Decarbonizing The U.S. Grid: An Optimization-Based Study

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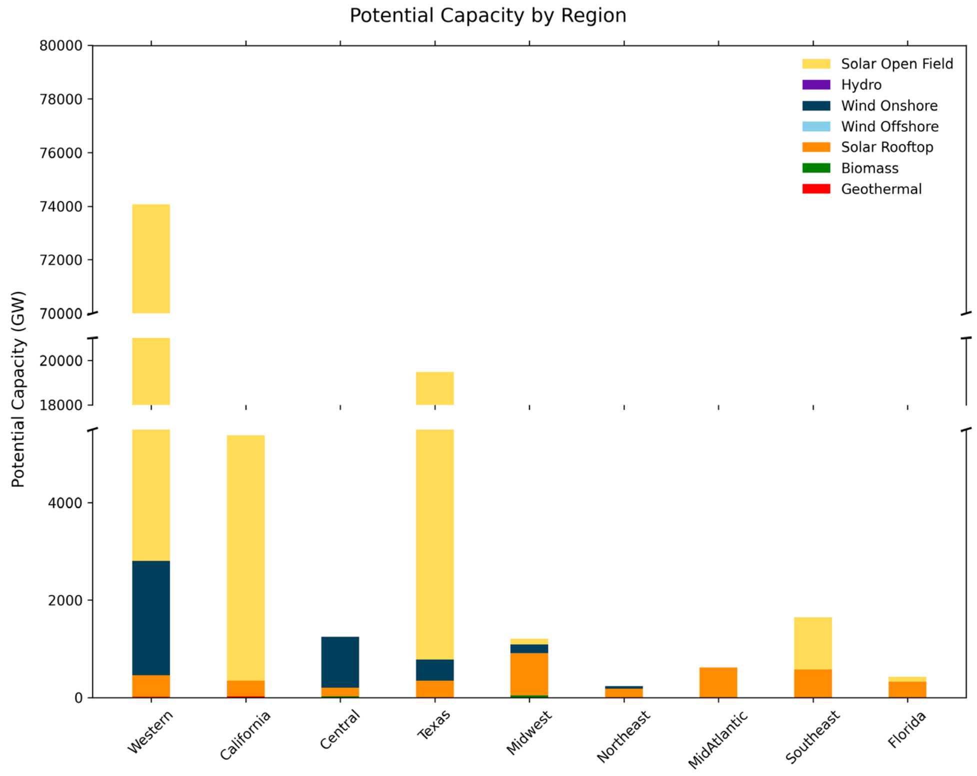
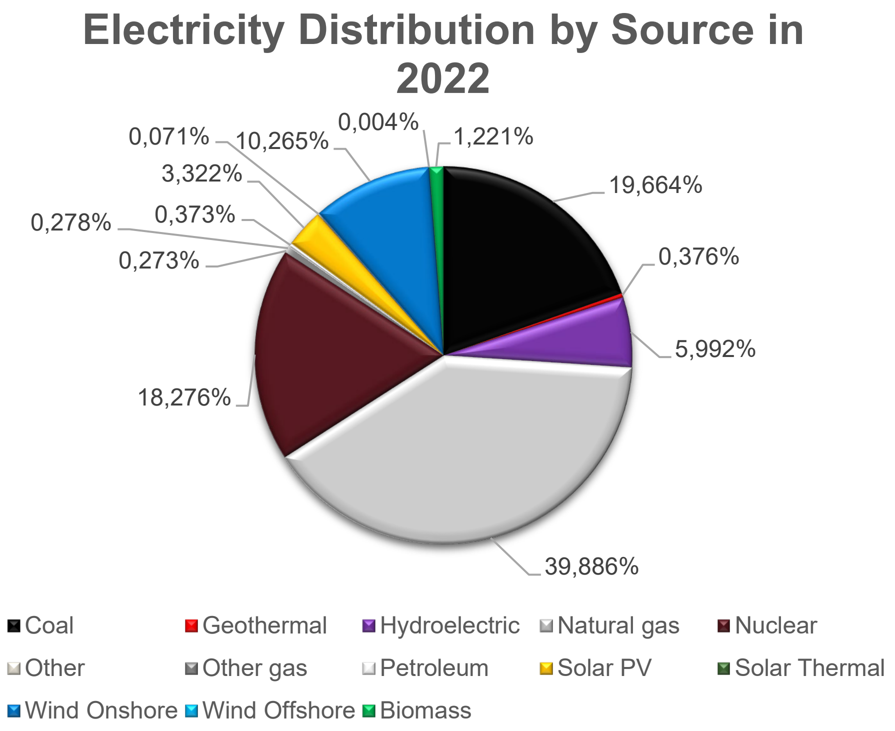
Why the USA?

- Largest electricity market: Over 4,000 TWh annual generation, diverse energy mix.
- Regional diversity: Varying renewables potential.
- Key role in global decarbonization: ~ 2Gt of CO_2 emissions from electricity alone in 2022.
- Aging infrastructure: Many power plants & transmission networks require modernization.



