Solar and Storage Integration in the Southeast

Economics, Reliability, Operations

October 3, 2024

This work was funded by the U.S. Department of Energy Solar Energy Technologies Office, under Contract No. DE-AC02-05CH11231.

Agenda

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- Background
  - Project Overview
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  - Methods and Scenarios
- Results
  - Capacity expansion
  - Generation and emissions
  - Economics
  - Reliability
  - Operations
- Key Takeaways

Webinar Logistics

- We are recording the webinar.
- Because of the large number of participants, everyone is muted.
- Please use the Q&A box to send us questions at any time during the presentation.
- We will put the link to the slides in the chat box.
- We will also send links to the recording and slides to everyone registered for this webinar in a few days.

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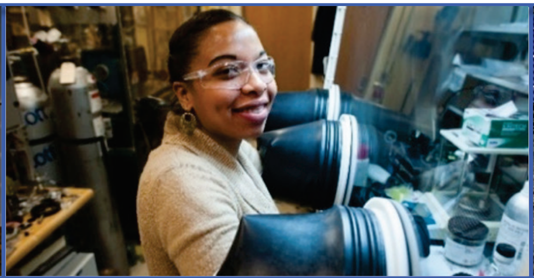
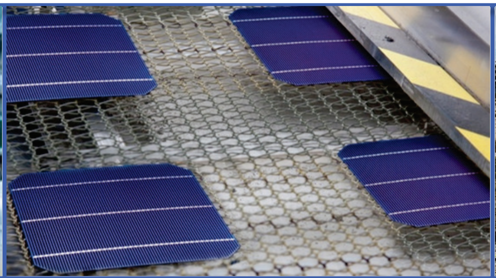
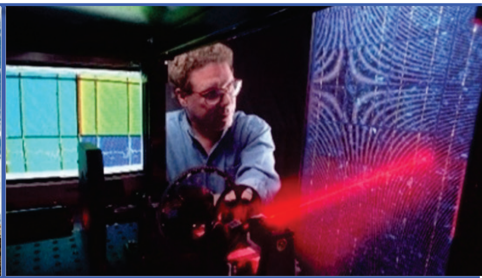
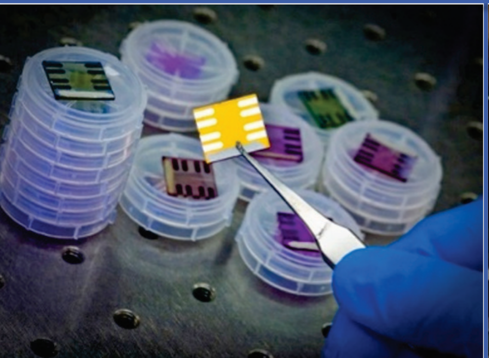
Ammar Qusaibaty

Solar Energy Technology Office


Background

Project Team

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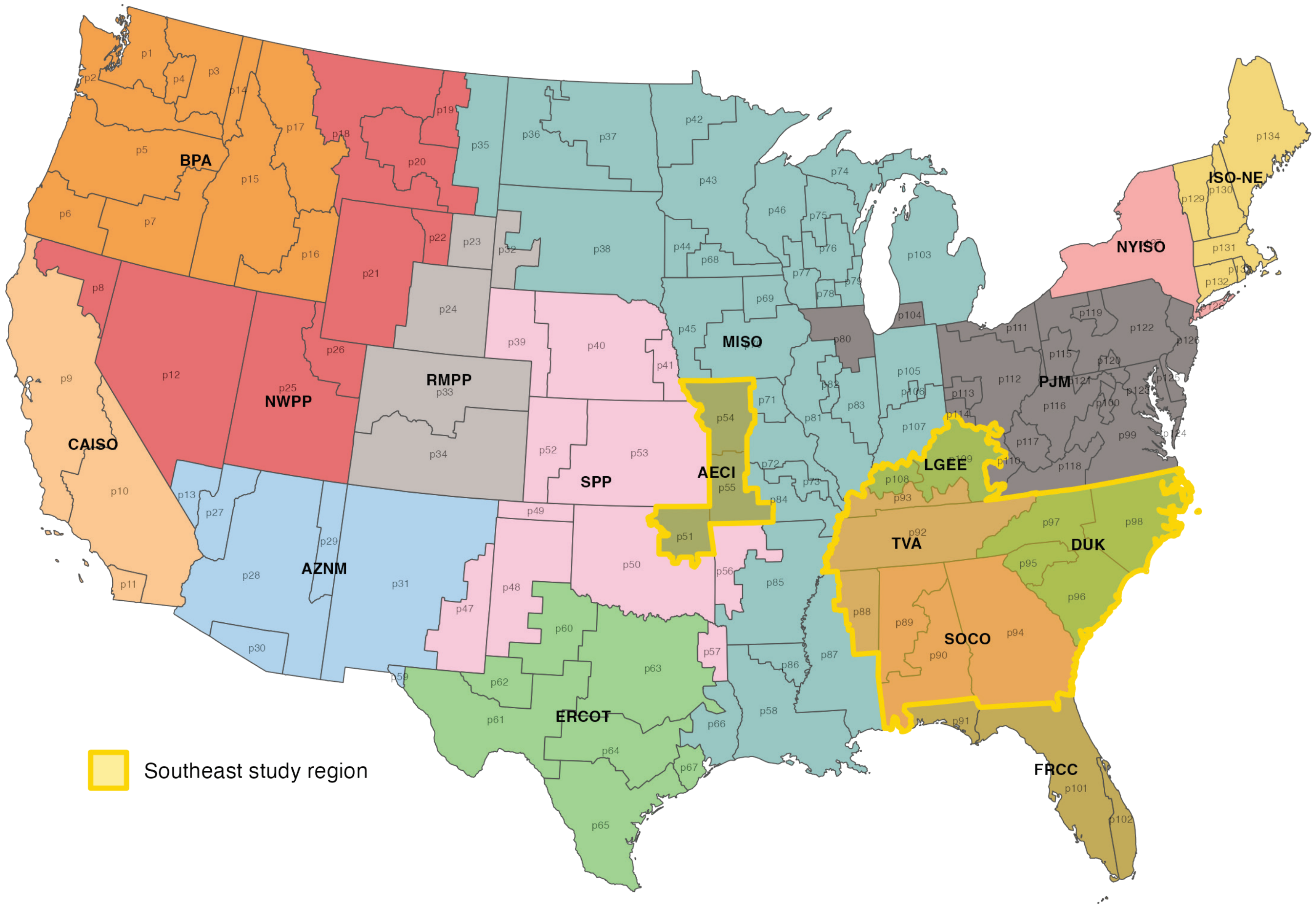
Project Overview

- Overall project goal: Understand changes in electricity system economics, reliability, resource adequacy, and operations in the U.S. Southeast with higher levels of solar and storage, and with different levels of operational coordination among utilities (“regional coordination”)
- Project consists of three studies:
  - **Solar-storage integration study (Phase 1)**: How do higher levels of solar and storage impact economics, reliability, and operations, with different levels of regional coordination?
  - **Solar forecasting and storage study (Phase 2)**: How will better solar forecasting change operations? How should storage be optimally operated and modeled incorporating solar forecast uncertainty?
  - **Resource adequacy in energy-limited systems study (Phase 3)**: How do higher levels of solar and storage impact resource adequacy and the value of demand-side resources in providing resource adequacy?
- Project has a research focus
  - No policy recommendations, not responding to active regulatory proceedings

Solar-Storage Integration Study: Geographic Scope and Time Horizon

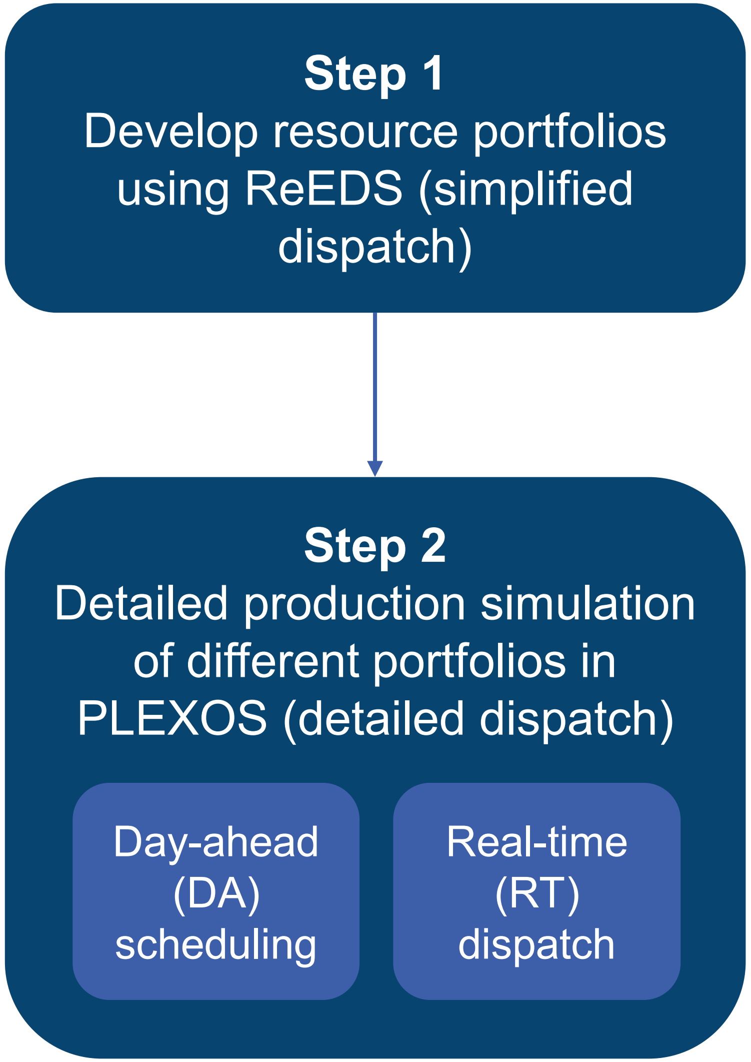
- Study focused on 5 balancing regions in the Southeast: AECI, Duke Carolinas (DUK), LG&E & KU (LGEE), Southern Company (SOCO), TVA
  - Focus was on geographic aggregations rather than individual utilities
  - Did not include Florida
  - All models included the rest of the U.S.
- Some results also include neighboring regions: Florida (FRCC), MISO-PJM-SPP (MPS)
- Study year is 2035



