

Weather-Informed Energy Systems Utilizing the WIS:dom Optimization Model

Prepared By:

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Prepared For:

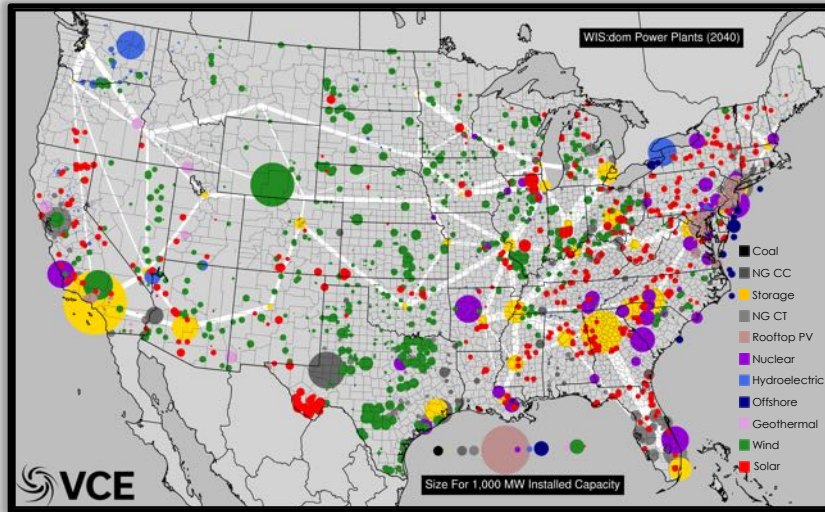
The Payne Institute, Colorado School of Mines

May 3rd, 2018

Disclaimer:

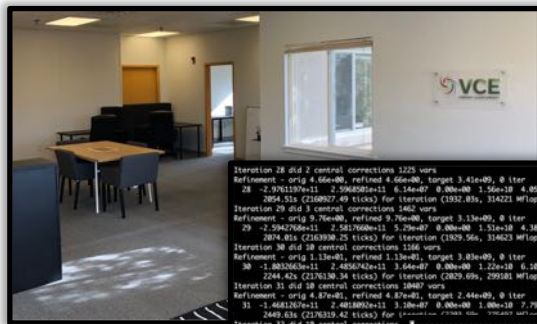
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Vibrant Clean Energy



Purpose of Vibrant Clean Energy, LLC:

- Reduce the cost of electricity and help evolve economies to near zero emissions;
- Co-optimize transmission, generation, storage, and distributed resources;
- Increase the understanding of how Variable Generation impacts and alters the electricity grid and model it more accurately;
- Agnostically determine the least-cost portfolio of generation that will remove emissions from the economy;
- Determine the optimal mix of VG and other resources for efficient energy sectors;
- Help direct the transition of heating and transportation to electrification;
- License WIS:dsm optimization model and/or perform studies using the model;
- Ensure profits for energy companies with a modernized grid;
- Assist clients unlock and understand the potential of high VRE scenarios, as well as zero emission pathways.

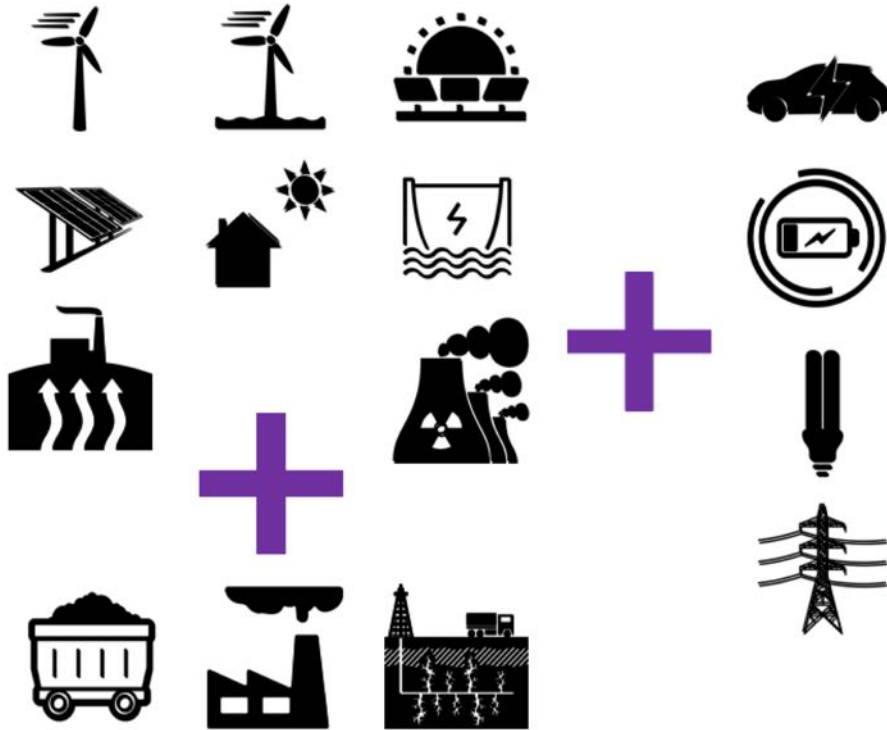


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Iteration 18 did 2 central corrections 1225 vars
Refinement - orig 4.66e+00, refined 4.66e+00, target 3.41e+00, 0 iter
29 -2.39e+10e+11 2.50e+00e+11 6.14e+07 0.00e+00 1.56e+18 4.85e+03
2854.51s (2168027.49 ticks) for iteration (332.81s, 314221 Mflops for lin. solve)
Iteration 19 did 3 central corrections 1262 vars
Refinement - orig 9.76e+00, refined 9.76e+00, target 3.13e+00, 0 iter
29 -5.94e+10e+11 2.51e+00e+11 5.79e+07 0.00e+00 1.51e+18 4.38e+03
2874.81s (2183980.21 ticks) for iteration (332.56s, 314423 Mflops for lin. solve)
Iteration 30 did 18 central corrections 1166 vars
Refinement - orig 1.11e+01, refined 1.11e+01, target 3.80e+00, 0 iter
30 -1.88e+10e+11 2.48e+00e+11 3.64e+07 0.00e+00 1.22e+18 6.18e+03
2244.42s (2176130.34 ticks) for iteration (2829.61s, 299181 Mflops for lin. solve)
Iteration 31 did 18 central corrections 18807 vars
Refinement - orig 4.87e+01, refined 4.87e+01, target 2.44e+00, 0 iter
31 -1.46e+10e+11 2.48e+00e+11 3.18e+07 0.00e+00 1.06e+18 7.79e+03
2469.63s (2176319.42 ticks) for iteration (2829.61s, 299181 Mflops for lin. solve)
Iteration 32 did 18 central corrections 18807 vars
Refinement - orig 6.40e+01, refined 6.40e+01, target 2.44e+00, 0 iter
32 -1.22e+10e+11 2.38e+00e+11 2.74e+07 0.00e+00 1.06e+18 7.79e+03
2427.35s (2176319.41 ticks) for iteration (2829.61s, 299181 Mflops for lin. solve)
Iteration 33 did 18 central corrections 18807 vars
Refinement - orig 9.95e+01, refined 9.95e+01, target 2.44e+00, 0 iter
33 -1.01e+10e+11 2.38e+00e+11 2.74e+07 0.00e+00 1.06e+18 7.79e+03
2416.47s (2176319.37 ticks) for iteration (2829.61s, 299181 Mflops for lin. solve)
Iteration 34 did 4 central corrections 18807 vars
Refinement - orig 6.35e+01, refined 6.35e+01, target 2.44e+00, 0 iter
34 -2.26e+10e+11 2.38e+00e+11 2.74e+07 0.00e+00 1.06e+18 7.79e+03
2343.84s (2163380.64 ticks) for iteration (2829.61s, 299181 Mflops for lin. solve)
Iteration 35 did 18 central corrections 18807 vars
Refinement - orig 2.11e+02, refined 2.11e+02, target 2.44e+00, 0 iter
35 -2.87e+10e+11 2.38e+00e+11 2.74e+07 0.00e+00 1.06e+18 7.79e+03
2343.84s (2163380.64 ticks) for iteration (2829.61s, 299181 Mflops for lin. solve)
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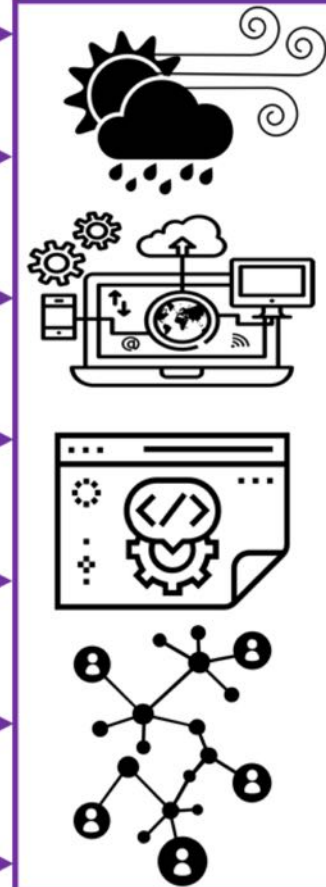
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Copyright Vibrant Clean Energy, LLC
Adapted From Original Version November 1st, 2016
Final Version August 31st, 2017
Weather-Informed energy Systems design, operations and markets
WIS:dsm (Planning and Dispatch Modes)
EDF National Variant
Written to depict the transition of the US electric sector
Particular attention is paid to the nuclear plants
Version 1.4
Dr Christopher T M Clark
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The WIS:dom Optimization Model

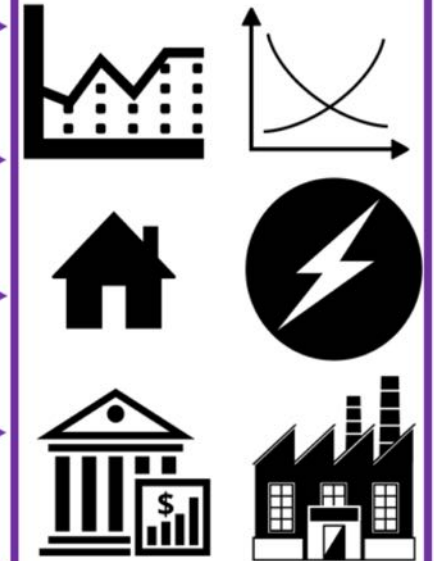
Detailed Input Data



WIS:dom



Numerous Objectives Output



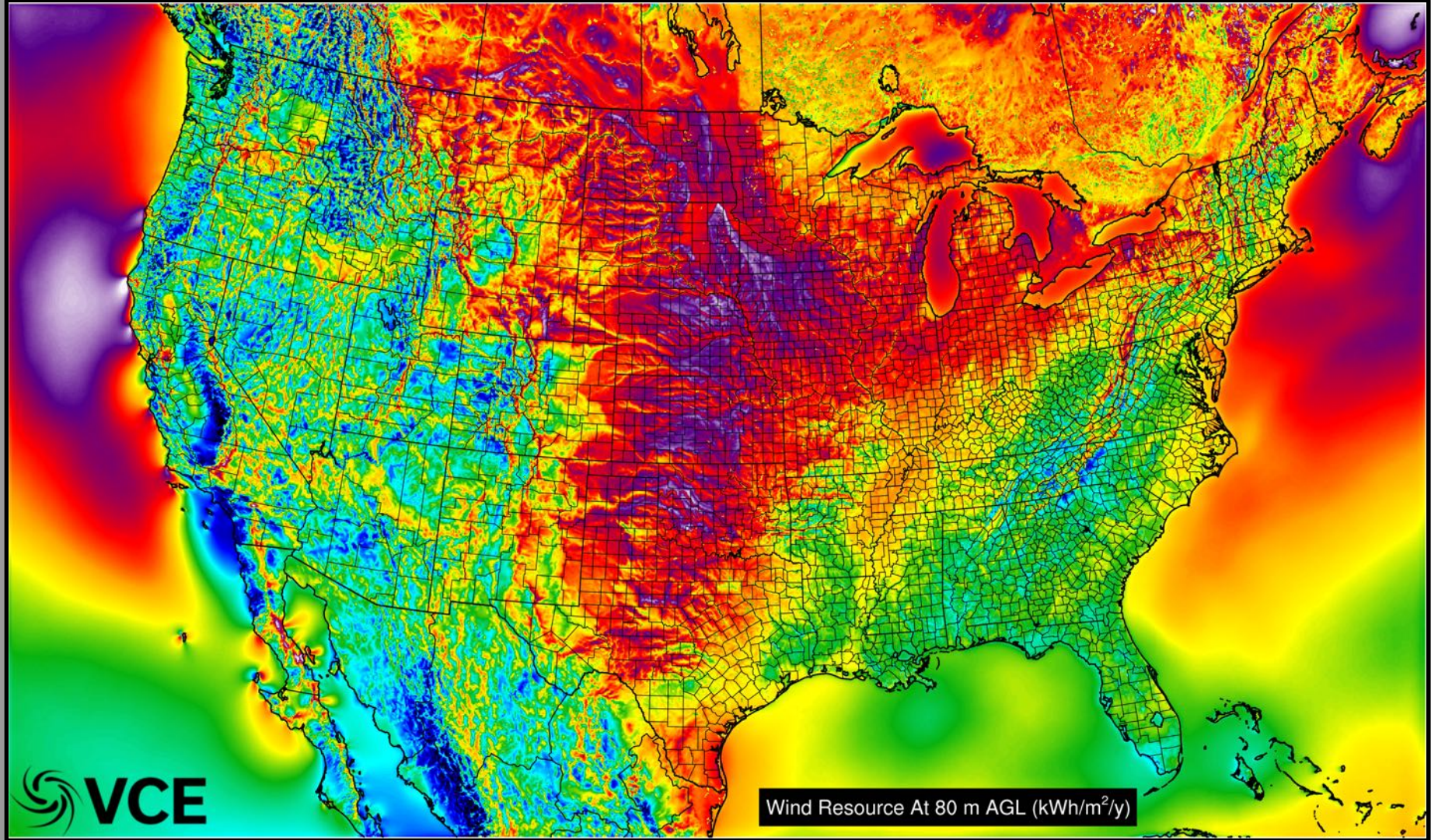
WIS:dom Is a Synthesis Model

WIS:dom is the **only** combined capacity expansion and production cost model. It combines:

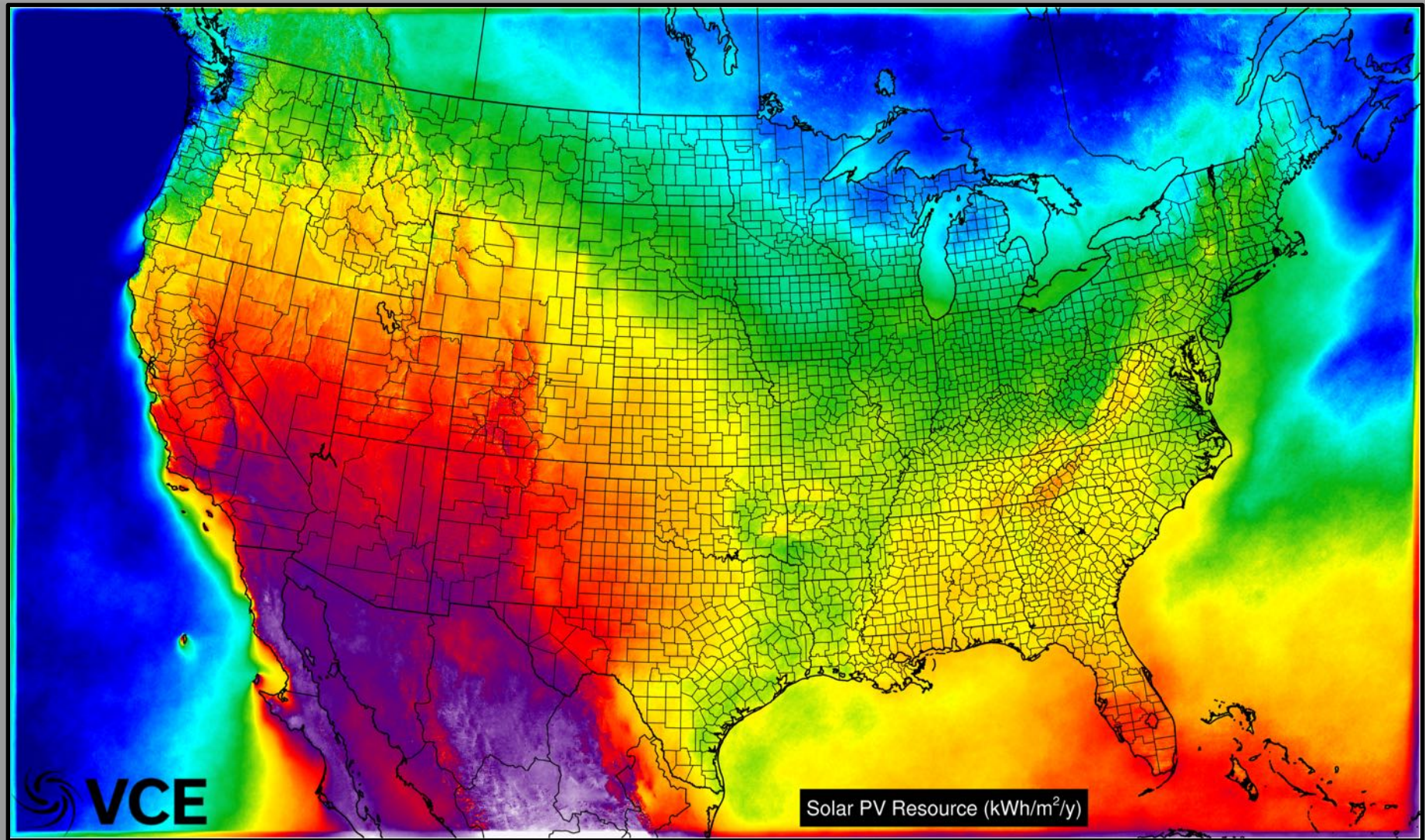
- ✓ Continental-scale (globally capable), spatially-determined co-optimization of transmission, generation and storage expansion while simultaneously determining the dispatch of these sub systems at 13-km or 3-km, hourly or 5-minutely resolution;
- ✓ Dispatch includes:
 - Individual unit commitments, start-up, shutdown profiles, and ramp constraints;
 - Transmission power flow, planning reserves, and operating reserves;
 - Weather forecasting and physics of weather engines;
 - Detailed hydro modeling;
 - High granularity for weather-dependent generation;
 - Existing generator and transmission asset attributes such as heat rates, line losses, power factor, variable costs, fixed costs, capital costs, fuel costs, etc.;
- ✓ Large spatial and temporal horizons;
- ✓ Policy and regulatory drivers such as PTC, ITC, RPS, etc.;
- ✓ Detailed investment periods (2-, 5-, or 10- year) out past 2050;
- ✓ **100 - 10,000x increased resolution** compared with nearest competitor for VRE, load, and conventional generator descriptions.

