Advanced Modeling of New Energy Systems for Deep Decarbonization

Prepared By:

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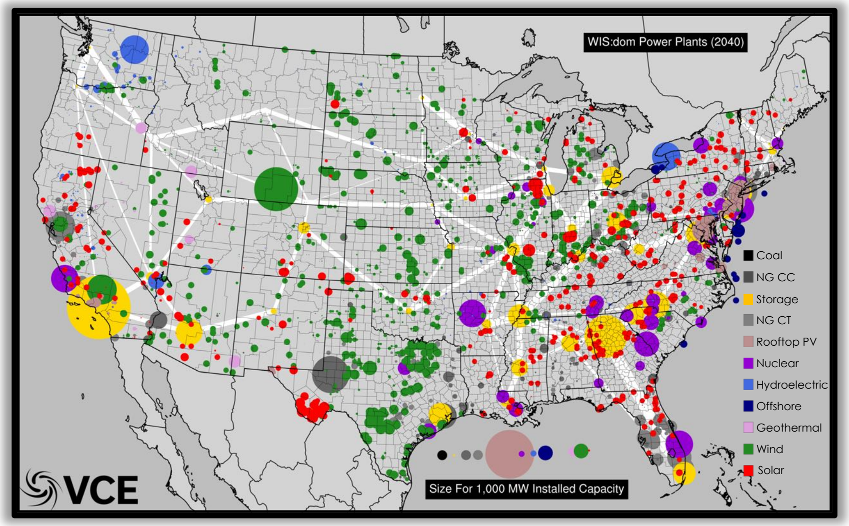
Prepared For:

Columbia University

October 19th, 2018

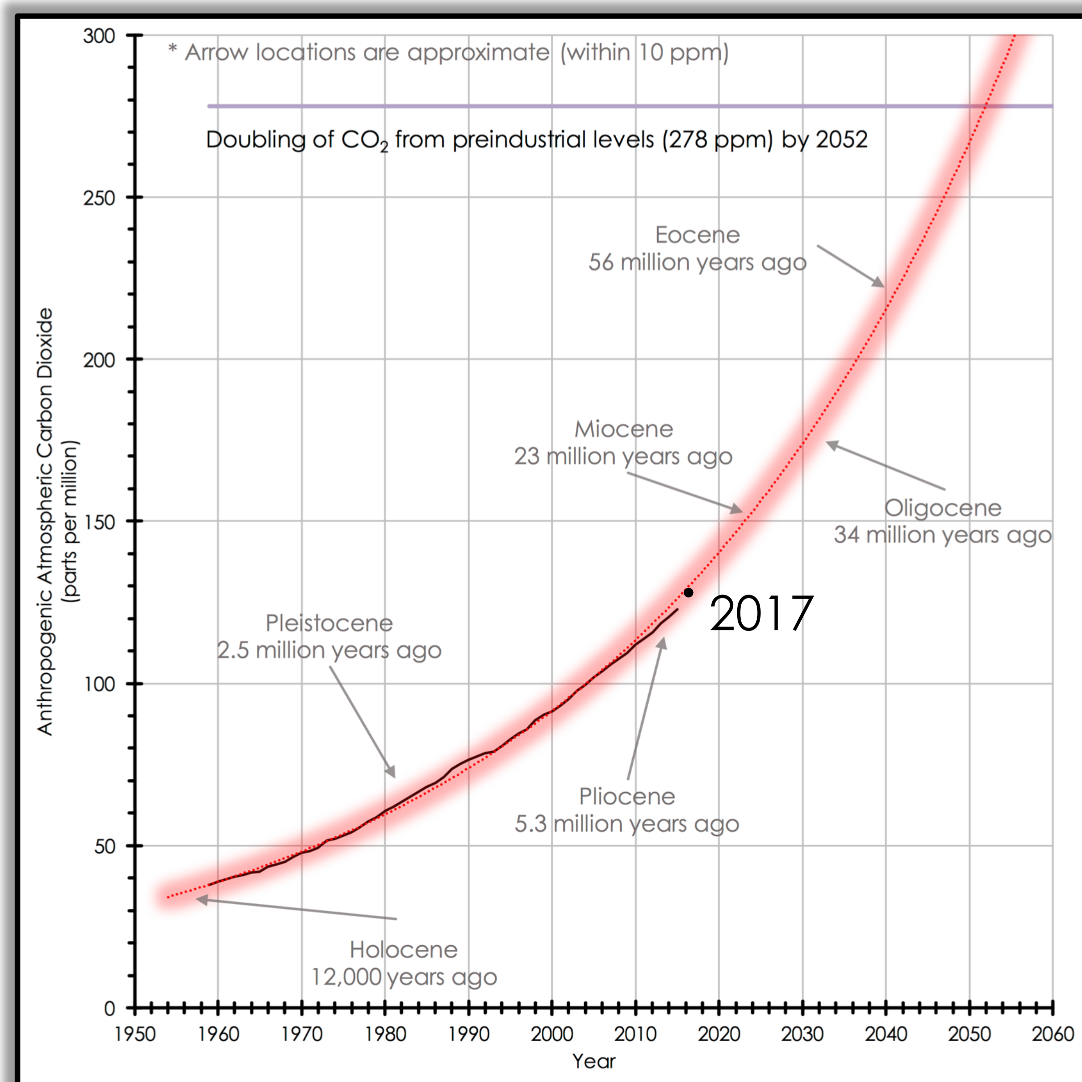
Who Are We: Vibrant Clean Energy



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:dom 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.

Why Do What We Do?



Emissions keep rising faster and faster…

How Does Weather Work?

Global Heat Transfer Drives Wind & Solar Constantly

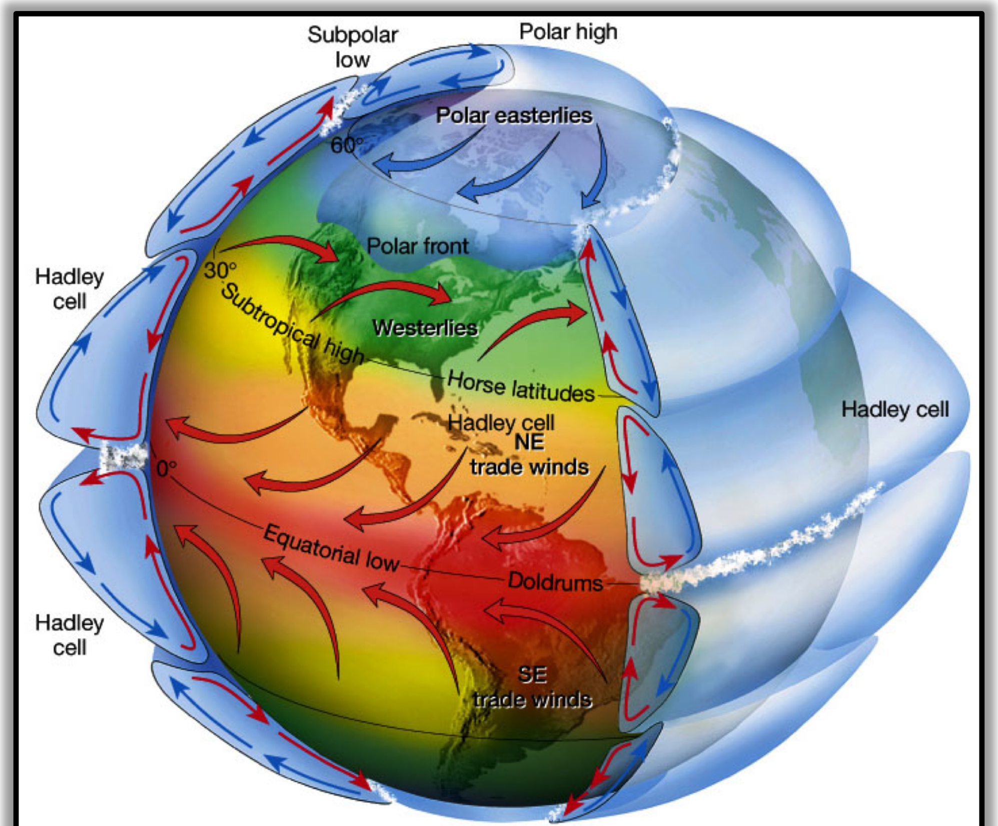


Image Credit: Figure 7.5 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001

This global heat engine runs **constantly** driving wind and cloud patterns.

Processes ***are well understood***.

Driven By Solar Irradiance & Earth-Sun Distance.

Therefore "variability" is a **local effect**.

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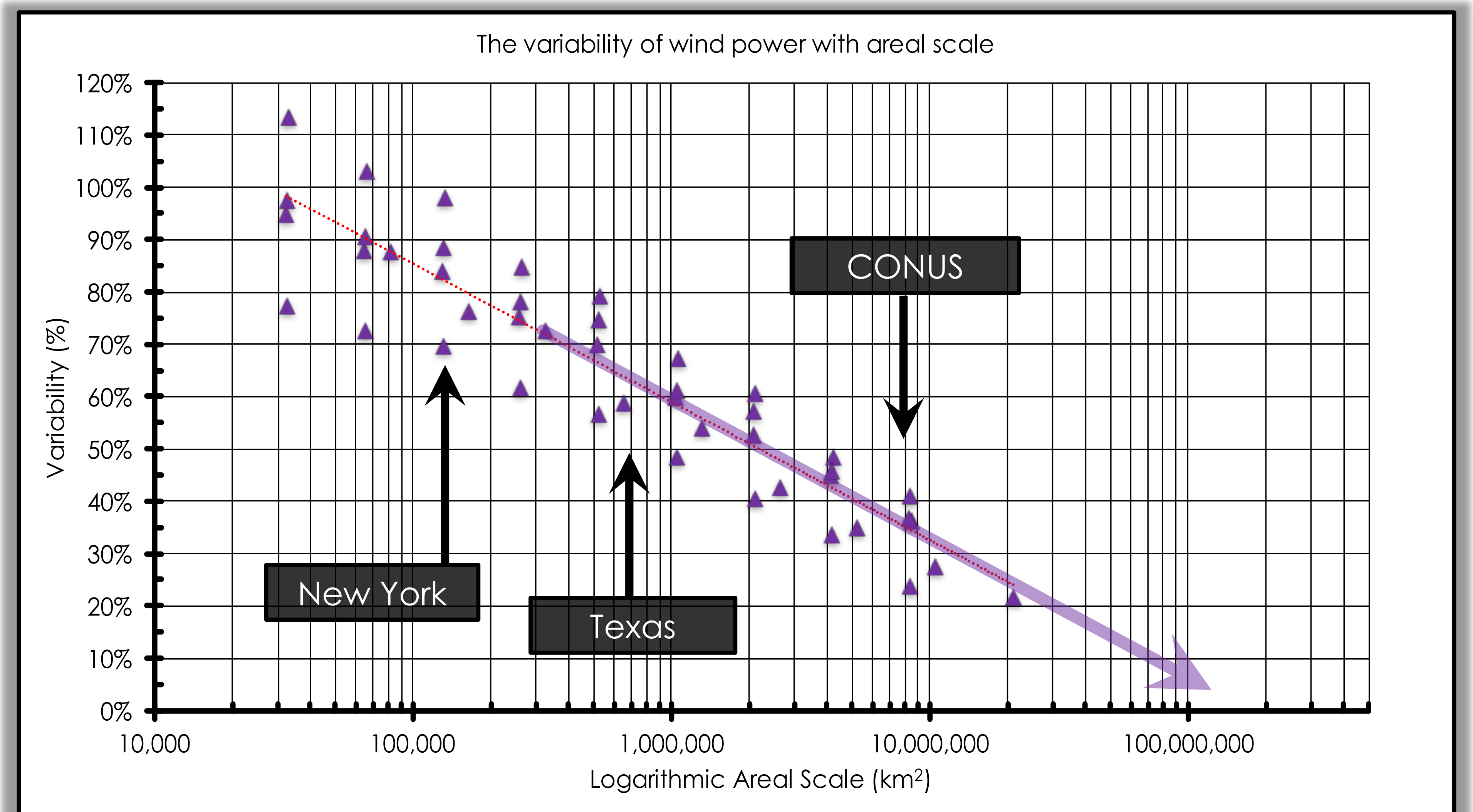
Variability Of Wind & Solar Shrinks With Larger Areas



Wind & solar ***can back each other up*** using their nature

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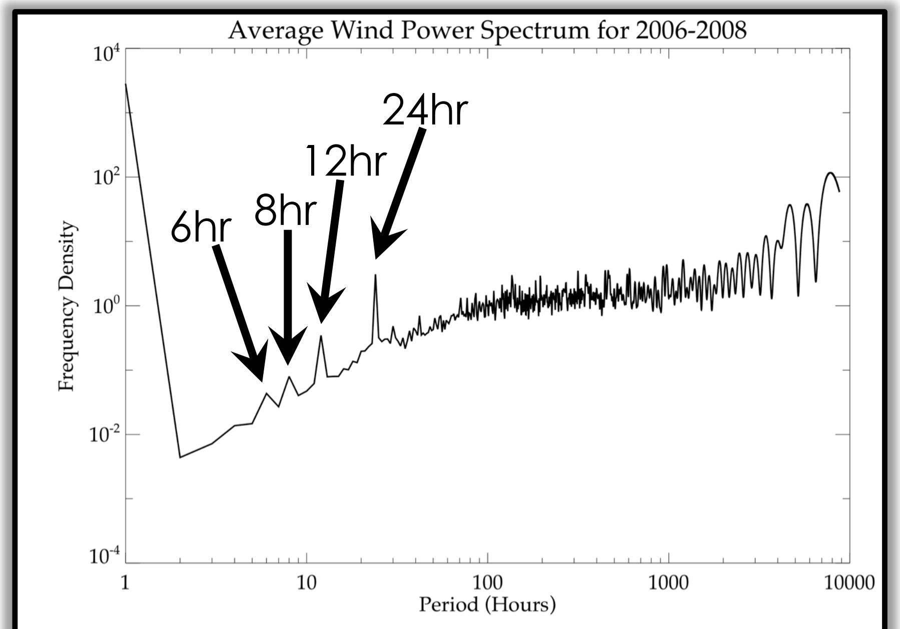
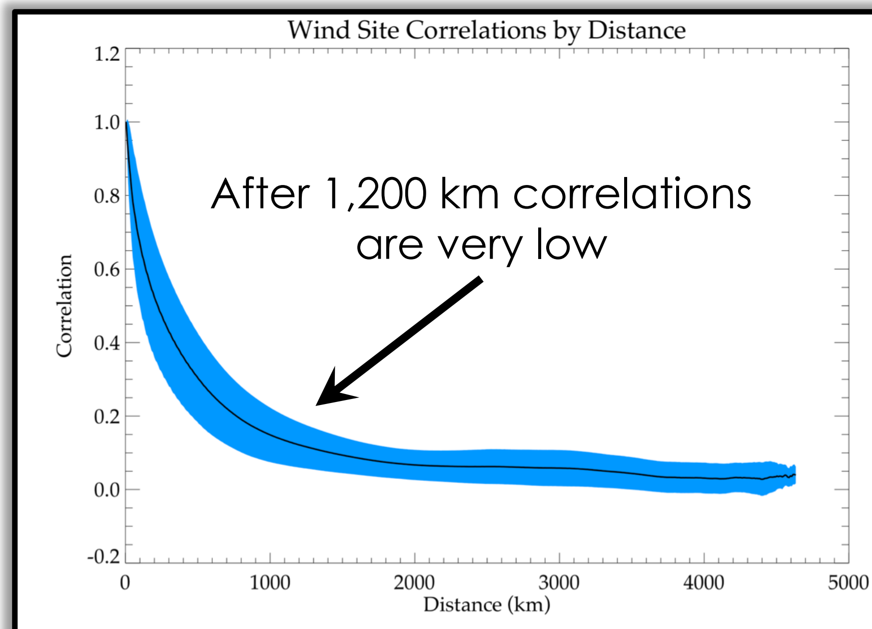
Wind & Solar Are Created By Chaotic Not Random Processes

Therefore, patterns emerge that can be taken advantage of!

