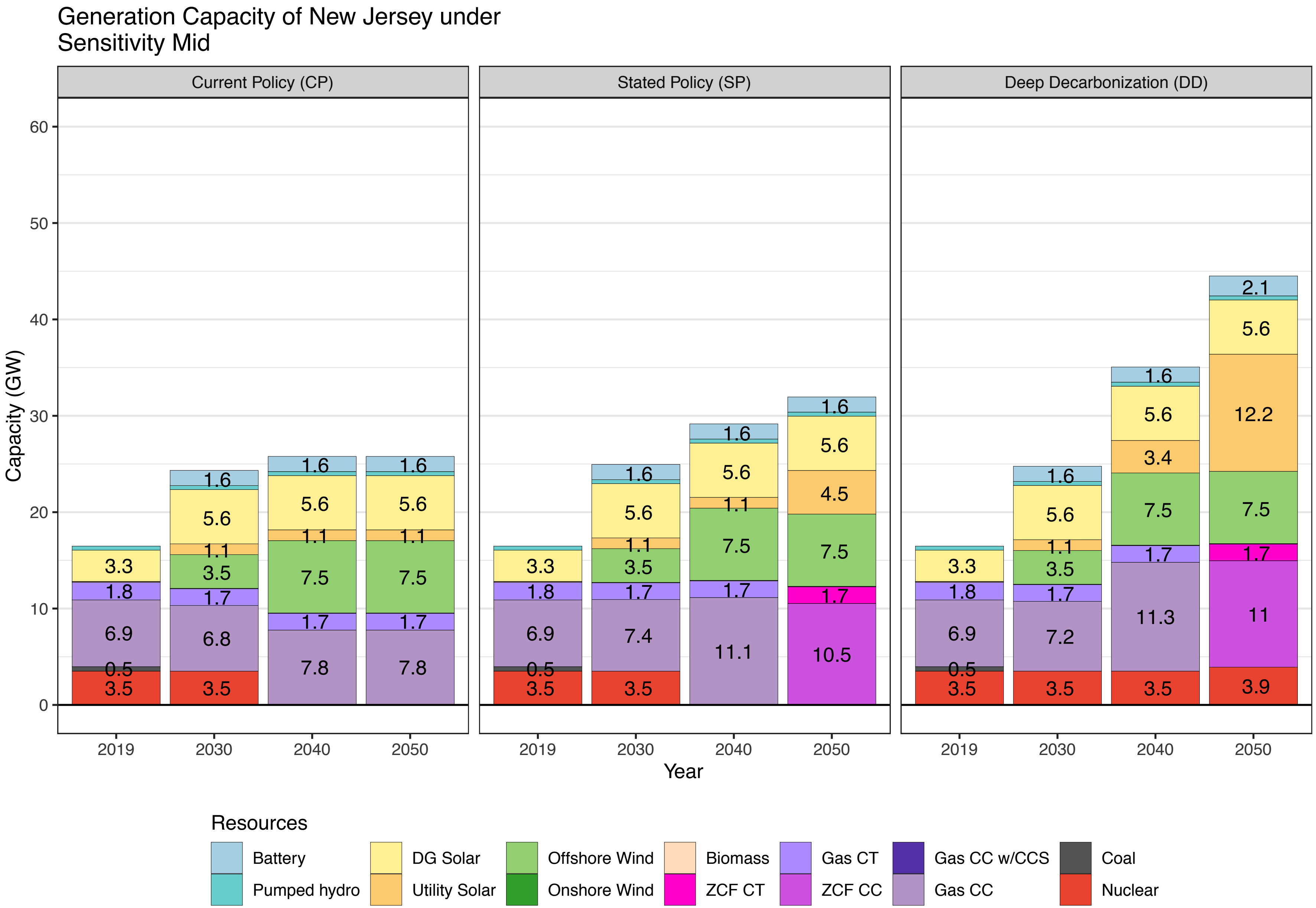
Summary of Sensitivity Results

Under Stated Policies (SP and its variants), **New Jersey's generation capacity mix is mostly insensitive to the renewable/battery capital cost and natural gas prices.** By 2050, the NJ in-state generating capacity will significantly increase compared to today and features a diverse mix of solar (distributed and utility solar), offshore wind, and combined cycle and combustion turbine capacity burning zero-carbon fuels at low utilization rates (as 'clean firm' capacity). Furthermore,

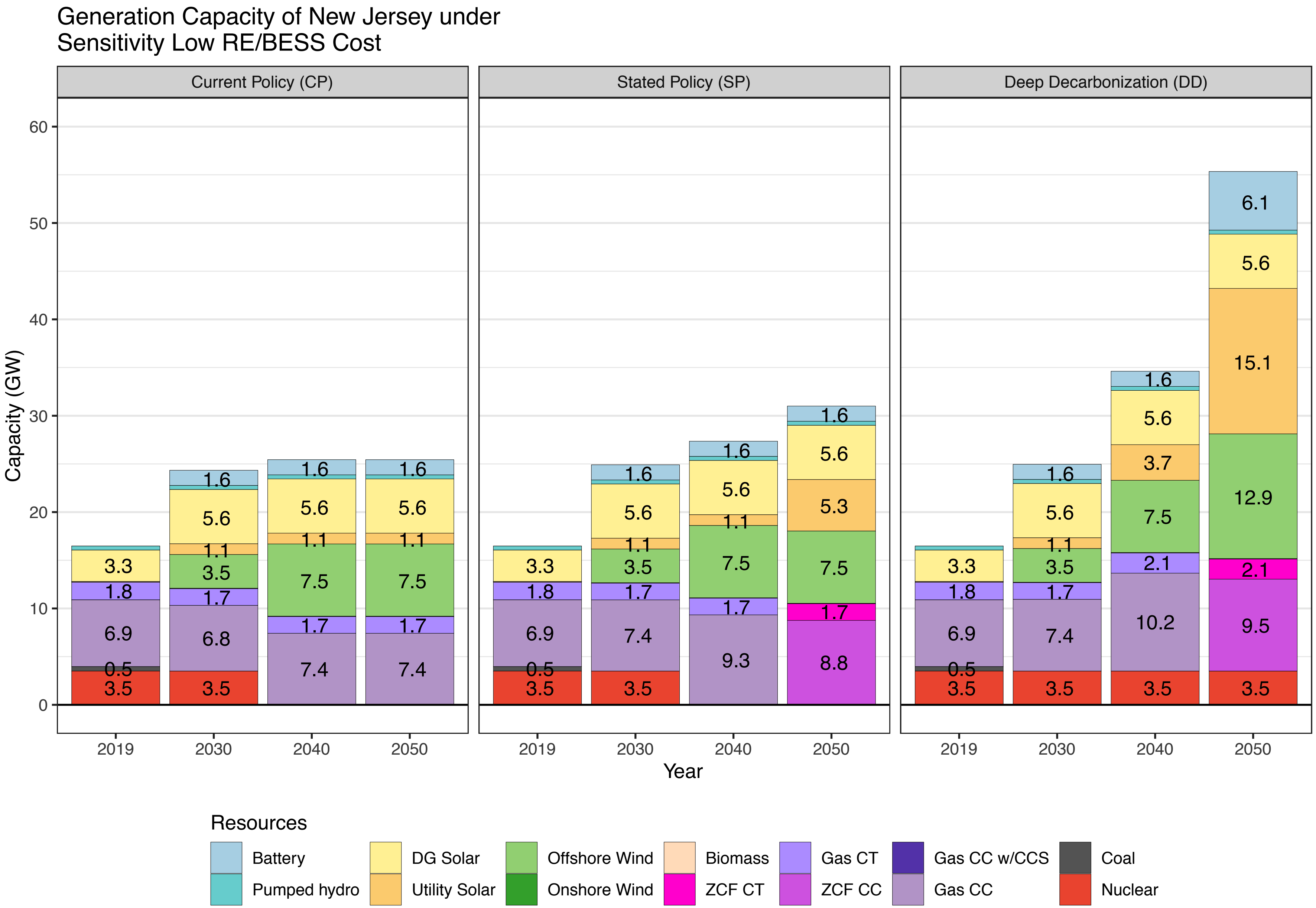
1. **Nuclear will not survive without ongoing ZEC payments (or similar policy support) after 2030**, except for the high natural gas price case. In this case, the model retains where only a fraction of the existing capacity, a result of approximations inherent in linear programming (in reality, either all capacity would be retained, or none), indicating that the economics of existing reactors is on a knife's edge even in this sensitivity scenario.
2. **Offshore wind and battery capacity will not expand beyond the state mandates under any sensitivity, except where in-state generation is prioritized.**
3. Prioritizing 80% in-state generation drives nuclear expansion from 2041-2050 when 100% carbon-free electricity is required, despite seeing the retirement of nuclear in 2031-2040 planning period (due to the myopic nature of staged expansion modeling in this study), indicating that **retaining existing nuclear remains a robust strategy if in-state resources are prioritized.**
4. **New combined-cycle capacity is added in all scenarios** (with ~8-12 GW by 2040 vs 6.9 GW in 2019) **and converted to zero-carbon fuel (ZCF) in 2050. All existing combustion turbine capacity is also retained and converted to ZCF in 2050.**

Unlike SP, **under the Deep Decarbonization scenario** (wherein the whole PJM and neighboring regions also purse deep decarbonization), **New Jersey's generation capacity mix is sensitive to the cost assumptions**, with the roles of battery storage, utility-scale solar, offshore wind, and new nuclear capacity all varying significantly across sensitivities. **The findings that existing nuclear can survive without ongoing ZEC payments after 2030 and that NJ will reduce its reliance on imports by building more in-state generation than SP hold across sensitivities.**

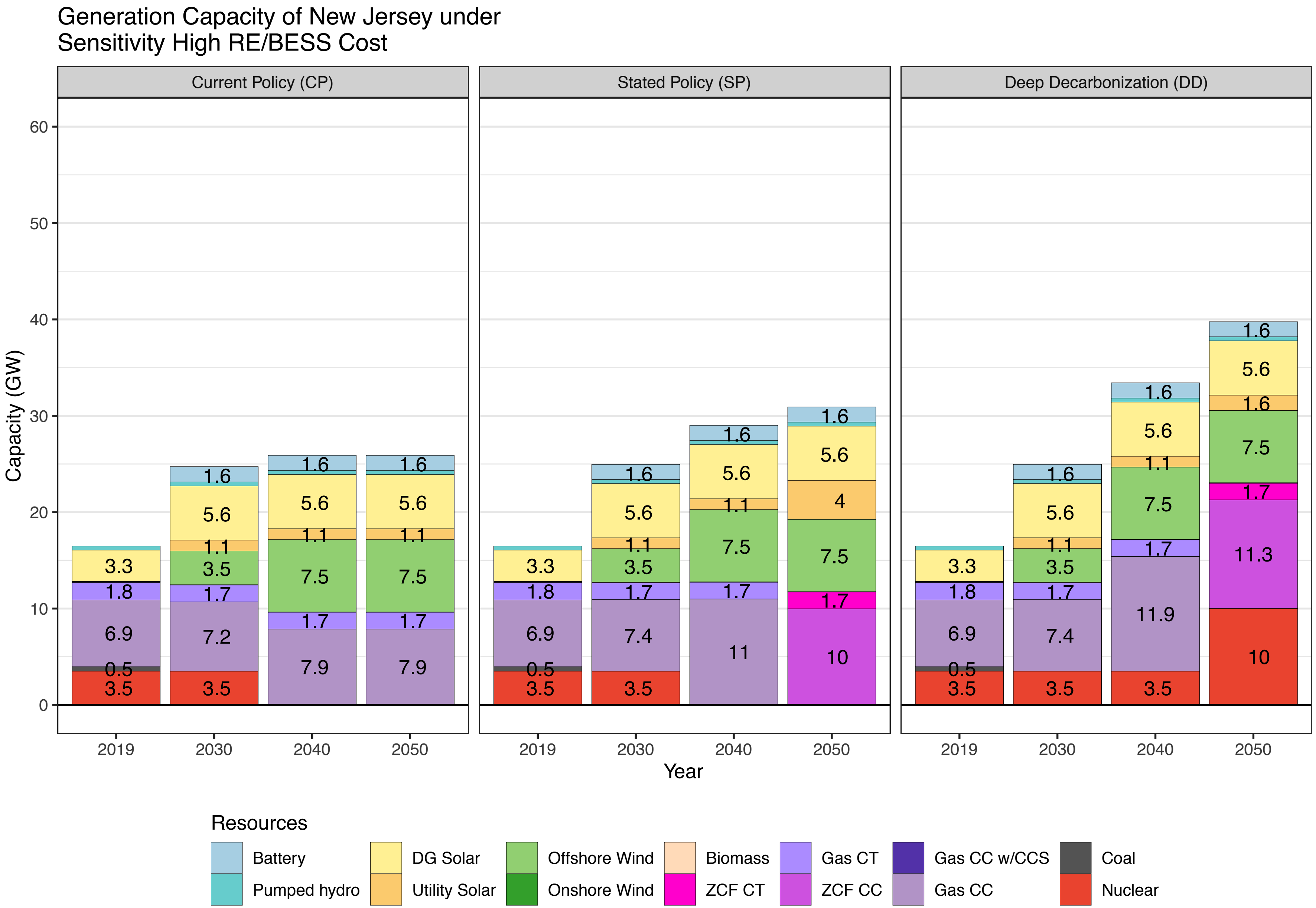
NJ Capacity in CP/SP/DD (Mid)



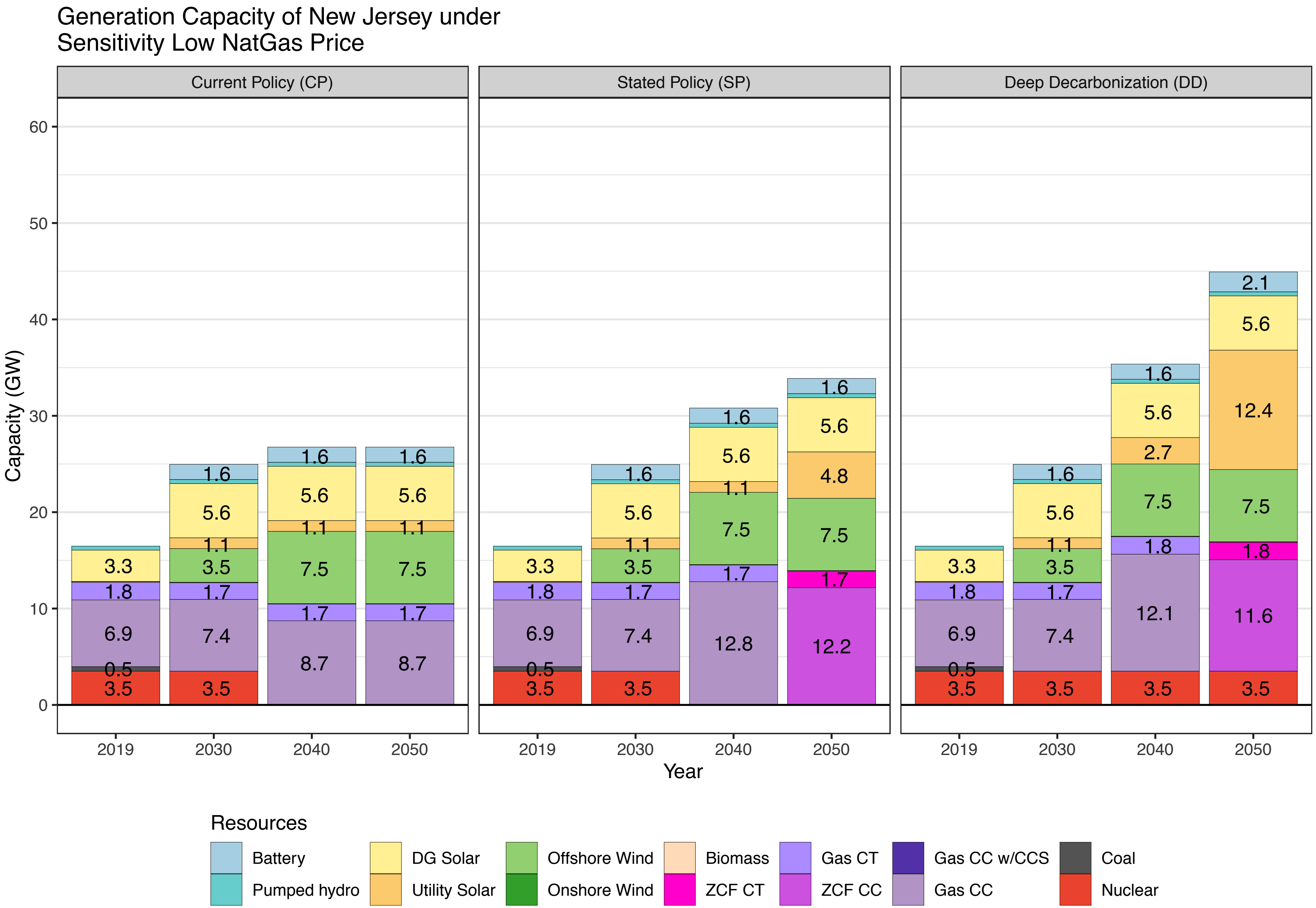
NJ Capacity in CP/SP/DD (Low RE/BESS Cost)



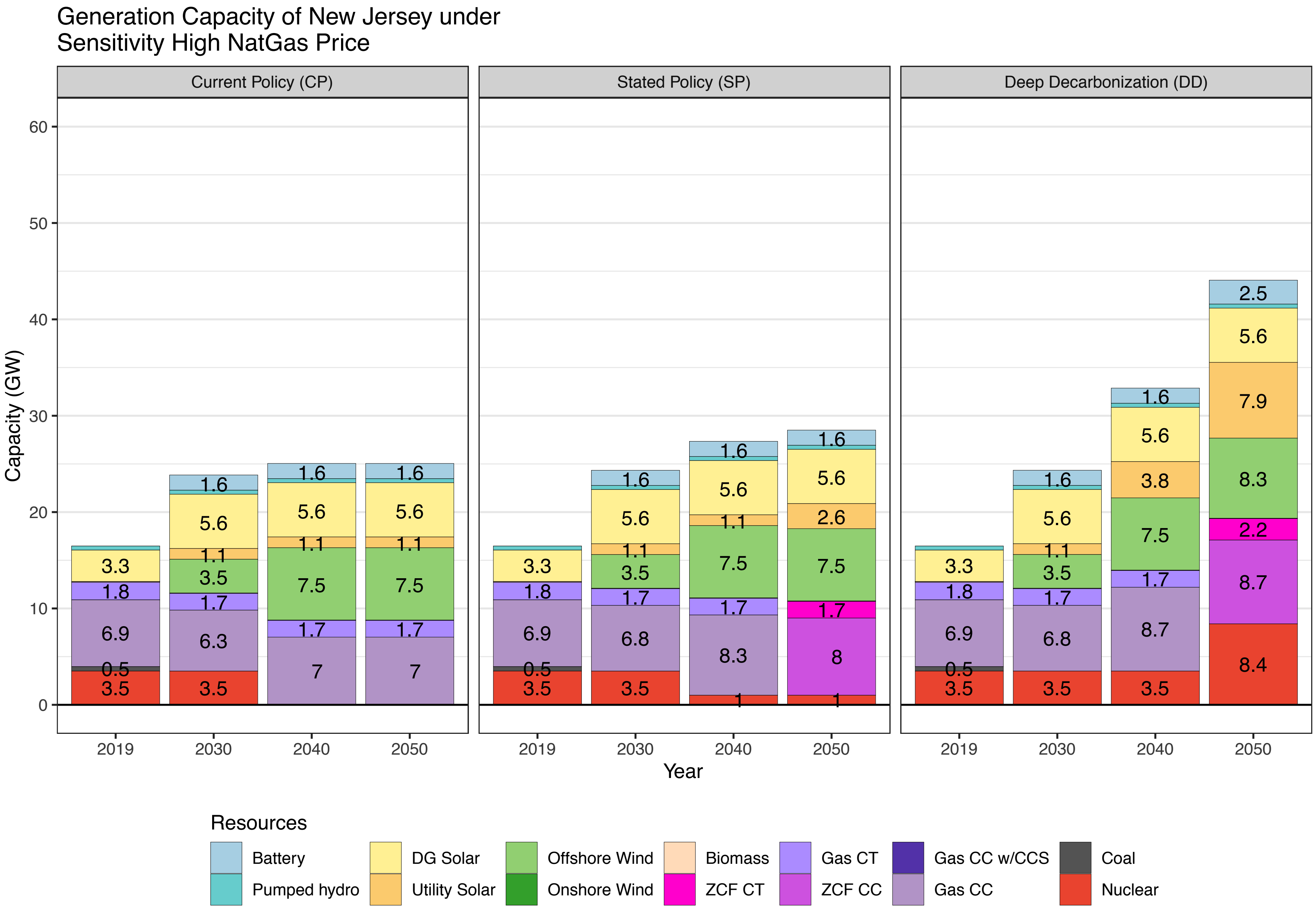
NJ Capacity in CP/SP/DD (High RE/BESS Cost)



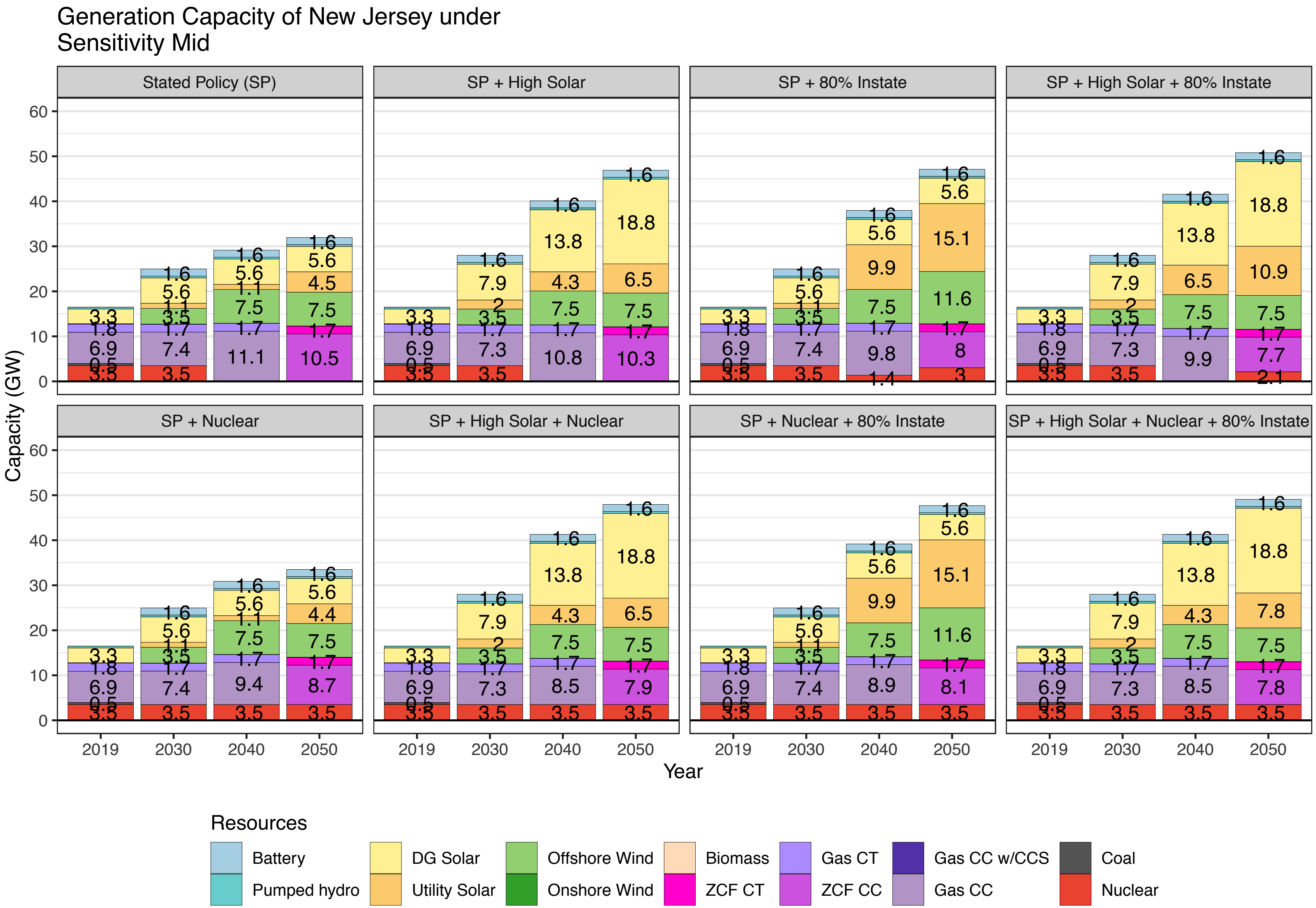
NJ Capacity in CP/SP/DD (Low Nat. Gas Price)



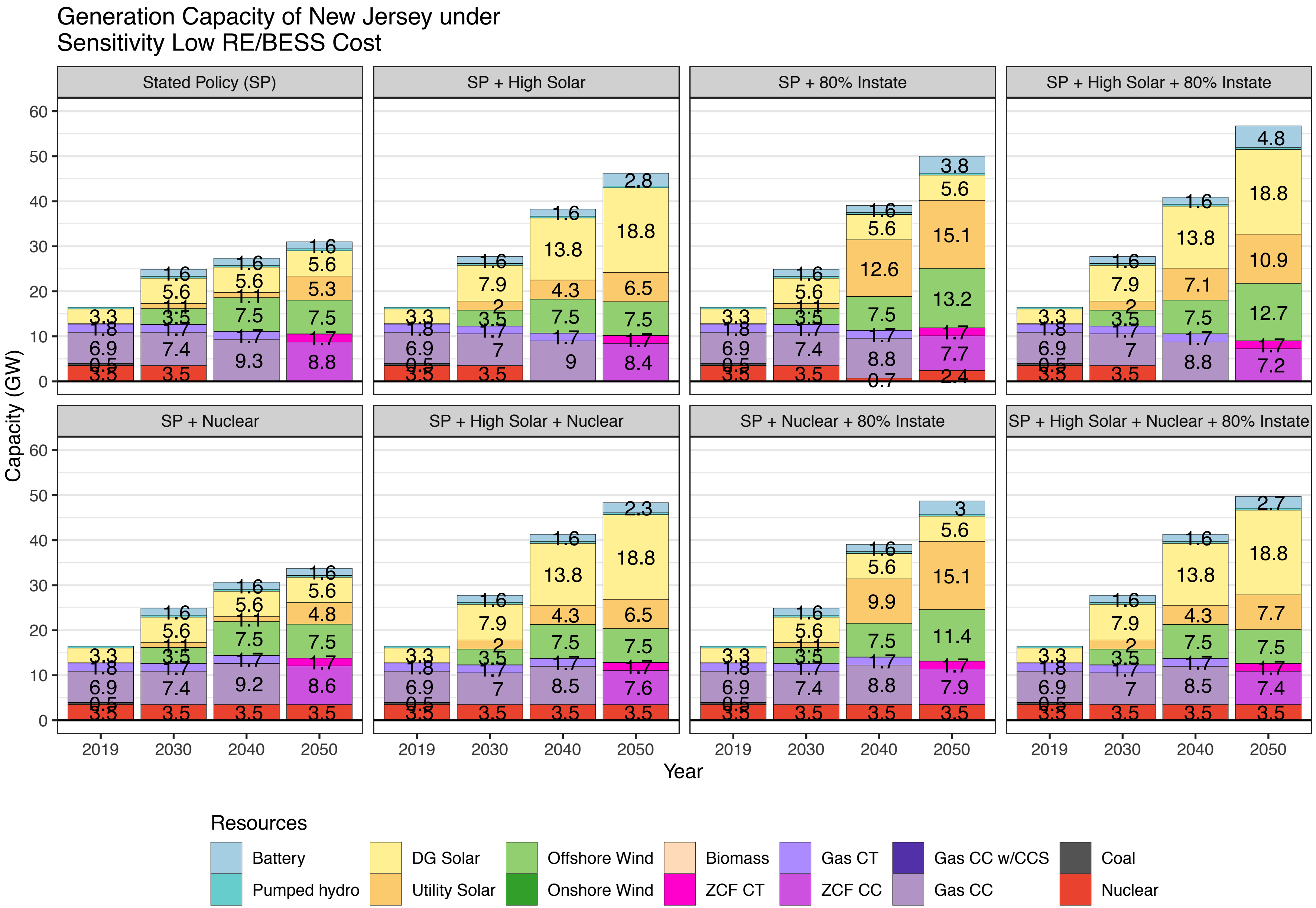
NJ Capacity in CP/SP/DD (High Nat. Gas Price)



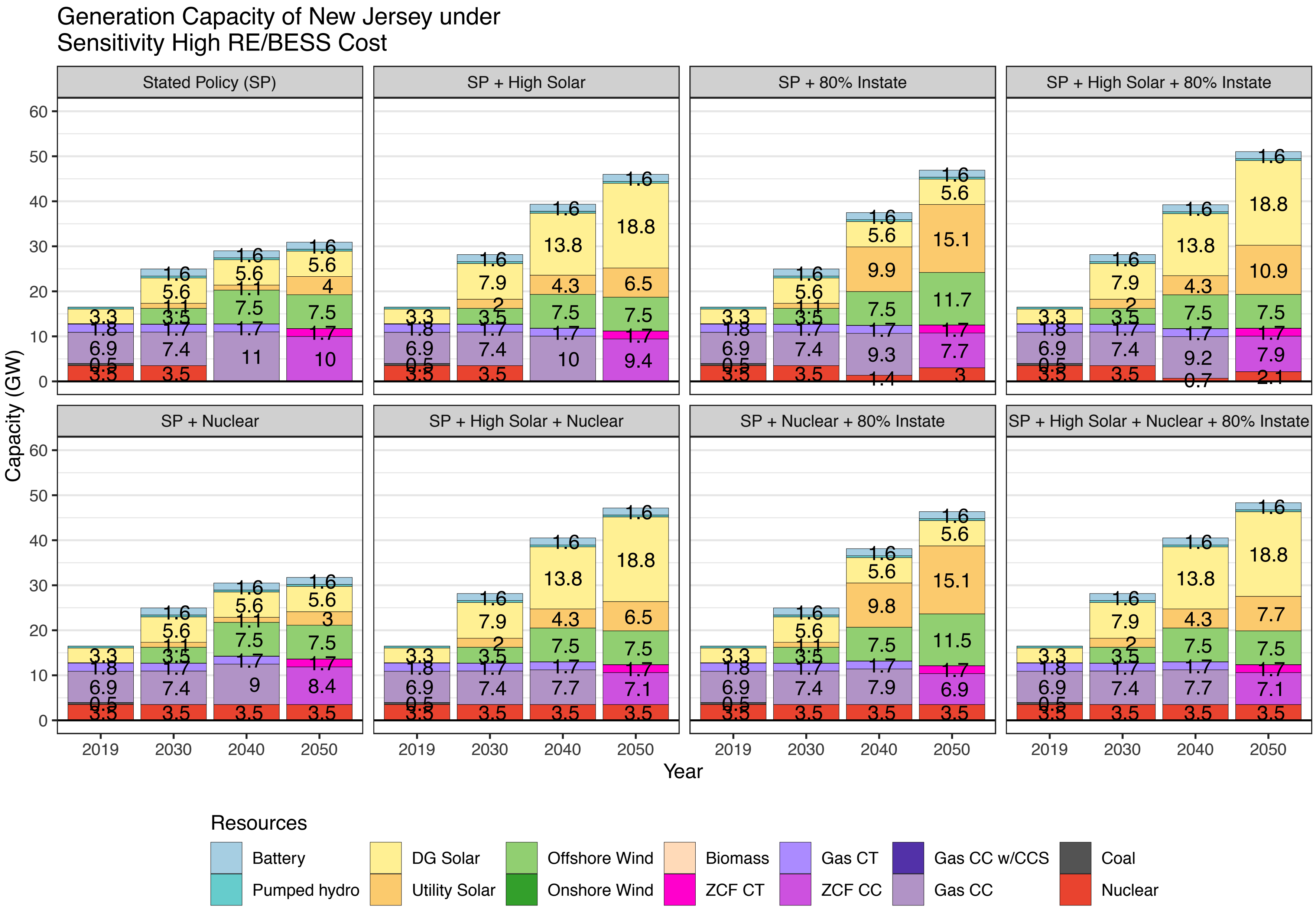
NJ Capacity of SP Policy Variants (Mid)



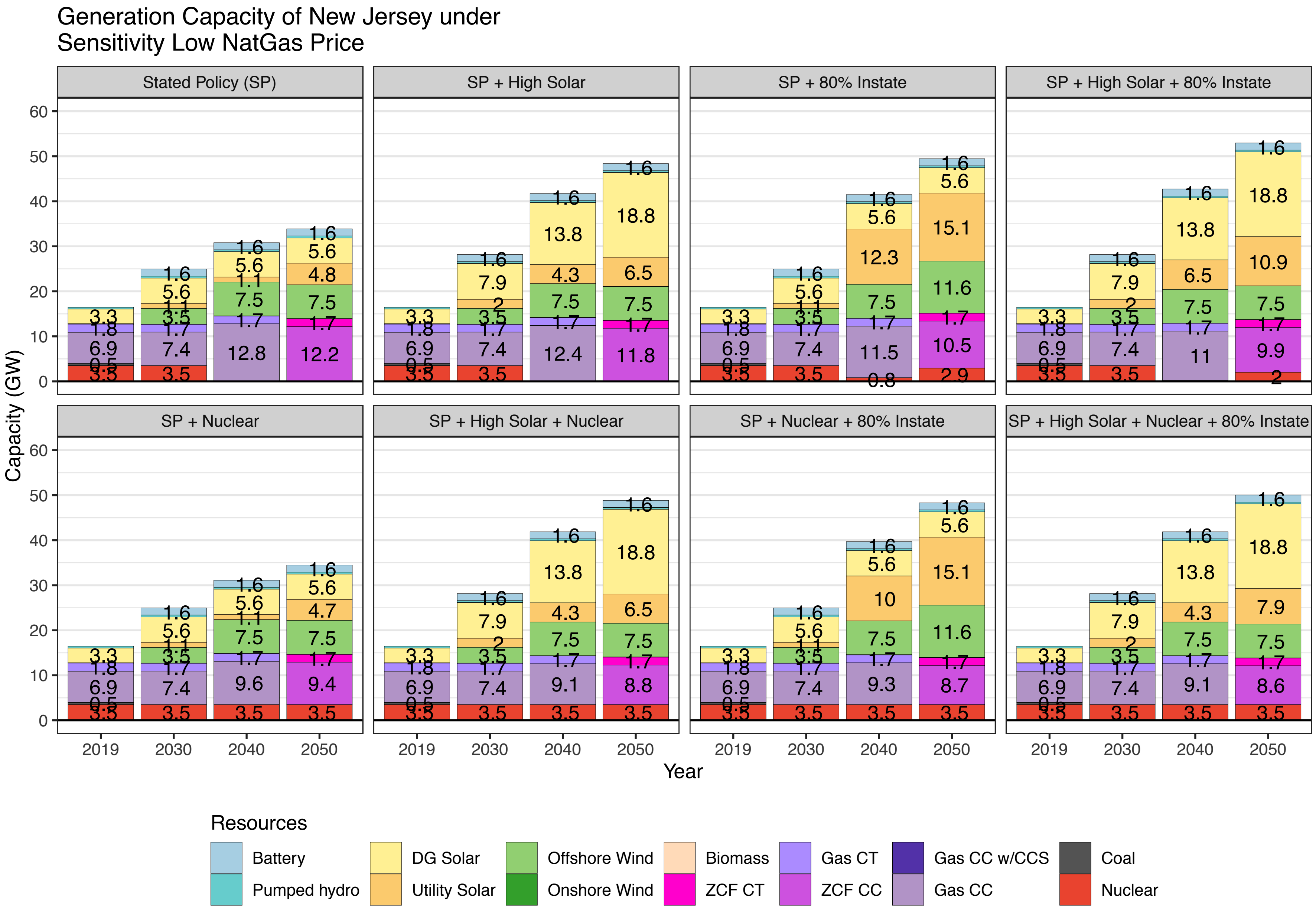
NJ Capacity of SP Policy Variants (Low RE/BESS Cost)



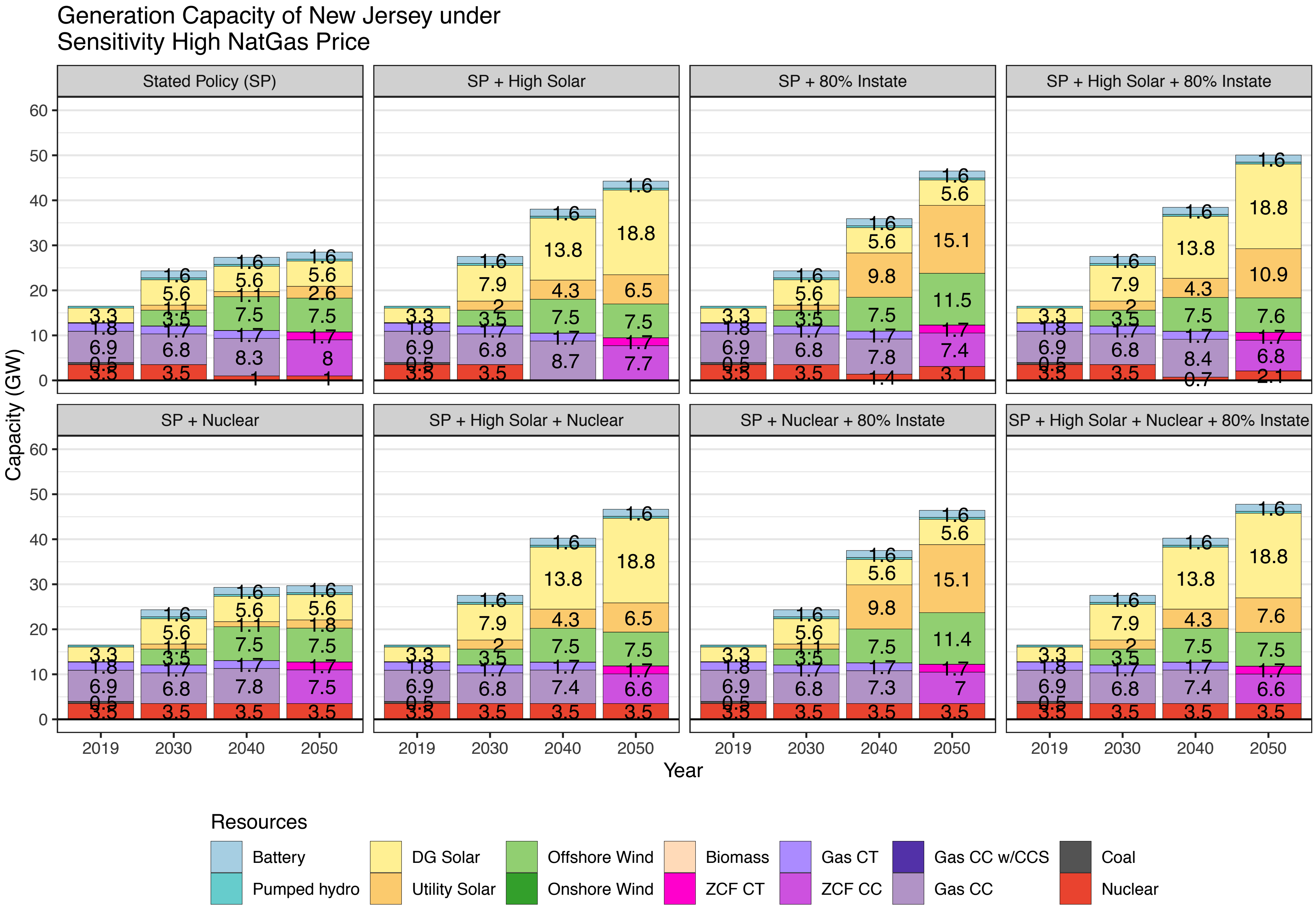
NJ Capacity of SP Policy Variants (High RE/BESS Cost)



NJ Capacity of SP Policy Variants (Low Nat. Gas Price)



NJ Capacity of SP Policy Variants (High Nat. Gas Price)



NJ Generation Output

Summary of Sensitivity Results

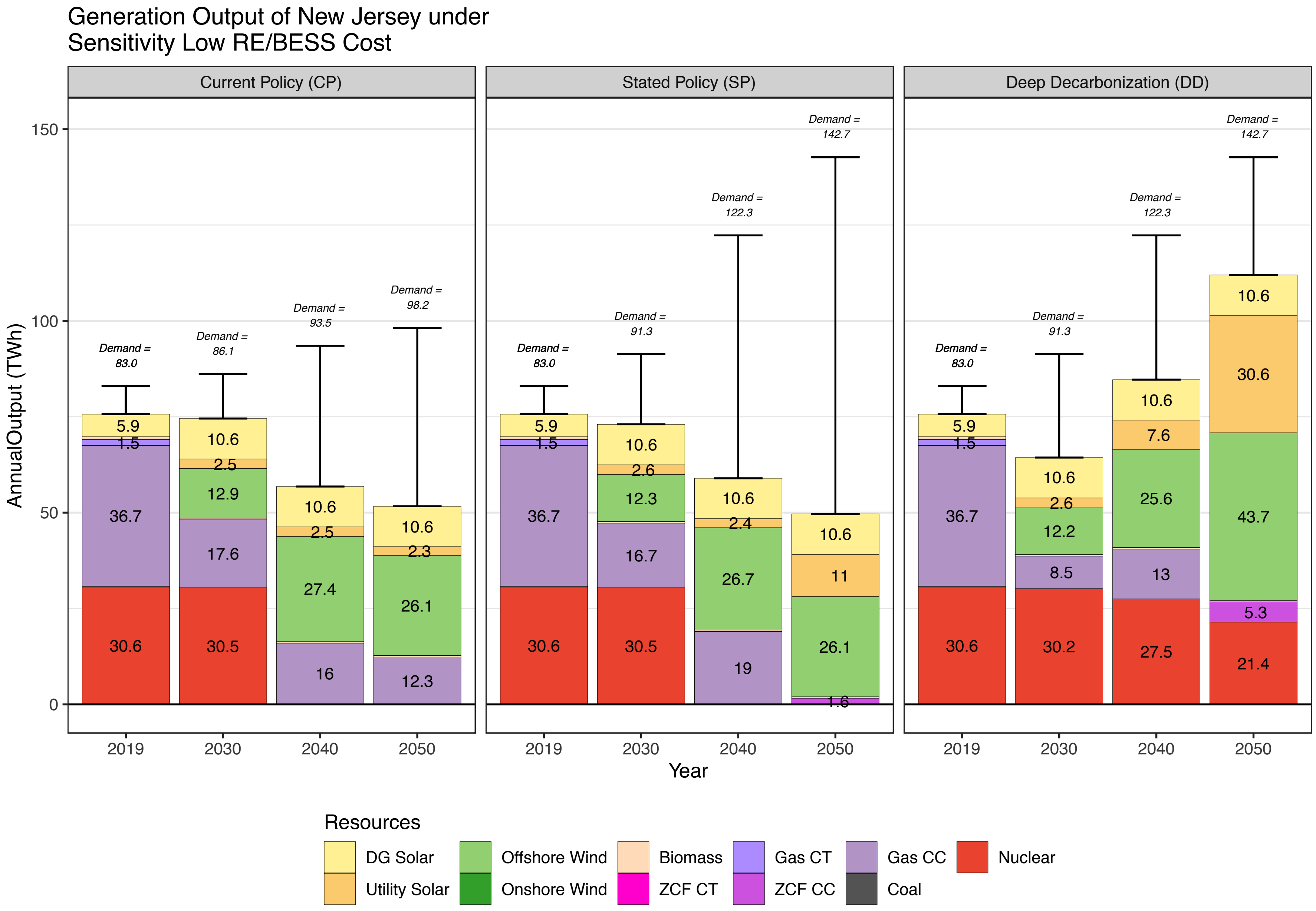
Under Stated Policies (and its variants), **New Jersey's generation output mix is mostly insensitive to the renewable/battery capital cost and natural gas prices, except for the natural gas-fired electricity in the 2040s. By 2050, NJ will significantly increase its reliance on imports if no in-state clean generation support is provided**. Retaining existing nuclear capacity (through ZECs or similar policy support) and/or prioritizing in-state generation greatly reduced NJ's reliance on imports to reach a 100% carbon-free electricity supply.

Unlike SP, **under the Deep Decarbonization scenario, New Jersey's generation mix is sensitive to the cost assumptions**, with energy contributions from utility-scale solar, offshore wind, new nuclear capacity, zero-carbon fuel combustion, and imports all varying significantly across sensitivities.