What Do Models Need To Consider?

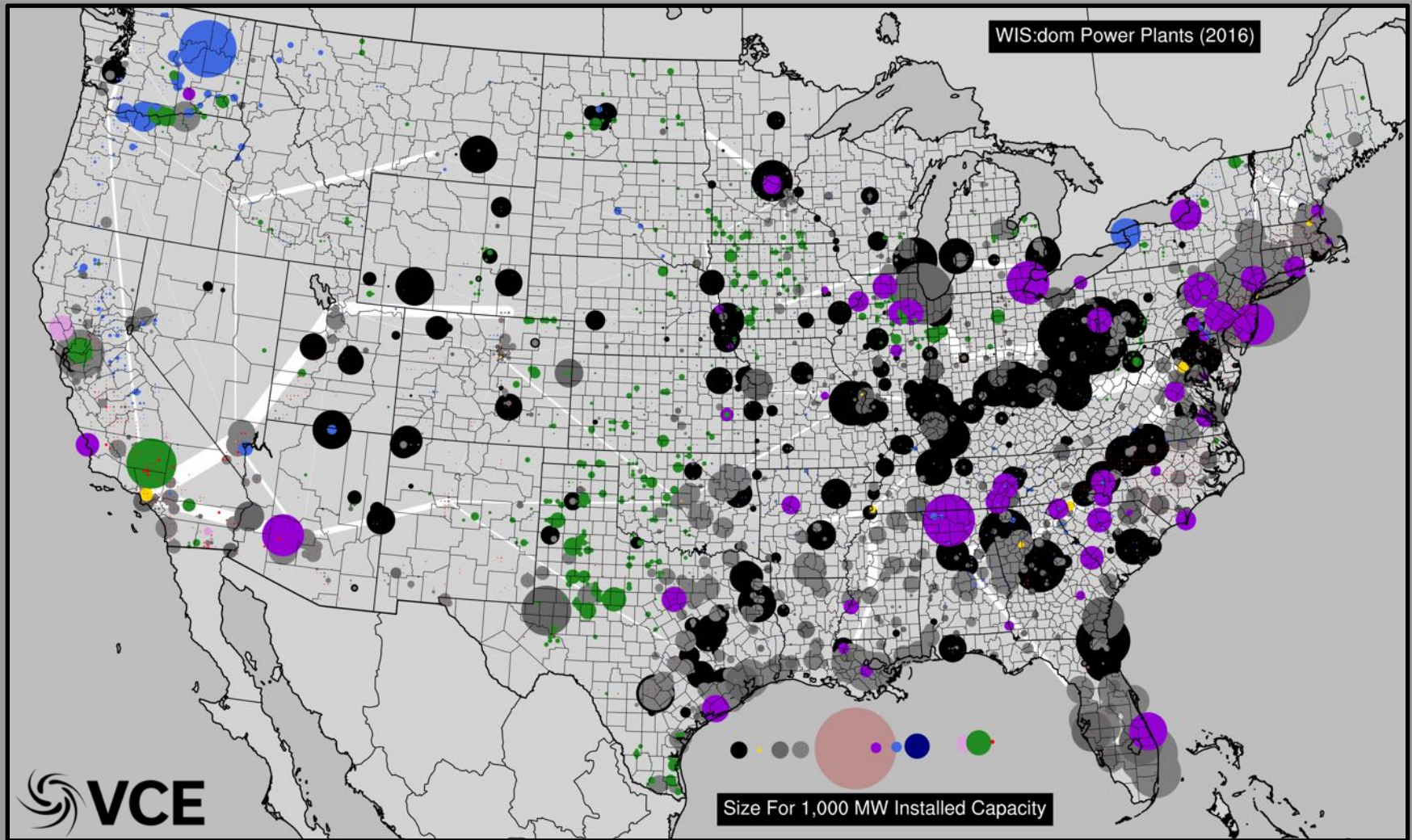
Wind Resource at 3-km Resolution



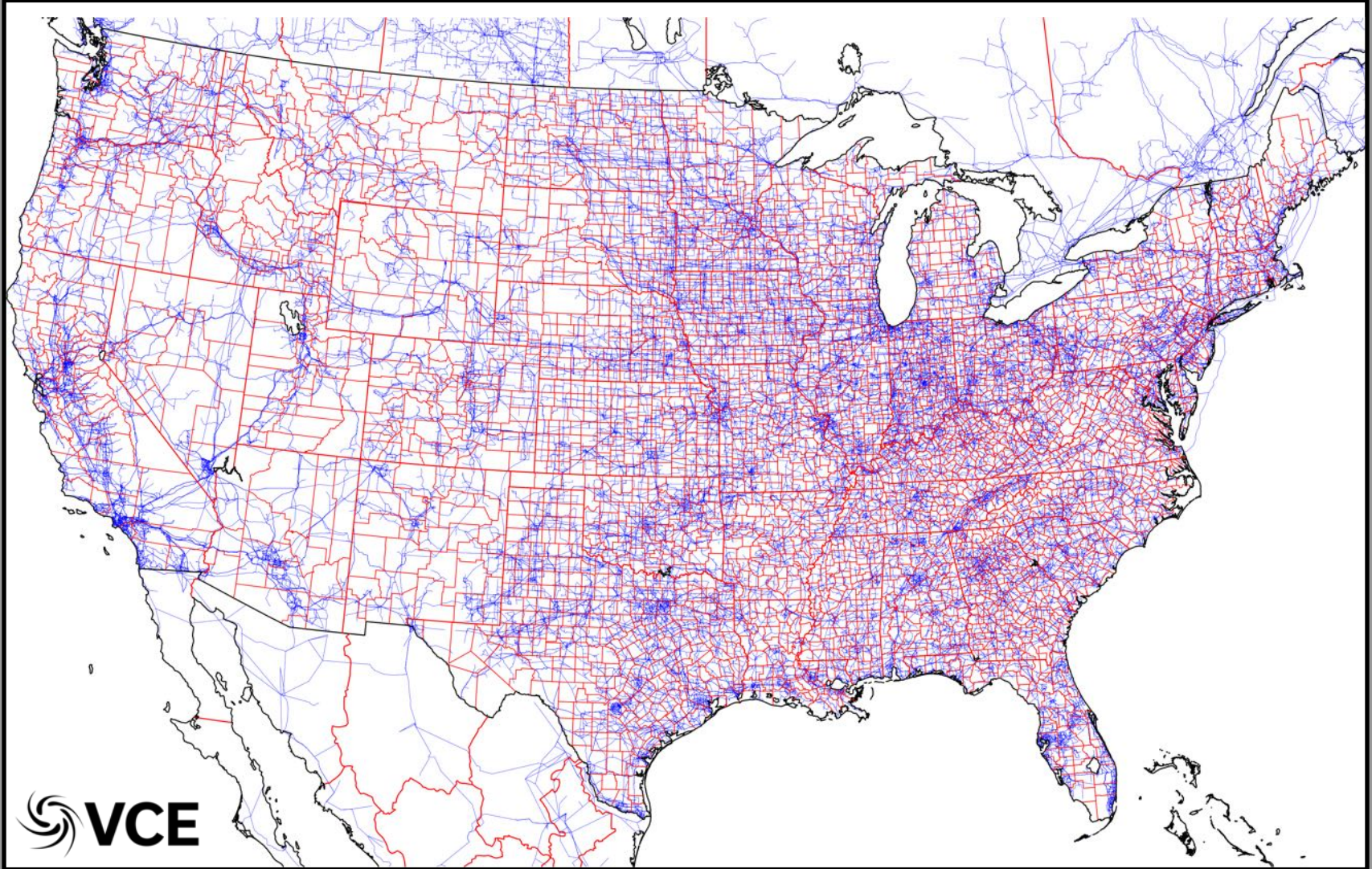
Solar PV Resource at 3-km Resolution



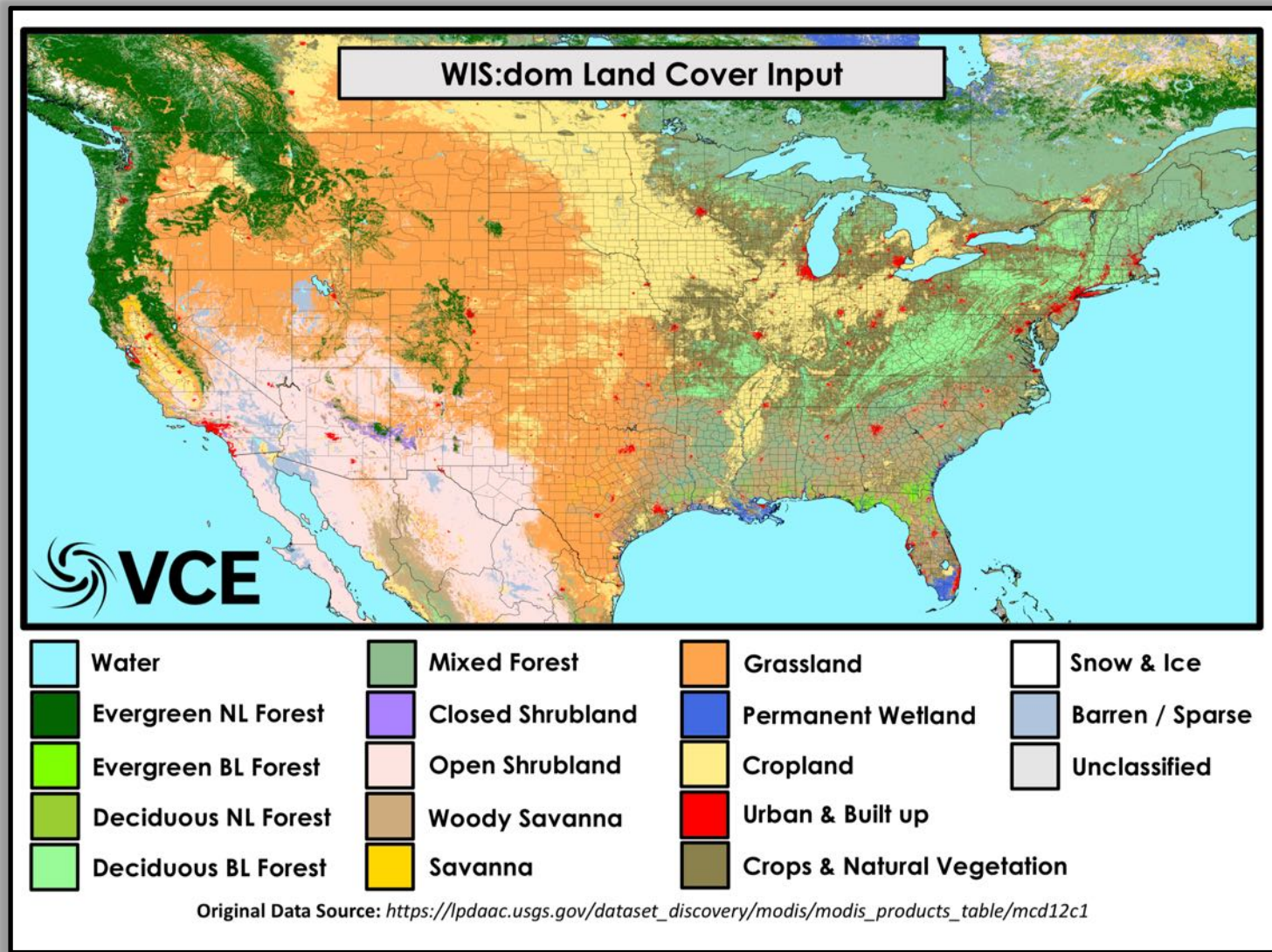
Existing Generators (2017)



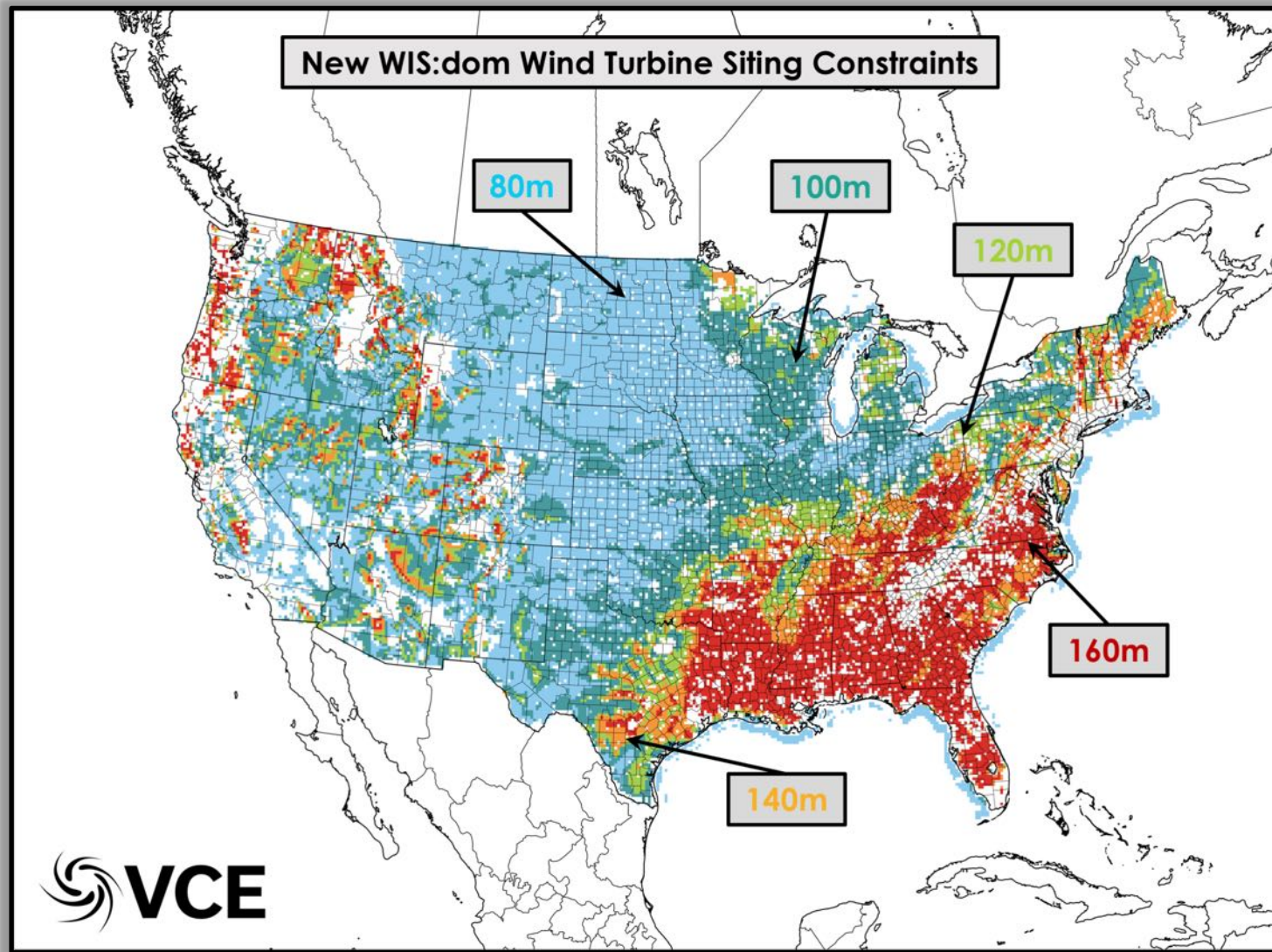
Existing Electricity Transmission (2017)