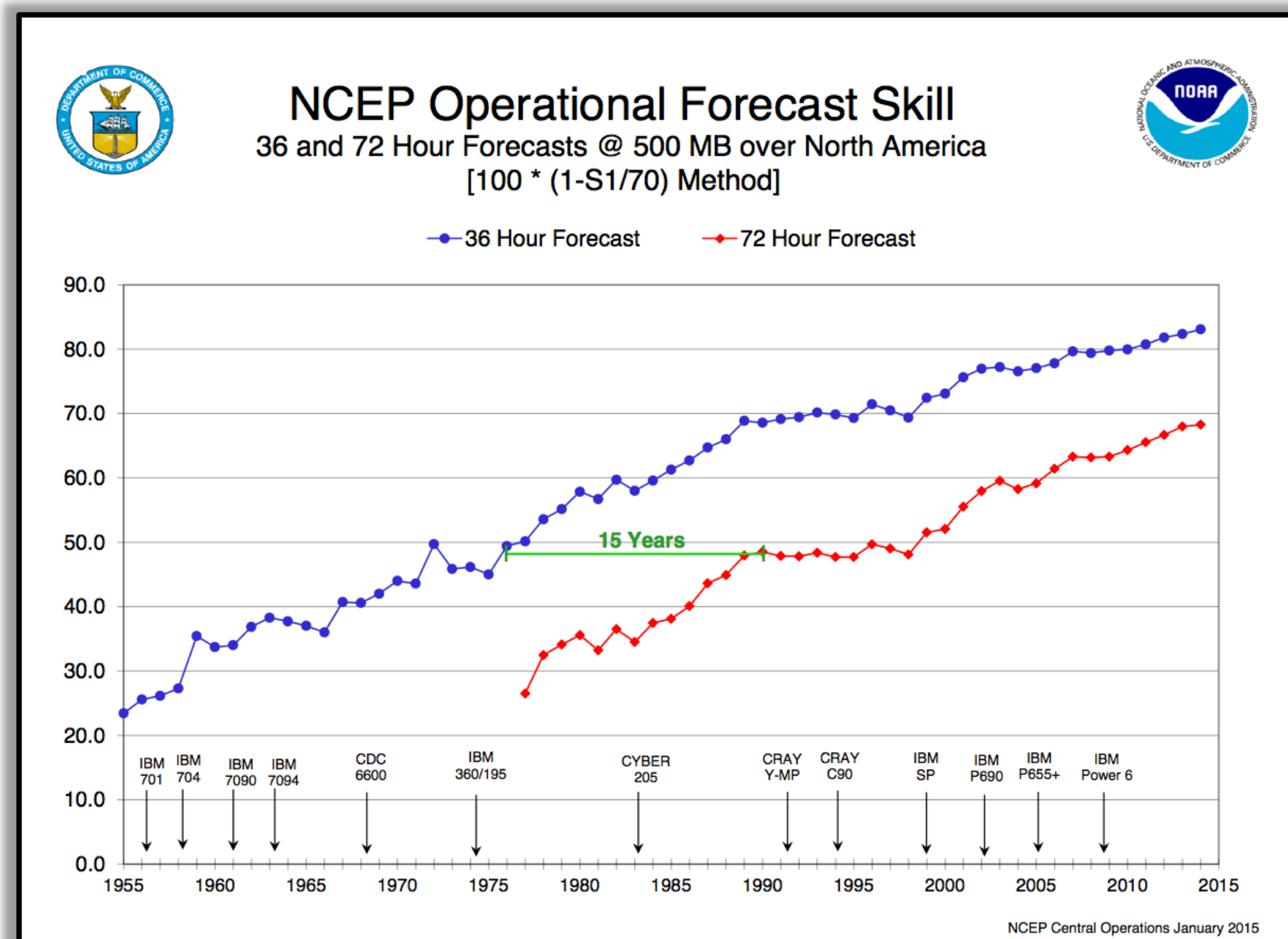




Energy Density Accumulates At Predictable Times & Sites Decorrelate Rapidly

Weather Forecasts Are Always Improving

Forecasts Accurate Enough To Rely On For Large Areas (local errors cancel)



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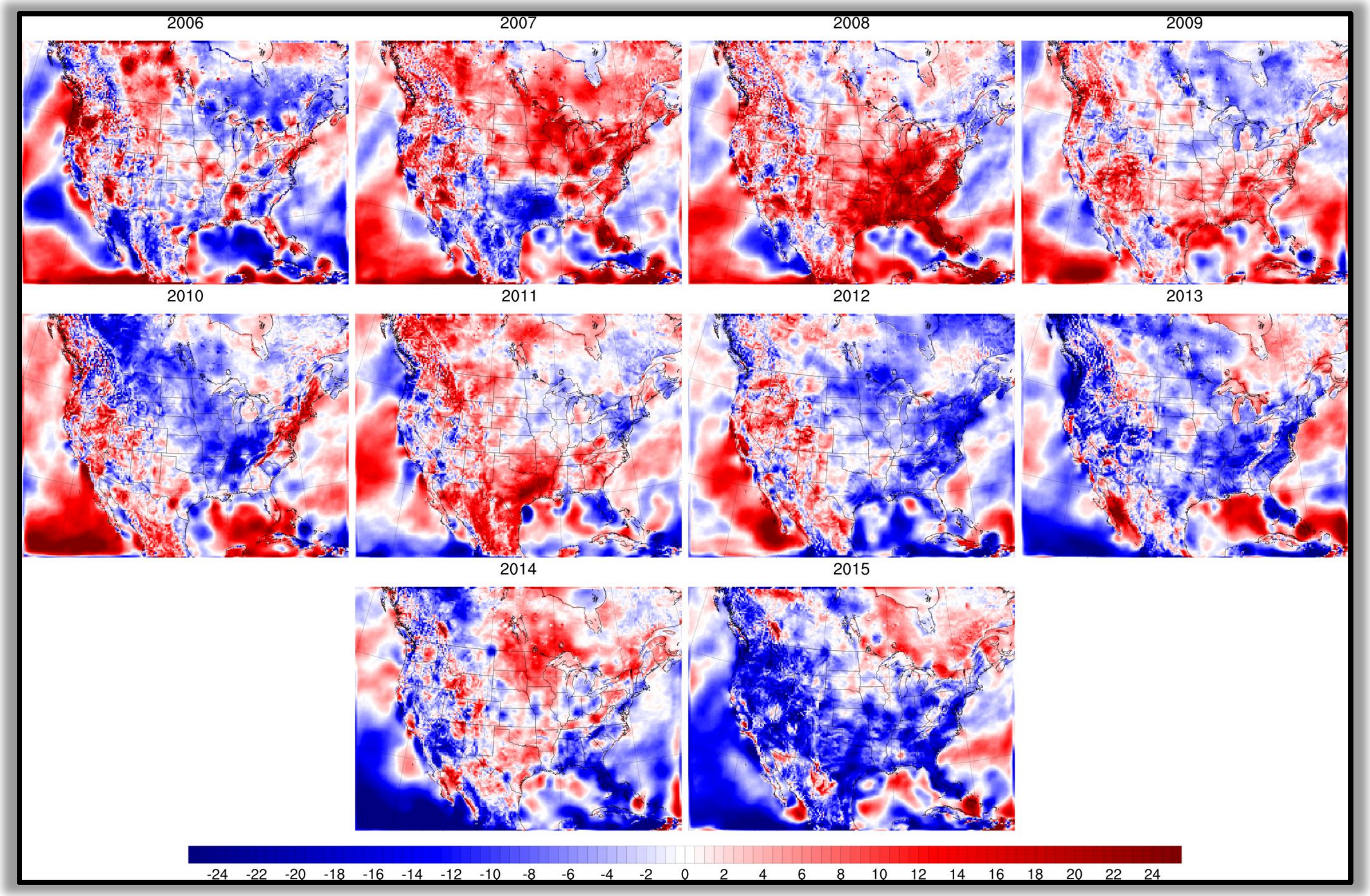
Wind & Solar Are Variable So Need Careful Consideration

Long-term, high-resolution data are essential to understand the processes



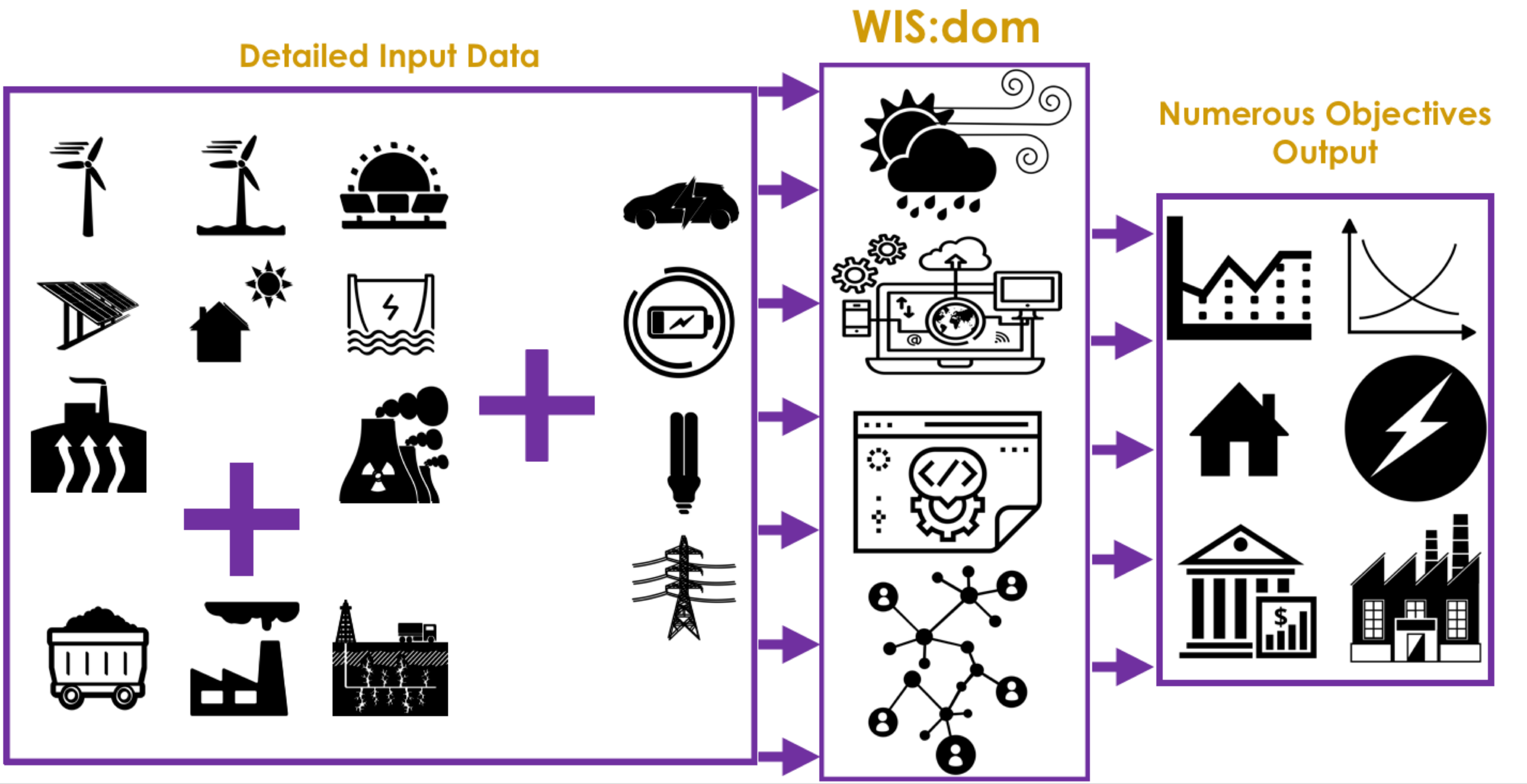
There is no "gut feeling" or "randomness" about the weather!

What Modeling Exists?

What Most Models Currently Do

- For production cost – typically short time periods & small geographic scope;
- For capacity expansion – typically coarse data, large region, but simplified / no dispatch;
- Typically many models do not consider demand side resources, transmission, storage, or other emerging technologies (EVs, heat pumps, water heaters, etc.);
- Disaggregation of components of the system leads to inefficient future projections and diminishes value of certain resources;
- Simpler modeling does not allow foresight beyond "knowns", for example, emergent behavior of market design, co-optimization of DERS, utility generation, transmission, and storage, reducing reliance on thermal generation for reserves, etc.
- Ignoring the changing environment, i.e. outside a specific BAA will lead to over investment and stranded assets / addition costs to rate payers, as the external regions will impact the internal dynamics of the BAA.

Pushing The Envelope: The WIS:dom Model



What Models Can & Should Do

WIS:dom is the ***only*** (others should follow) 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.
- ✓ ***Designed, operated and supported by small team.***

WIS:dom Is a Blended Capacity Expansion and Production Cost Model

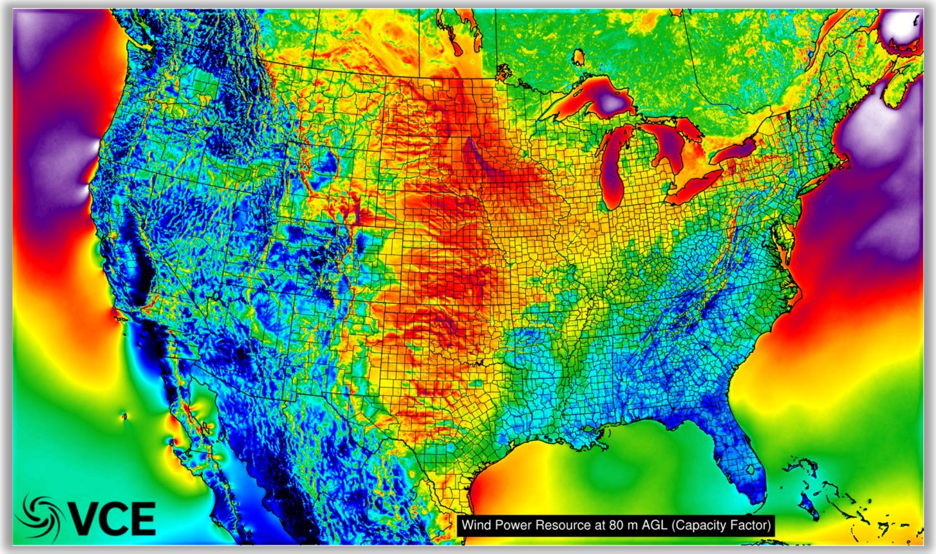
Models	Nation Scale	Trans Expan	Gen Expan	Gen Plan Spatially	Trans Plan Spatially	Temp Res	Spat Res (km^2)	Physics of Weather	Forecasts	W+S Tech count	Hydro Modeling	Global Capable	Disaggregate	Horizon	Invest Periods	Hardware	Elec Power Flow Realized
ReEDs	Y	Y	Y	N*	Y	17	2,472 (NA only)	N	N	3	N	N	Time slices, most T constrained	2050	5	Desktop; HPC	N
Switch	N	Y	Y	Y	Y	288	25	N	N	4-5	N	N*	WECC only and temporal splicing	2050	5	Desktop	N
GE Maps	N	Y*	Y	Y	N	760	~2500 (NA only)	N	N	3	N	N*	Only small areas	1 YR	1	Desktop LInux cluster	DC no loss
ABB Grid View	N	Y*	Y	Y	N	760	~2500 (NA only)	N	N	3	N	N*	Only small areas	1 YR	1	Desktop LInux cluster	DC no loss
Plexos	N	N	Y	N	N	8766	4 (no standard)	N	Y	3	Some	Y	Only small areas	1 YR	1	Desktop LInux cluster; HPC	DC (plus AC, but only technically)
WIS:dom	**Y**	**Y**	**Y**	**Y**	**Y**	**8766 / yr 10 years US 1 year Global**	**9 - USA 49 - Globe (all at hourly resolution)**	**Y**	**Y**	**Wind 35; Solar 40; Storage included**	**Detailed using weather and hydro data**	**Y**	**None: couples high granularity with large space temporal horizons**	**2015 to 2050 2015 to 2100**	**7-16: blind and seer mode**	**High powered servers; Powerful Desktops; Simpler Version Laptops**	**DC with losses, Kirchhoff laws, reliability, substations and existing lines**
IAM	Y	N	Y	N	N	1-100	250,000	Y	N	3-5	Y	Y	Long time averages; low spatial res	2100	10	Desktop all the way to HPC	N

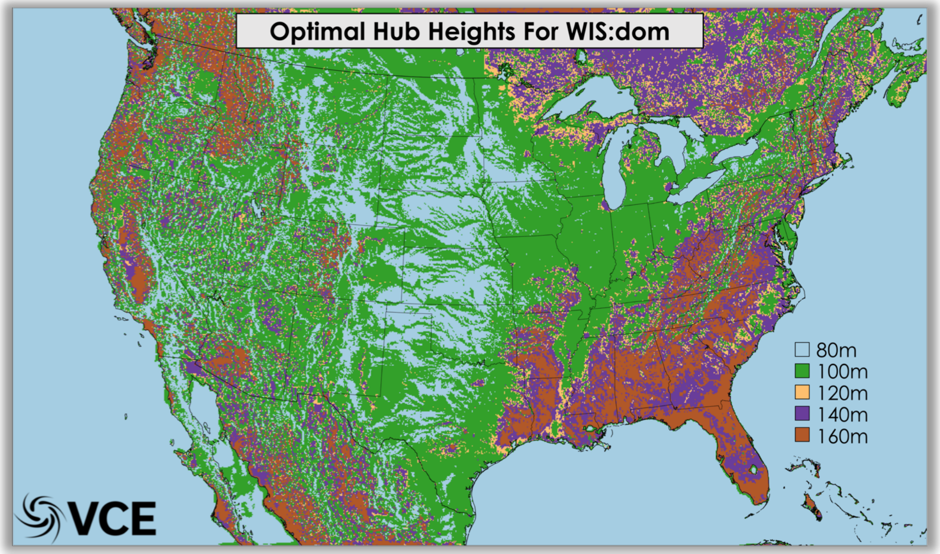
Logical Equations in WIS:dom

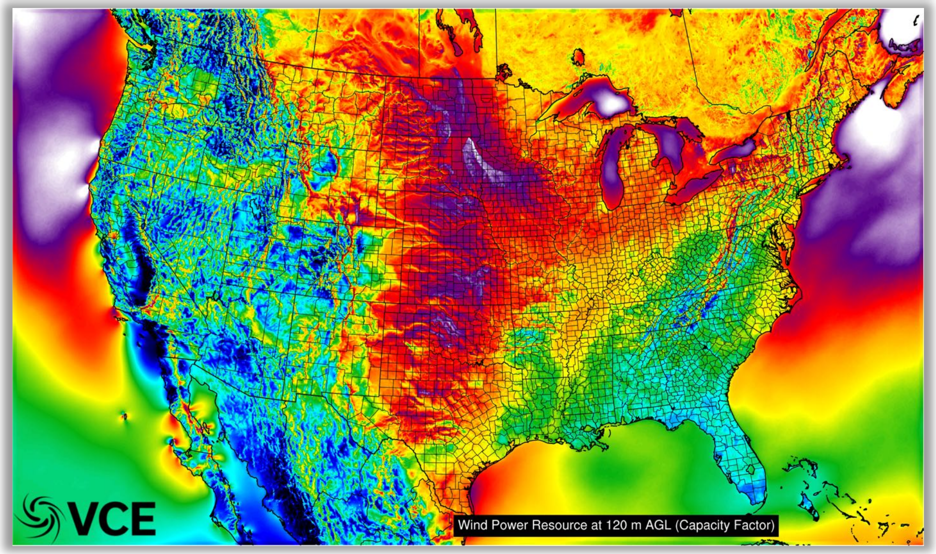
Constraint ID	Equation Name	Equation Purpose	Impact Estimation
1	Total System(s) Cost Objective	To define the objective that is being minimized	**Critical** Other objectives may alter solutions significantly
2	Reliable Dispatch Constraint	Enforce WIS:dom meets demand in each region each hour without 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 artifically 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 invesments are not substantially altered. For WECC, the impact is much higher

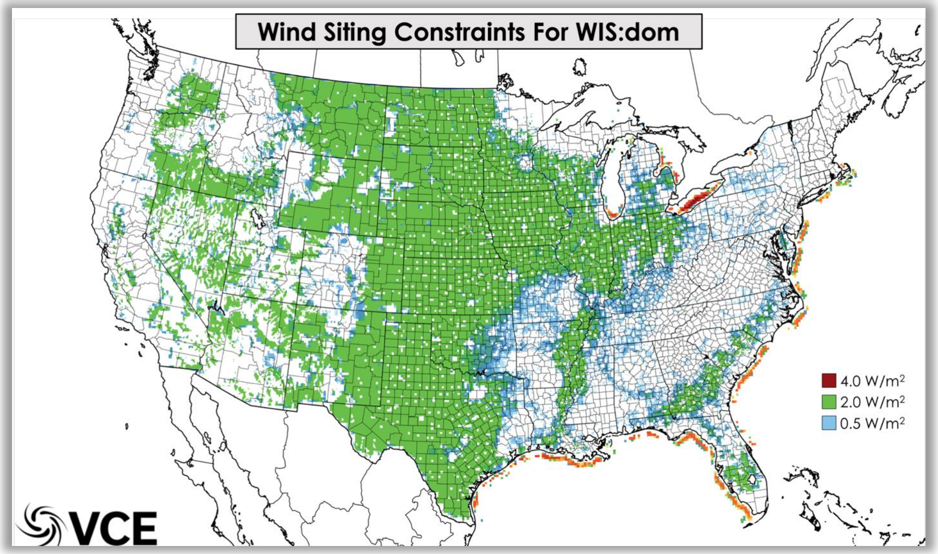
What Weather Details Does WIS:dom Include?