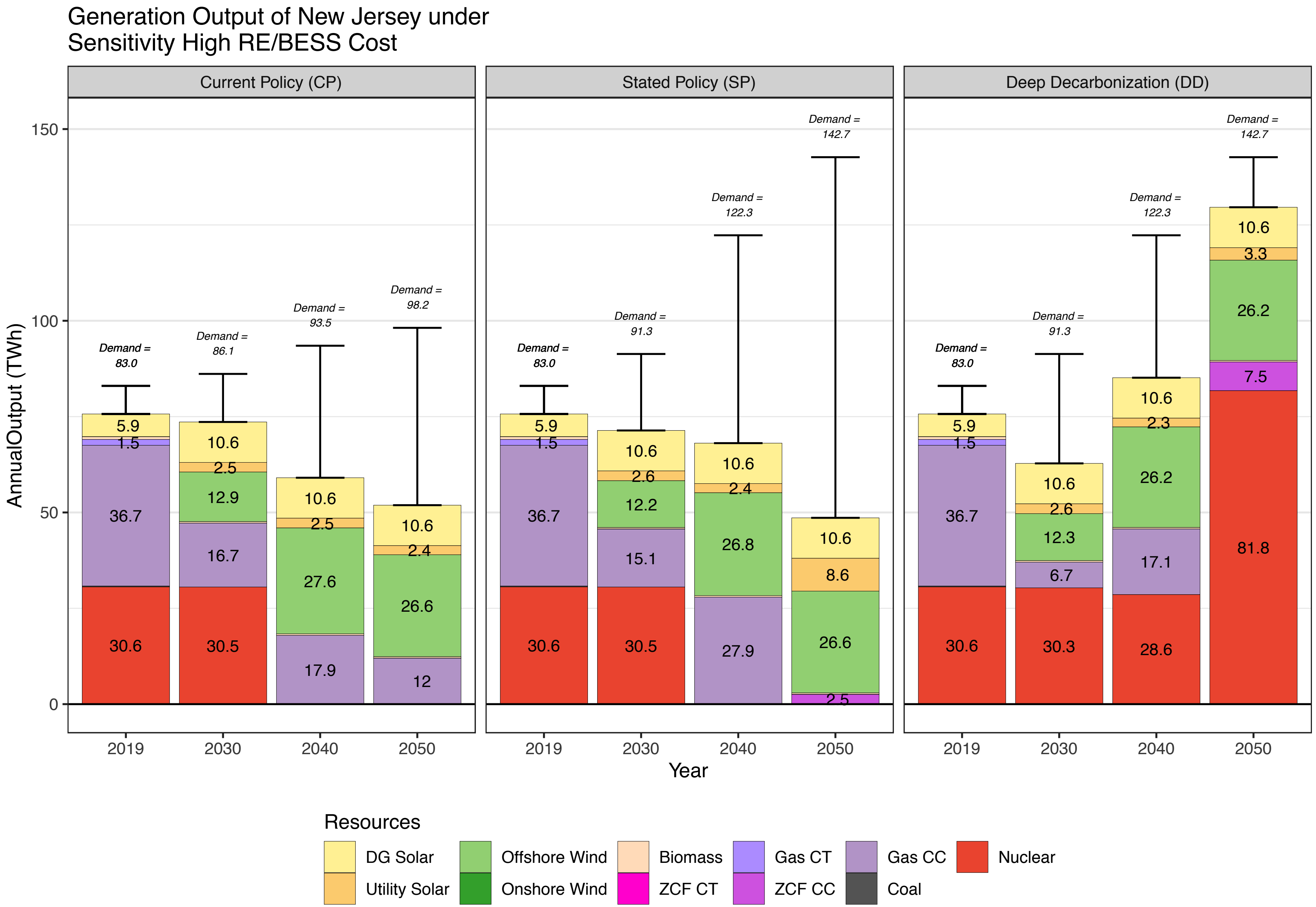
Note: 2019 reported generation is based on simulated model outcomes from GenX model and may differ from historical generation. See Appendix – Validation of 2019 PJM GenX dispatch simulation results vs. historical.

NJ Generation Output in CP/SP/DD (Mid)

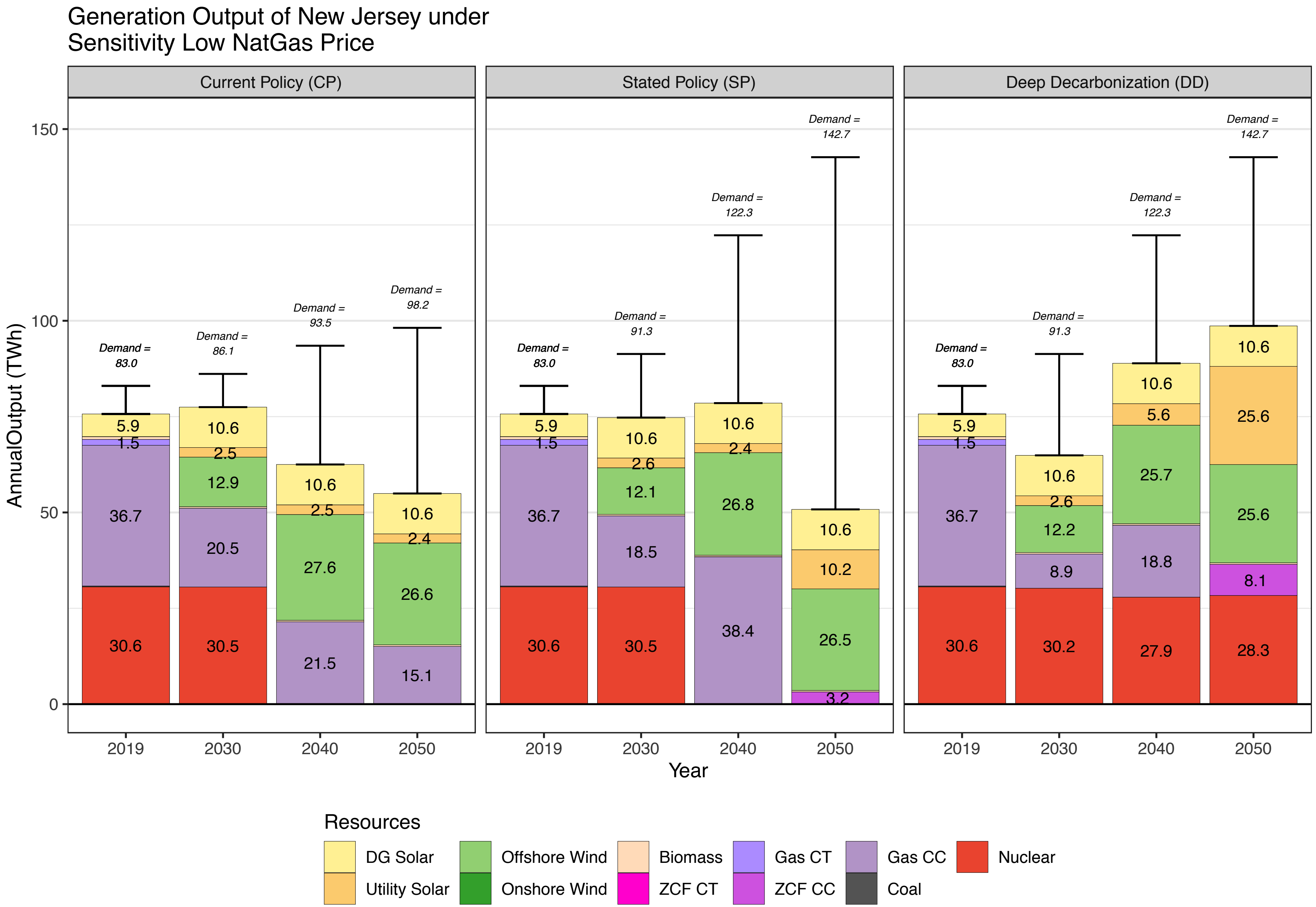
NJ Generation Output in CP/SP/DD (Low RE/BESS Cost)



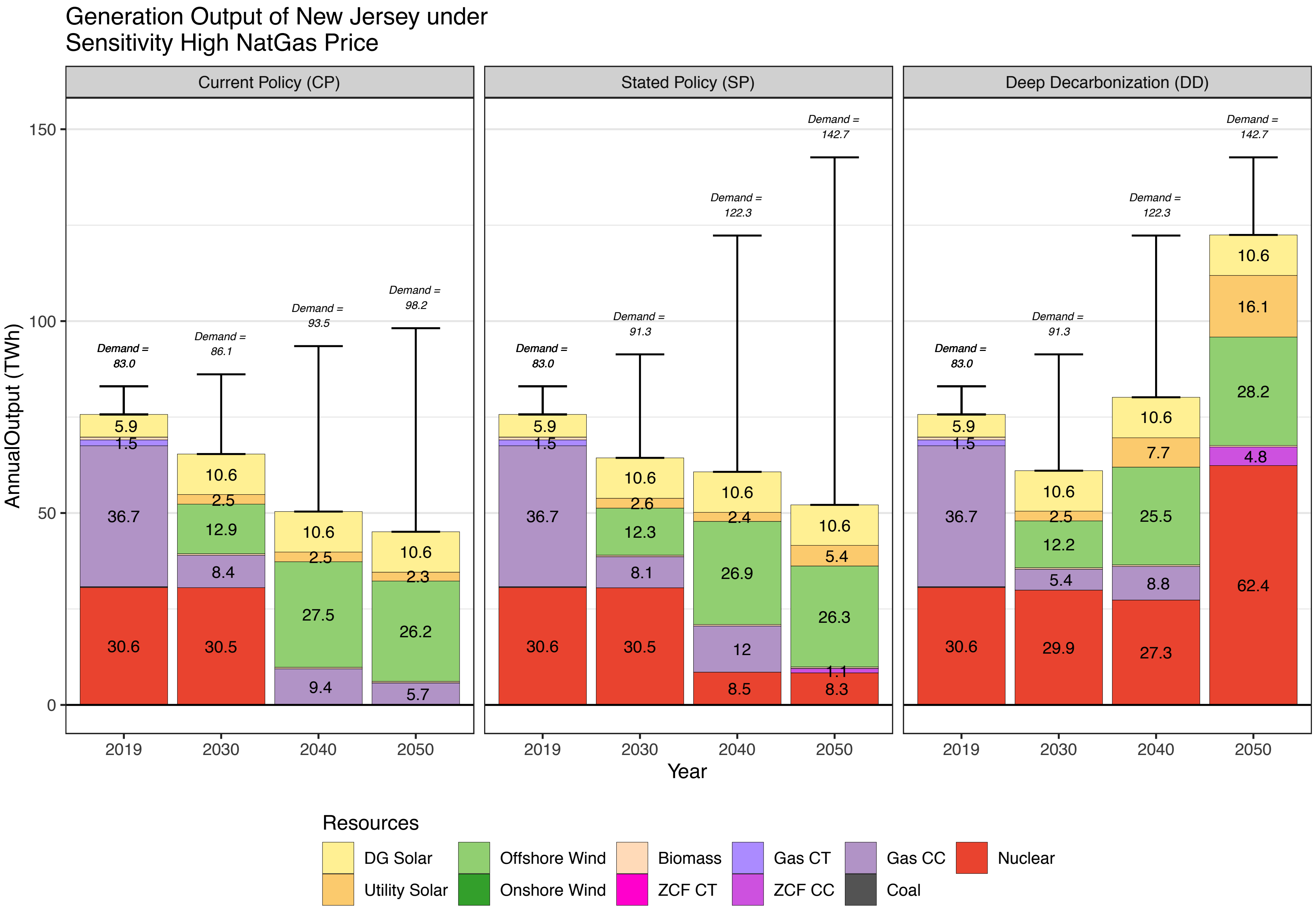
NJ Generation Output in CP/SP/DD (High RE/BESS Cost)



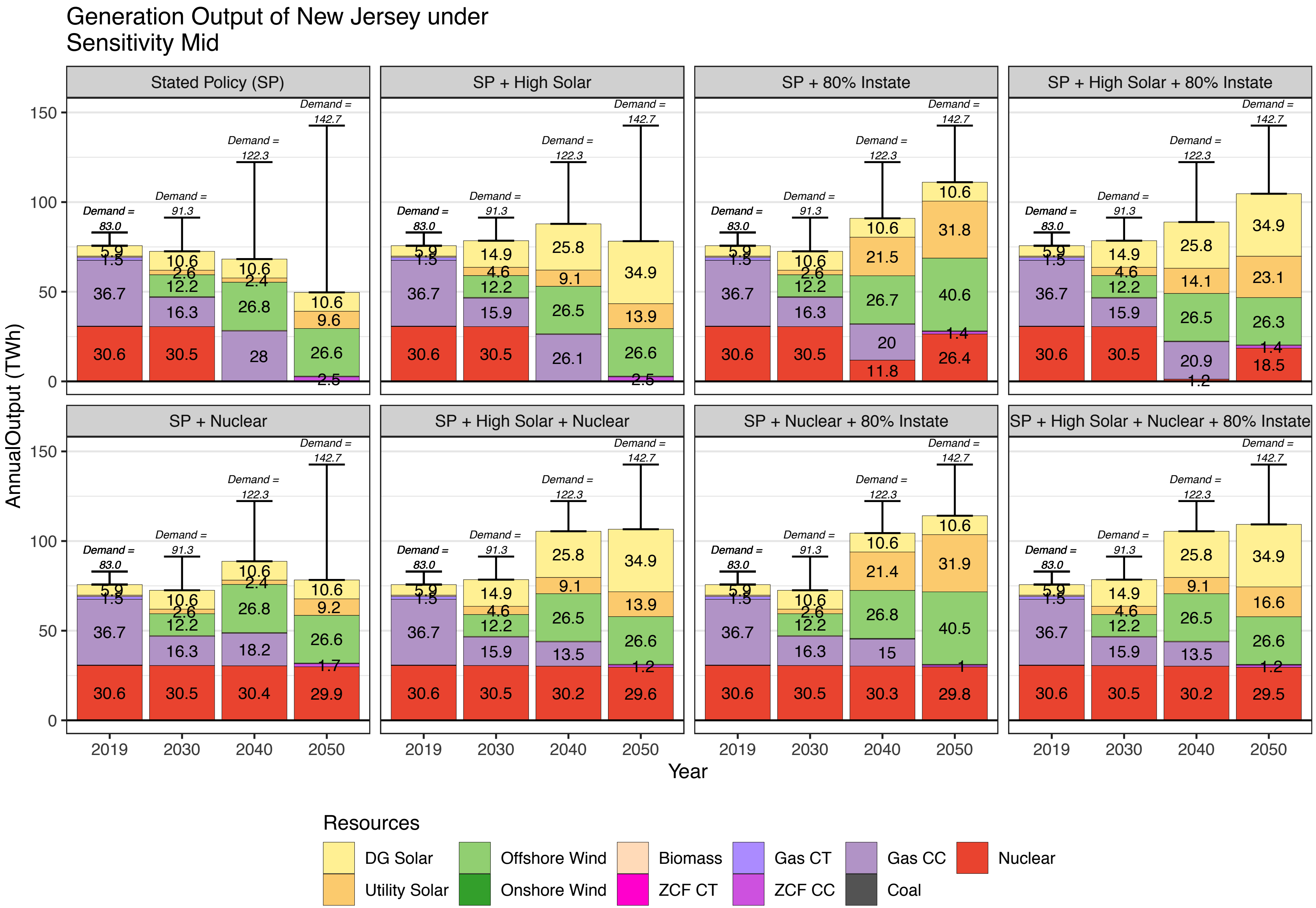
NJ Generation Output in CP/SP/DD (Low Nat. Gas Price)



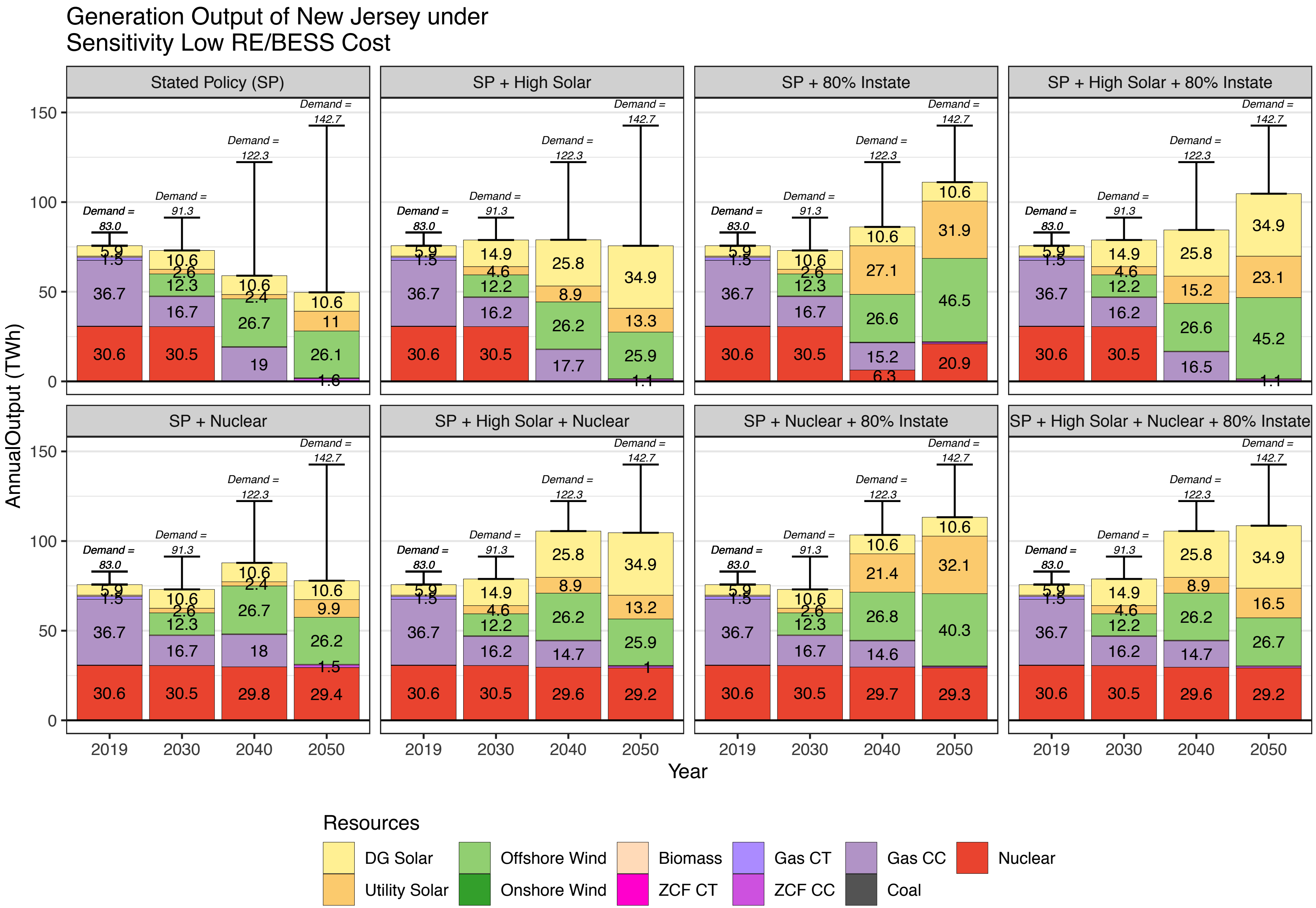
NJ Generation Output in CP/SP/DD (High Nat. Gas Price)



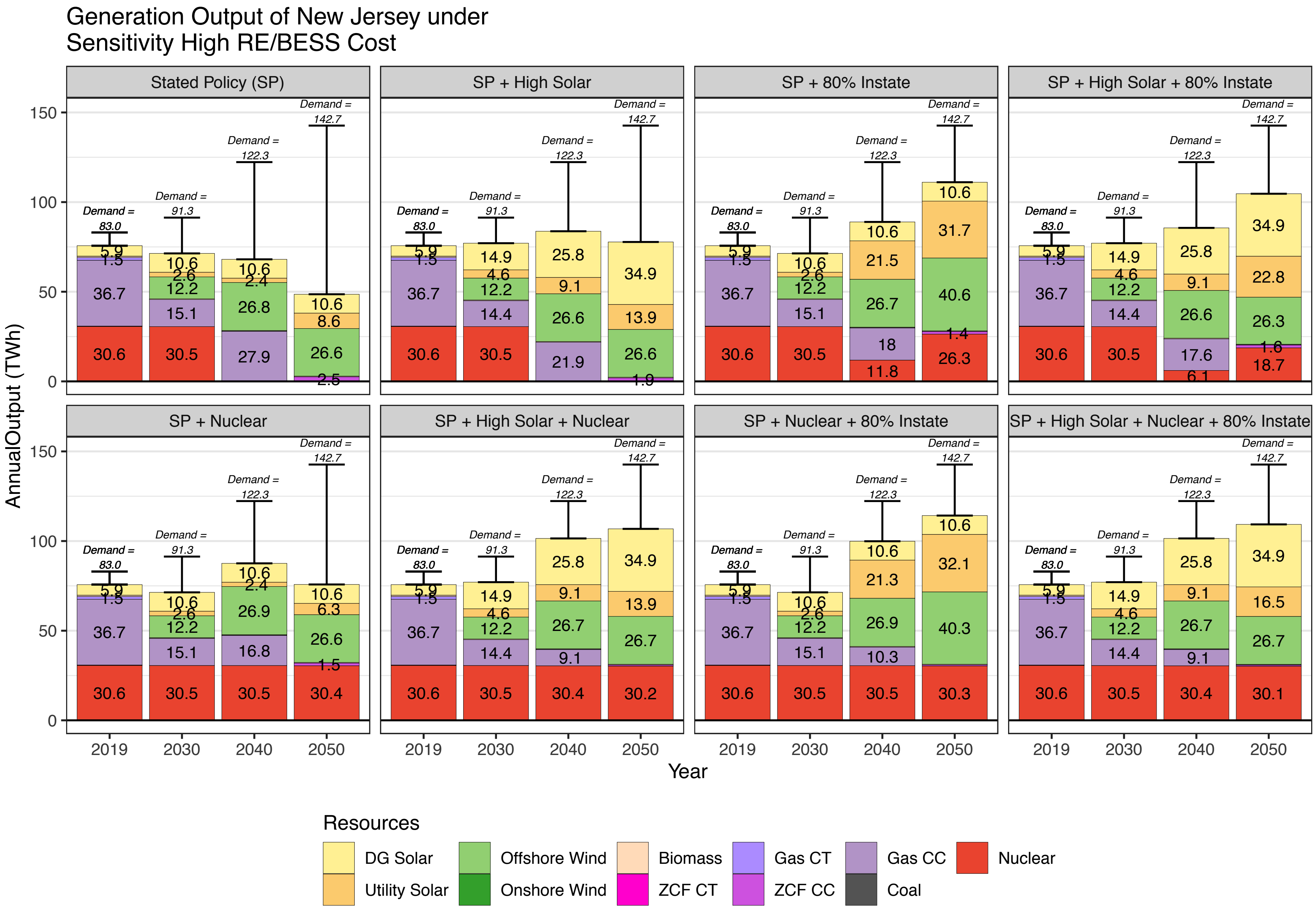
NJ Generation Output in SP Policy Variants (Mid)



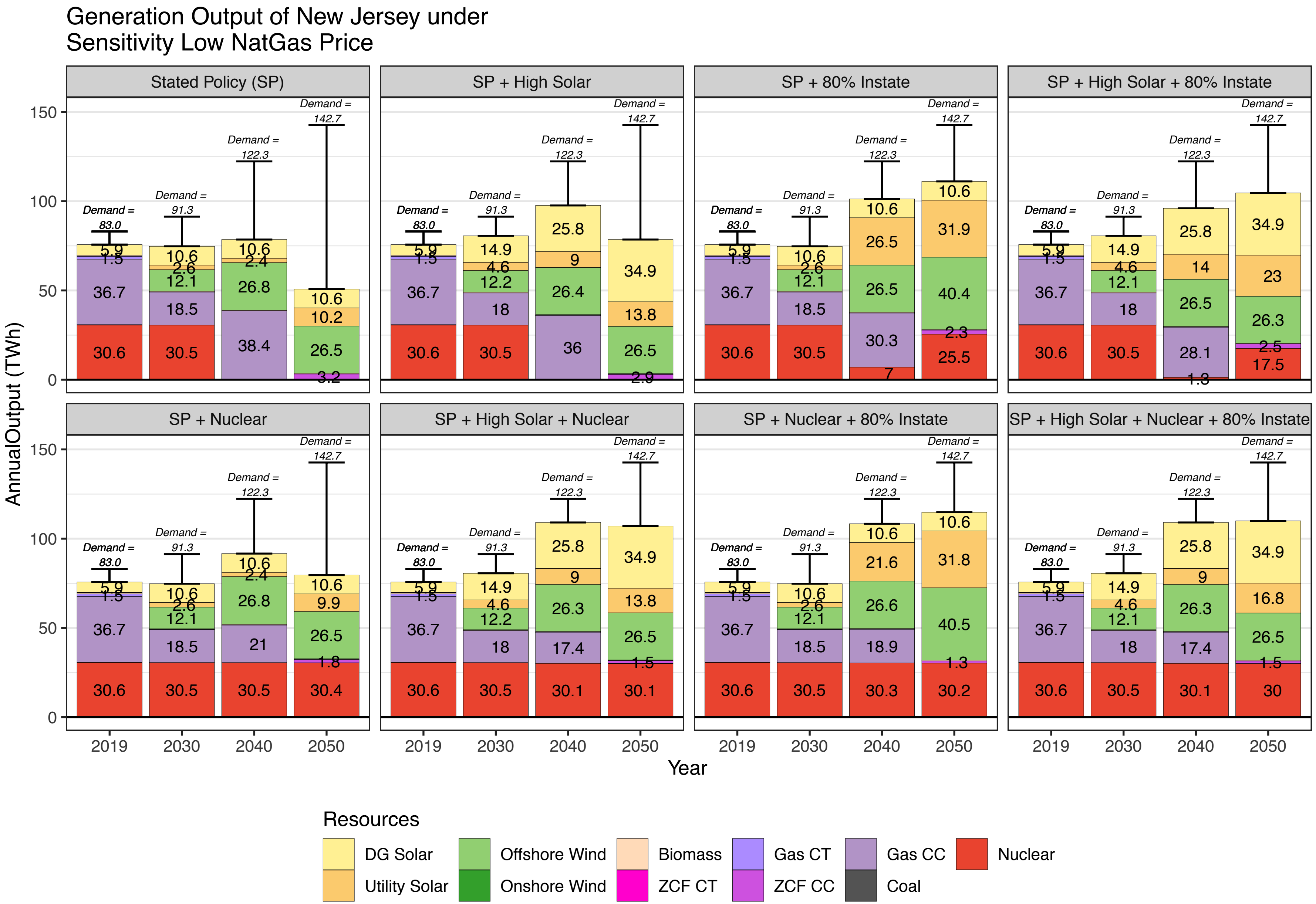
NJ Generation Output in SP Policy Variants (Low RE/BESS Cost)



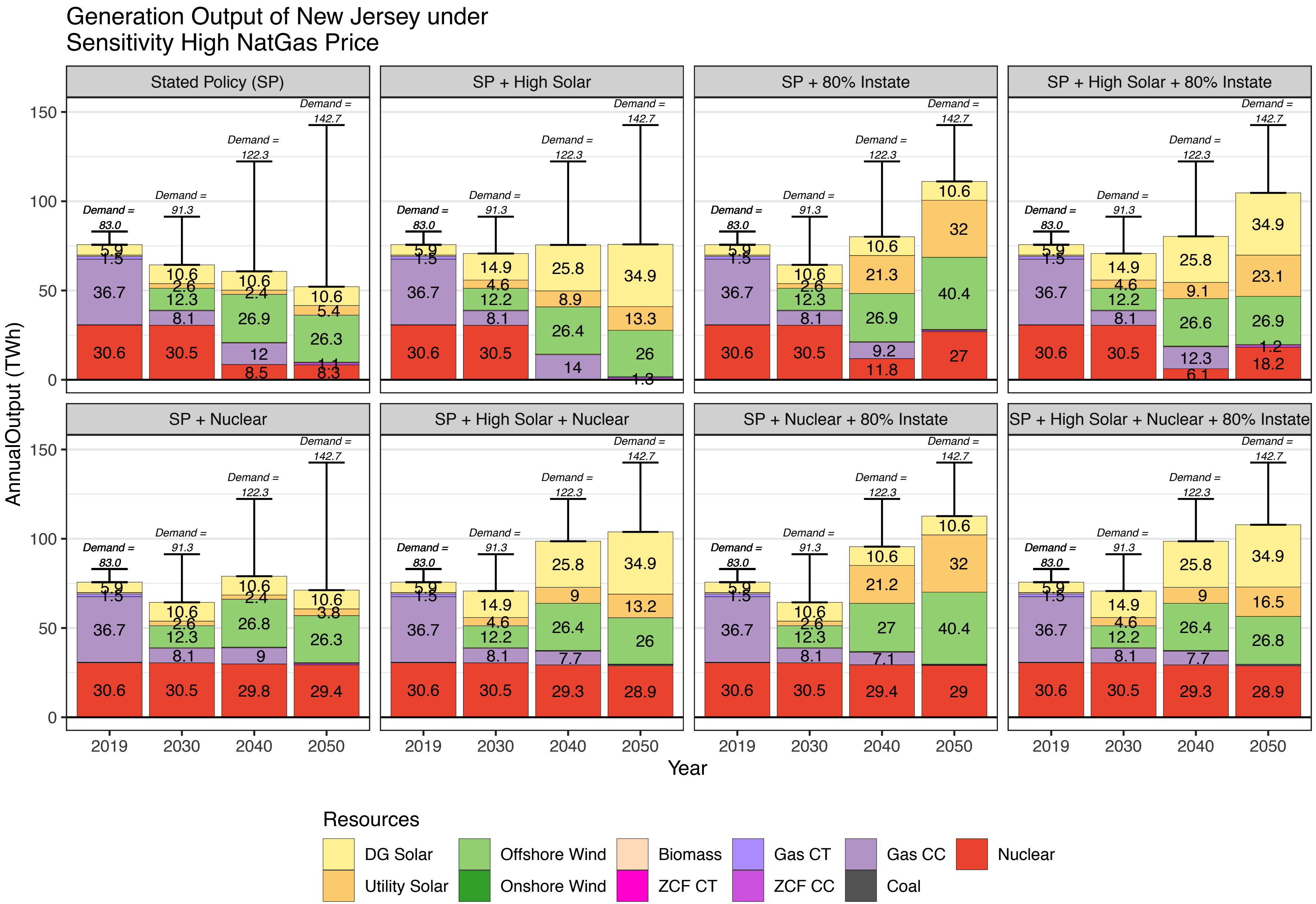
NJ Generation Output in SP Policy Variants (High RE/BESS Cost)



NJ Generation Output in SP Policy Variants (Low Nat. Gas Price)



NJ Generation Output in SP Policy Variants (High Nat. Gas Price)



NJ Load Serving Entity Cost

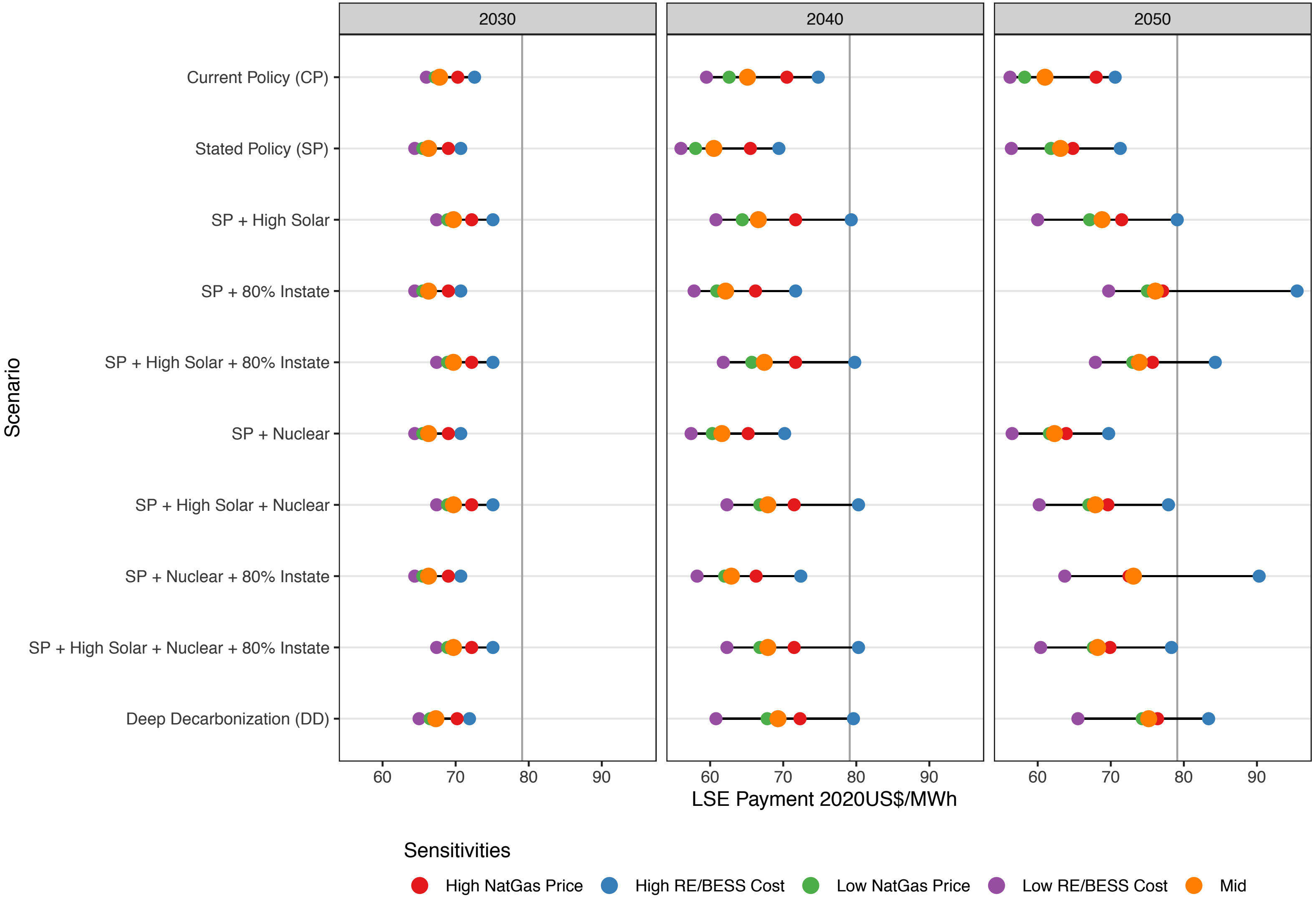
Summary of Sensitivity Results

These sensitivity results demonstrate that cost of electricity supply incurred by NJ load-serving entities (LSEs, and thus electricity consumers) are sensitive to the different cost assumptions, especially in the 2040s and 2050s. However, a variety of conclusions are robust to sensitivities, including:

1. **Under Stated Policies, a transition to 100% carbon-free electricity supply by 2050 results in reductions in electricity supply costs relative to 2019 costs**, with costs to LSEs ranging from -29% to -10% vs 2019 costs.
2. **Prioritizing in-state generation**, whether via a focus on solar or in-state clean energy in general, **will significantly increase costs relative to the least cost Stated Policies pathway.**
3. **If an in-state generation is prioritized, retaining existing nuclear power will lower costs for LSEs and NJ electricity consumers in 2050.**
4. **If the rest of PJM and its neighboring regions also pursue deep decarbonization goals** (as in the Deep Decarbonization scenarios) **the costs for NJ LSEs will be higher.**

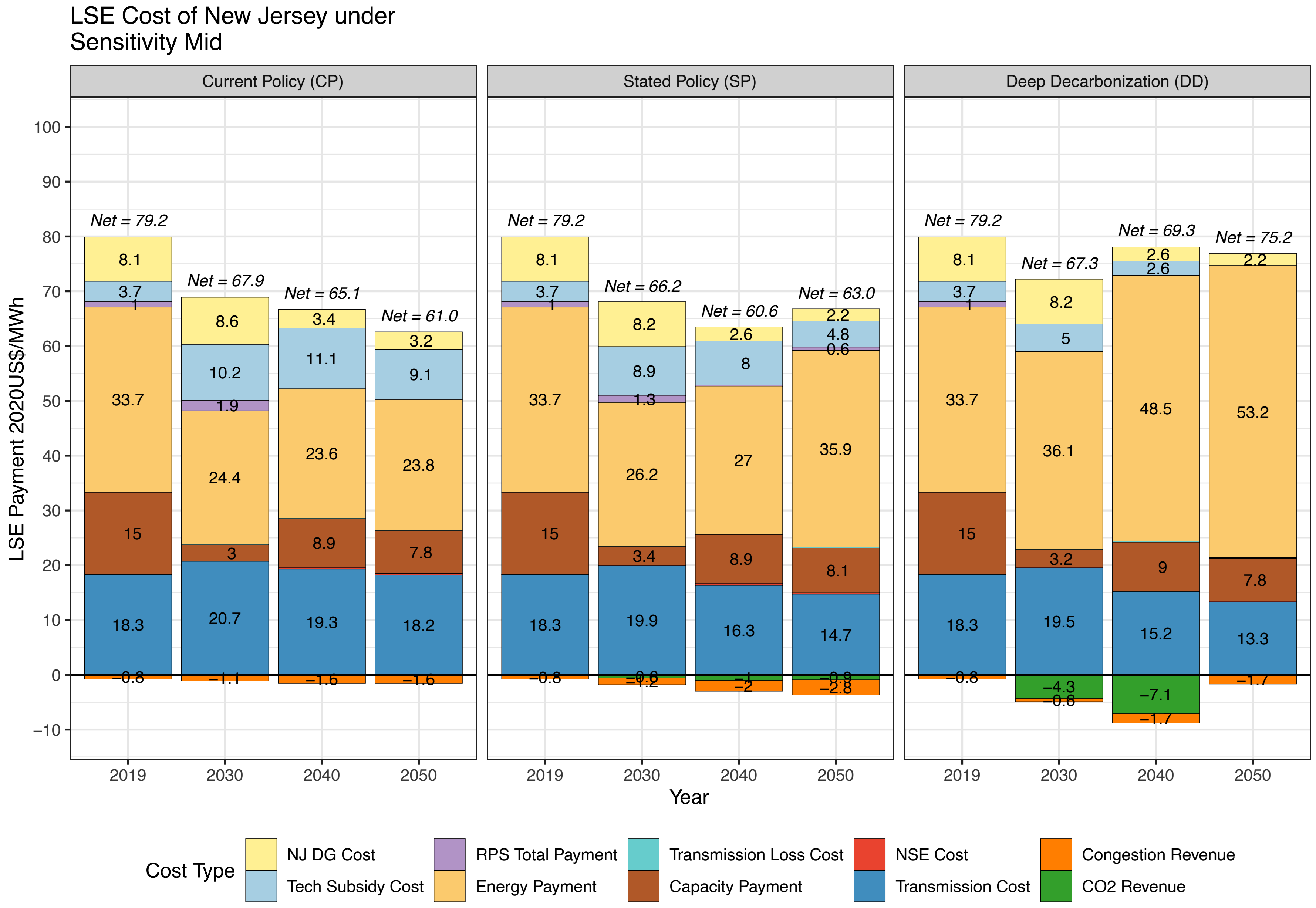
Note: Total electricity bills may increase with electrification as total volume of electricity consumption increases, while total expenditures on energy (including fuels and heating) will likely decline. However, this report does not make any attempt to quantify total bill impacts or distribution of costs across customer classes or usage patterns.

Overview of NJ LSE Cost in all cases

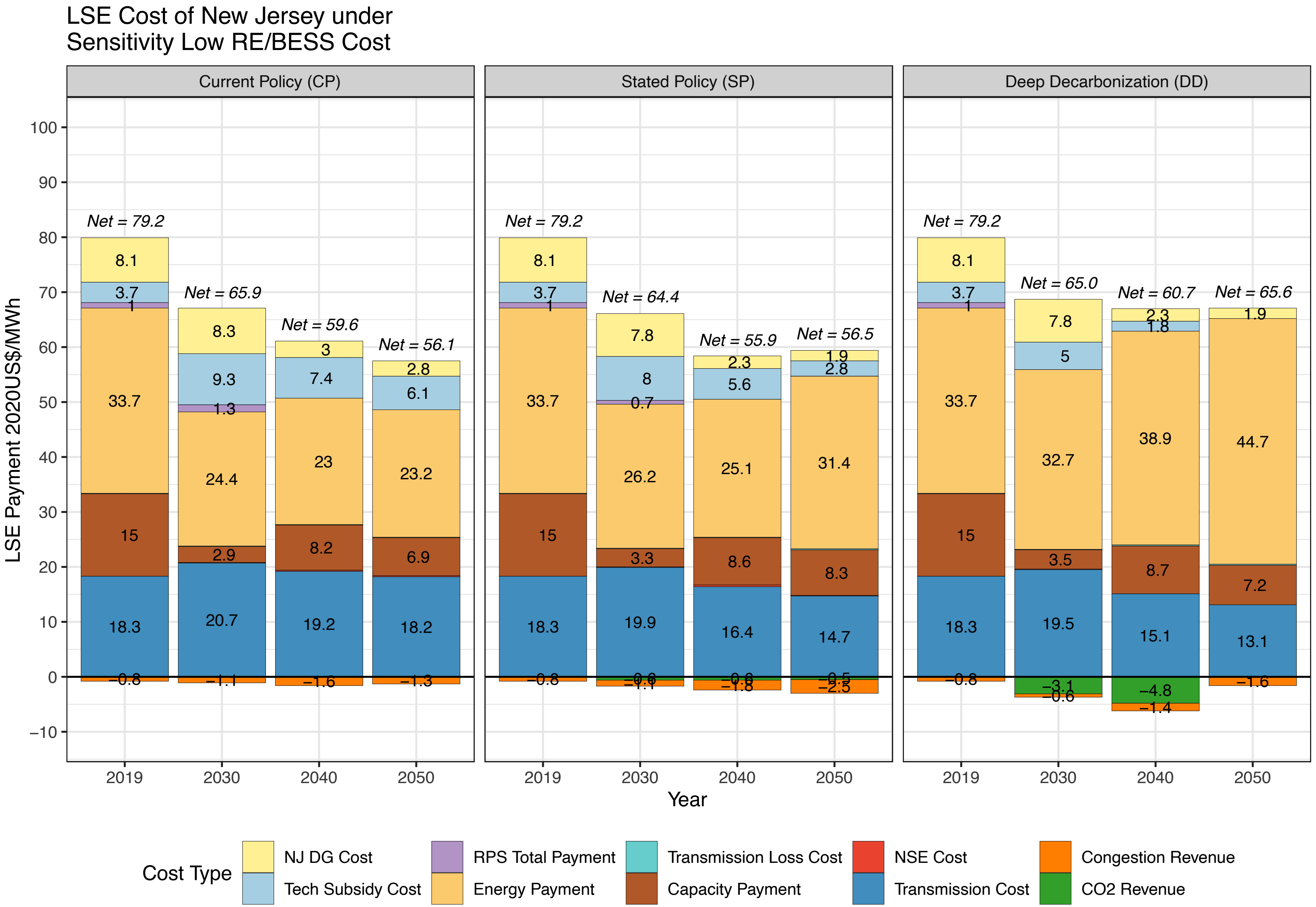


Vertical lines show the 2019 NJ LSE cost of $79.2/MWh (for 2019 LSE cost benchmark calculation, check the Appendix – "2019 LSE Cost Benchmark.")

