APPENDIX

PRINCETON UNIVERSITY

ZERO LAB

Zero-carbon Energy Systems Research and Optimization Laboratory

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

Summary for Decision Makers

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

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Access and download full report, data, and other resources at **https://zenodo.org/record/6345571**

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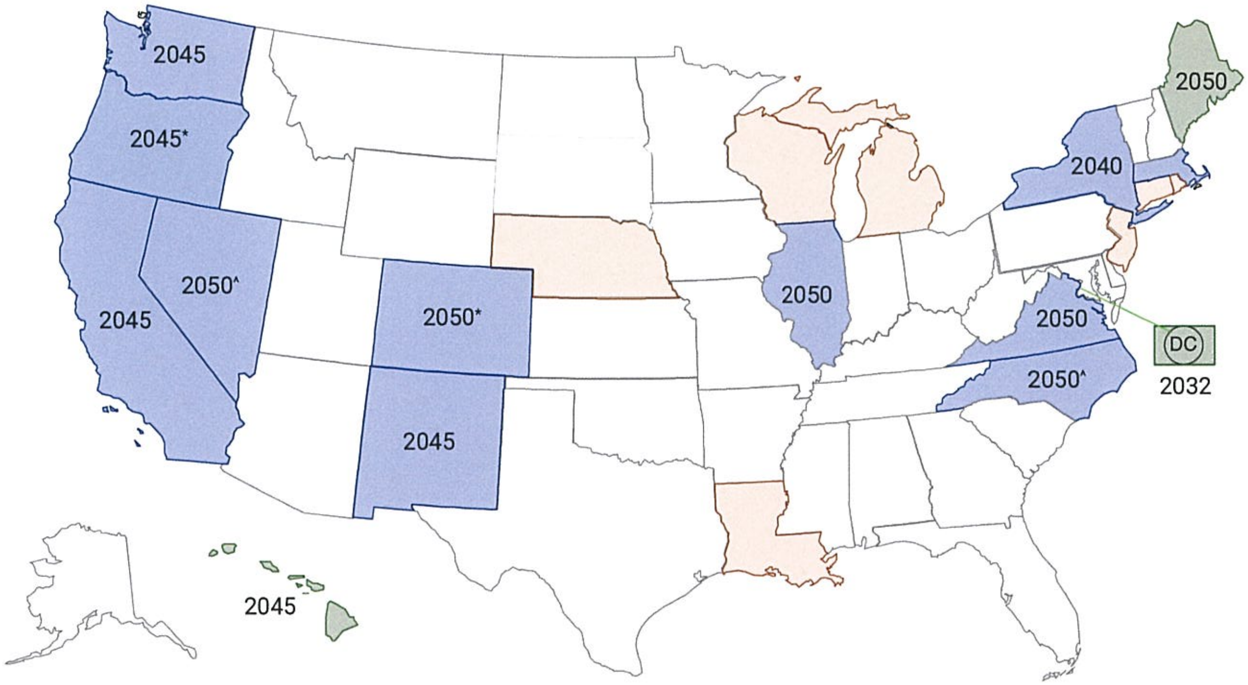
New Jersey is among a vanguard of states pursuing a transition to a 100% carbon-free electricity system.



- States with legislative requirements of 100% carbon-free electricity supply, carbon-neutral electricity, 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/

3x

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* included comprehensive modeling of pathways to transform the state's energy system (the "Integrated Energy Plan") and outlined 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 nuclear units, 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 requirement by 2030 and 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.

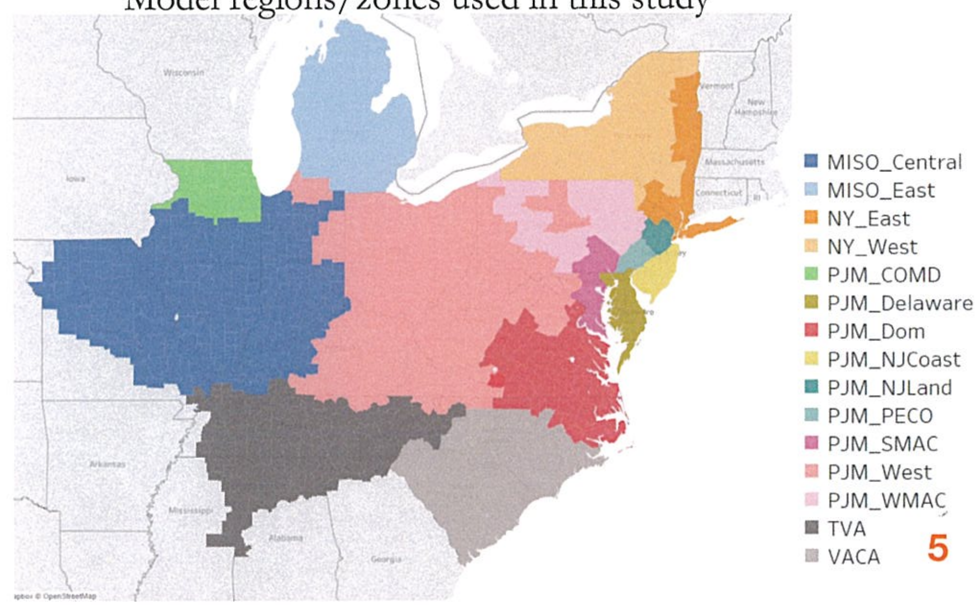
4x

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, 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, two in NJ, 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



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Key findings

1. A transition to **100% carbon-free electricity is feasible while maintaining reliability and with reductions in bulk electricity supply costs** (-25% to -5% 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 (-20% to +4% 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 -13% to +11% relative to 2019 costs if all states in the region pursue 100% carbon-free electricity.

6x

Key technology options

- The least-cost pathway includes substantial expansion of **utility-scale solar**, new gas **combined cycle capacity** and conversion 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.

7x

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 if 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 load and help compensate for increasing demand for 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 of half a billion dollars annually for NJ consumers.
- 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 should be converted to run on zero-carbon fuel by 2050 when 100% carbon-free electricity is required.
- NJ will need to **expand transmission** to increase deliverability between the coastal area and inland area in the near term to integrate offshore wind as well as significantly strengthen ties to neighboring PJM & NY areas in the longer term to enable greater imports.

8x

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) 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.

9x

Overview of scenarios

Three main scenarios modeled in this study:

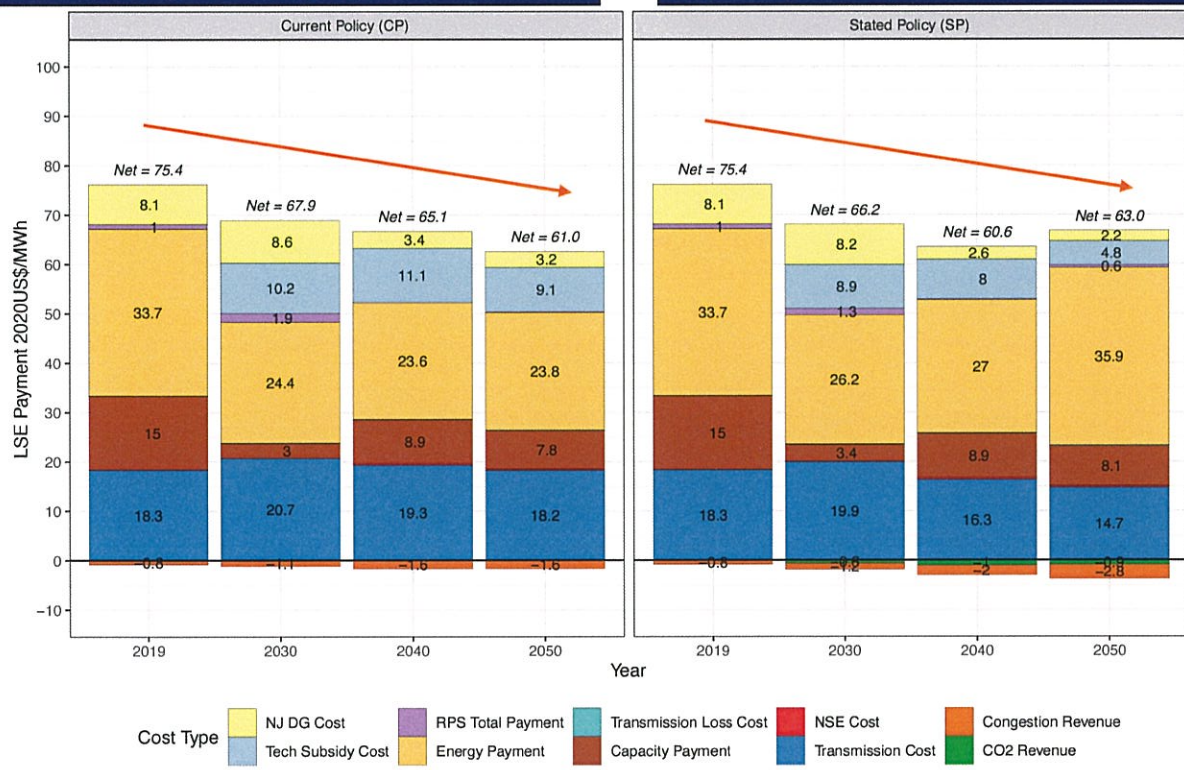
1. **Current Policies (CP):** a business-as-usual (BAU) scenario, with all electricity sector-related legislation and regulation as codified as of the end of 2020. Policies include state renewable portfolio standard (RPS) and clean electricity standard (CES) policies, technology-specific RPS carve-outs (e.g., distributed solar) and 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. This includes for New Jersey 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 and 90% by 2040.