WIS:dom Contains Detailed Weather and Siting Datasets









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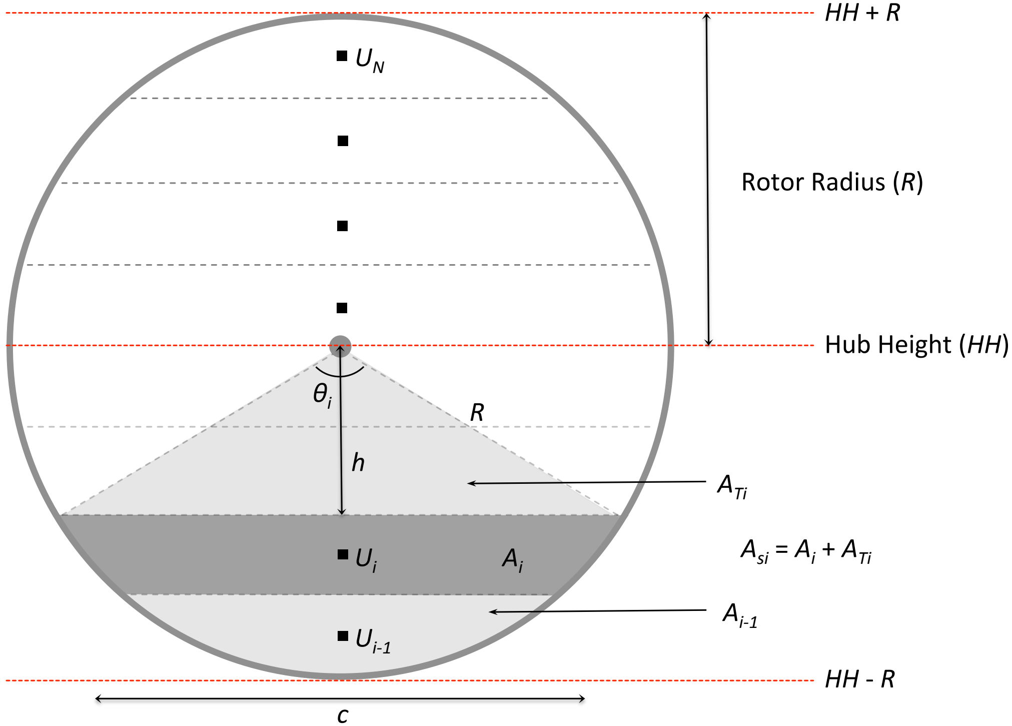
Creating VRE Resources

General Process: Wind



$$U_\eta = \sqrt{u_\eta^2 + v_\eta^2}$$

$$U_i = \frac{u_i \cdot u_H + v_i \cdot v_H}{U_H}$$

$$A_i = A_{Si} - A_{Ti} - \sum_{j=0}^{i-1} A_j, \quad i \geq 1$$

$$A_{Si} = \frac{\theta_i}{2\pi} \cdot \pi R^2 = \frac{\theta_i R^2}{2}$$

$$A_{Ti} = \frac{1}{2} \cdot c \cdot h = R \sin\left(\frac{\theta_i}{2}\right) R \cos\left(\frac{\theta_i}{2}\right) = \frac{R^2}{2} \sin \theta_i$$

$$\alpha_i = \frac{A_i}{A} = \frac{(\theta_i - \sin\theta_i)}{2\pi} - \frac{1}{A} \sum_{j=0}^{i-1} A_j, \quad i \geq 1$$

$$U_R = \sum_{i=1}^{N} \alpha_i \cdot U_i$$

* We also perform the same technique to obtain the Rotor Equivalent Density, Temperature and Clouds

Clack et al., *Wind Energy*, 2016

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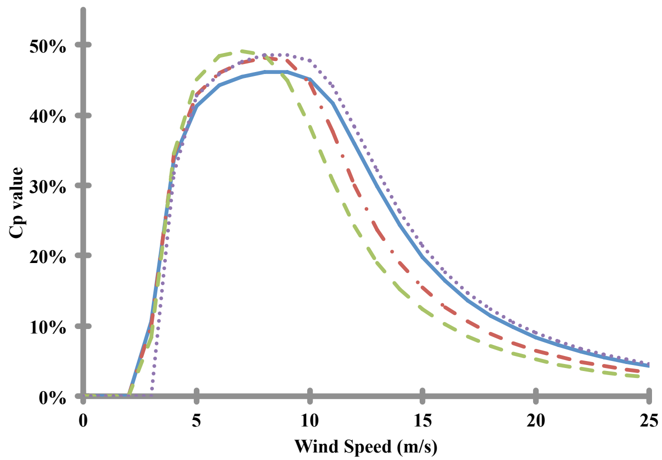
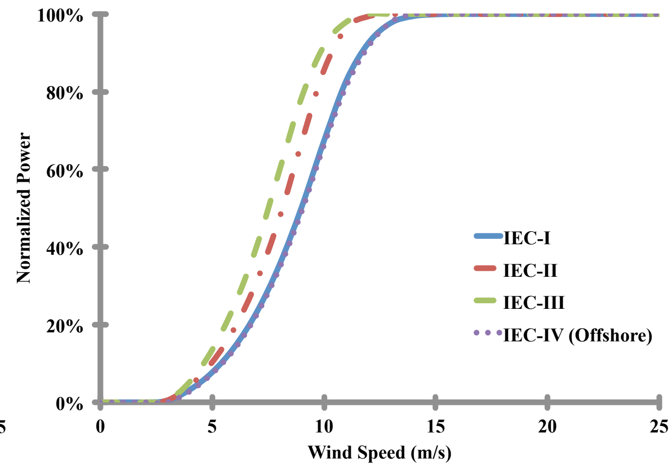
Creating VRE Resources

General Process: Wind

$$P_w = \frac{d[E_w(U(t))]}{dt} = \frac{d}{dt}\left[\frac{1}{2}\cdot A\cdot\rho(t)\cdot L(t)\cdot U^2(t)\right] = \frac{\rho A U^3}{2}\left[1+\left(\frac{\int U\,dt}{U}\right)\left(\frac{1}{\rho}\frac{d\rho}{dt}+\frac{2}{U}\frac{dU}{dt}\right)\right]$$



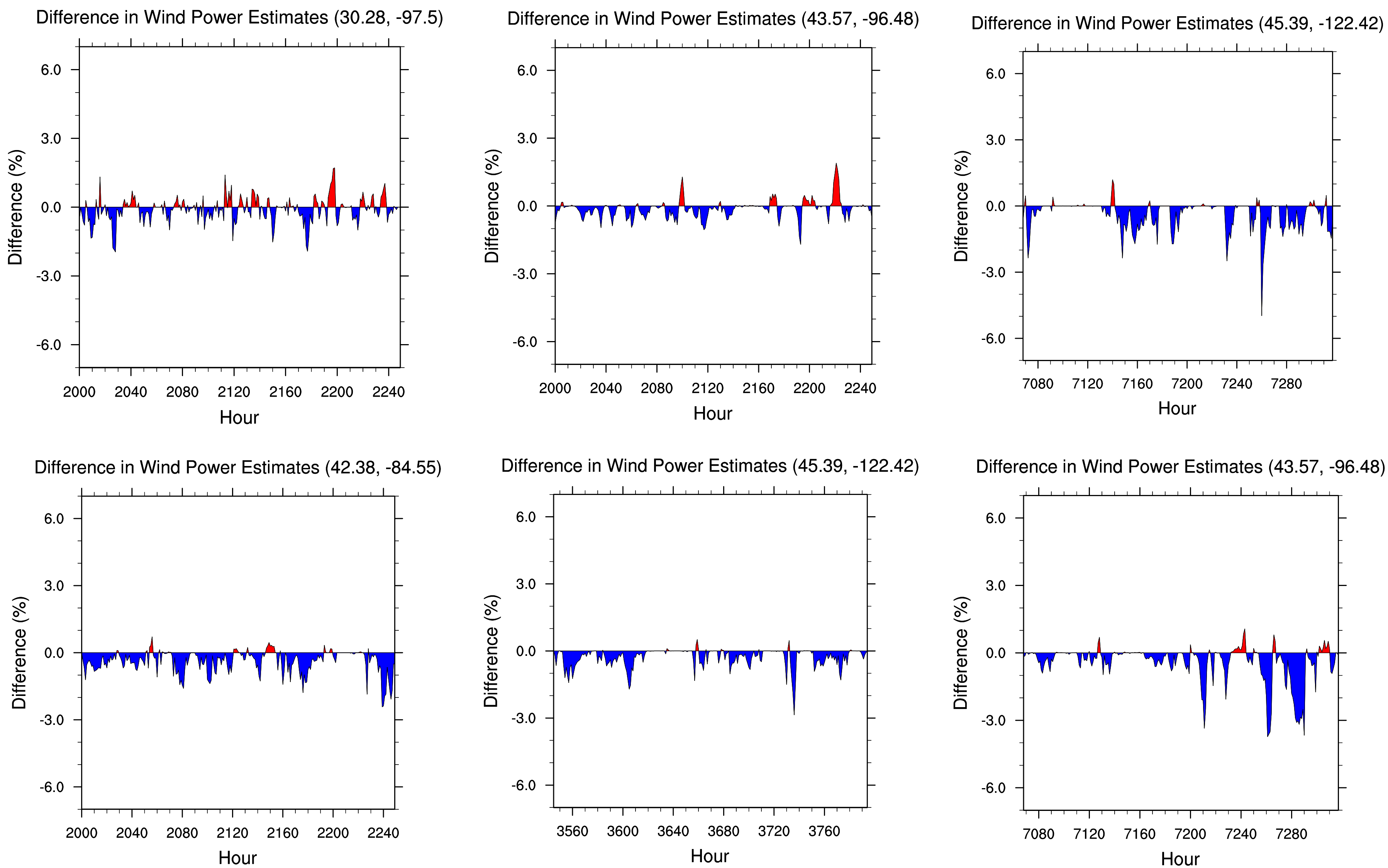


	Turbine	Rated Power (MW)	Cut-In Speed (m/s)	Max Output Speed (m/s)	Cut-Out Speed (m/s)	Rotor Diameter (m)
IEC-I	Siemens 3.0 MW	3.0	3.0	14.0	25.0	101.0
	Gamesa G80	2.0	4.0	17.0	25.0	80.0
	Nordex N90HS	2.5	4.0	14.0	25.0	90.0
	Vestas V90	3.0	4.0	14.0	25.0	90.0
IEC-II	Vestas V112	3.0	3.0	13.0	25.0	112.0
	Siemens 2.3 MW	2.3	3.0	13.0	25.0	93.0
	GE1.6 82.5	1.6	4.0	12.0	25.0	82.5
	GE2.5xl	2.5	3.0	14.0	25.0	100.0
IEC-III	Vestas V100	1.8	3.0	12.0	20.0	100.0
	GE1.6-100	1.6	3.0	12.0	25.0	100.0
	Repower 3.2M	3.2	3.0	12.0	22.0	114.0
IEC-IV	Siemens 3.6 MW	3.6	4.0	14.0	25.0	107.0
	GE4.1MW	4.1	4.0	14.0	25.0	113.0
	Repower 6M	6.15	3.5	14.0	30.0	126.0

Clack et al., *Wind Energy*, 2016

Creating VRE Resources

General Process: Wind



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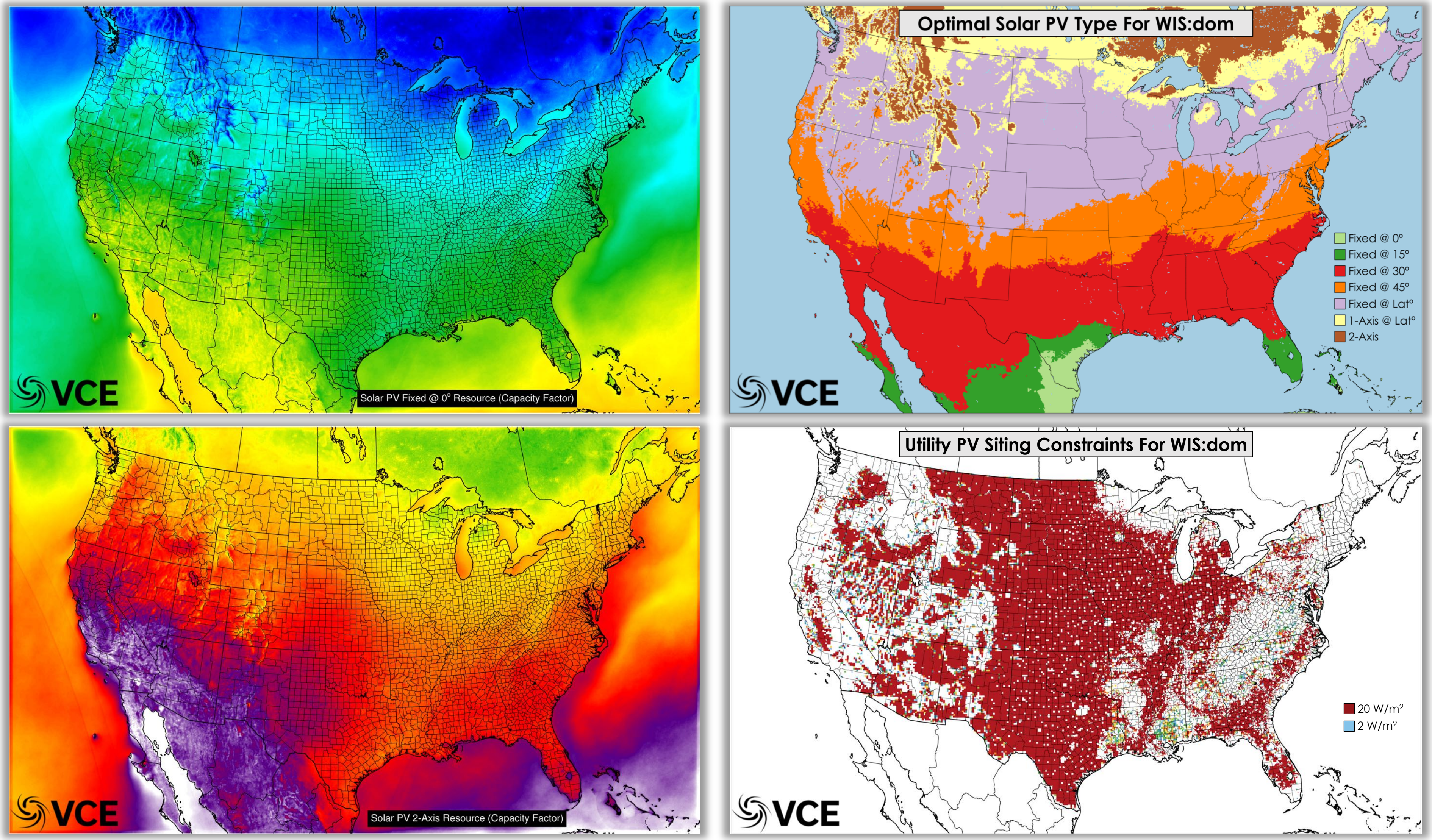
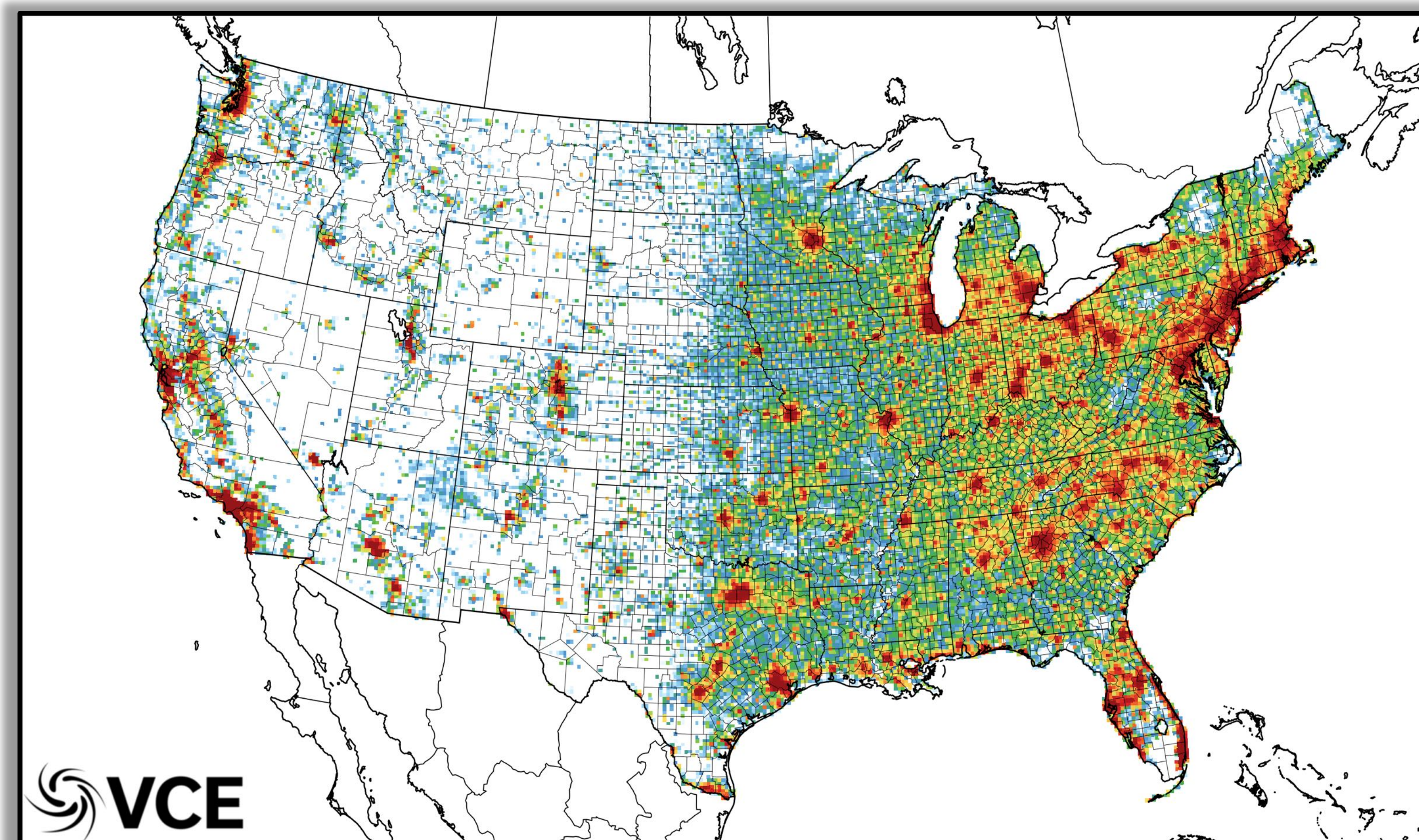
WIS:dom Contains Detailed Weather and Siting Datasets