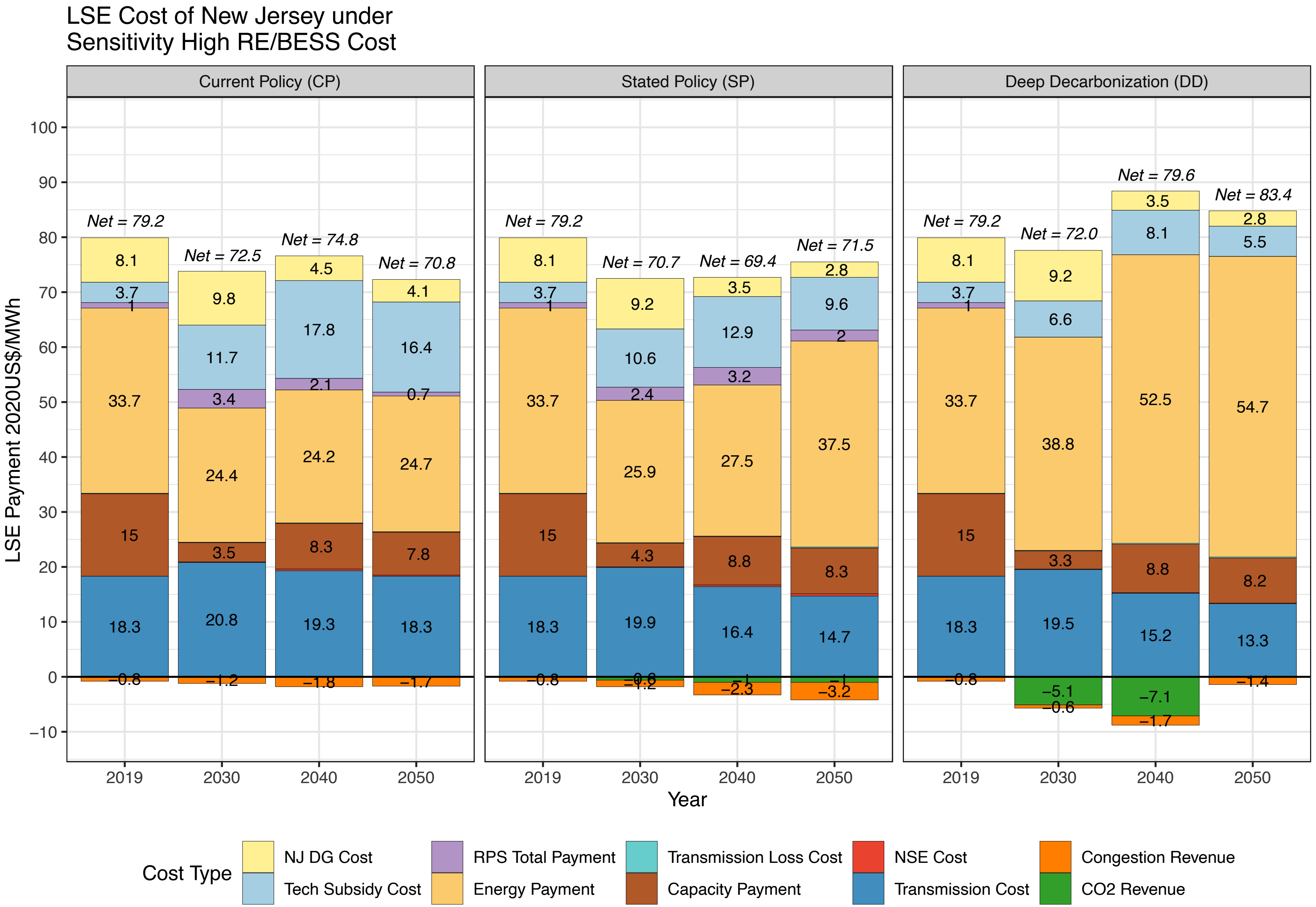
NJ LSE Cost of SP/CP/DD (Mid)



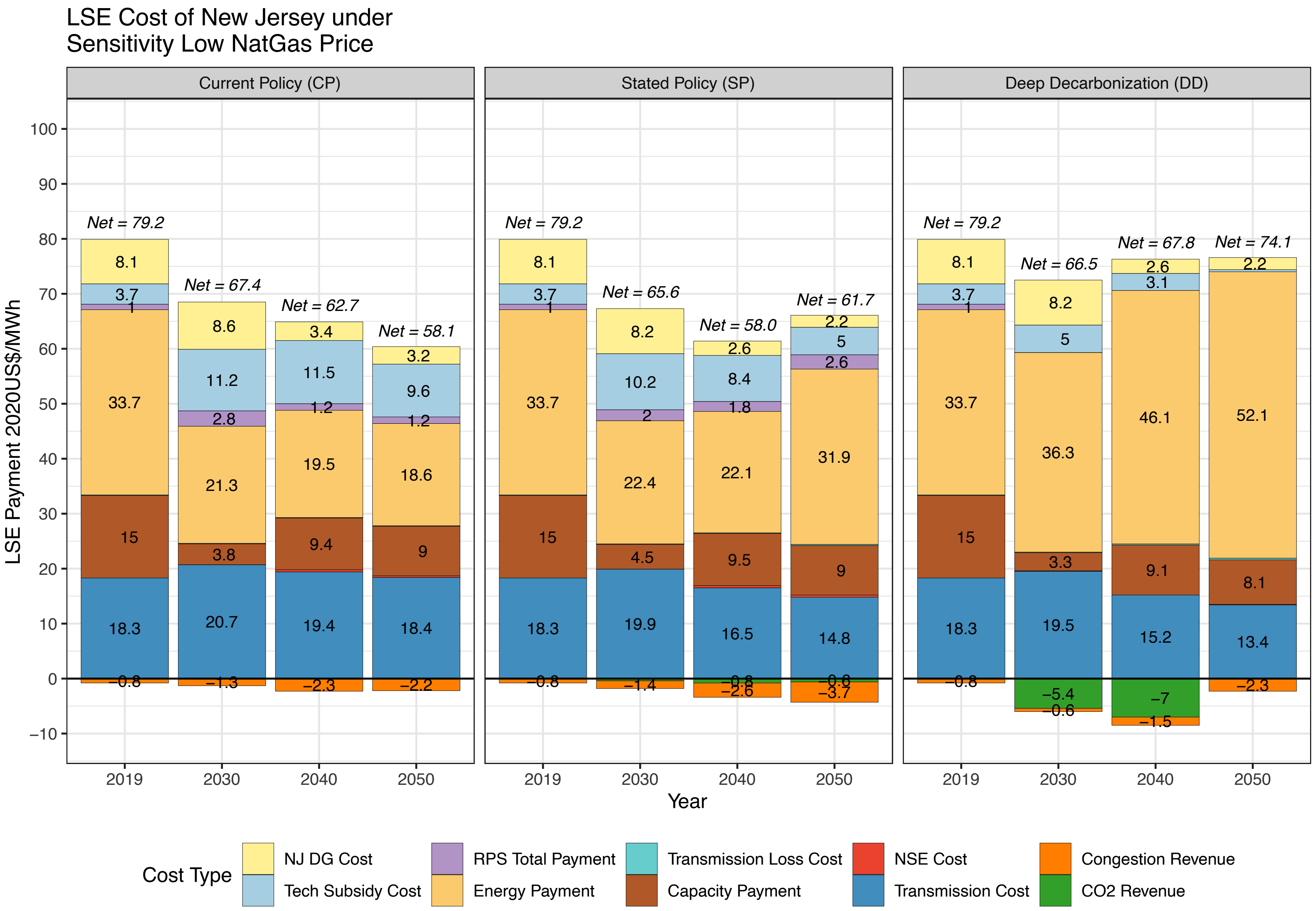
NJ LSE Cost of SP/CP/DD (Low RE/BESS Cost)



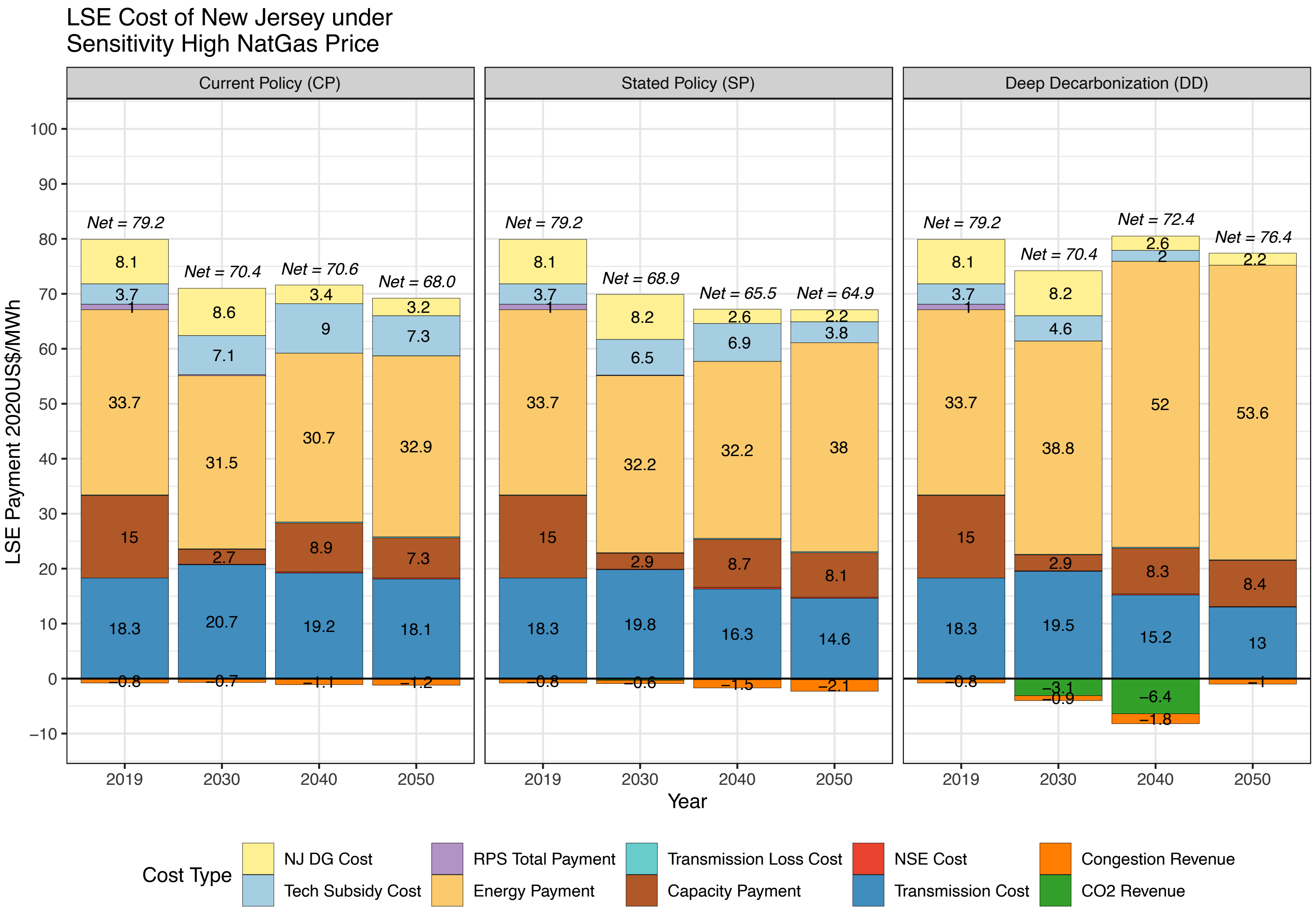
NJ LSE Cost of SP/CP/DD (High RE/BESS Cost)



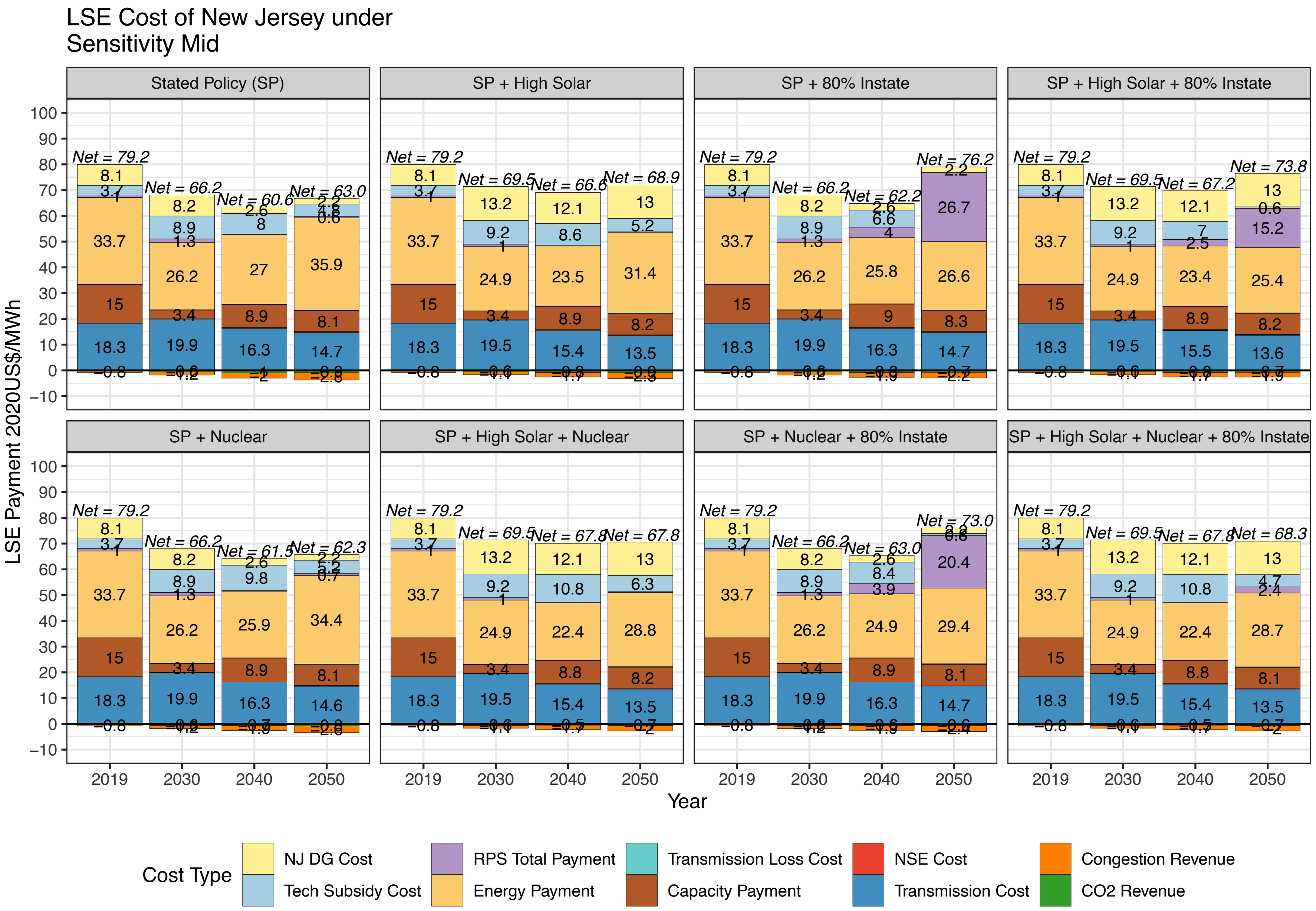
NJ LSE Cost of SP/CP/DD (Low Nat. Gas Price)



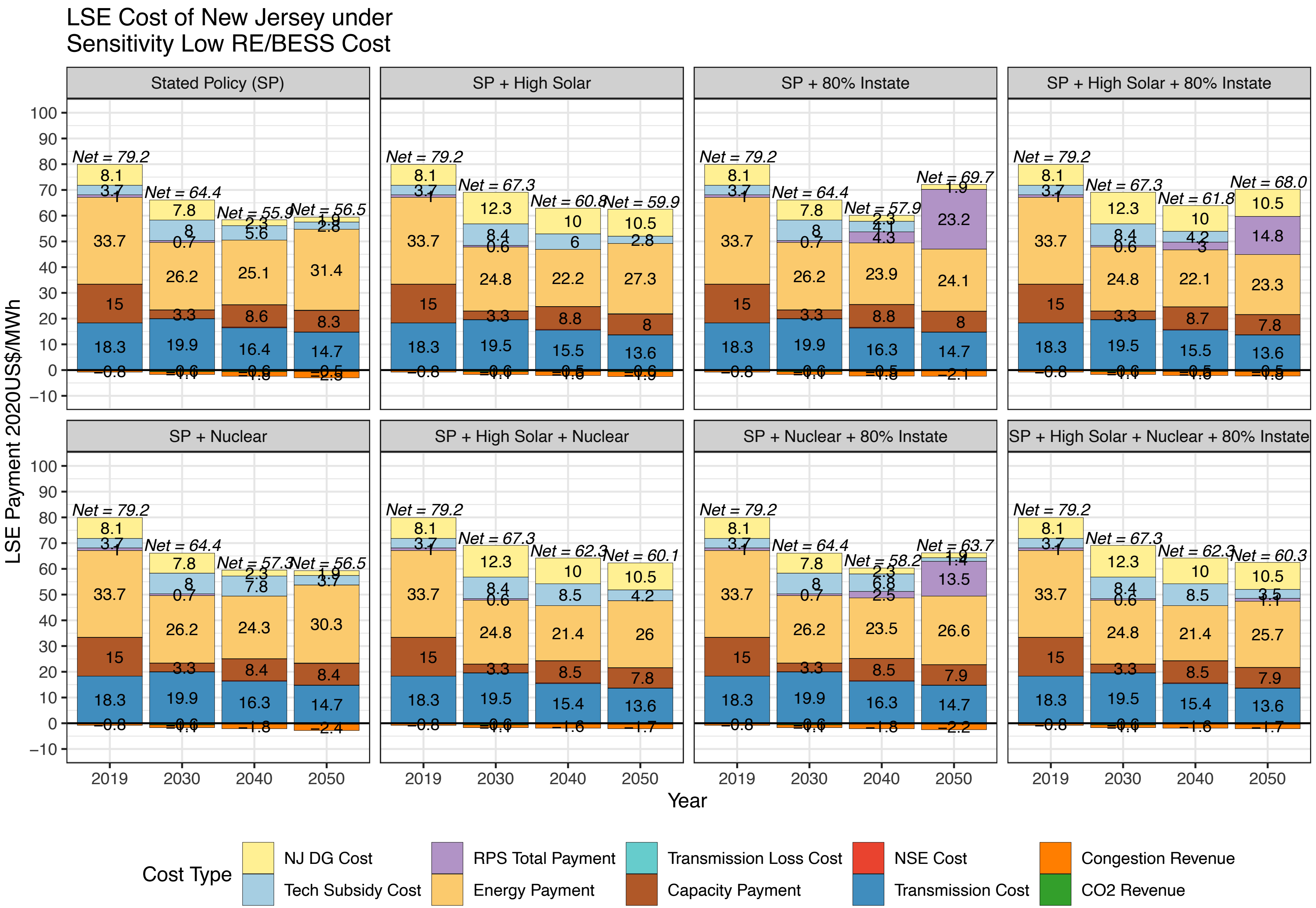
NJ LSE Cost of SP/CP/DD (High Nat. Gas Price)



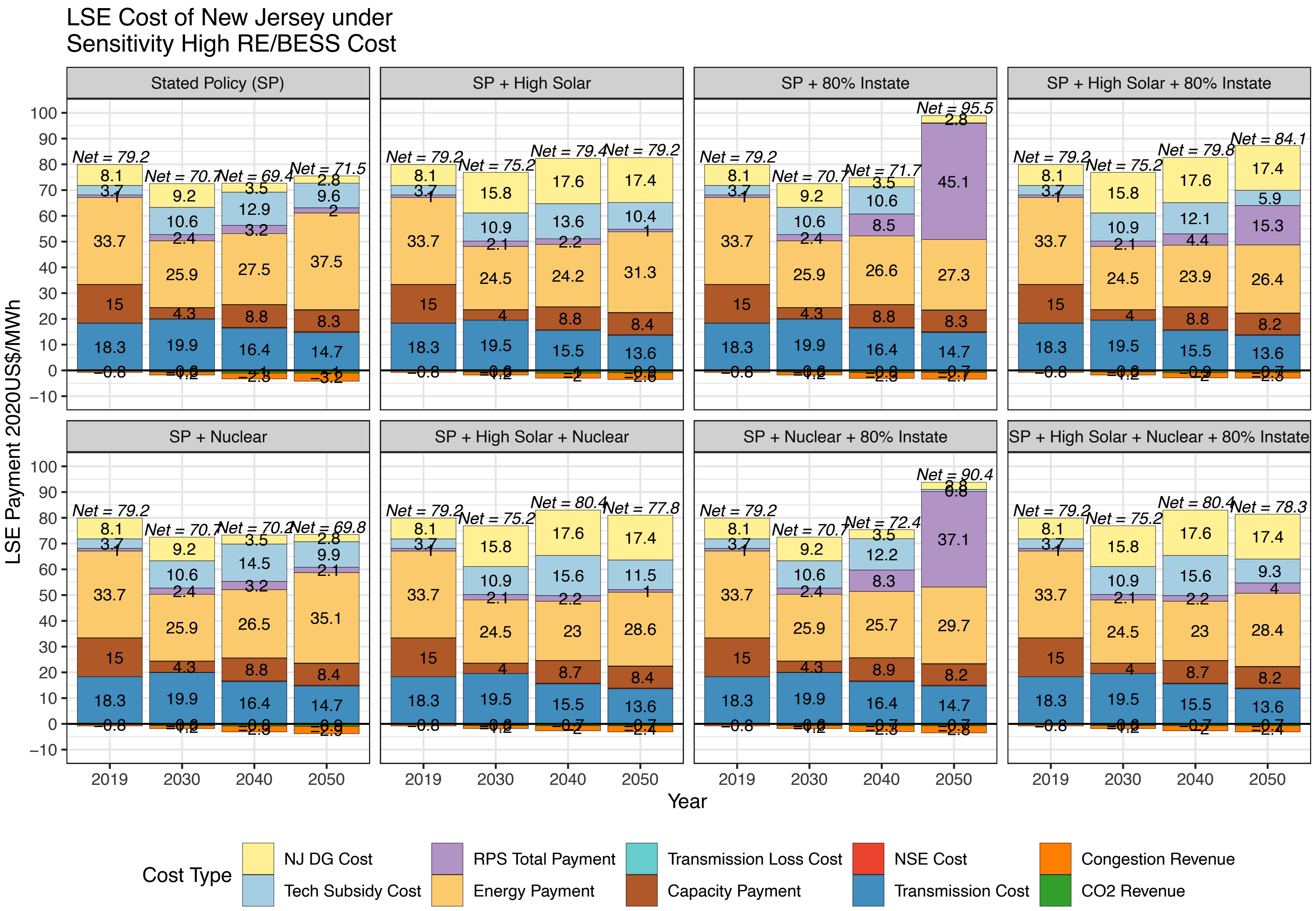
NJ LSE Cost of SP Policy Variants (Mid)



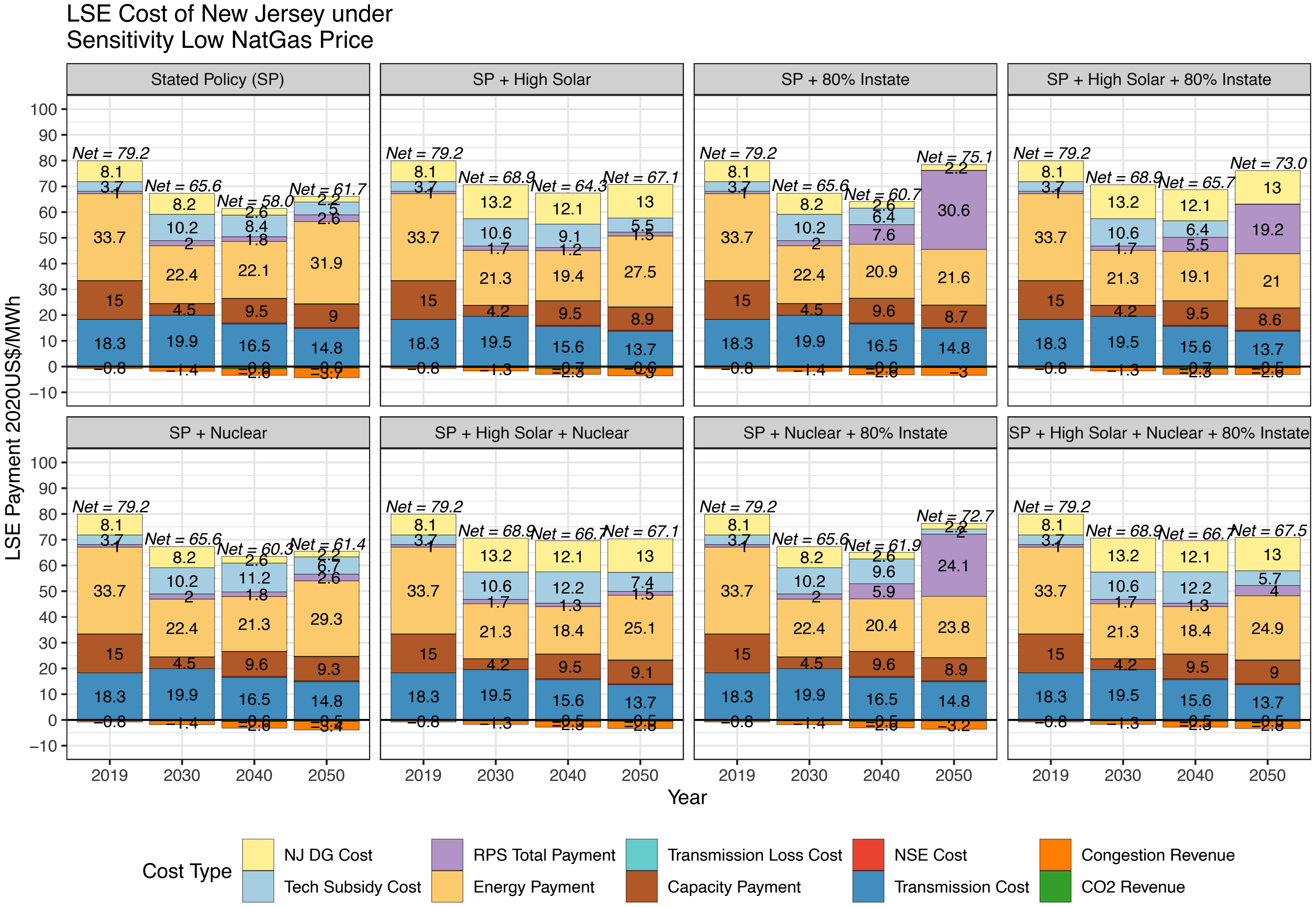
NJ LSE Cost of SP Policy Variants (Low RE/BESS Cost)



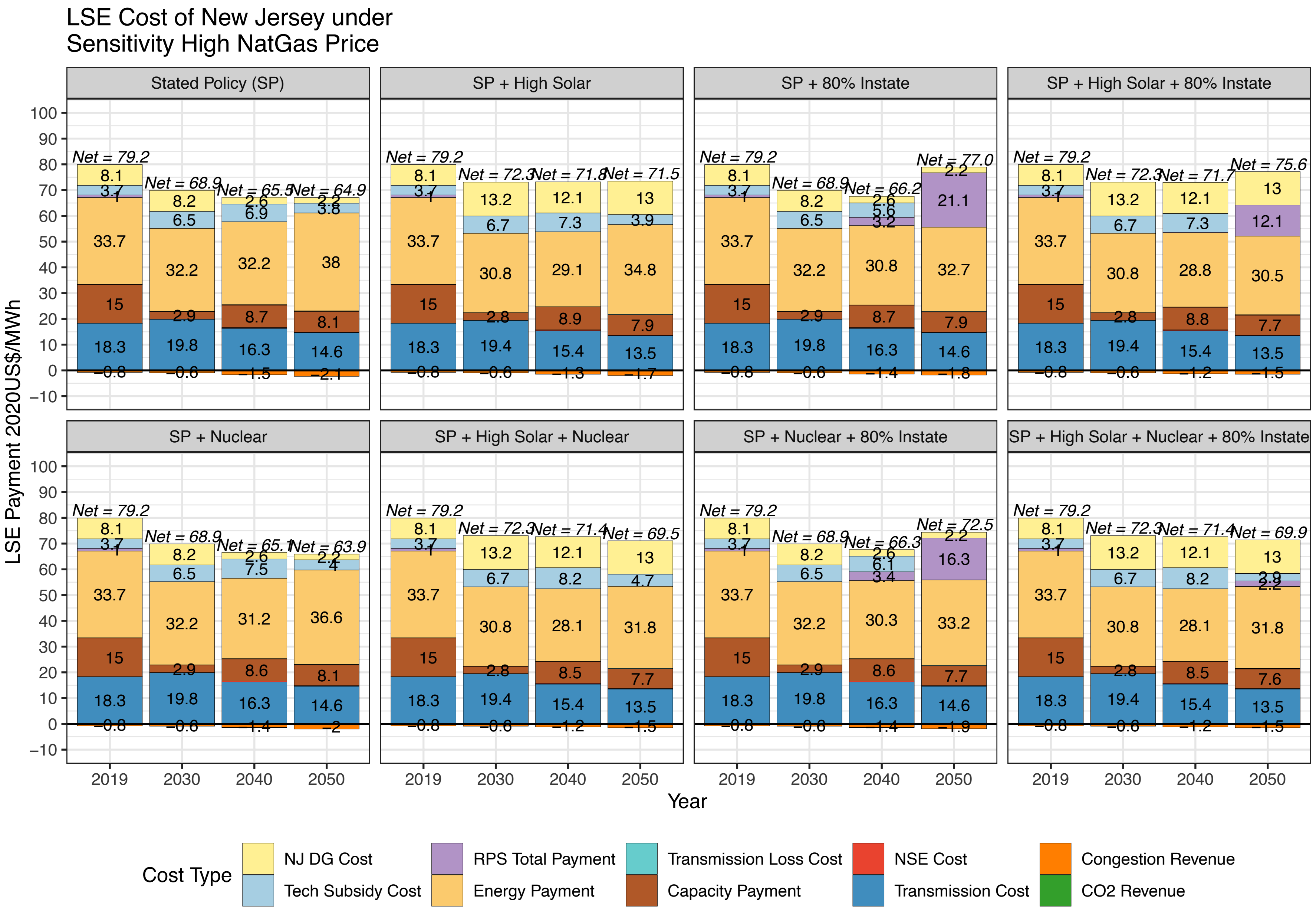
NJ LSE Cost of SP Policy Variants (High RE/BESS Cost)



NJ LSE Cost of SP Policy Variants (Low Nat. Gas Price)



NJ LSE Cost of SP Policy Variants (High Nat. Gas Price)



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Electricity Price Duration Curves of NJ Zones

Sensitivities – Electricity Price Duration Curves of NJ Zones

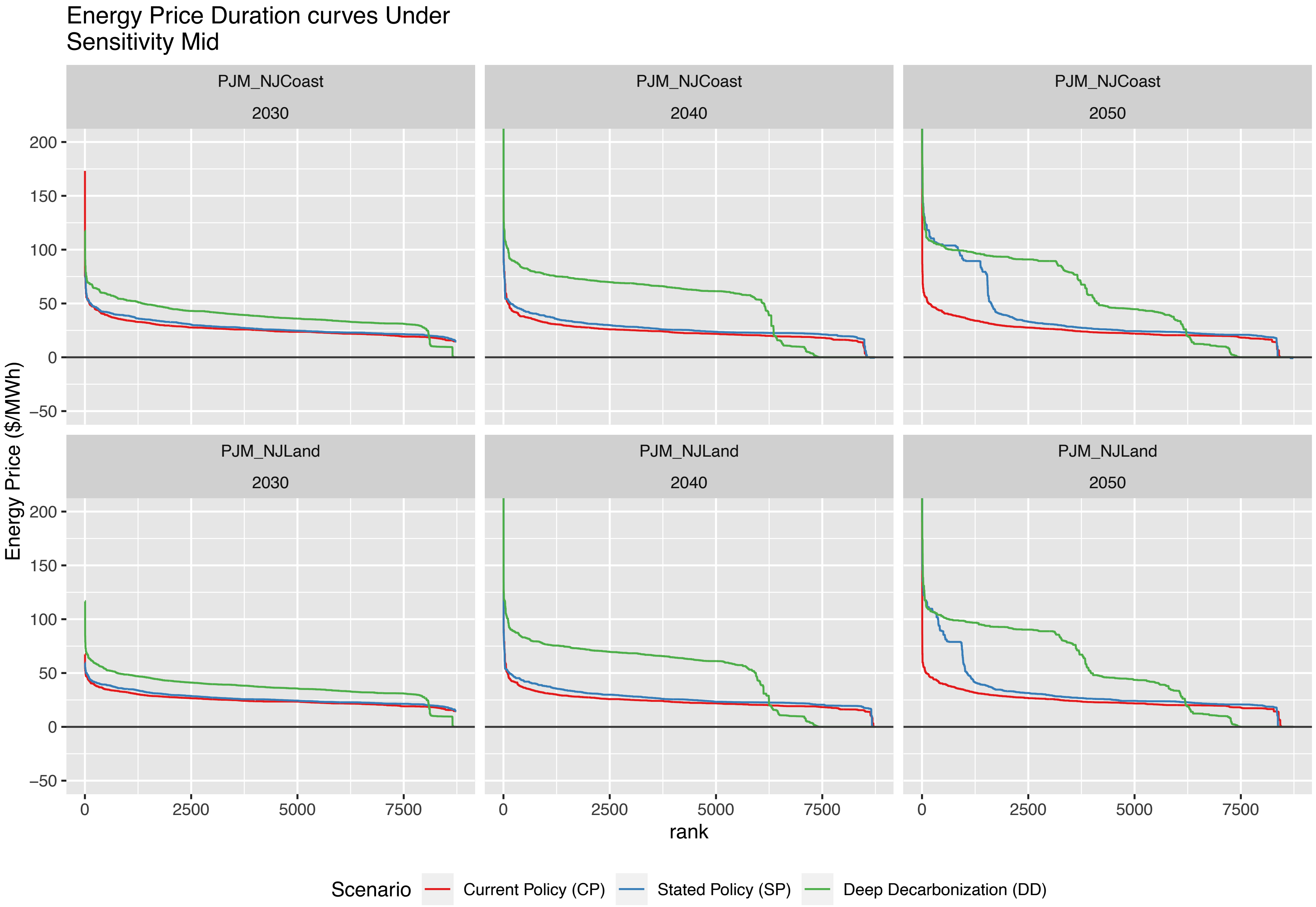
Summary of Sensitivity Results

Sensitivity analyses show that **the annual distribution of electricity prices**, as illustrated by the locational marginal price (LMP) duration curves shown in this section, **varies across cost assumptions**, e.g., for the same scenario, low RE/BESS cost leads to more frequent zero prices. However, the common observations are:

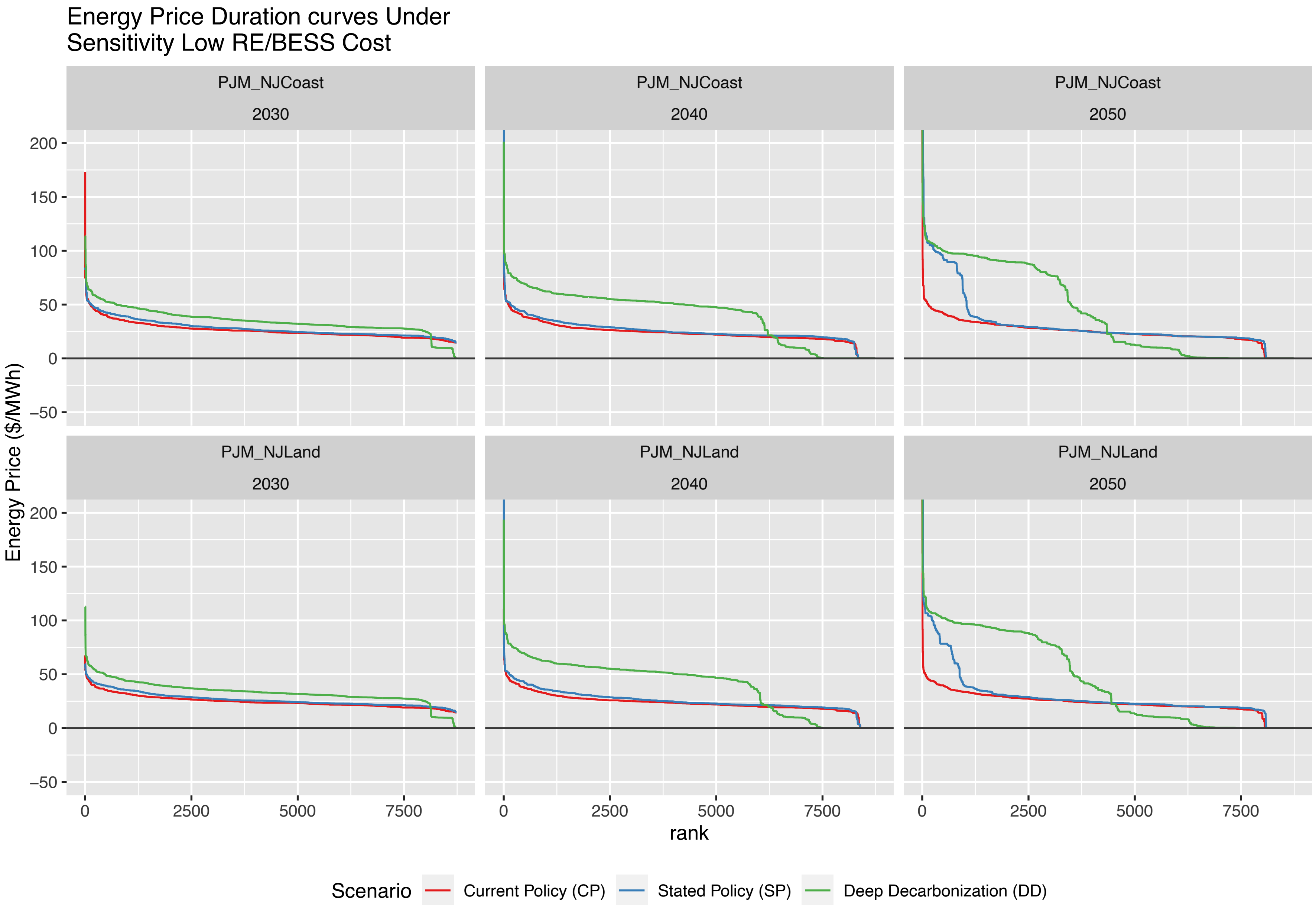
- **CP vs SP**: **LMP duration curves of Current Policies and Stated Policies scenarios do not deviate until 2050**, when the locational marginal prices of New Jersey are sometimes set by zero-carbon fuel-burning combined cycles.
- **SP vs DD:** LMP duration curves shows that **prices in Deep Decarbonization are significantly higher than Stated Policies on average**, due to the carbon price included in the marginal cost of emitting generators. However, zero price periods are more frequently as well, given the larger role of wind and solar in DD scenarios.
- **Zero or negative prices in the New Jersey coastal area are more frequent than inland area because of the interconnection of offshore wind and transmission congestions** preventing transmission to interior population centers, especially if in-state clean generation requirement is in place.

Note: Reported electricity prices reflect the dual value of the demand balance constraint in each model zone, and are approximately equivalent to day-ahead zonal locational marginal prices (LMPs) as computed in PJM's electricity market.

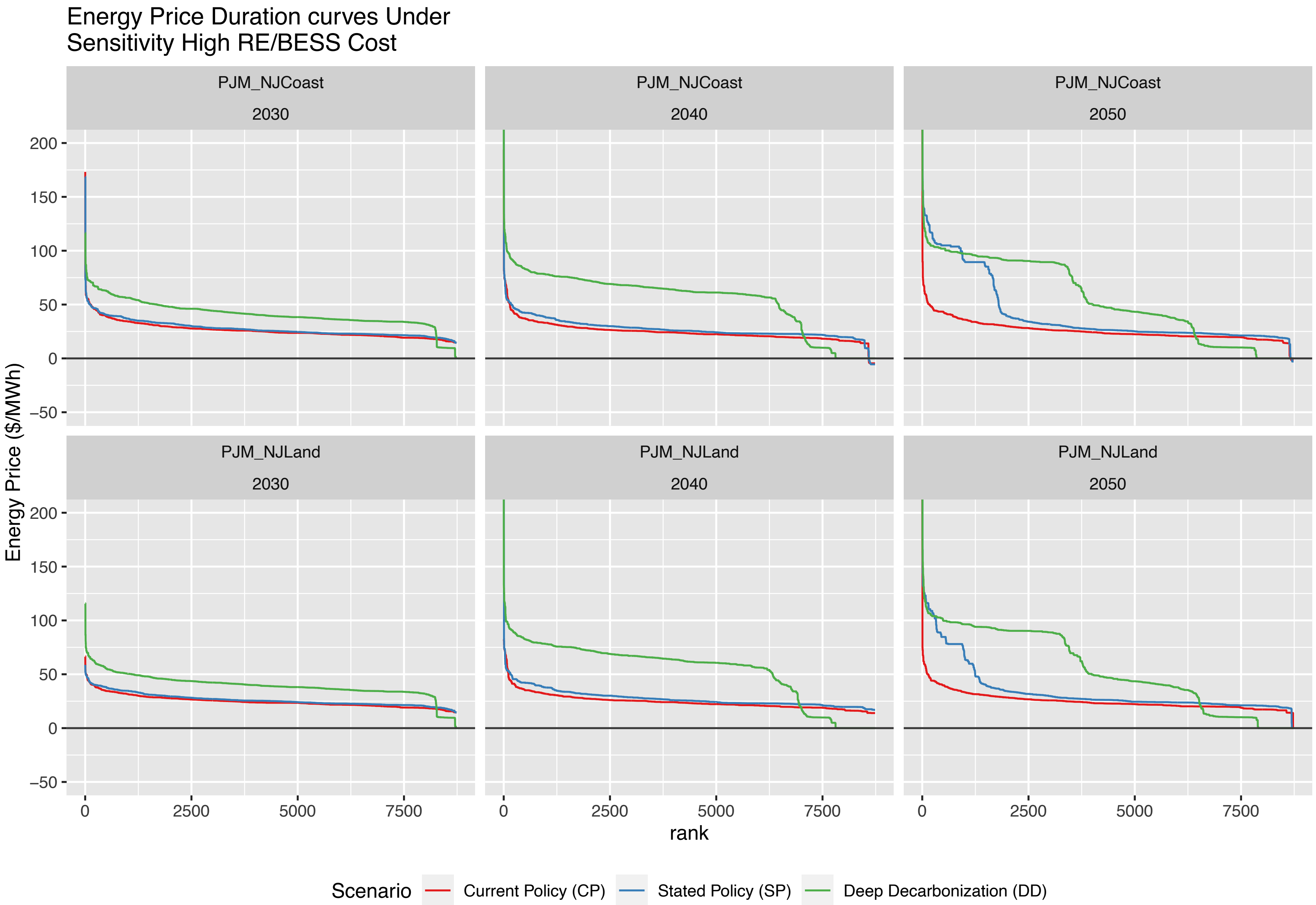
Price Duration Curves of NJ Zones (Mid)



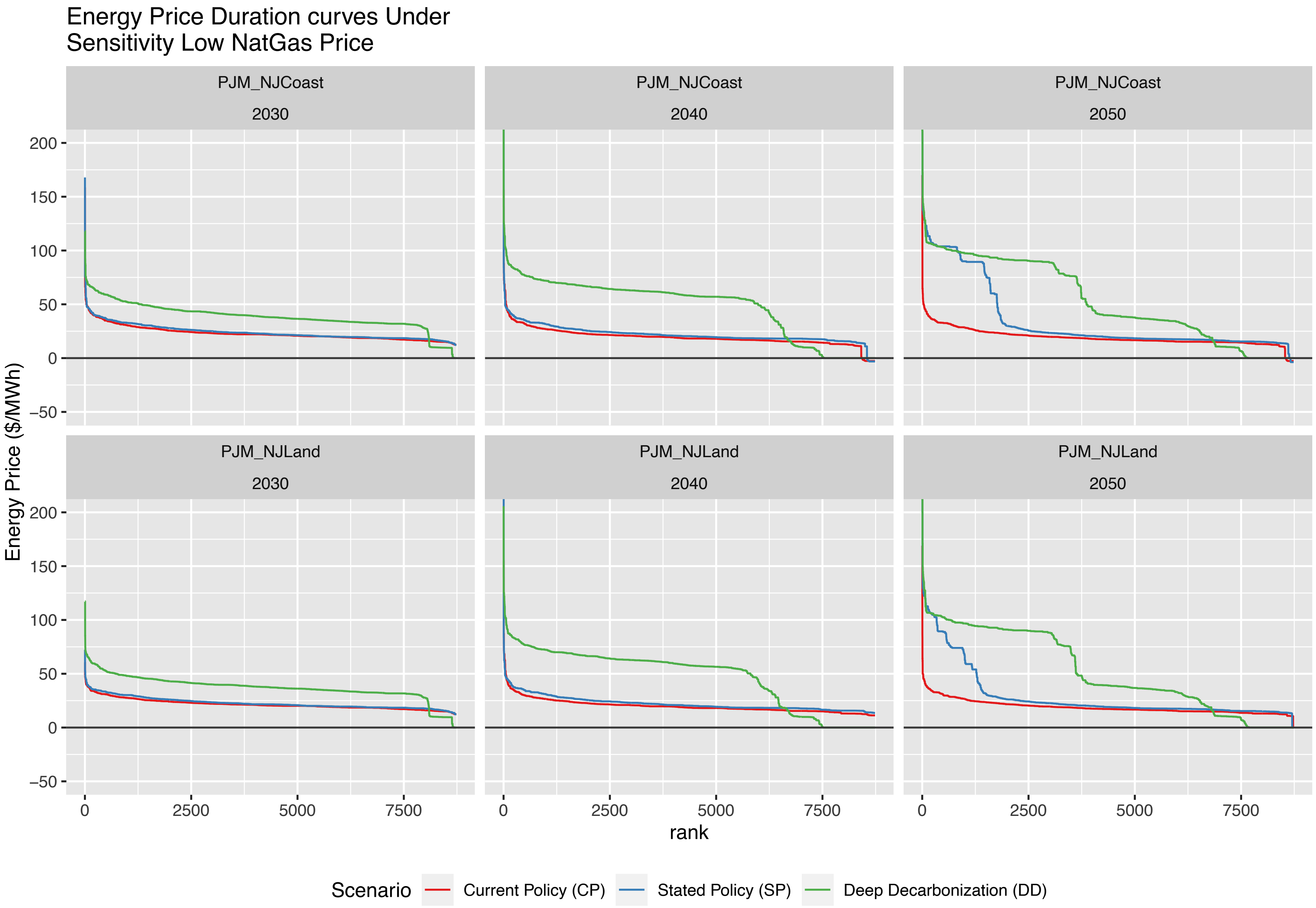
Price Duration Curves of NJ Zones (Low RE/BESS Cost)



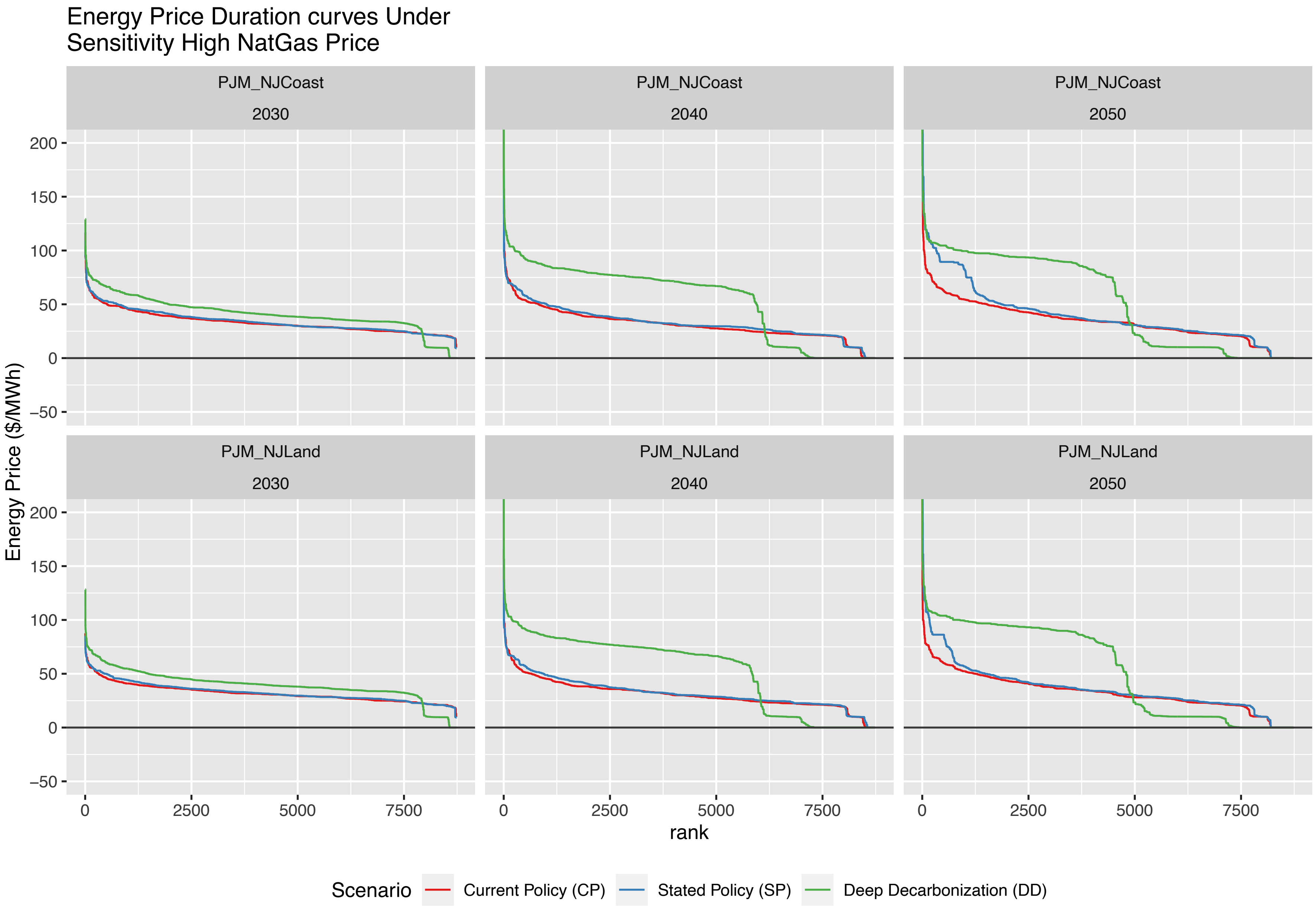
Price Duration Curves of NJ Zones (High RE/BESS Cost)