10x

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 19%

SP: Under Stated Policies, a 100% emission-free electricity supply will cost NJ electricity consumers 16% less than payments for bulk electricity supply* in 2019 (spanning 5%-25% cost decrease across the range of possible futures modeled)



*** Note: 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.

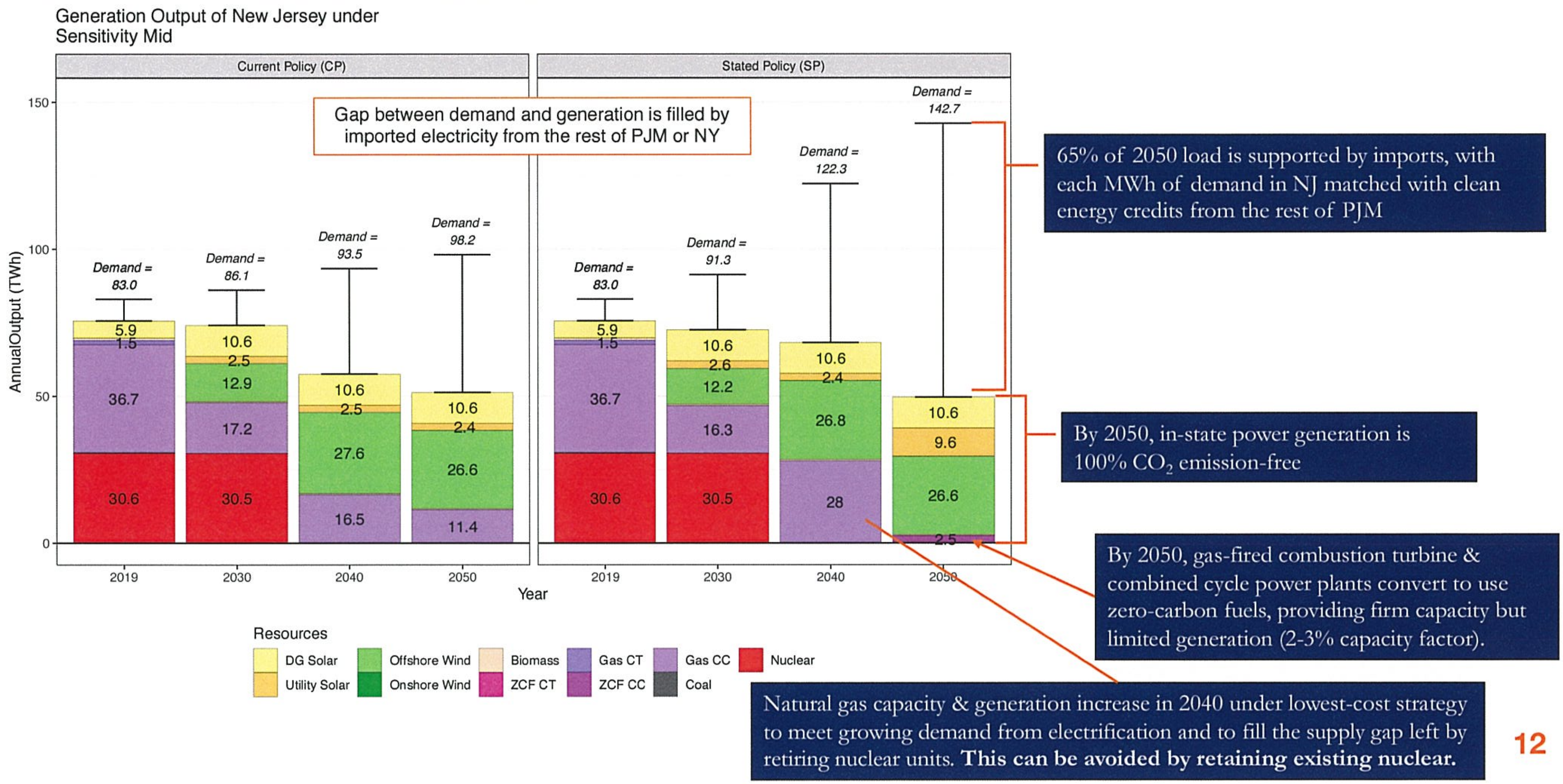
We do not make an attempt to assess potential costs or savings related to impacts of distributed solar PV on distribution networks, which are out of scope for this study, but relevant for consideration of the full cost/benefit of distributed solar installation.

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.

11X

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



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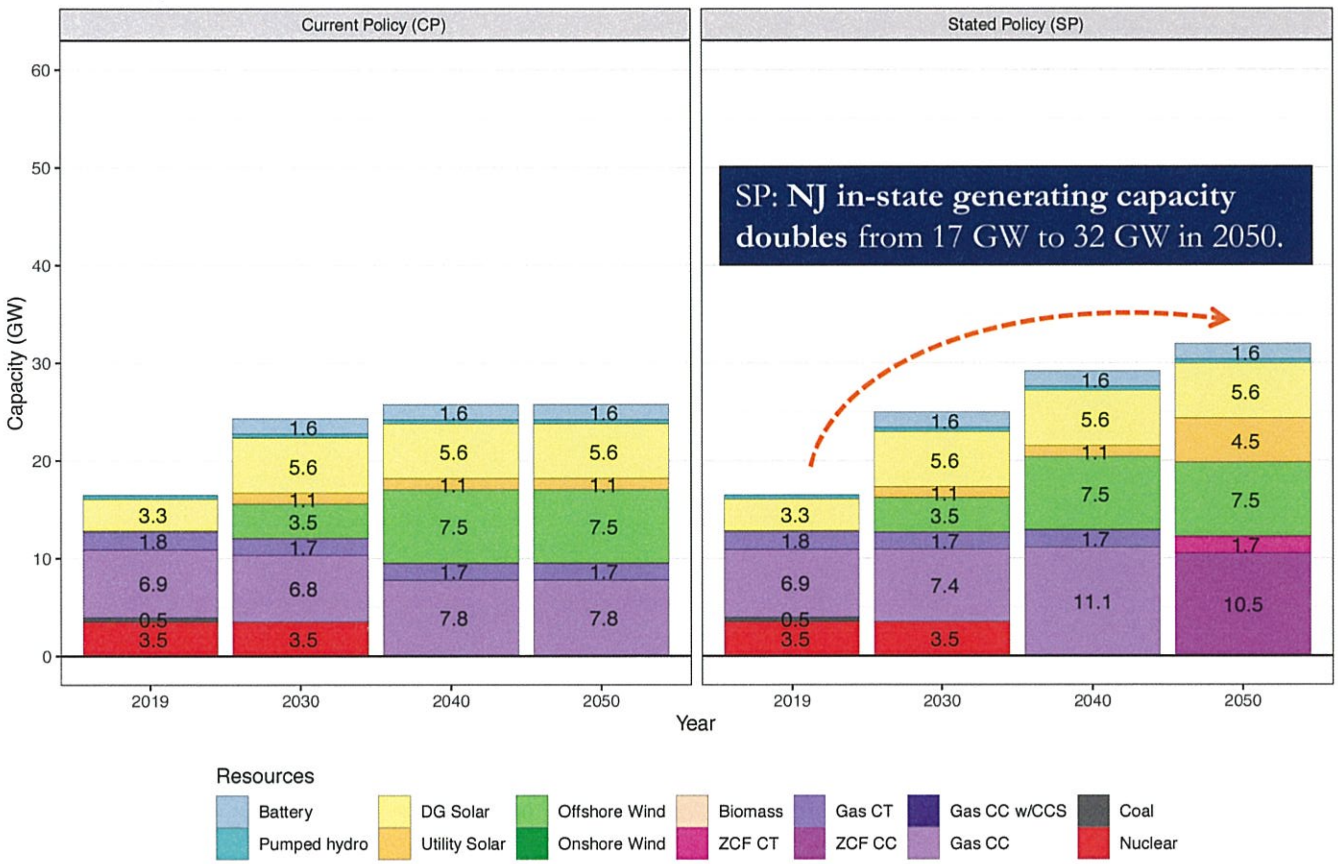
The lowest-cost strategy to reach 100% carbon-free electricity sees New Jersey's installed generating capacity double by 2050, formed by a diverse and clean resource mix.