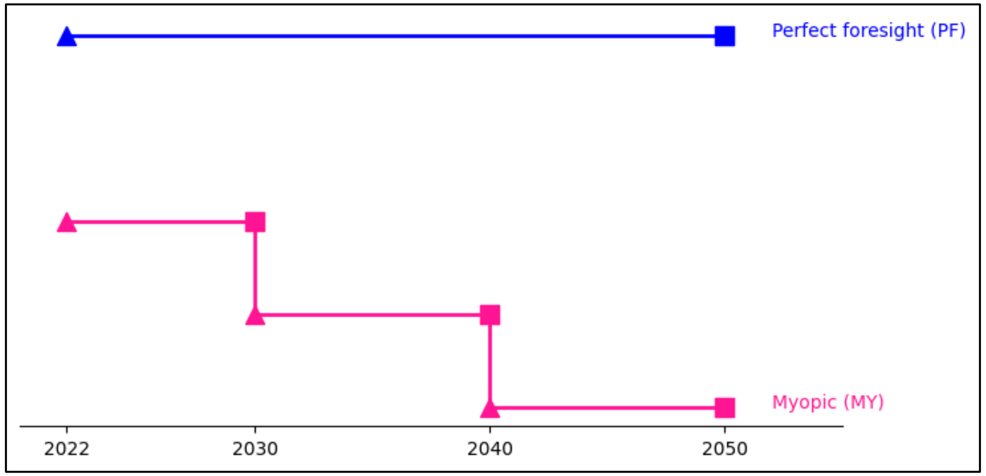


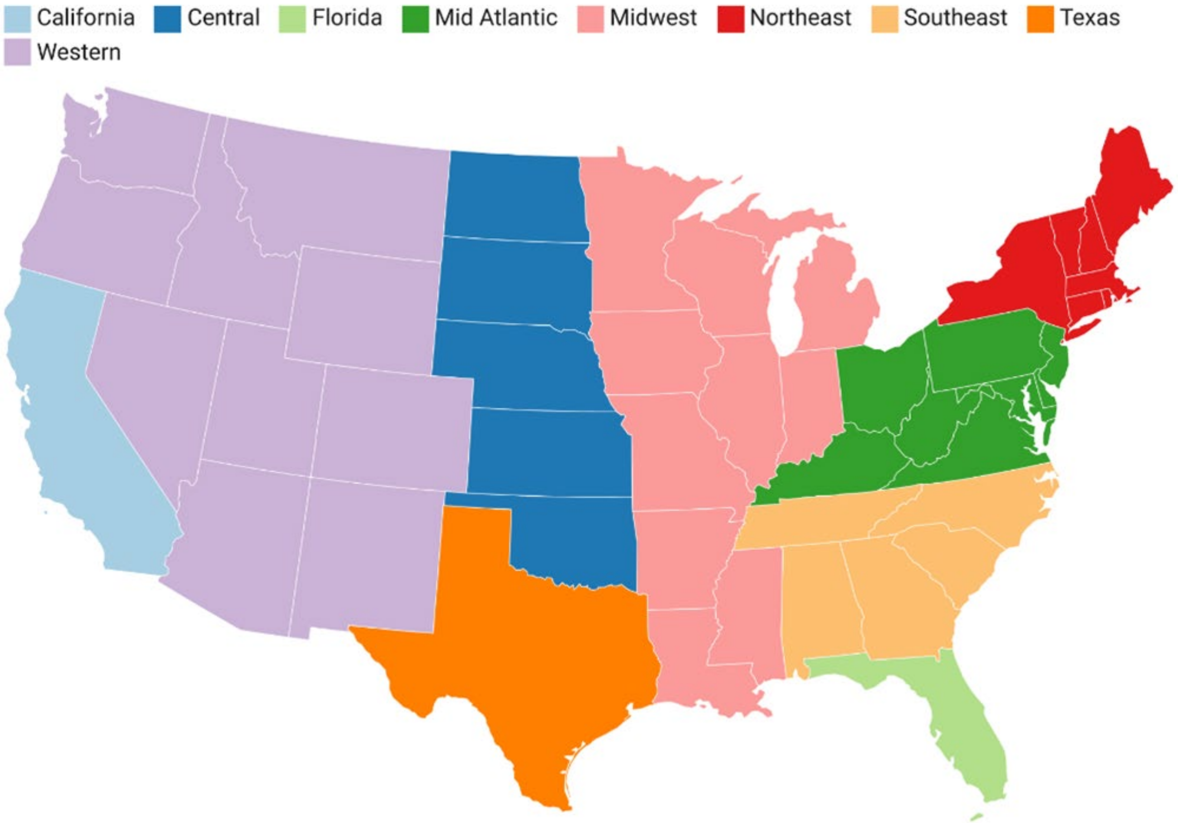
Research Questions

- How does the U.S. grid evolve from 2030–2050 under different scenarios?
- How do energy mixes and optimal investments shift with demand, technology costs, and CO_2 pricing?
- How sensitive are outcomes to CCS, hydrogen, and battery costs?
- How do policy uncertainty and potential rollbacks affect decarbonization and the roles of renewables, fossil fuels, and nuclear?

Model and Methodology Overview

- **Model**: urbs - open-source energy optimization tool
- **Base Year**: 2022
- **Optimization Years**: 2030, 2040, 2050
- **Analysis**: Regression-based electricity demand projections; WEO - Cost Projections and assumptions
- **Approach**: Myopic decision-making with future rollovers





Model and Methodology Overview

Inputs

- Technology & cost data
- Electricity & hydrogen demand
- Renewable potentials
- Storage data
- Transmission data
- Policy & scenario parameters

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Linear Optimization (urbs core)

- **Objective:** Minimize cost or CO_2
- **Constraints:** Capacity & efficiency limits, potential storage and transmission operational limits, policy restrictions