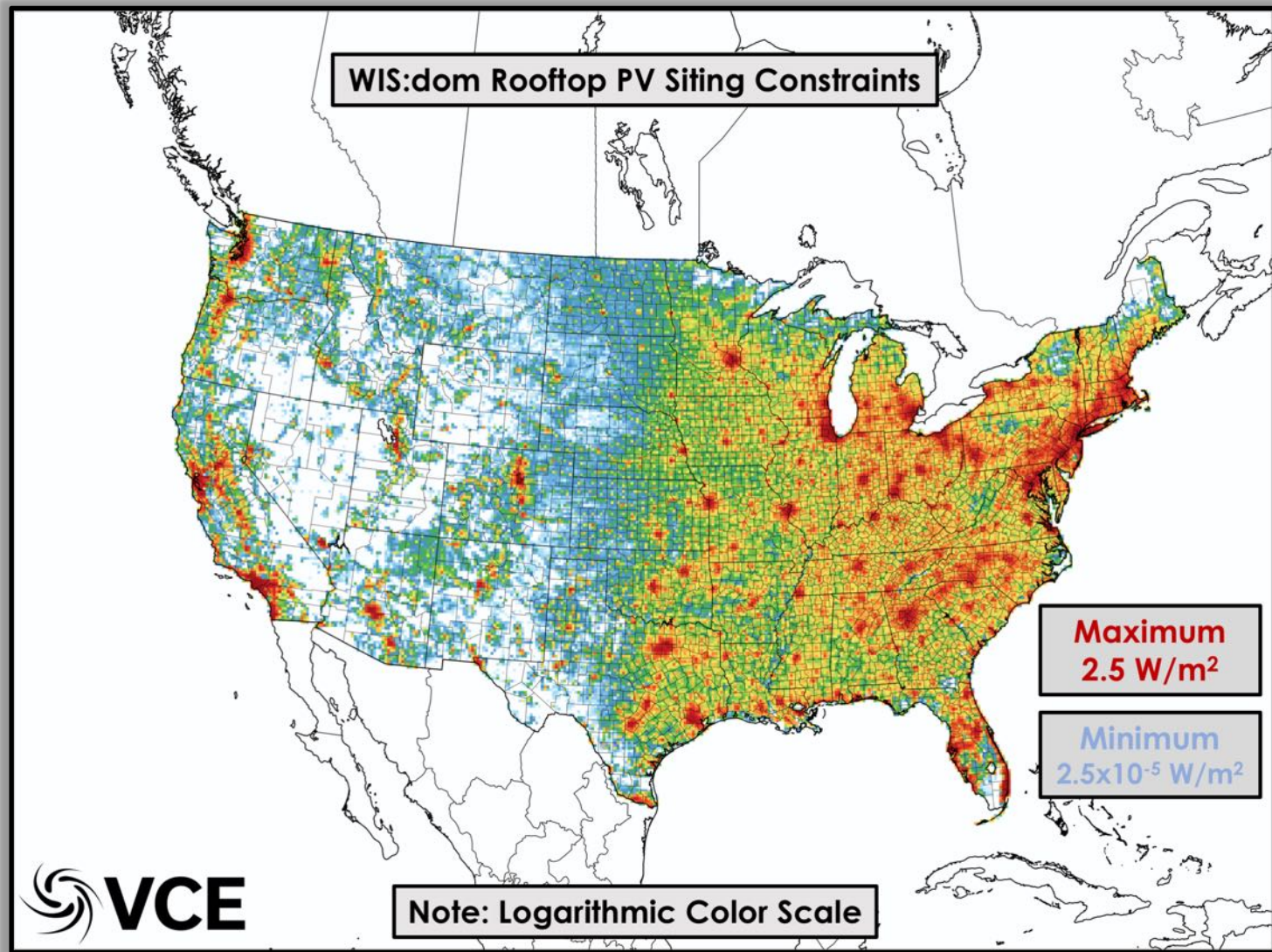
Landcover Inputs For Siting Constraints



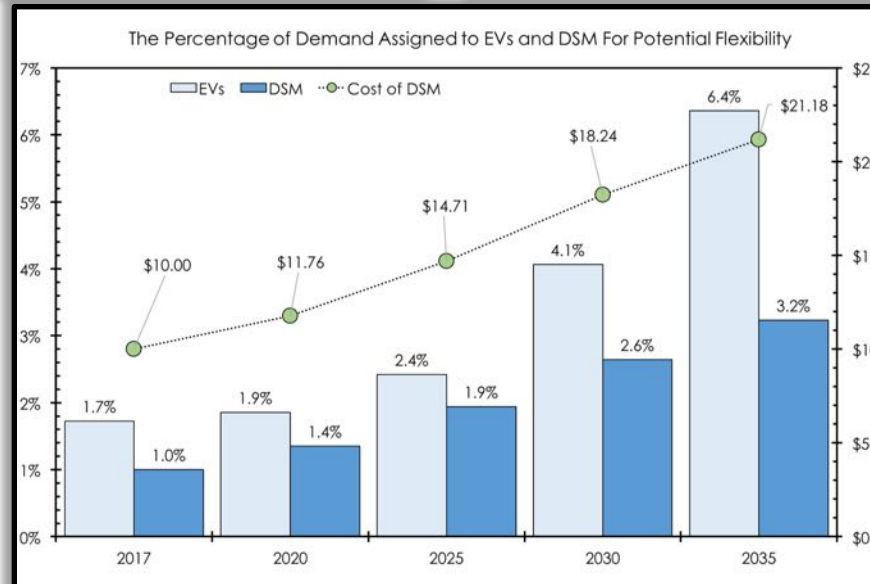
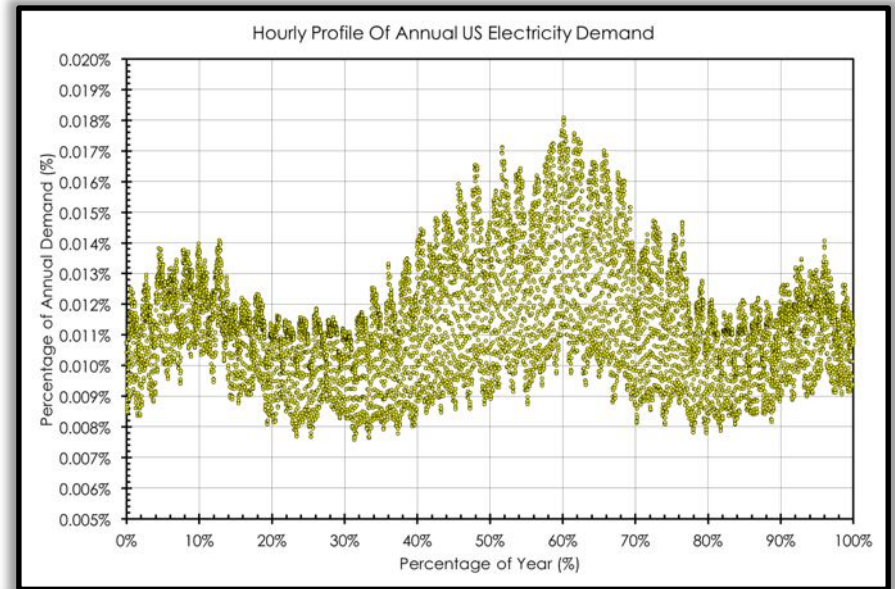
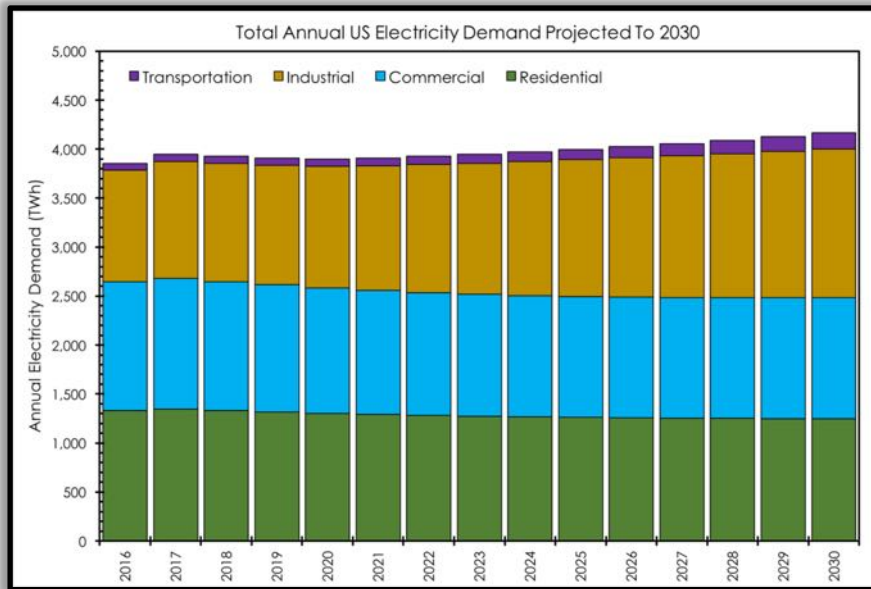
Optimal Hub Heights Mapped in WIS:dom



Rooftop Solar Potential Mapped in WIS:dom



Demand-side Inputs



Dominant Logic Equations In WIS:dom

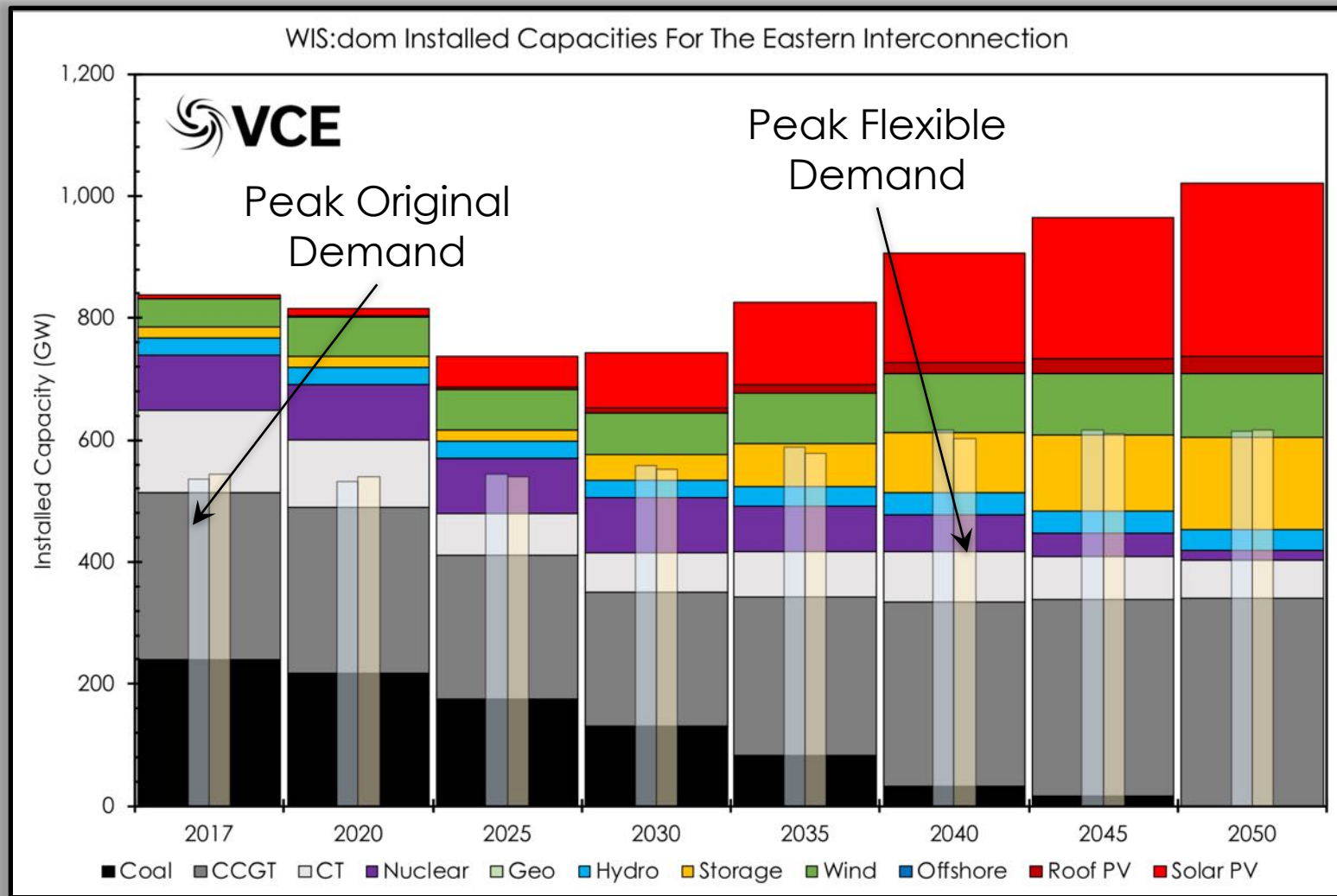
| Constraint ID | Equation Name | Equation Purpose | Impact Estimation |
|---------------|--|--|--|
| 1 | Total System(s) Cost Objective | To define the objective that is being minimized | Critical Other objectives may alter solutions significantly |
| 2 | Reliable Dispatch Constraint | Enforce WIS:dom meets demand in each region each hour without fail | Critical Strict enforcement of zero loss of load |
| 3 | Market Clearing Price Adjustment | Allowing WIS:dom to estimate the dispatch stack & attribute price vs cost | Critical Different market structures could impact deployment choices |
| 4 | DSM Balancing Constraint | Ensures that DSM providers can balance their demand | High Changing the description of DSM and costs could alter solutions |
| 5 | Transmission Power Flow Constraint | Produces the optimal power flow matrix and associated losses | Critical Transmission power flow significantly impacts dispatch and deployment |
| 6 | Transmission Capacity Constraint | Calculates the capacity of each transmission line | Critical Without this constraint, power flow could become artificially large |
| 7 | Planning Reserve Constraint | Ensure planning reserve margins are maintained | High Capacity credit for VREs can alter deployment decisions |
| 8 | Coal, NGCC, NGCT, Nuclear, Hydro, Geo Capacity Constraints | Maintain the capacity of generators above their peak production | High Without the constraints generations can be incredibly based on marginal costs alone |
| 9 | Storage Power & Energy Capacity Constraints | Complex equations & constraints to determine the utilization of storage | Critical Storage correctly modeled can change all investment decisions and dispatch |
| 10 | Coal, NGCC, NGCT, Nuclear, & Geo P_min Constraints | Constraints that force WIS:dom to adhere to P_min attributes for thermal generators | Medium P_min enforcement has lower impacts on decision |
| 11 | RPS & Emission Constraints | To enable WIS:dom to understand policy, regulatory and societal limitations | Critical When emissions enforced investment decisions are completely changed |
| 12 | Generator & Transmission Capacity Expansion Constraints | To require WIS:dom to keep investments in new generation & transmission to specific levels | Low-Medium Very tight enforcement could impact decisions, but realistic values do not substantial change solutions |
| 13 | Coal, NGCC, NGCT, Nuclear, & Geo Ramping Constraints | Describing the speed at which generators can alter their output for WIS:dom | Medium Faster ramping thermal generation is more favorable in lower emission scenarios, so this constraint impacts decisions in those cases |
| 14 | DER Deployment & Cost Constraints | Specifies to WIS:dom the amount of DERs to be constructed and/or cost to system of these assets | Low Has minimal impact on the overall system costs and investment decisions of utility scale generators |
| 15 | CIL & CEL Constraints | Describe the import & export limits between markets, countries, states, and interconnections | Medium-High Transmission expanding from existing lines & the addition of market impacts can dramatically alter decisions in some high emission reduction scenarios |
| 16 | Spatial Limitation Constraint | Allow WIS:dom to understand the space requirement for generators and competition for land use | Medium Without this constraint land use can be over used and over count the amount of generation in a location/site |
| 17 | Extraction Limits For VRE | Determines the limits to VRE extraction for nearby sites | Medium Impactful for wind siting considerations but much lower for solar PV siting |
| 18 | Nuclear & Hydro Dispatch Schedule | Informs WIS:dom that nuclear and hydro must conform to addition constraints regarding the water cycle, water temperature, and refuelling | Low-Medium Nuclear suffers a small amount due to offline times & hydro flexibility limited by constraint to assist with other VREs |
| 19 | Relicense / Repower Decision | Facilitates WIS:dom opting to relicense or repower an existing nuclear or VRE site | Medium-High Repowering can substantially improve existing sites at lower cost, while relicensing enable nuclear to remain within markets for longer |
| 20 | Load / Weather Forecast Error Estimator | Enables WIS:dom to detect regions with poor weather and/or load forecasts for consideration during investment decisions | Low-Medium Load & weather forecasts are small enough over EI markets that the investments are not substantially altered. For WECC, the impact is much higher |

WIS:dom Consider Numerous Factors For The Optimization Of The Electricity Grid

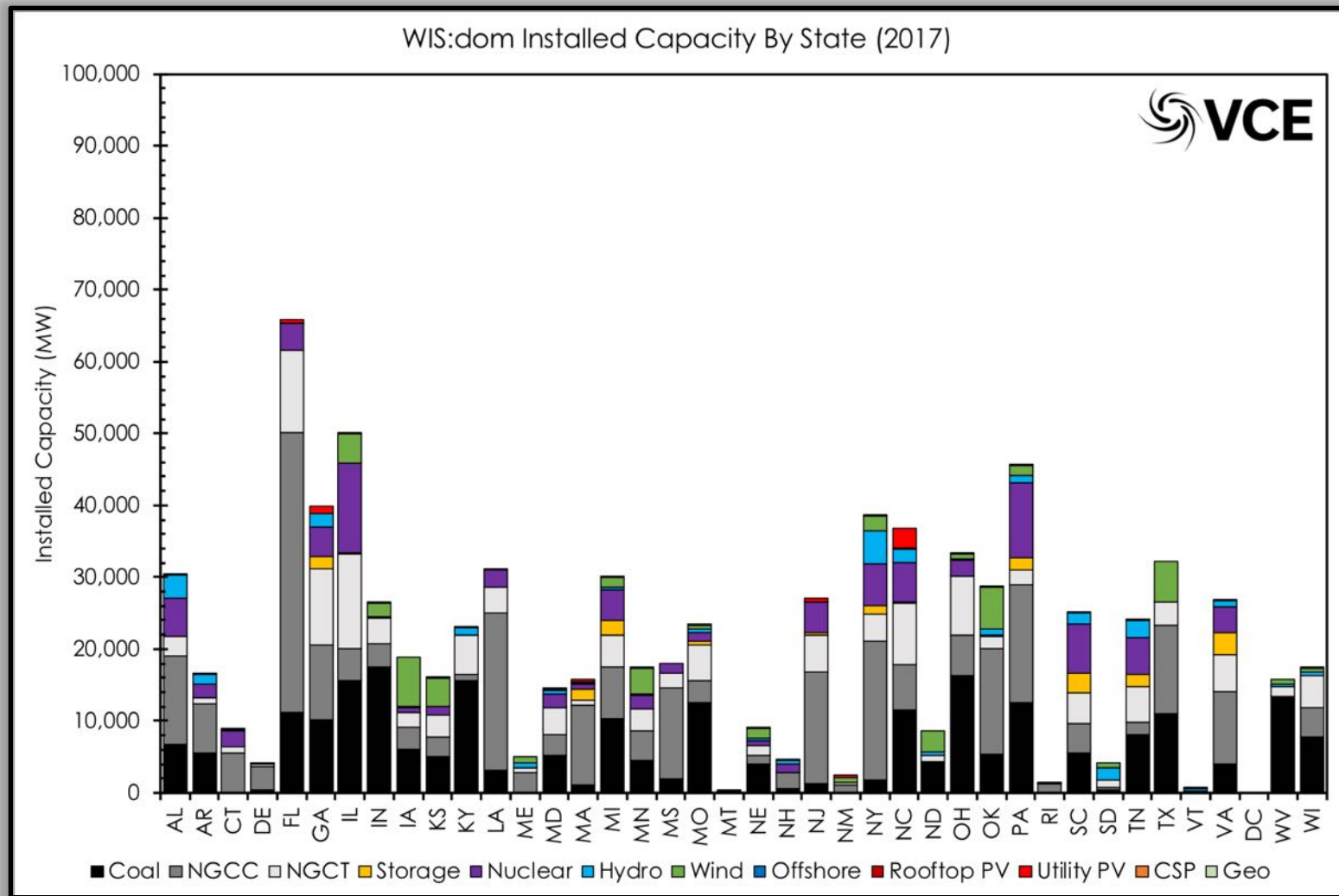
| Input ID | Input Name | Existing | New |
|----------|-----------------------------|--|--|
| 1 | Heat Rate | All Current Thermal Data | NREL ATB 2017 Value |
| 2 | Minimum Load | All Current Thermal Data | Fleet Average |
| 3 | Power Factors | All Current Generator Data | Fleet Average |
| 4 | Fuel Costs | All Current Thermal Data For Multiplier | NREL ATB 2017 Value |
| 5 | Fixed O&M Costs | All Current Generator Data | NREL ATB 2017 Value |
| 6 | Non-fuel Variable O&M Costs | All Current Generator Data | NREL ATB 2017 Value |
| 7 | Capital Costs | All Current Generator Data | NREL ATB 2017 Value |
| 8 | Relicense / Repower Costs | All Existing Nuclear, Wind, and Solar Generators | 45% For VRE, N/A For Nuclear |
| 9 | Discount Rates | Uses Same Rate as "New" | 5.87% Real |
| 10 | Economic Lifetimes | All Current Generator Data | NREL ATB 2017 Value |
| 11 | Transmission Costs | Uses Same Cost As "New" | ABB / Blended Existing Costs |
| 12 | Transmission Topolgy | Current Above 69 kV Aggregated To Reduced Form | New Lines Allowed Within WIS:dom; constrained by user |
| 13 | Demand | Current Demand By Sector | Growth Estimates Provided By Sector By VCE |
| 14 | Weather / Power Data | N/A | One Year Of Hourly Power Data For Wind & Solar Over El |
| 15 | Policy & Regulations | Apply All Existing Policies & Regulations | Input As Constraints On Future Scenarios |
| 16 | Locational Multiplier | N/A | Black & Veatch / NREL Public Data Combined By VCE |