Generation Capacity of New Jersey under Sensitivity Mid



The least-cost pathway to 100% carbon-free electricity includes **expansion of utility-scale solar** and **new gas combined cycle capacity,** 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 ZEC support beyond 2030.

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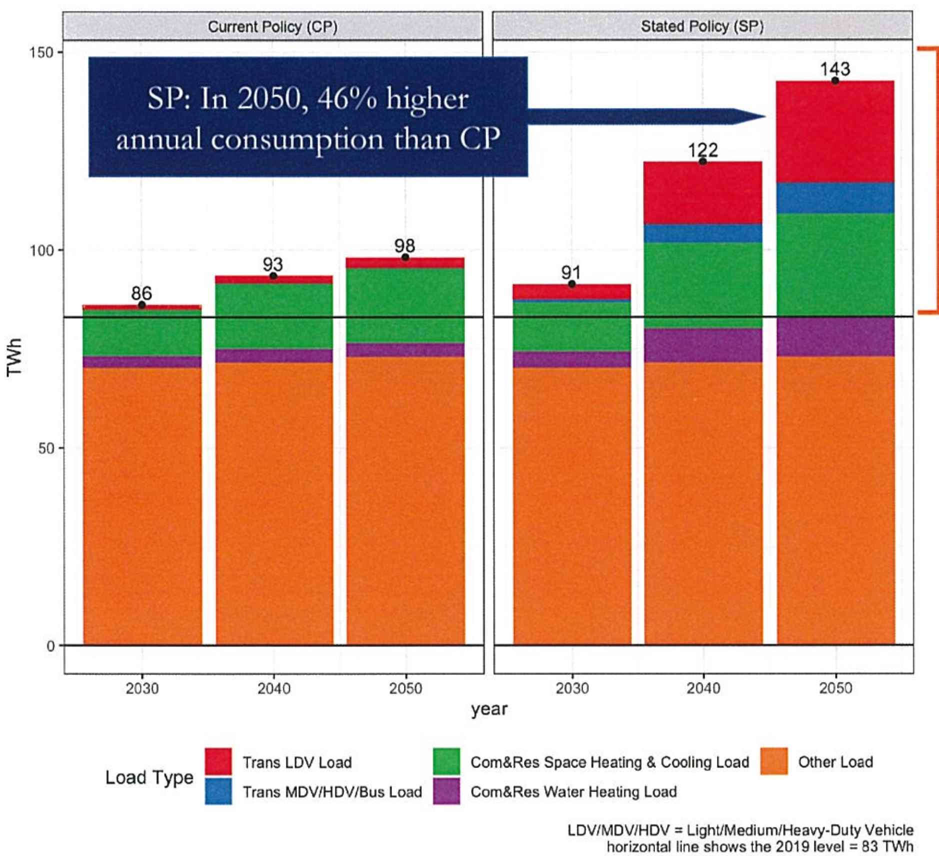
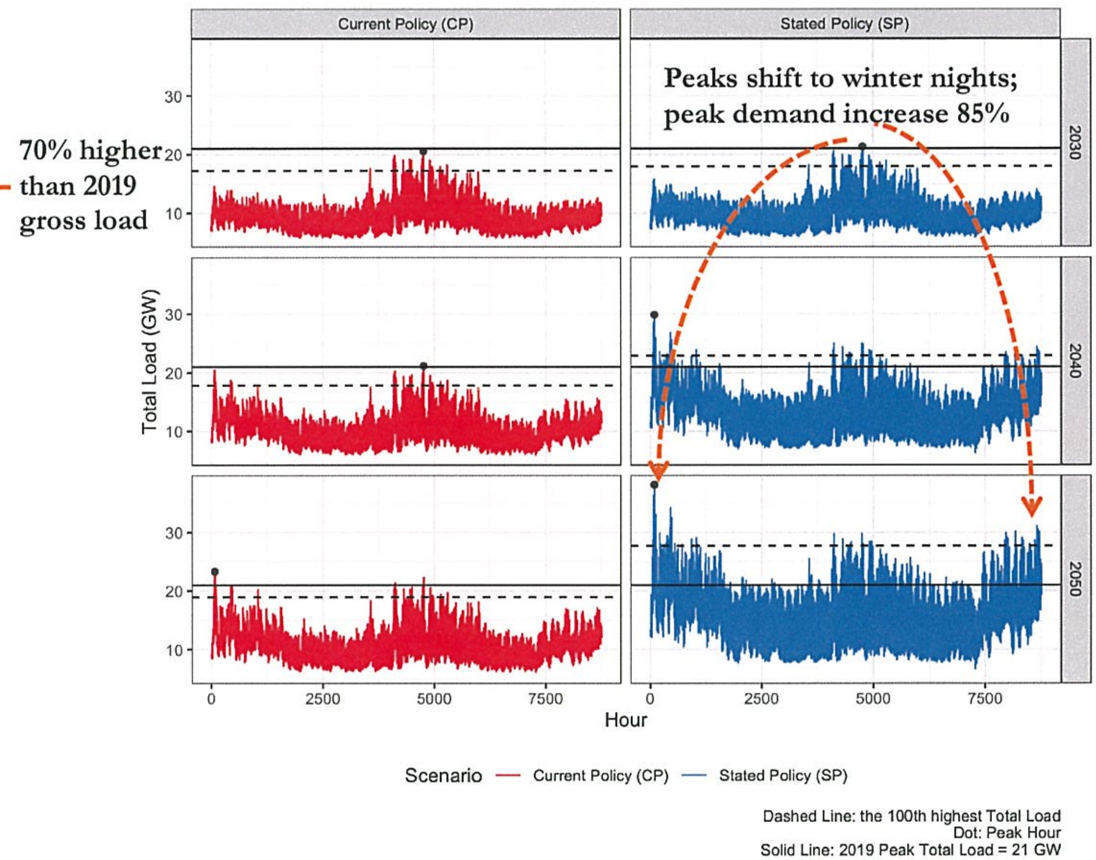
Electricity demand could increase significantly and patterns of consumption shift dramatically (from summer afternoon to winter overnight peak demand) due to electrification of vehicles and buildings





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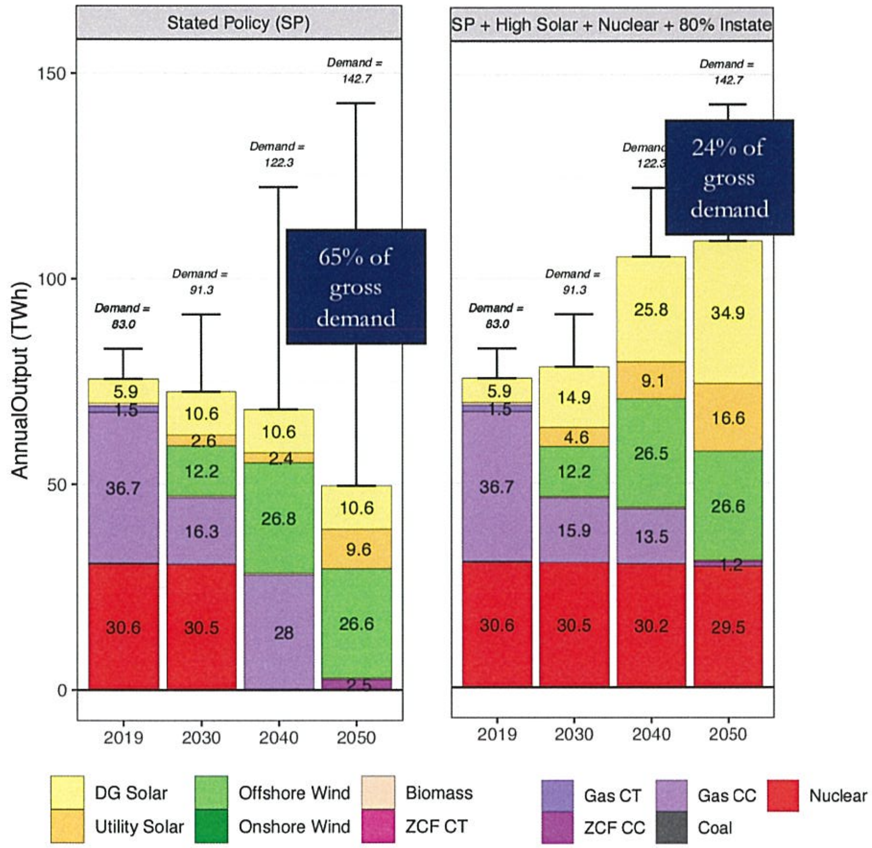
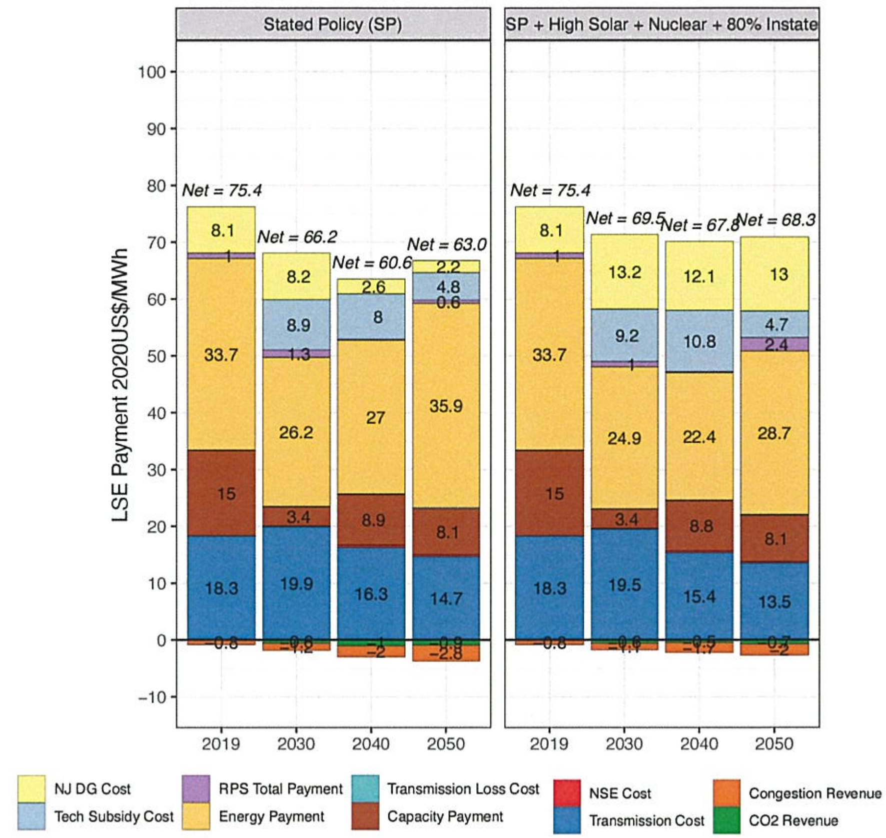
The lowest-cost pathways to 100% carbon-free electricity depart from NJ's current policy approach, which prioritizes in-state and distributed generation