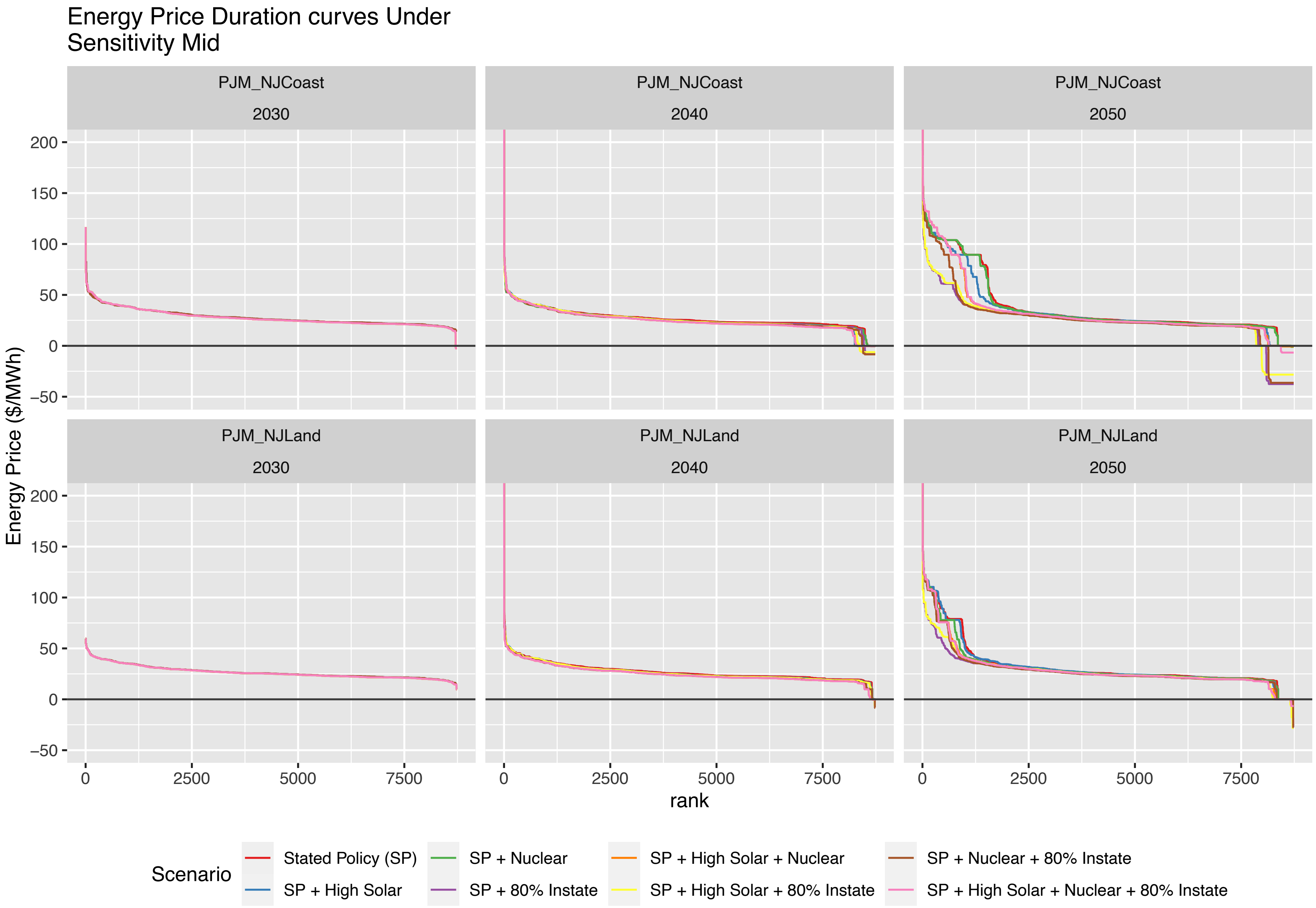
Price Duration Curves of NJ Zones (Low Nat. Gas Price)



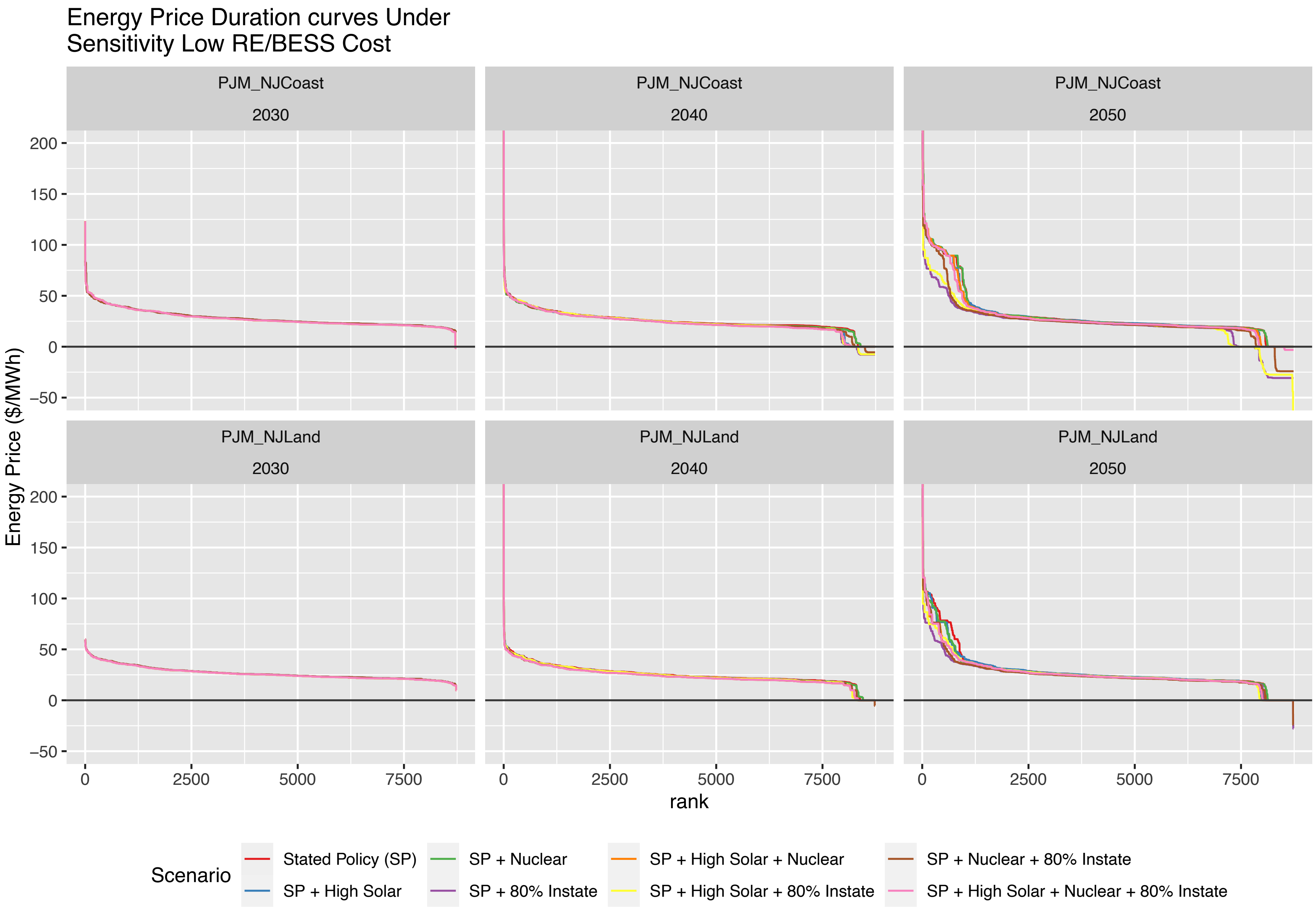
Price Duration Curves of NJ Zones (High Nat. Gas Price)



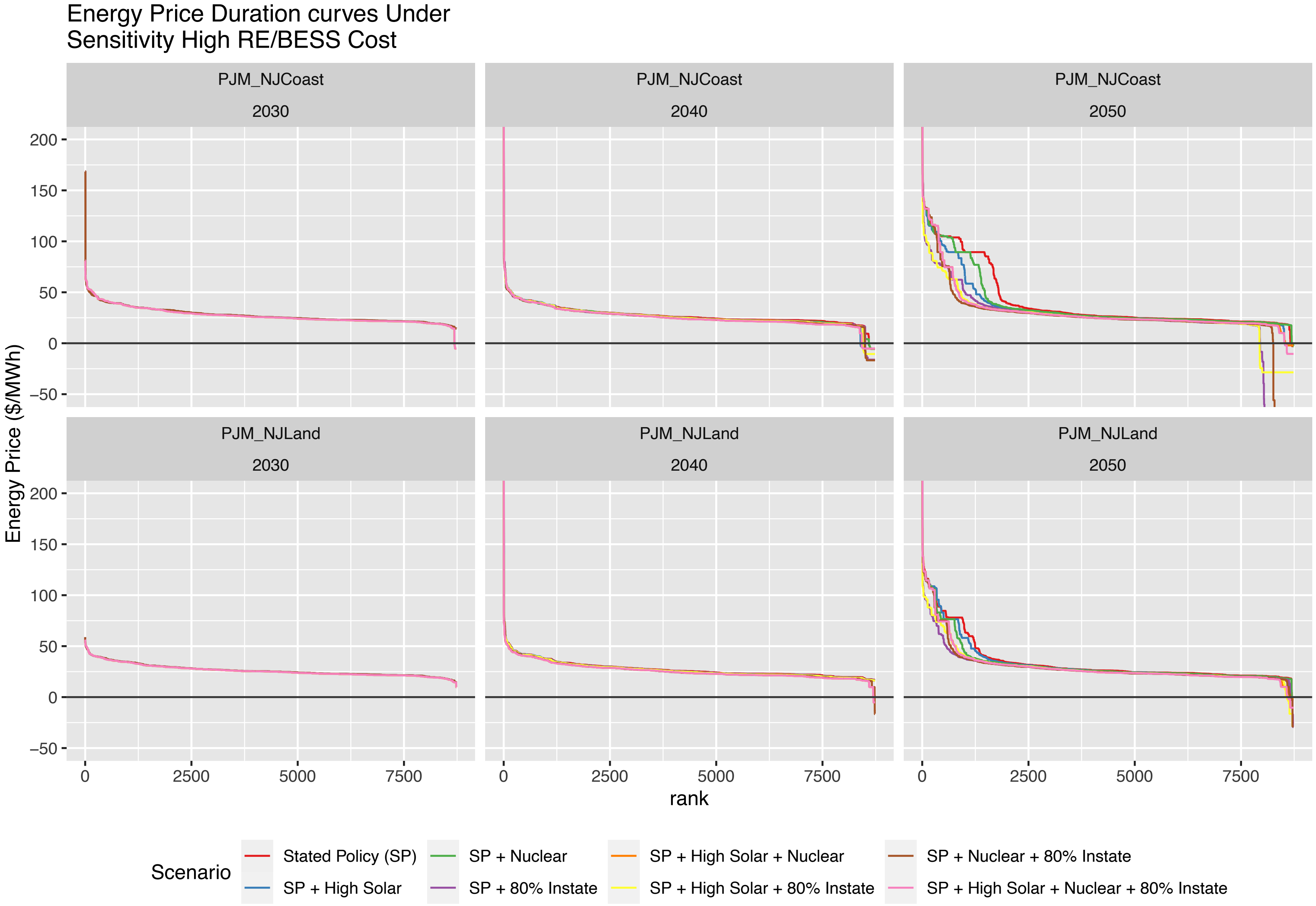
Price Duration Curves of NJ Zones in SP Policy Variants (Mid)



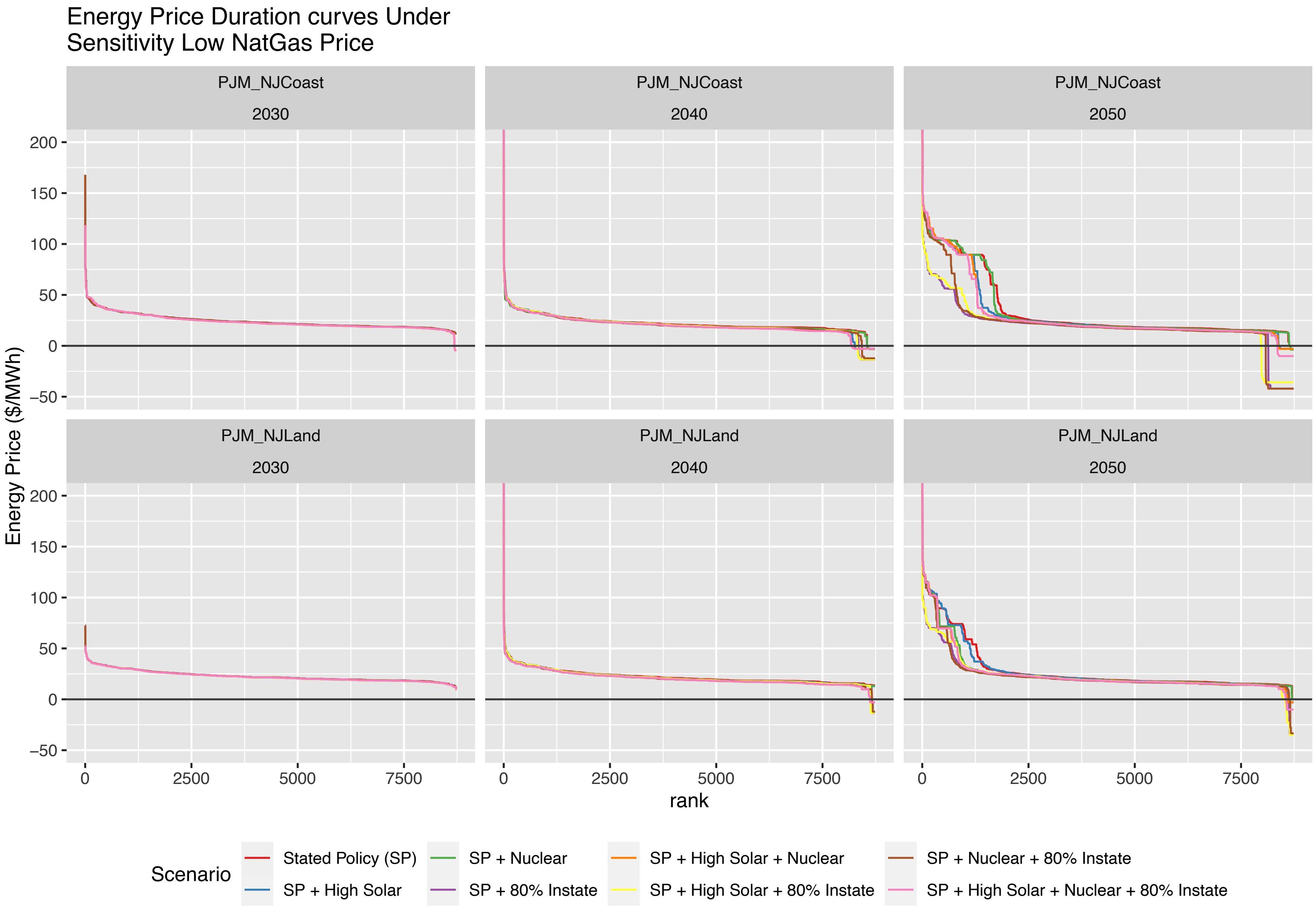
Price Duration Curves of NJ Zones in SP Policy Variants (Low RE/BESS Cost)



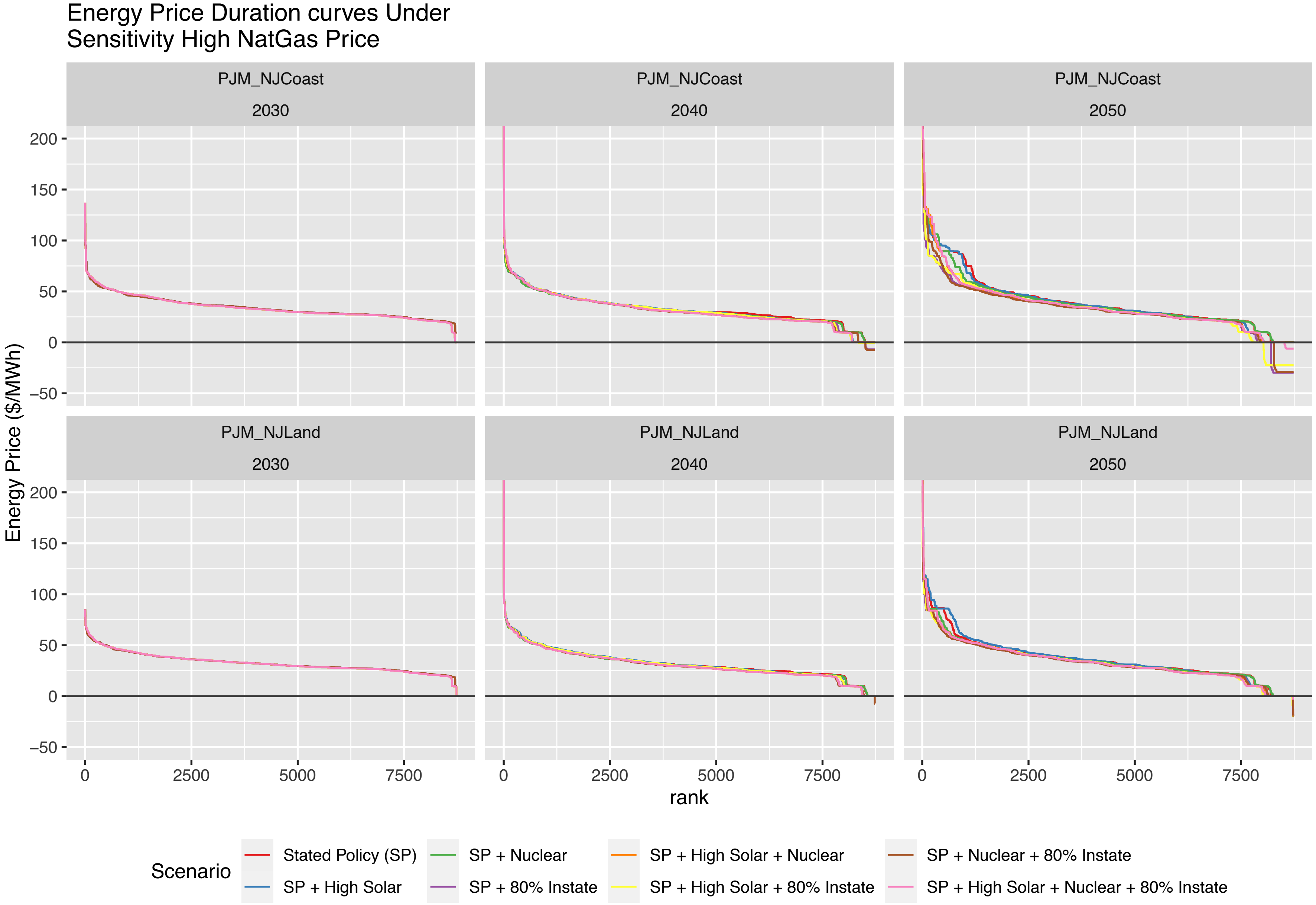
Price Duration Curves of NJ Zones in SP Policy Variants (High RE/BESS Cost)



Price Duration Curves of NJ Zones in SP Policy Variants (Low Nat. Gas Price)



Price Duration Curves of NJ Zones in SP Policy Variants (High Nat. Gas Price)



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Captured Energy Price of NJ Offshore Wind and Solar

Sensitivities – Captured Energy Price of NJ Offshore Wind and Solar

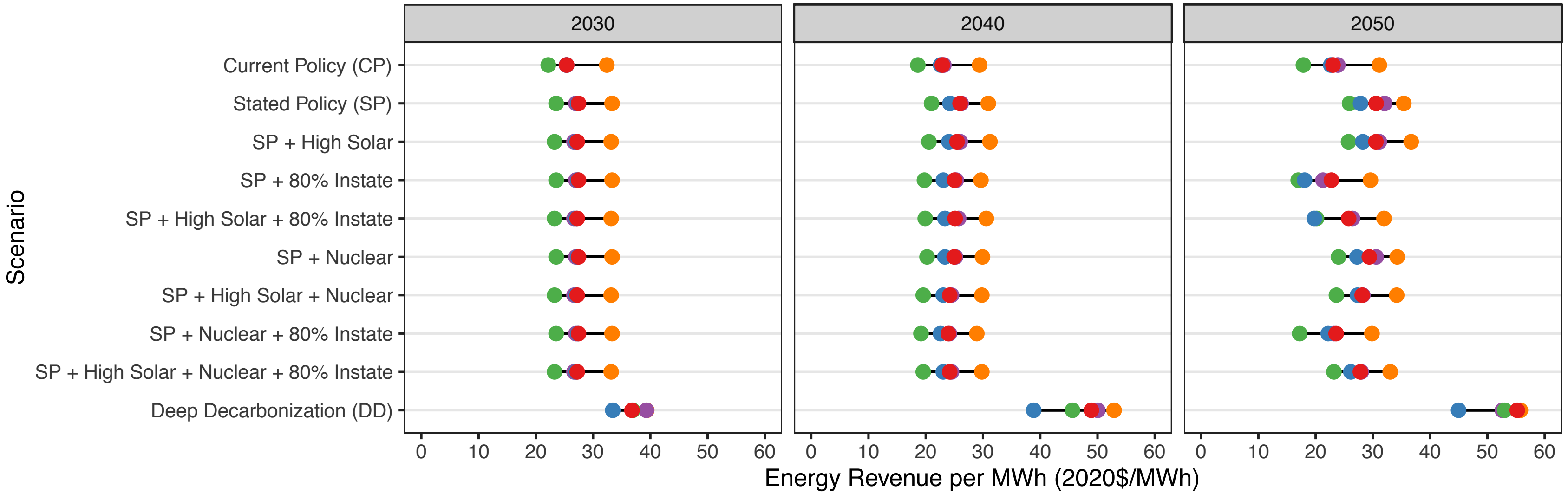
Summary of Sensitivity Results

- **CP vs SP and SP's variants:** Though exact numbers differ, the captured energy prices of NJ offshore wind and solar do not vary much across scenarios until 2050.
- **SP vs DD:** The deep decarbonization of PJM and its neighboring regions will significantly raise the captured energy prices of New Jersey offshore wind and solar due to impact of emissions limits on energy market prices.

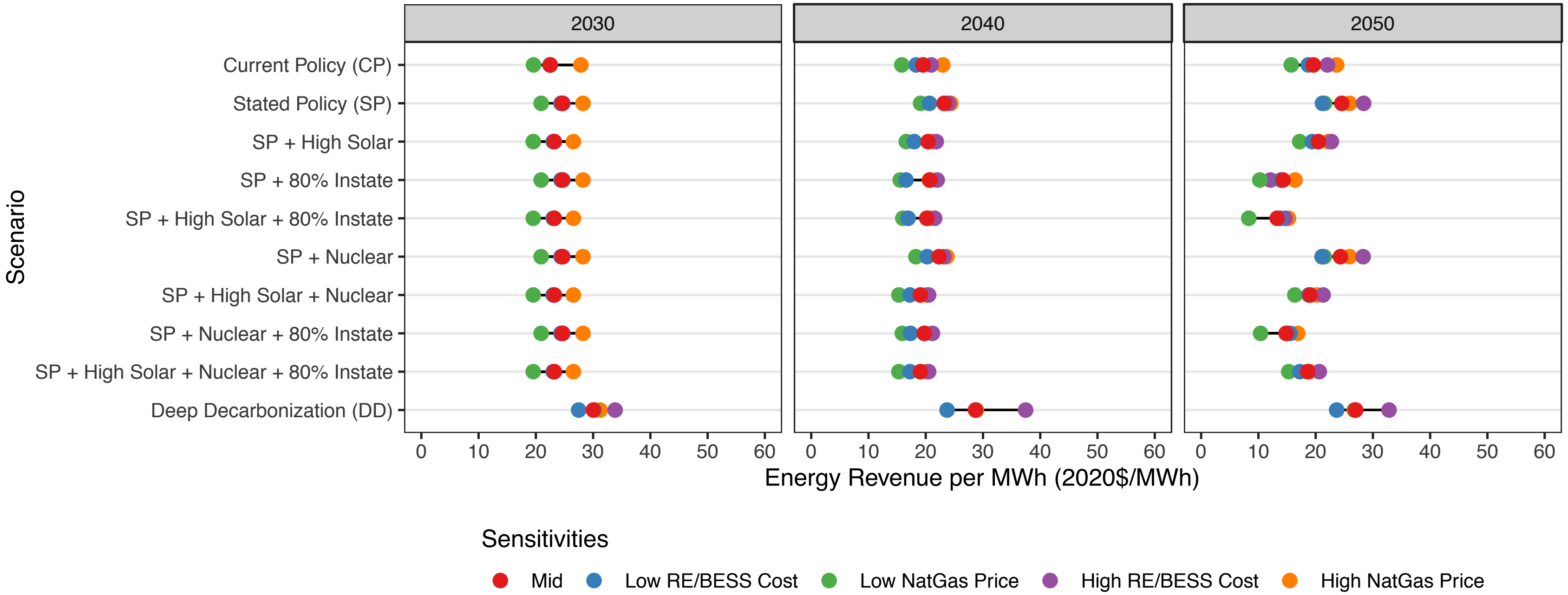
Note: This metric is calculated as the total annual energy revenue earned by a resource from electricity generation (equal to the sum of hourly zonal locational marginal price and hourly generation) divided by the total annual energy output from the resource.

Captured Energy Price in all cases

NJ offshore wind



NJ Solar



NJ Existing Nuclear Revenue/Cost Breakdown

Sensitivities – NJ Existing Nuclear Revenue/Cost Breakdown

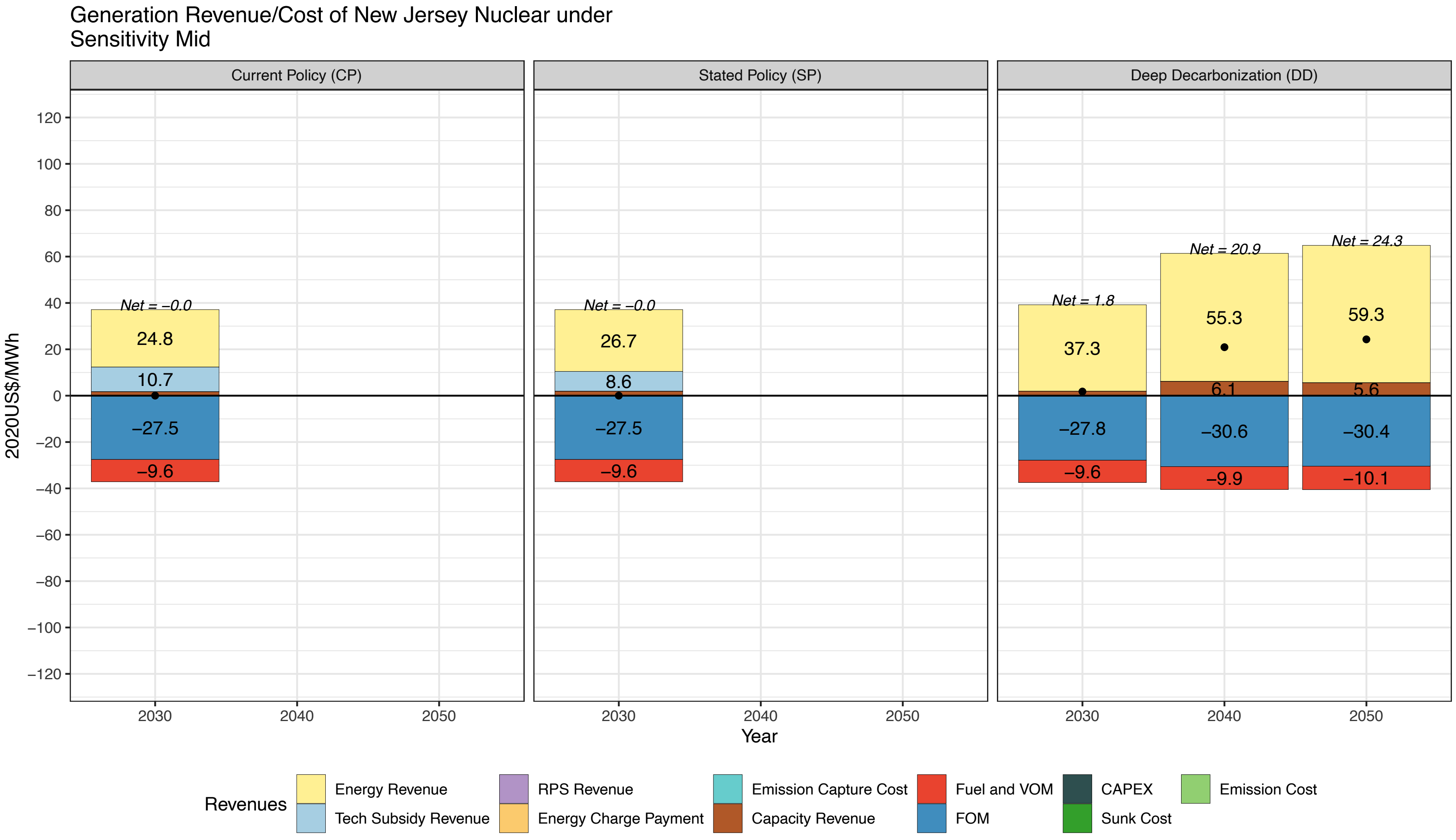
Summary of Sensitivity Results

If current zero emissions certificate (ZEC) payments expires, existing NJ nuclear units will not survive after 2030.

Keeping existing NJ nuclear capacity requires a declining subsidy over time.

NJ Existing Nuclear Revenue/Cost Breakdown in CP/SP/DD (Mid)

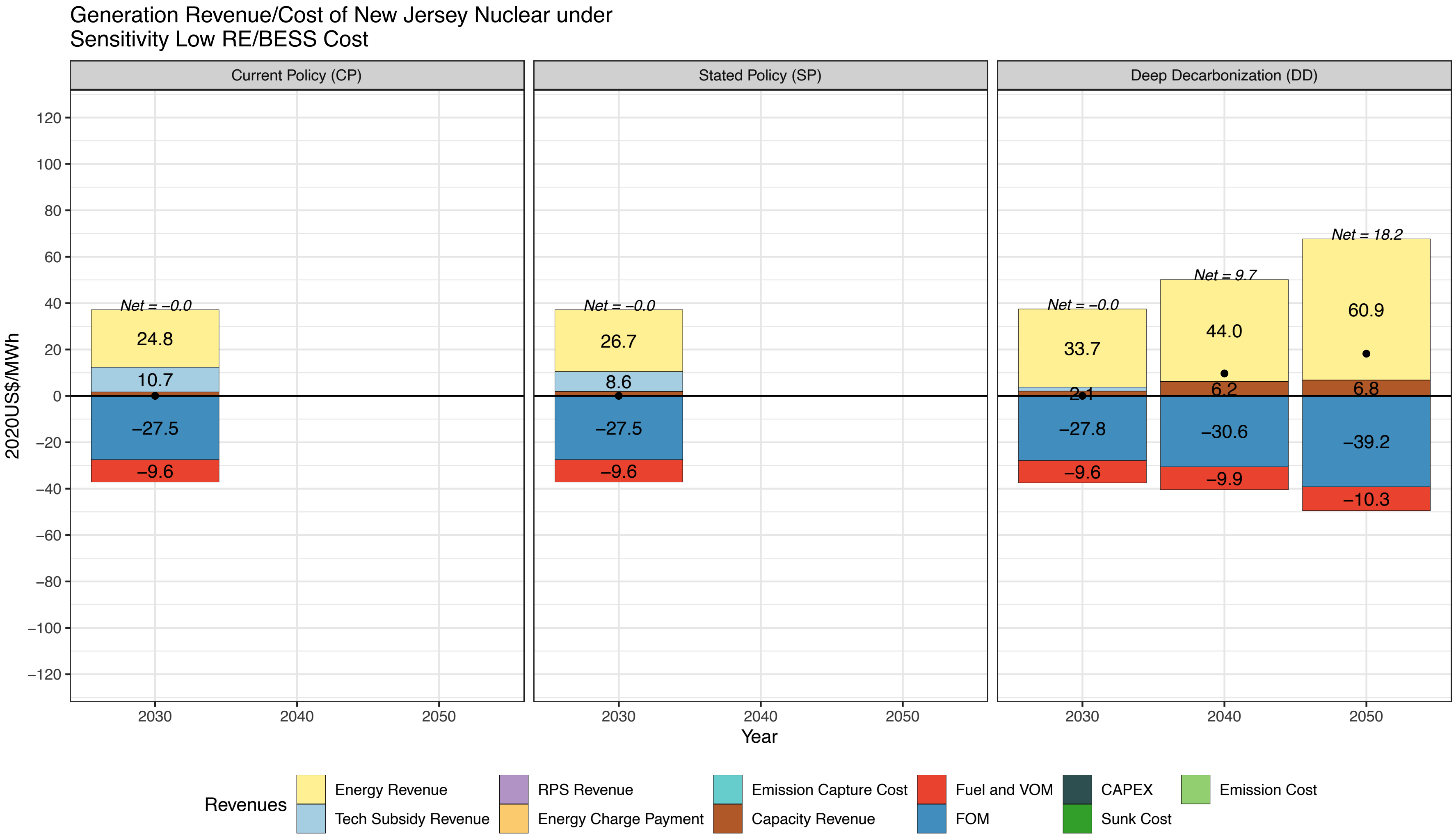
Note: the unit is $/MWh



Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in CP/SP/DD (Low RE/BESS Cost)

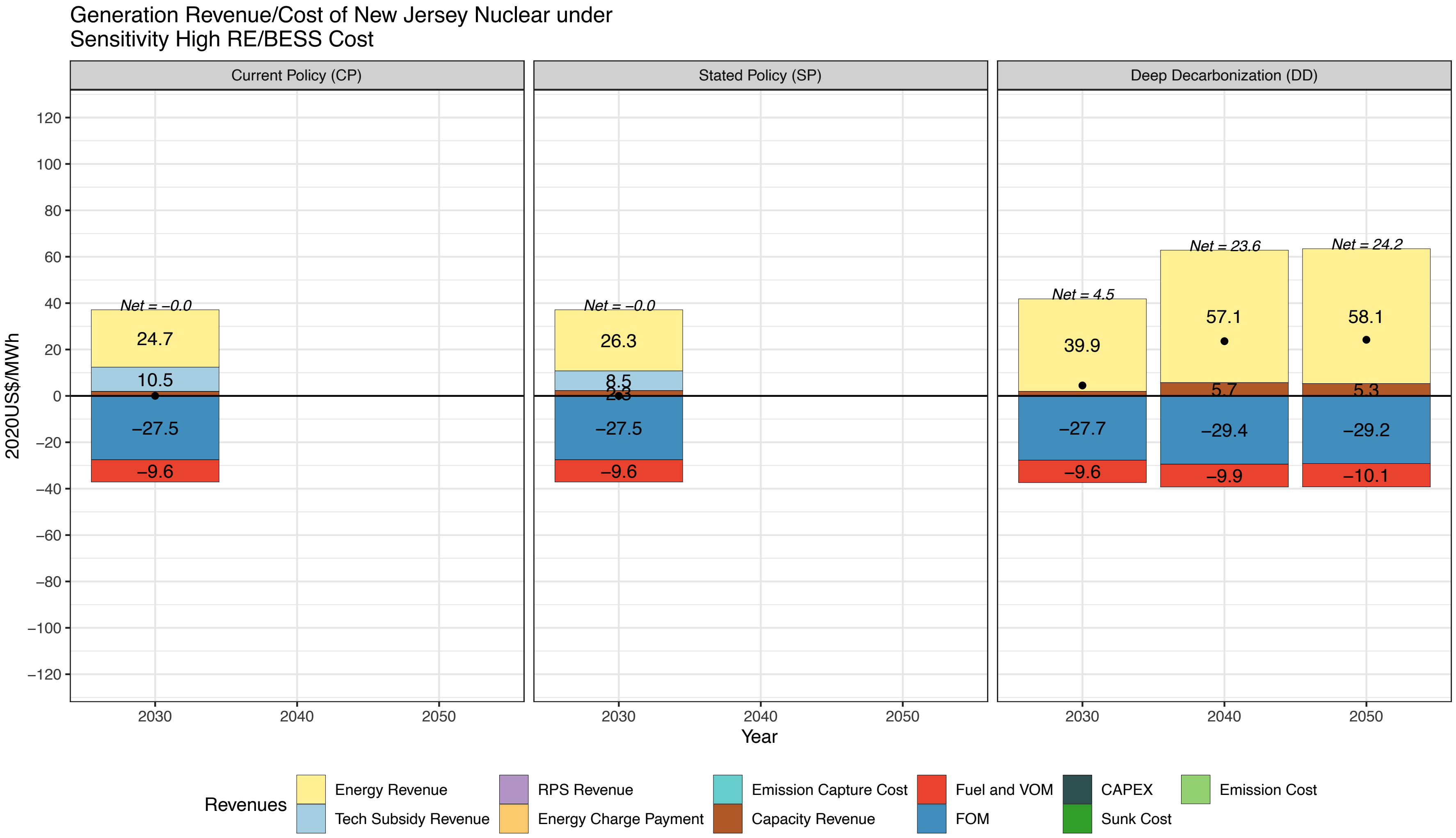
Note: the unit is $/MWh



Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in CP/SP/DD (High RE/BESS Cost)

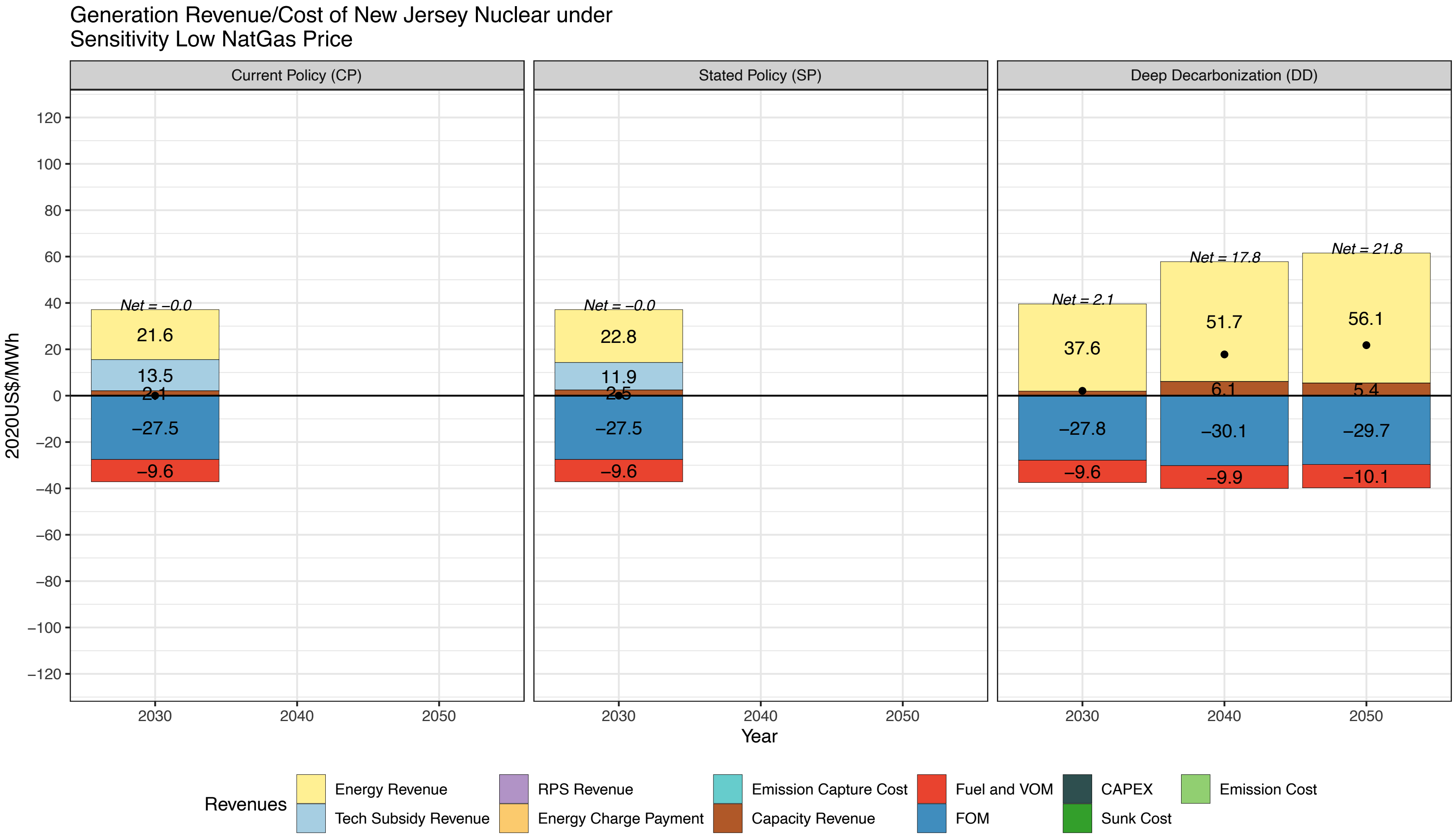
Note: the unit is $/MWh



Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a “risk premium” that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in CP/SP/DD (Low Nat. Gas Price)

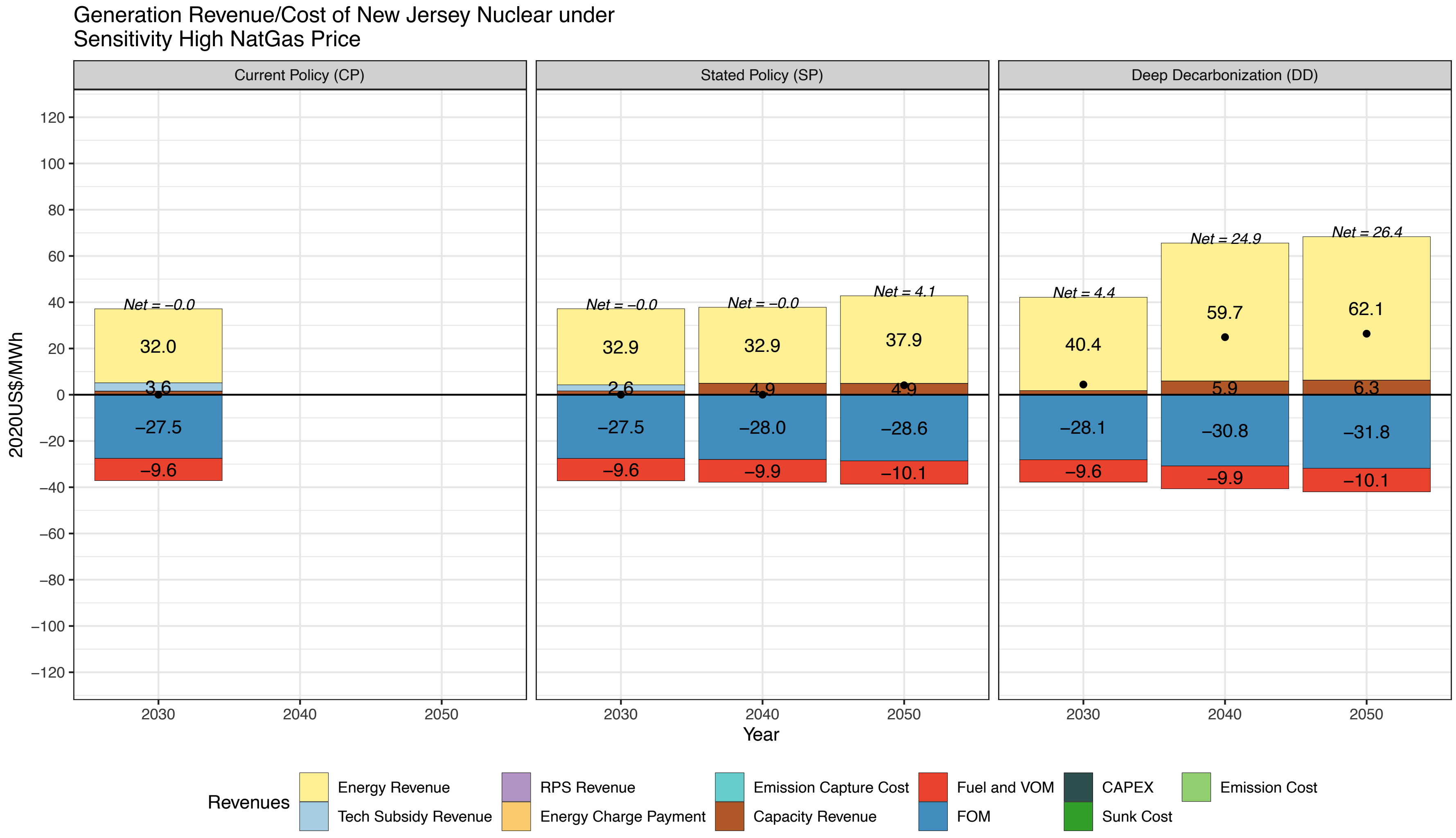
Note: the unit is $/MWh



Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in CP/SP/DD (High Nat. Gas Price)