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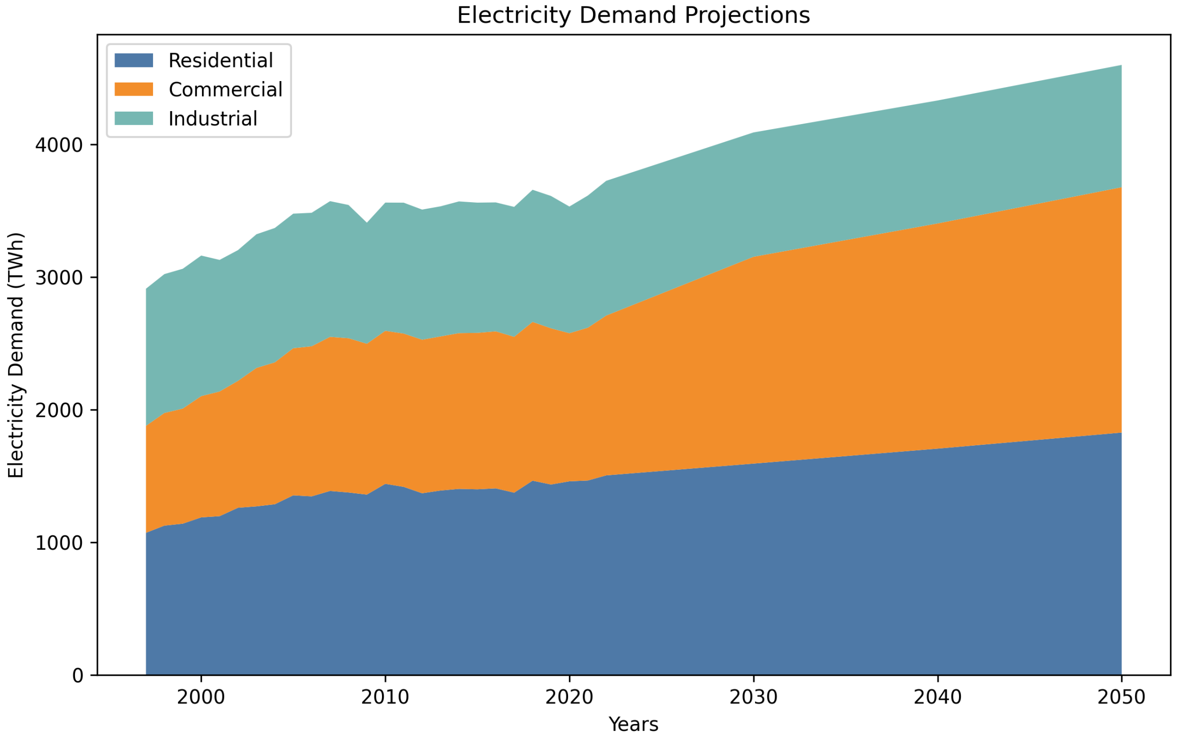
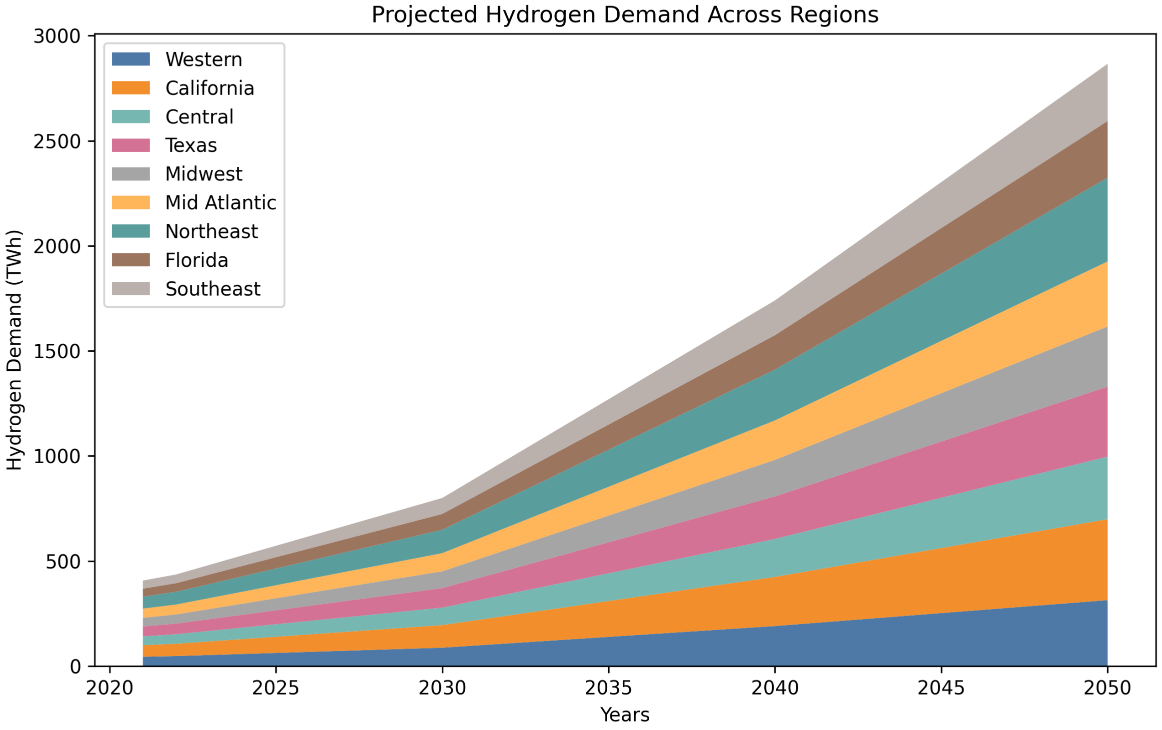
Outputs

- Generation mix
- Installed capacities
- System costs
- CO_2 emissions
- Storage & transmission use and installations

Demand Projections





- Total Electricity Demand: Residential + Commercial + Industrial + EV
  - Reference Demand: ~20% EV penetration by 2050 [~20TWh]
  - High Demand: ~100% EV penetration by 2050 [~100TWh]
- Residential, Commercial, Industrial: Exponential regression based projection.
- Hydrogen Projections based on assumptions from WEO NZE reports.