Eastern Interconnection Study: *Economically-Driven*

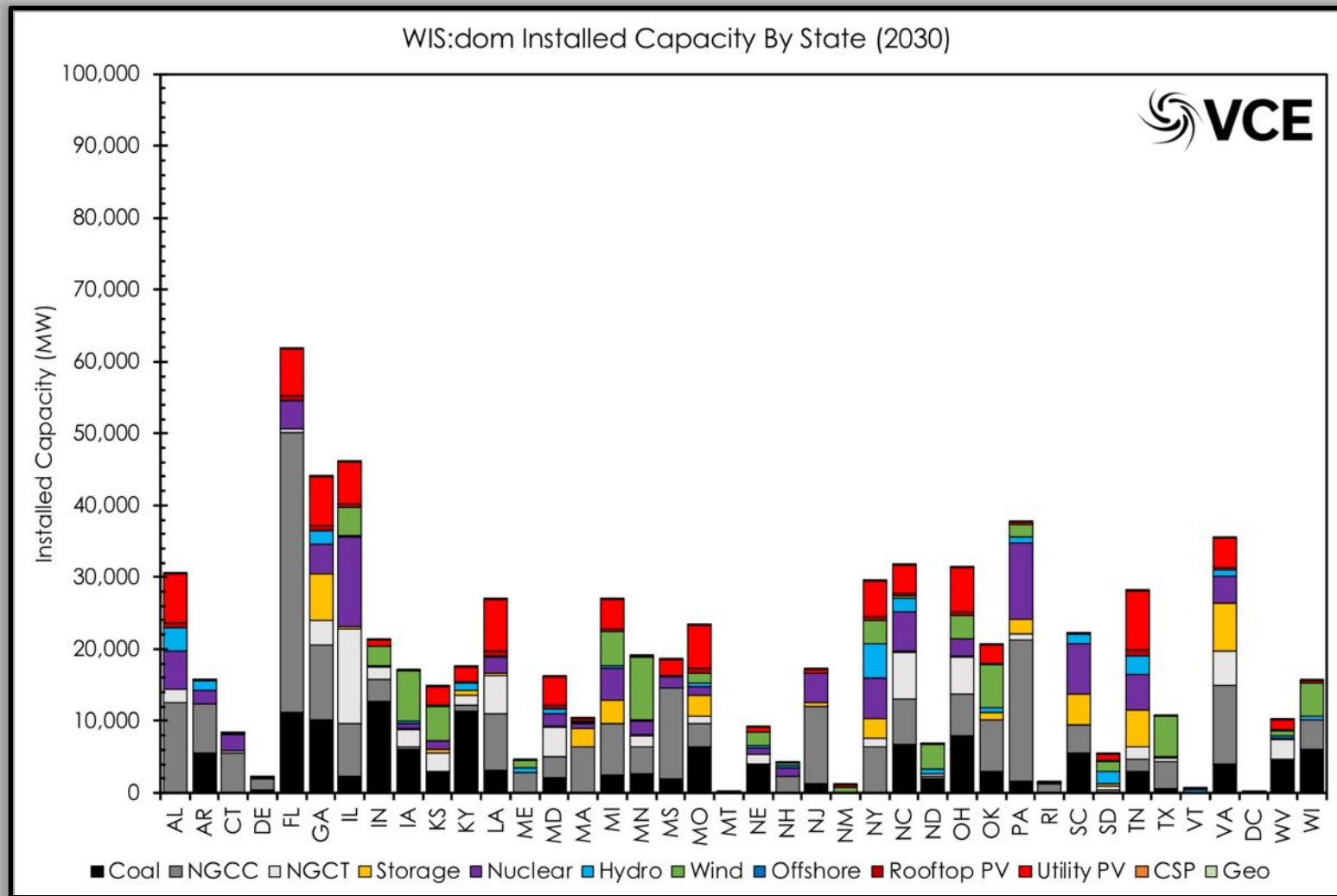
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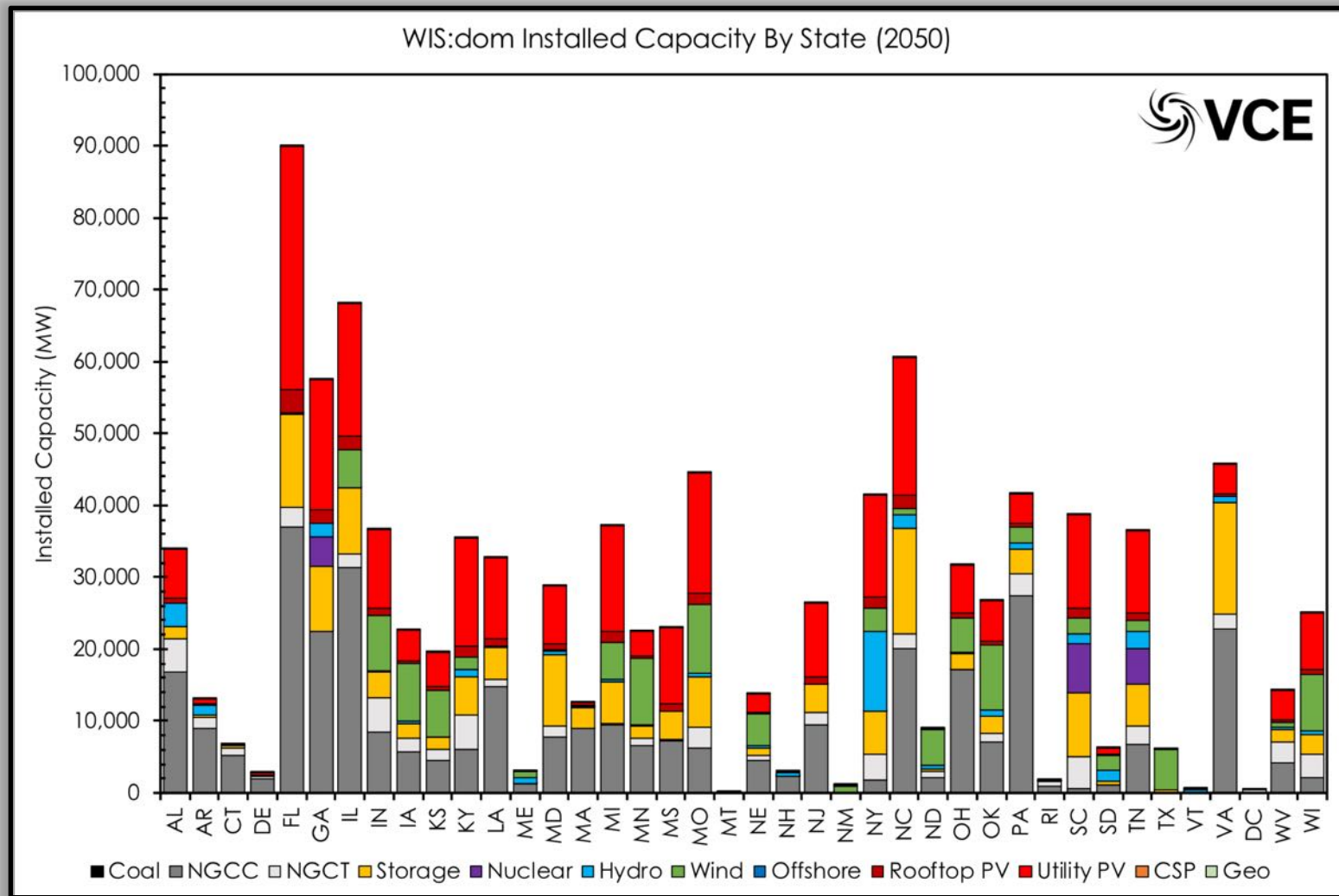
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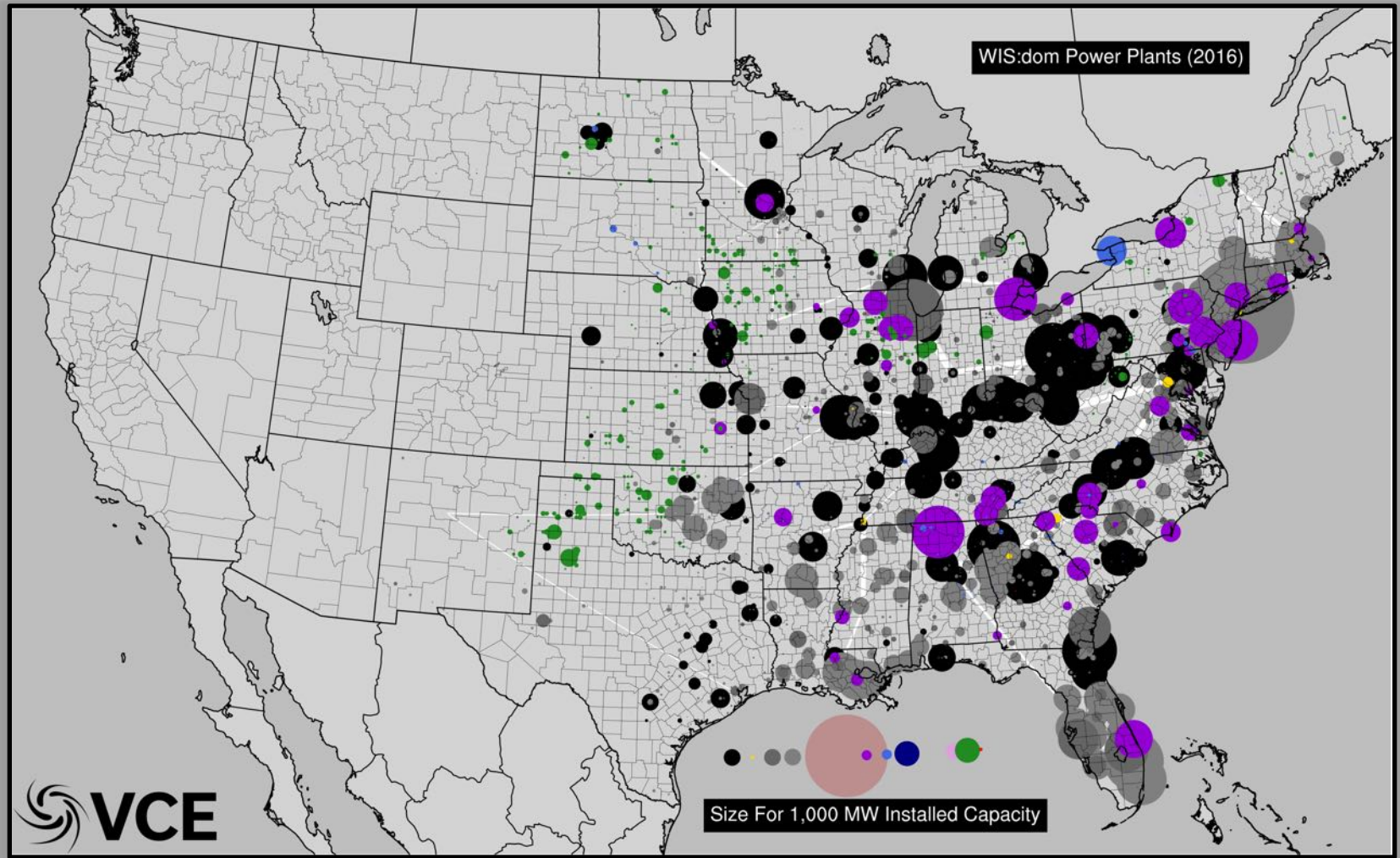
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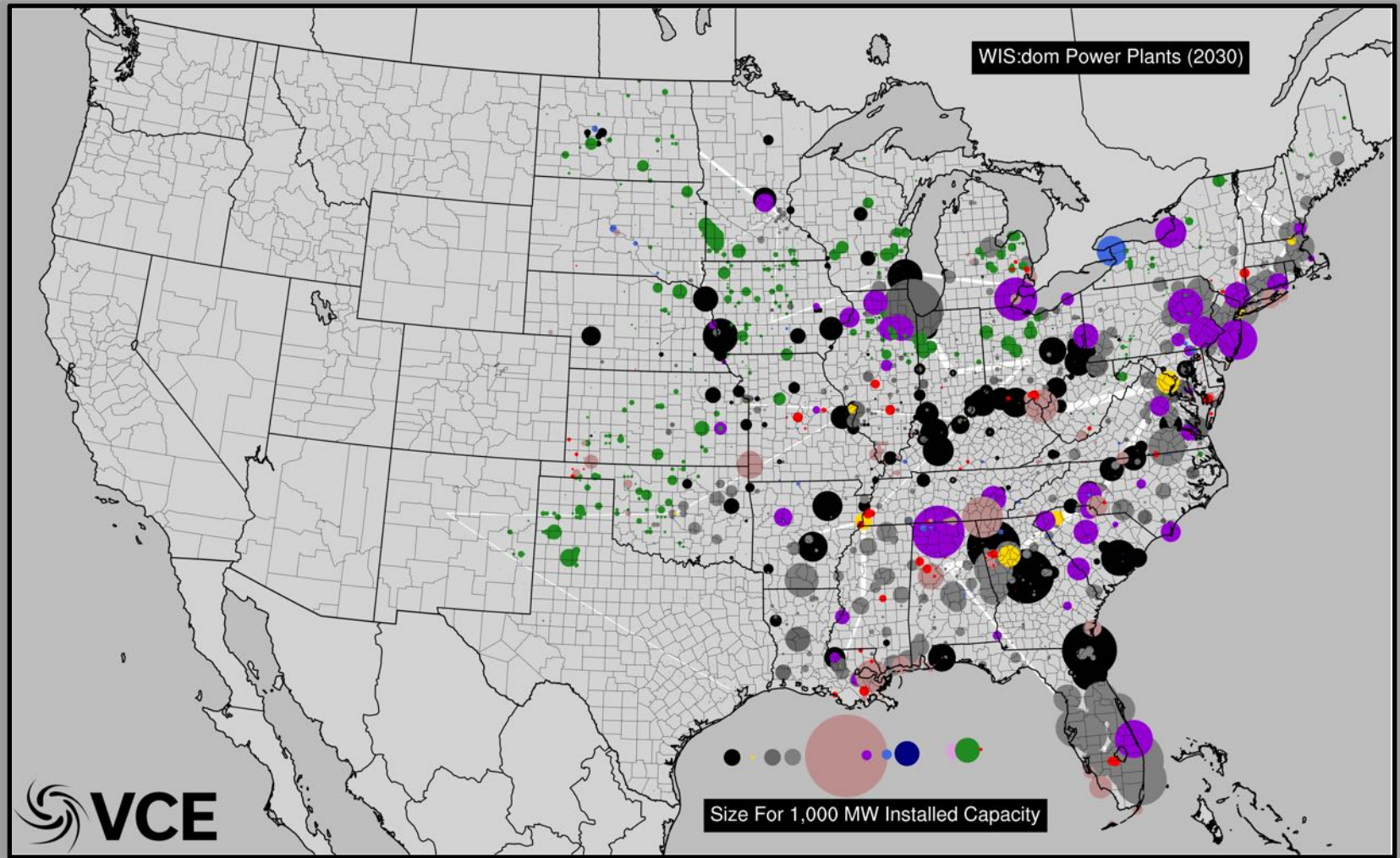