Advanced Screening For Rooftop PV

Note: Logarithmic Color Scale



Maximum
2.5 W/m^2

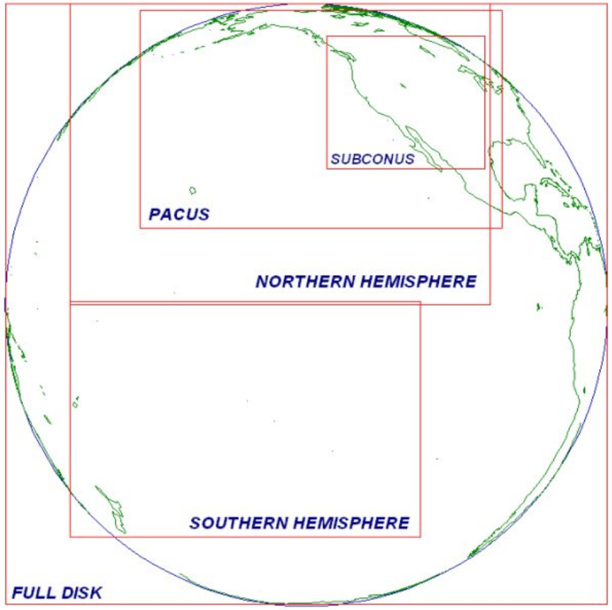
Minimum
2.5×10^{-5} W/m^2

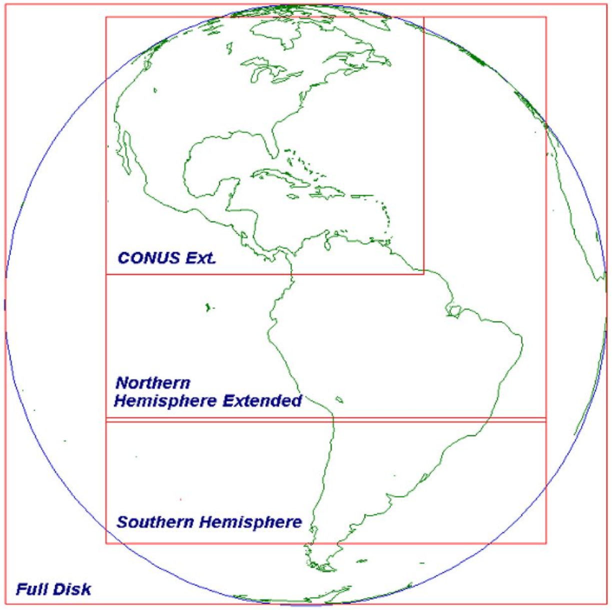
Creating VRE Resources

General Process: Solar

1. Obtain the ***3-km HRRR*** (High-Resolution Rapid Refresh) ***hourly*** data that includes 3-D volume of atmosphere over North America. Contains (1059 x 1799 x 51) data points for each variable.

2. Obtain the ***1- and 4-km GOES*** Satellite ***15-minute*** data for all of North America. The North America data is at a higher refresh rate that the full-disk scans. The reflectance values are for different wavelengths or "bands" – ***visible***, ***4-micron***, ***11-micron***, ***13-micron***, and ***water vapor***. VCE utilizes ***CONUS Ext***. and ***PACUS*** from the GOES satellites.





Clack, JAMC, 2017

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Creating VRE Resources

General Process: Solar

$$Y_{n\times p} = Z_{n\times(r+1)}\beta_{(r+1)\times p} + \epsilon_{n\times p},$$

$$E(\epsilon_{(i)}) = 0, \quad \text{Cov}(\epsilon_{(i)}, \epsilon_{(k)}) = \sigma_{ik} I, \quad i, k = 1, 2, ..., p.$$

- We have p(=3) irradiance fields to calculate and n(=631,645) observation of each field. The observations are taken from 15 high quality measurement sites (NOAA SURFRAD & SOLRAD)

- The regressors (β) are the satellite data (5 wavelengths), the HRRR weather variables (SW, LW, temperature, wind, elevation, etc.), the top of atmosphere irradiance, the zenith angle, the azimuth angle, and the declination angle.

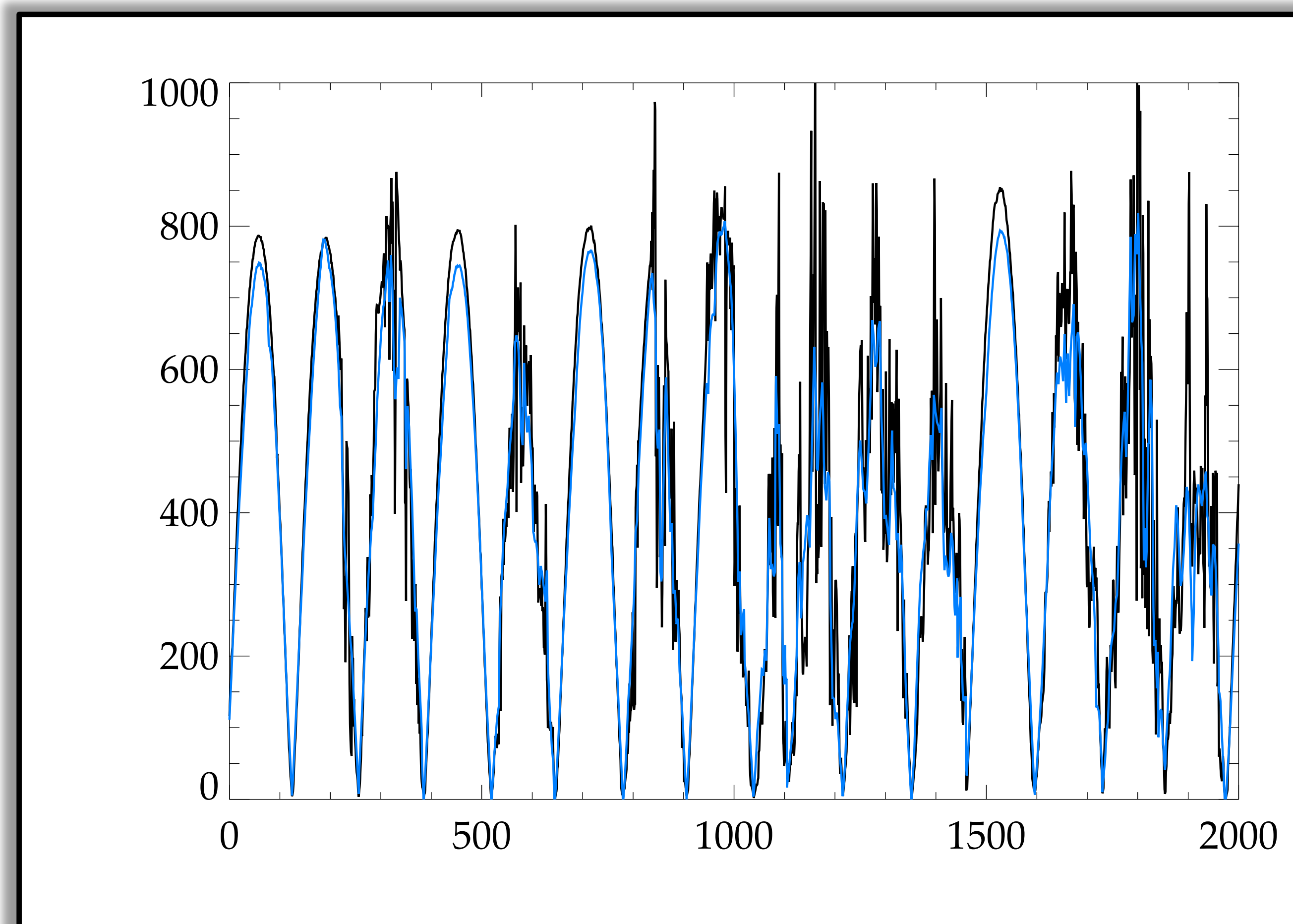
- The measurements are taken for each of the weather years, the closest 5-minute interval and aligned to the correct UTC time

- The data is quality controlled, and all night-time measurements were removed. The regression is trained at sites that are dispersed across the USA.

- Separate regressions are performed with and without satellite data, so that when no satellite is available an approximation is made.

Creating VRE Resources

General Process: Solar



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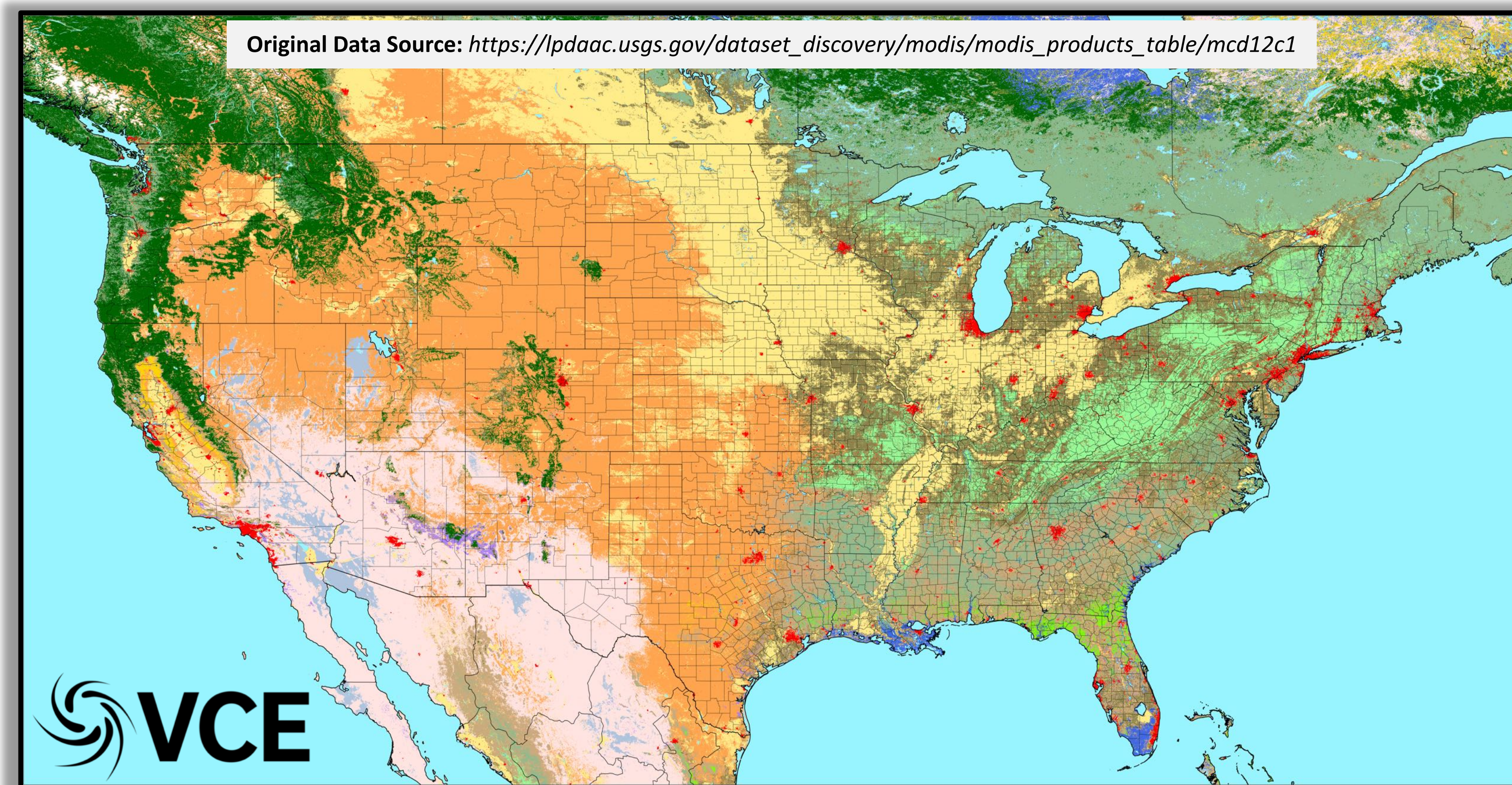
What Initialization Considerations Are Required?

Land Use Dataset



- Water
- Evergreen NL Forest
- Evergreen BL Forest
- Deciduous NL Forest
- Deciduous BL Forest
- Mixed Forest
- Closed Shrubland
- Open Shrubland
- Woody Savanna
- Savanna
- Grassland
- Permanent Wetland
- Cropland
- Urban & Built up
- Crops & Natural Vegetation
- Snow & Ice
- Barren / Sparse
- Unclassified