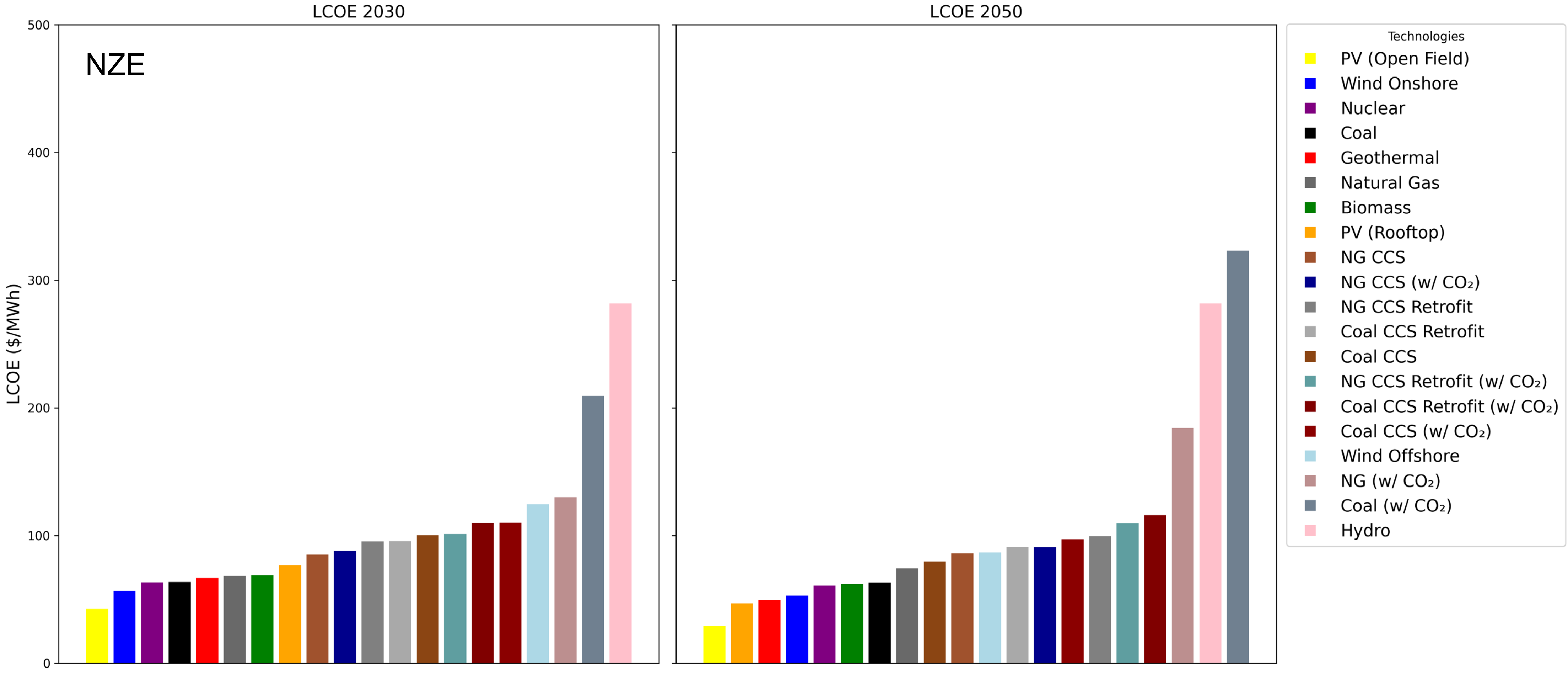
Scenario Design

Variations:

- **Electricity demand:** Reference; High Demand
- **Technology costs:** STEPS (current policy); APS (optimistic); NZE (net-zero)
- **CO_2 restrictions:** With and without carbon costs and limit
- **Sensitivity:** CCS, Nuclear Expansion, Hydrogen Integration
- ***Trump government:* *Lower climate ambition, weaker incentives for renewables***

Scenario	Cost Type	Demand	CO_2 Pricing	CO_2 Limit	Nuclear Expansion	CCS Imple-mentation	Hydrogen Integration
STEPS	STEPS	Reference					
STEPS_HD	STEPS	High					
APS	APS	Reference					
APS_HD	APS	High					
NZE	NZE	Reference					
NZE_HD	NZE	High					
APS_CO_2	APS	Reference	✓				
NZE_CO_2+	NZE	Reference	✓	✓			
NZE_CCS	NZE	Reference				✓	
NZE_CCS_CO_2+	NZE	Reference	✓	✓		✓	
NZE_NUC	NZE	Reference			✓		
NZE_CCS_NUC	NZE	Reference	✓	✓	✓	✓	
NZE_HYD	NZE	Reference					✓
NZE_HYD_CO_2+	NZE	Reference	✓	✓			✓

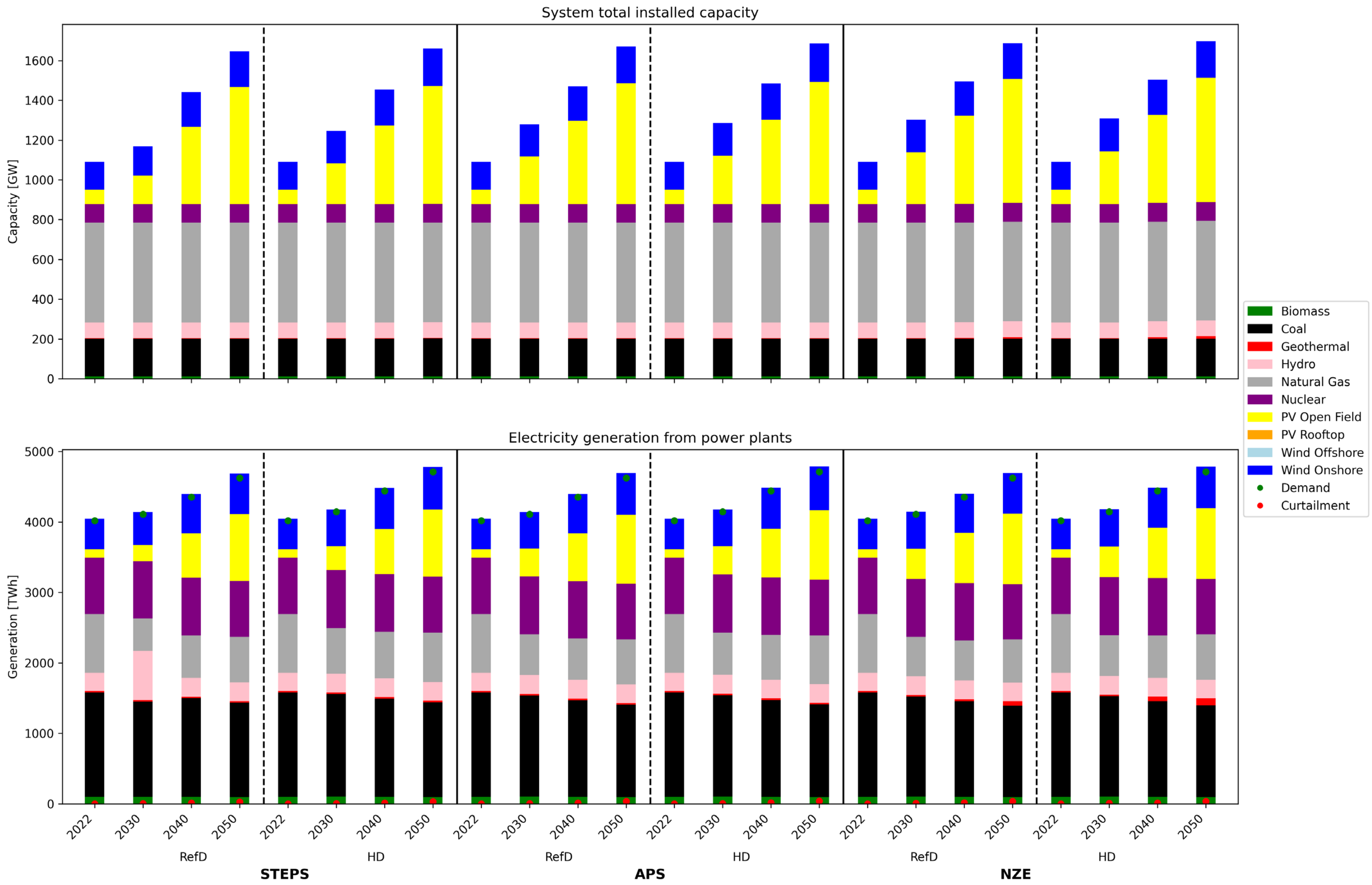
LCOE



- 2030: Solar PV, rooftop PV, onshore wind = low-cost; fossil + CCS = mid-cost
- 2050: Renewables cluster at low-cost; unabated fossil + CCS = high-cost (carbon price impact)
- STEPS/APS: Similar trends