General Approach

- Two-step modeling approach
  - Capacity expansion model (ReEDS)
  - Production simulation model (PLEXOS)
- Study focused on operations
- Resource portfolios:
  - No regional coordination of resource investments
  - Endogenous transmission expansion
  - Includes Inflation Reduction Act (IRA)

  (see Additional Slides for more on ReEDS assumptions)
- Two-stage PLEXOS modeling
  - Day-ahead: hourly dispatch, forecast errors for solar and wind
  - Real-time: 15-minute dispatch, actual solar and wind profiles
- Balancing regions held reserves to address solar and wind forecast error



Scenario Framework

- **Resource scenarios** – higher levels of solar and storage
- **Regional coordination scenarios** – different levels of regional coordination

Regional Coordination Scenario	Resource Scenario				
	Base solar and storage	Medium solar		High solar	
		Low storage	High storage	Low storage	High storage
Lower coordination	BPBS_LC	MPLS_LC	MPHS_LC	HPLS_LC	HPHS_LC
Higher coordination	BPBS_HC	MPLS_HC	MPHS_HC	HPLS_HC	HPHS_HC
Single balancing region	BPBS_SB	MPLS_SB	MPHS_SB	HPLS_SB	HPHS_SB

These labels are used throughout the slides.

Scenario Framework: Resource Scenarios

- **Resource scenarios** – higher levels of solar and storage (identical for different coordination scenarios)

Level (Region-Wide)	Resource Scenario				
	Base solar and storage	Medium solar		High solar	
		Low storage	High storage	Low storage	High storage
UPV share of installed capacity	27%	33%	39%	42%	43%
UPV installed capacity	76 GW	100 GW	133 GW	174 GW	182 GW
Energy storage installed capacity	19 GW	25 GW	46 GW	57 GW	71 GW
UPV to energy storage ratio	4.0	4.0	2.9	3.0	2.6

UPV is utility-scale PV; energy storage includes battery, pumped hydro, and compressed air energy storage

Results

Results List

Capacity expansion

- Generation and transmission expansion (from ReEDS)

Generation

- Annual generation, monthly generation, and daily average dispatch (from PLEXOS)

Emissions

- CO_2 emissions

Economics

- Production and market costs

Reliability

- Load and reserve violations; reserves and reserve sharing

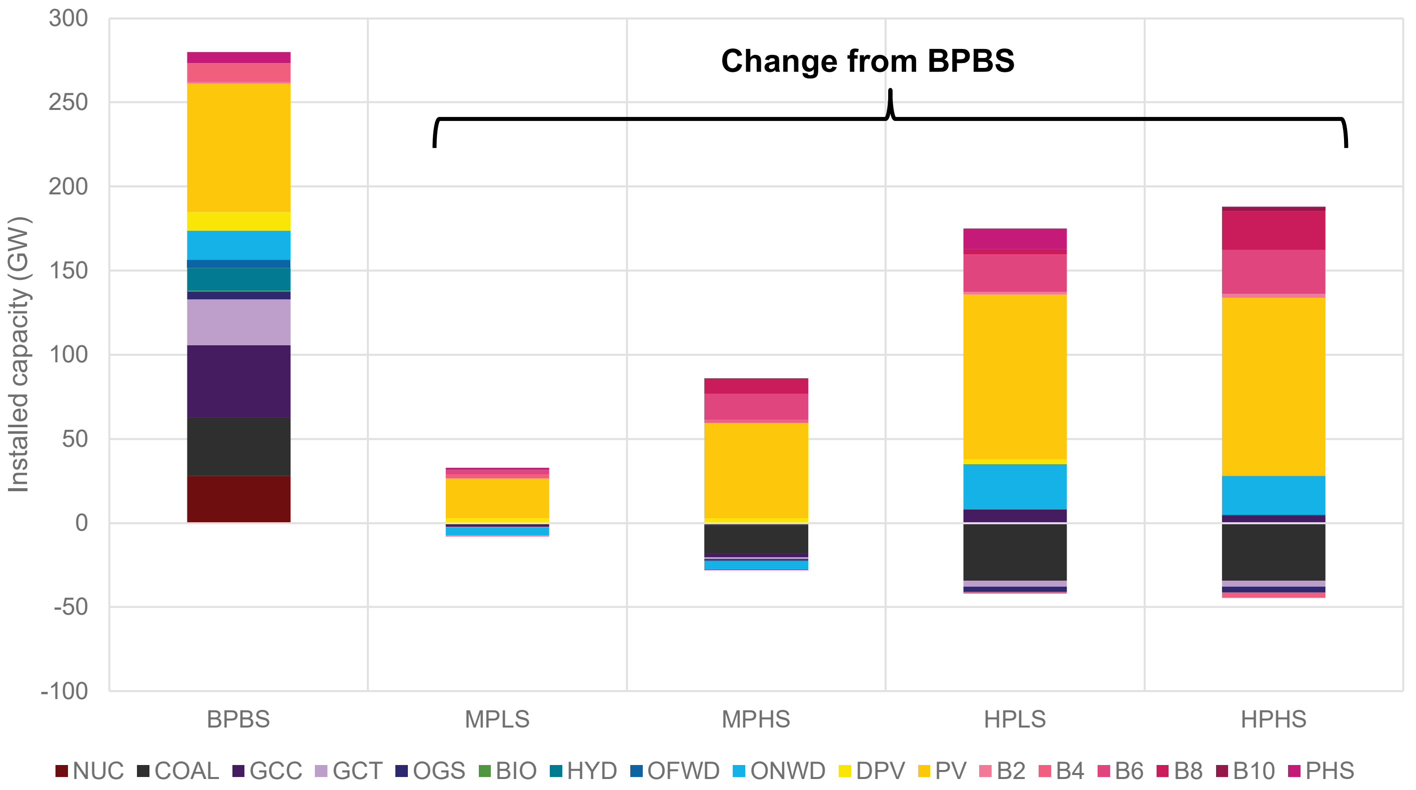
Operations

- Reserve provision, storage energy management, transmission flows and utilization

Capacity Expansion: Southeast Region Resource Mix

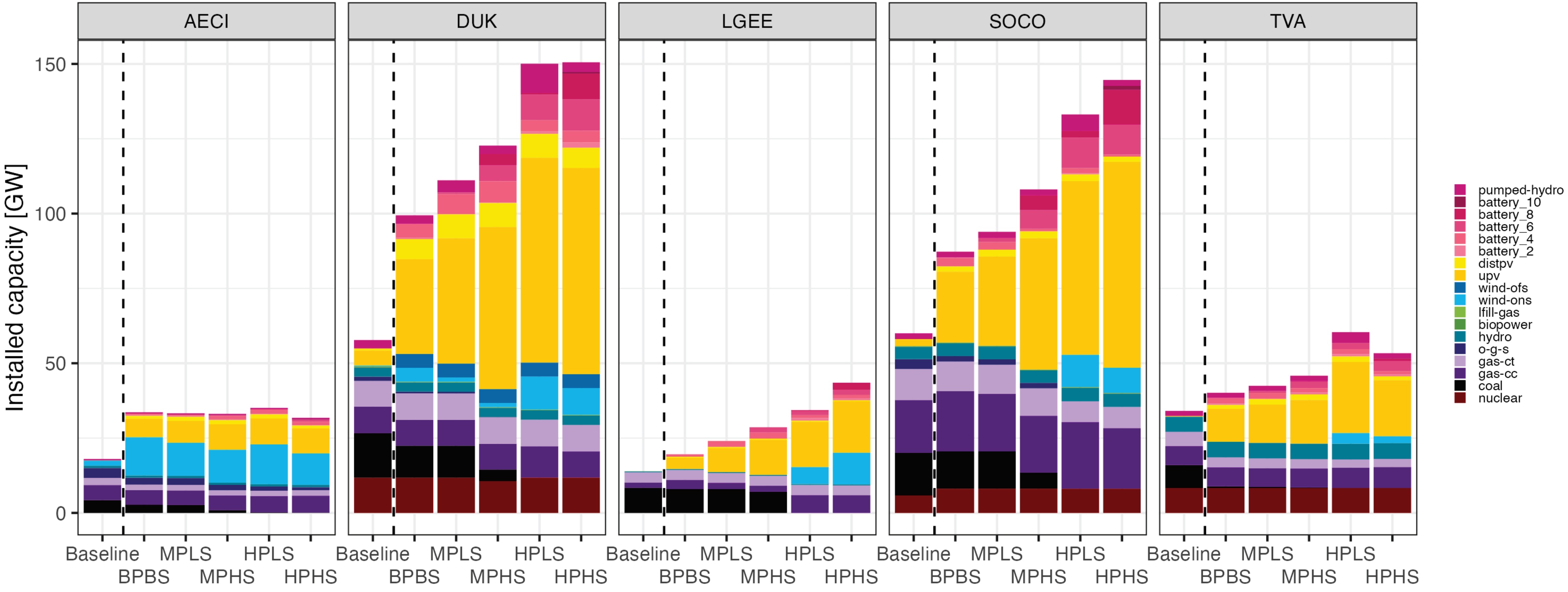
- Resource interactions in capacity expansion (ReEDS) modeling had a significant impact on the results
- Changes in inputs (e.g., lower battery costs) that increased storage also increased PV, but more in MP than HP
  - +2 GW PV per +1 GW storage in MPHS, but only +0.5 GW PV per 1 GW storage in HPHS
- Changes in inputs that increased PV (e.g., lower PV costs) in MP reduced wind and coal relative to BPBS
- Changes in inputs that increased PV in HP (e.g., carbon tax) increased wind and reduced coal relative to BPBS