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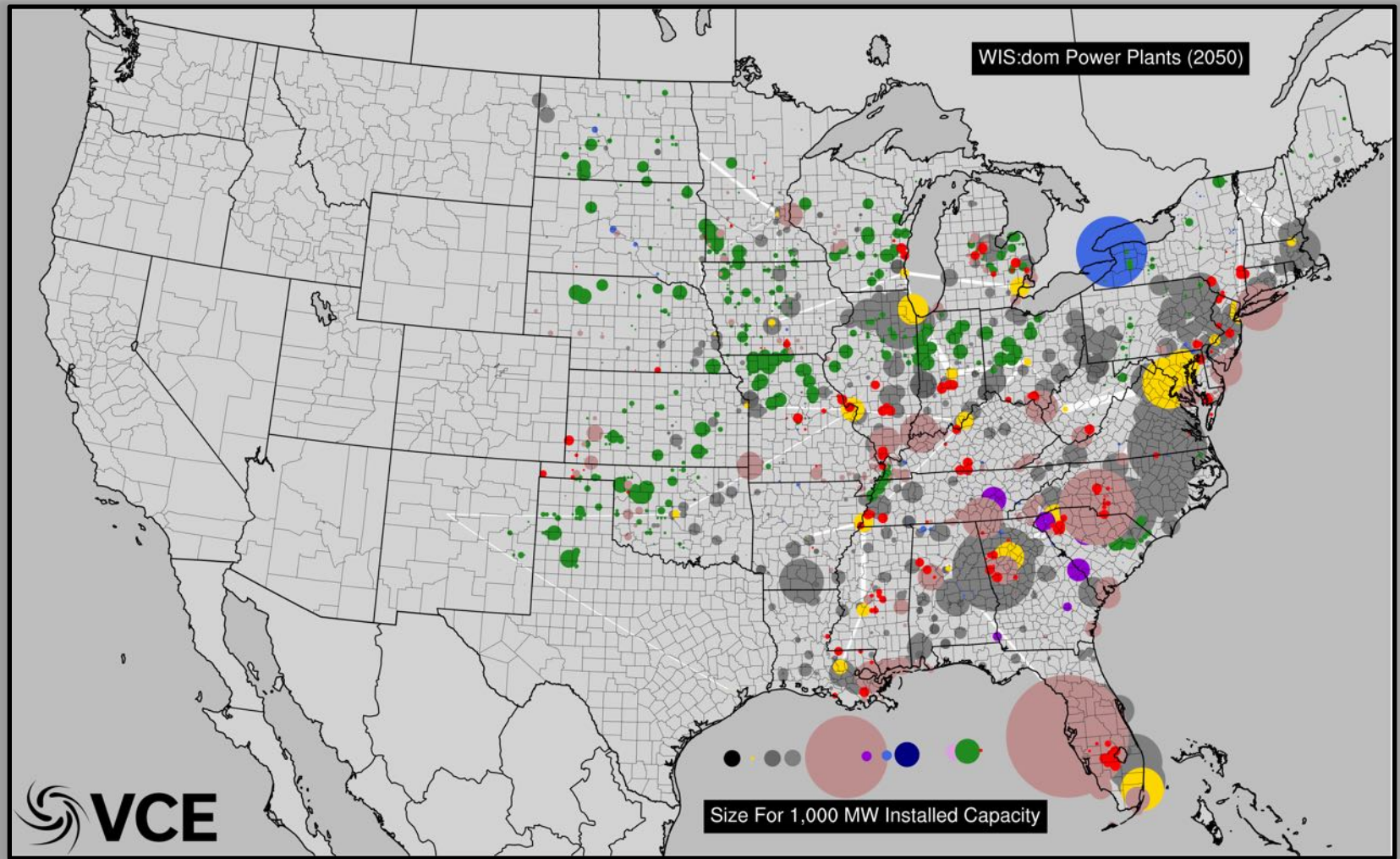
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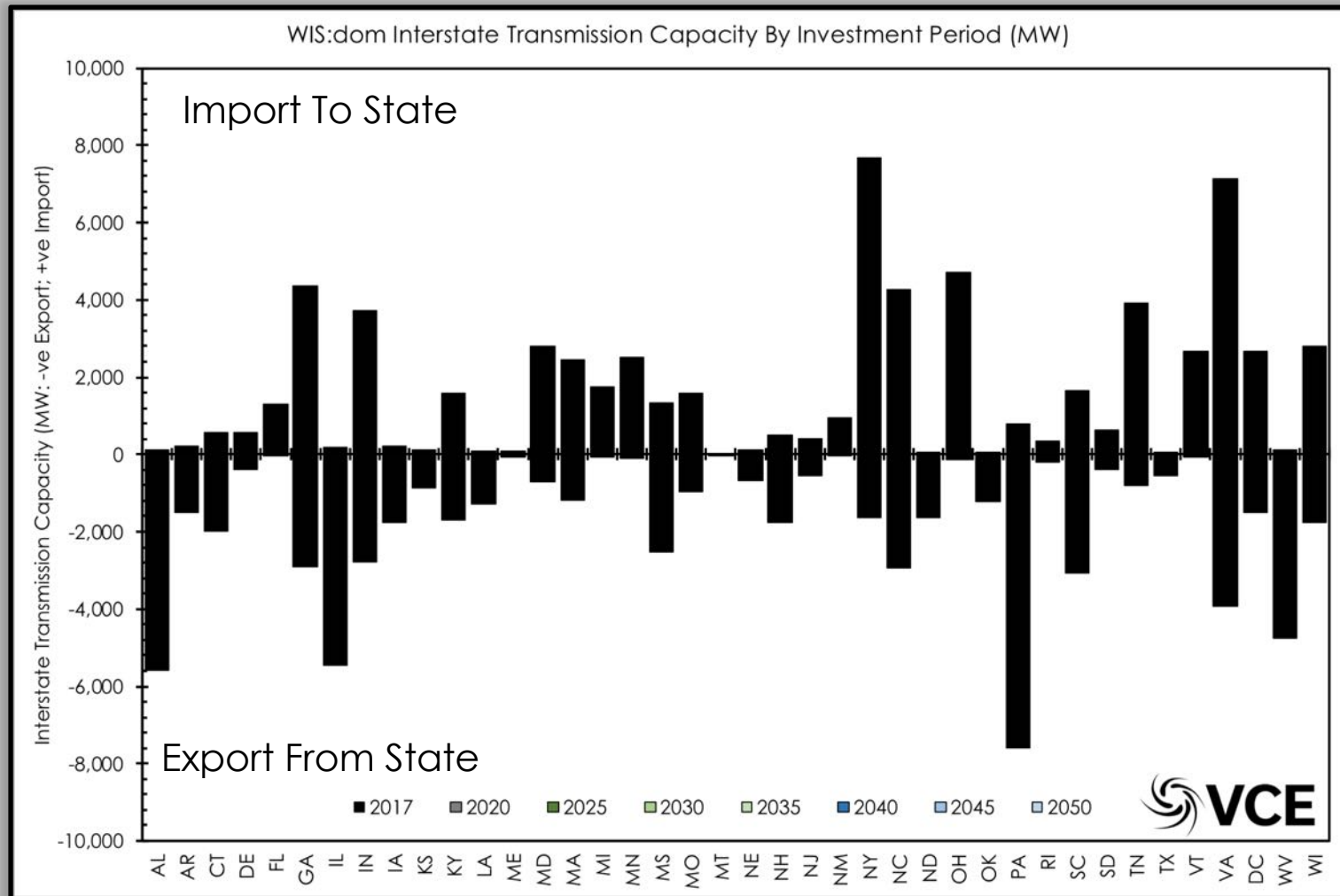
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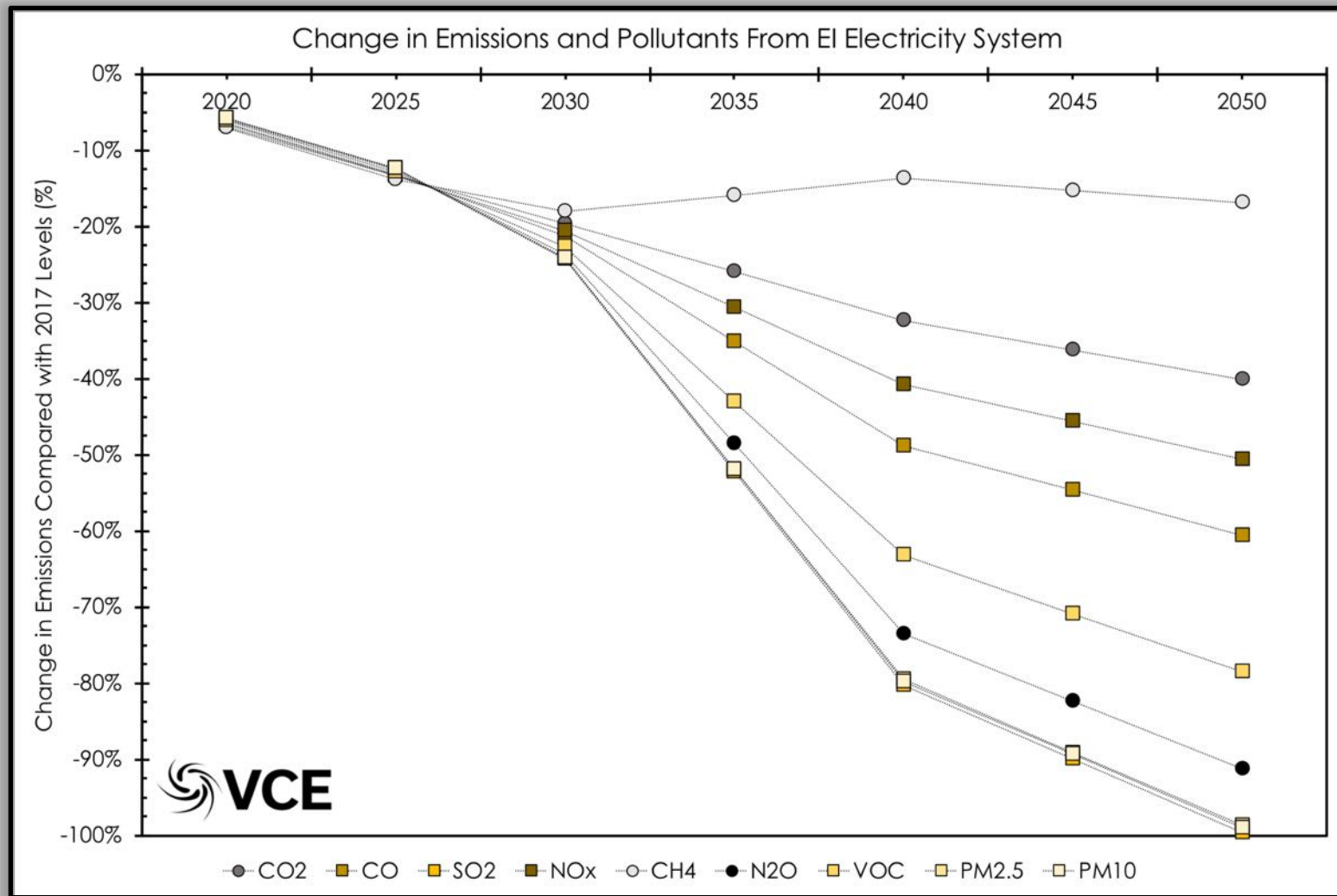
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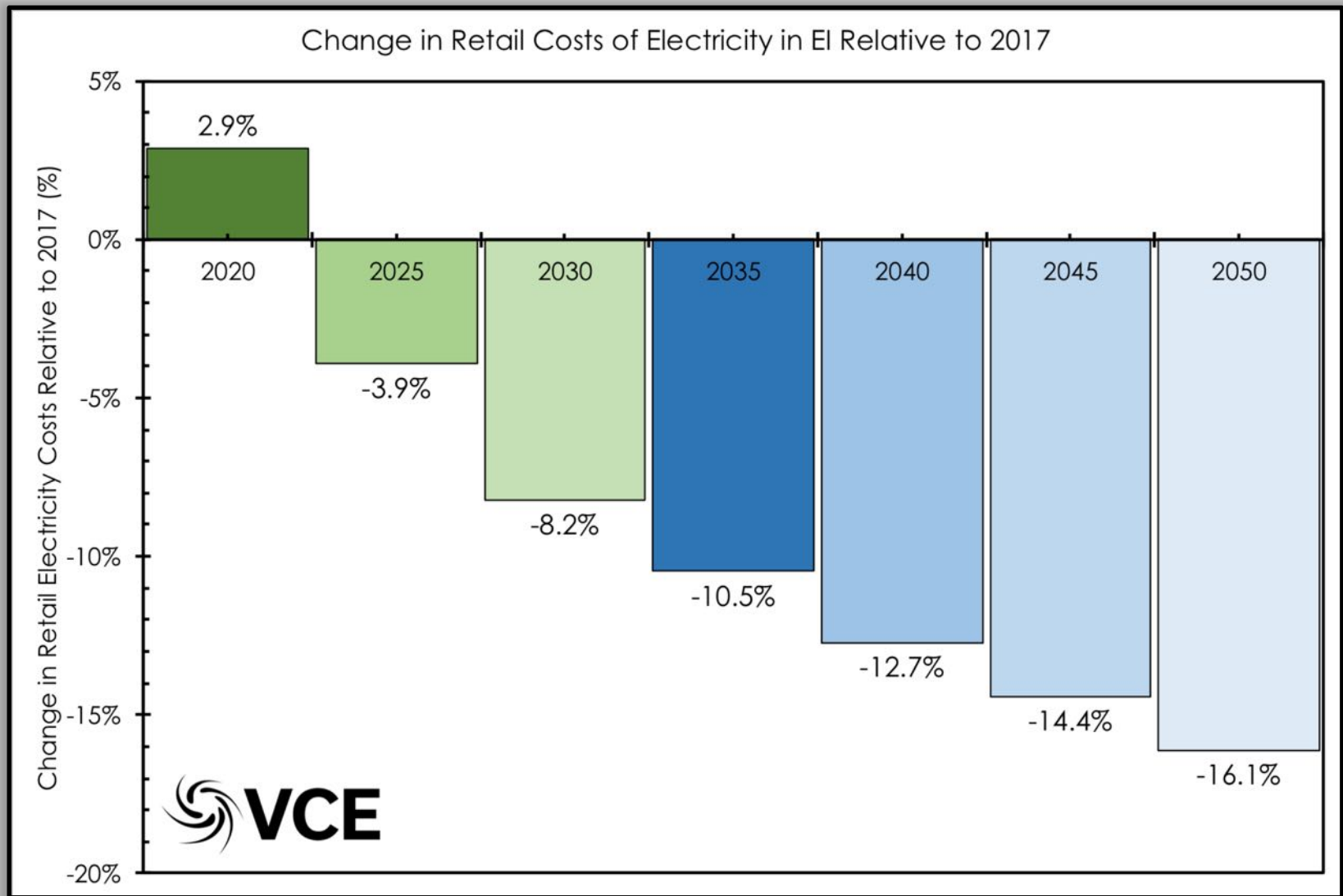
Installed Transmission Capacities