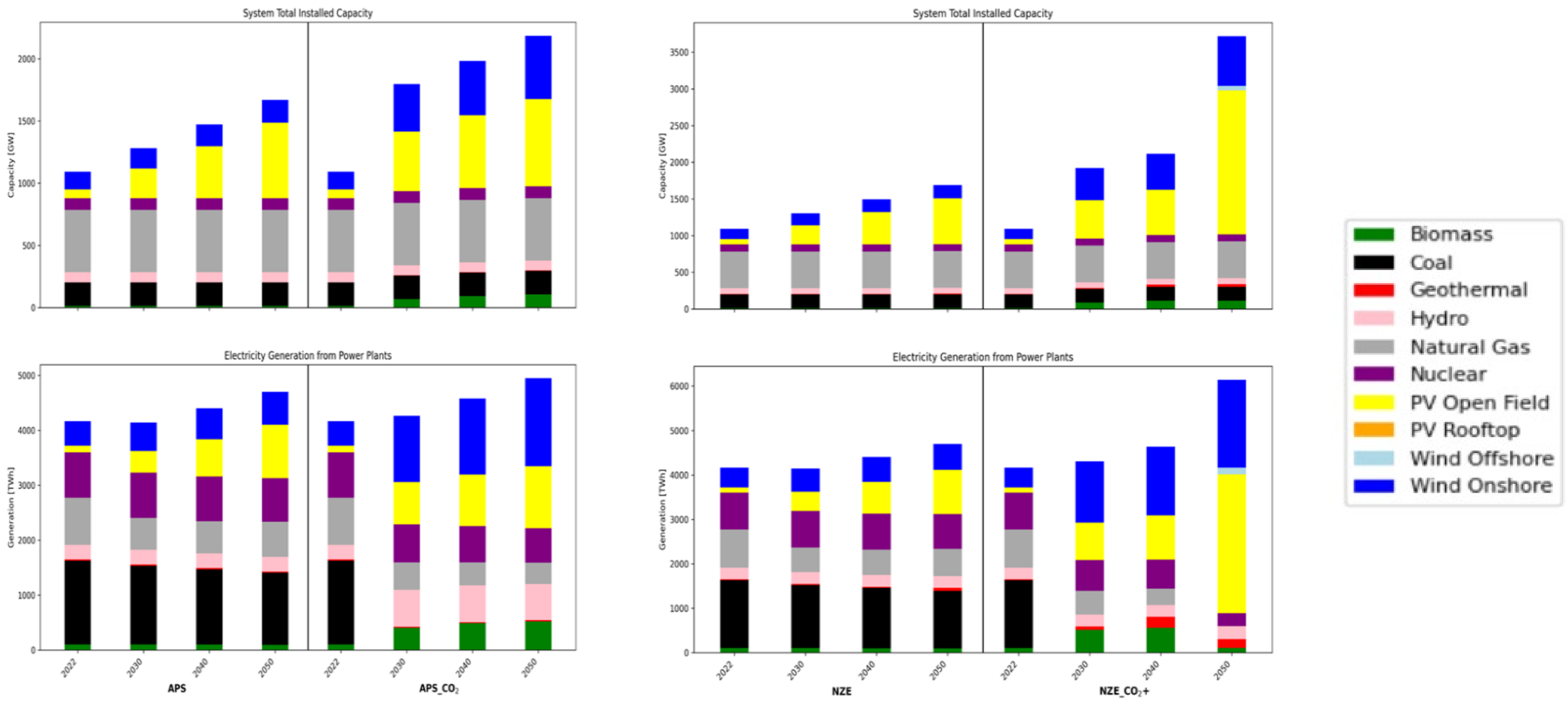
Results - Cost & Demand Sensitivities: STEPS, APS, NZE

- PV Open Field & Onshore Wind dominate capacity growth to 2050
  - 600 GW PV deployment; wind adds 30 - 50 GW depending on scenario
- Coal and gas remain significant unless carbon constraints applied
- Demand increases (HD) show minimal impact on mix or costs
- Deployment policy costs have minor influence on system evolution



Results - APS_CO_2 & NZE_CO_2+

APS cost with CO_2 pricing & NZE cost with CO_2 pricing and gradually increasing emission limit