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.





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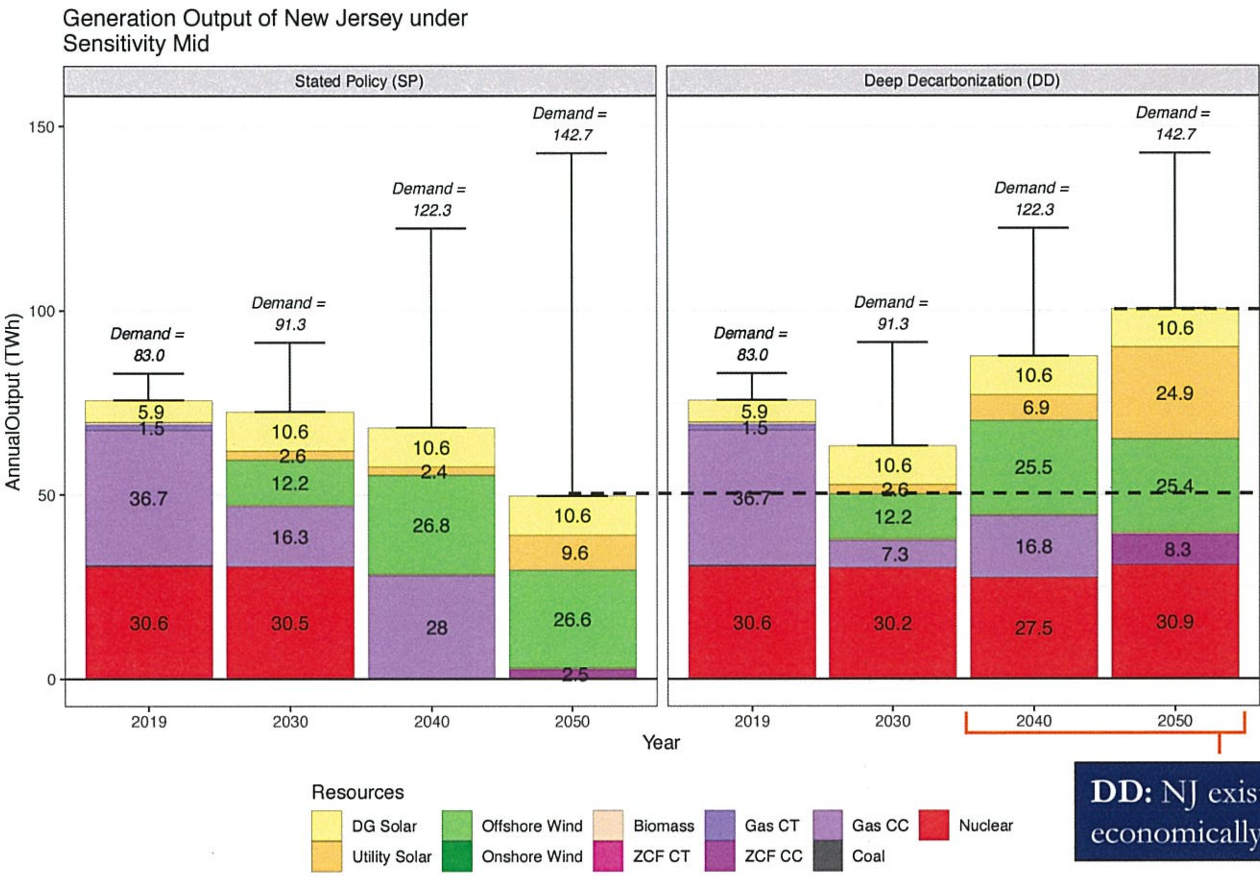
If all states in the region follow New Jersey on the path to deep decarbonization, greater demand for clean electricity across the region drives up import costs and NJ relies more on in-state clean energy resources.



DD: As a result of more expensive import cost, 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.

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).