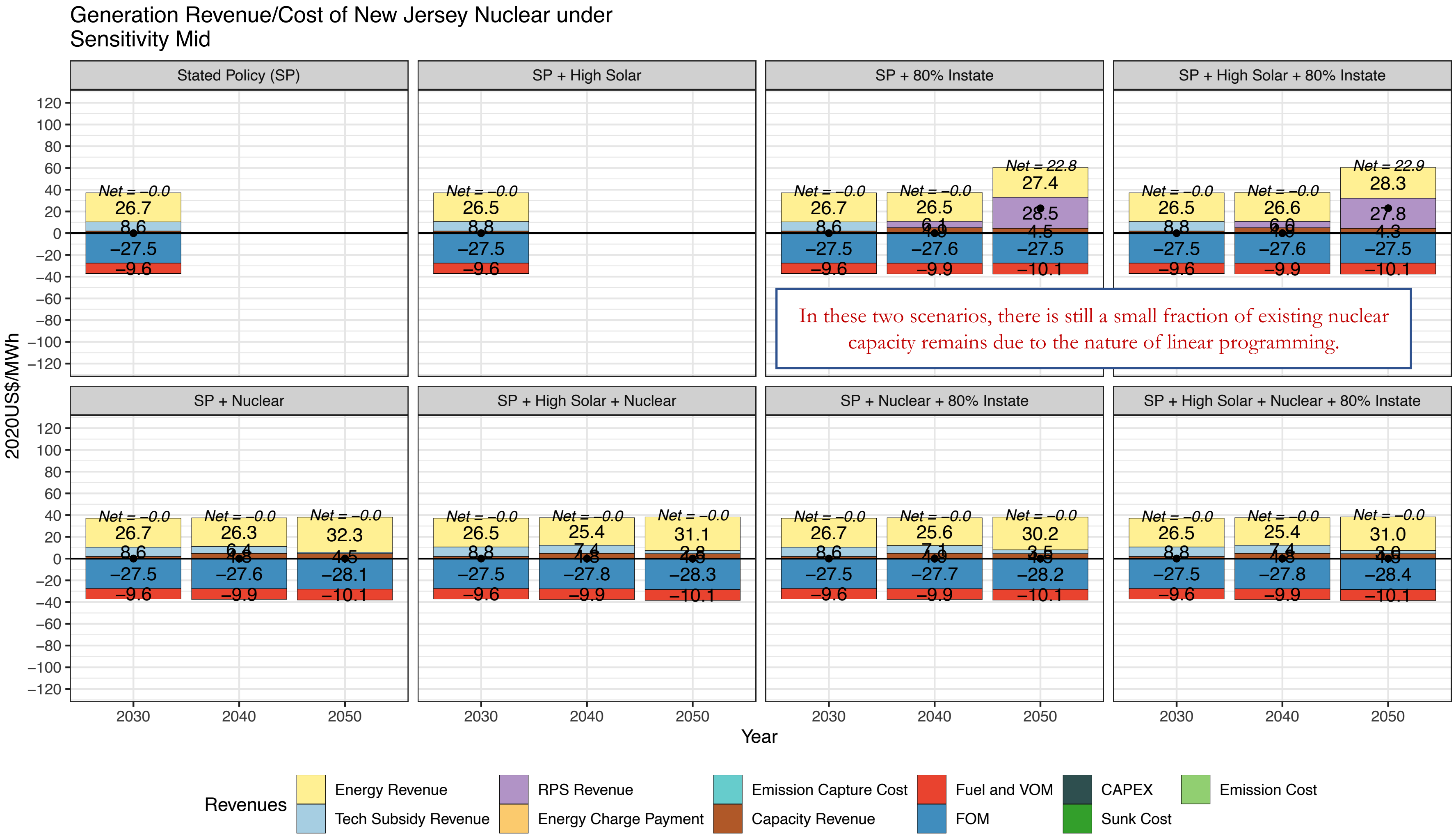
Note: the unit is $/MWh



Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in SP Policy Variants (Mid)

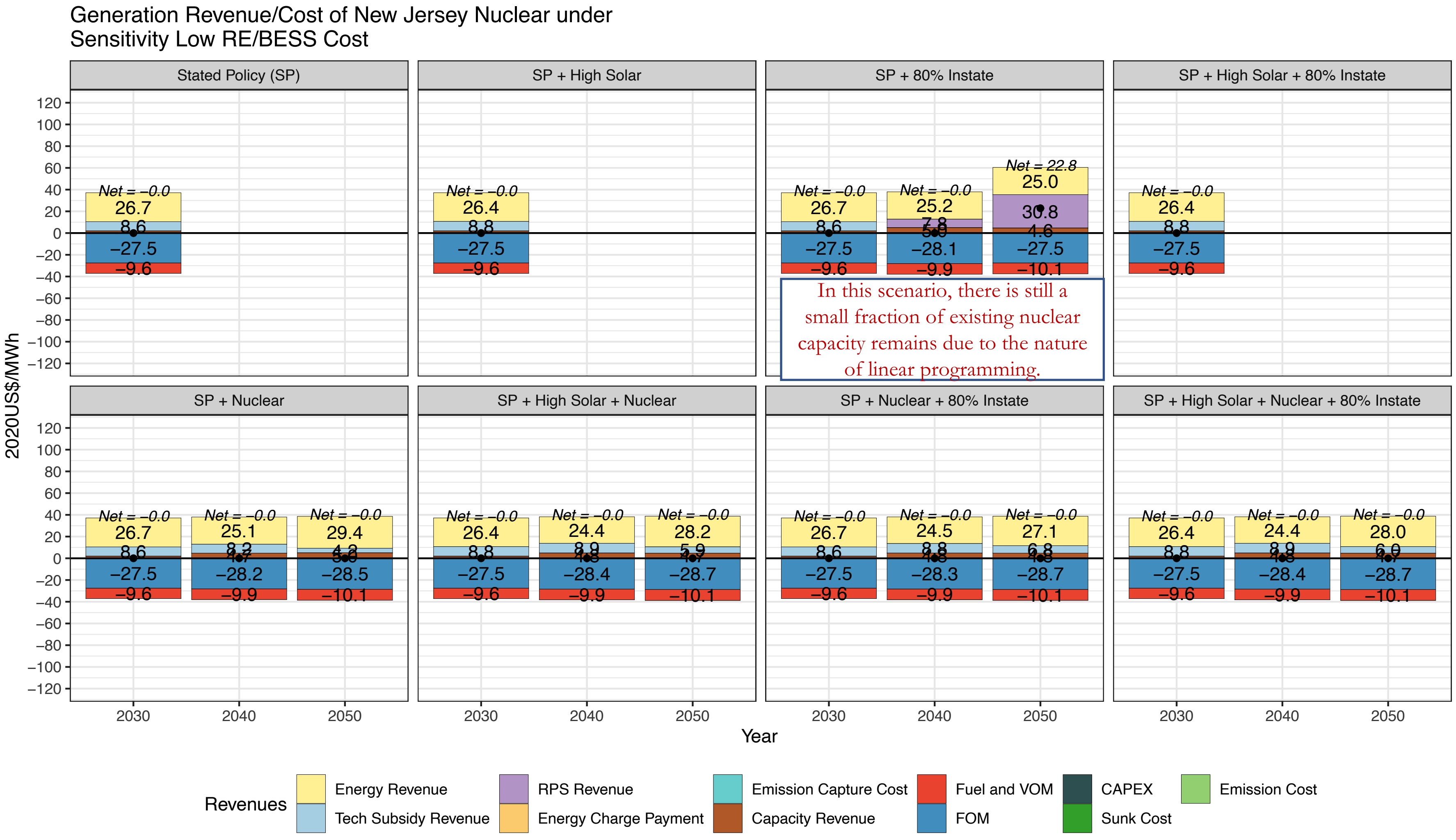
Note: the unit is $/MWh



Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in SP Policy Variants (Low RE/BESS Cost)

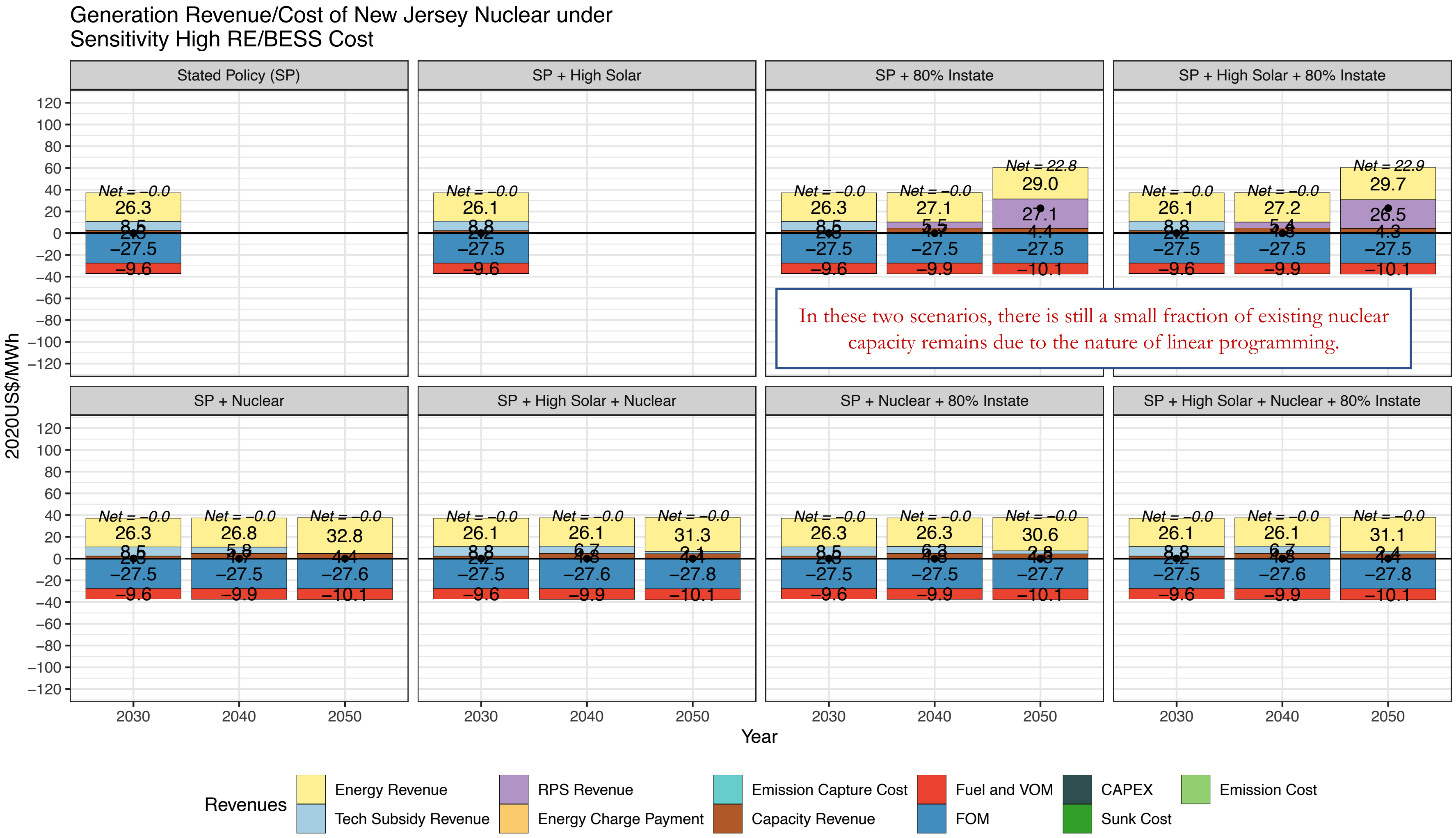
Note: the unit is $/MWh



Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in SP Policy Variants (High RE/BESS Cost)

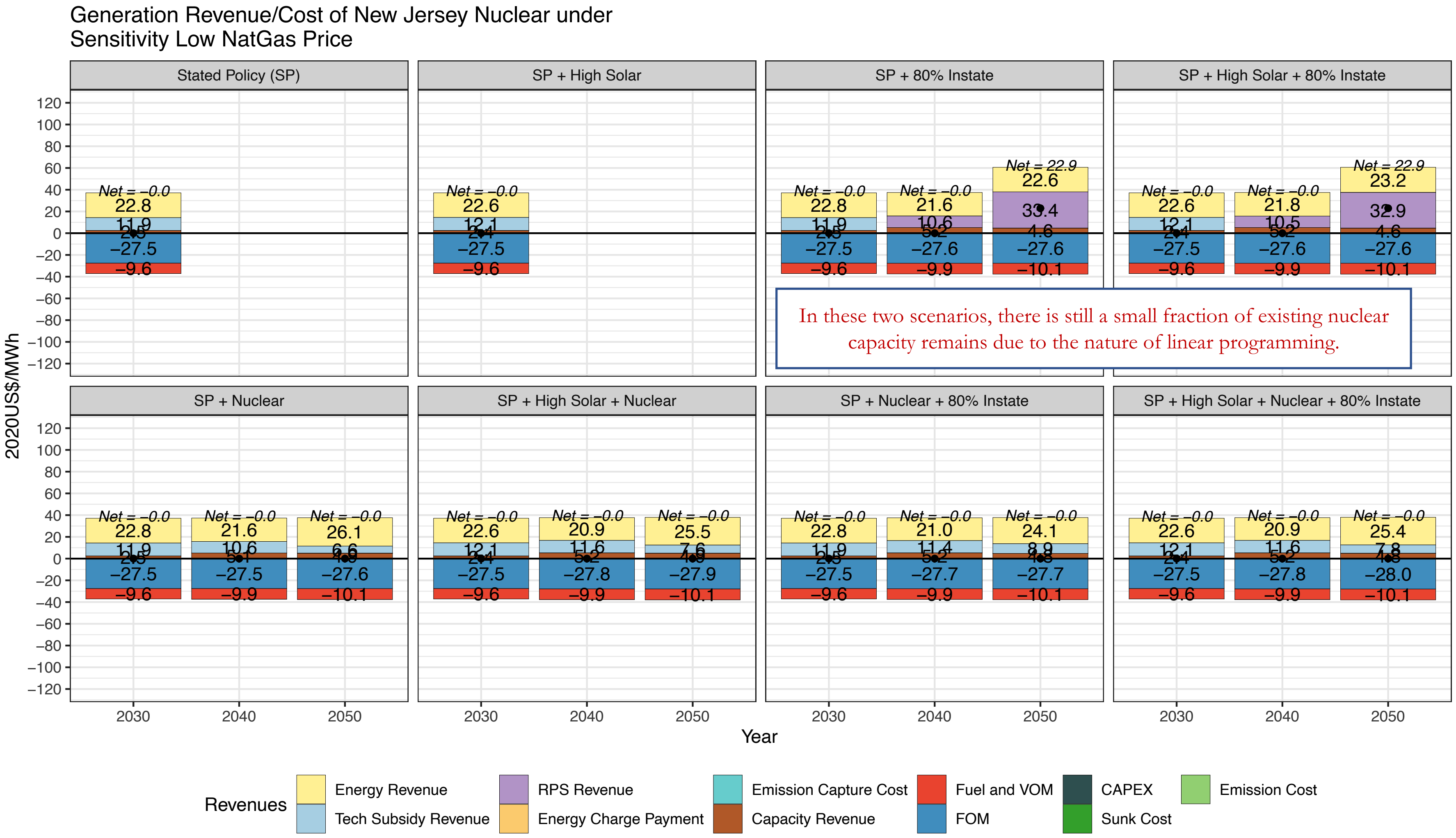
Note: the unit is $/MWh



Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in SP Policy Variants (Low Nat. Gas Price)

Note: the unit is $/MWh

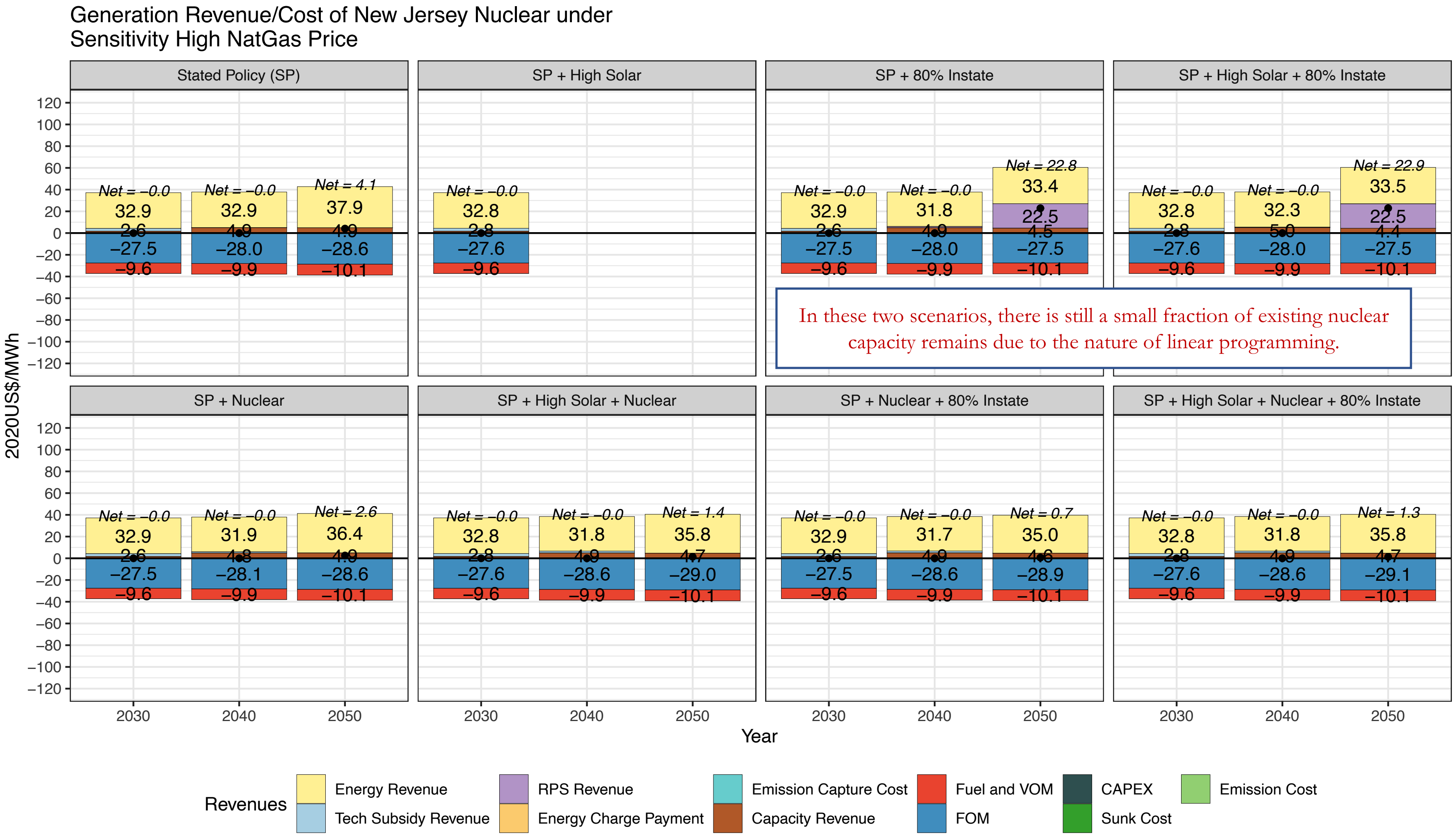


In these two scenarios, there is still a small fraction of existing nuclear capacity remains due to the nature of linear programming.

Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Existing Nuclear Revenue/Cost Breakdown in SP Policy Variants (High Nat. Gas Price)

Note: the unit is $/MWh

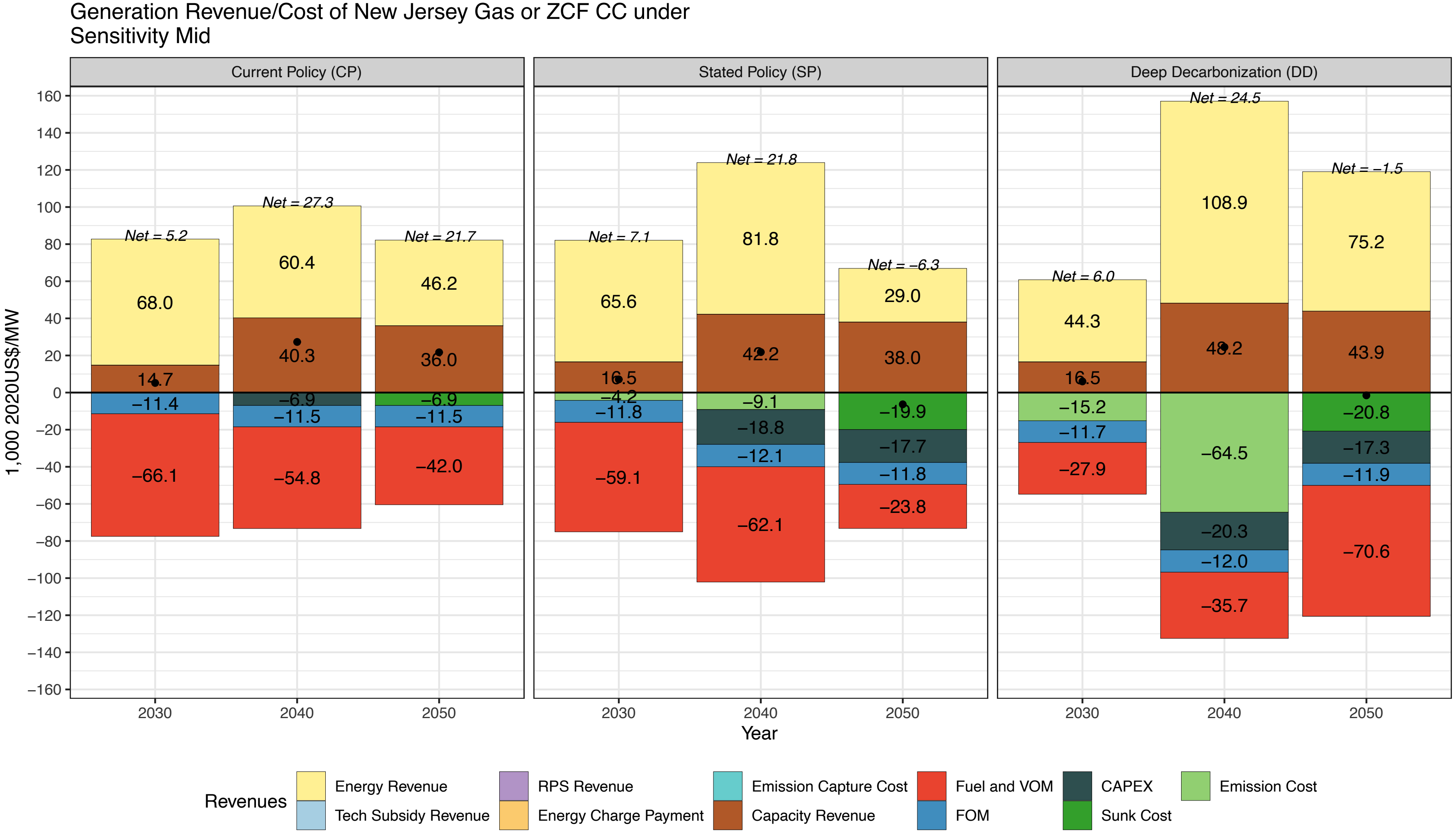


Note: GenX does not consider refueling outages so modeled nuclear capacity factor is ~100%. In reality, nuclear generators will earn less from the energy market due to refueling outages. Additionally, modeled fixed costs include average annual capital expenditures based on U.S. fleet-wide averages (varying based on reactor size and number of units at a site). Actual capital expenditures tend to be large, less frequent, and more uncertain, resulting in a "risk premium" that requires greater annual revenues than modeled herein in order for nuclear operators to cover the risk of unexpected capital expenditures.

NJ Combined Cycles Revenue/Cost Breakdown

NJ Combined Cycles Revenue/Cost Breakdown in CP/SP/DD (Mid)

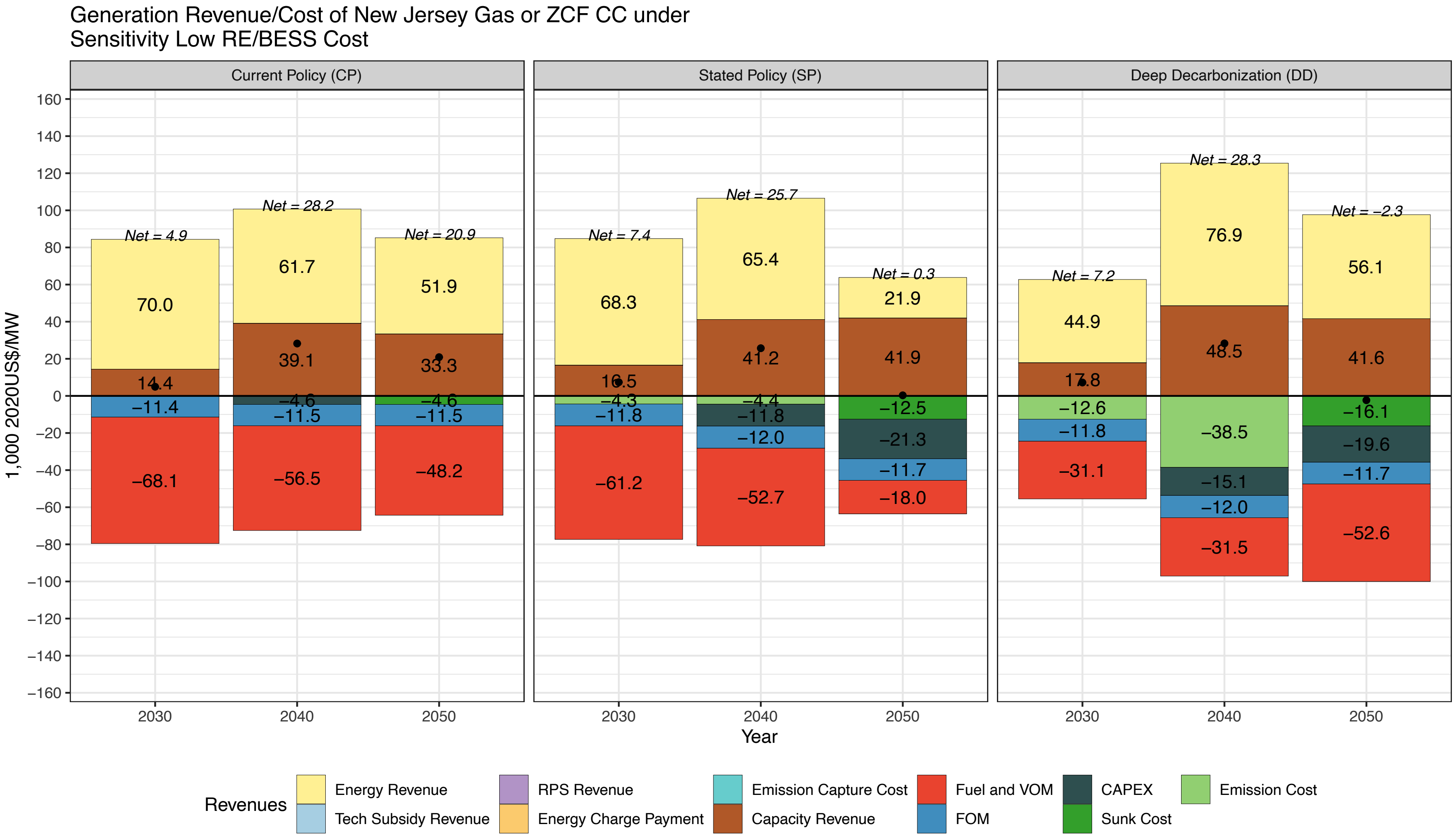
Note: the unit is 1000$/MW



Revenues and costs above reflect average of existing and newly expanded capacity. All newly built capacity in a given planning period receives zero net profit (due to equilibrium nature of expansion planning optimization model). Due to the myopic nature of the staged expansion model used in this study, resources may experience net negative revenues in subsequent planning periods if sunk costs are considered, but they will always earn sufficient revenue to cover ongoing fixed and variable costs. Note that for gas generators online in 2019, sunk costs are assumed to be fully recovered prior to 2030.

NJ Combined Cycles Revenue/Cost Breakdown in CP/SP/DD (Low RE/BESS Cost)

Note: the unit is 1000$/MW



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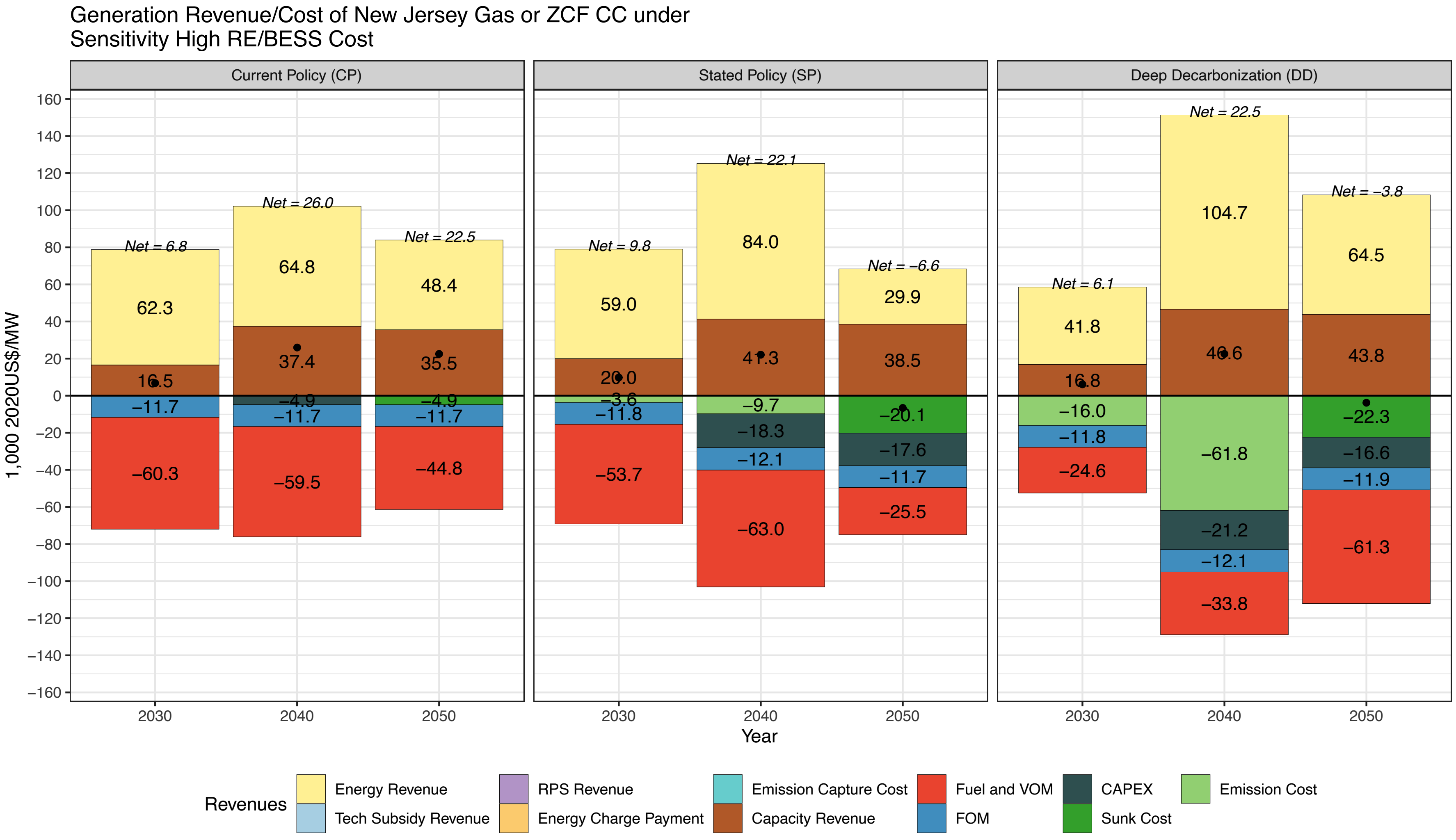
NJ Combined Cycles Revenue/Cost Breakdown in CP/SP/DD (High RE/BESS Cost)

Note: the unit is 1000$/MW



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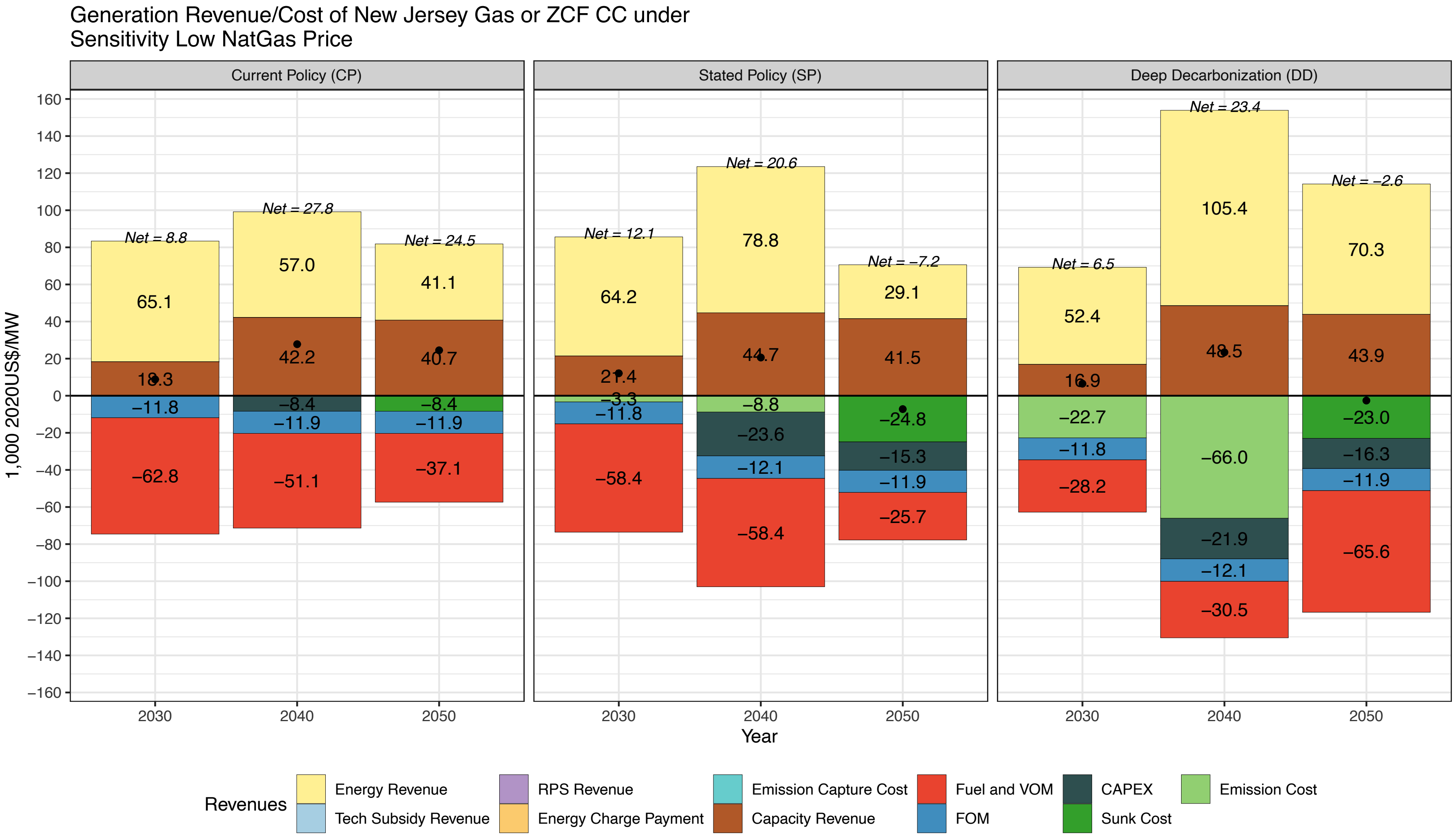
NJ Combined Cycles Revenue/Cost Breakdown in CP/SP/DD (Low Nat. Gas Price)

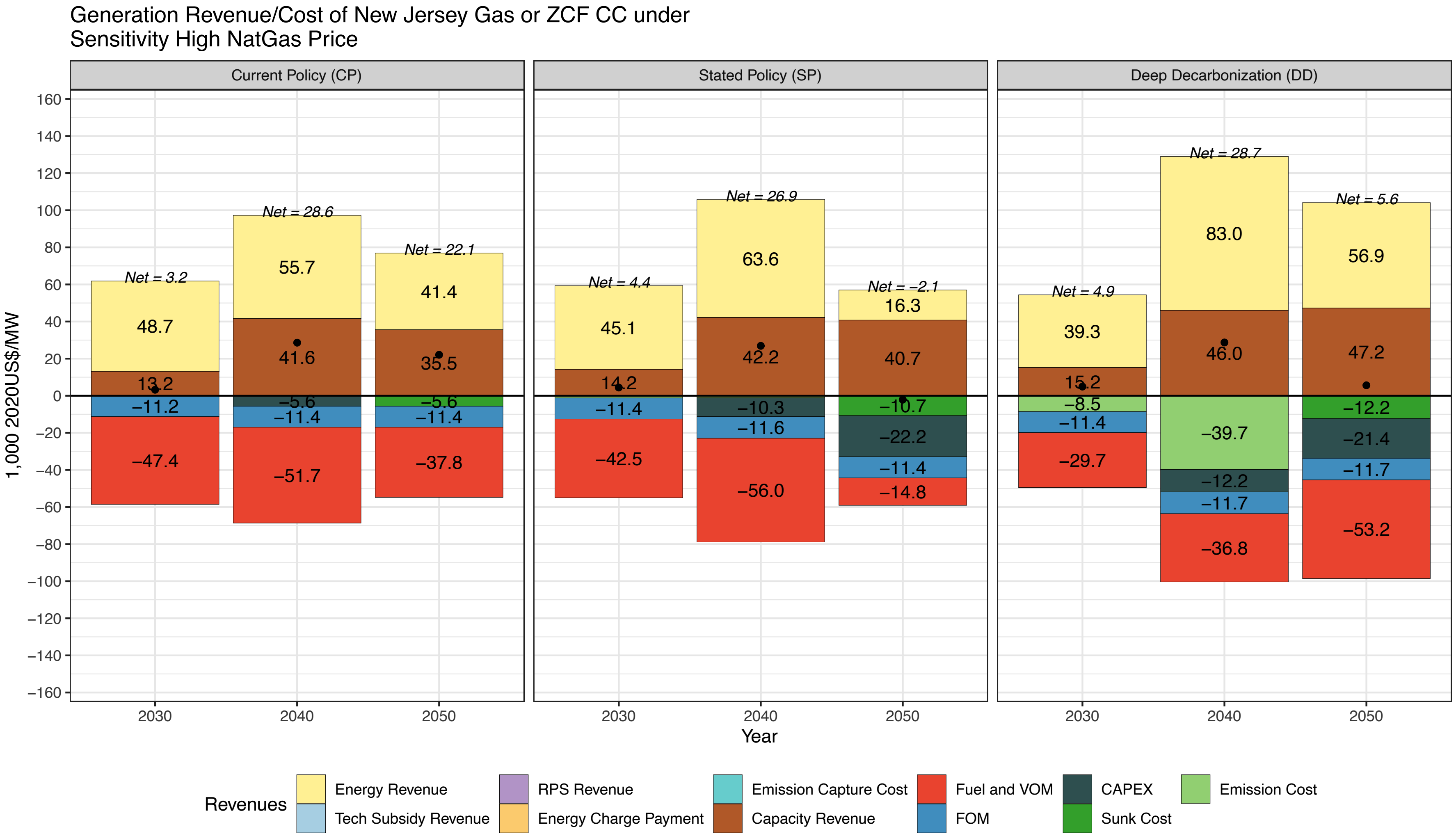
Note: the unit is 1000$/MW



Revenues and costs above reflect average of existing and newly expanded capacity. All newly built capacity in a given planning period receives zero net profit (due to equilibrium nature of expansion planning optimization model). Due to the myopic nature of the staged expansion model used in this study, resources may experience net negative revenues in subsequent planning periods if sunk costs are considered, but they will always earn sufficient revenue to cover ongoing fixed and variable costs. Note that for gas generators online in 2019, sunk costs are assumed to be fully recovered prior to 2030.

NJ Combined Cycles Revenue/Cost Breakdown in CP/SP/DD (High Nat. Gas Price)

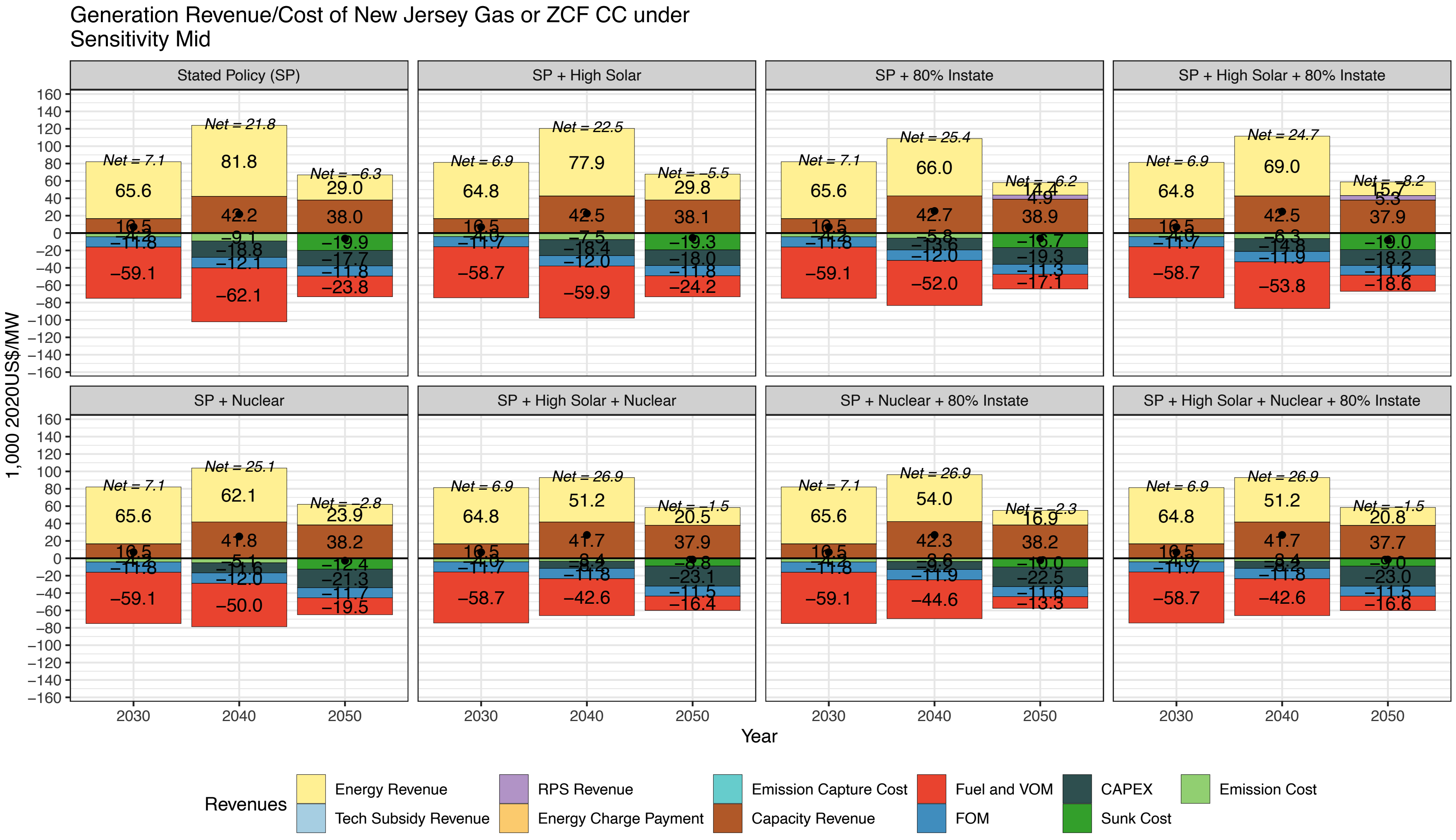
Note: the unit is 1000$/MW



Revenues and costs above reflect average of existing and newly expanded capacity. All newly built capacity in a given planning period receives zero net profit (due to equilibrium nature of expansion planning optimization model). Due to the myopic nature of the staged expansion model used in this study, resources may experience net negative revenues in subsequent planning periods if sunk costs are considered, but they will always earn sufficient revenue to cover ongoing fixed and variable costs. Note that for gas generators online in 2019, sunk costs are assumed to be fully recovered prior to 2030.