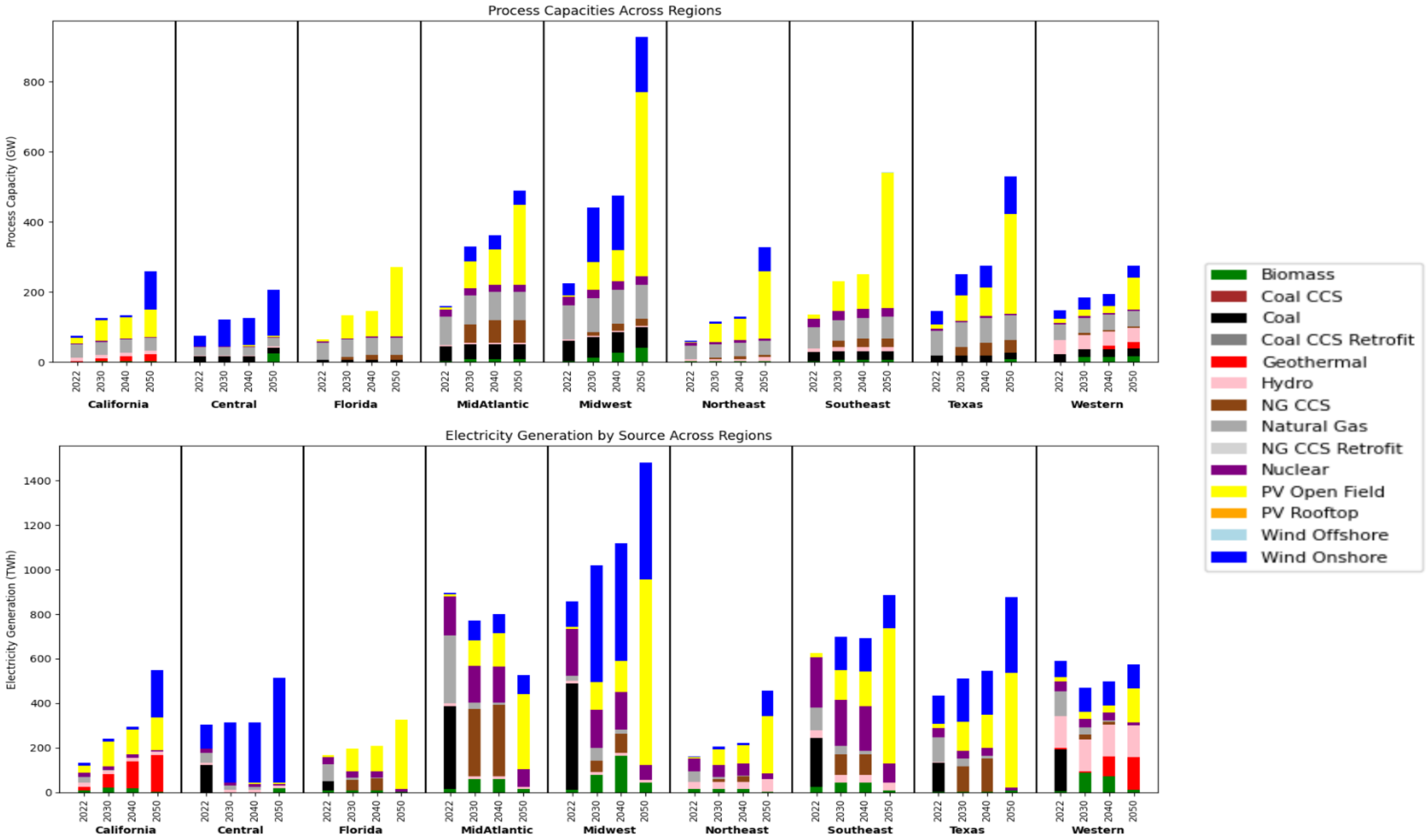


- Clear effect of CO_2 restrictions; Emissions cap + CO_2 pricing - full fossil phaseout by 2050
- PV and wind dominate all new additions
- In APS, only with a CO_2 cost - near-total Coal phaseout by 2050 and Natural Gas significantly declines
- Electricity mix shifts toward low-carbon with a moderate cost increase

Results - NZE_CCS & NZE_CCS_CO_2+

NZE cost with CCS implementation & NZE cost with CCS implementation and CO_2 pricing with a gradually increasing emission limit

- In NZE_CCS, without CO_2 policy, CCS is unused, coal and gas persist, and PV slowly leads renewable growth.
- CO_2 cap + pricing enables moderate CCS deployment
- 2040: 16% of electricity from Natural Gas with CCS due to policy incentives
- 2050: CCS phases out to meet net-zero target
- Battery storage plays critical role in balancing clean energy mix

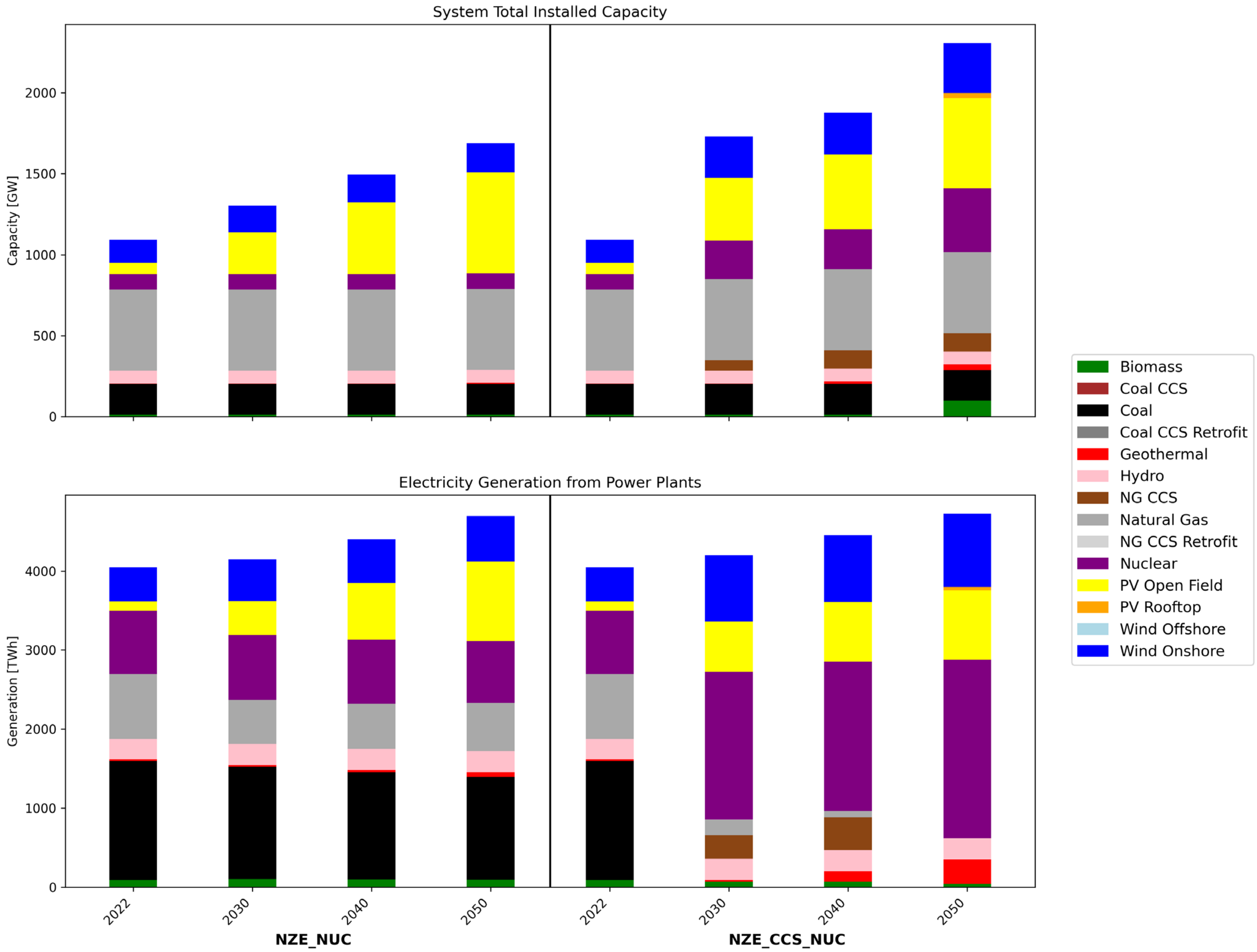


NZE_CCS_CO_2+

Results - NZE_NUC & NZE_CCS_NUC

NZE cost with nuclear expansion permitted & NZE cost with CCS, nuclear expansion and CO_2 pricing and gradually increasing emission limit