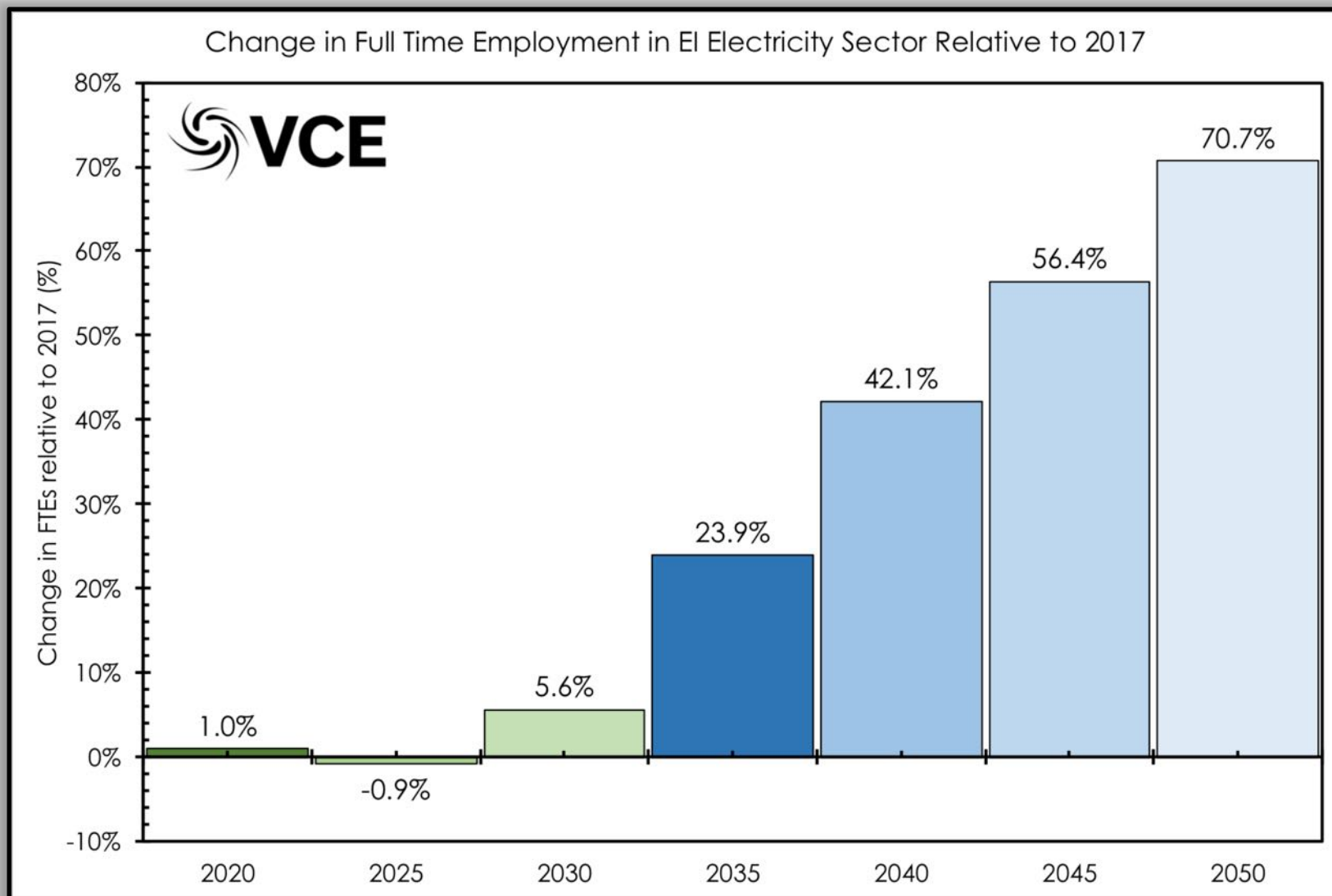
Changes in Emissions & Pollutants



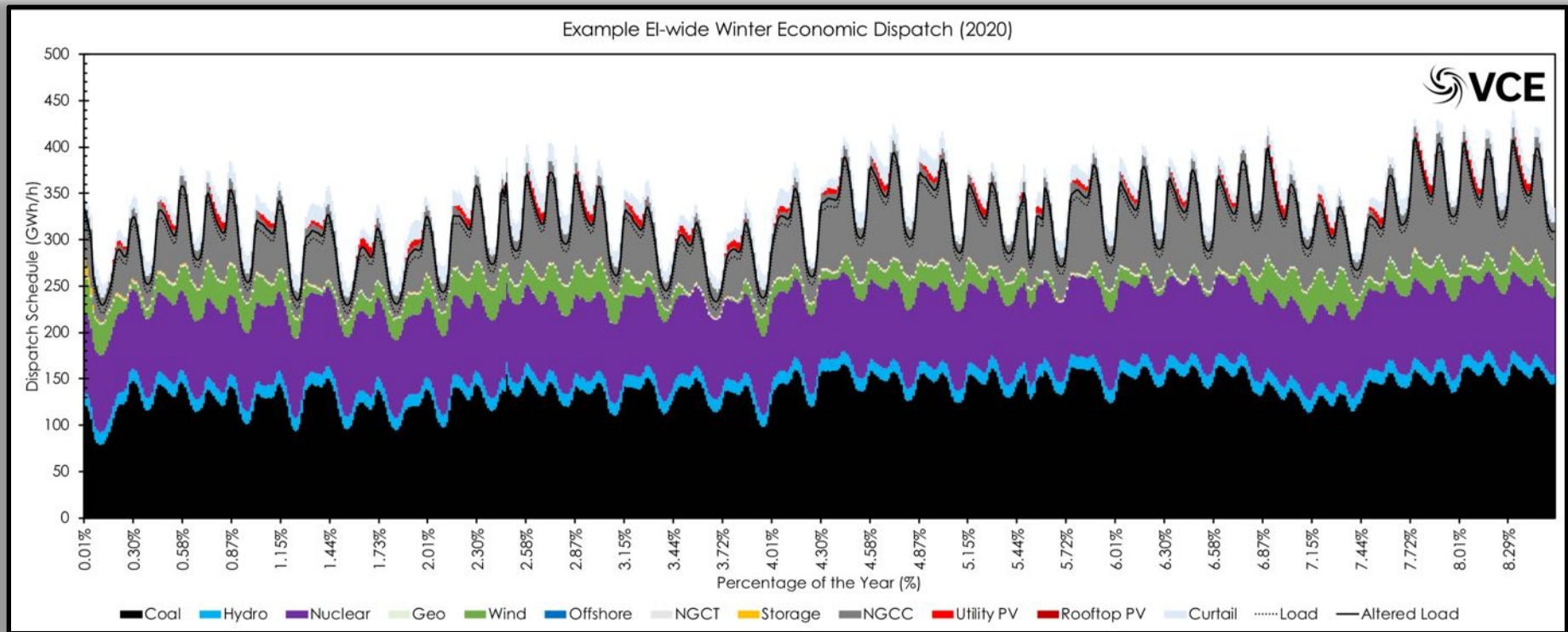
Cost Changes Compared with 2017



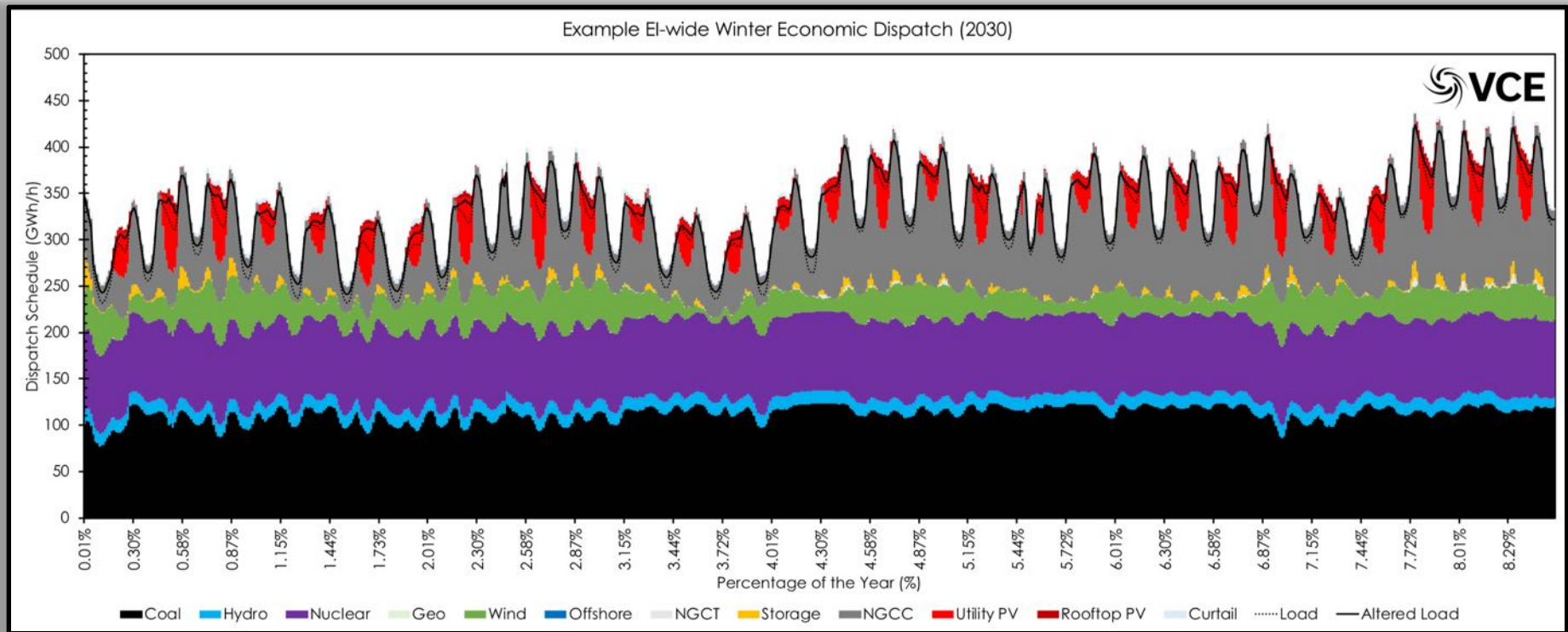
Job Changes Compared with 2017



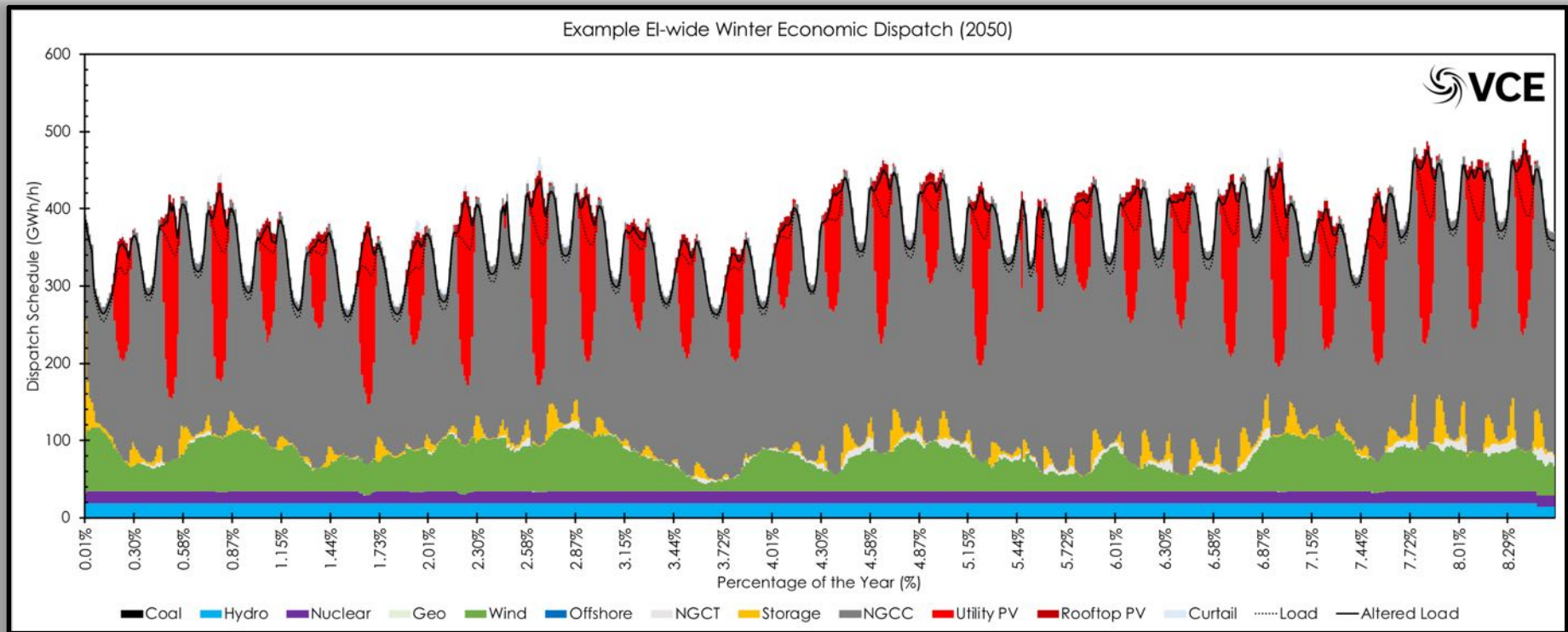
Economic Dispatch



Economic Dispatch

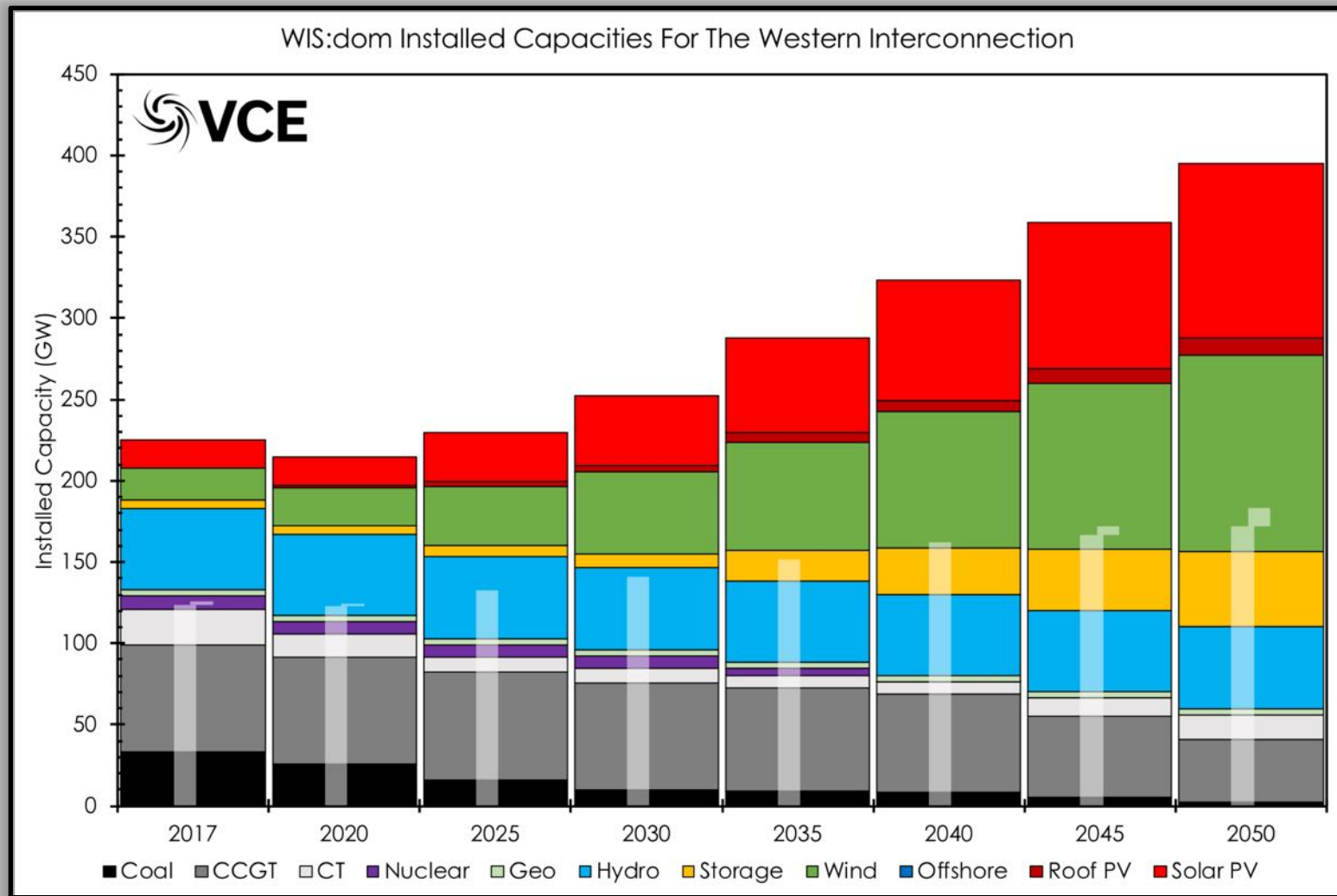


Economic Dispatch

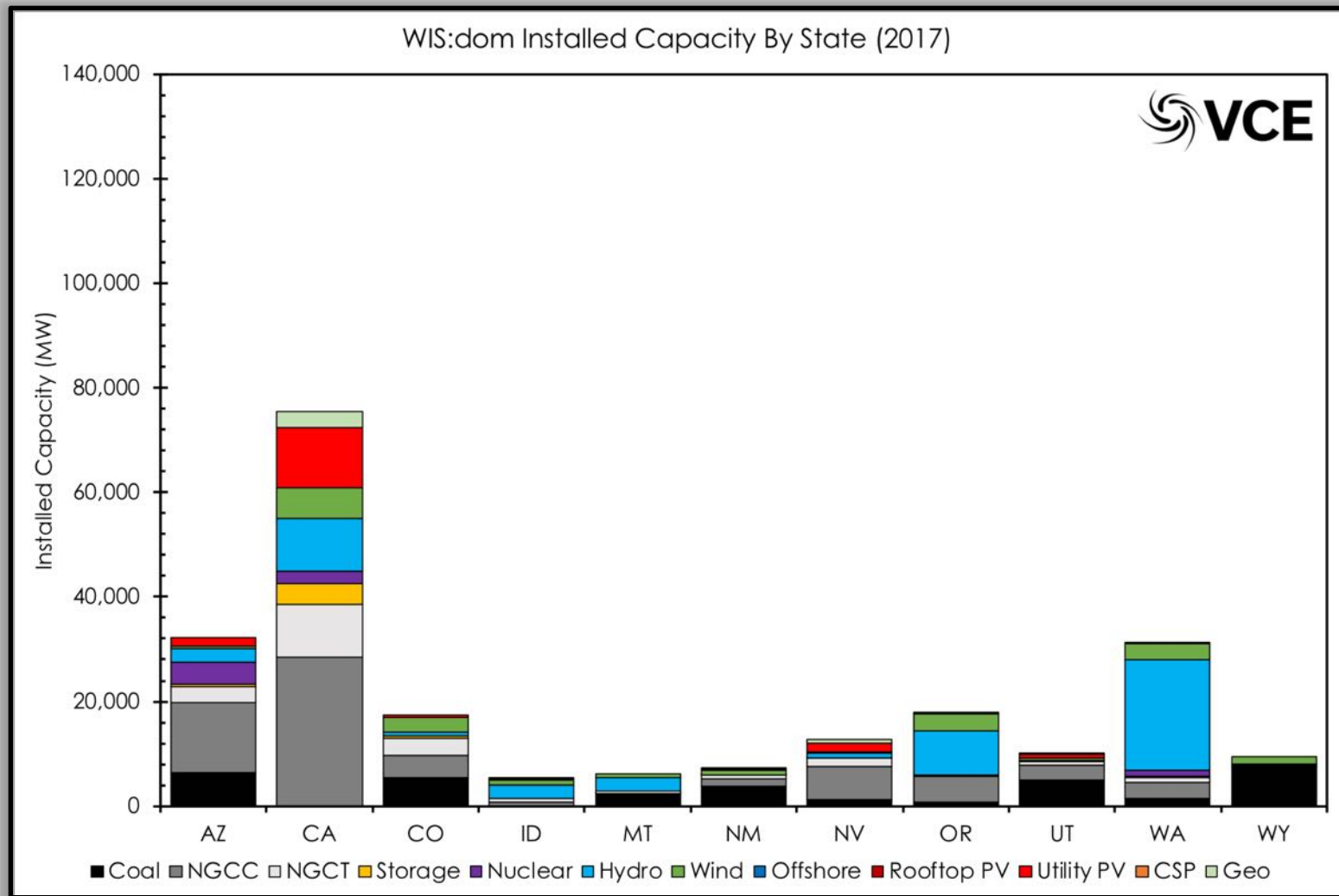


Western Interconnection Study: *Economically Driven*

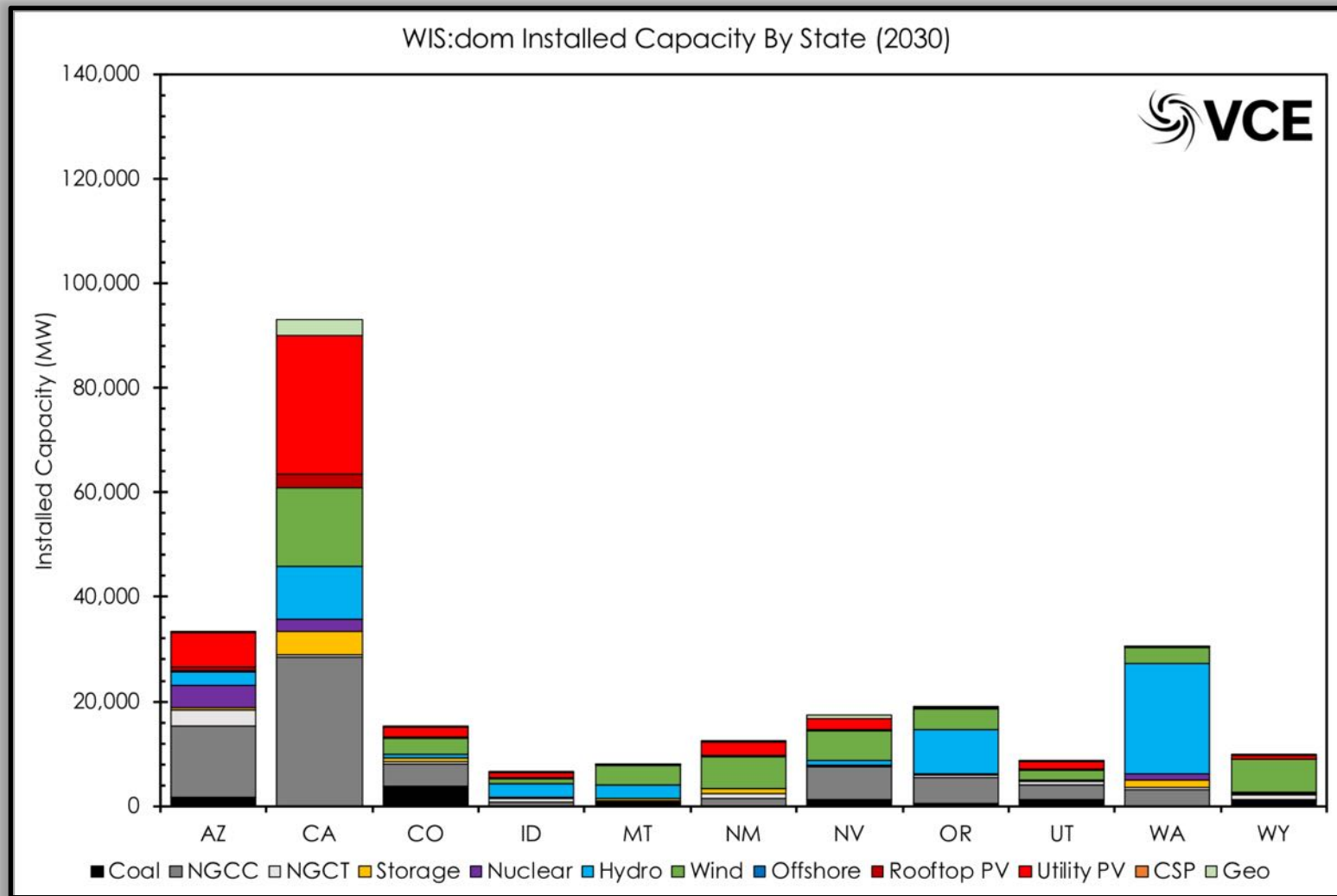
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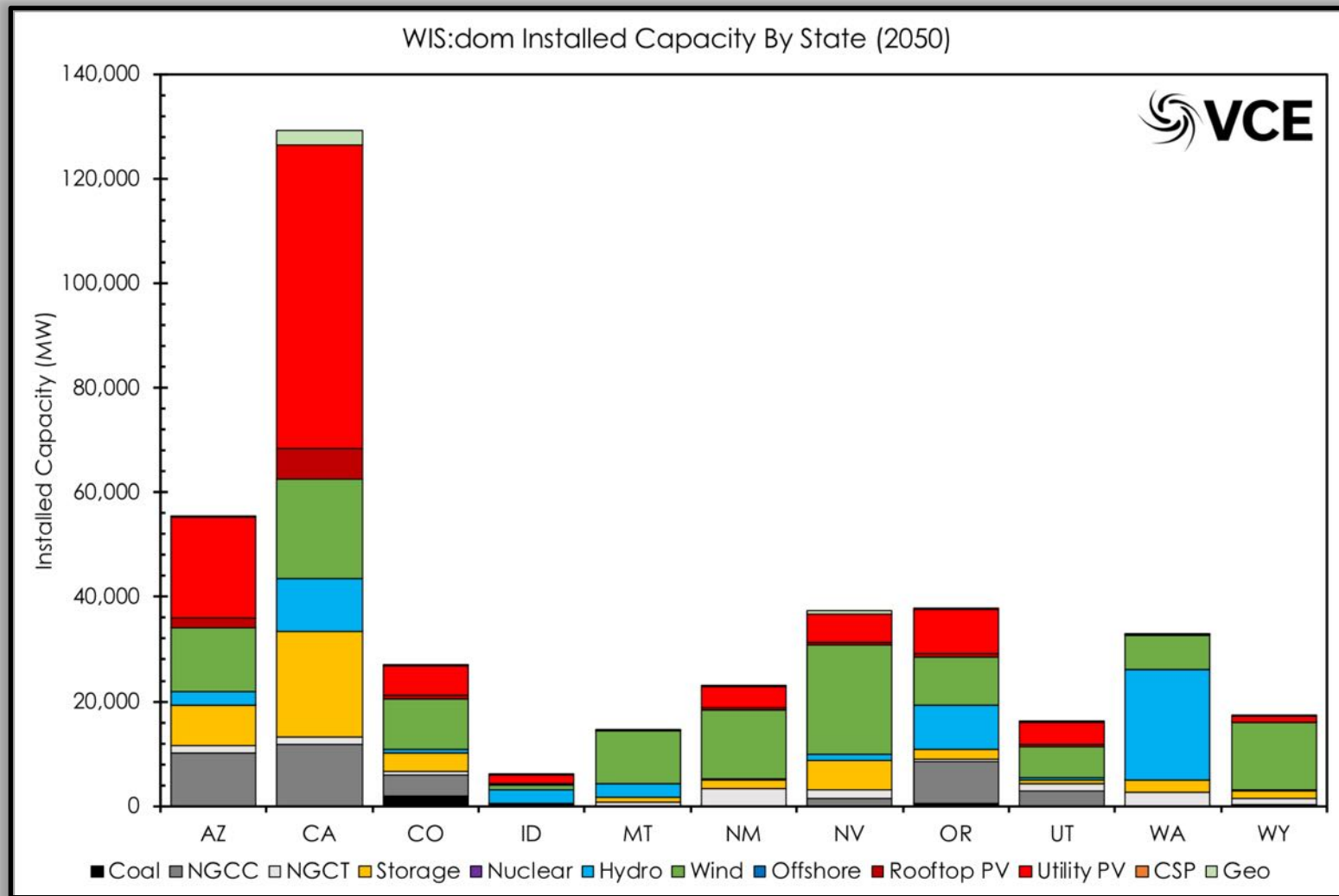