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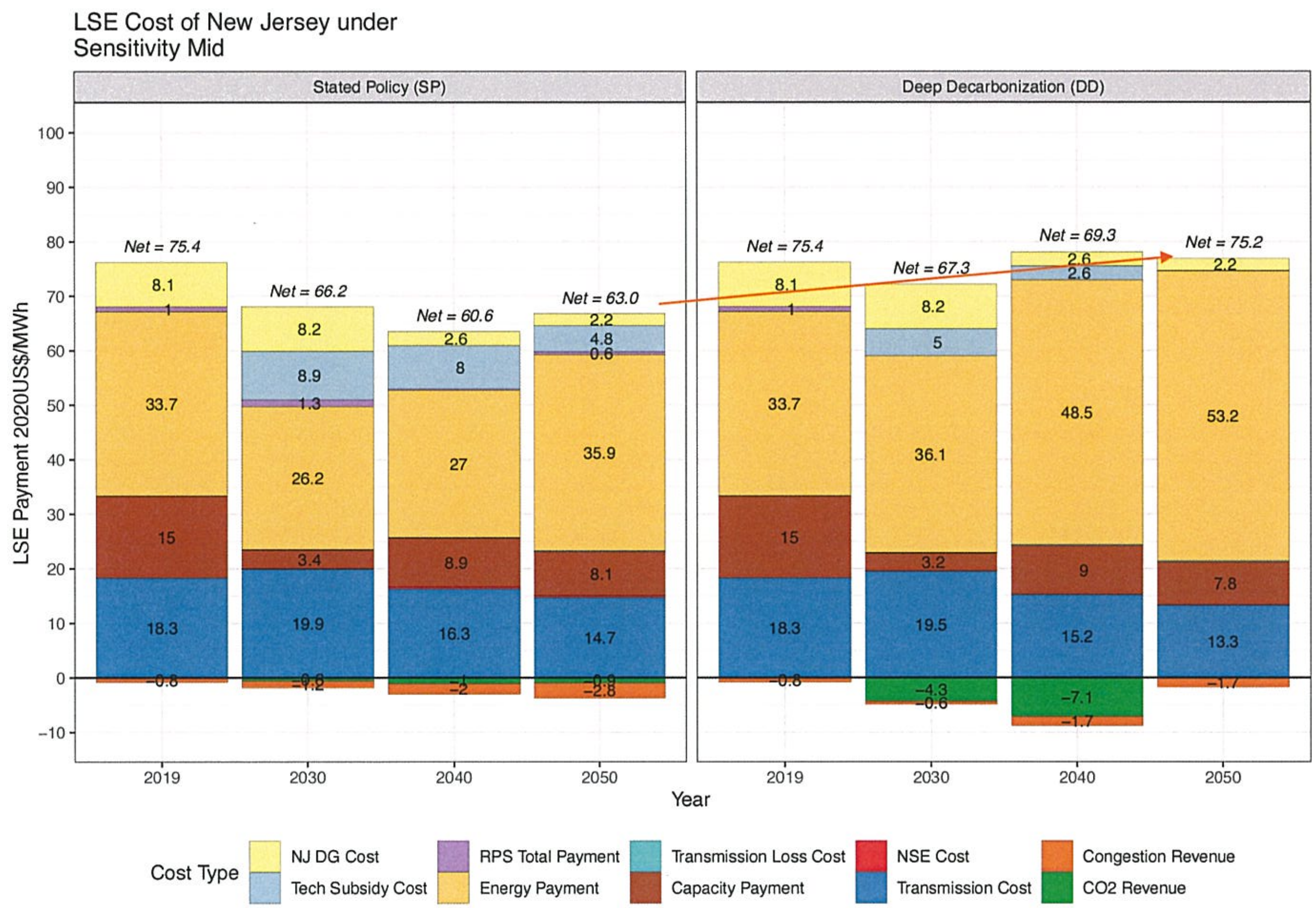
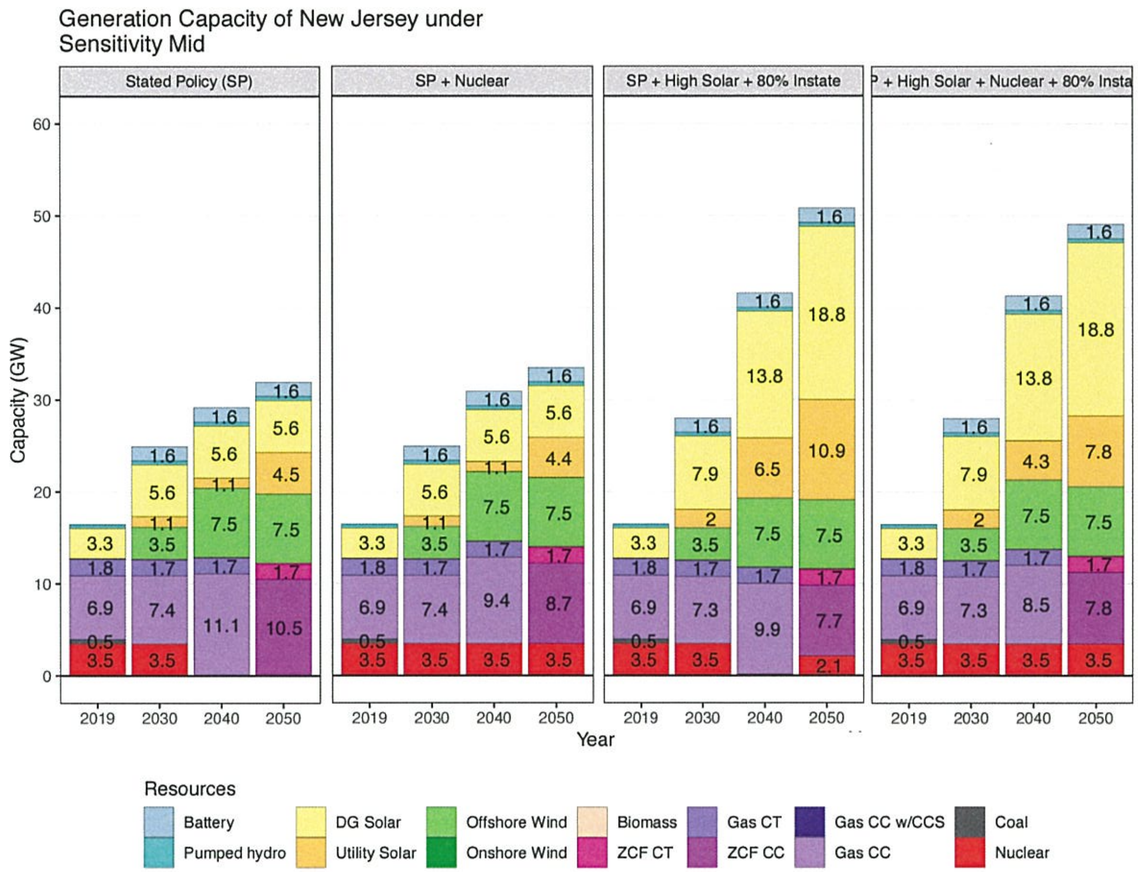
If all states in the region pursue parallel deep decarbonization goals, the costs of reaching 100% carbon-free electricity in NJ increase by 16-20% in 2050 and range from -13% to +11% relative to 2019 costs.



17x

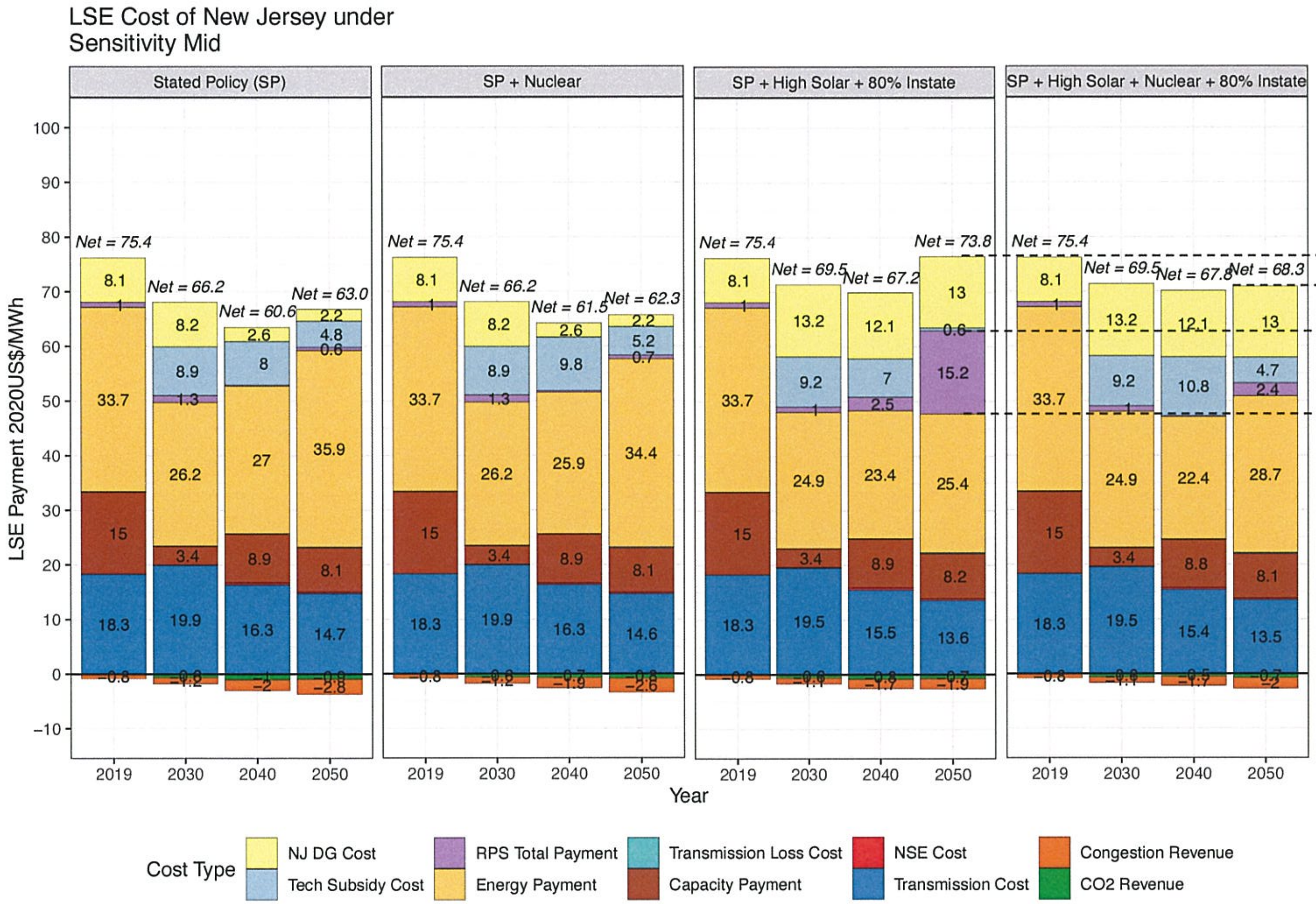
Preserving NJ's nuclear generators can reduce dependence on imports and avoid an increase in natural-gas fired generation and associated CO_2 emissions and air pollution in the 2030s



- 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.

18X

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% emission-free supply goal, retaining existing nuclear capacity will reduce New Jersey 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 offshore wind and new nuclear built in 2050 to reach 100% carbon-free supply with 80% of generation from in-state.