NJ Combined Cycles Revenue/Cost Breakdown in SP Policy Variants (Mid)

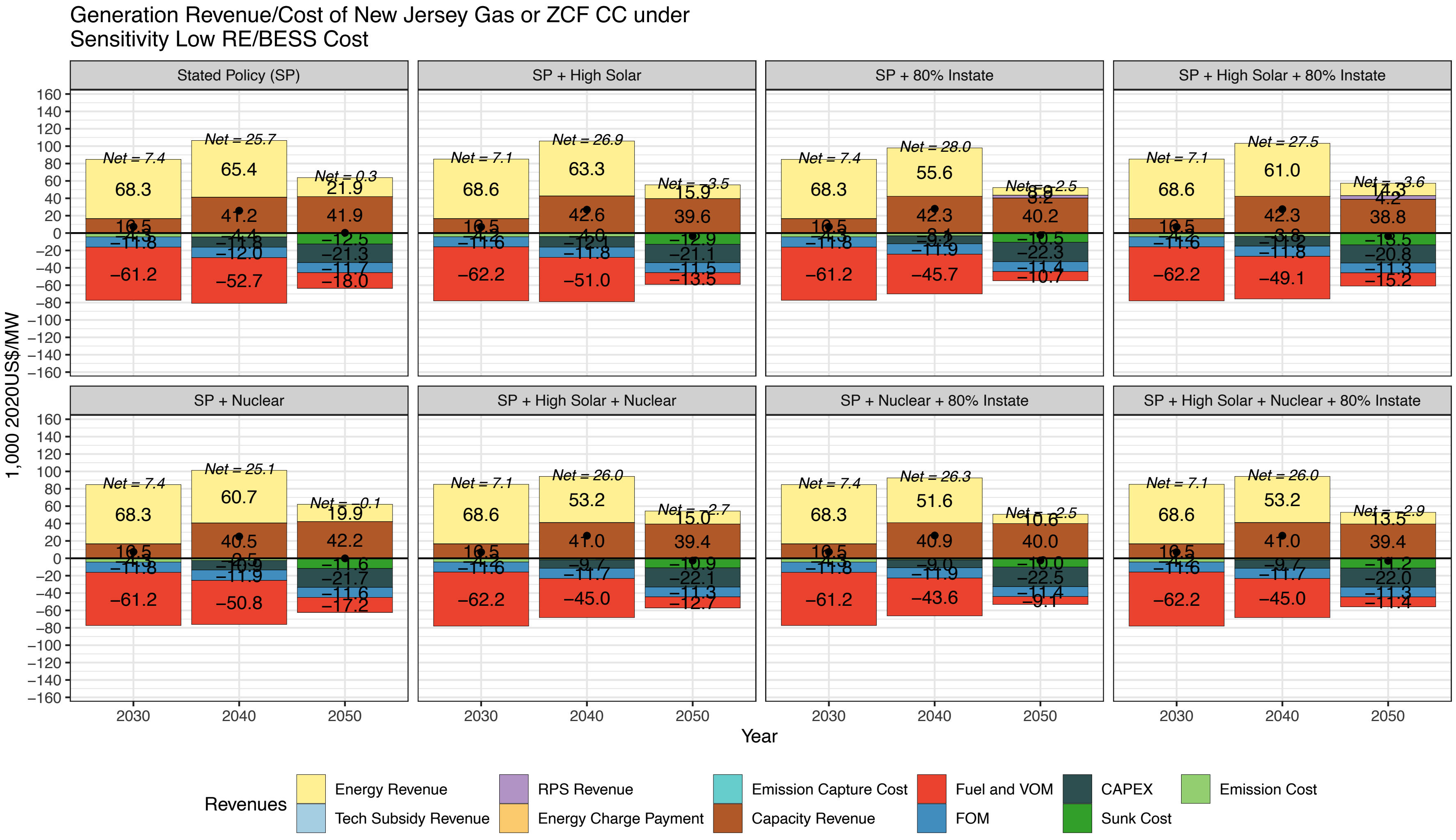
Note: the unit is 1000$/MW



Revenues and costs above reflect average of existing and newly expanded capacity. All newly built capacity in a given planning period receives zero net profit (due to equilibrium nature of expansion planning optimization model). Due to the myopic nature of the staged expansion model used in this study, resources may experience net negative revenues in subsequent planning periods if sunk costs are considered, but they will always earn sufficient revenue to cover ongoing fixed and variable costs. Note that for gas generators online in 2019, sunk costs are assumed to be fully recovered prior to 2030.

NJ Combined Cycles Revenue/Cost Breakdown in SP Policy Variants (Low RE/BESS Cost)

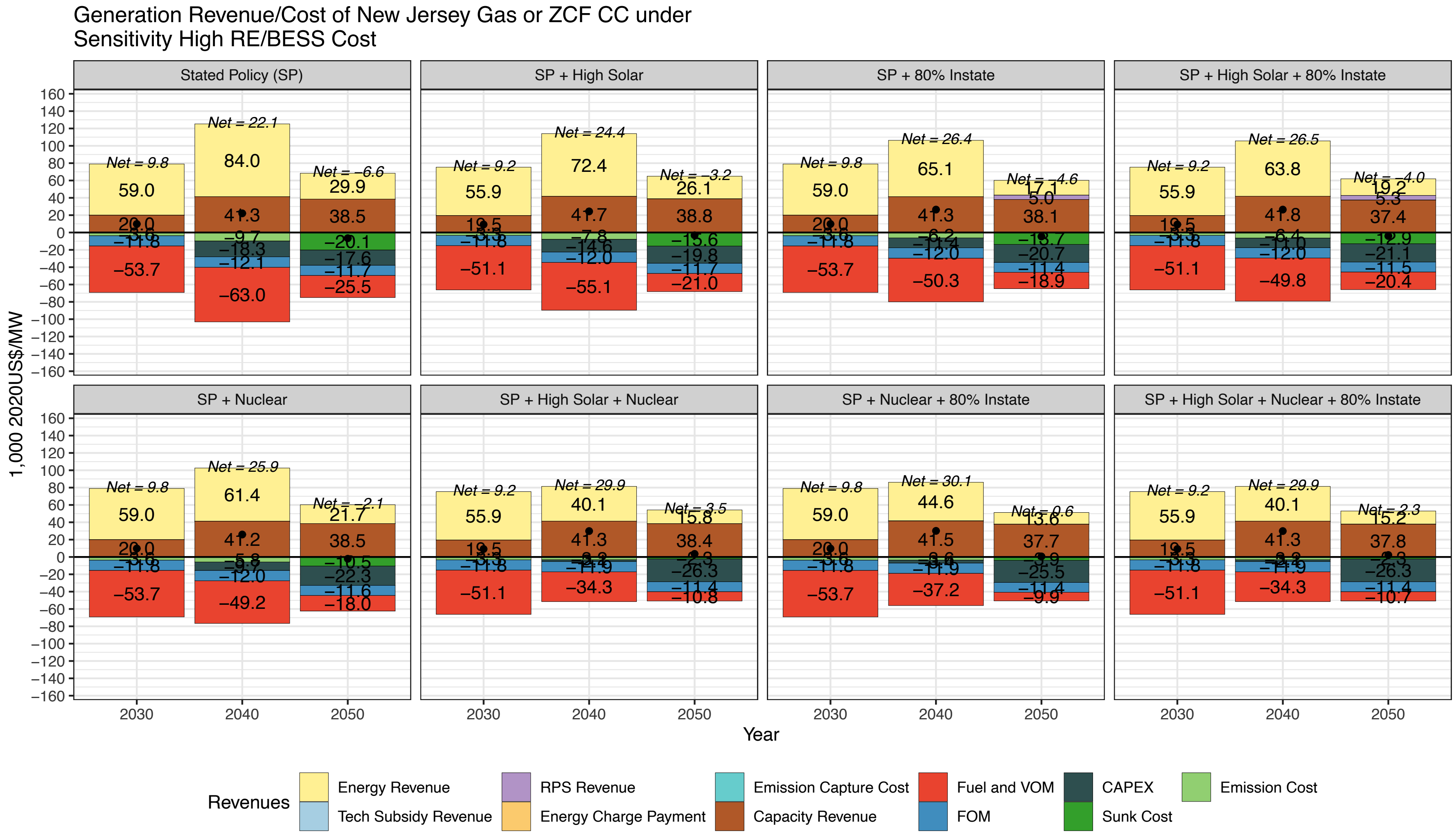
Note: the unit is 1000$/MW



Revenues and costs above reflect average of existing and newly expanded capacity. All newly built capacity in a given planning period receives zero net profit (due to equilibrium nature of expansion planning optimization model). Due to the myopic nature of the staged expansion model used in this study, resources may experience net negative revenues in subsequent planning periods if sunk costs are considered, but they will always earn sufficient revenue to cover ongoing fixed and variable costs. Note that for gas generators online in 2019, sunk costs are assumed to be fully recovered prior to 2030.

NJ Combined Cycles Revenue/Cost Breakdown in SP Policy Variants (High RE/BESS Cost)

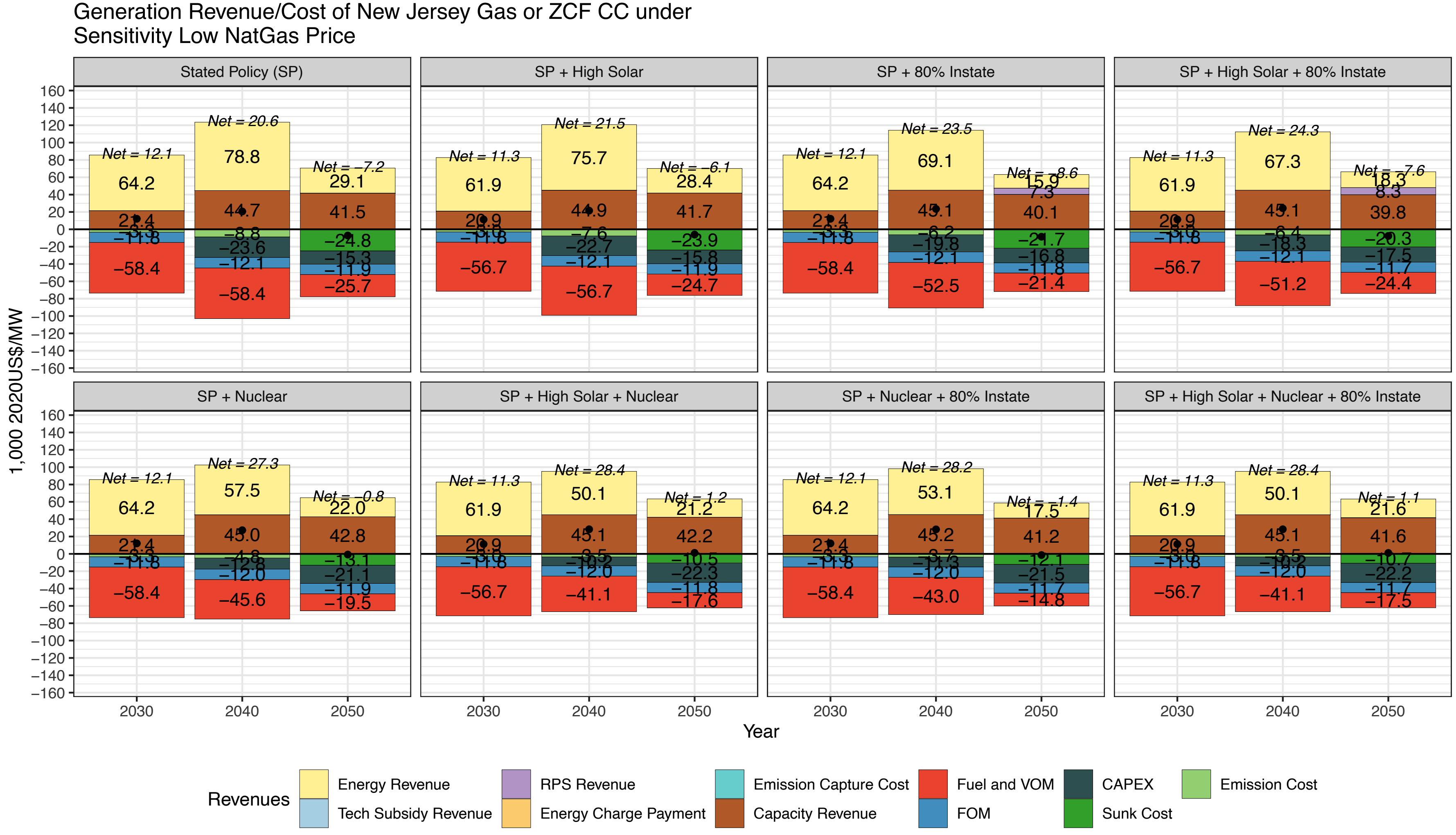
Note: the unit is 1000$/MW



Revenues and costs above reflect average of existing and newly expanded capacity. All newly built capacity in a given planning period receives zero net profit (due to equilibrium nature of expansion planning optimization model). Due to the myopic nature of the staged expansion model used in this study, resources may experience net negative revenues in subsequent planning periods if sunk costs are considered, but they will always earn sufficient revenue to cover ongoing fixed and variable costs. Note that for gas generators online in 2019, sunk costs are assumed to be fully recovered prior to 2030.

NJ Combined Cycles Revenue/Cost Breakdown in SP Policy Variants (Low Nat. Gas Price)

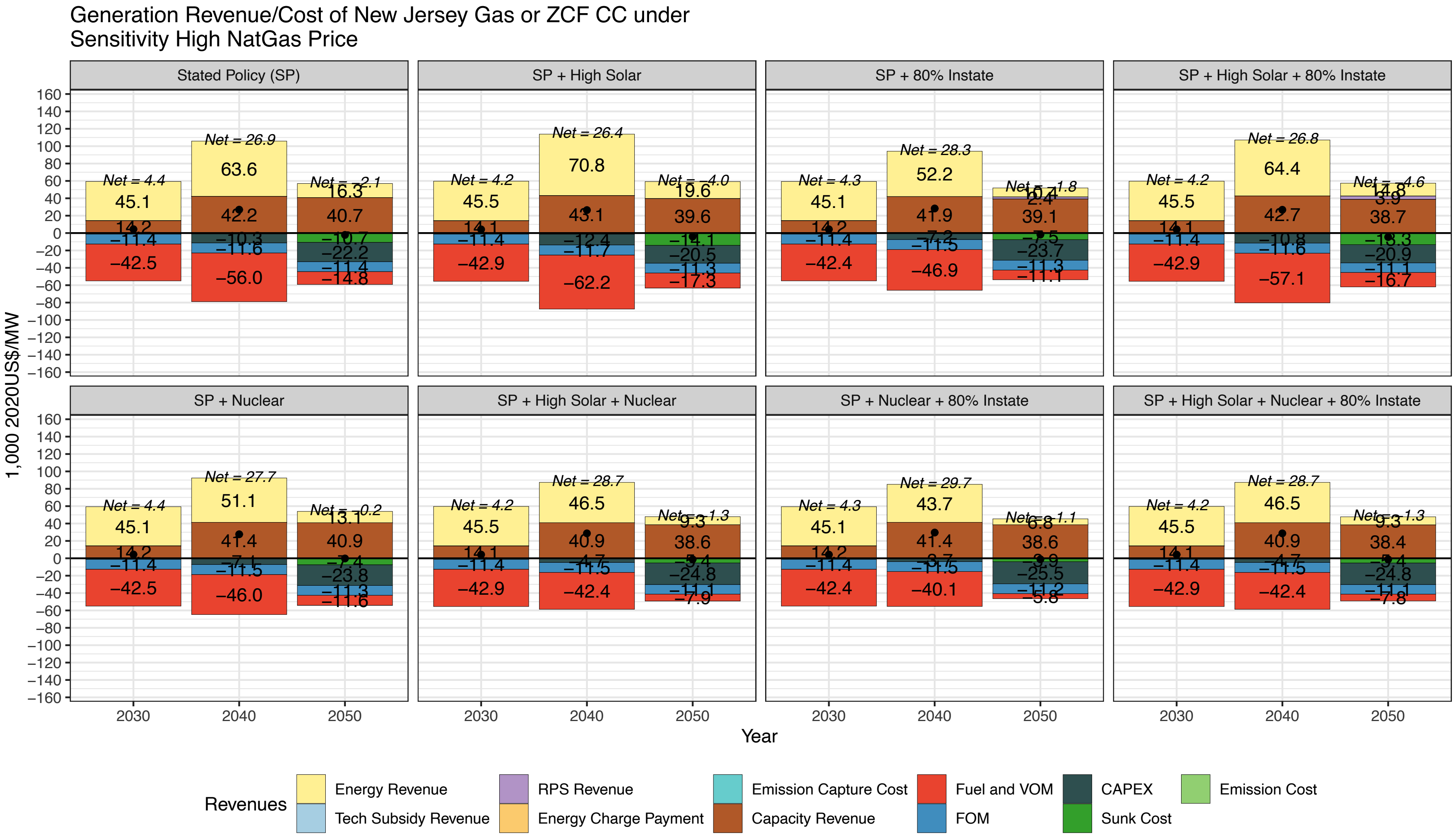
Note: the unit is 1000$/MW



Revenues and costs above reflect average of existing and newly expanded capacity. All newly built capacity in a given planning period receives zero net profit (due to equilibrium nature of expansion planning optimization model). Due to the myopic nature of the staged expansion model used in this study, resources may experience net negative revenues in subsequent planning periods if sunk costs are considered, but they will always earn sufficient revenue to cover ongoing fixed and variable costs. Note that for gas generators online in 2019, sunk costs are assumed to be fully recovered prior to 2030.

NJ Combined Cycles Revenue/Cost Breakdown in SP Policy Variants (High Nat. Gas Price)

Note: the unit is 1000$/MW



Revenues and costs above reflect average of existing and newly expanded capacity. All newly built capacity in a given planning period receives zero net profit (due to equilibrium nature of expansion planning optimization model). Due to the myopic nature of the staged expansion model used in this study, resources may experience net negative revenues in subsequent planning periods if sunk costs are considered, but they will always earn sufficient revenue to cover ongoing fixed and variable costs. Note that for gas generators online in 2019, sunk costs are assumed to be fully recovered prior to 2030.

Technology-specific Subsidies

Sensitivities – Technology-specific Subsidies

Interpreting the calculated subsidy values:

- The calculated **Total Subsidy** reported in this section includes revenues from Class I renewable energy credits, clean energy credits for state CES (in Stated Policies), in-state renewable/clean energy credit (if 80% in-state requirement is established), and technology-specific subsidies, e.g., additional specific supports for offshore wind and ZEC payments for nuclear.
- The **DG subsidy** reported here only applies for new DG solar built after 2022 and differs from the legacy SREC program and TREC of New Jersey. This subsidy is calculated as the remaining revenue requirement to cover the cost of new NJ DG solar installed in that planning period, that is, the subsidy is equal to the levelized cost of energy for incremental DG solar capacity minus energy cost-savings to LSEs from net-load reductions from DG solar generation. The value of avoided energy costs is assumed to be transferred to DG customers via retail rate design. Because DG solar is also eligible for class I RPS policy and state CES (in Stated Policies), the DG subsidy calculated here is inclusive of the value of class I RECs or contributions to CES requirements.

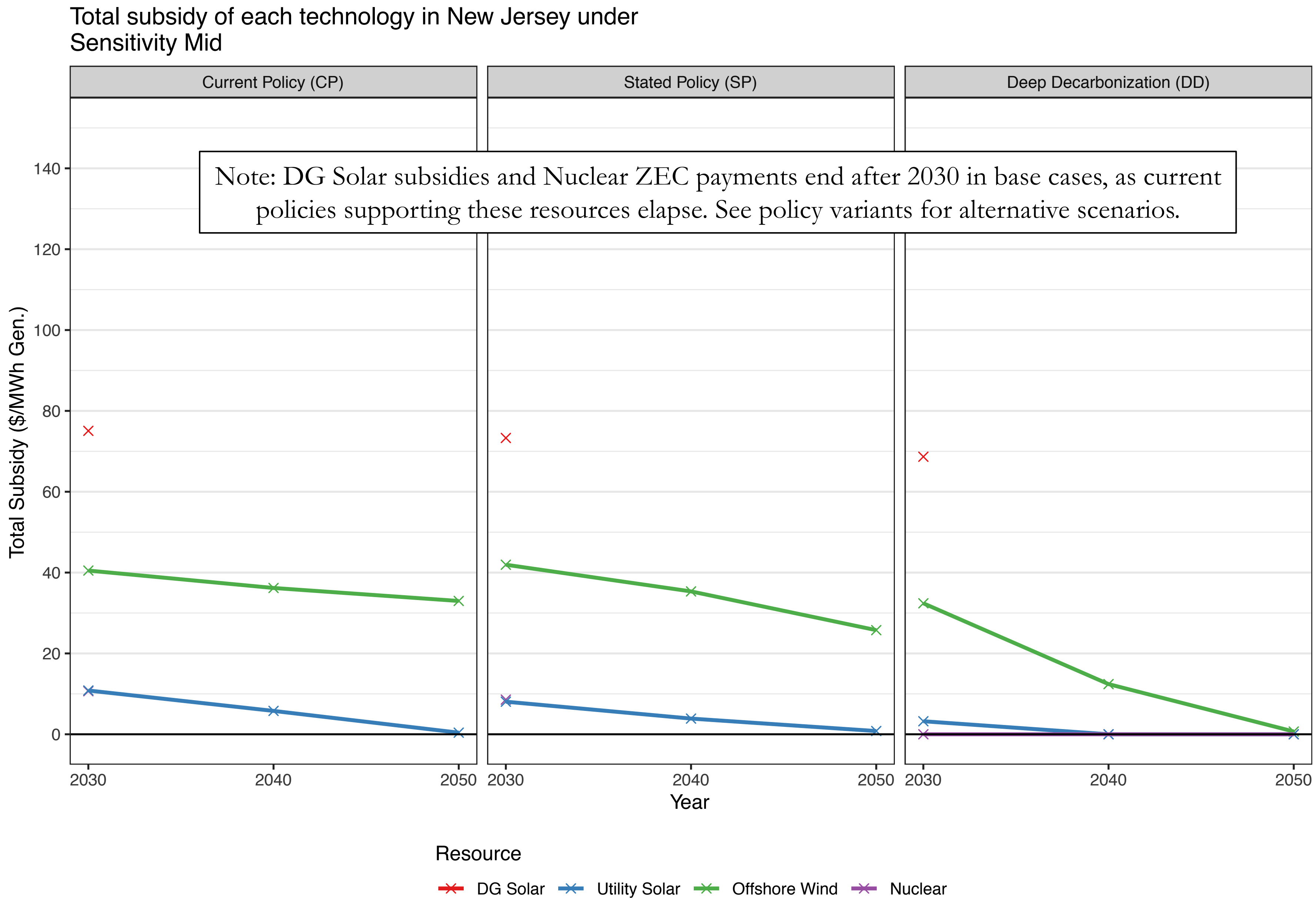
  Important notes:

  - **DG solar subsidy estimates do not account for net impacts (costs or benefits) for distribution networks.** Impacts on distribution networks are not considered in this study.
  - Additionally, **we apply a 'no-rent' assumption here**, with the subsidy value exactly covering the net revenue requirements of DG owners. If there is a net rent transfer from LSE (DG solar credit payer) to the DG owner, the DG subsidy cost paid by the LSEs will be higher than calculated herein.
  - Credit for **avoided transmission or capacity reserve requirement costs are not calculated** for DG solar. If these values are computed and transferred via retail rates, required subsidy payments could be lower than computed here.
  - See "Appendix – Distributed Solar Cost" for additional discussion.

Summary of Sensitivity Results

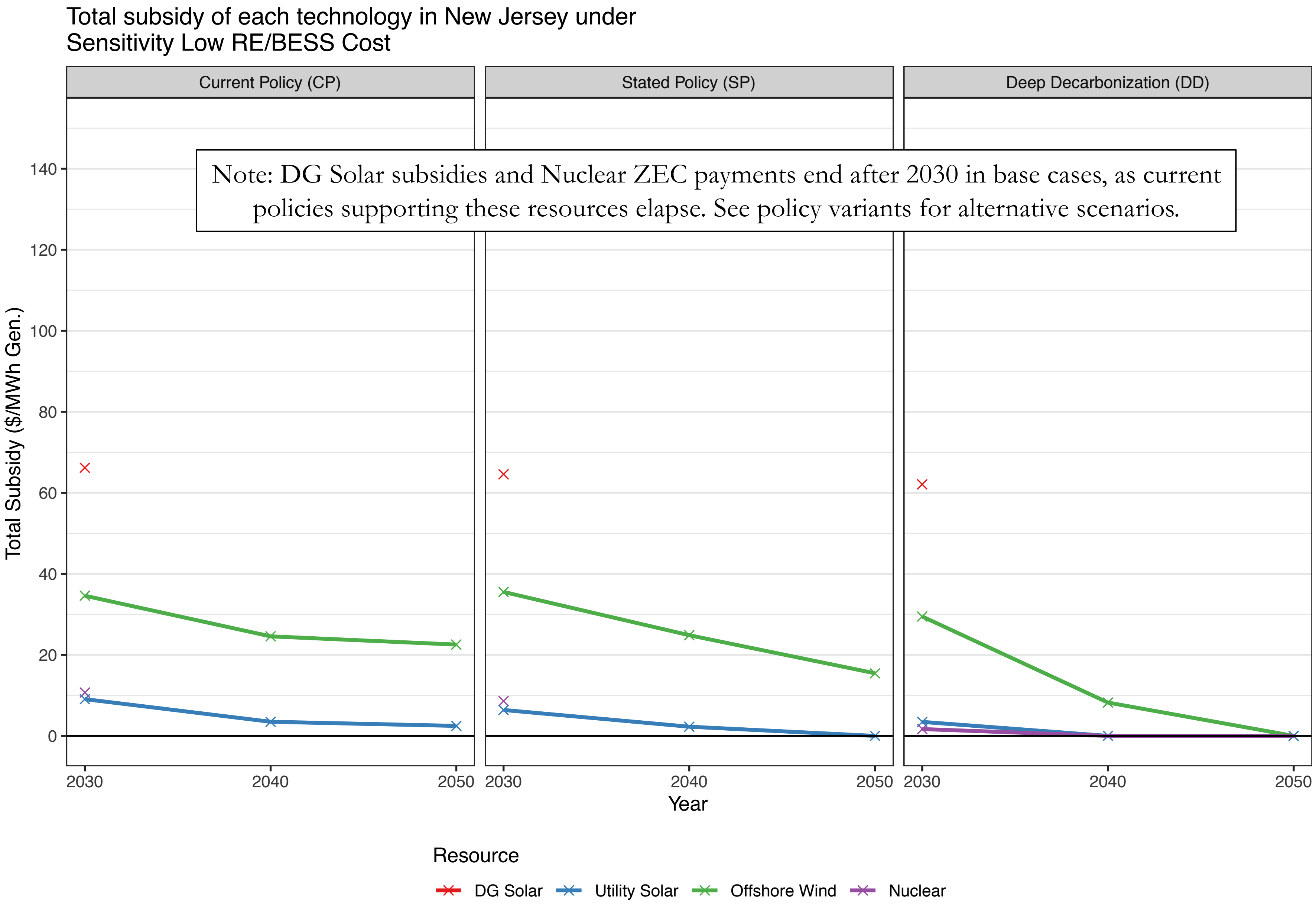
- **CP vs SP and SP variants:**
    - The **subsidies needed for distributed solar are significantly higher than the offshore wind**;
    - **Utility solar requires the lowest subsidy of all renewable options**, which only includes Class I RECs.
    - **The exact level of subsidy strongly varies depending on the sensitivities** of the capital cost of renewable energy: the higher the cost, the higher the needed subsidy. The natural gas price also affects subsidy levels, but to a less extent.
    - **Subsidies required to retain nuclear power (in cases that do so) are on par or cheaper than subsidy required for utility-scale solar**, the lowest cost renewable option.
- **SP vs DD:** If all states in PJM (and neighbors) pursue deep decarbonization goals, energy prices are higher (reflecting a modeled carbon constraint) and thus, required subsidies for NJ clean resources are lower than in SP.

Technology-specific Subsidies (CP/SP/DD) – (Medium)



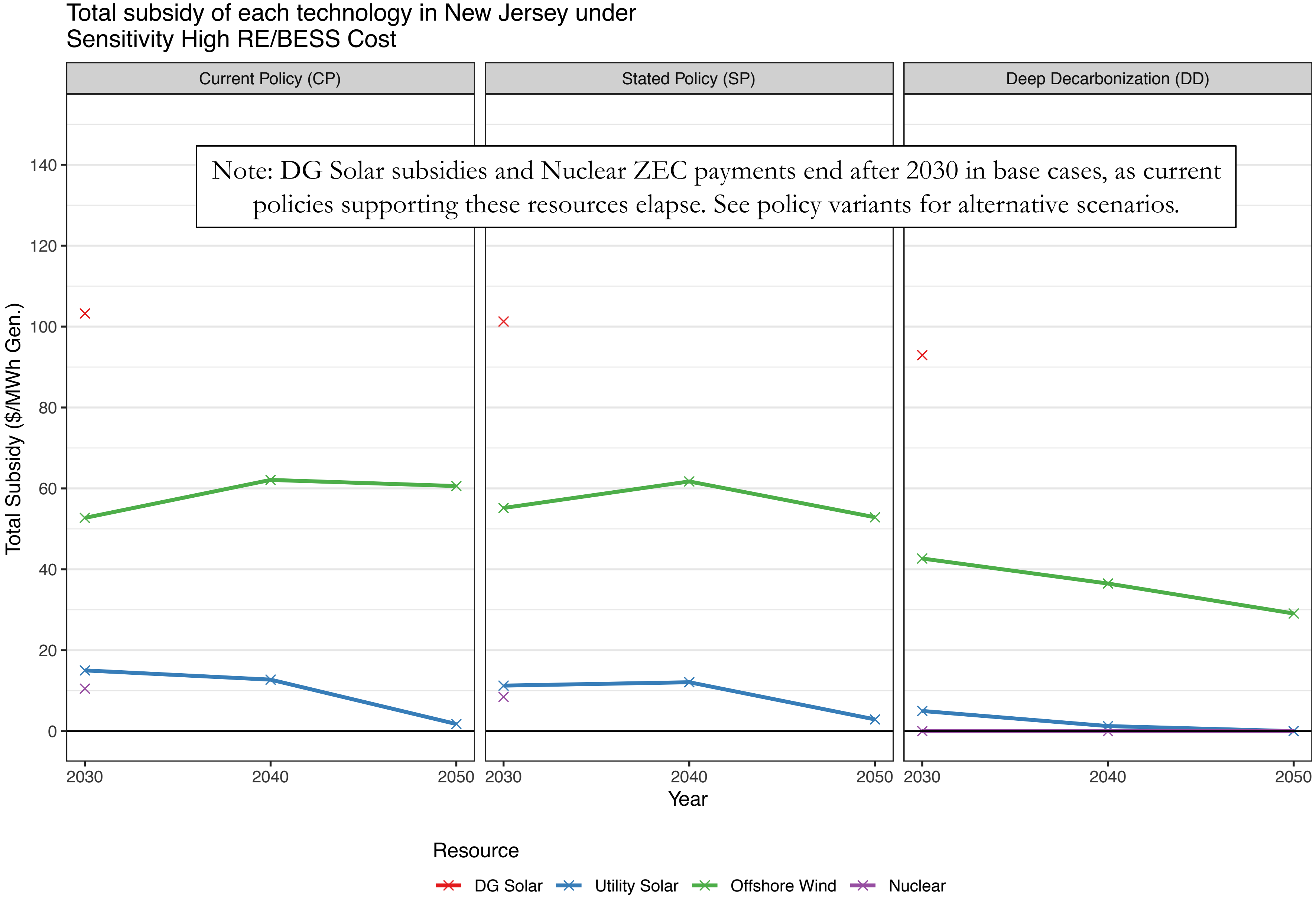
Note: DG Solar subsidies and Nuclear ZEC payments end after 2030 in base cases, as current policies supporting these resources elapse. See policy variants for alternative scenarios.

Technology-specific Subsidies (CP/SP/DD) - (Low RE/BESS Cost)



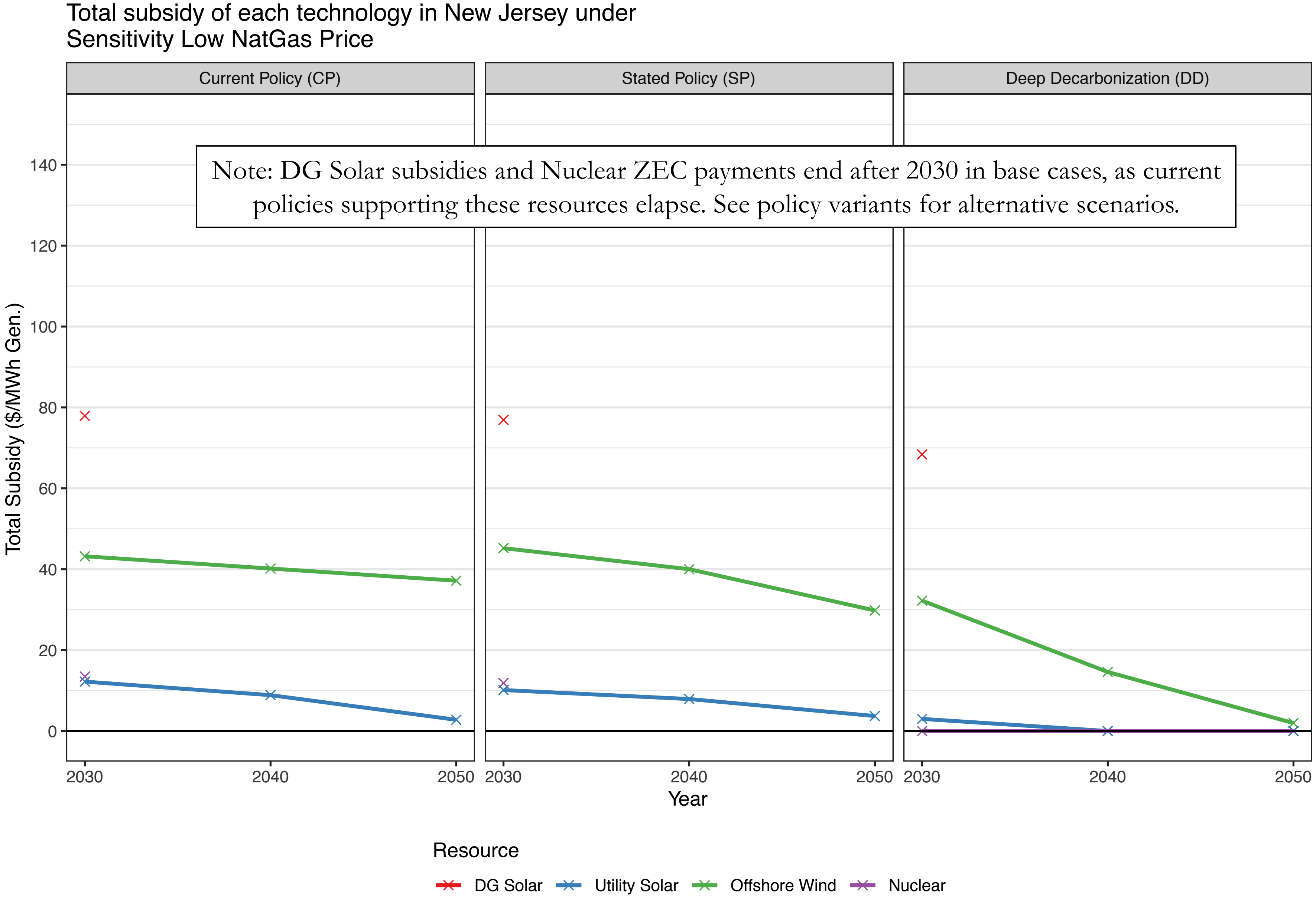
Note: DG Solar subsidies and Nuclear ZEC payments end after 2030 in base cases, as current policies supporting these resources elapse. See policy variants for alternative scenarios.

Technology-specific Subsidies (CP/SP/DD) - (High RE/BESS Cost)



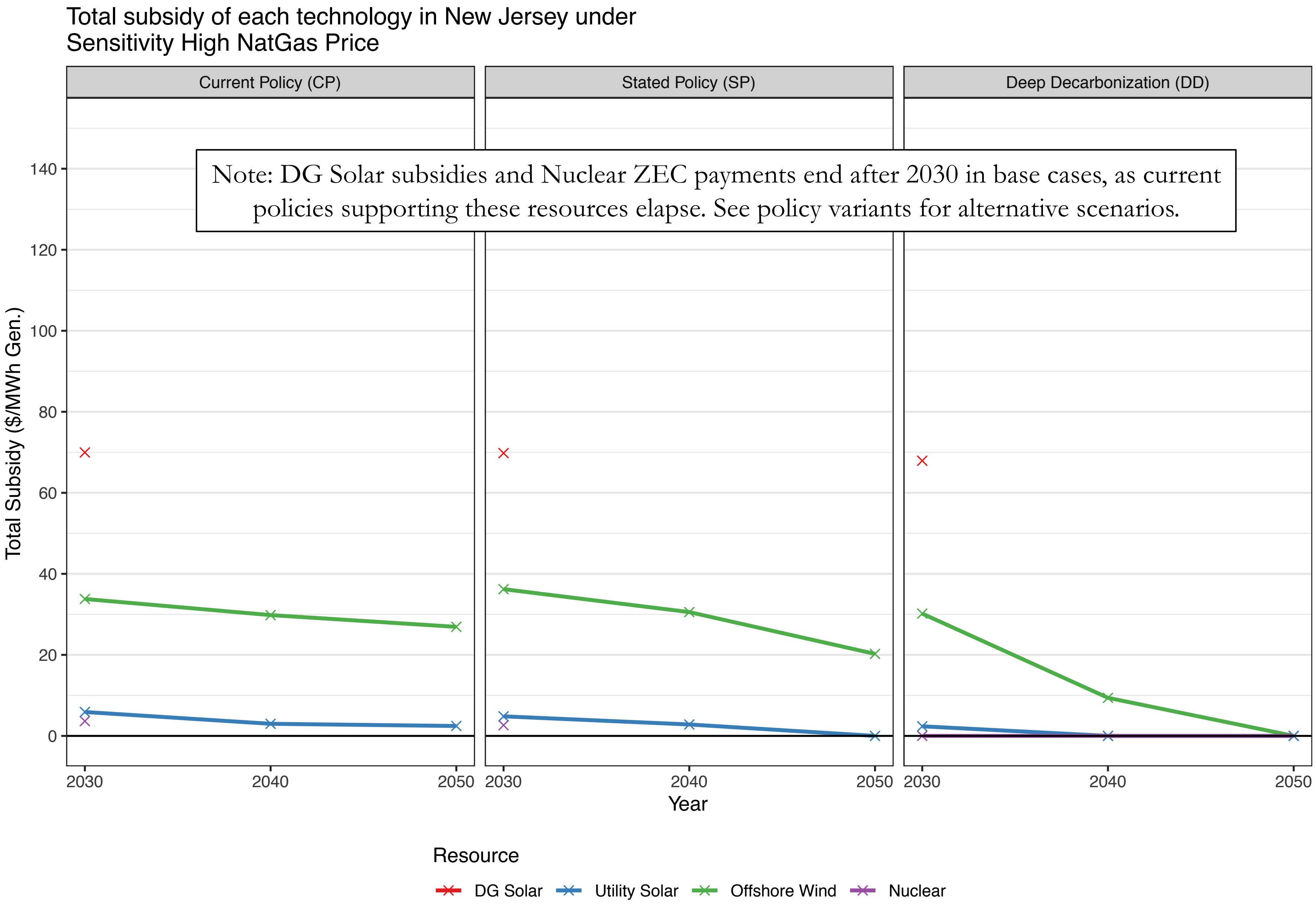
Note: DG Solar subsidies and Nuclear ZEC payments end after 2030 in base cases, as current policies supporting these resources elapse. See policy variants for alternative scenarios.

Technology-specific Subsidies (CP/SP/DD) – (Low Nat. Gas Price)



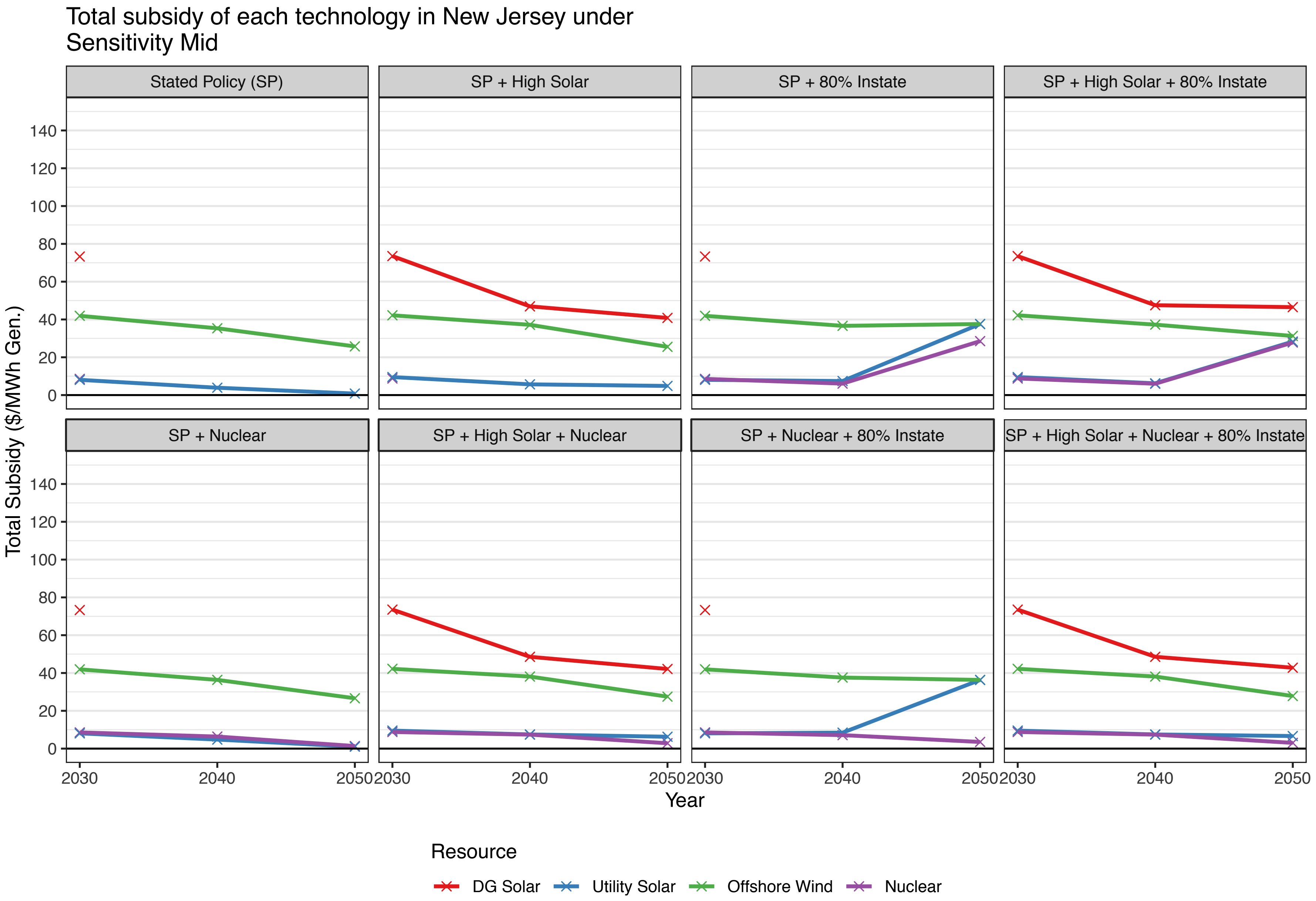
Note: DG Solar subsidies and Nuclear ZEC payments end after 2030 in base cases, as current policies supporting these resources elapse. See policy variants for alternative scenarios.

Technology-specific Subsidies (CP/SP/DD) – (High Nat. Gas Price)

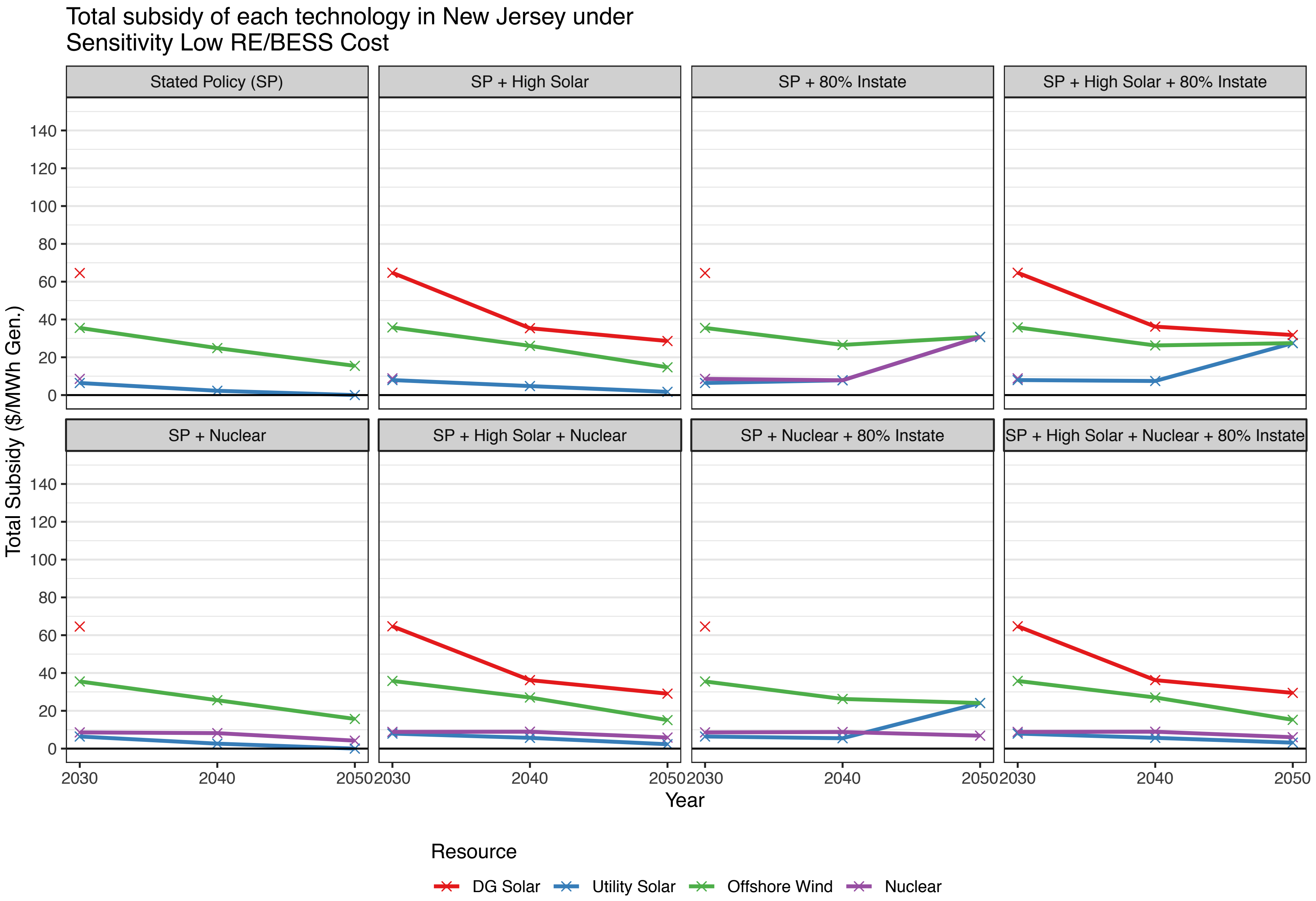


Note: DG Solar subsidies and Nuclear ZEC payments end after 2030 in base cases, as current policies supporting these resources elapse. See policy variants for alternative scenarios.