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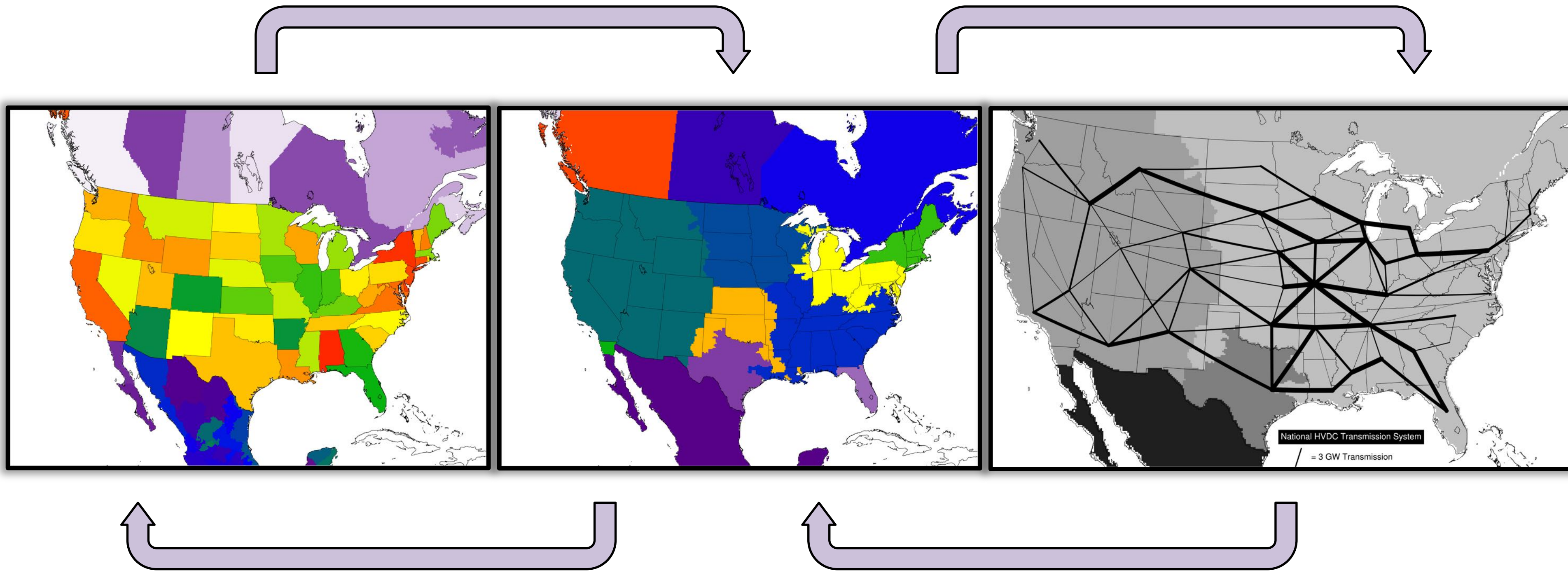
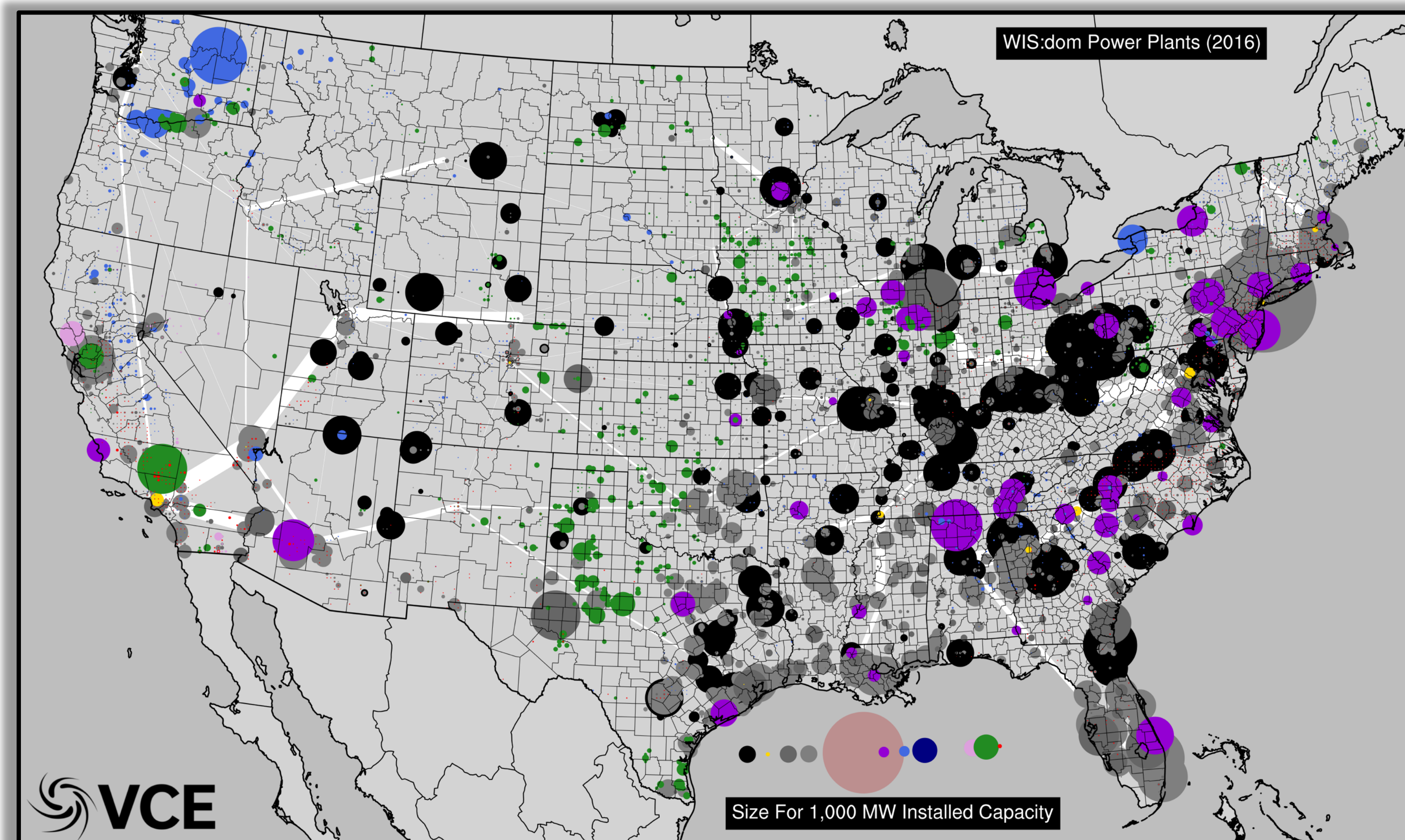
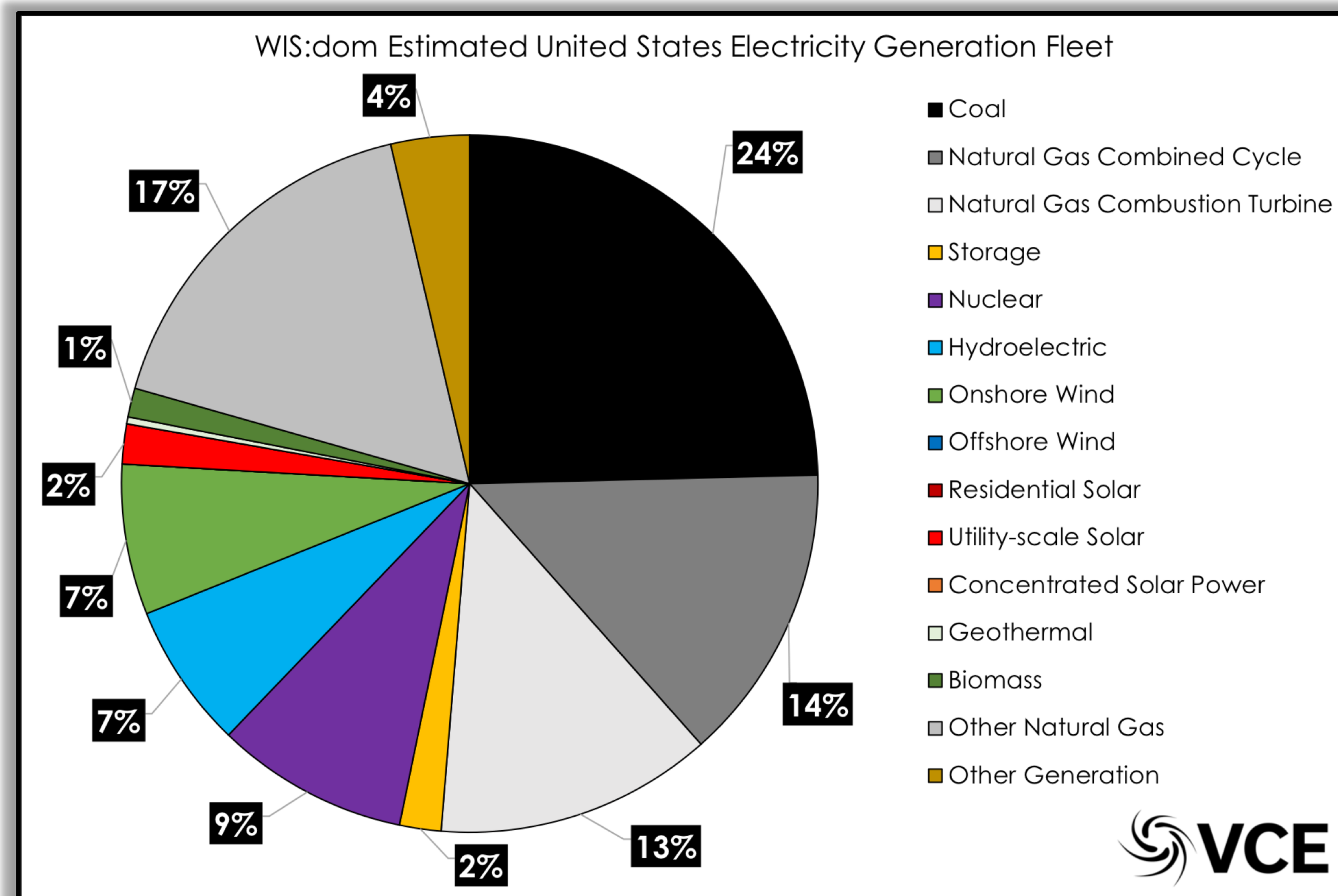
WIS:dom Considers Numerous Scales Simultaneously