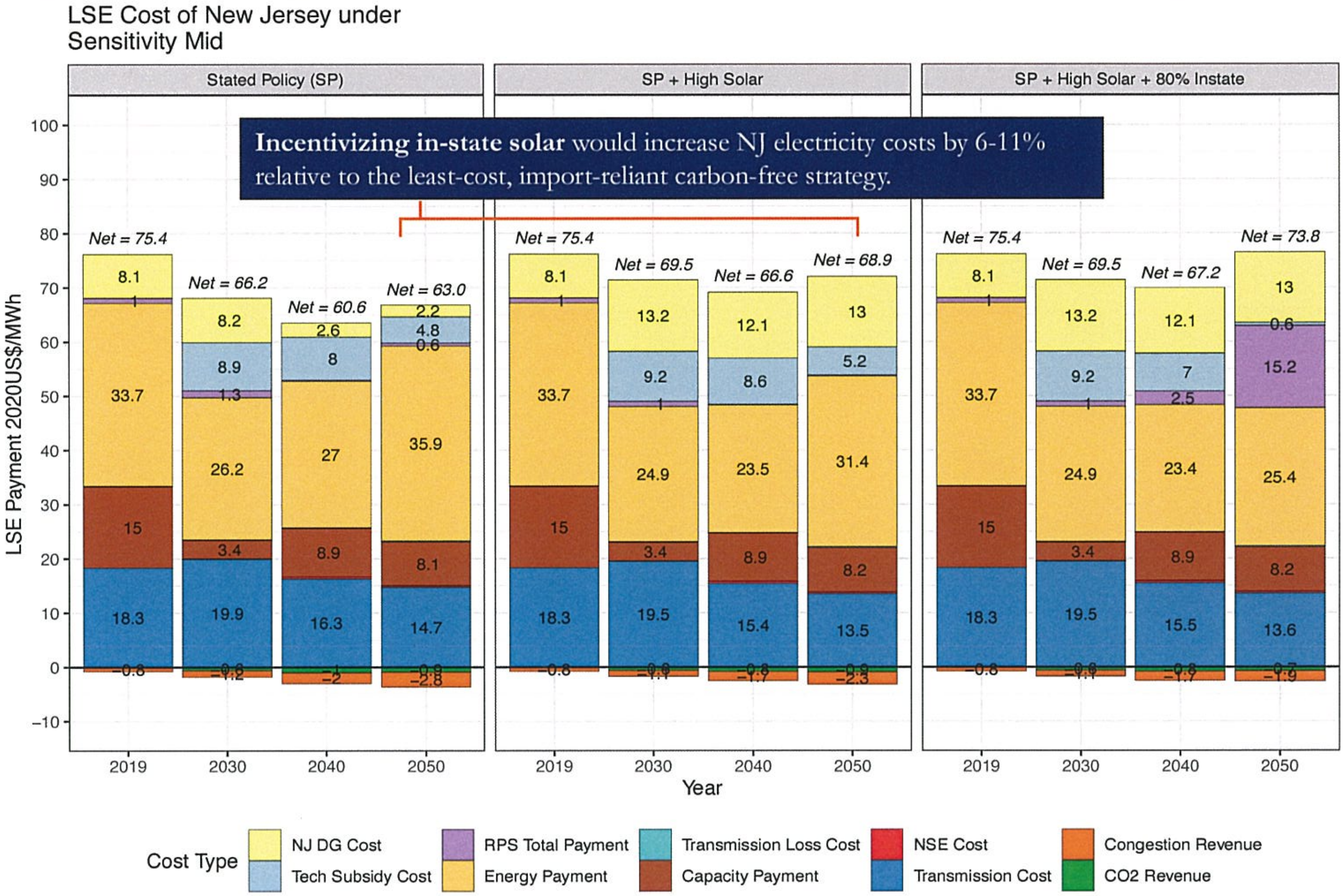
19x

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 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).



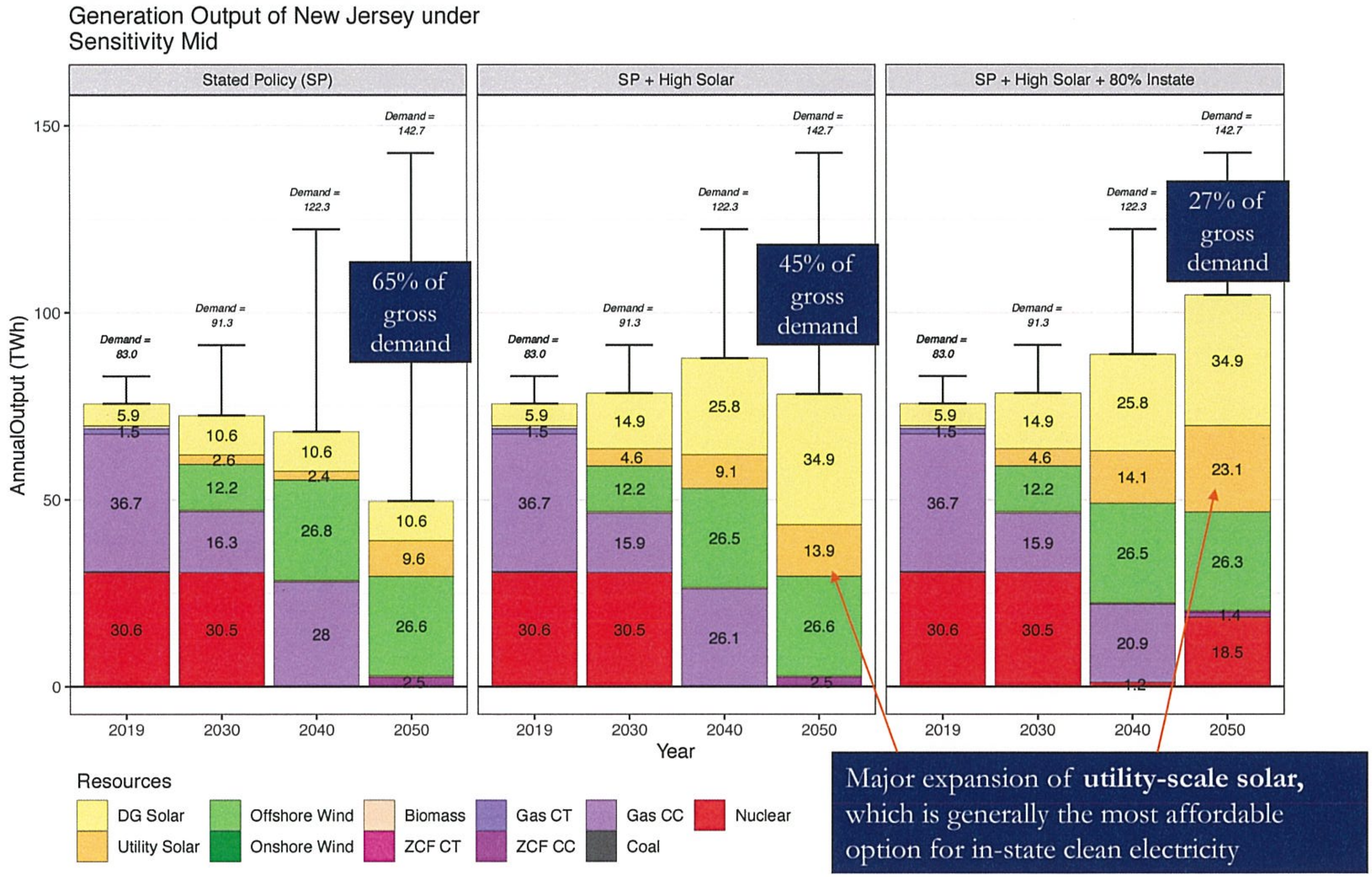
20x

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

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).