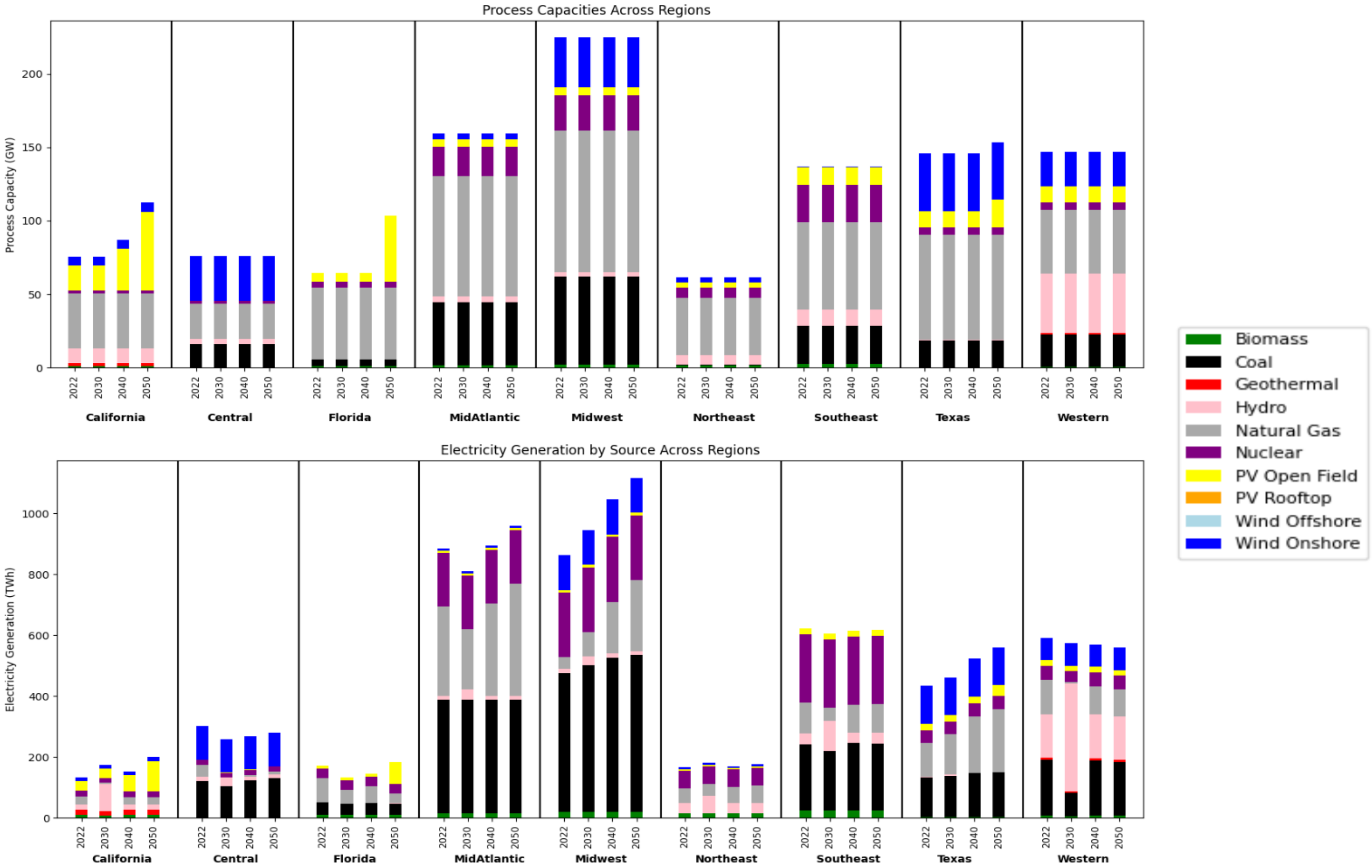
- No CO_2 policy: nuclear remains at current levels, minimal new investment
- With CO_2 limits: nuclear expands to ~50% by 2050
- Enables stable, low-carbon baseload
- CCS_NUC scenario lowers emissions with manageable cost rise



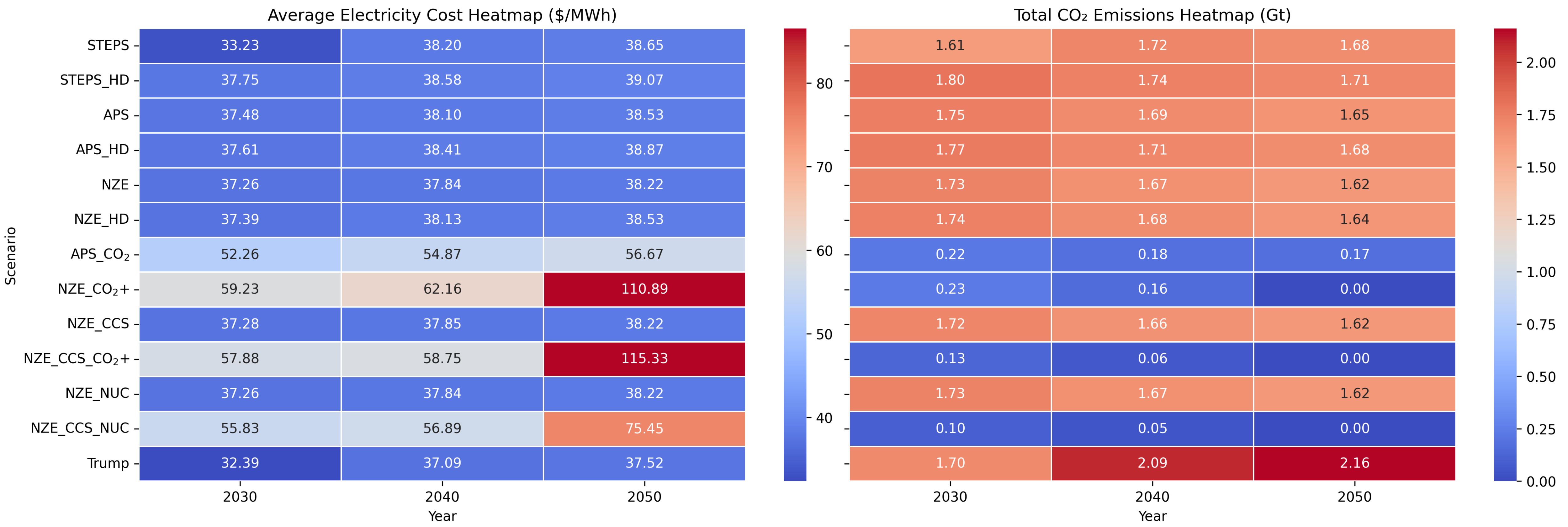
Results - Trump Administration

STEPS cost with no CO_2 restricitions and increased cost of renewables and electricity storage