Installed capacity (BPBS) and change in installed capacity in the Southeast region relative to BPBS



Scenario Framework: Resources by Balancing Region

- **Resource scenarios** – higher levels of solar and storage

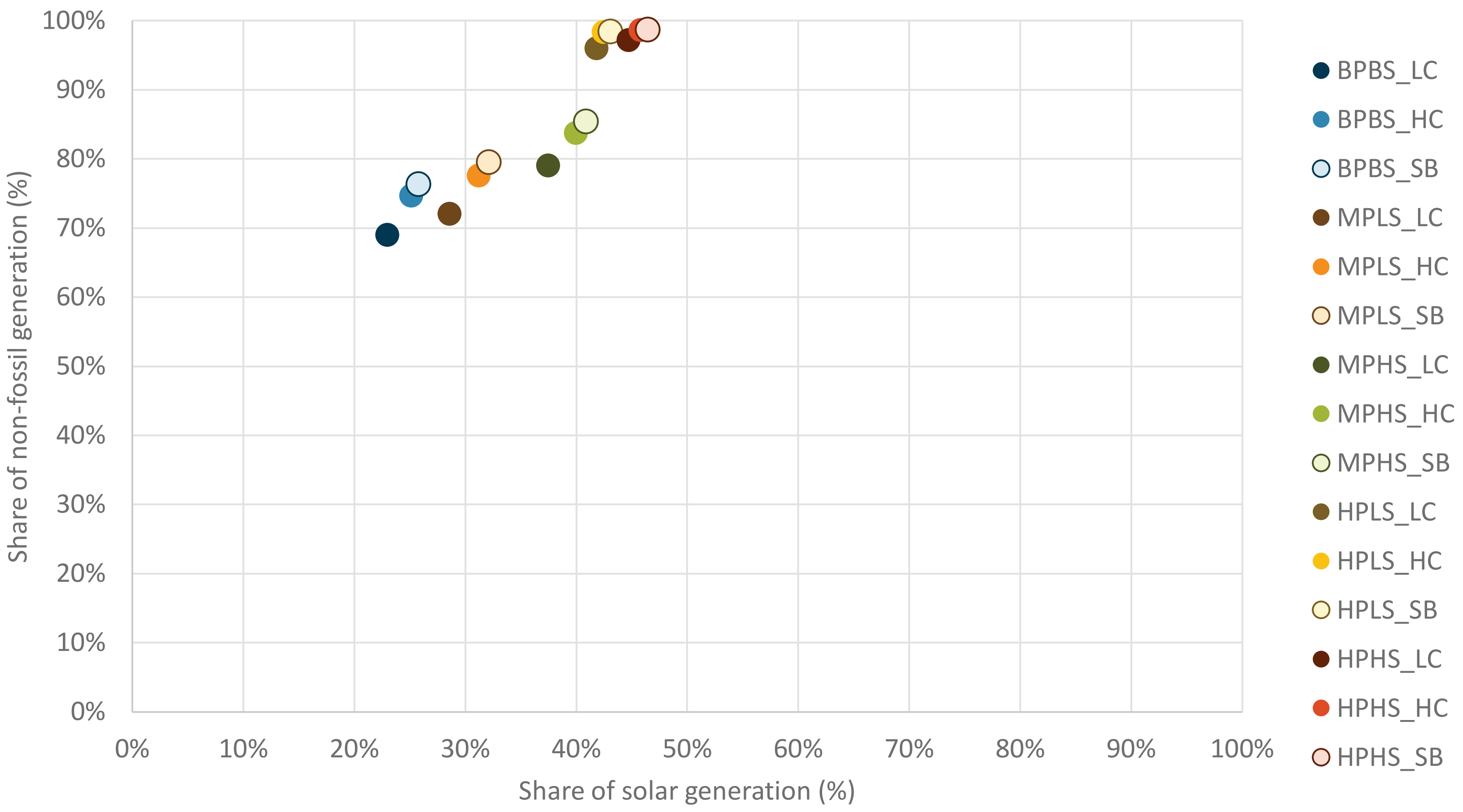


Baseline = 2020 values as estimated by ReEDS

Generation: Solar and Non-Fossil Generation

- Scenarios formed a continuum from 23% to 46% solar and 69% to 99% non-fossil (share of total generation) in the Southeast region
- Results provide useful benchmarking for operations, costs, emissions at different levels of solar and storage

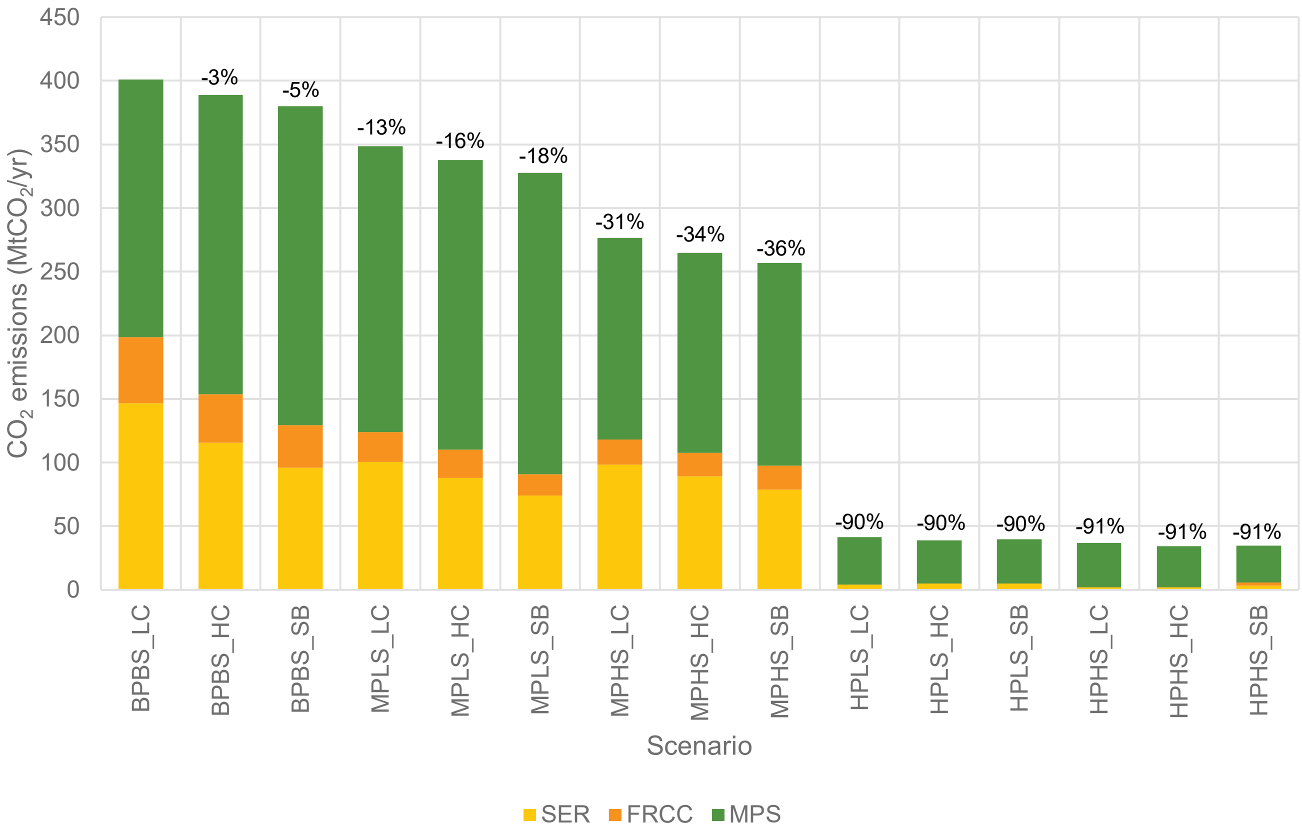
Shares of solar and non-fossil generation in the Southeast region by scenario