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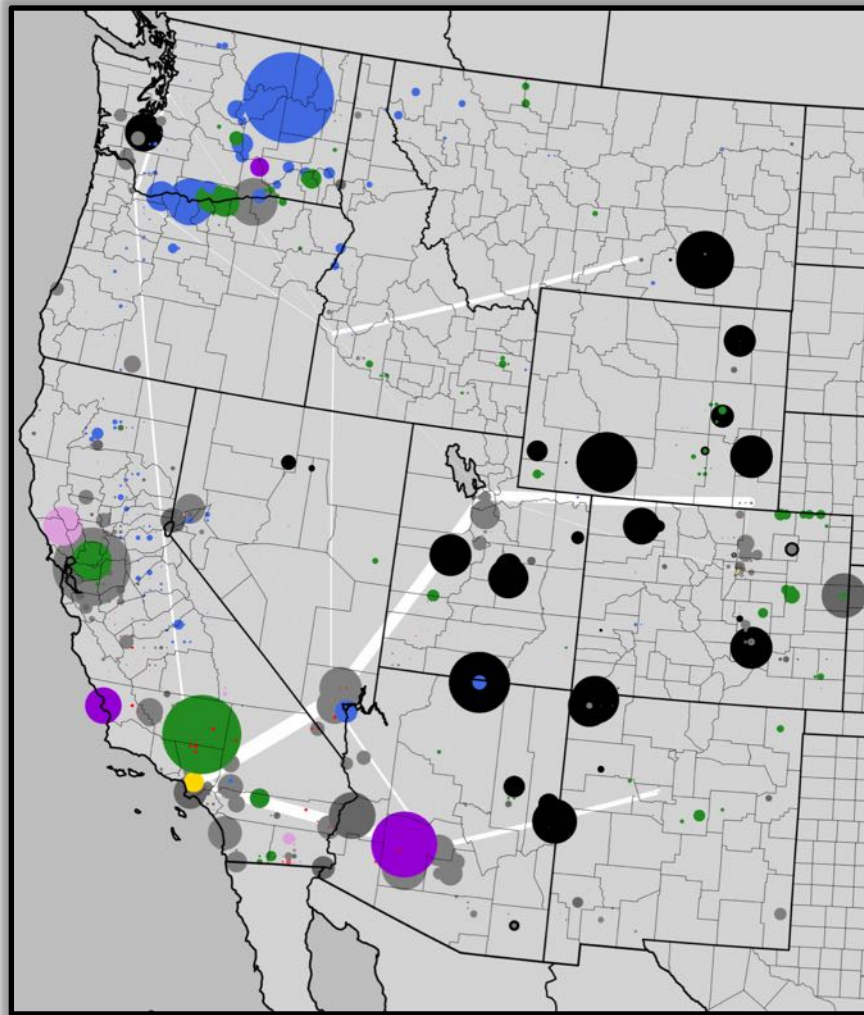
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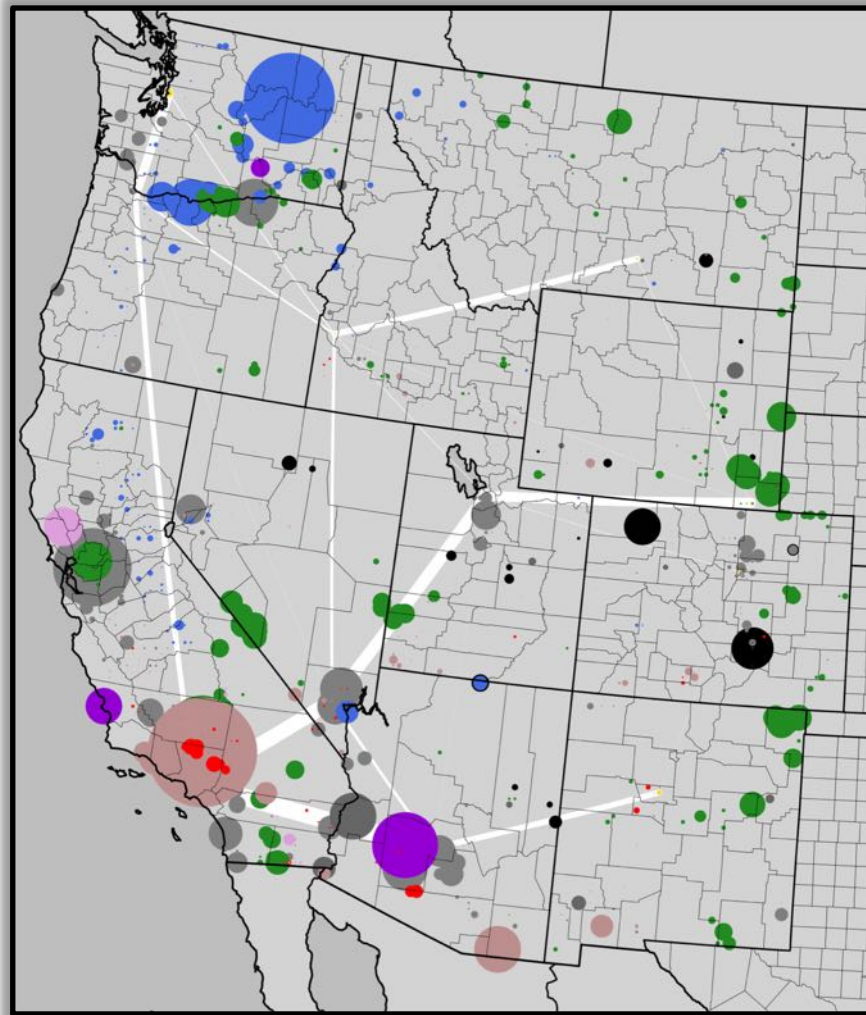
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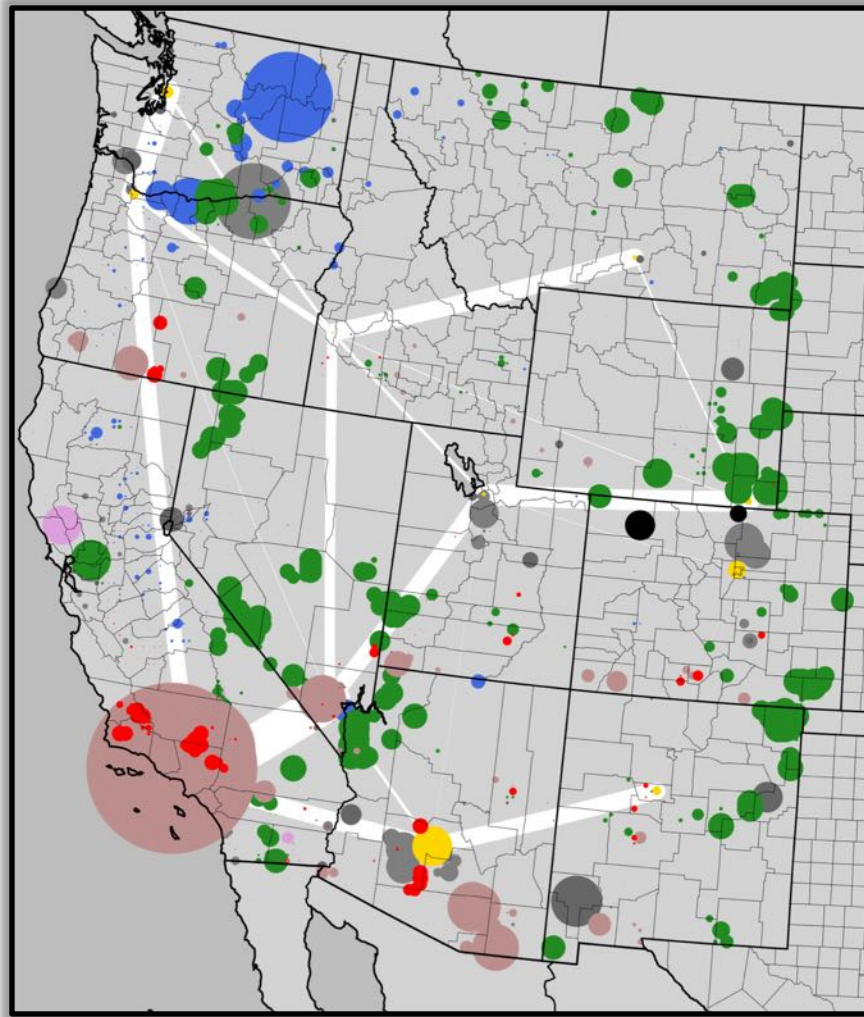
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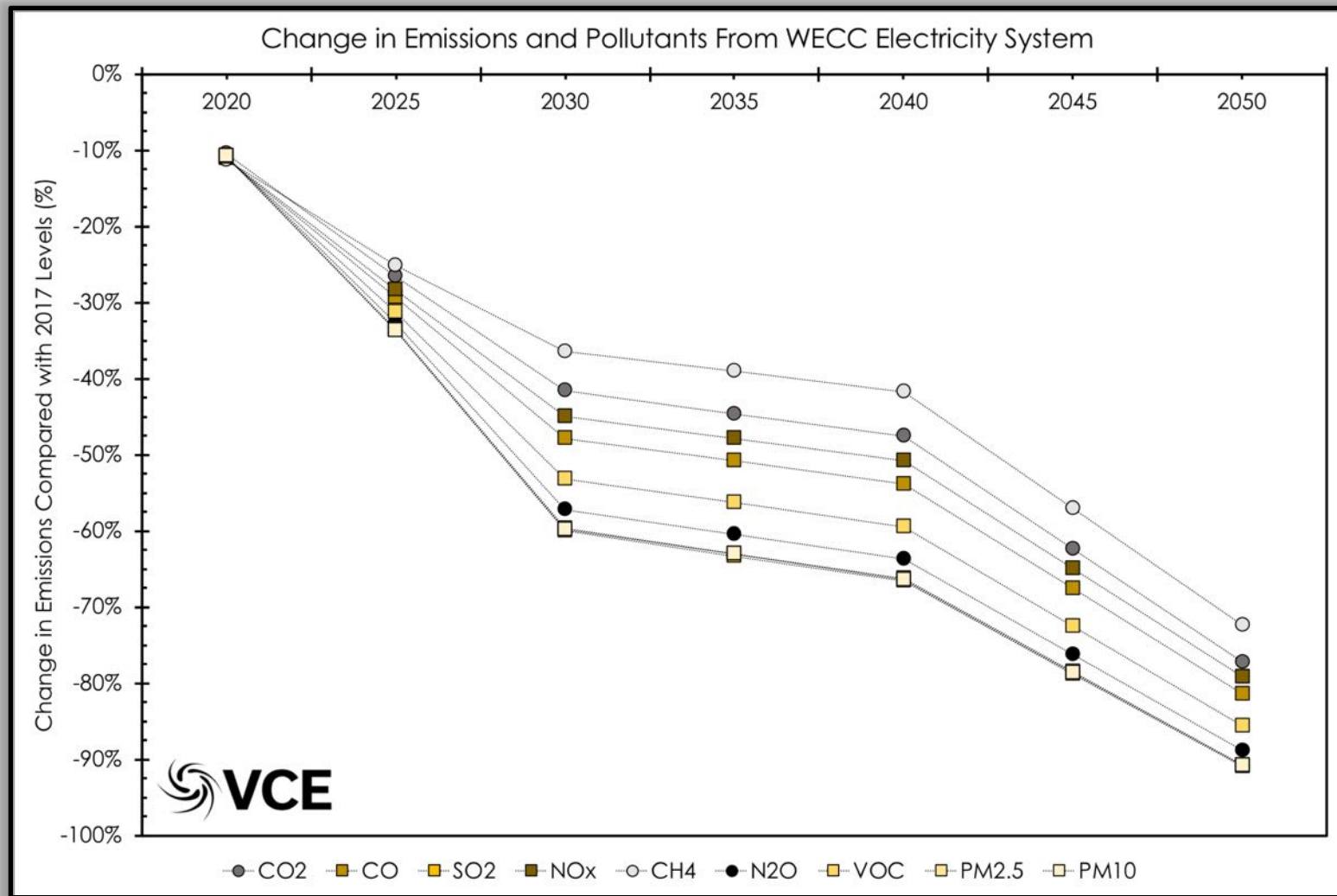
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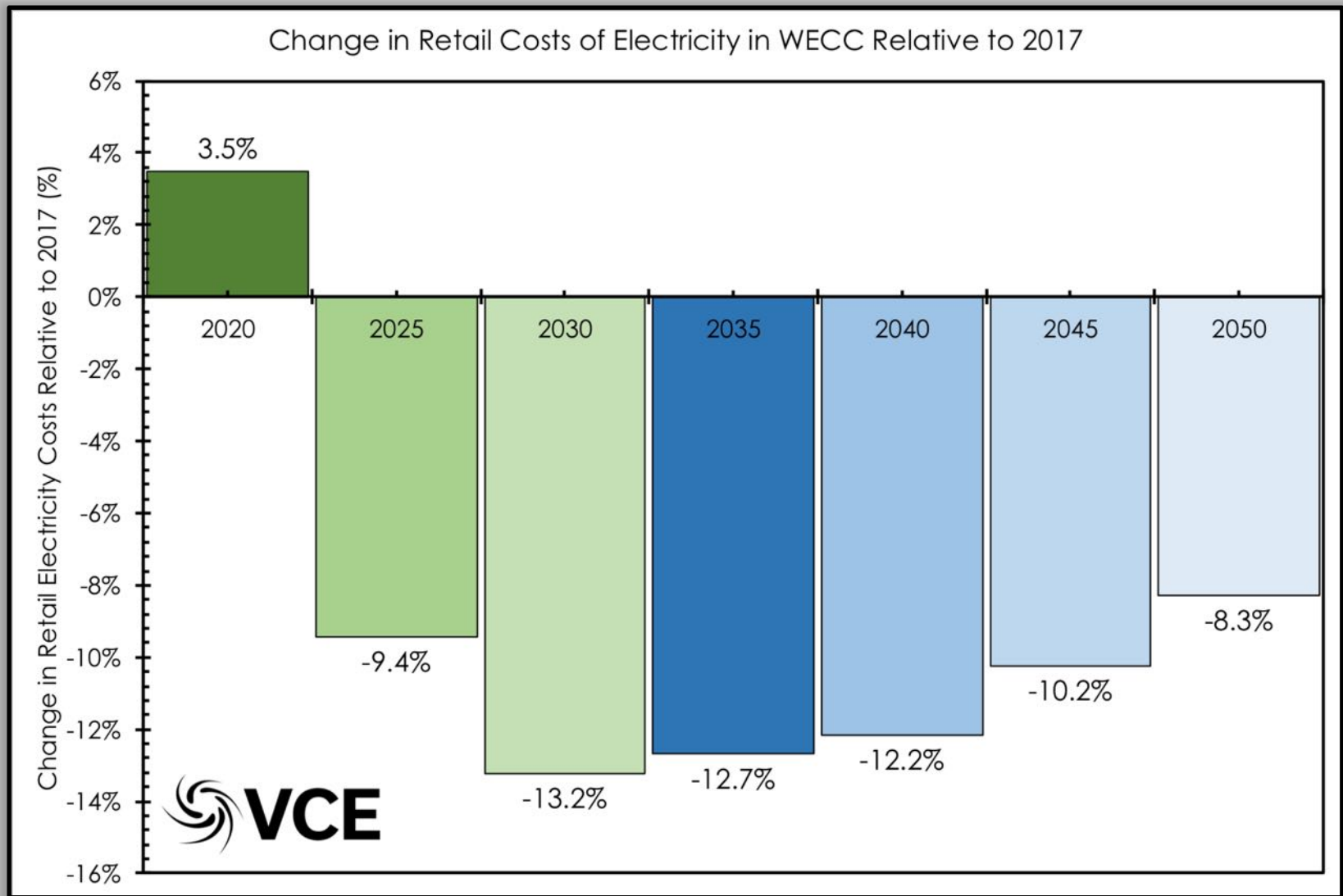
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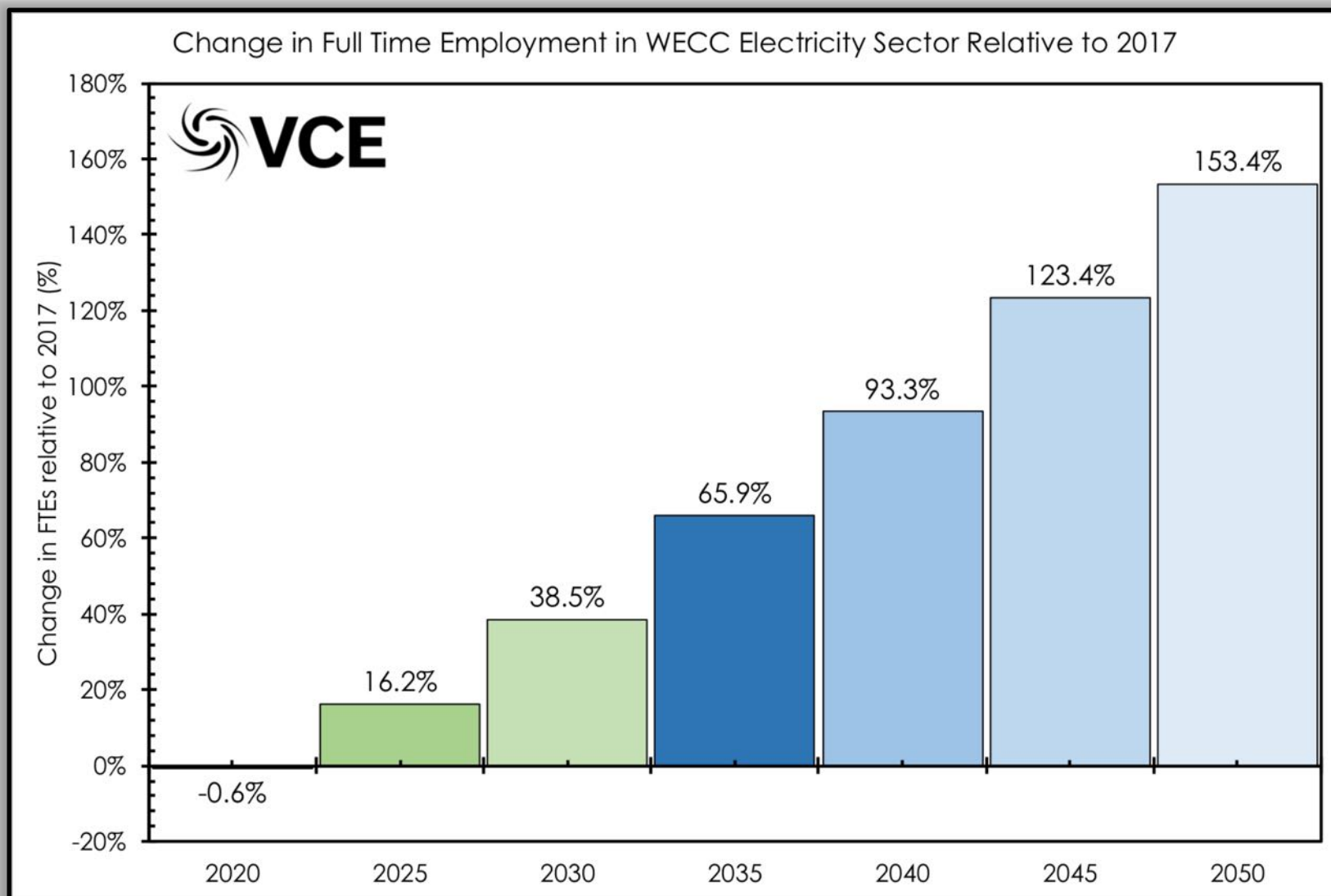
Changes in Emissions & Pollutants