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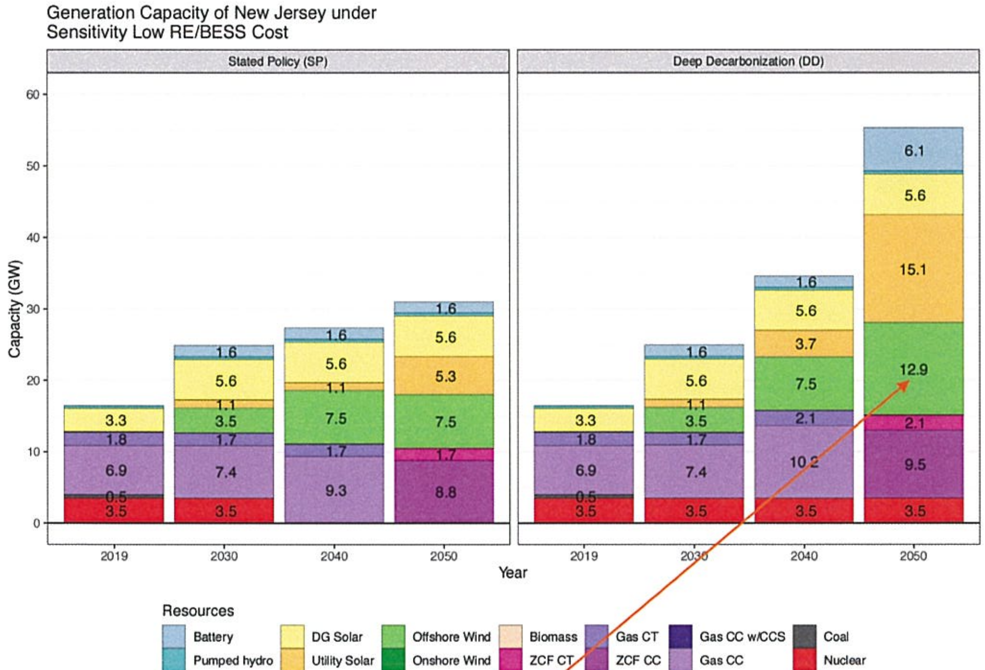
Offshore wind is one of the more expensive options for NJ decarbonization and is rarely deployed beyond current mandated levels across scenarios modeled in this report



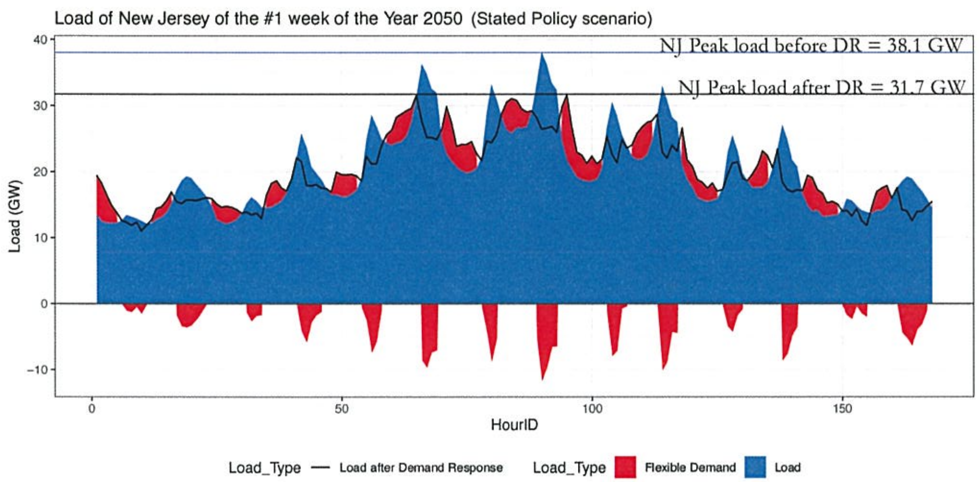
Deep Decarbonization scenario (DD): **Offshore wind (OSW) can help hedge NJ against the potential for higher import costs.** Assuming low capital cost projections for OSW, other renewables, and storage (*Low RE/BESS* cost sensitivity), OSW expands beyond the current state mandate to 12.9 GW in the year 2050 in this scenario.

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

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

22x

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.

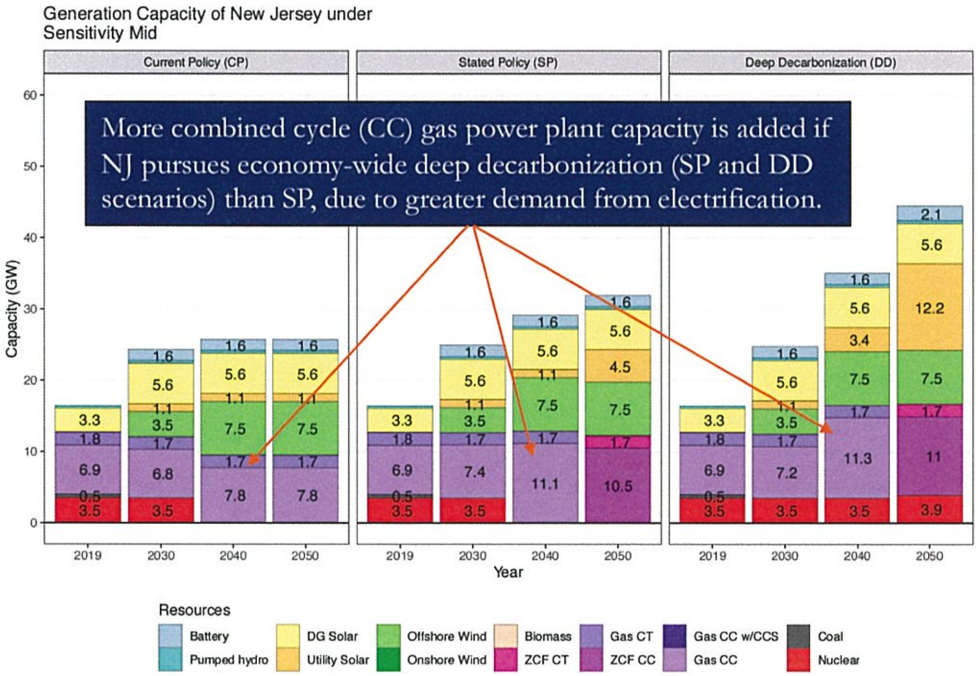
Impact of flexible load shifting on New Jersey electricity supply costs (SP scenario)

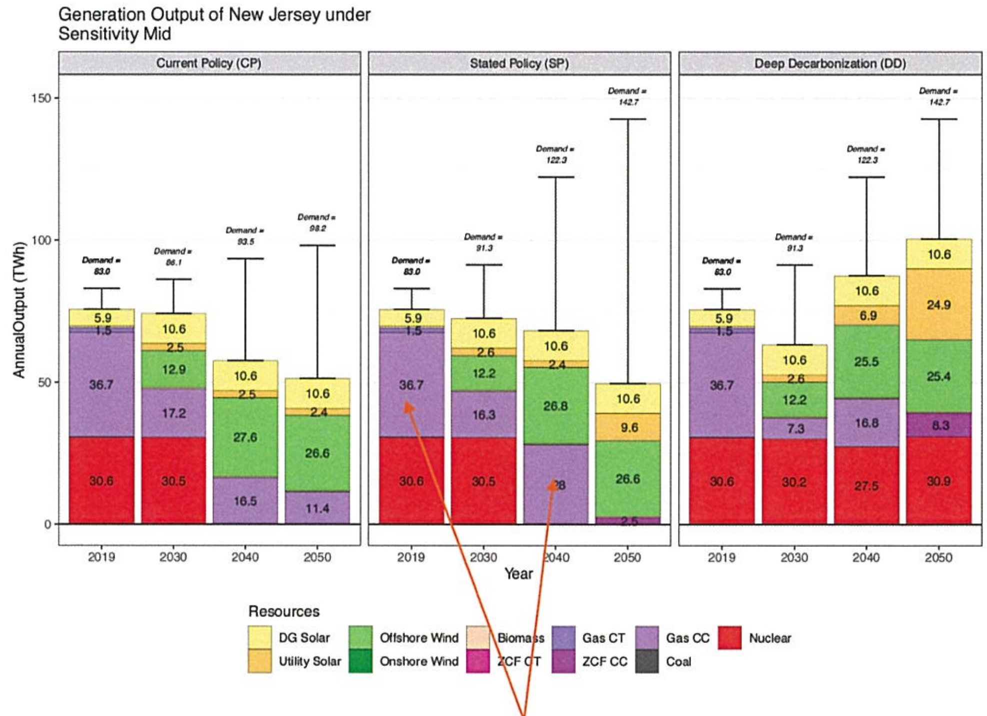
Year | Scenario	SP & No Flexible Load	Stated Policy (SP)	Diff.
2030	67.1	66.2	-\$0.9/MWh
2040	62.9	60.6	-\$2.3/MWh
2050	67.1	63.0	-\$4.1/MWh