CO_2 Emissions

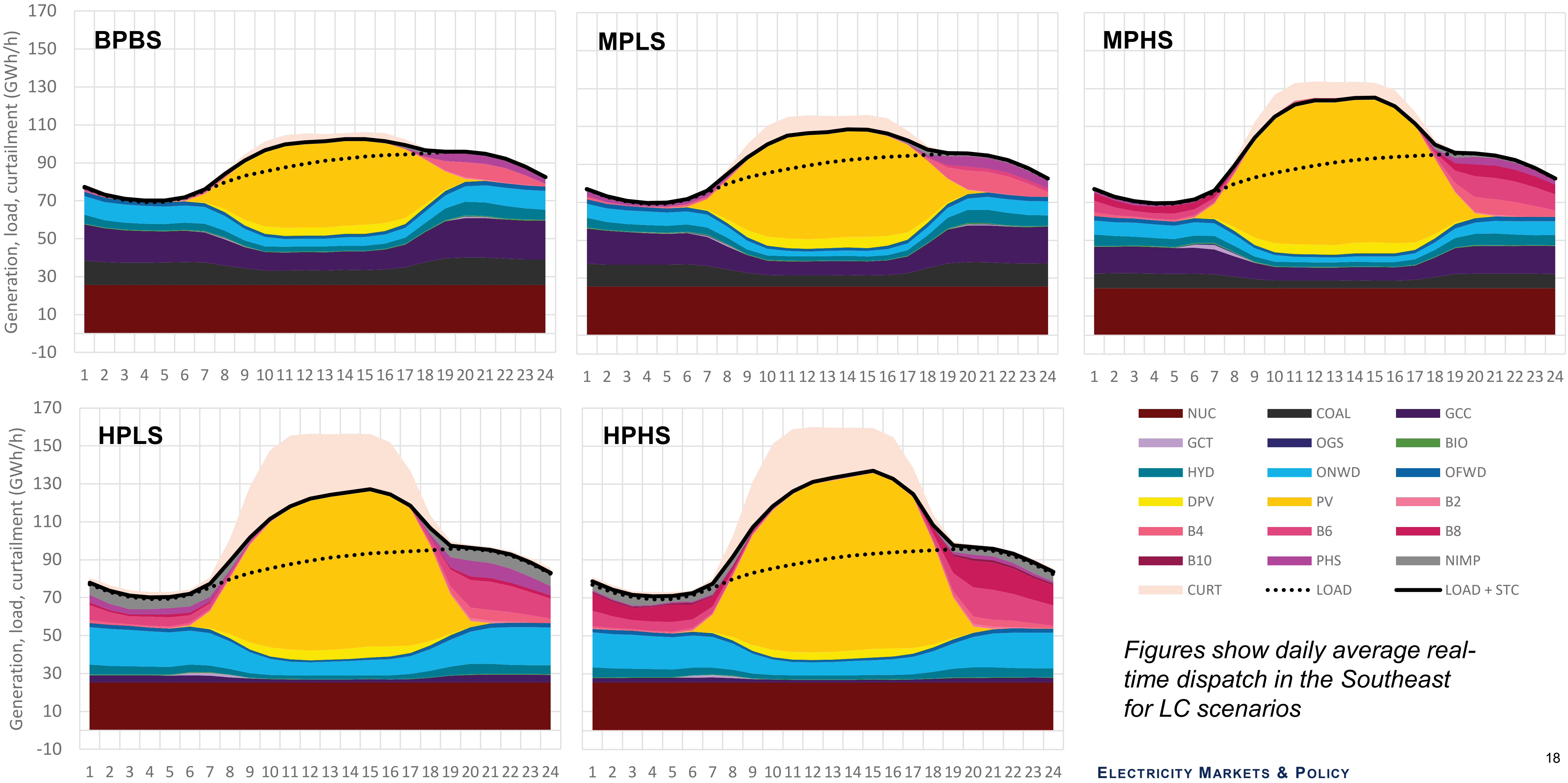
- Total region-wide (SER, FRCC, MPS) CO_2 emissions declined across resource scenarios and almost to zero in HP scenarios
  - As a reference point, total SER-FRCC-MPS CO_2 emissions in the BPBS_LC scenario were ~65% lower than 2022 emissions
- Higher coordination (HC and SB scenarios) reduced total region-wide CO_2 emissions by 3%-7% relative to the LC scenarios but led to significant emissions shifting between regions
- Impact of higher coordination on CO_2 emissions was relatively small in absolute terms in the HP scenarios

CO_2 emissions by region and percent reduction from BPBS_LC



Notes: Percentages above the columns are percent change from the BPBS_LC scenario

Generation: Daily Average Dispatch



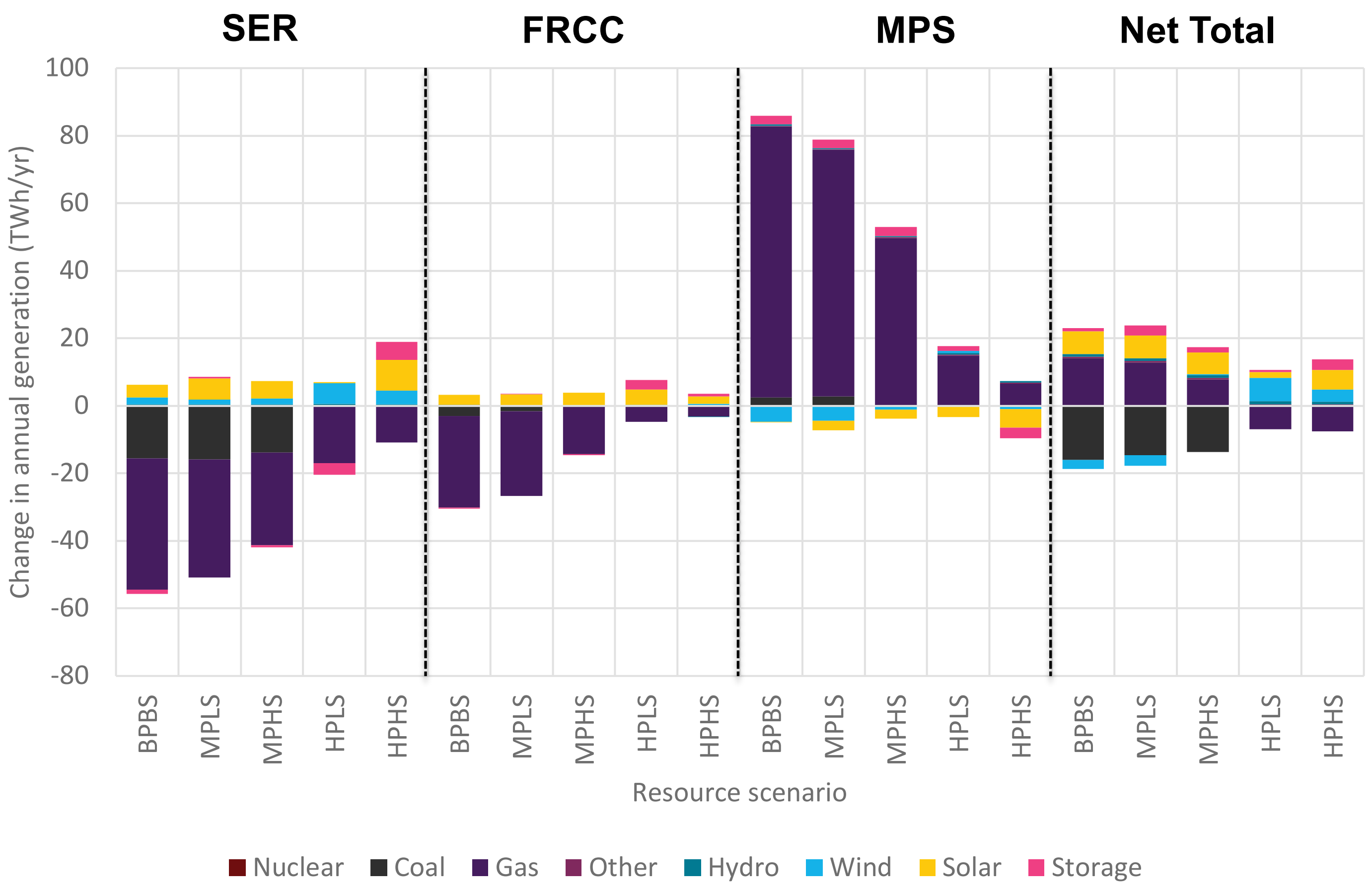
Figures show daily average real-time dispatch in the Southeast for LC scenarios

Generation: Higher Coordination Scenarios

- Lower hurdle rates* in HC scenarios led to large shifts in gas and coal generation in BPBS and MP scenarios
  - Reflected regional differences in fuel costs and coal-gas-solar-wind interactions
- On net ("net total"), in BPBS and MP scenarios gas and solar displaced coal (and some wind); in HP scenarios wind and solar displaced gas

** In the LC scenarios, DA and RT hurdle rates were $10/MWh and $5/MWh (2004$, $15/MWh and $8/MWh in 2022$); in the HC scenarios, DA and RT hurdle rates were $5/MWh and $0/MWh; the HC scenario allowed sharing of load following spinning reserves while the LC scenario did not*