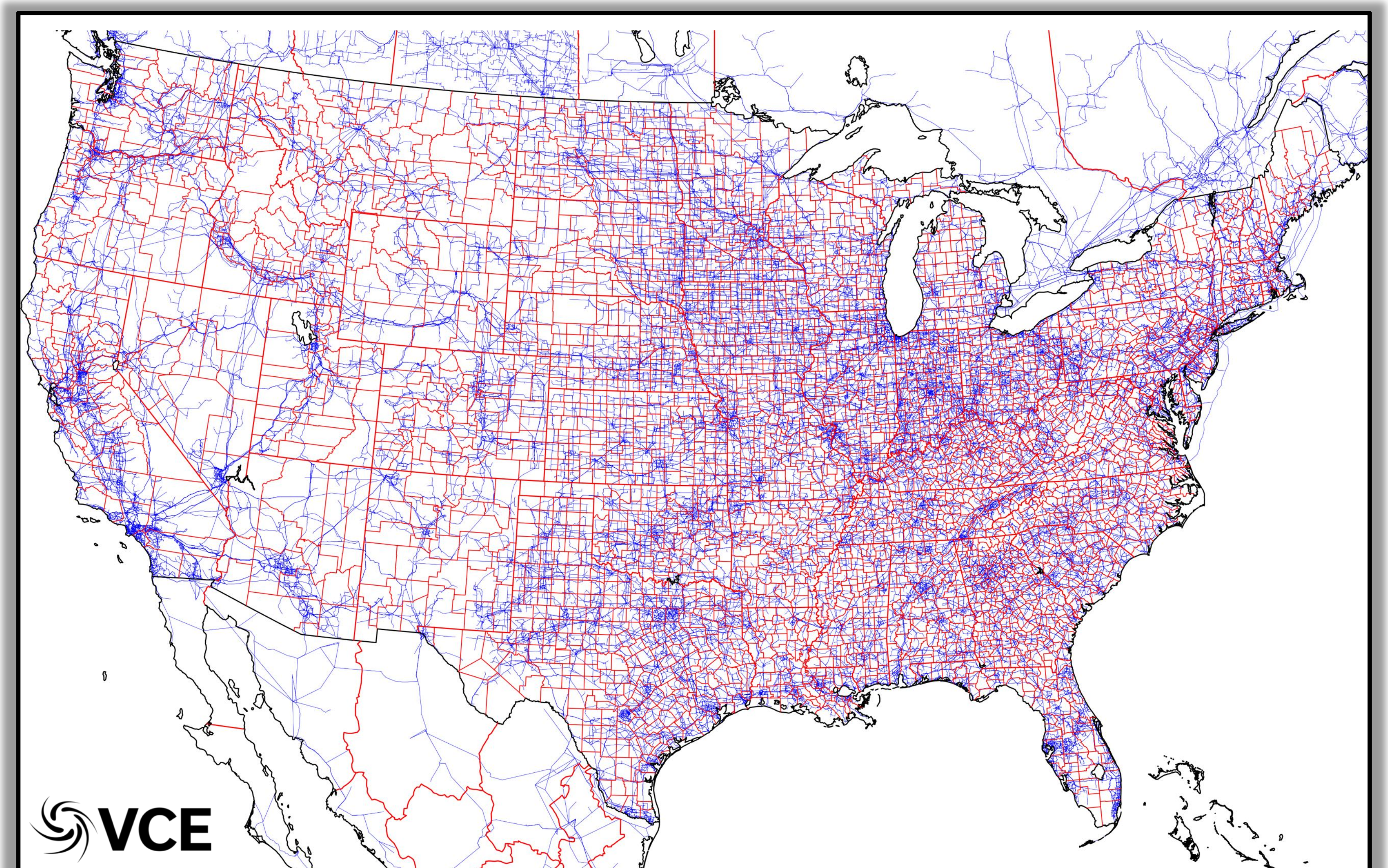
Start from Today: Generators



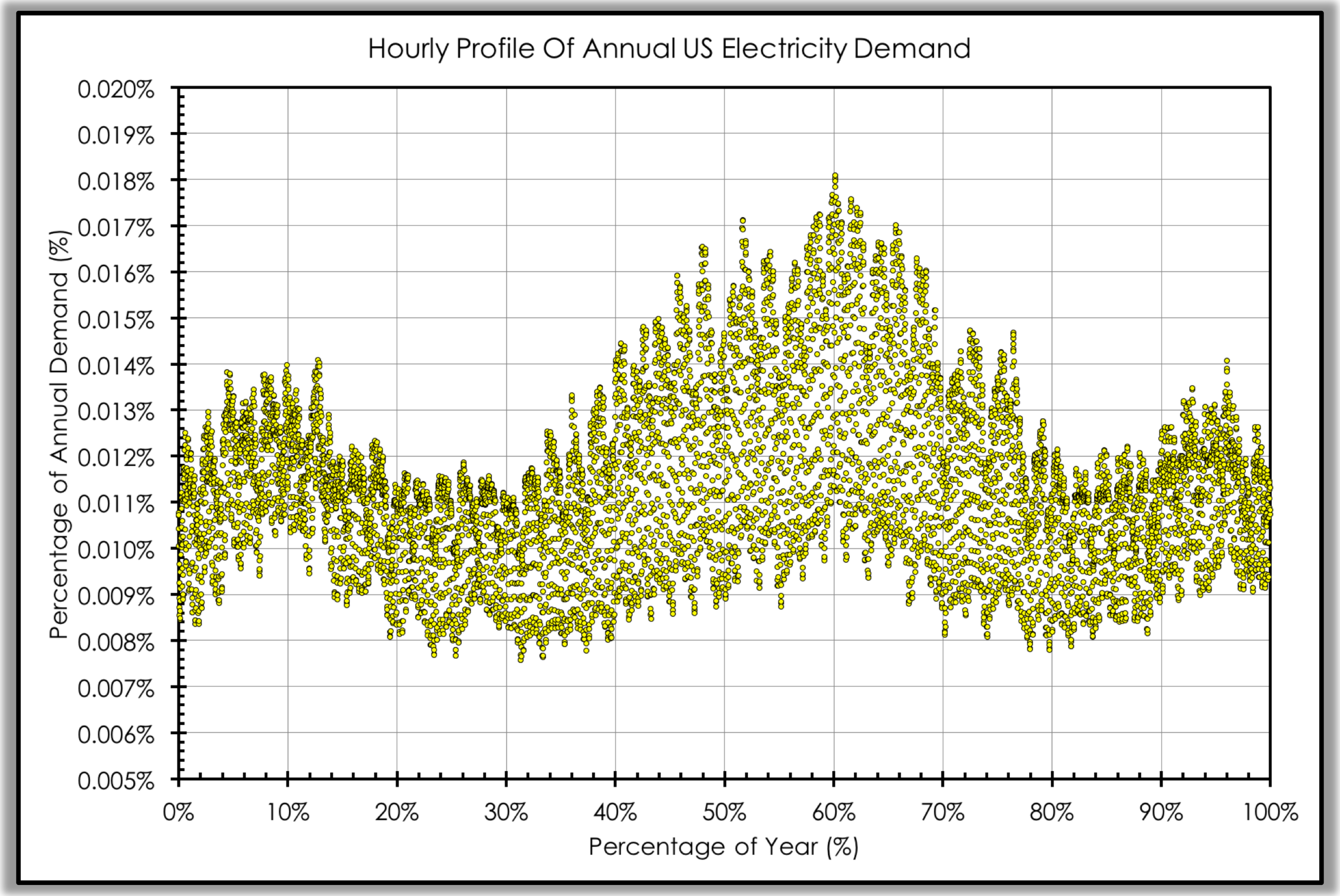
Start from Today: Generators



Start from Today: Electricity Transmission



All Demands (for each regions) Must be Weather-Aligned



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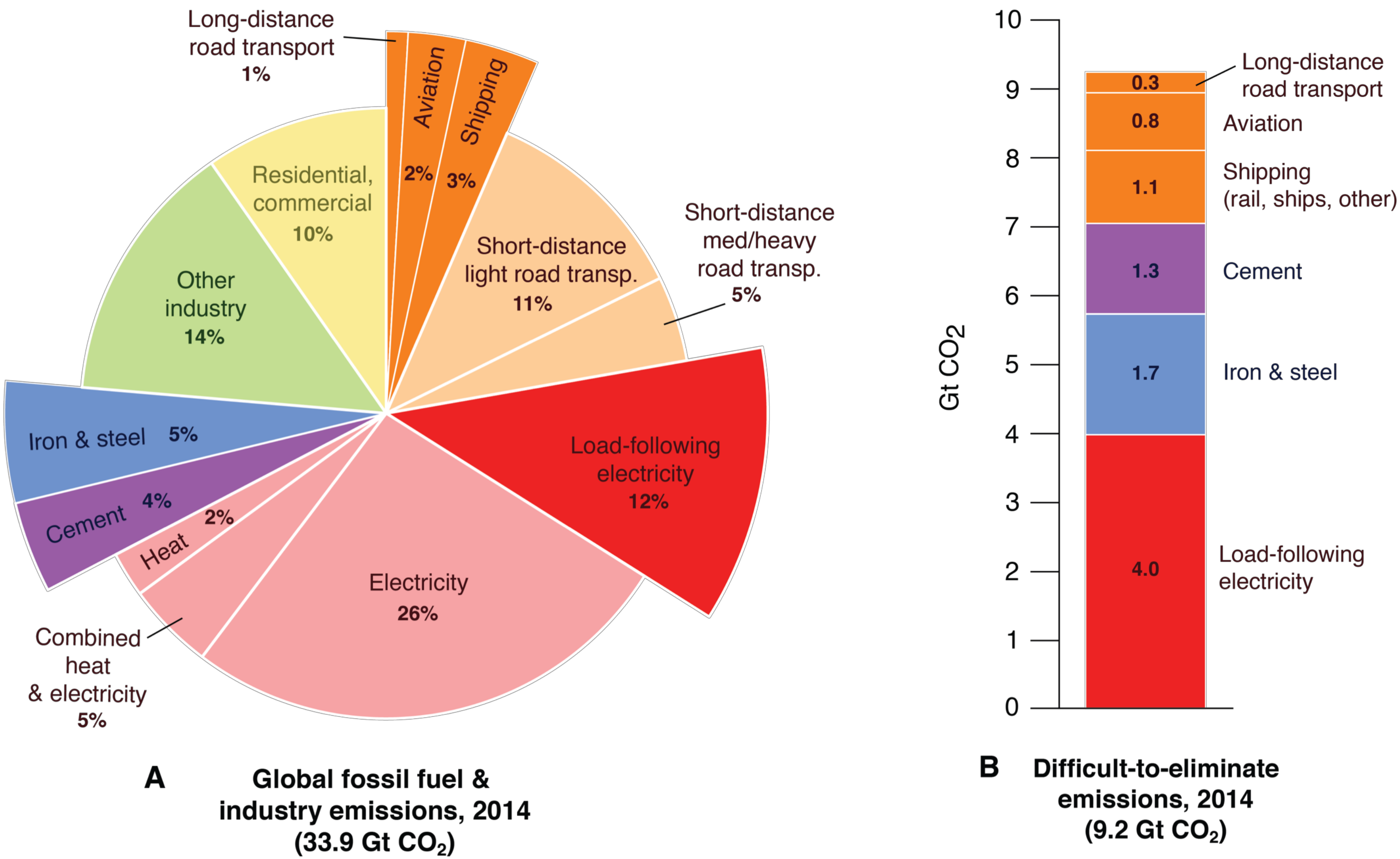
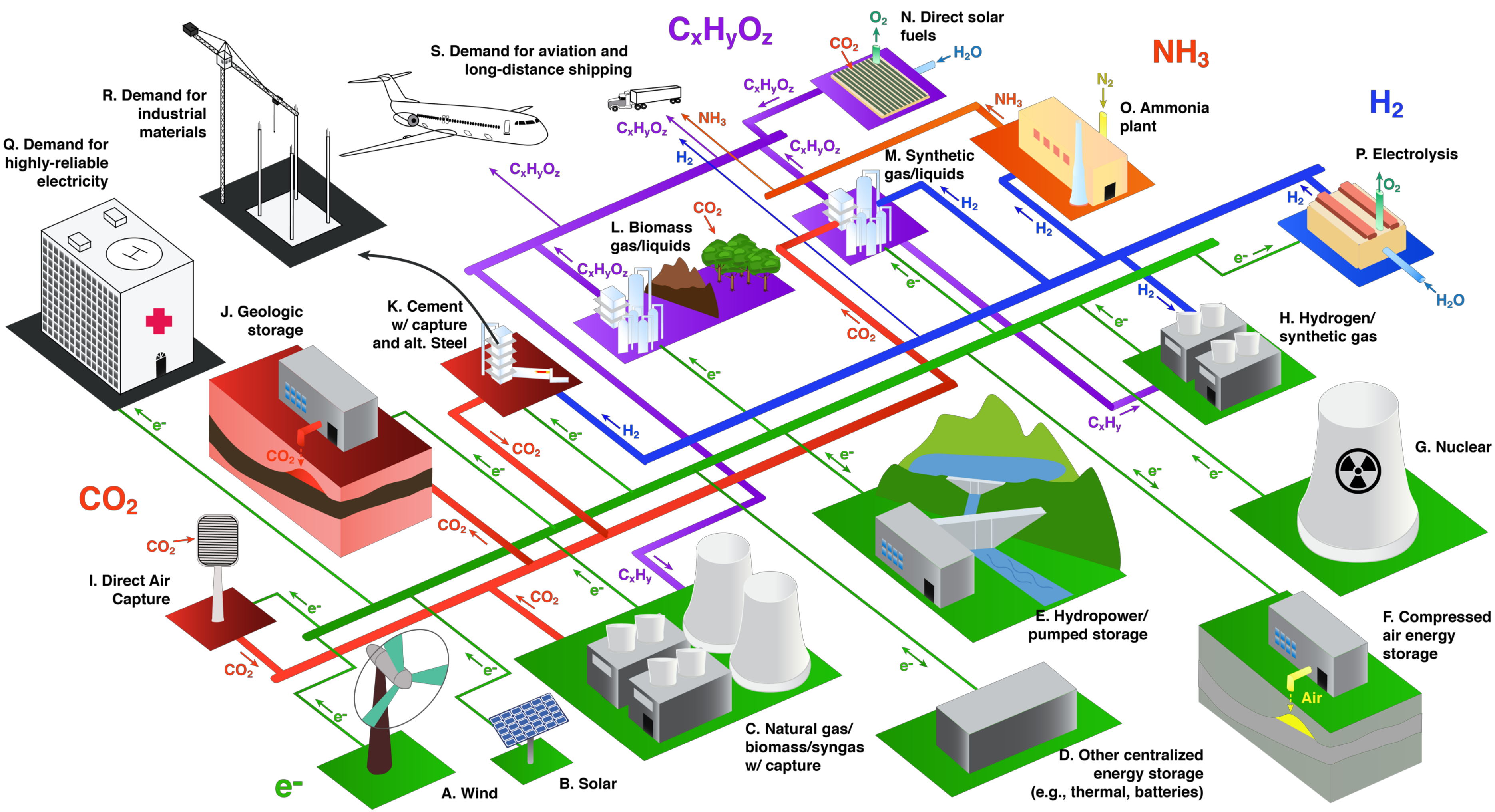
What About Electrification?

Electricity Is Not All Energy



Davis et al. *Science*, 2018

The Whole Economy Needs Energy



Davis et al. *Science*, 2018

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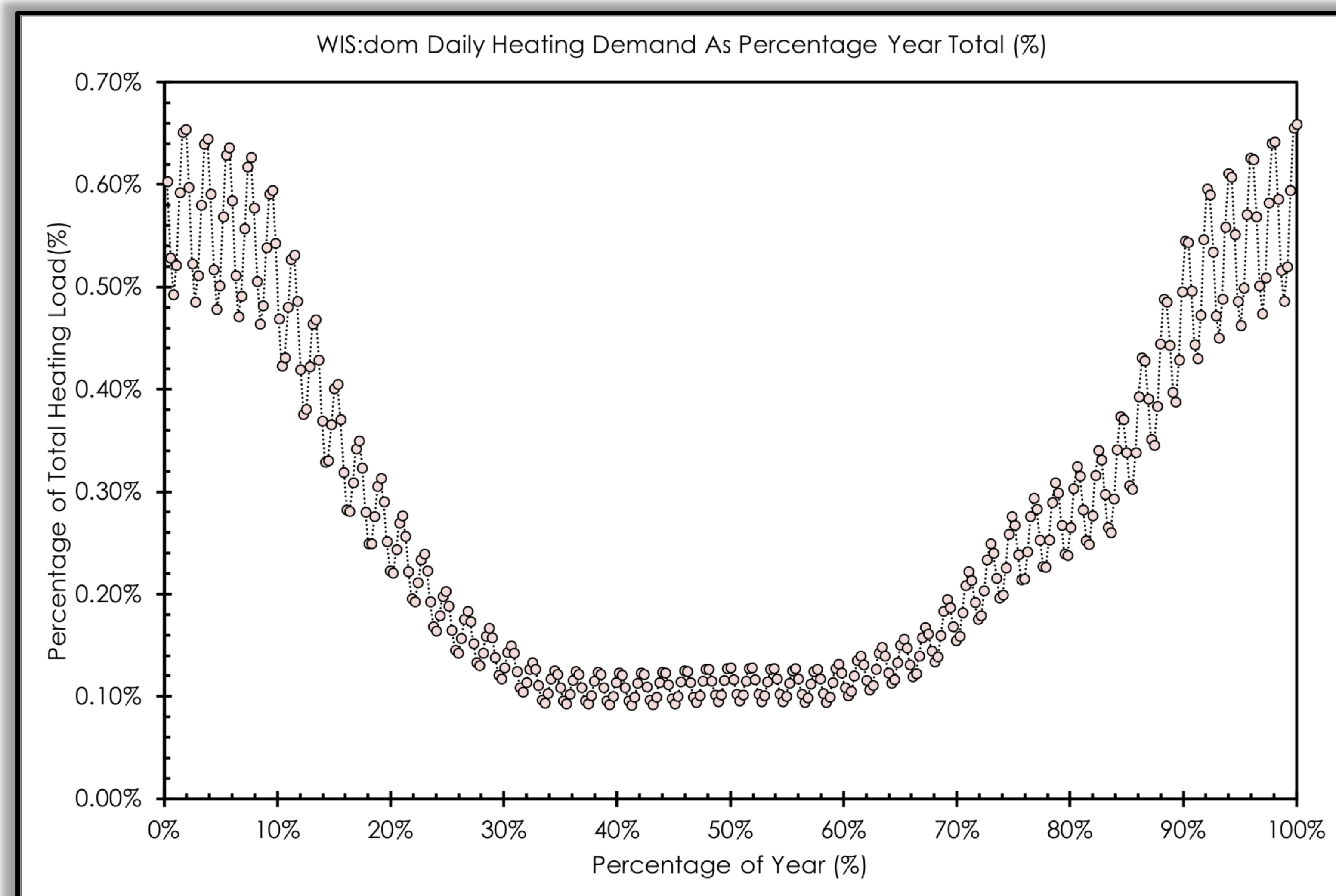
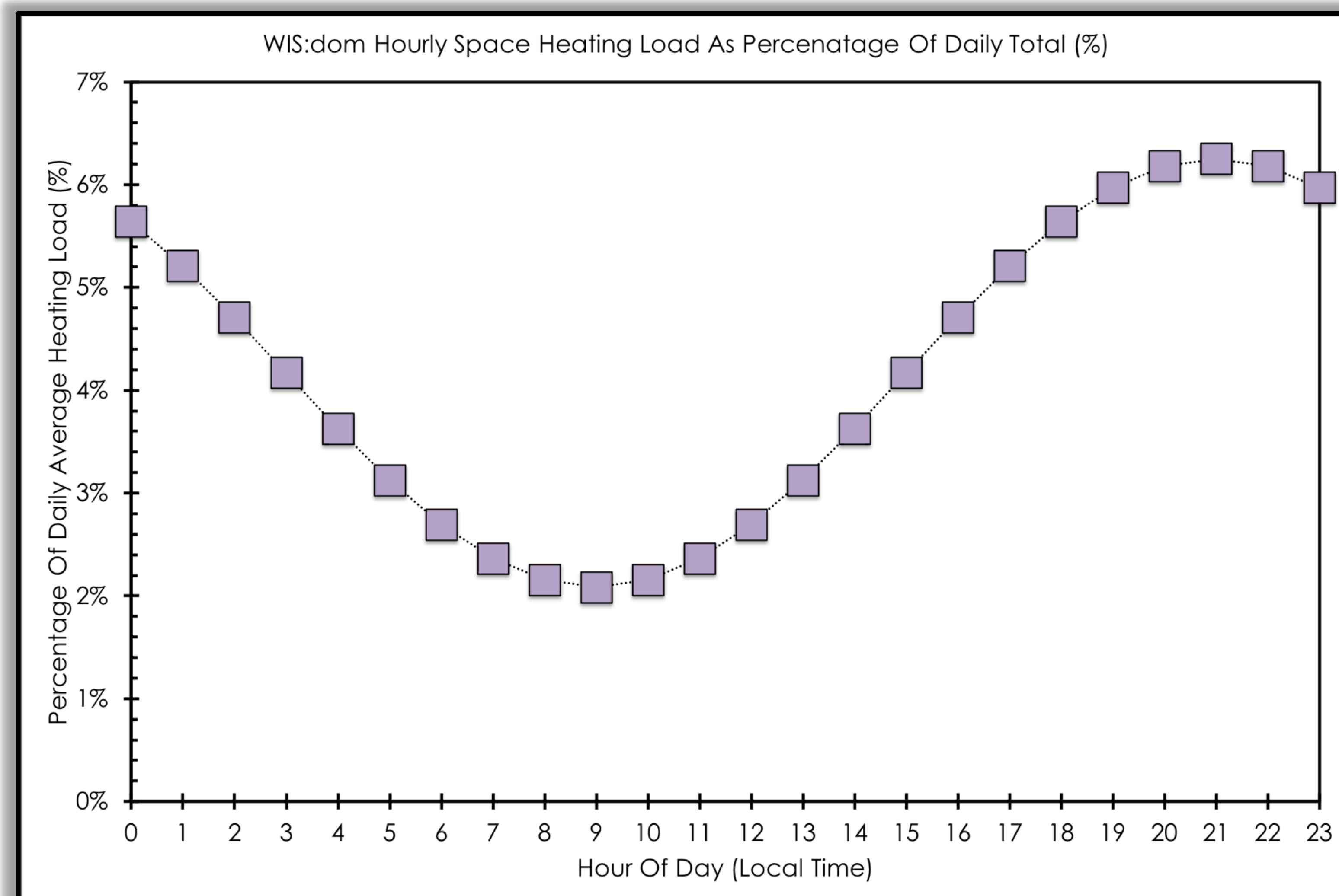
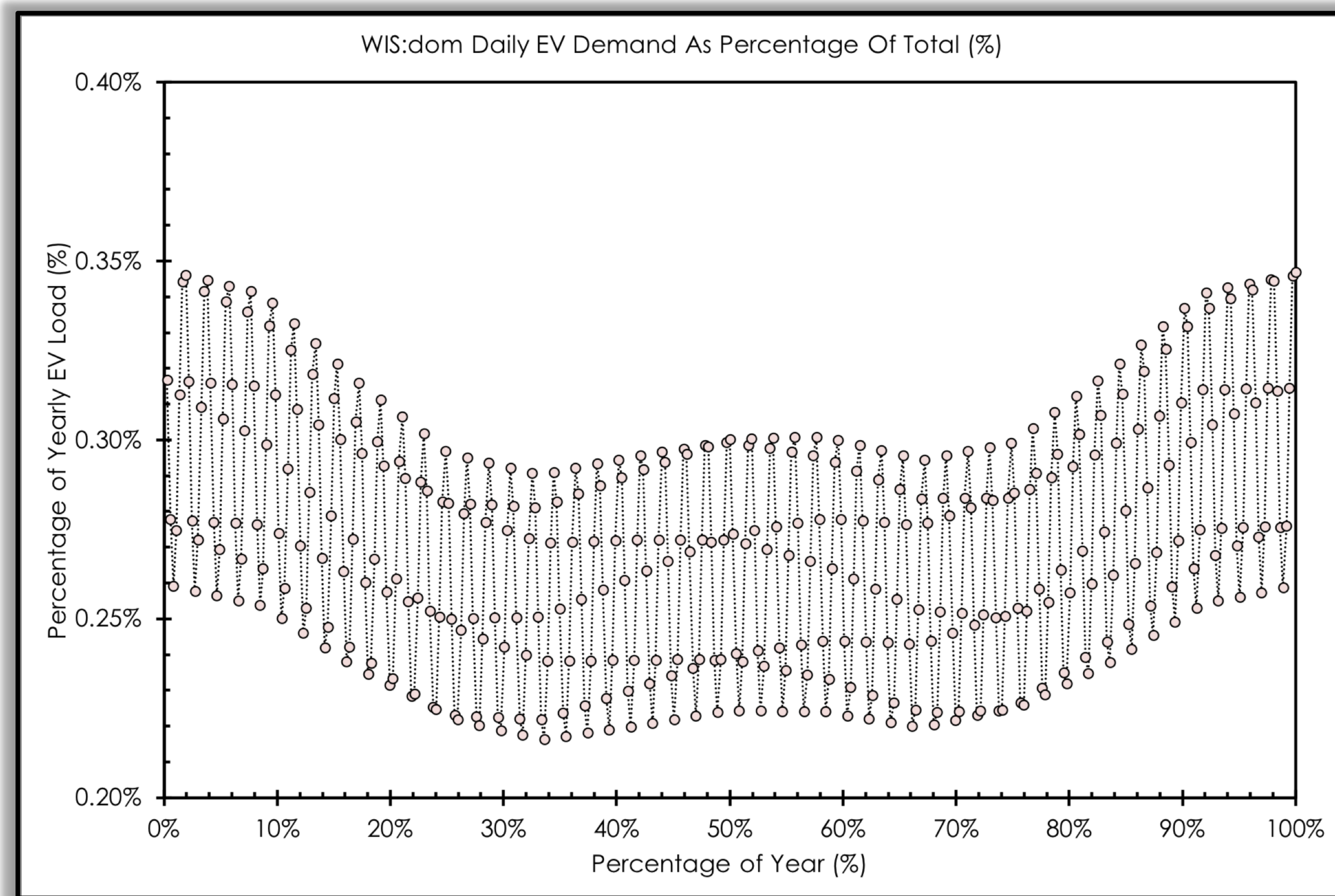
Addition Heating Demands (Daily)



Addition Heating Demands (Hourly)



Addition Transportation Demands (Daily)