- No CO_2 cost or restrictions; fossil fuels remain dominant
- Renewables grow due to cost advantage but slowly
- Coal and gas capacity not replaced



Results - System Cost and Emission Outcomes

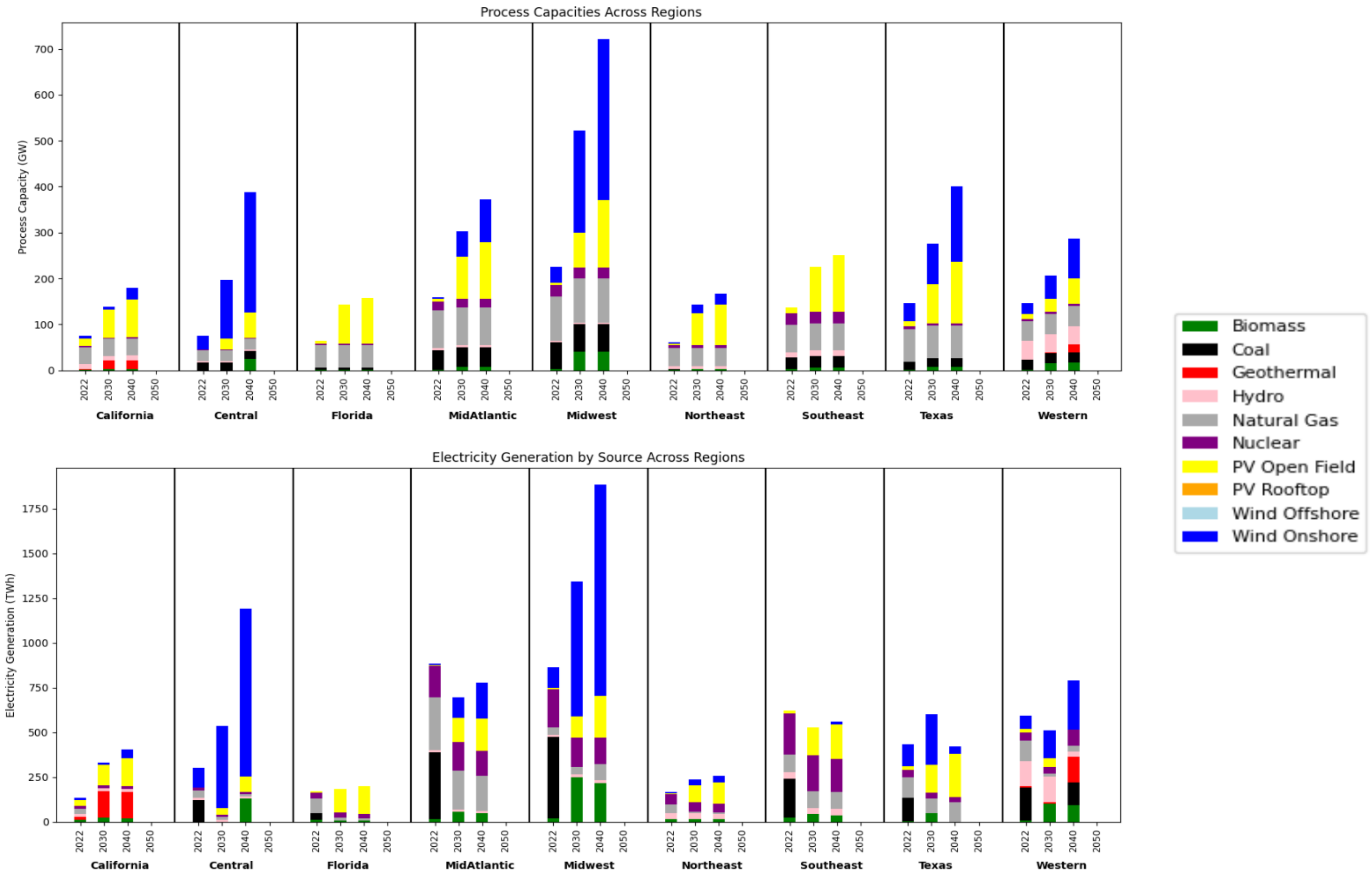


- STEPS/APS: stable costs, poor emissions (1.6+ Gt by 2050)
- NZE_CO_2+ & CCS_CO_2+: net-zero, but highest costs
- Nuclear reduces price impact in NZE_CCS_NUC (only ~30% cost rise) despite drastic decarbonization
- Trade-off: cost vs climate performance clearly visible

Results - NZE_HYD & NZE_HYD_CO_2+

NZE cost with integrated hydrogen infrastructure & NZE cost with hydrogen and CO_2 pricing and gradually increasing emission limit

- In NZE_HYD, the mix stays NZE-like but electrolysis demand drives huge PV growth (>2000 GW by 2050).
- Grid becomes highly renewable due to strict CO_2 limits
- Electrolysis adds major load to electricity demand
- Model infeasible in 2050 - system unable to meet combined electricity and hydrogen demand



NZE_HYD_CO_2+

Conclusion & Outlook

- Solar PV and onshore wind are the most cost-effective technologies across all scenarios.
- The Trump Administration scenario yields the lowest system cost but results in the highest CO_2 emissions, highlighting the trade-off between affordability and sustainability.
- High CO_2 pricing accelerates fossil fuel phase-out and supports faster clean energy transition.
- A balanced trade-off is achieved in CCS + Nuclear (NZE_CCS_NUC) scenarios, combining emission cuts with manageable system costs.
- CCS adoption is moderate due to high costs.
- Stable policy, technological innovation, and strategic system planning are essential for a resilient, low-carbon electricity future, all balanced with a framework that ensures consumer affordability.

Thank You for your Attention!

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