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

23x

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



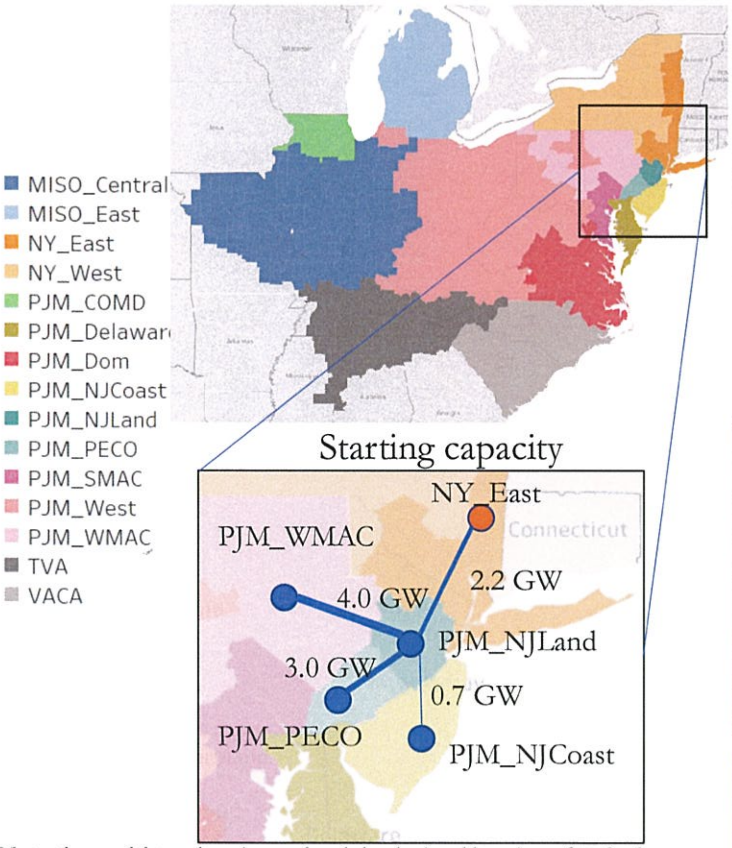


CC capacities expand from 2019 but gas-fired generation (and associated emissions) decrease, indicating that CCs derive an increasing share of value from capacity payments and less frequent but high-price periods.

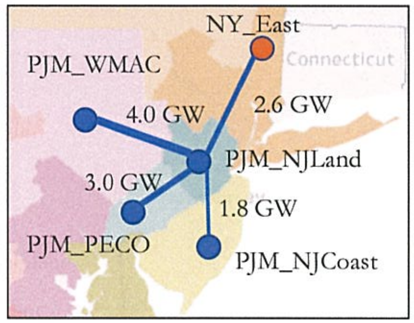
By 2050, gas-fired capacity converts to run on zero-carbon fuel (ZCF) to meet 100% carbon-free requirements in SP and DD scenarios.

24x

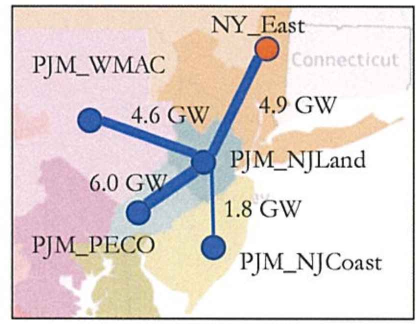
NJ will need to expand transmission between coastal and inland areas in the near term to integrate offshore wind as well as significantly strengthen ties to neighboring PJM & NY areas in the longer term



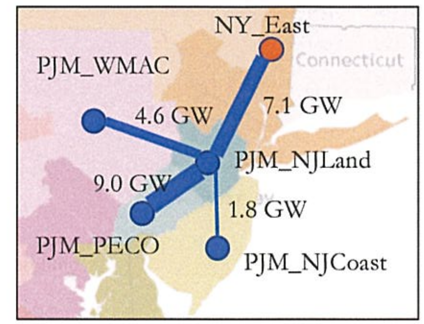
Note: the model topology is zonal and the depicted location of nodes here are for demonstrative purposes only. Lengths of lines do not have physical meanings. Widths of lines are proportional to the inter-zonal transmission capability. Blue nodes represent PJM zones; orange are neighboring region zones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



CP 2030

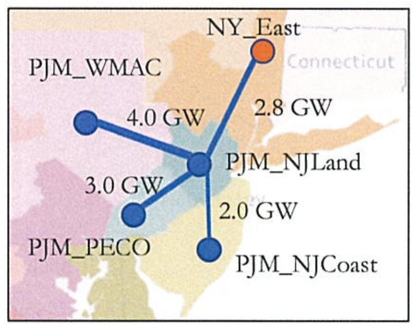


CP 2040

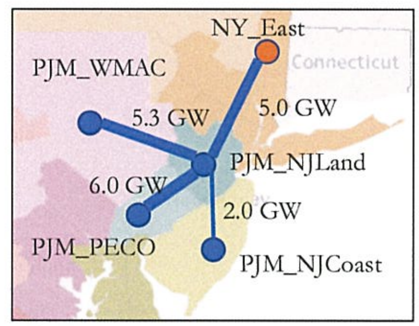


CP 2050 (+12.6 GW since 2021)

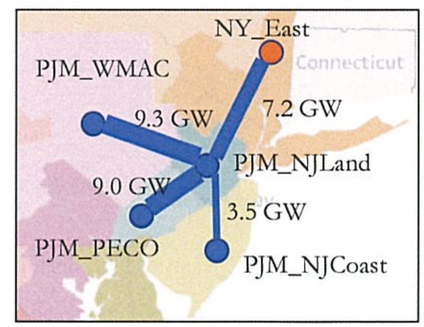
SP 2030



SP 2040

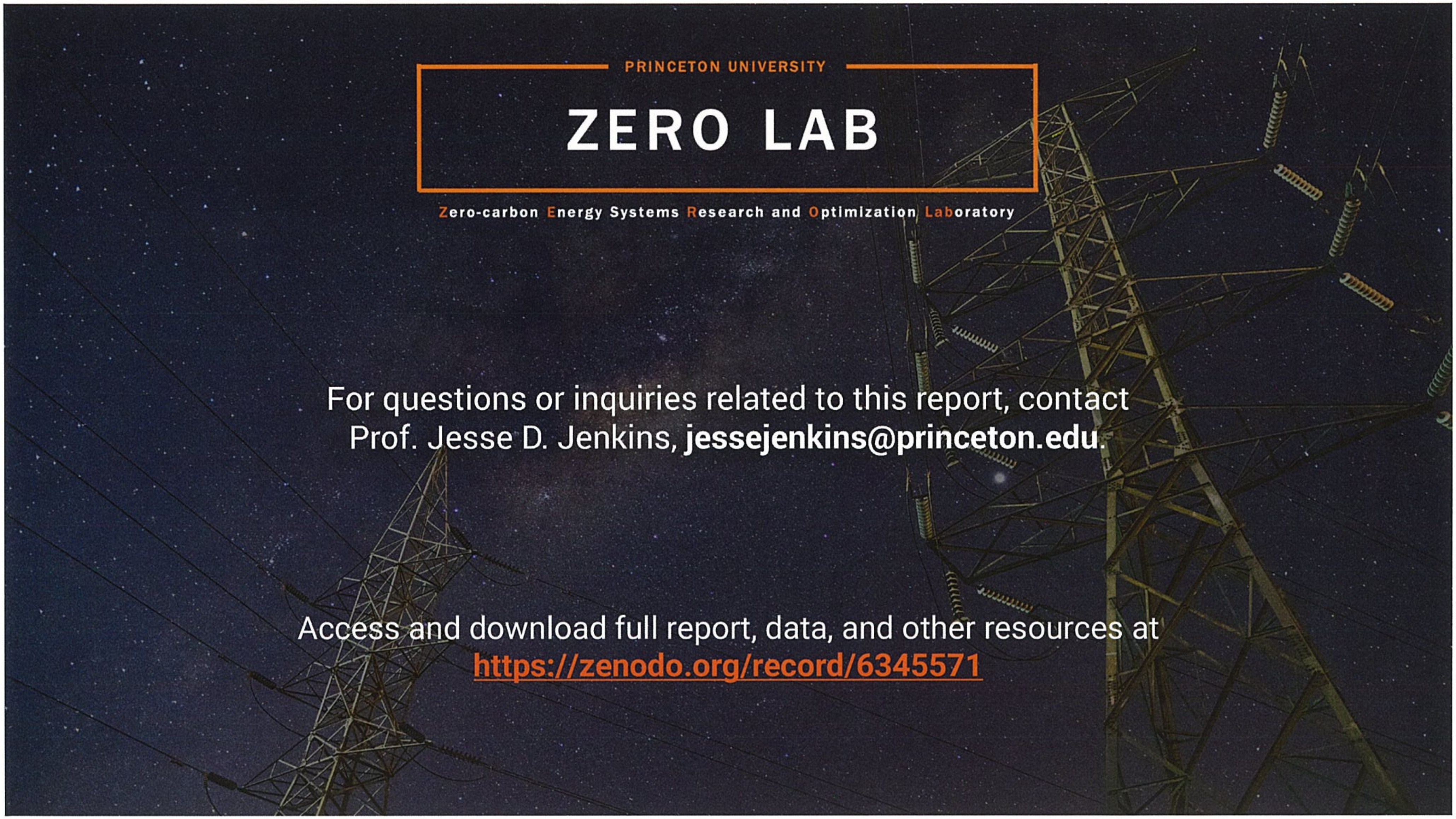


SP 2050 (+19.1 GW since 2021)



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

25x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