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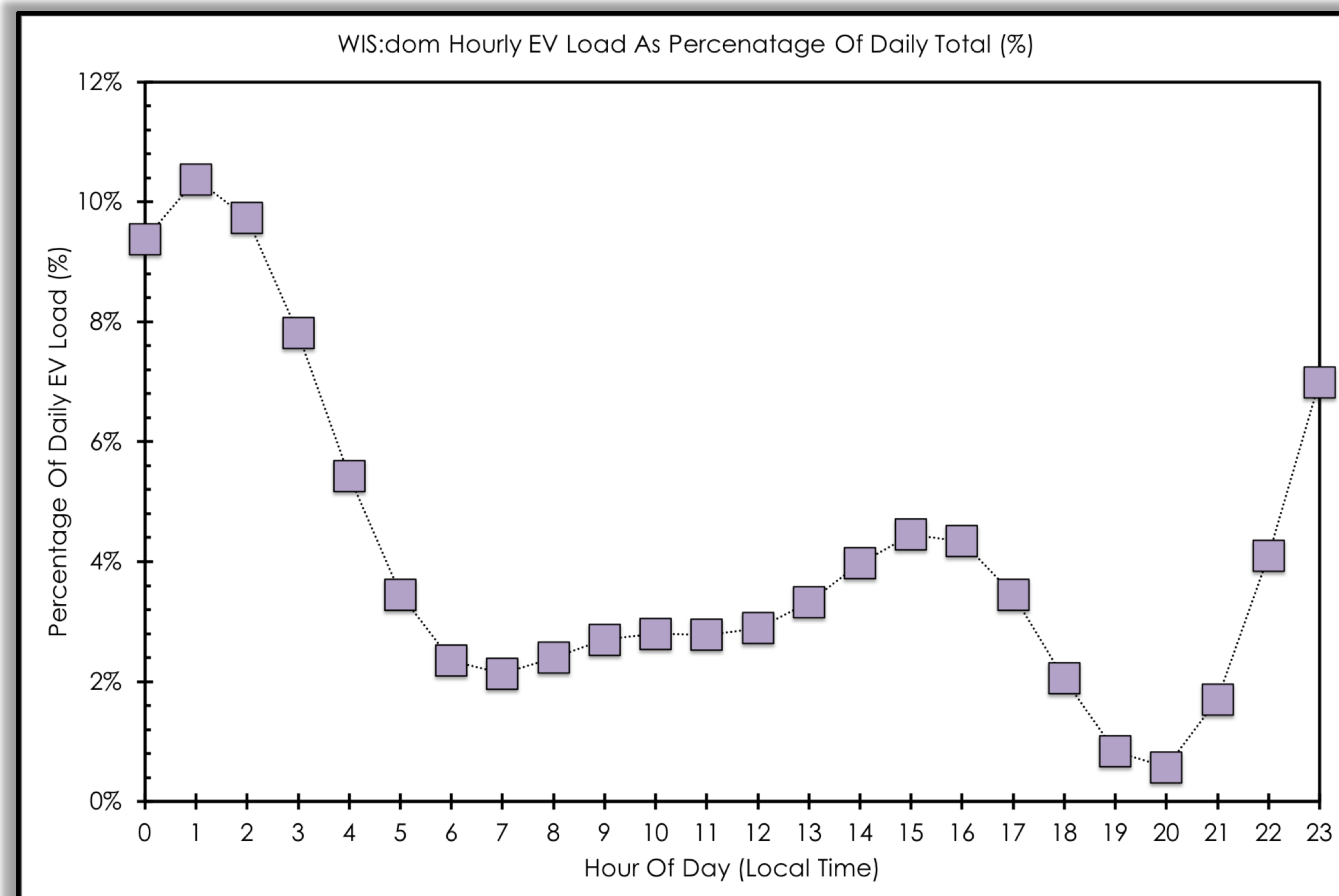
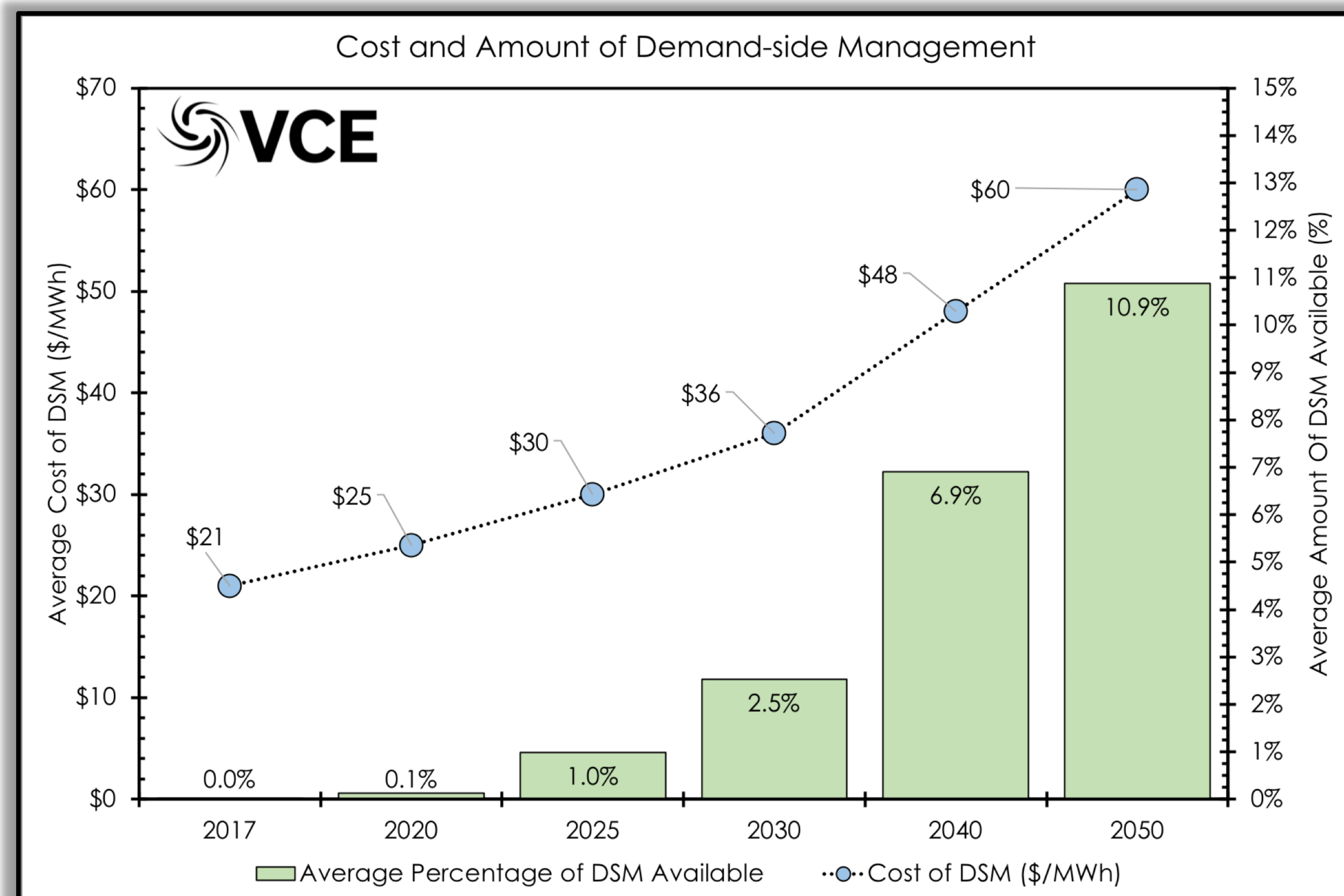
Addition Transportation Demands (Hourly)



Demand-side Resources Create Flexibility



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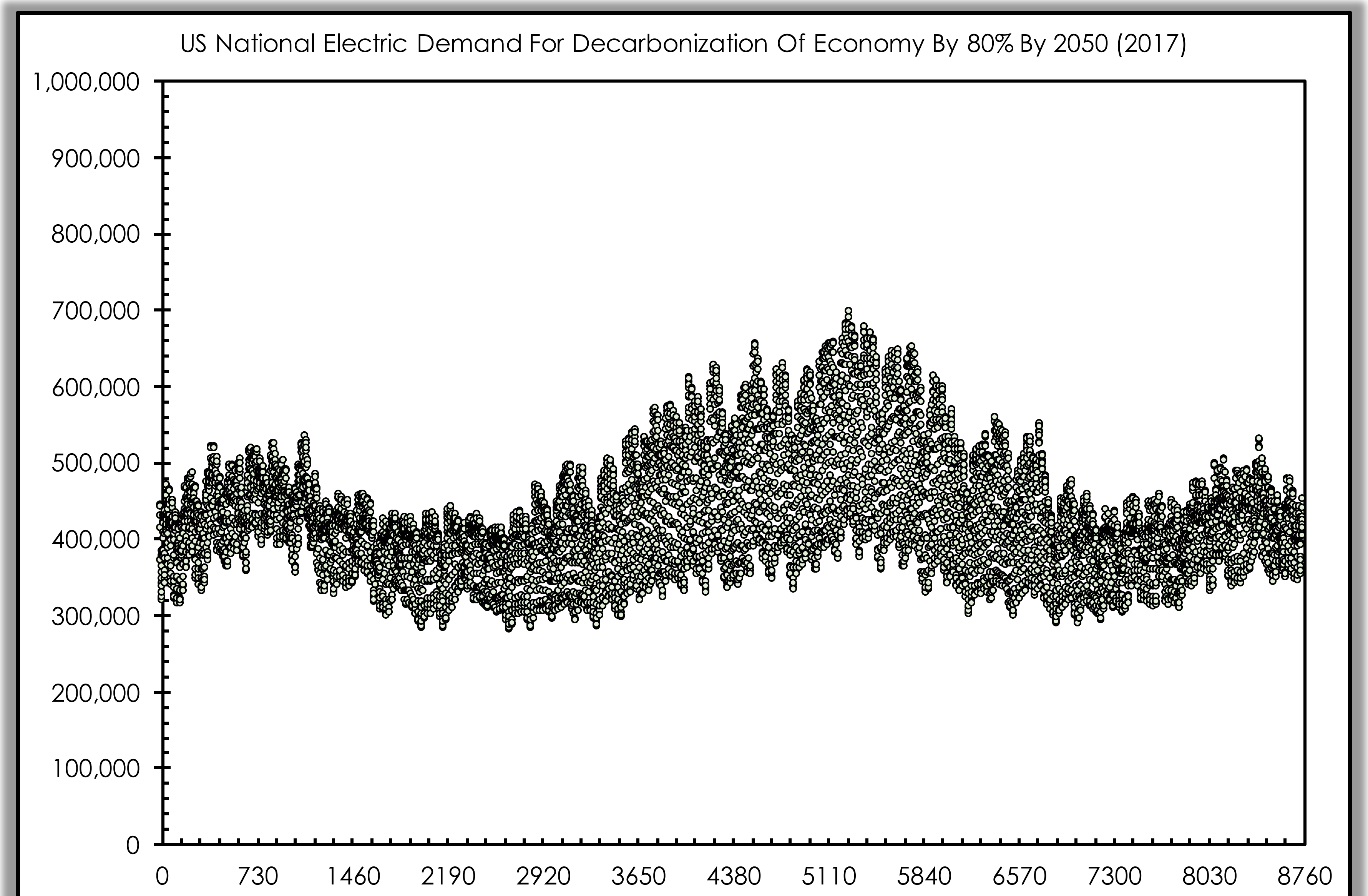
Load Initialization & Forecasts



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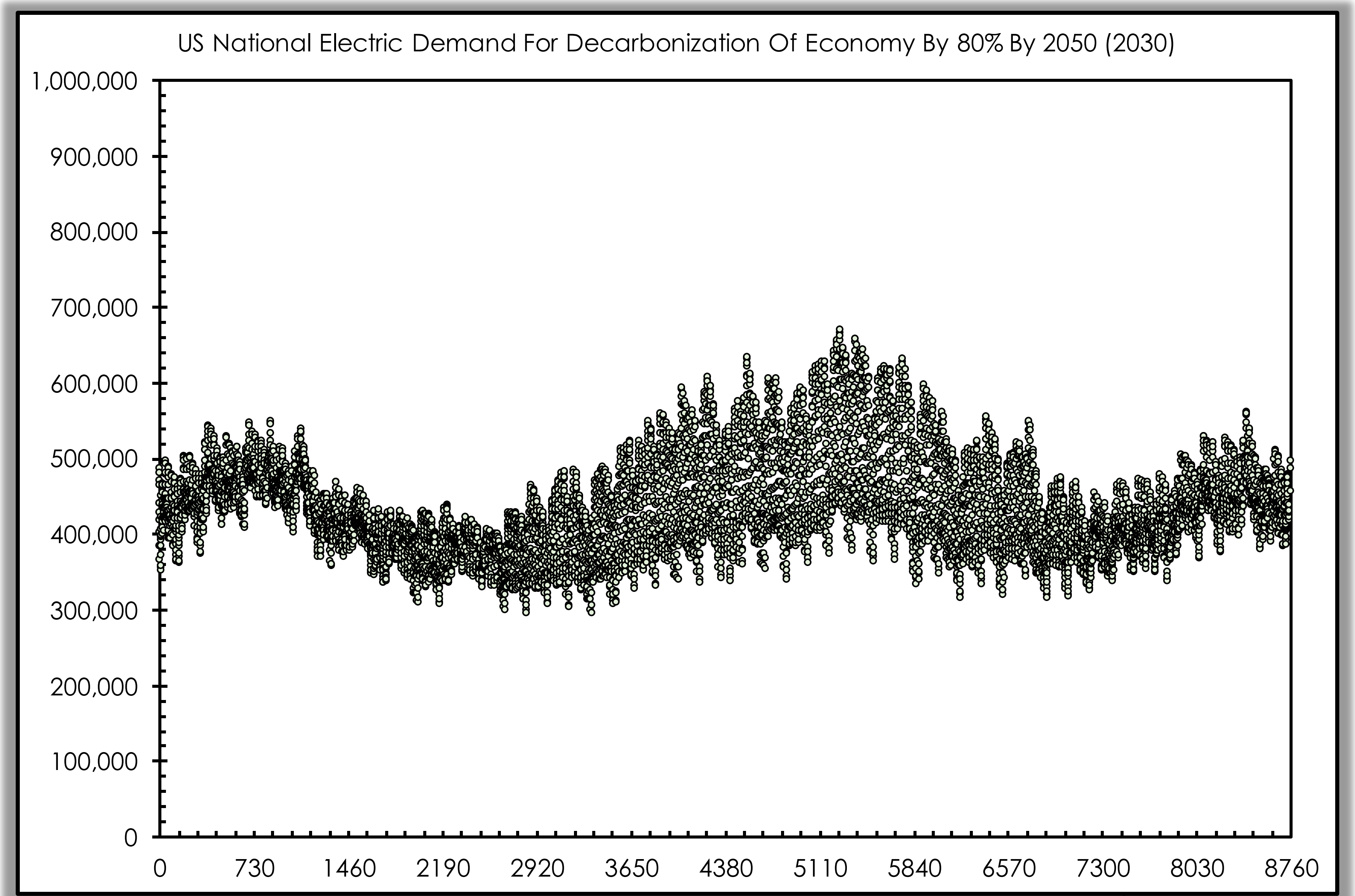
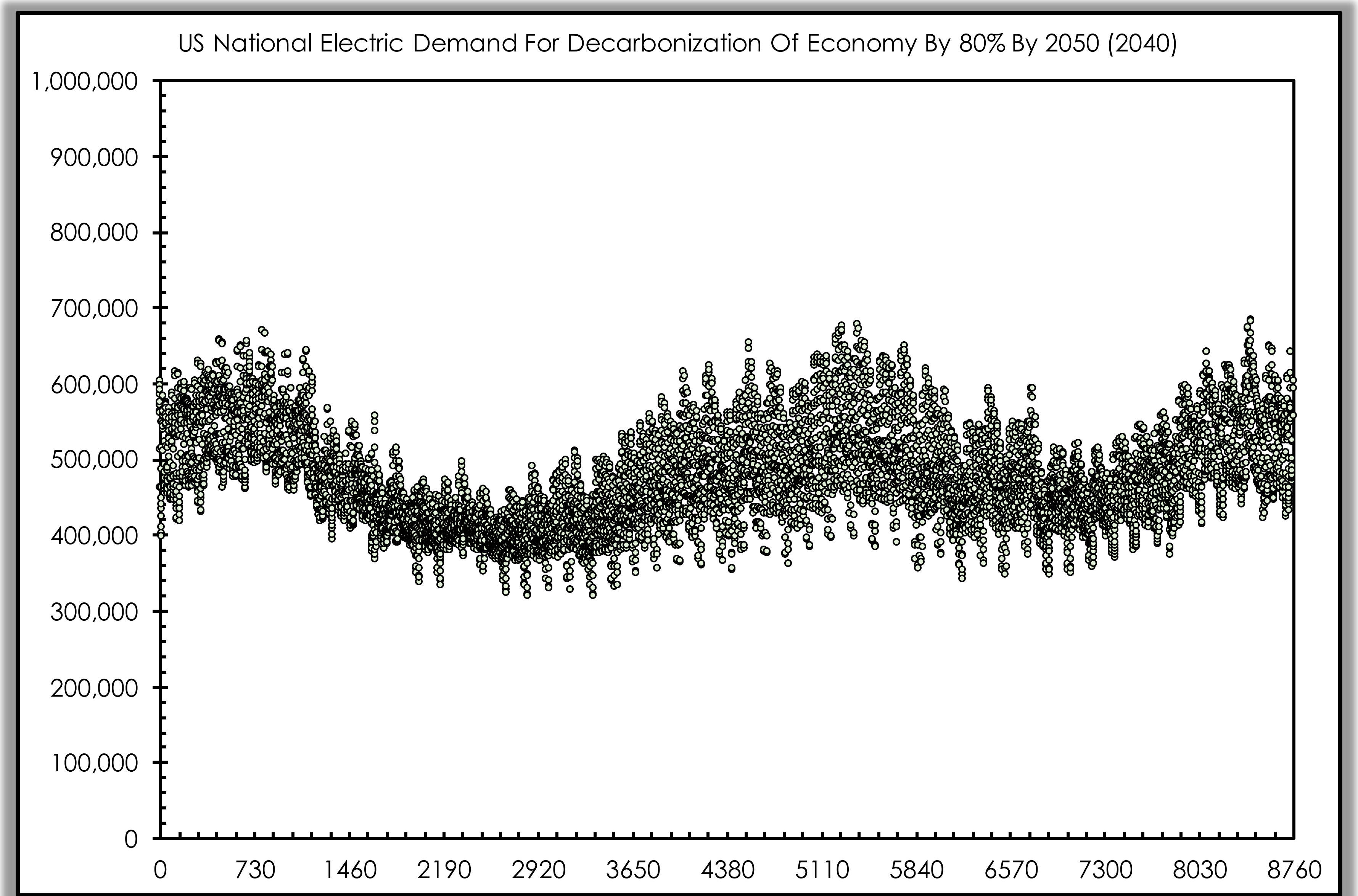
Load Initialization & Forecasts