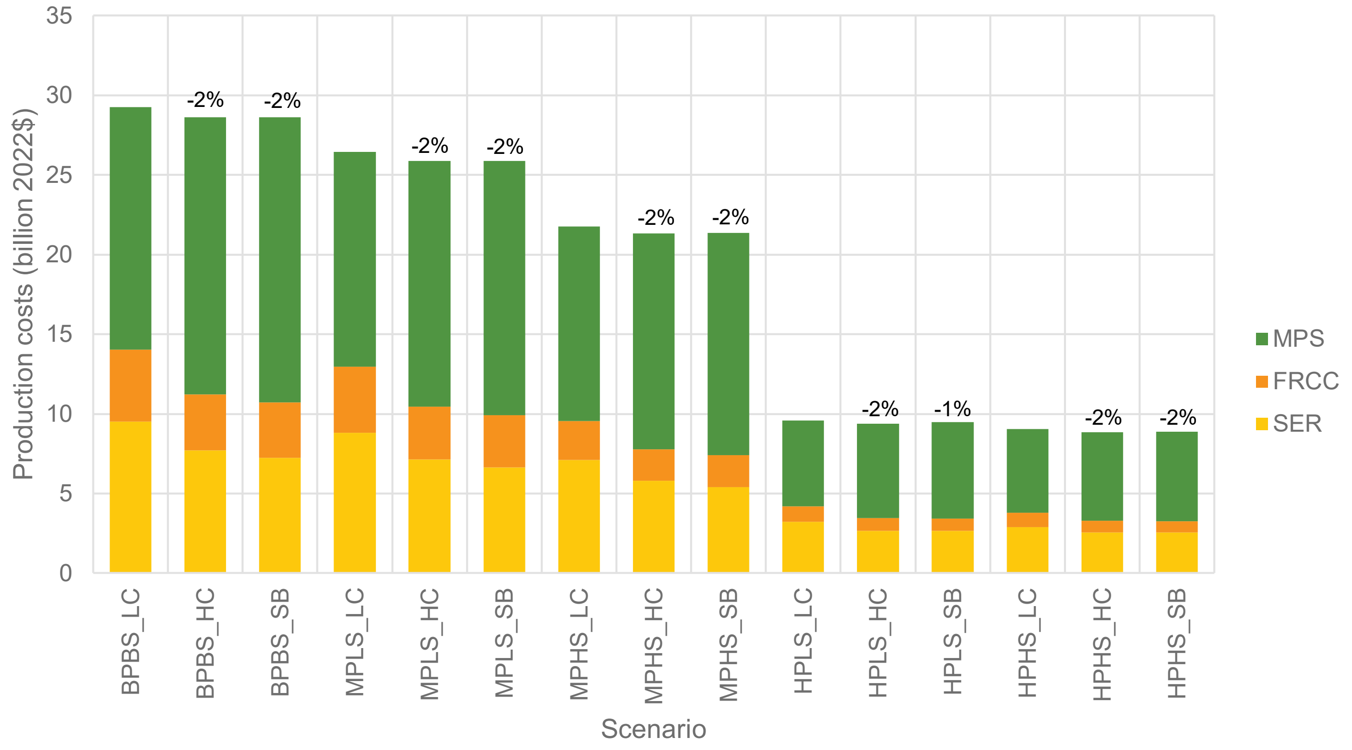
Change in annual generation from LC to HC scenario by region



Economics: Production Costs

- Production costs declined (10%-70%) in higher solar scenarios
- Across scenarios, higher coordination resulted in total (SER, FRCC, MPS) production cost savings of ~2%
  - Consistent with estimates of cost savings from the creation of organized markets (MISO, SPP)
- Cost savings from higher coordination declined in absolute terms with higher solar due to lower fuel costs
  - Savings declined from ~$600 million (BPBS, MPLS) to ~$400 million (MPHS) to ~$100-$200 million (HPLS, HPHS)
- Significant cost shifting across regions from changes in gas and coal dispatch

Production costs by region and percent reduction from LC scenarios

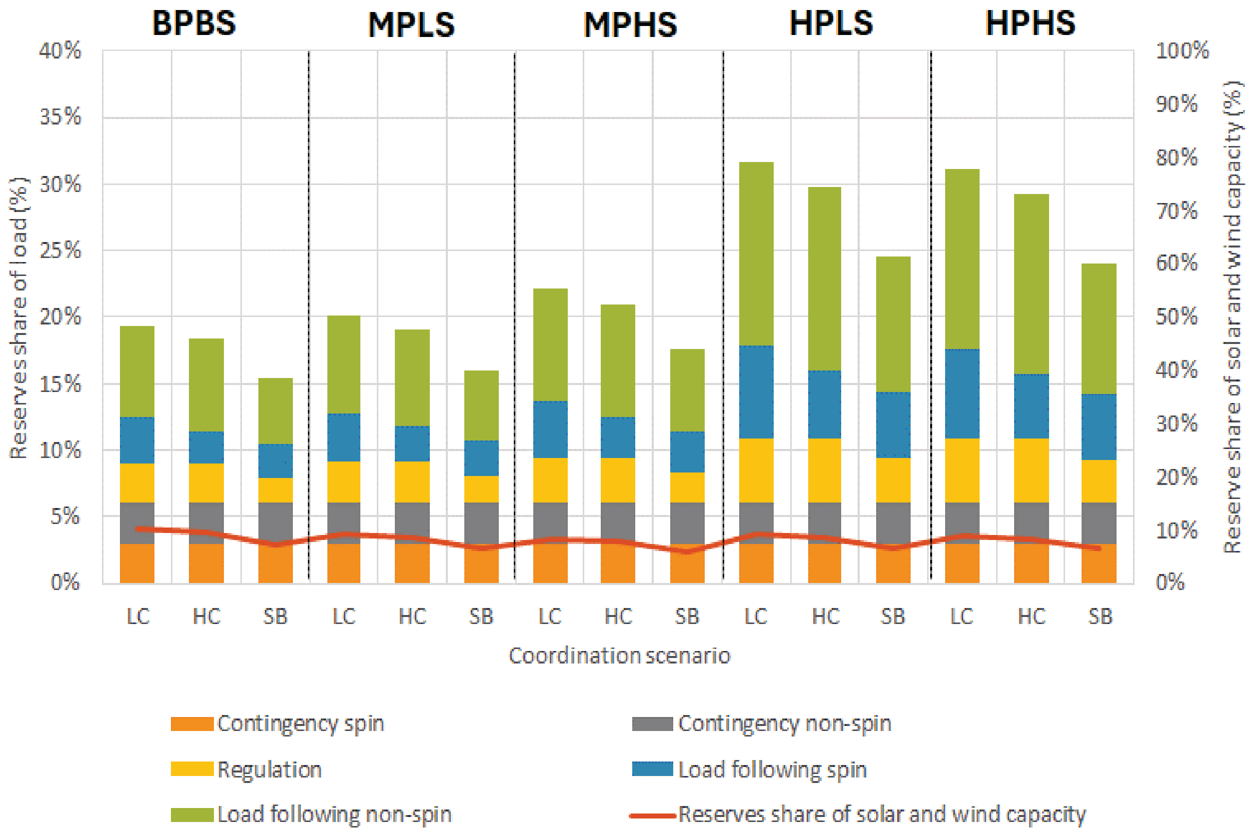


Note: Percentages above the columns are percent change from LC scenarios; production costs include real-time fuel, variable O&M, and start costs and day-ahead start costs

Reliability: Reserve Requirements

- For the Southeast region, reserve requirements incorporated solar and wind forecast errors
  - Non-spinning load following reserves covered infrequent, larger forecast errors
- Day-ahead (DA) reserve requirements increased from 16%-19% of load (BPBS scenarios) to 24%-32% (HP scenarios)
  - Increase was approximately linear with solar and wind installed capacity (~6%-10% of capacity)
  - Real-time reserves increased from 8%-9% (BPBS) to 9%-11% (HP scenarios)
- Within Southeast region, sharing forecast error-related reserves reduced DA reserve requirements by 5%-23% across scenarios
  - $90-$1,240 million per year ($0.12-$1.68/MWh) in total reserve cost savings; in several scenarios, largest savings from pooling non-spinning reserves
- Operational value of reserve sharing tended to fall with higher levels of solar due to lower energy and reserve prices

Reserves share of load and solar/wind capacity



Reliability: Load and Reserve Violations

- No load violations occurred within the Southeast region; DA and real-time (RT) reserve violations were relatively infrequent and mostly small
- Reserve sharing reduced DA reserve violations, but largest reductions in reserve violations were from sharing non-spinning load following (forecast error) reserves and being able to hold reserves anywhere in the region (SB scenario)
- Effects of reserve sharing were most significant for smaller balancing regions
- Extent of reserve violations related to model coordination

DA reserve violations in the Southeast region by scenario

Scenario	BPBS	MPLS	MPHS	HPLS	HPHS
LC	Count: 125 Avg short: 3% Max short: 18%	Count: 123 Avg short: 3% Max short: 19%	Count: 78 Avg short: 2% Max short: 11%	Count: 296 Avg short: 2% Max short: 15%	Count: 101 Avg short: 1% Max short: 5%
HC	Count: 99 Avg short: 5% Max short: 50%	Count: 114 Avg short: 3% Max short: 46%	Count: 42 Avg short: 2% Max short: 12%	Count: 236 Avg short: 1% Max short: 5%	Count: 80 Avg short: 2% Max short: 11%
SB	Count: 3 Avg short: 3% Max short: 9%	Count: 5 Avg short: 3% Max short: 5%	Count: 1 Avg short: 1% Max short: 1%	Count: 2 Avg short: 4% Max short: 6%	Count: 2 Avg short: 5% Max short: 9%

RT reserve violations in the Southeast region by scenario

Scenario	BPBS	MPLS	MPHS	HPLS	HPHS
LC	Count: 135 Avg short: 10% Max short: 40%	Count: 92 Avg short: 10% Max short: 43%	Count: 41 Avg short: 7% Max short: 24%	Count: 144 Avg short: 3% Max short: 14%	Count: 50 Avg short: 3% Max short: 14%
HC	Count: 67 Avg short: 11% Max short: 33%	Count: 78 Avg short: 10% Max short: 38%	Count: 51 Avg short: 8% Max short: 34%	Count: 187 Avg short: 3% Max short: 17%	Count: 55 Avg short: 3% Max short: 11%
SB	Count: 28 Avg short: 2% Max short: 4%	Count: 5 Avg short: 2% Max short: 3%	Count: 6 Avg short: 1% Max short: 2%	Count: 4 Avg short: 0% Max short: 1%	Count: 5 Avg short: 1% Max short: 2%

Notes: Counts are the number of time intervals in which there is an operating (load following, contingency, regulation) reserve violation in a balancing region. Average reserve shortages (avg short) are the average amount of reserves lost in reserve shortage events. Maximum reserve shortages (max short) are the maximum amount of reserves lost in reserve shortage events.