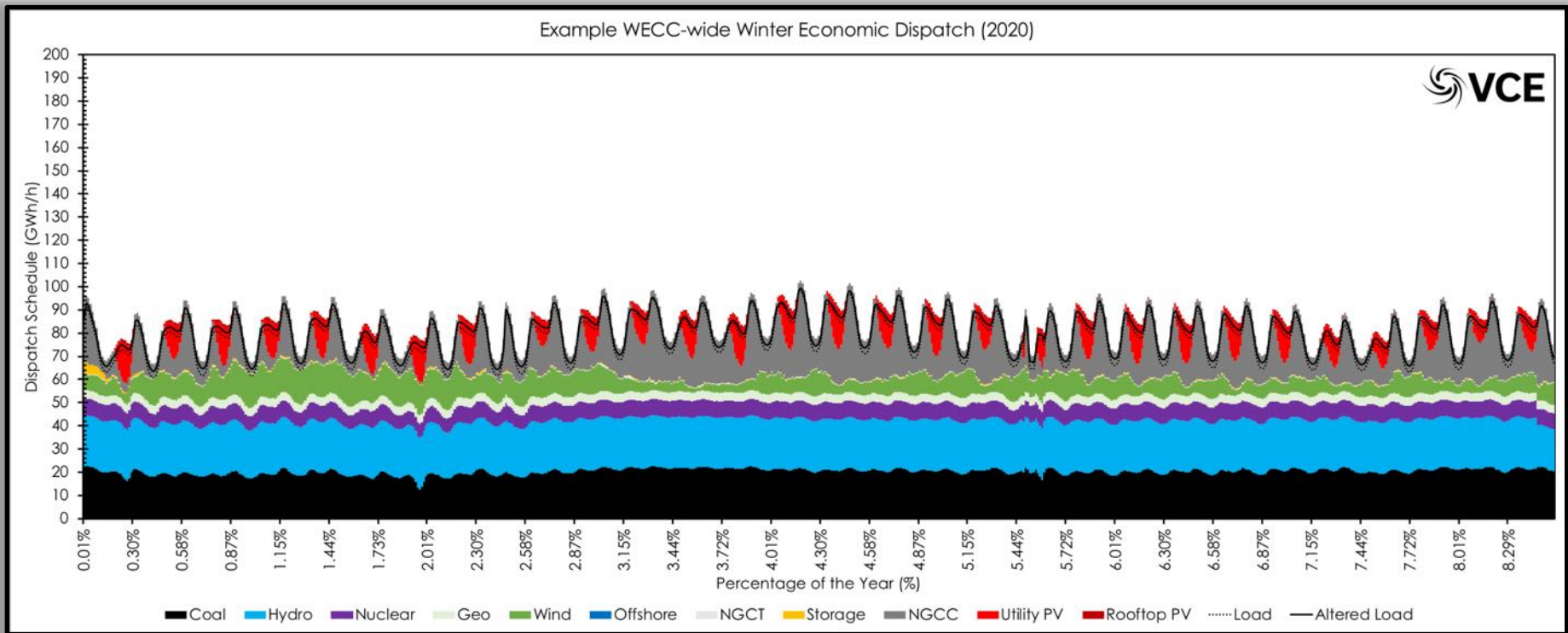
Cost Changes Compared with 2017



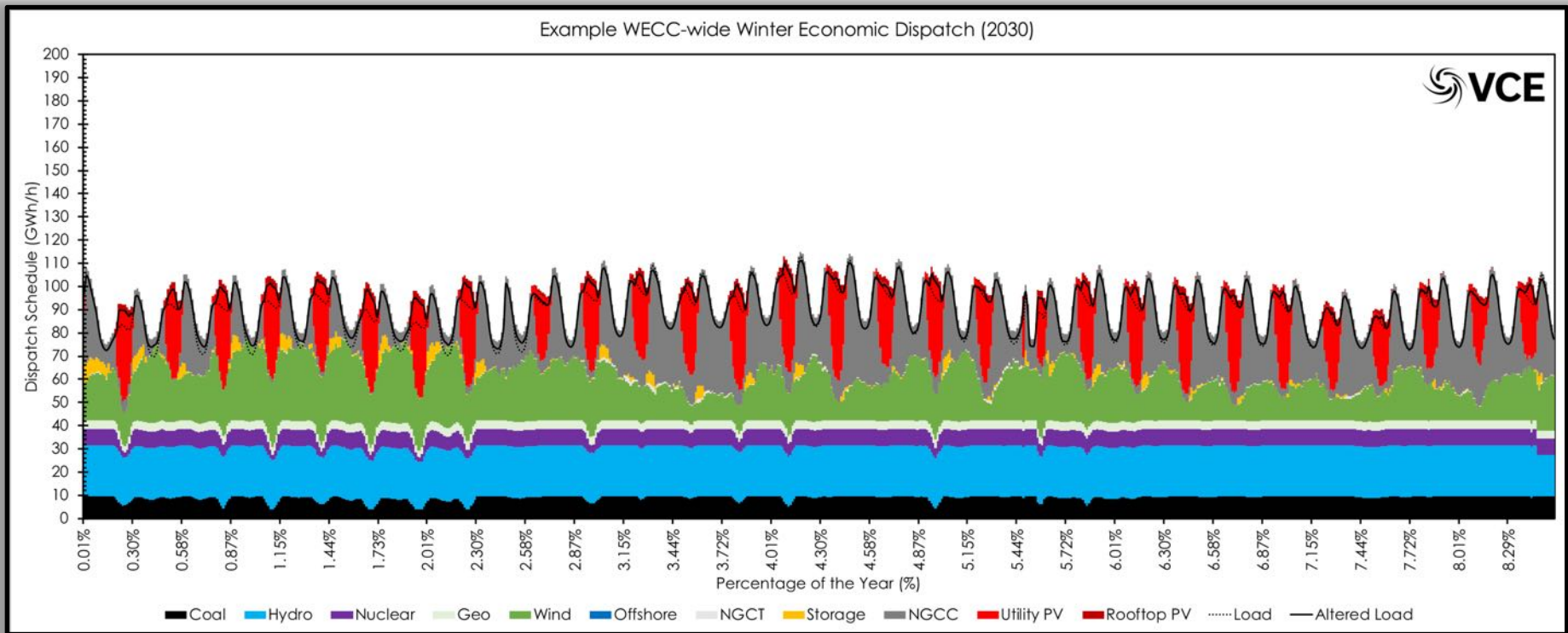
Job Changes Compared with 2017



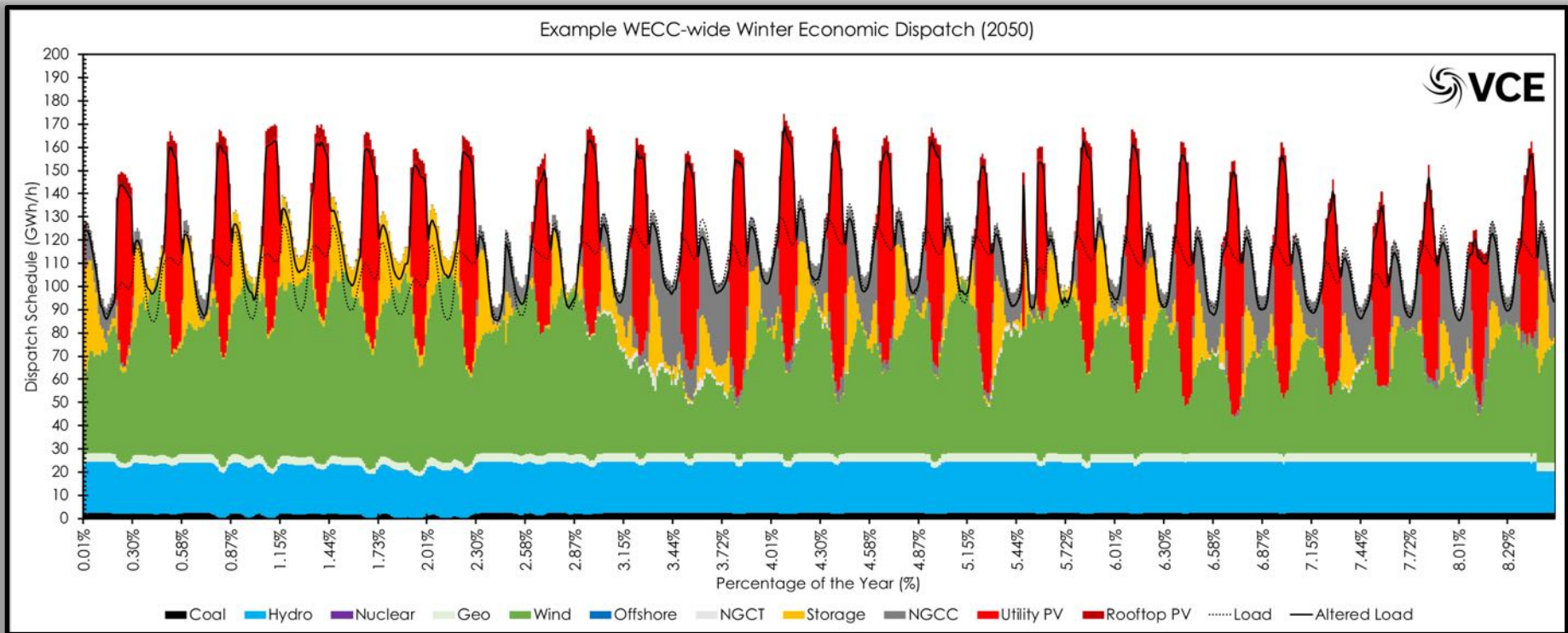
Economic Dispatch



Economic Dispatch



Economic Dispatch



Thank You

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