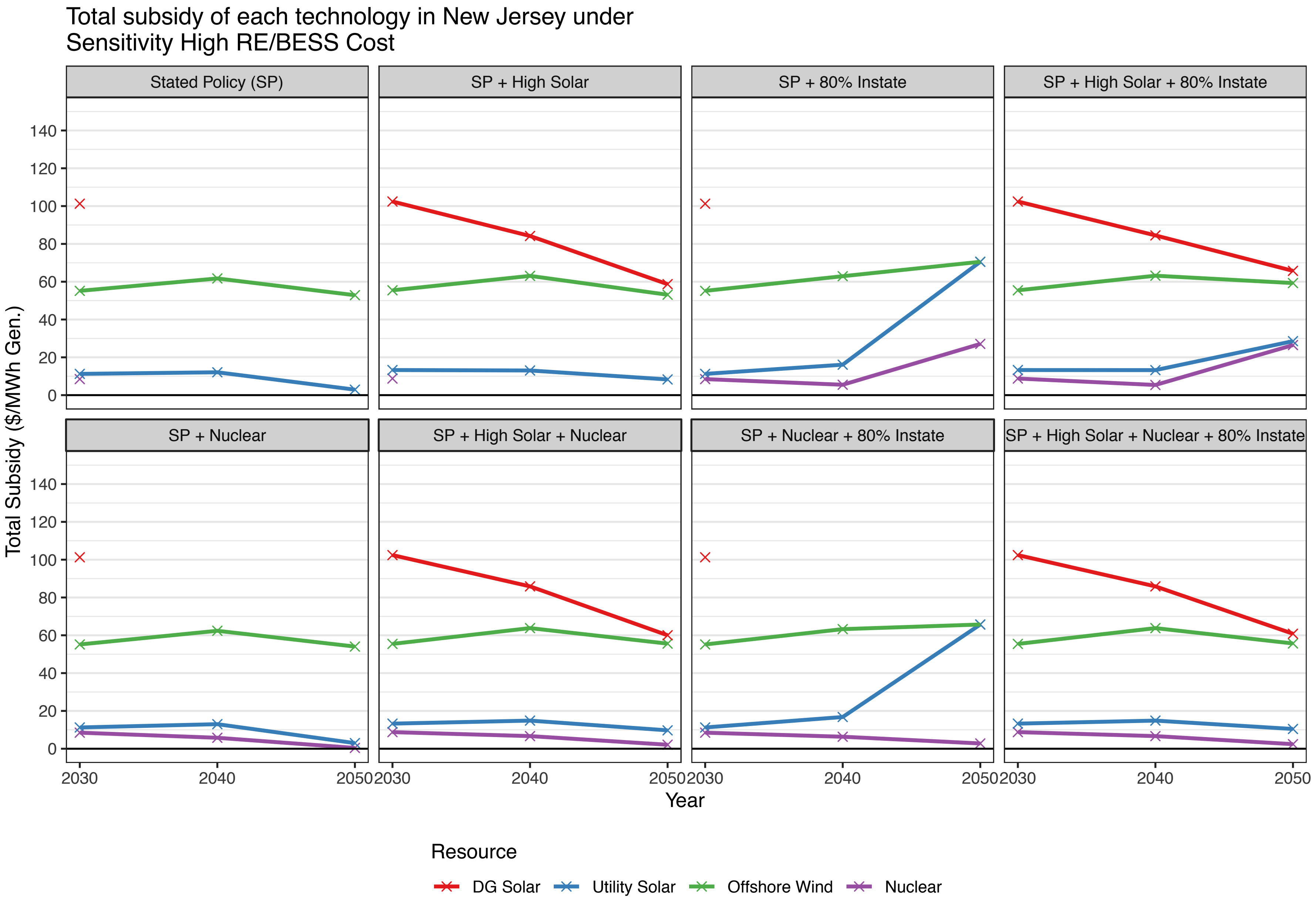
Technology-specific Subsidies in SP Policy Variants (Mid)



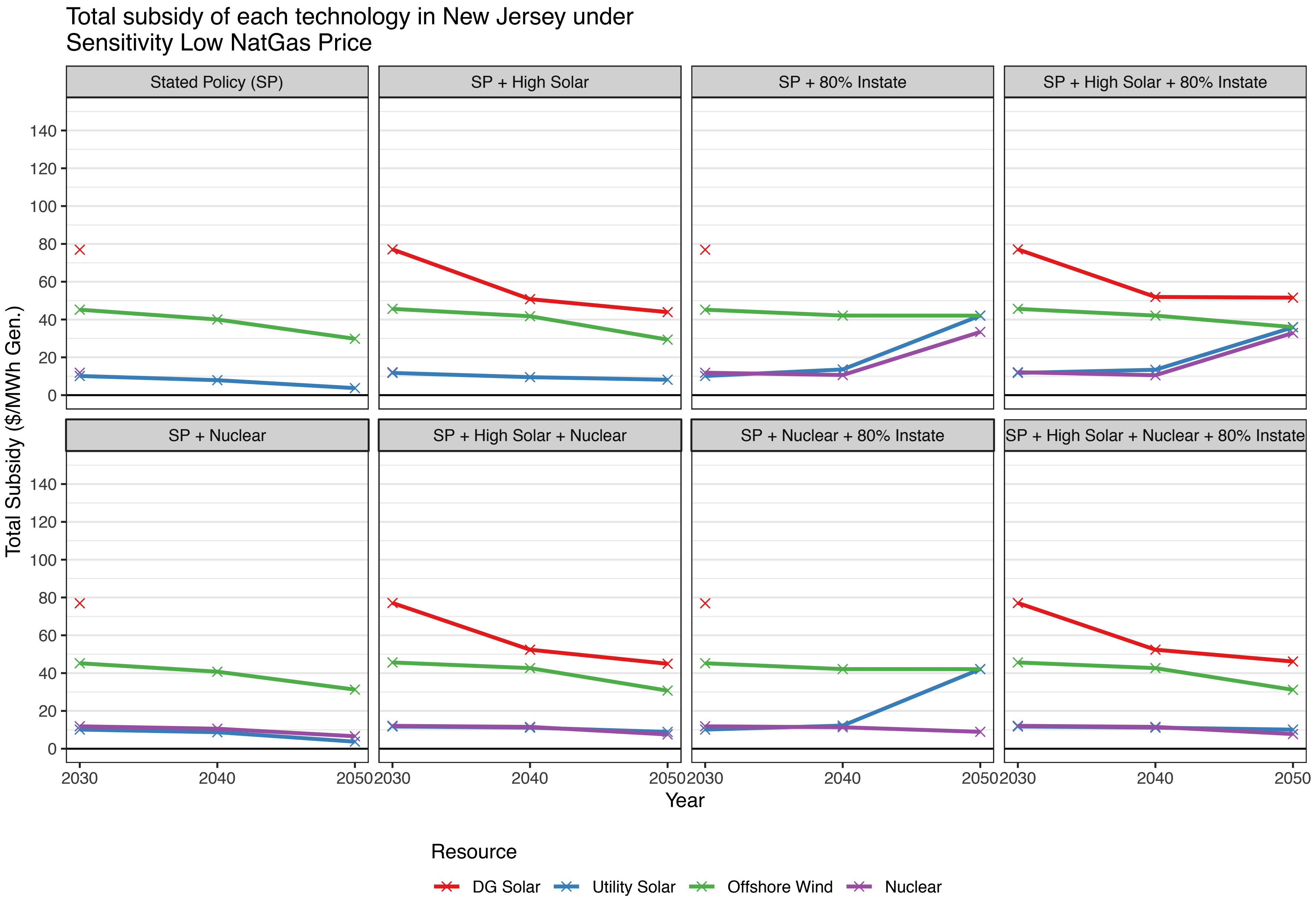
Technology-specific Subsidies in SP Policy Variants (Low RE/BESS Cost)



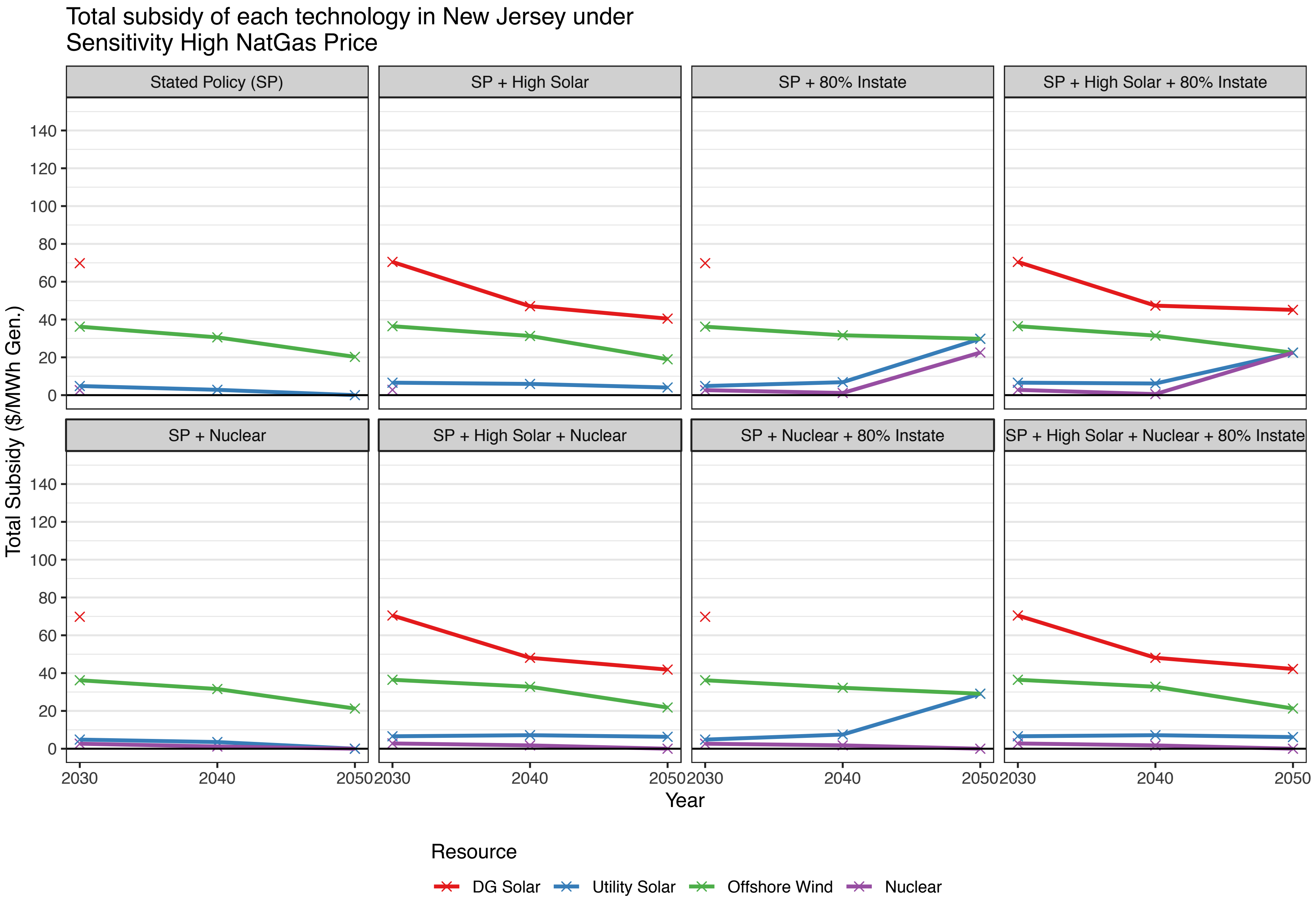
Technology-specific Subsidies in SP Policy Variants (High RE/BESS Cost)



Technology-specific Subsidies in SP Policy Variants (Low Nat. Gas Price)



Technology-specific Subsidies in SP Policy Variants (High Nat. Gas Price)



Capacity Value of New Jersey Offshore Wind, Solar, and Battery Storage

Notes and caveat on capacity values calculated in this study

Interpreting the capacity value reported by this study:

There are multiple capacity value calculation procedures, and final results will be sensitive to the procedure itself and the load shapes + variable energy shapes used in this study.*

Capacity values calculated in this study should be treated as approximate given use of sample periods (18 weeks are selected in this study to represent operations and associated costs over the full planning year), single weather year (2012), and simple 80% derate for inter-annual variability and should be examined more closely in future work.

In this study, capacity value is calculated as:

- The total amount of output contributed by the resource during hours when the capacity reserve margin constraints are binding, derated by 80% to reflect potential inter-annual variability not captured in the modeled weather year, divided by installed capacity (in MW) of the resource.
- There are two capacity reserve margin constraints modeled in this study: A PJM system-wide constraint (PJM-System) and a separate zonal constraint for the Eastern Mid-Atlantic Area Council (EMAAC), which is often binding in the PJM Reliability Pricing Model (aka capacity market auctions).

Note that this calculation procedure is different from PJM's expected load carrying capability (ELCC) calculation which is based on LOLE (loss of load expectation) (A. Levitt, 2021). And consequently, results can differ significantly.

The PJM ELCC approach calculates capacity value as, if simply put:

- How much load can be added to the system if one unit of the resource is added to the system, while keeping the reliability level the same (e.g., the same level of LOLE).

*For example, see PJM's ELCC calculation: Andrew Levitt, "How Effective Load Carrying Capability ("ELCC") Accreditation Works," PJM, April 20, 2021, [Available]: https://www.pjm.com/-/media/committees-groups/committees/pc/2021/20210420-special/20210420-item-03b-how-effective-load-carrying-capability-works.ashx

Sensitivities – Capacity Value of NJ Offshore Wind, Solar, and Battery Storage

Summary of Sensitivity Results

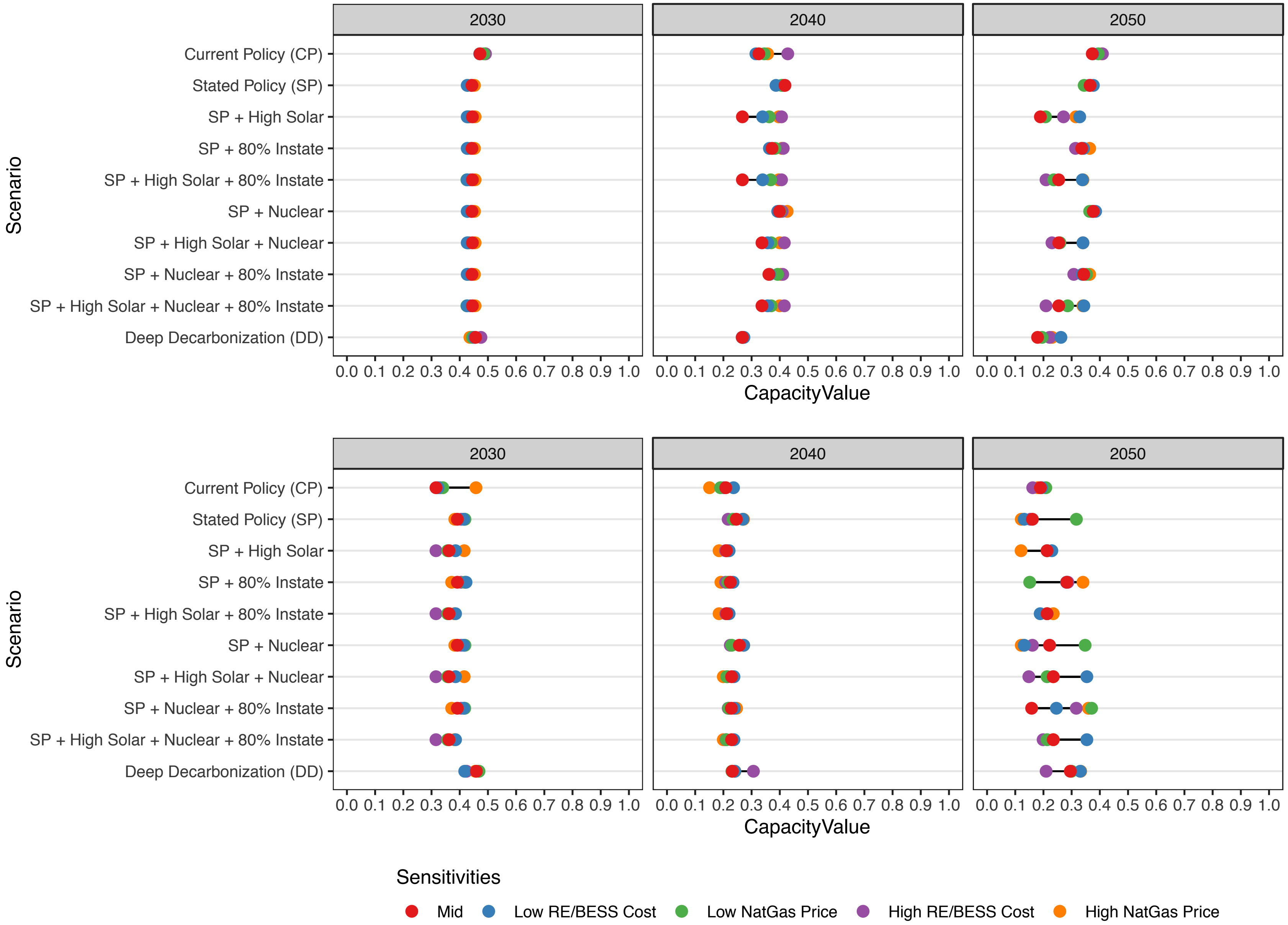
The capacity value results share two common observations:

- **For solar or wind, the higher the installed capacity is, the lower capacity value these resources receive, indicating steadily declining marginal capacity value** (consistent with other studies; e.g. compare capacity values of 2030, 2040, and 2050).
- **The capacity values are sensitive to the cost assumptions**. Combining this observation with the fact that New Jersey's generation capacity and output is not very sensitive to the cost assumptions (because, in part, NJ's solar and offshore wind are policy-driven; see Sensitivities for NJ Capacity and Generation above), we can conclude that the capacity value of New Jersey resources is sensitive to the installed capacity of the rest of the PJM system.

NJ Solar Capacity Value

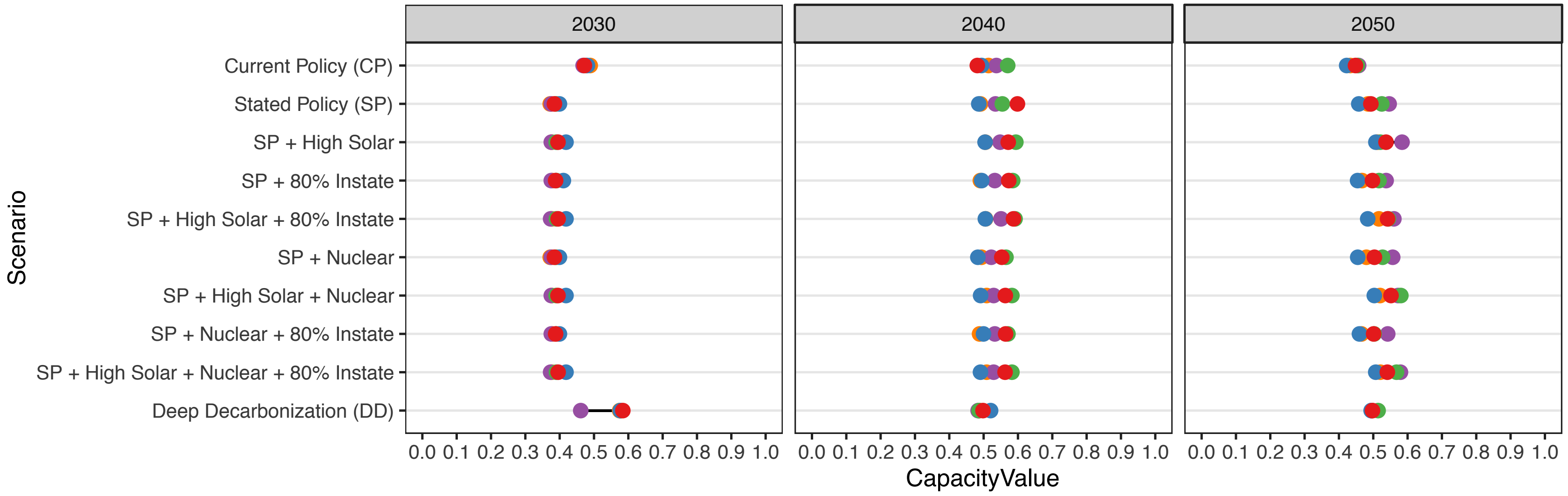
PJM-System

PJM-EMAAC

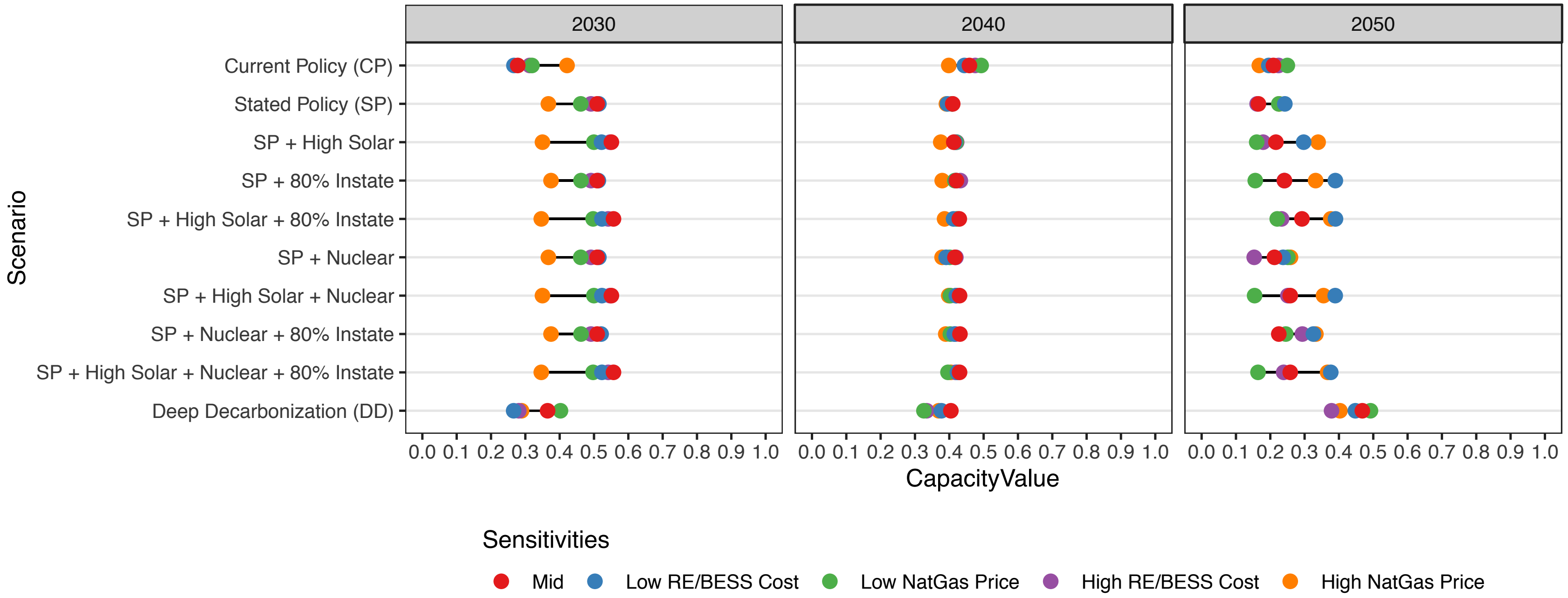


NJ Offshore Wind Capacity Value

PJM-System

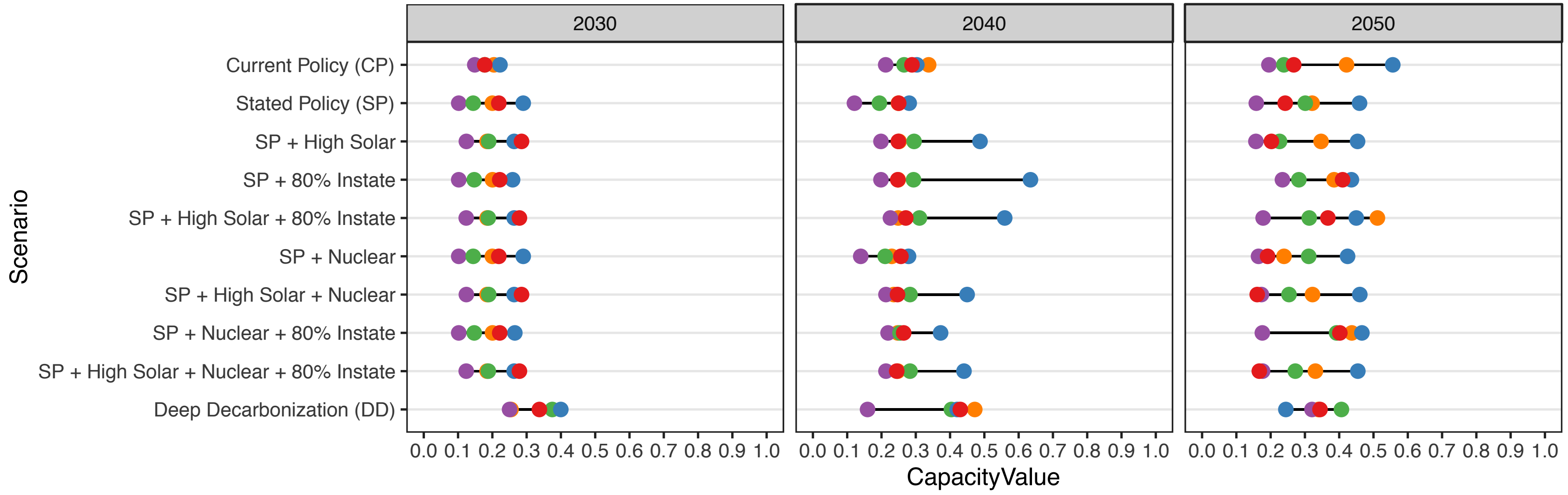


PJM-EMAAC

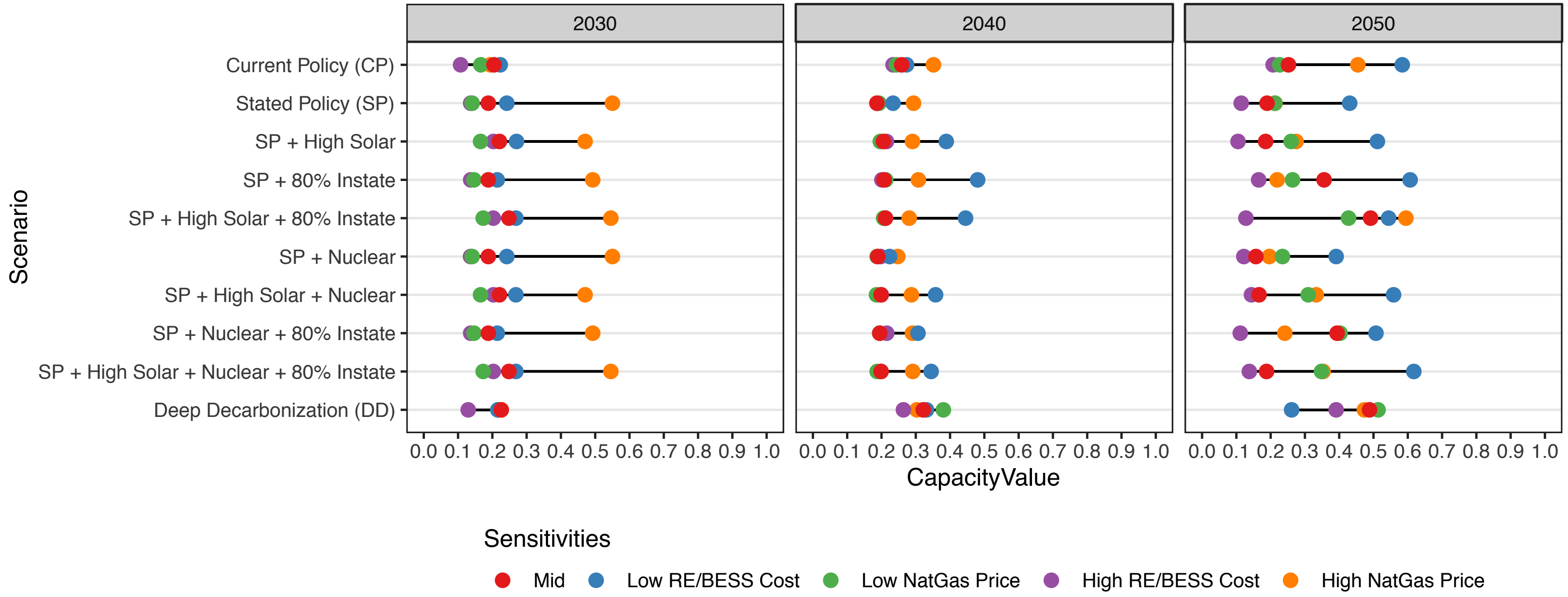


NJ Battery Storage Capacity Value

PJM-System



PJM-EMAAC



Findings and Implications

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 CO_2 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.

Appendices

Appendix – New Jersey Electrification Assumptions

- In **SP** scenarios, states with legislated economy-wide deep decarbonization goals as of 2020 (NY, NJ, VA) experience rapid electrification consistent with these emissions goals. In **DD** scenarios, all states experience this rapid electrification.
- Electrification happens in commercial water heating, commercial space heating & cooling, residential water heating, residential space heating & cooling, and transportation sectors.
- Electrification stock values are from the Princeton *Net-Zero America* study (Larson et al. 2021, see http://netzeroamerica.princeton.edu) consistent with the study's E+ high electrification scenario.
- Hourly demand profiles for each subsector are derived from the NREL *Electrification Futures Study* (Mai et al. 2018, see https://data.nrel.gov/submissions/127). Demand profiles for light-duty electric vehicle charging are modified to reflect the influence of temperature on charging efficiency and vehicle range, using functional form derived from Yuksel & Michalek 2015 and with temperature for each day of the year 2012 (our climate year) from observations for the most populated city of each state (e.g. Newark for NJ). Note EV profiles from the NREL *EFS* study assume operation on the average temperature of the year 2012: 55 F.
- Costs associated with EV and heat pump rebates or other policies to support electrification are not included in this report.
- Total electricity bills may increase with electrification as total volume of electricity consumption increases, while total expenditures on energy (including fuels and heating) will likely decline. However, this report does not make any attempt to quantify total bill impacts or distribution of costs across customer classes or usage patterns.

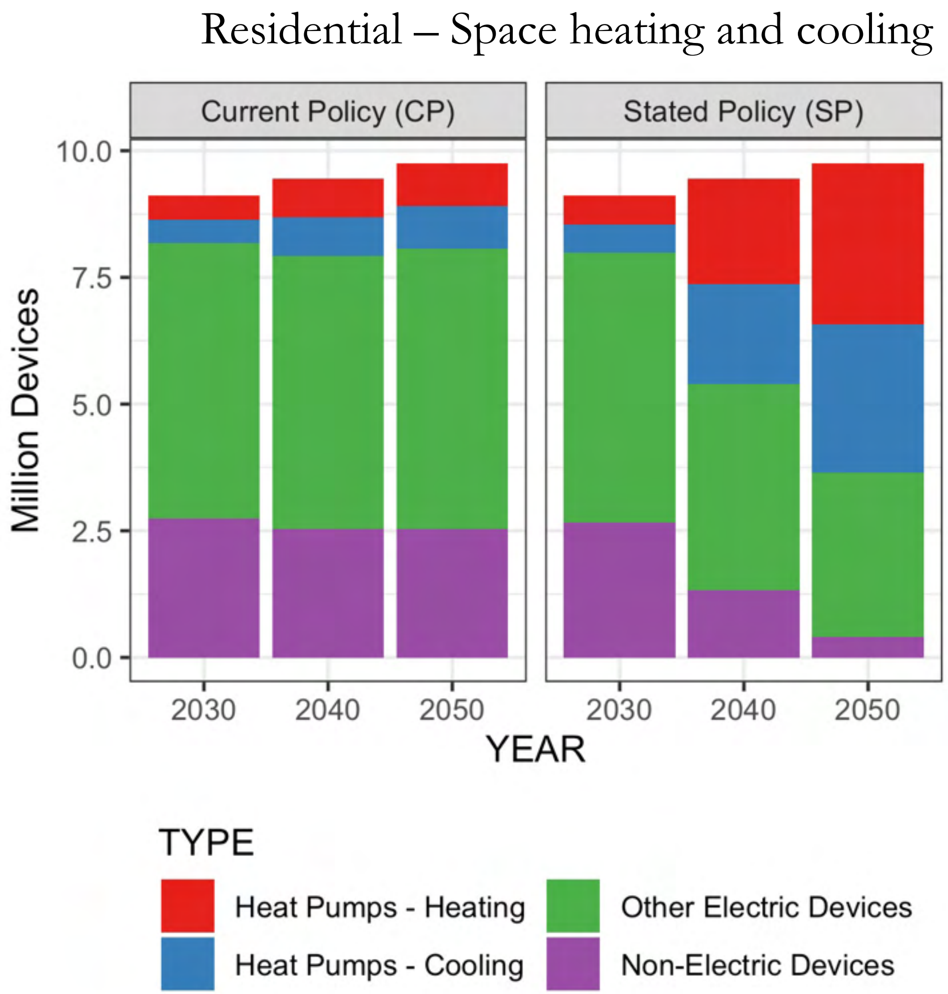
Larson, et al., 2021, *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, Final report, Princeton University, Princeton, NJ, 29 October. https://netzeroamerica.princeton.edu/

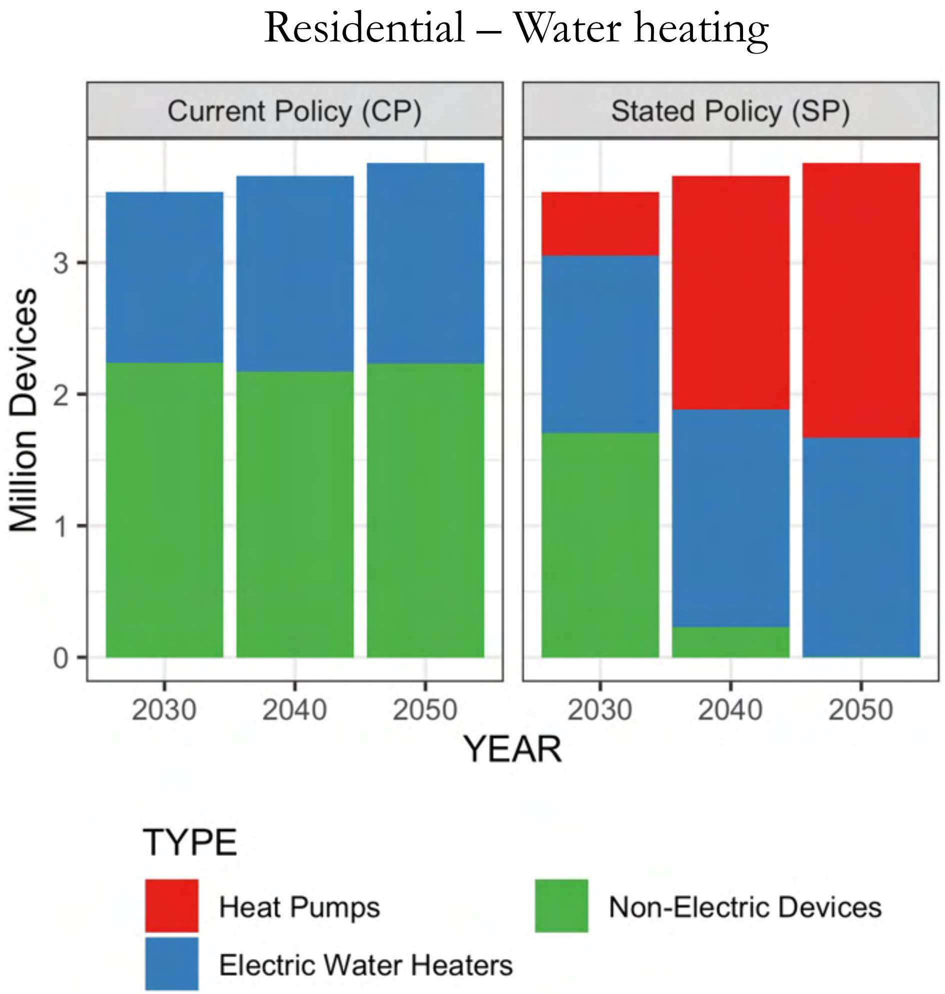
Mai et al., 2018, *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States*. National Renewable Energy Laboratory. NREL/TP-6A20-71500. https://doi.org/10.2172/1459351. See data repository at https://data.nrel.gov/submissions/127

Yuksel and Michalek, 2015, "Effects of Regional Temperature on Electric Vehicle Efficiency, Range, and Emissions in the United States," *Environ. Sci. Technol.*, 49: 3974-3080, https://www.cmu.edu/me/ddl/publications/2015-EST-Yuksel-Michalek-EV-Weather.pdf

Appendix – New Jersey Electrification (Residential Sector)

- This slide shows electrification of residential subsectors of New Jersey.

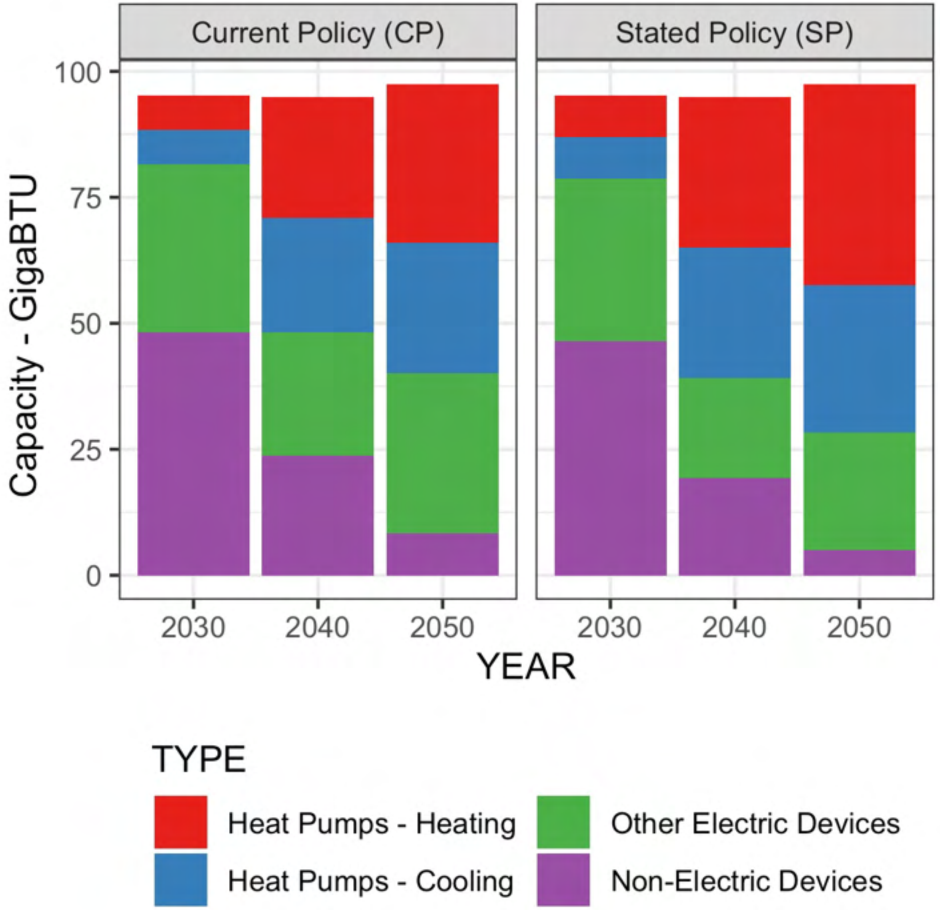




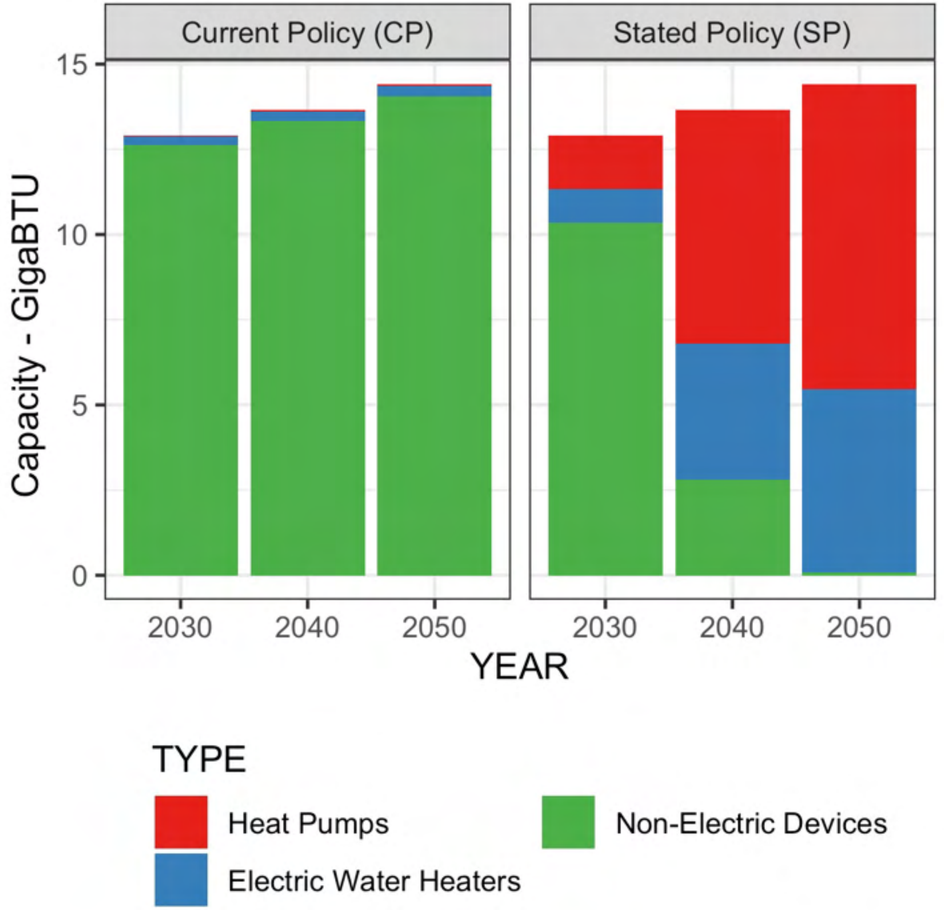
Appendix – New Jersey Electrification (Commercial Sector)

- This slide shows electrification of commercial subsectors of New Jersey.

Commercial – Space heating and cooling



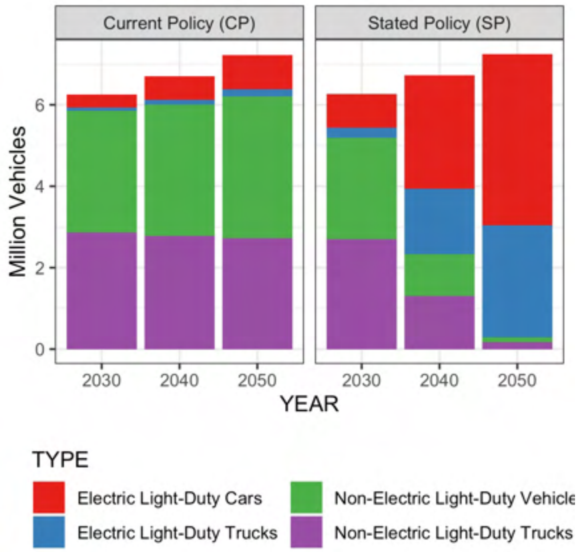
Commercial – Water heating



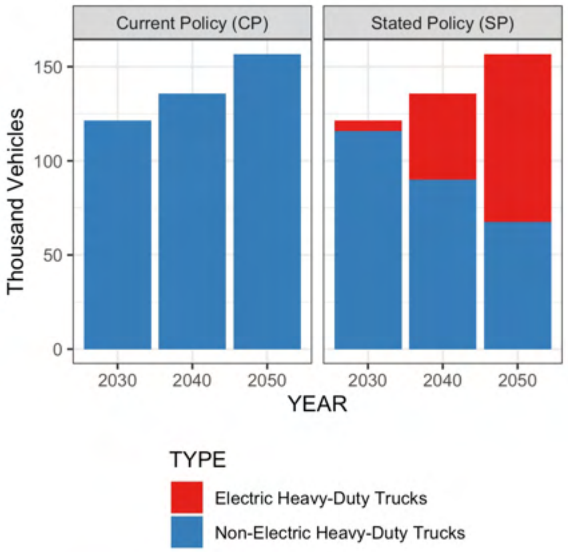
Appendix – New Jersey Electrification (Transportation Sector)

- This slide shows electrification of the transportation sector of New Jersey.