Reliability: Changing Nature of Reserve Violations

- Reserve shortages are an indicator of system stress
- Differences in reserve violations across scenarios provide insights on changes in system stress
  - In the BPBS scenarios, 64%-92% of DA and RT reserve violations in the Southeast region occurred during 19:00-21:00 (hour beginning, H.B.), but in the HP scenarios, only 6%-31% of violations occurred in this window
  - In RT, a large share of violations (~70% in MPHS LC and HC) occurred during 5:00-8:00 (H.B.), especially following low solar days
- Reserve violations during solar ramp periods could have been addressed with through sub-hourly day-ahead scheduling and changes in storage operations

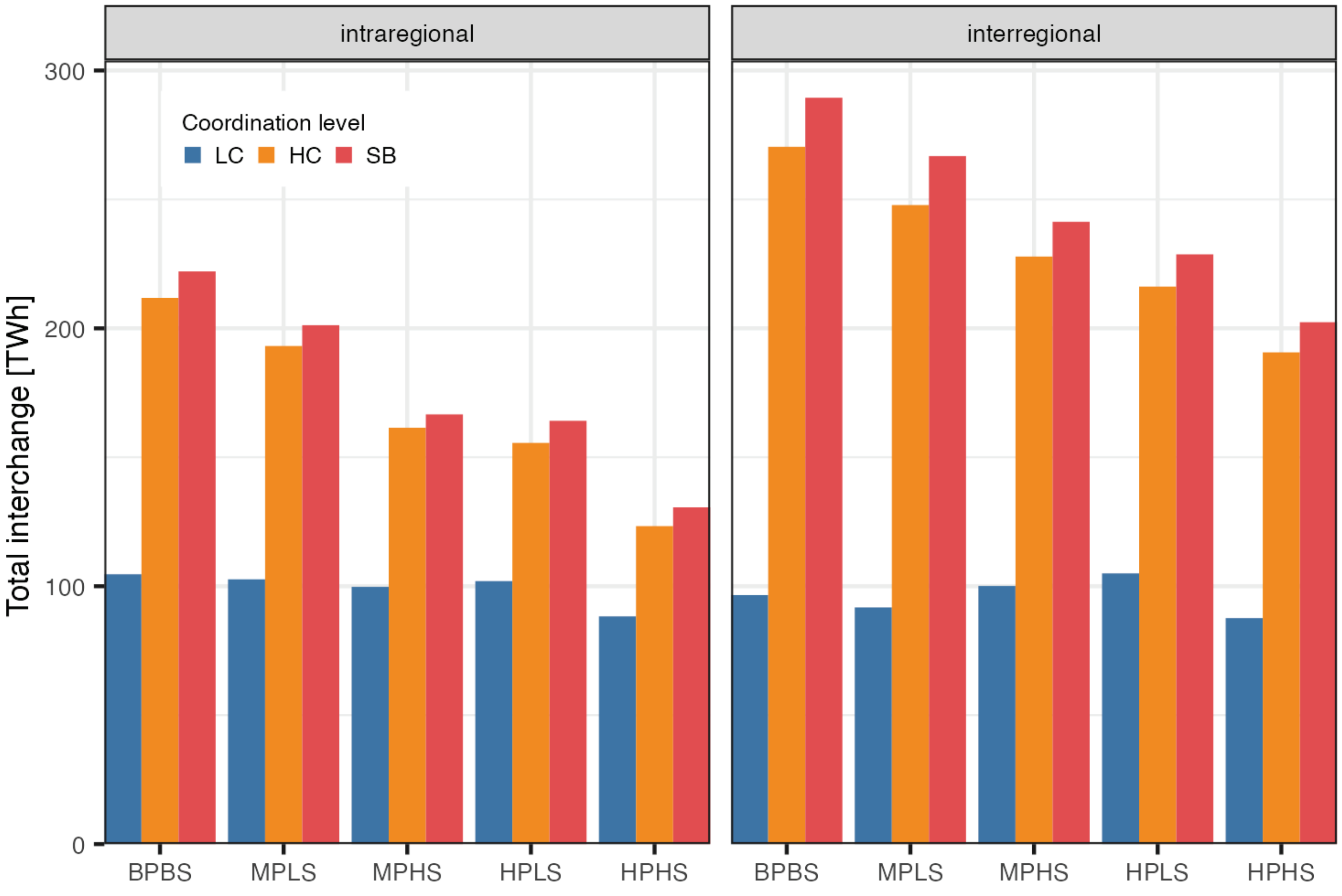
Reserve violations (MW-h) by hour and month, MPHS_LC scenario

	Month											
Hour	1	2	3	4	5	6	7	8	9	10	11	12
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	47	0	0	0	0	0	0
5	0	0	0	0	100	578	118	0	0	0	0	0
6	0	0	193	0	0	59	0	261	271	172	28	0
7	0	132	168	0	0	0	0	0	0	421	0	0
8	266	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	31	0	0	0
20	0	0	0	0	184	221	706	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

Operations: Transmission Flows in Higher Solar Systems

- Lower hurdle rates significantly increased transmission flows and utilization
- With lower hurdle rates, transmission flows were higher between the Southeast and its neighbors than within the Southeast
- Higher solar and storage tended to reduce transmission flows and net imports to the Southeast
- Southeast became a net exporter during the day and a net importer at night, especially during the winter

Intraregional and interregional transmission flows by scenario

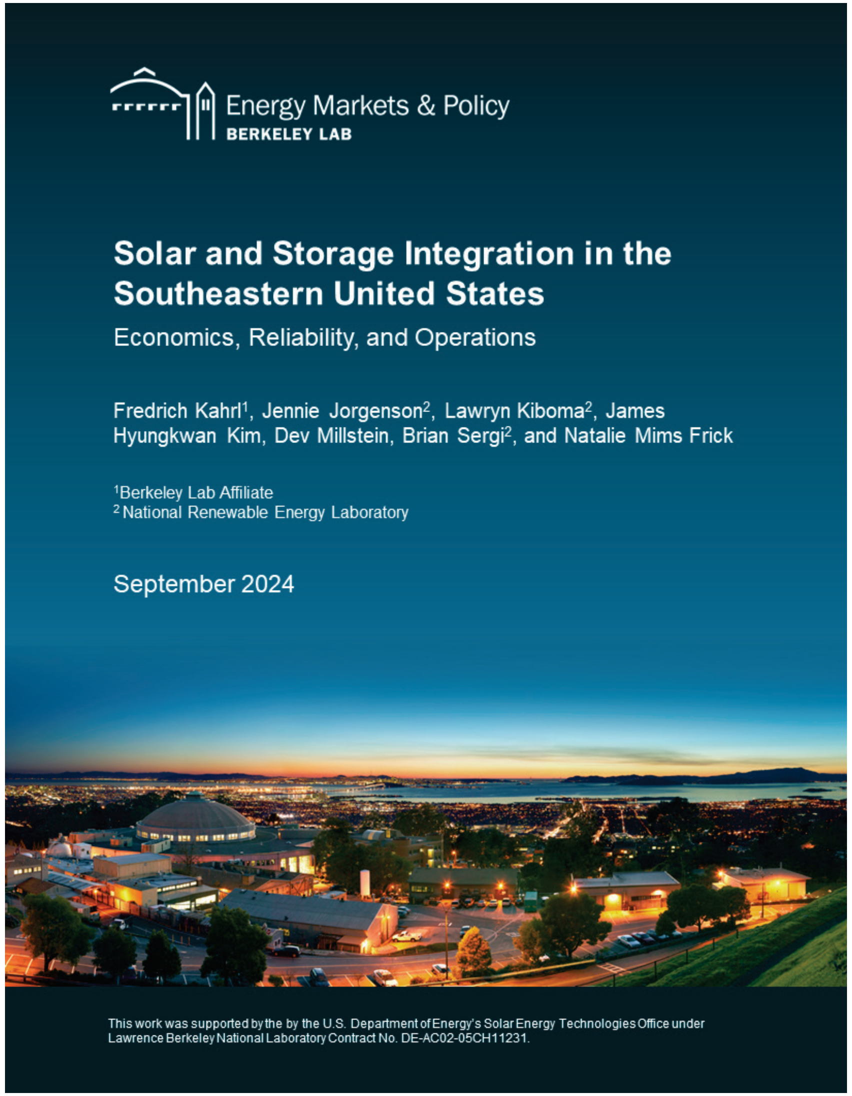


Key Takeaways

Key Takeaways

- With current solar and storage technology costs, there may be limits to the amount of solar photovoltaic (PV) generation that the Southeast can economically absorb; beyond that, wind from within the region or from neighboring regions may provide a lower cost means of reducing CO_2 emissions
- Energy storage is a critical enabling resource in electricity systems with higher levels of solar; getting storage investments and operations “right” will require careful resource planning
- Closer operational coordination among balancing area authorities in the Southeast – such as through an energy imbalance market (EIM) with reserve sharing or a regional transmission organization (RTO) – may not be necessary for reliably operating systems with high levels of solar and storage, but closer coordination would likely reduce costs, lower emissions, and enhance reliability
- Sharing reserves to manage solar and wind forecast errors, and in particular larger, less frequent errors, can significantly lower reserve requirements and reserve costs
- Higher levels of solar (~30%-40%) may require new metrics for valuing the benefits of operational coordination and transmission investments, in addition to production cost savings
- Different reliability and operational concerns emerge at different levels of solar and storage, though planners and operations should be able to anticipate these concerns and address them

Report and Contacts



Thank you!

Report and resource portfolios are available at: https://emp.lbl.gov/publications/solar-and-storage-integration

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Additional Material

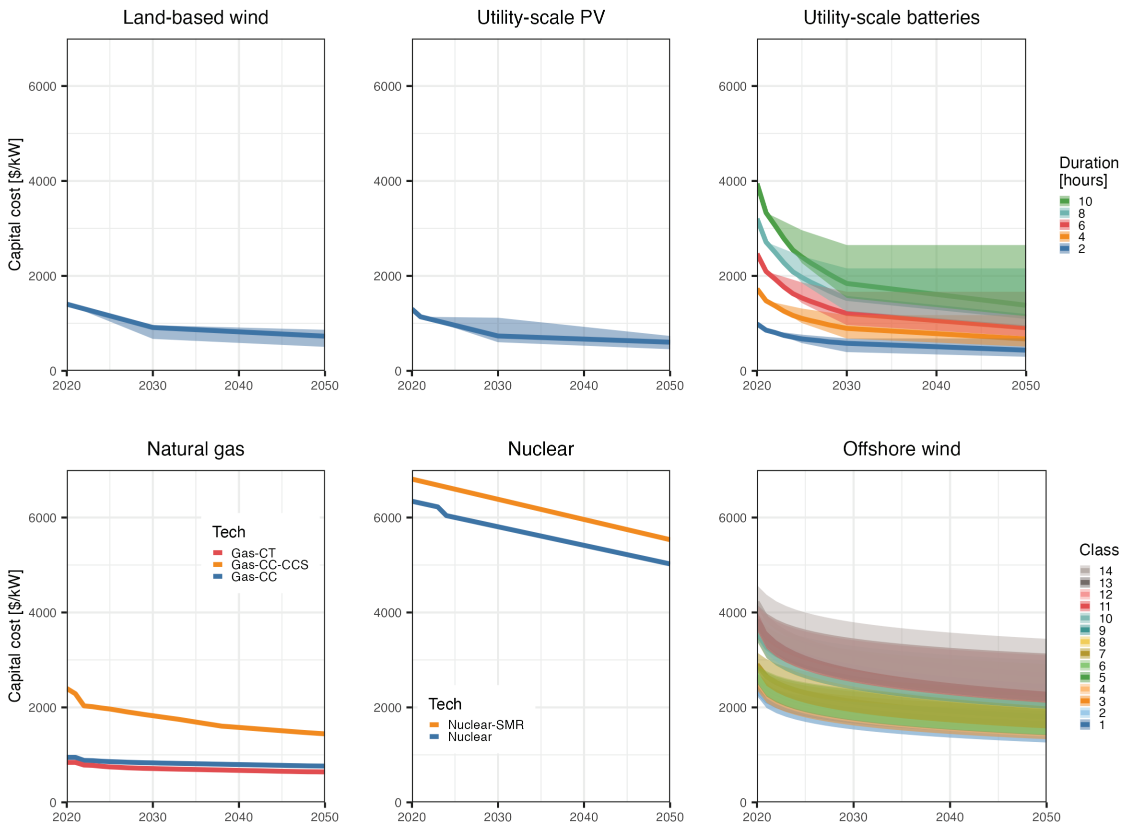
Resource Scenarios: Overview of ReEDS Input Assumptions

	BPBS	MPLS	MPHS	HPLS	HPHS
Battery costs	conservative	conservative	advanced	conservative	advanced
Carbon tax	none	none	none	yes	yes
Coal retirements	accelerated	accelerated	accelerated	n/a	n/a
DPV adoption	mid case	low-cost case	low-cost case	low-cost case	mid case
Utility-scale PV costs	moderate	advanced	advanced	moderate	advanced

Resource Scenarios: ReEDS Input Assumptions

- **Coal retirements**: retirement dates moved up by 20 years
- **Cost scenarios:** based on NREL's Annual Technology Baseline (ATB) 2022 projections
- **Rooftop PV:** fixed adoption based on projections from dGen model
  - Adoption scenarios vary with cost of rooftop PV; projections connected to cost assumptions for utility-scale PV
- **Carbon tax**: applied to build high PV scenarios
  - $46/tCO_2$ in 2022, increasing to $88/tCO_2$ by 2035 ($2022)
  - Applied to investment decisions in ReEDS but not carried over to PLEXOS

ATB 2022 cost projections

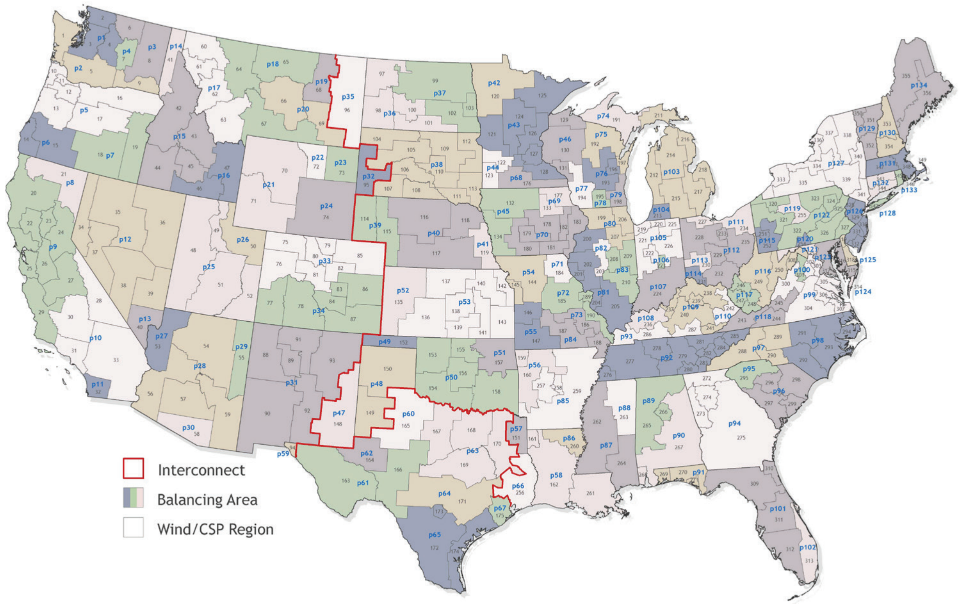


Cost ranges reflect differences from low (advanced) and high (conservative) cost cases

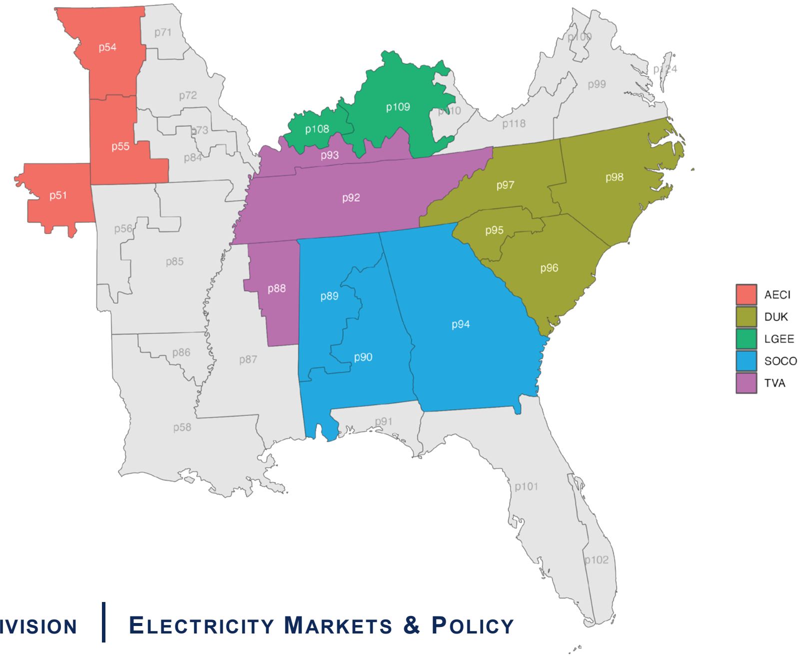
Resource Scenarios: ReEDS Inputs and Model Assumptions

- 3-year timesteps modelling investments through 2035
- Model represents dispatch using 17 timeslices
  - 4 times-of-day (morning, afternoon, evening, night) x 4 seasons (winter, spring, summer, fall) + 1 timeslice representing peak hours (top 40 summer hours)
- Hurdle rate of 7.5 $/MWh ($2022) applied to transmission flows between ReEDS balancing areas
- Operating reserves must be procured in each ReEDS balancing area (no trade)
- Entire continental U.S. modeled