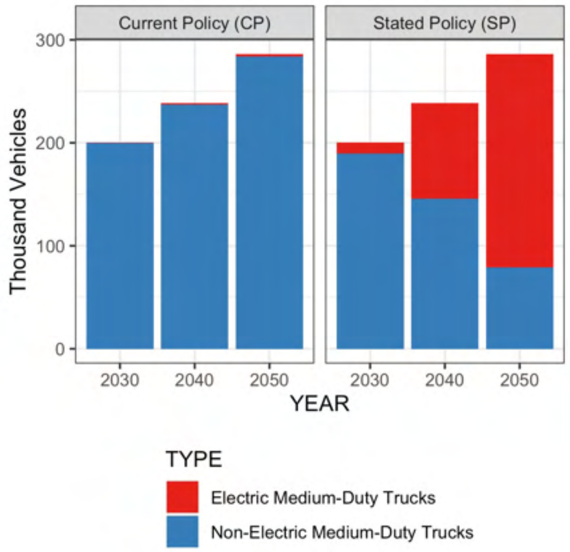
Transportation Light-Duty vehicles



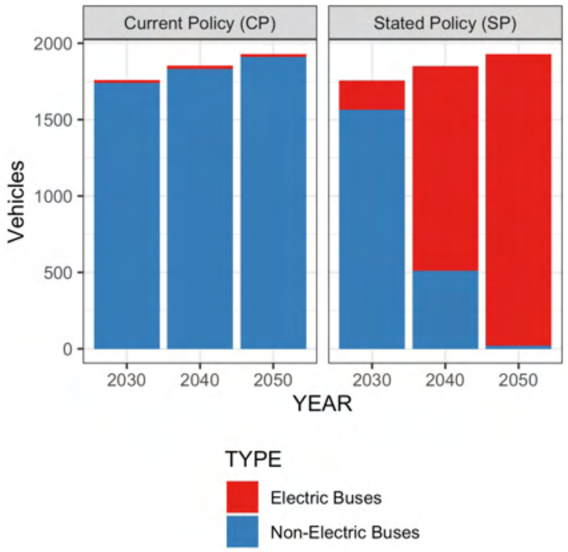
Transportation Heavy-Duty Vehicles



Transportation Medium-Duty vehicles

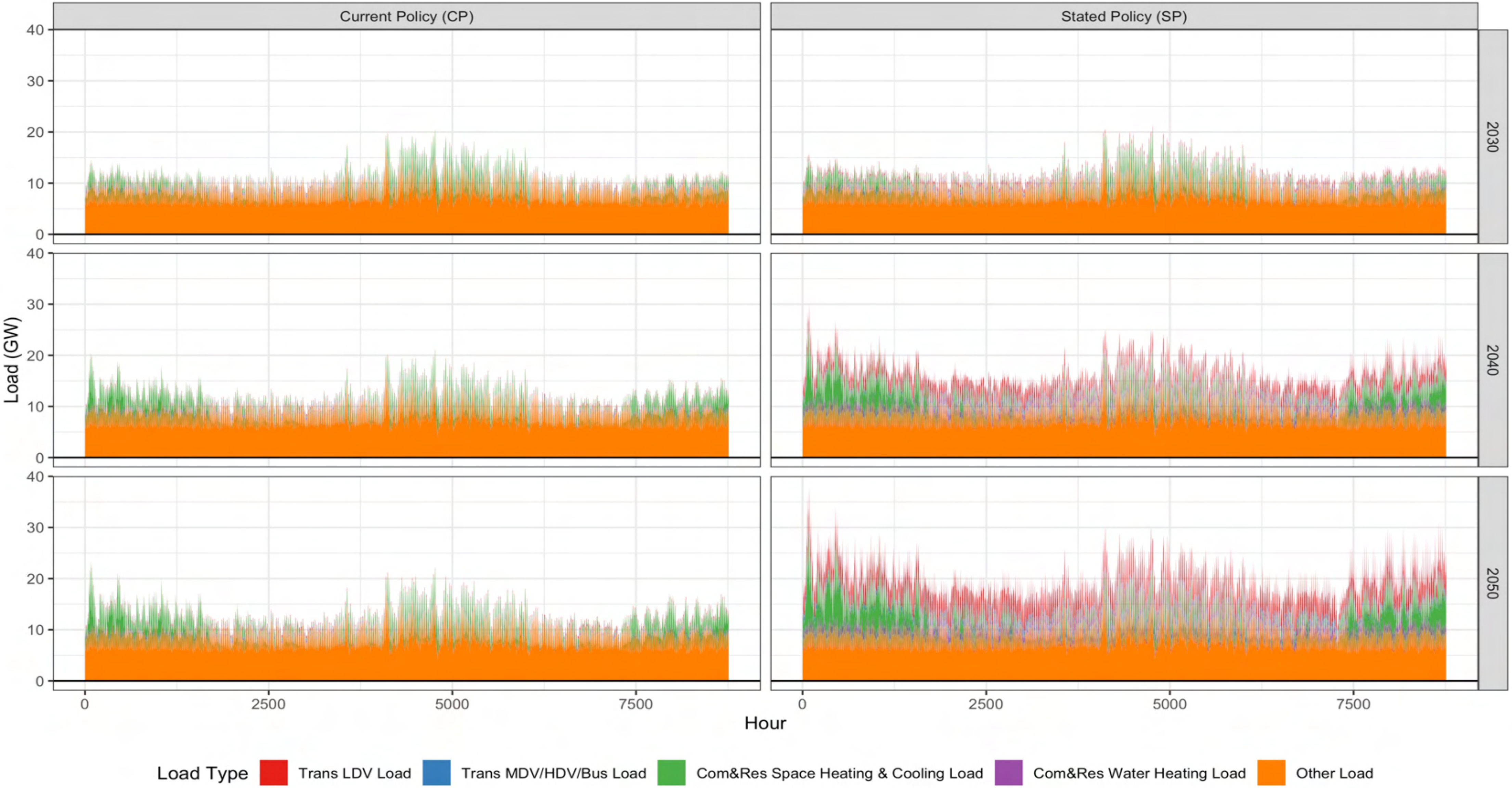


Transportation Transit buses



Appendix – Decomposition of New Jersey Load Time-Series

- This slide shows the decomposition of total New Jersey load by subsector and illustrates impacts of electrification.



Appendix – New Jersey DG & Utility-level solar mandates

- By June 2021, New Jersey had installed 3,655 MWdc of solar (which we assume are 100% at the distribution level), of which 14 MWdc are community solar projects. As of June 2021, there was an additional 770 MWdc capacity in the pipeline, including 58 MWdc of community solar. The pipeline reports released after June 2021 may include more projects which we ignore in this report. (New Jersey Board of Public Utilities 2021)
- There is 78 MWdc community solar remaining to be built by the Project Year 2 of the Community Solar pilot program. (78 MWdc = 150 MWdc – 14 MWdc – 58 MWdc). (New Jersey Board of Public Utilities 2021)
- The New Jersey Solar Act of 2021 will incentivize an additional 150 MWdc/year of community solar and 300 MWdc/year of net-metering solar from 2022-2026. (Karabinchak et al. 2021) This is added into the existing solar capacity as default DG capacity in 2030.
- As a result, the **total modeled DG solar capacity in New Jersey by 2030 is 6,753 MWdc** assuming no new policy. 40% of the DG generation is assumed to be consumed onsite.
- The New Jersey Solar Act of 2021 also requires and provides incentives for installation of 300 MWdc/year of grid-scale solar. This requirement, 1,500 MWdc in total by 2030, is **modeled as a technology-specific requirement of at least 1,119 MWac of grid-scale solar by 2030,** assuming an inverter loading ratio of 1.34.

NJ BPU, "Installed and Pipeline NJ DG Capacity," 2021, Available: https://njcleanenergy.com/renewable-energy/project-activity-reports/solar-activity-report-archive;
NJ BPU, "Installed NJ DG Capacity Report, Jun 2021," 2021, Available: https://njcleanenergy.com/files/file/TI%20Program/FY22/Jun/REPORT%20-%20INSTALLED%20-%20June%202021.xlsx;
NJ BPU, "Pipeline NJ DG Capacity Report, Jun 2021," 2021, Available: https://njcleanenergy.com/files/file/SRP/Installation%20Reports/2021/REPORT%20-%20PIPELINE%20-%20June%202021%20-%20v2.xlsx;
Karabinchak et al., "A4554 Solar Act of 2021," 2021, Available: https://www.njleg.state.nj.us/2020/Bills/A5000/4554_U1.PDF.

Appendix – Distributed Solar Cost

- The distributed solar cost estimate used in the 2019 benchmark LSE cost is obtained from New Jersey BPU (2020) and totals $671M, all in the form of SREC payments. This is calculated as a weighted average of $597M in energy year (EY) 2019 (inflated to $605M in 2020USD) and $719M in EY 2020.
- The DG capacity in 2030-2050 can be separated into three groups, and each induces a different cost to the LSEs.

1. **DG capacity supported by the SREC program** costs $227M in 2030 (payments under this program terminate before 2040).
   - These distributed solar capacities include all the installed capacity built between 2016-2019 (1,540 MWdc, or 1,283 MWac with assumed 1.2 inverter loading ratio). With an AC capacity factor of 0.204, this is about 2.3 TWh SREC supply. The cost per MWh for SRECs is modeled as 80% of the Solar Alternative Compliance Payment (SACP), given that historical SREC prices have been close to SACP. In 2030, the NJ SACP equals to $158/MWh, and 80% of the $158/MWh deflated to 2020USD is $98.74/MWh. Thus, SREC costs that will appear in year 2030 = $98.74/MWh * 2.3 TWh = $227M. Prior to 2020, projects were eligible for SRECs for 15 years, and after 2020, the eligibility term for SRECs was shortened to 10-years. SREC costs thus end before 2040.
2. **DG capacity supported by the TREC program** costs $178M in 2030 (payments under this program terminate before 2040).
   - These distributed solar capacities include all TREC supported solar capacity installed or in the pipeline as of June 2021 and the 78 MWdc community solar identified in the "Appendix – New Jersey DG & Utility-level solar mandate". The total is 1,144 MWdc. These capacities are then separated into different project types per TREC rules, and each type receives a different TREC price, ranging from 60% to 100% of $152/MWh. After deflating to 2020 USD, total TREC payments amount to $178M in 2030. Projects are eligible for TREC payments for 15 years, so costs under this program end before 2040.
3. **The DG solar capacity that is supported by the New Jersey Solar Act of 2021 & additional solar capacity in High Solar policy variants**.
   - It is still not fully clear how these DG solar installation will be supported by new NJ rules to implement the New Jersey Solar Act of 2021. In this report, we model the cost by adding the annualized fixed cost of this group of DG solar to the LSE cost. Initial 2020 fixed cost (year 2020 CAPEX, and Fixed O&M) is obtained from the NREL System Advisor Model employed by NJ BPU and Cadmus (Cadmus, 2020). Obtained cost data for 2020 are then scaled up and down depending on the Renewable/Battery cost sensitivities scenario and the future cost curves calculated from NREL ATB 2020. The final fixed costs employed by the model are summarized on p. 21 ("New Jersey Distributed Solar Cost"). Because the full annualized fixed costs for these new solar capacities are added to the LSE cost breakdown, we assume LSEs retain all the cost savings from DG: including avoided energy payments and renewable/clean energy credits. See "Sensitivities – Technology-specific Subsidies" (p. 93) for additional important notes on this method.

NJ BPU 2021, "RPS Report Summary 2005-2020,"Available: https://njcleanenergy.com/files/file/rps/RPS%20Summary%20Report%20EY%202005-2020.pdf
Cadmus, 2020, "Cadmus Modeling Inputs Excel Sheets," Available: https://njcleanenergy.com/files/file/NJ%20Solar%20-%20SP%20Project%20Model%20-%20SAM%20Inputs%20-%20external%202020-08-10.xlsx

Appendix – 2019 New Jersey LSE Cost Benchmark

- 2019 LSE cost benchmark is estimated by combining a 2019 dispatch simulation data conducted with GenX for this study and data from the PJM Interconnection.
  - Our 2019 simulation suggests that the energy payment (including transmission loss payment) of New Jersey was $2,579M.
  - We also calculated that PJM-level transmission congestion revenue was $678M. Because the 2019 PJM metered load was 787 GWh and New Jersey metered load was 77 TWh, we allocate $66M in transmission congestion revenue to NJ LSEs.
  - Under the current Zero Emissions Certificates subsidy program for NJ nuclear power plants, each electricity distribution company is to file a tariff that will collect $4/MWh from its retail customers; this is about $308M in 2019. This amounts to ~$11.5 per MWh in 2019 (given total generation from Hope Creek and Salem reactors of 26,757 GWh according to IAEA Public Reactor Information System).
  - Transmission payments by New Jersey LSEs totaled $1,512M in 2019. This is the total of Annual Transmission Revenue Requirements of zones AE, JCPL, PSEG and RECO in the year 2019 and inflated to 2020 USD.
  - Capacity payments cost NJ LSEs $1,724M for delivery year 2018-2019 (sum of products of UCAP Obligation and Final Zonal Net Load Price of AE, JCPL, PSEG, and RECO, inflated to 2020 USD), and $899M in 2019-2020. NJ's weighted average capacity payment for calendar year 2019 is thus $1,242M.
  - Next, we add back the imputed cost savings from distributed solar (3261 MWac in our 2019 simulation) because GenX treats DG as a negative load by default.
    - 2019 DG's energy savings: By multiplying the LMP time-series of the 2019 simulation and the DG profile, we imputed that the DG's energy cost saving is $225M.
  - NJ Class I RPS payments in calendar year 2019 totaled $86M (NJ BPU, the weighted average of EY 2019 and EY 2020, in 2020 USD), and the SREC cost was $671M (see NJ BPU 2021, reference on p. 122).
- The total net payment of New Jersey in 2019 is: $2,579M - $66M + $308M + $1,512M + $1,242M + $225M + $86M + $671M= $6,249M; the LSE cost per MWh is thus $6,249M/82.9 TWh = $79.2/MWh, where the 82.9 TWh is the total gross load of New Jersey.

PJM Interconnection, "Annual Transmission Revenue Requirements and Rates," 2019. [Available]: https://www.pjm.com/-/media/markets-ops/settlements/network-integration-trans-service-2019.ashx
PJM Interconnection, "2018/2019 Final Zonal Scaling Factors, UCAP Obligations, Zonal Capacity Prices, & Zonal CTR Credit Rates," 2018. [Available]: https://pjm.com/-/media/markets-ops/rpm/rpm-auction-info/2018-2019-final-zonal-ucap-obligations-capacity-prices-ctr-credit-rates.ashx.
PJM Interconnection, "2019/20 Final Zonal Scaling Factors, UCAP Obligations, Zonal Capacity Prices, & Zonal CTR Credit Rates," 2019. [Available]: https://pjm.com/-/media/markets-ops/rpm/rpm-auction-info/2019-2020/2019-2020-final-zonal-ucap-obligations-capacity-prices-ctr-credit-rates.ashx

Appendix – Other assumptions of LSE cost calculation

- **The scope of this report is limited to the wholesale electricity supply and transmission-level. Distribution network costs are not included in LSE baseline costs, and this study does not attempt to estimate any cost/benefit related to the impact of distributed solar or storage or flexible demand on distribution network costs.**
- We assume LSEs (or consumers) are responsible for payments covering the full cost of distributed Solar PV that is built after 2022 (see "Appendix – Distributed Solar Cost", p. 122), and thus, the savings from distributed solar PV (e.g., from energy) are also retained by LSEs/consumers. This means, on the plots of LSE cost breakdown:
  1. NG DG cost = the total annualized capital and fixed O&M cost of distributed solar PV installed after 2022 + legacy payments for SREC and TREC programs (if any).
  2. Energy payments have been lowered by the cost-savings from distributed solar PV, which reduce net load at the PJM level.
  3. RPS payment has been lowered by the cost-savings from distributed solar PV, which can generate RECs & offset the RPS eligible load.
- Additional settlement assumptions include:
  1. We assume the congestion revenue of PJM is completely allocated to LSEs through financial transmission right auctions and distributed in proportion to load across all LSEs.
  2. The LSEs/consumers are who ultimately pay for any transmission expansion expenses incurred during the study period.
  3. The energy payment is calculated assuming load purchased from the wholesale market at location marginal prices computed at the model zone level, and thus the potential saving from signing bilateral long-term power purchase agreement contracts are ignored.
  4. The carbon cap-and-trade revenue is allocated to LSEs in proportion to load across all LSEs.
  5. Existing transmission cost: transmission costed New Jersey $1,825M 2020 USD in 2021 ($1,953M in nominal 2021 USD). We add this cost into the total transmission cost component of the LSE cost breakdown in 2030/2040/2050, on top of the incremental transmission expansion expenses incurred within GenX. We thus make the simplifying assumption that replacement capital expenditures equal depreciation to maintain a constant revenue requirement for existing transmission assets going forward.

PJM Interconnection, "Annual Transmission Revenue Requirements and Rates," 2021. [Available]: https://www.pjm.com/-/media/markets-ops/settlements/network-integration-trans-service-jan-2021.ashx.

Appendix – Nuclear & Zero Emission Certificate

- From the modeling perspective, GenX prevents nuclear capacity from retiring by having a constraint as a lower bound on capacity equal to the current installed capacity (e.g. Salem and Hope Creek generating stations). The shadow price of this constraint (call it C) is technically a capacity-valued subsidy in unit of $/MW. This value is equivalent to the minimum additional revenue per MW of capacity (in addition to revenues derived from energy and capacity markets and CES attribute payments, if any) required to keep these nuclear units at minimum break-even profit, given the cost assumptions used in this study.
- However, once the nuclear capacity is kept from retiring at the required level, it will be operated around-the-clock with maximum capacity factor (CF, e.g., 100%) of each modeling year; this makes the output of the nuclear power constant across scenarios and policy variants, and an equivalent production-valued subsidy (call it P) can be calculated as $P = C/(CF \times 8760 \text{ hours})$.
- Note that cost assumptions for nuclear units used in this study are generic for the U.S.-wide fleet and vary based on reactor size and number of units. These costs include estimates of annual average capital expenditures and refueling costs are averaged across annual generation and included in variable fuel costs for generation. In reality, nuclear operators incur occasional significant capital outlays (e.g. for repairs or equipment replacement) to continue operations, and refueling operations occur on approximately 18 month cycles. Actual expenditures are thus more variable year to year than the annual averages used herein. Assumed costs may therefore differ from actual costs incurred by Salem or Hope Creek, and subsidy values should be treated as estimates.

Appendix – Flexible Demand

This study assumes similar flexible demand assumption shown in NREL's *Electrification Futures Study* (Mai et al. 2018). The assumptions are shown below. GenX only models delay of the flexible demand.

		Light Duty-EV	Water Heating	Space Heating & Cooling Demand
Fraction of demand of each type available for flexible scheduling	2030	67%	13%	11%
	2040	79%	18%	21%
	2050	90%	25%	30%
Maximum Delay Time (hours)		5	4	2

Mai et al., 2018, *Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States*. National Renewable Energy Laboratory. NREL/TP-6A20-71500. https://doi.org/10.2172/1459351.

Appendix – New Jersey Starting Resources (excluding Distributed Generation)

	Resource	Cluster	Capacity (MW)	FOM ($/MW-year)	VOM ($/MWh)	Heat Rate (MMBTU/MWh)
PJM_NJCoast	Biomass	1	23.0	122,976	5.75	16.42
	Coal	1	463.0	71,920	1.88	13.98
	NGCC	1	1,591.8	13,379	4.12	8.01
	NGCT	1	1,106.6	12,127	4.66	11.57
	Onshore Wind	1	7.5	43,205	-7.20*	NA
PJM_NJLand	Biomass	1	22.6	122,976	5.80	16.57
	Hydro Pump Storage	1	420.0	40,608	0.00	NA
	NGCC	1	4,907.0	10,424	3.60	7.36
	NGCC	2	623.8	16,492	4.55	8.99
	NGCC	3	318.5	16,492	4.55	5.93
	NGCT	1	336.2	9,919	4.66	12.97
	NGCT	2	290.0	12,452	4.66	28.41
	Nuclear	1	3,500.2	240,117	2.32	10.46

- Starting wind receives wind PTC of $7.2/MWh. This value represents the net present value equivalent of the full PTC value available for ten years, averaged over the 30-year asset life used in our modeling.
- The coal power of 463 MW in New Jersey are the Logan Generating Plant and the Chambers Carneys Point Cogen Generating Plant. Both are scheduled for retirement and neither capacity is retained in any of the cases for the 2030-2050 period.
- Note that starting NGCC/CT that survives until 2050 SP/DD are given options to switch to burn zero-carbon fuel, which incurs a cost equal to 50% of the CAPEX for new candidate NGCC/CG units. For NGCC/CTs built after 2021, fuel switching is assumed to be free.

Appendix – Fuel Price: 2030 Natural Gas Price (Low Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela-ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	3.99	3.93	5.03	5.16	4.30	4.77	3.86	4.13	4.13	3.30	5.07	3.34	3.30	3.75	4.35
Feb.	4.26	3.43	3.95	4.00	3.29	3.33	3.44	3.59	3.59	2.71	3.66	2.87	2.71	3.27	3.57
Mar.	3.93	3.71	3.49	3.5	3.52	3.16	3.97	3.34	3.34	2.59	3.50	3.00	2.59	3.30	3.68
Apr.	3.08	3.15	2.47	2.48	2.90	2.82	3.61	2.34	2.34	2.25	3.11	2.72	2.25	3.45	3.57
Ma	2.94	3.06	2.33	2.32	2.78	2.73	3.38	2.35	2.35	2.17	3.00	2.55	2.17	3.00	3.36
Jun.	2.77	2.85	2.27	2.28	2.71	2.51	2.96	2.23	2.23	2.04	2.77	2.37	2.04	2.94	3.19
Jul.	2.75	2.84	2.18	2.15	2.73	2.45	2.85	2.32	2.32	2.04	2.71	2.31	2.04	2.78	3.05
Aug.	2.68	2.65	2.03	1.99	2.73	2.34	2.64	2.25	2.25	1.80	2.55	2.16	1.80	2.69	3.03
Sep.	2.79	2.93	2.00	1.97	2.81	2.61	2.80	2.22	2.22	1.68	2.76	2.23	1.68	2.85	3.28
Oct.	2.49	2.48	1.87	1.83	2.4	2.17	2.55	2.17	2.17	1.51	2.33	2.01	1.51	2.91	3.07
Nov.	3.13	3.2	2.74	2.78	3.01	3.08	3.39	2.48	2.48	2.22	3.32	2.53	2.22	2.96	3.39
Dec.	3.12	2.77	2.88	2.95	2.63	3.11	3.77	2.40	2.40	2.13	3.34	2.40	2.13	2.95	3.36

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference. Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Appendix – Fuel Price: 2040 Natural Gas Price (Low Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela-ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	4.20	4.13	4.88	5.01	4.16	4.63	3.84	4.00	4.00	3.20	5.04	3.23	3.20	3.73	4.32
Feb.	4.47	3.61	3.83	3.88	3.18	3.23	3.42	3.49	3.49	2.63	3.64	2.78	2.63	3.25	3.55
Mar.	4.13	3.90	3.38	3.40	3.41	3.07	3.94	3.24	3.24	2.52	3.48	2.91	2.52	3.29	3.65
Apr.	3.24	3.31	2.39	2.41	2.81	2.74	3.59	2.27	2.27	2.19	3.09	2.63	2.19	3.43	3.55
Ma	3.09	3.22	2.26	2.25	2.70	2.65	3.36	2.28	2.28	2.11	2.99	2.47	2.11	2.98	3.35
Jun.	2.91	3.00	2.21	2.21	2.62	2.44	2.95	2.17	2.17	1.98	2.76	2.29	1.98	2.93	3.17
Jul.	2.89	2.98	2.11	2.09	2.64	2.38	2.84	2.26	2.26	1.98	2.7	2.23	1.98	2.77	3.04
Aug.	2.82	2.79	1.97	1.93	2.64	2.27	2.63	2.19	2.19	1.75	2.54	2.09	1.75	2.68	3.02
Sep.	2.93	3.08	1.95	1.91	2.72	2.53	2.79	2.15	2.15	1.63	2.74	2.16	1.63	2.83	3.26
Oct.	2.62	2.61	1.82	1.77	2.32	2.11	2.54	2.11	2.11	1.47	2.32	1.95	1.47	2.90	3.06
Nov.	3.29	3.36	2.66	2.7	2.92	2.99	3.37	2.40	2.40	2.15	3.3	2.45	2.15	2.95	3.37
Dec.	3.28	2.91	2.79	2.86	2.55	3.02	3.75	2.33	2.33	2.06	3.32	2.32	2.06	2.93	3.35

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference. Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Appendix – Fuel Price: 2050 Natural Gas Price (Low Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela-ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	4.21	4.14	4.85	4.97	3.92	4.60	3.62	3.97	3.97	3.18	4.76	3.05	3.18	3.52	4.08
Feb.	4.48	3.62	3.80	3.85	3.00	3.21	3.23	3.46	3.46	2.61	3.44	2.62	2.61	3.07	3.35
Mar.	4.14	3.91	3.36	3.37	3.21	3.04	3.72	3.22	3.22	2.50	3.29	2.74	2.50	3.10	3.45
Apr.	3.25	3.32	2.38	2.39	2.65	2.72	3.39	2.26	2.26	2.17	2.92	2.48	2.17	3.24	3.35
Ma	3.10	3.23	2.24	2.24	2.54	2.63	3.18	2.26	2.26	2.09	2.82	2.33	2.09	2.82	3.16
Jun.	2.92	3.01	2.19	2.19	2.47	2.42	2.78	2.15	2.15	1.97	2.60	2.16	1.97	2.76	2.99
Jul.	2.90	2.99	2.10	2.07	2.49	2.36	2.68	2.24	2.24	1.96	2.55	2.10	1.96	2.61	2.87
Aug.	2.83	2.79	1.95	1.92	2.49	2.25	2.48	2.17	2.17	1.74	2.40	1.97	1.74	2.53	2.85
Sep.	2.94	3.09	1.93	1.90	2.56	2.51	2.63	2.13	2.13	1.62	2.59	2.04	1.62	2.67	3.08
Oct.	2.63	2.62	1.80	1.76	2.19	2.09	2.39	2.09	2.09	1.46	2.19	1.83	1.46	2.73	2.89
Nov.	3.30	3.37	2.64	2.68	2.75	2.96	3.18	2.39	2.39	2.13	3.12	2.31	2.13	2.78	3.18
Dec.	3.29	2.92	2.77	2.84	2.40	3.00	3.54	2.31	2.31	2.05	3.14	2.19	2.05	2.77	3.16

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference. Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Appendix – Fuel Price: 2030 Natural Gas Price (Medium Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela-ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	4.80	4.73	6.07	6.22	5.22	5.75	4.45	4.97	4.97	3.98	5.84	4.05	3.98	4.33	5.01
Feb.	5.12	4.13	4.76	4.82	3.99	4.02	3.96	4.33	4.33	3.27	4.22	3.48	3.27	3.77	4.12
Mar.	4.72	4.46	4.20	4.23	4.27	3.81	4.57	4.03	4.03	3.13	4.04	3.65	3.13	3.81	4.24
Apr.	3.71	3.79	2.97	3.00	3.53	3.40	4.16	2.82	2.82	2.72	3.59	3.30	2.72	3.98	4.12
Ma	3.54	3.68	2.81	2.80	3.38	3.29	3.90	2.83	2.83	2.62	3.46	3.10	2.62	3.46	3.88
Jun.	3.33	3.43	2.74	2.75	3.29	3.03	3.42	2.69	2.69	2.47	3.20	2.88	2.47	3.39	3.68
Jul.	3.31	3.42	2.62	2.59	3.31	2.95	3.29	2.80	2.80	2.45	3.13	2.80	2.45	3.21	3.52
Aug.	3.23	3.19	2.44	2.40	3.31	2.82	3.05	2.72	2.72	2.17	2.94	2.62	2.17	3.11	3.50
Sep.	3.36	3.52	2.42	2.38	3.41	3.14	3.23	2.67	2.67	2.03	3.18	2.71	2.03	3.29	3.78
Oct.	3.00	2.99	2.26	2.20	2.91	2.62	2.94	2.62	2.62	1.82	2.69	2.44	1.82	3.36	3.55
Nov.	3.76	3.85	3.30	3.35	3.66	3.71	3.90	2.99	2.99	2.67	3.83	3.07	2.67	3.42	3.90
Dec.	3.76	3.34	3.47	3.55	3.19	3.75	4.35	2.89	2.89	2.56	3.85	2.91	2.56	3.40	3.88

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference. Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Appendix – Fuel Price: 2040 Natural Gas Price (Medium Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela0-ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	5.15	5.07	6.23	6.39	5.34	5.91	4.59	5.11	5.11	4.08	6.03	4.15	4.08	4.47	5.17
Feb.	5.48	4.42	4.89	4.95	4.08	4.13	4.09	4.45	4.45	3.36	4.36	3.56	3.36	3.89	4.25
Mar.	5.06	4.78	4.32	4.34	4.37	3.92	4.72	4.14	4.14	3.21	4.17	3.73	3.21	3.93	4.37
Apr.	3.97	4.06	3.06	3.08	3.61	3.49	4.29	2.90	2.90	2.79	3.70	3.38	2.79	4.11	4.25
Ma	3.79	3.95	2.88	2.88	3.46	3.38	4.02	2.91	2.91	2.69	3.57	3.17	2.69	3.57	4.00
Jun.	3.57	3.67	2.81	2.82	3.36	3.11	3.52	2.77	2.77	2.53	3.30	2.94	2.53	3.50	3.79
Jul.	3.54	3.66	2.70	2.67	3.39	3.04	3.40	2.88	2.88	2.52	3.23	2.87	2.52	3.31	3.63
Aug.	3.46	3.42	2.51	2.46	3.39	2.90	3.14	2.79	2.79	2.23	3.04	2.68	2.23	3.20	3.61
Sep.	3.60	3.77	2.48	2.44	3.48	3.23	3.33	2.75	2.75	2.09	3.28	2.77	2.09	3.39	3.90
Oct.	3.21	3.20	2.32	2.26	2.98	2.69	3.03	2.69	2.69	1.87	2.77	2.50	1.87	3.46	3.66
Nov.	4.03	4.12	3.39	3.44	3.74	3.81	4.03	3.07	3.07	2.75	3.95	3.14	2.75	3.52	4.03
Dec.	4.02	3.57	3.56	3.65	3.27	3.86	4.49	2.97	2.97	2.63	3.97	2.98	2.63	3.51	4.00

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference.
Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Appendix – Fuel Price: 2050 Natural Gas Price (Medium Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela0-ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	5.63	5.54	6.70	6.87	5.61	6.35	4.79	5.49	5.49	4.39	6.29	4.36	4.39	4.66	5.40
Feb.	5.99	4.83	5.25	5.32	4.29	4.43	4.27	4.78	4.78	3.61	4.55	3.74	3.61	4.06	4.44
Mar.	5.53	5.22	4.64	4.66	4.59	4.21	4.93	4.45	4.45	3.45	4.35	3.92	3.45	4.11	4.57
Apr.	4.34	4.44	3.28	3.31	3.79	3.75	4.48	3.12	3.12	3.00	3.86	3.55	3.00	4.29	4.44
Ma	4.15	4.31	3.10	3.09	3.63	3.63	4.20	3.13	3.13	2.89	3.73	3.33	2.89	3.73	4.18
Jun.	3.90	4.02	3.02	3.03	3.53	3.35	3.68	2.97	2.97	2.72	3.45	3.09	2.72	3.65	3.96
Jul.	3.87	4.00	2.90	2.86	3.56	3.26	3.55	3.09	3.09	2.71	3.37	3.01	2.71	3.46	3.79
Aug.	3.78	3.73	2.70	2.65	3.56	3.11	3.28	3.00	3.00	2.40	3.17	2.82	2.40	3.35	3.77
Sep.	3.93	4.13	2.67	2.62	3.66	3.47	3.48	2.95	2.95	2.24	3.43	2.91	2.24	3.54	4.08
Oct.	3.51	3.50	2.49	2.43	3.13	2.89	3.17	2.89	2.89	2.01	2.90	2.62	2.01	3.62	3.82
Nov.	4.41	4.50	3.65	3.70	3.93	4.10	4.21	3.30	3.30	2.95	4.12	3.30	2.95	3.68	4.21
Dec.	4.40	3.91	3.83	3.92	3.43	4.14	4.69	3.19	3.19	2.83	4.15	3.13	2.83	3.67	4.18

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference.
Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Appendix – Fuel Price: 2030 Natural Gas Price (High Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela0-ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	6.47	6.37	8.58	8.80	7.17	8.14	5.73	7.04	7.04	5.62	7.52	5.58	5.62	5.57	6.46
Feb.	6.89	5.56	6.74	6.82	5.49	5.68	5.10	6.13	6.13	4.63	5.44	4.79	4.63	4.86	5.30
Mar.	6.37	6.01	5.95	5.98	5.87	5.39	5.89	5.70	5.70	4.43	5.20	5.02	4.43	4.91	5.46
Apr.	4.99	5.11	4.21	4.24	4.85	4.81	5.36	4.00	4.00	3.84	4.62	4.54	3.84	5.12	5.30
Ma	4.77	4.96	3.97	3.96	4.65	4.65	5.02	4.01	4.01	3.70	4.46	4.27	3.70	4.45	5.00
Jun.	4.49	4.62	3.88	3.88	4.52	4.29	4.40	3.81	3.81	3.49	4.12	3.96	3.49	4.37	4.73
Jul.	4.46	4.60	3.71	3.67	4.56	4.18	4.24	3.96	3.96	3.47	4.03	3.85	3.47	4.13	4.53
Aug.	4.35	4.30	3.45	3.39	4.56	3.99	3.93	3.84	3.84	3.07	3.79	3.61	3.07	4.00	4.5
Sep.	4.53	4.75	3.42	3.36	4.69	4.45	4.16	3.78	3.78	2.87	4.10	3.73	2.87	4.23	4.87
Oct.	4.04	4.03	3.20	3.11	4.01	3.70	3.78	3.70	3.70	2.58	3.46	3.36	2.58	4.32	4.56
Nov.	5.07	5.18	4.67	4.74	5.03	5.25	5.03	4.23	4.23	3.78	4.93	4.22	3.78	4.40	5.03
Dec.	5.06	4.50	4.91	5.03	4.39	5.31	5.60	4.09	4.09	3.63	4.96	4.01	3.63	4.38	5.00

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference.
Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Appendix – Fuel Price: 2040 Natural Gas Price (High Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela0-ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	7.62	7.51	9.77	10.02	8.4	9.26	6.62	8.01	8.01	6.40	8.69	6.53	6.40	6.44	7.46
Feb.	8.12	6.55	7.66	7.76	6.42	6.47	5.90	6.98	6.98	5.26	6.29	5.60	5.26	5.61	6.13
Mar.	7.50	7.08	6.77	6.80	6.87	6.14	6.80	6.49	6.49	5.04	6.01	5.87	5.04	5.67	6.31
Apr.	5.88	6.02	4.79	4.82	5.68	5.47	6.19	4.55	4.55	4.37	5.34	5.31	4.37	5.92	6.13
Ma	5.62	5.85	4.52	4.51	5.44	5.29	5.80	4.56	4.56	4.21	5.15	4.99	4.21	5.15	5.77
Jun.	5.29	5.44	4.41	4.42	5.29	4.88	5.08	4.34	4.34	3.97	4.76	4.63	3.97	5.05	5.47
Jul.	5.25	5.42	4.22	4.18	5.33	4.76	4.90	4.51	4.51	3.95	4.66	4.51	3.95	4.77	5.24
Aug.	5.12	5.06	3.93	3.86	5.33	4.54	4.54	4.37	4.37	3.50	4.38	4.22	3.50	4.62	5.20
Sep.	5.33	5.59	3.89	3.82	5.48	5.06	4.81	4.30	4.30	3.27	4.73	4.36	3.27	4.89	5.63
Oct.	4.76	4.74	3.64	3.54	4.69	4.21	4.37	4.21	4.21	2.94	4.00	3.93	2.94	5.00	5.28
Nov.	5.97	6.10	5.32	5.39	5.89	5.97	5.81	4.81	4.81	4.30	5.69	4.94	4.30	5.08	5.81
Dec.	5.96	5.29	5.58	5.72	5.14	6.04	6.47	4.65	4.65	4.13	5.73	4.69	4.13	5.06	5.77

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference. Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

Appendix – Fuel Price: 2050 Natural Gas Price (High Level), $/MMBTU

Month	MIS_ Central	MIS_ East	NY_ East	NY_ West	PJM_C OMD	PJM_ Dela0- ware	PJM_ Dom	PJM_NJ Coast	PJM_NJ Land	PJM_ PECO	PJM_ SMAC	PJM_ WEST	PJM_ West MAC	SC_ TVA	SC_ VACA
Jan.	8.71	8.58	11.38	11.67	9.86	10.79	7.72	9.33	9.33	7.45	10.13	7.66	7.45	7.51	8.70
Feb.	9.28	7.48	8.93	9.03	7.54	7.53	6.87	8.13	8.13	6.13	7.33	6.58	6.13	6.54	7.14
Mar.	8.57	8.09	7.88	7.92	8.07	7.15	7.93	7.56	7.56	5.87	7.01	6.89	5.87	6.61	7.35
Apr.	6.72	6.87	5.58	5.62	6.66	6.37	7.22	5.30	5.30	5.09	6.22	6.24	5.09	6.90	7.14
Ma	6.42	6.68	5.26	5.25	6.39	6.16	6.77	5.32	5.32	4.91	6.01	5.86	4.91	6.00	6.73
Jun.	6.04	6.22	5.14	5.15	6.21	5.68	5.92	5.05	5.05	4.62	5.55	5.44	4.62	5.88	6.38
Jul.	6.00	6.19	4.92	4.86	6.26	5.54	5.71	5.25	5.25	4.6	5.43	5.29	4.60	5.56	6.11
Aug.	5.85	5.78	4.58	4.50	6.26	5.29	5.29	5.09	5.09	4.07	5.11	4.96	4.07	5.39	6.07
Sep.	6.09	6.39	4.53	4.45	6.44	5.89	5.60	5.01	5.01	3.81	5.52	5.12	3.81	5.70	6.56
Oct.	5.44	5.42	4.24	4.13	5.51	4.91	5.10	4.91	4.91	3.42	4.66	4.61	3.42	5.82	6.15
Nov.	6.82	6.97	6.20	6.28	6.92	6.96	6.77	5.60	5.60	5.01	6.64	5.80	5.01	5.92	6.77
Dec.	6.81	6.05	6.50	6.66	6.04	7.04	7.54	5.42	5.42	4.81	6.68	5.50	4.81	5.90	6.73

Natural Gas's carbon content: 0.0536 metric ton/MMBTU

Annual price is obtained from the price projection of AEO 2020; Low Level is the AEO High Resource Scenario; High Level is the AEO Low Resource Scenario; Medium is the AEO Reference. Natural gas prices are fluctuated based on 2019 state-level Natural Gas price report. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PEU_DMcf_m.htm

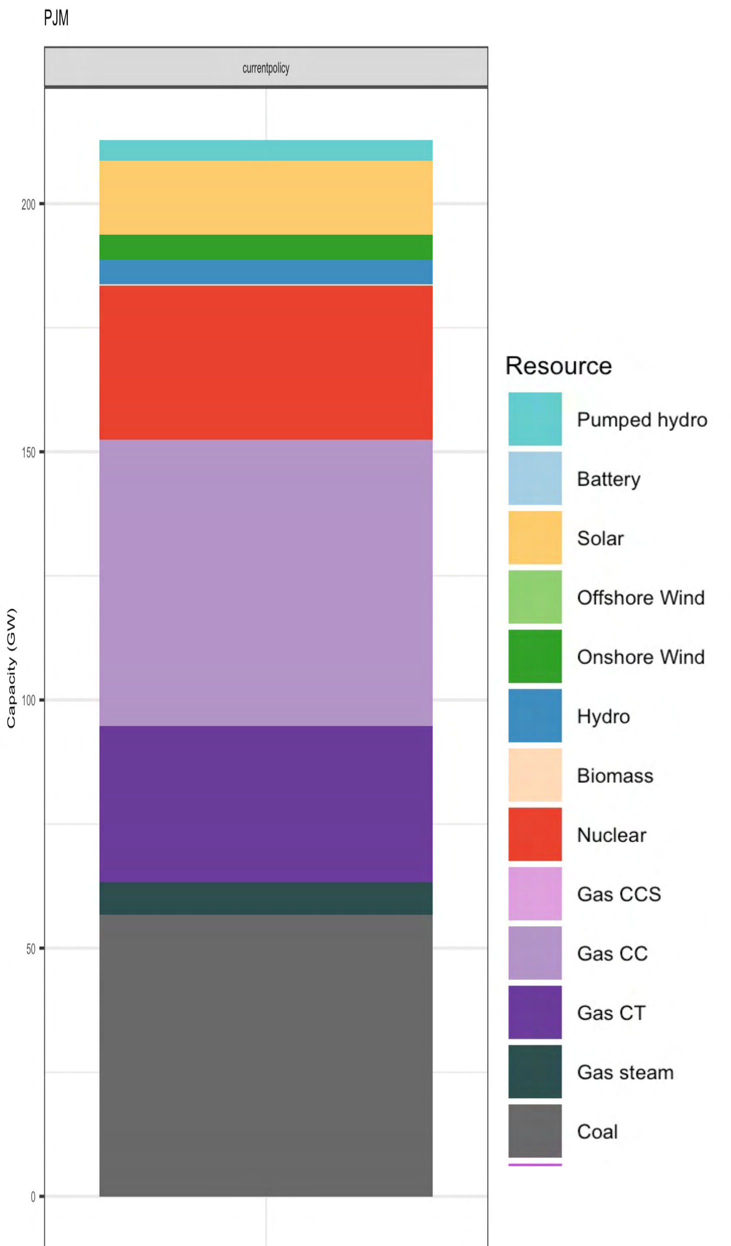
Appendix – Fuel Price: Other Fuels

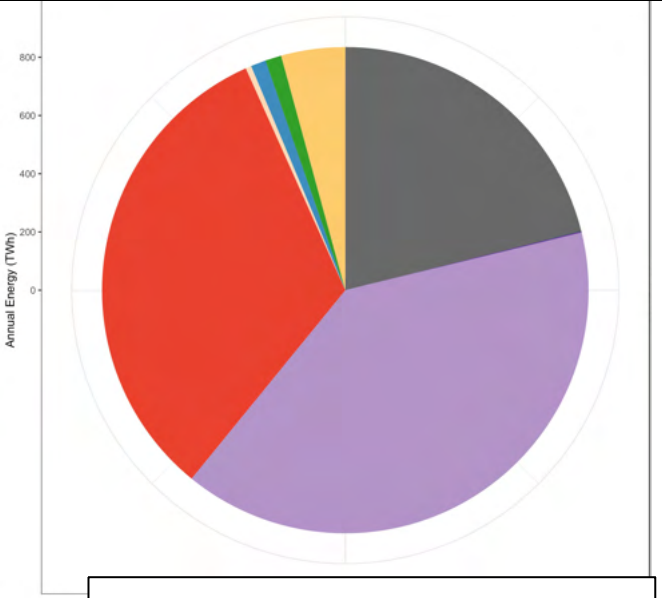
$/MMBTU	2030	2040	2050
Coal: West North Central	1.73	1.80	1.84
Coal: East North Central	1.92	1.90	1.87
Coal: Mid Atlantic	2.20	2.03	2.01
Coal: South Atlantic	2.57	2.53	2.53
Uranium	0.70	0.72	0.74
Zero Carbon Fuel	14.00	14.00	14.00

Coal's carbon content 0.09552 metric ton/MMBTU

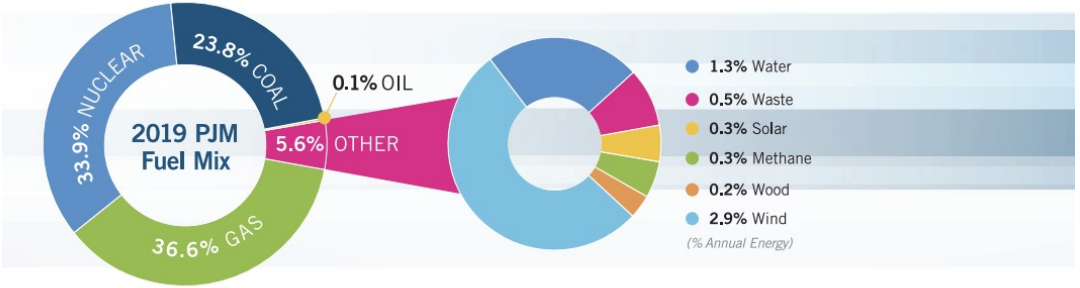
Annual price is obtained from the price projection of AEO 2020;
Zero Carbon Fuel price is from the Princeton *Net-Zero America* study (Larson et al. 2021) and reflects the approximate 2050 price for hydrogen in the E+ scenario. See Larson, et al., 2021, *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, Final report, Princeton University, Princeton, NJ, 29 October. https://netzeroamerica.princeton.edu/

Appendix – Validation of 2019 PJM GenX dispatch simulation results vs. historical

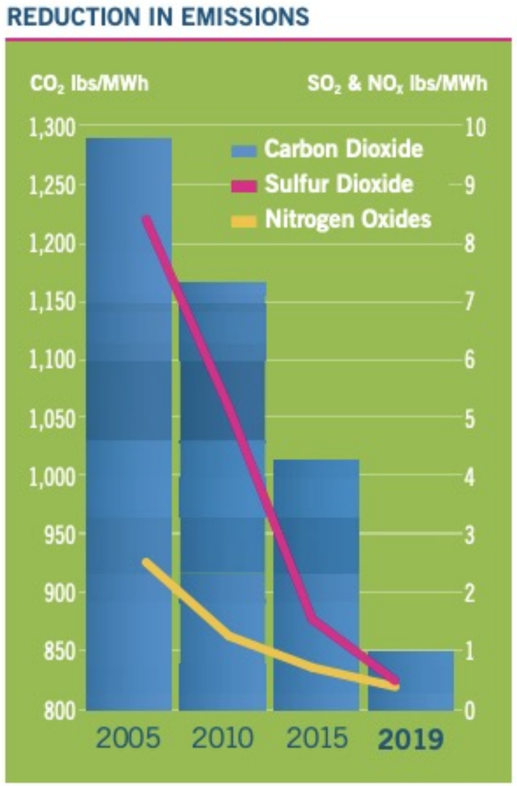




GenX 2019 Simulated Energy Shares (Actual):
Coal: 21% (23.8%)
Gas: 40% (36.6%)
Nuclear: 32% (33.9%)
Others: 7% (5.6%)



https://www.pjm.com/-/media/about-pjm/newsroom/annual-reports/2019-annual-report.ashx?la=en#:~:text=Over%20the%20course%20of%20the,and%20coal%20at%2024%20percent.



GenX Simulated Emissions Rate (Actual):
0.42 (0.39) Metric ton/MWh;

PRINCETON UNIVERSITY

ZERO LAB

Zero-carbon Energy Systems Research and Optimization Laboratory

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