ReEDS balancing areas



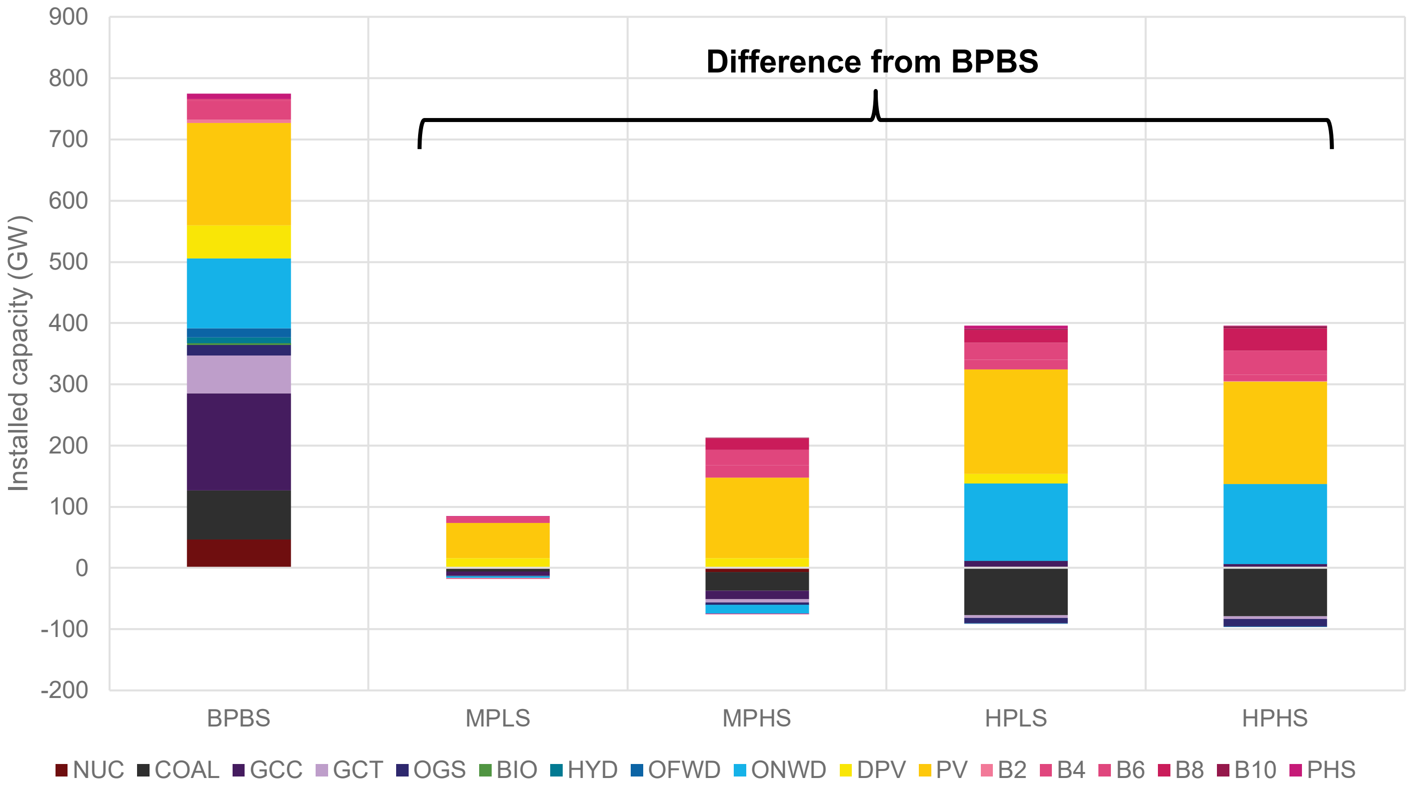
Southeast representation



Capacity Expansion: Neighboring Regions Resource Mix

- Changes in capacity mix in MISO, PJM, SPP, and FRCC were similar to those in the Southeast region
  - Due to nationally consistent inputs and assumptions in ReEDS
- In aggregate, neighboring regions had proportionately more wind and less nuclear than the Southeast
- Resource interactions in neighboring regions were similar to those in the Southeast region

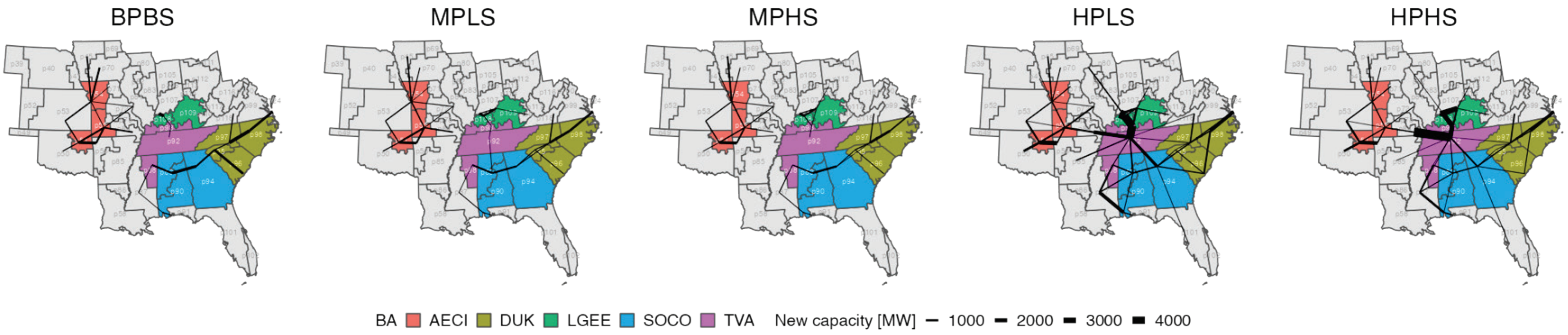
Installed capacity (BPBS) and change in installed capacity in neighboring regions relative to BPBS



Capacity Expansion: Transmission

- In the BP and MP (MPLS, MPHS) scenarios (2035), ReEDS expanded transmission capacity by 8%-10% relative to 2023, but increased capacity by 20%-26% in the HP (HPLS, HPHS) scenarios
  - MP scenarios had less expansion (+8%) than BP scenario (+10%)
  - In BP and MP scenarios, more than 50% of 10 largest expansions (by capacity) were within SER region
  - In HP scenarios, largest expansions were between MISO and TVA/LGEE, 10 largest expansions were all interregional
  - HS scenarios had less transmission build: MPHS (+7.7%) vs. MPLS (+8.5%) and HPHS (+20%) vs. HPLS (+26%)

ReEDS transmission expansion by scenario



Scenario Framework: Regional Coordination Scenarios

- **Regional coordination scenarios** – different levels of regional coordination

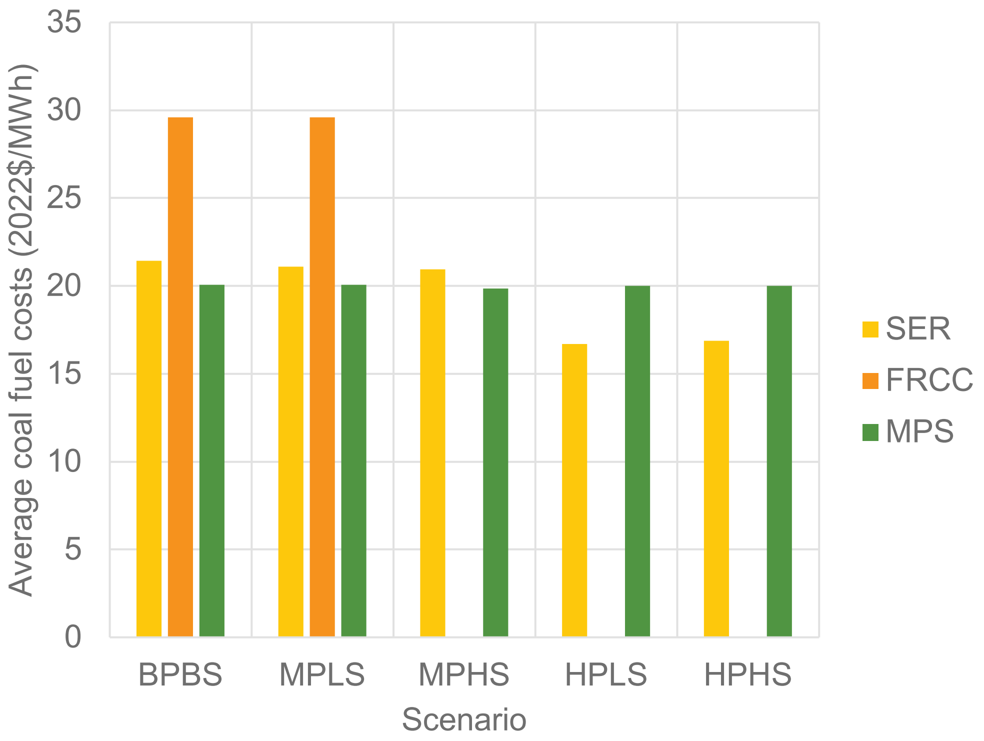
Regional Coordination Scenario	Hurdle Rate (DA / RT)	Shared Reserves	Non-Shared Reserves	Reserves Location
Lower coordination	\$10 / \$5	Spinning and non-spinning contingency	Spinning and non-spinning load following, regulation	Reserves held within each balancing region
Higher coordination	\$5 / \$0	Spinning load following, spinning and non-spinning contingency	Non-spinning load following, regulation	Reserves held within each balancing region
Single balancing region	\$0 / \$0	Spinning load following, spinning and non-spinning contingency regulation	None	Reserves held anywhere in Southeast region

Hurdle rates were the same within Southeast region between Southeast and other regions

Fuel Cost Assumptions

- Heat rates for different technologies were from ReEDS
  - Average gas heat rates were relatively similar across regions but coal heat rates varied more significantly
- Fuel (biomass, coal, natural gas, uranium) were based on *Annual Energy Outlook 2022* projections
- Average gas and coal generation fuel costs were higher in SER and FRCC than MPS

Average coal generation fuel costs



Average natural gas generation fuel costs