Load Initialization & Forecasts



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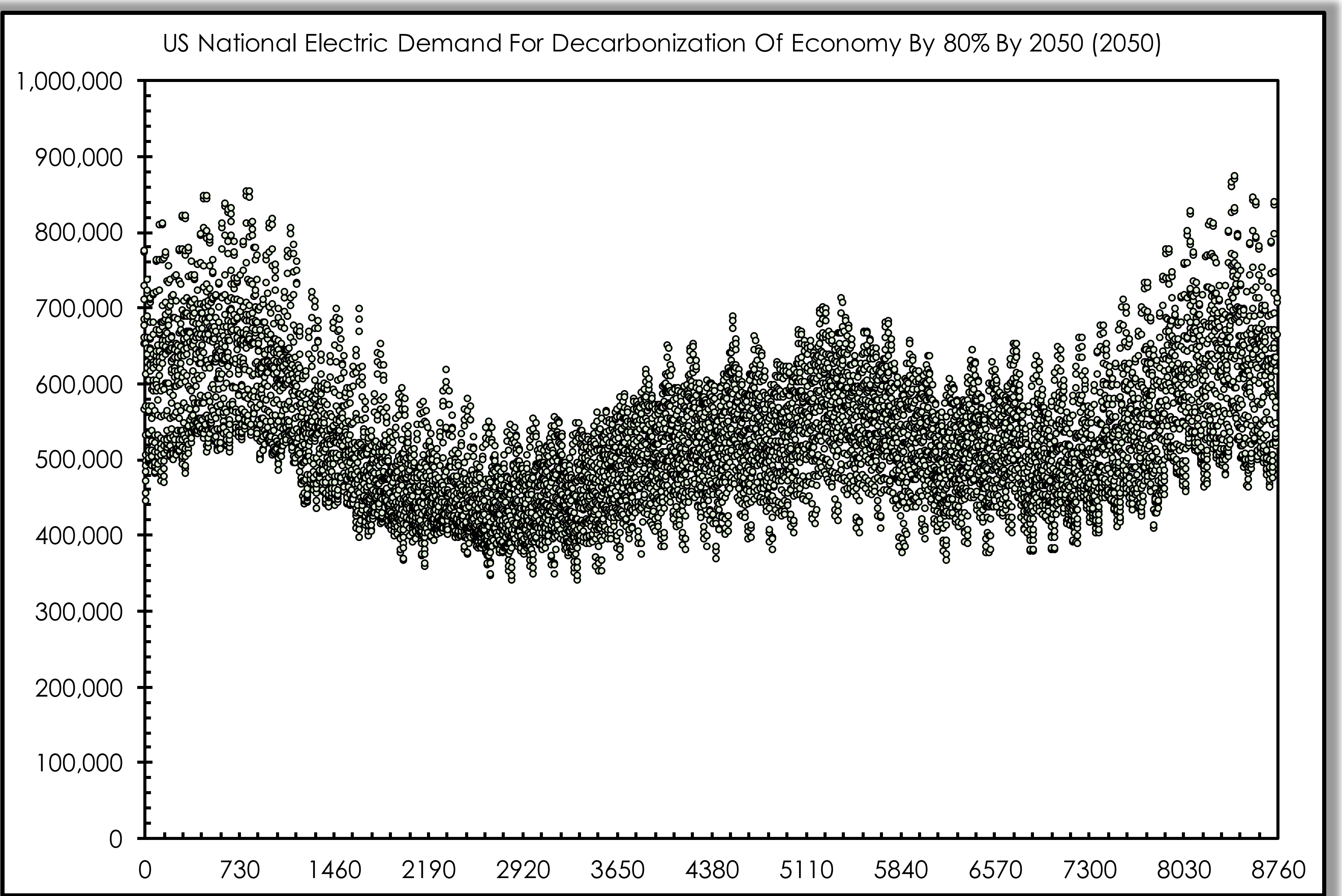
Load Initialization & Forecasts



Baseload generation is no longer a necessity

As long as generation is produced when needed, the source does not matter

Can replace baseload generation with ***a combination of***:

- ✓ Natural Gas flexible generation,
- ✓ Wind,
- ✓ Solar,
- ✓ Storage,
- ✓ Demand Side Management,
- ✓ Distributed Resources,
- ✓ Electrification of Heating & Transportation,
- ✓ Transmission Exchanges,
- ✓ Energy Efficiency.

NOTE: All these resources are modular, and allow trajectory correction if pathway is not achieving the desired goals.

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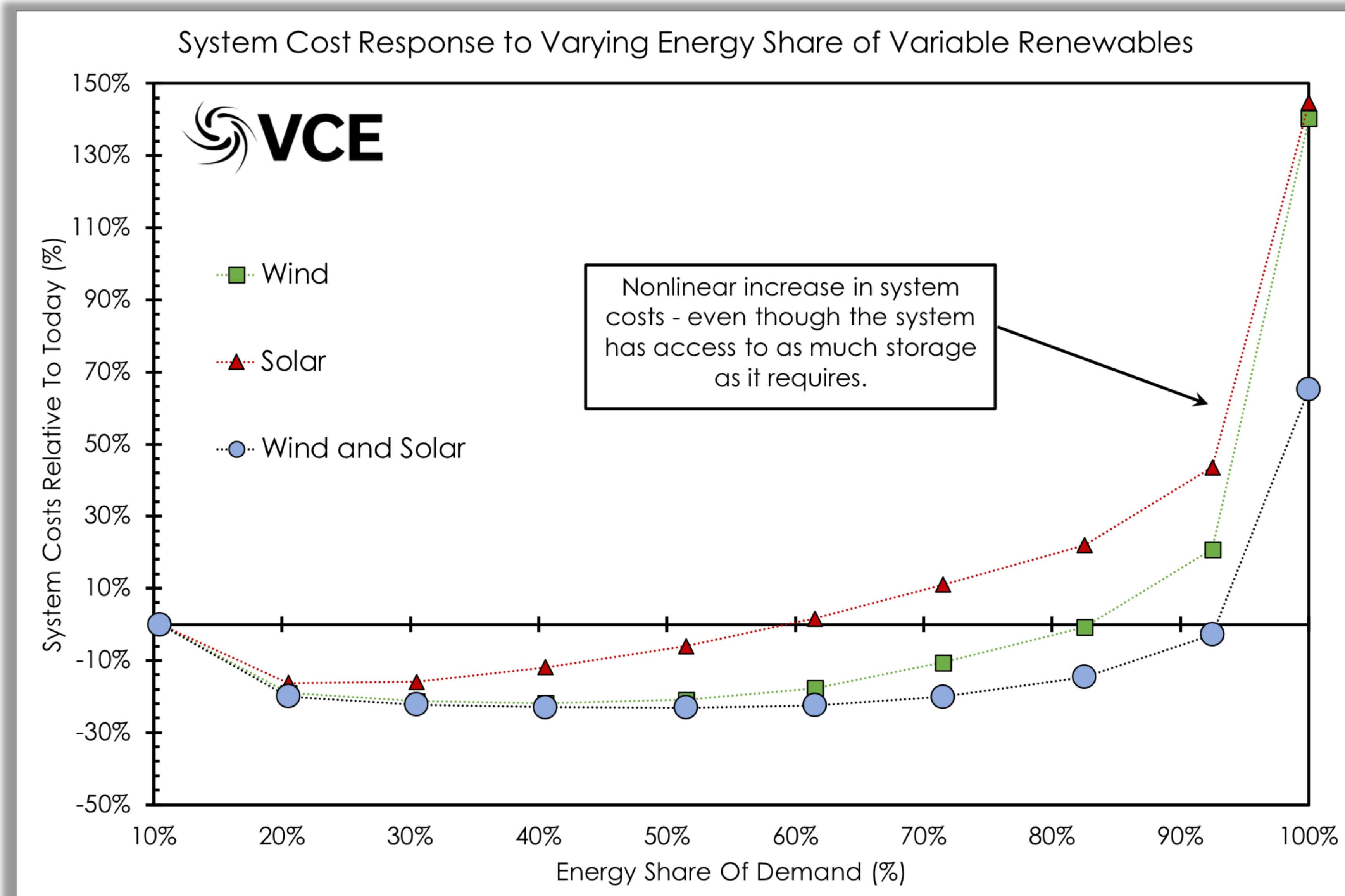
But, beware of utopian WWS solutions



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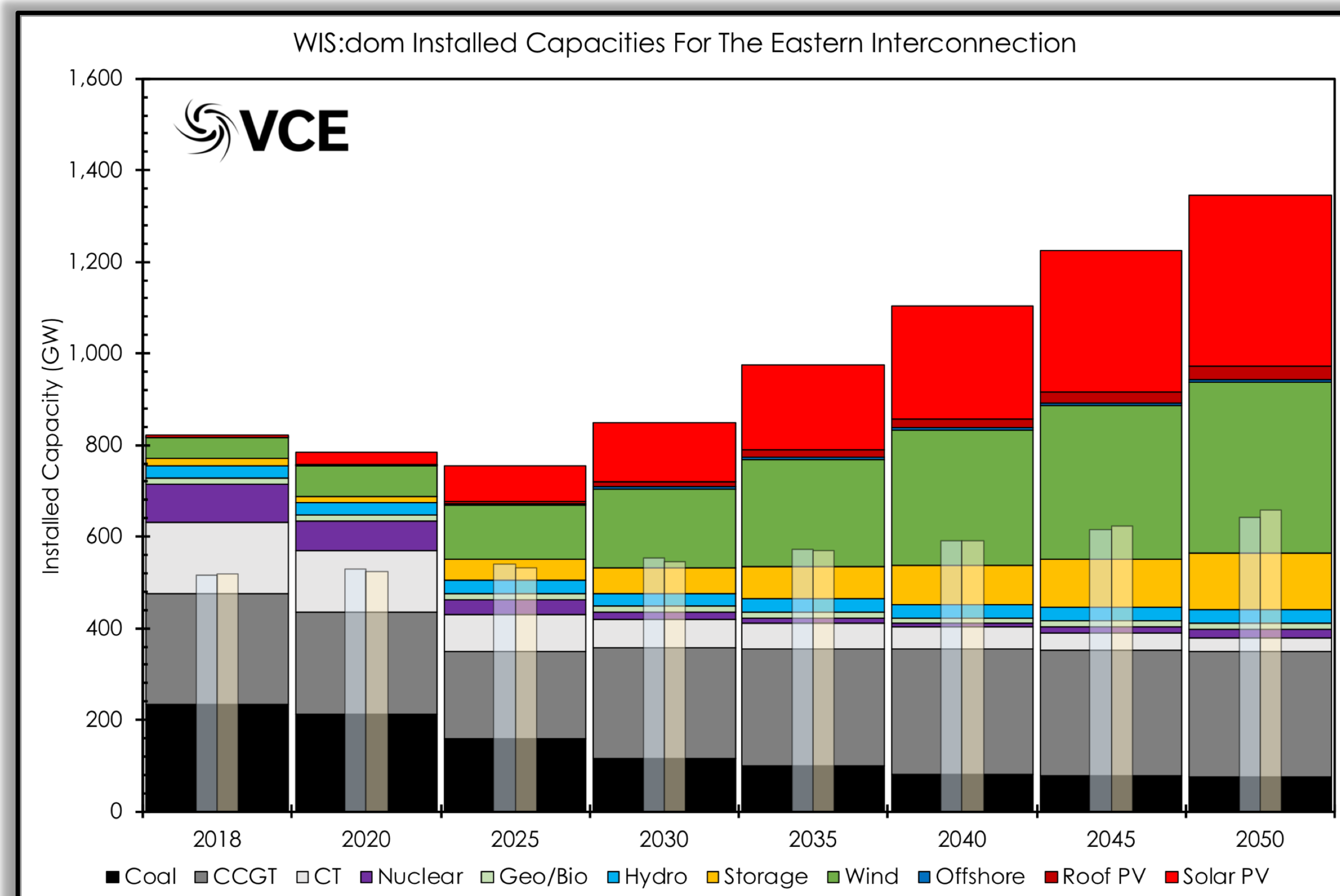
What About Some Results?

Eastern Interconnection Transition

Eastern Interconnection Installed Capacity



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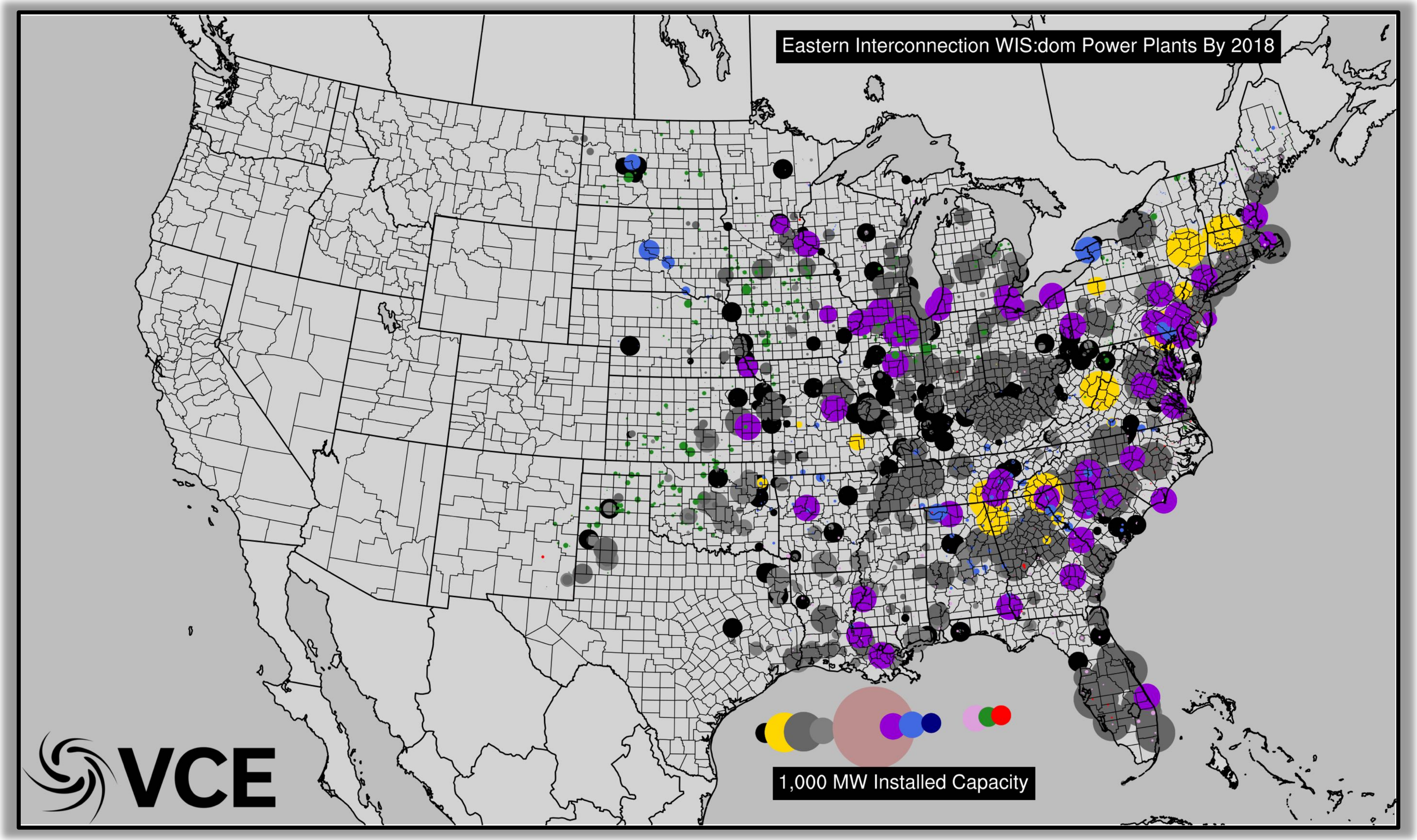
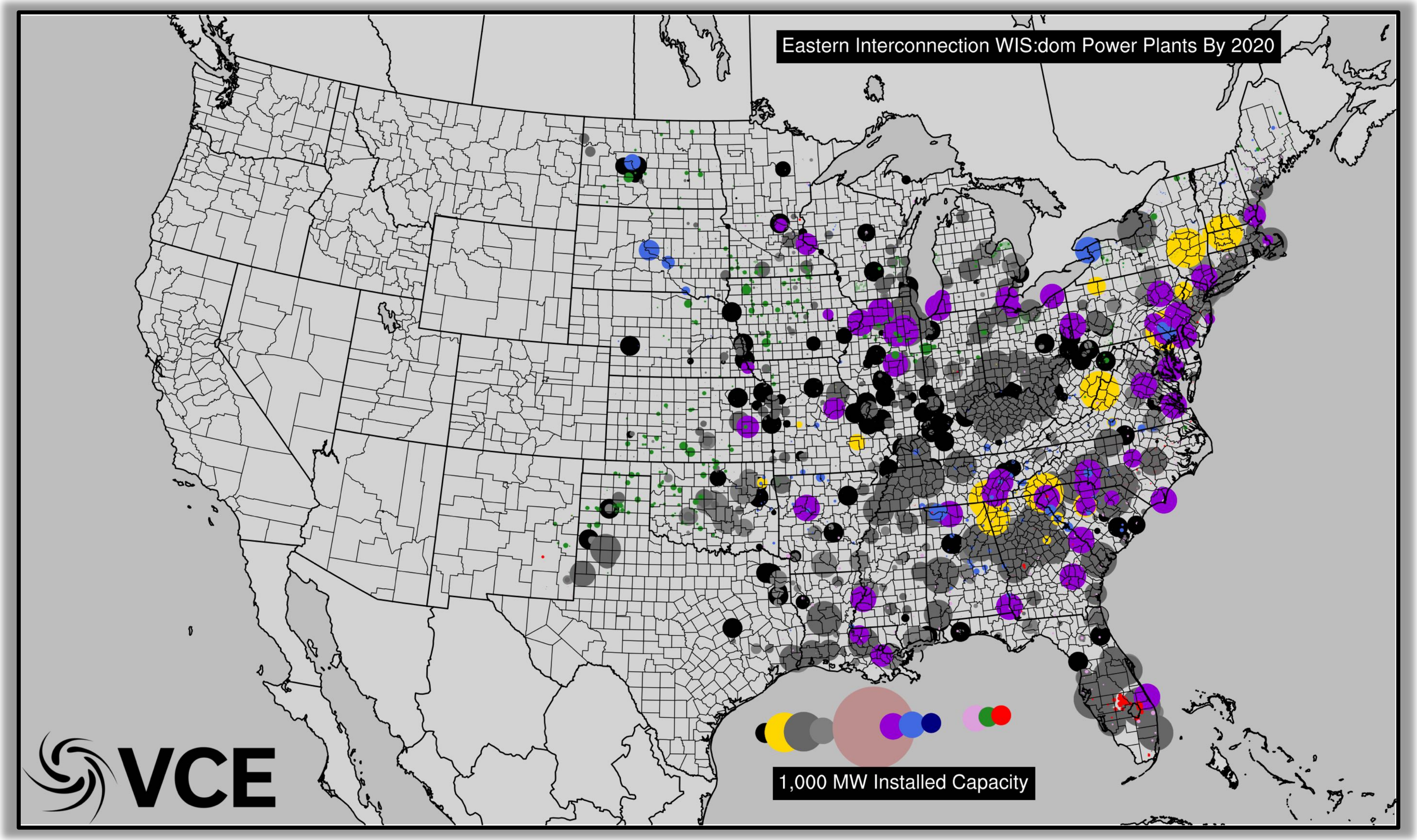
Installed Capacity (Geographic)



Installed Capacity (Geographic)



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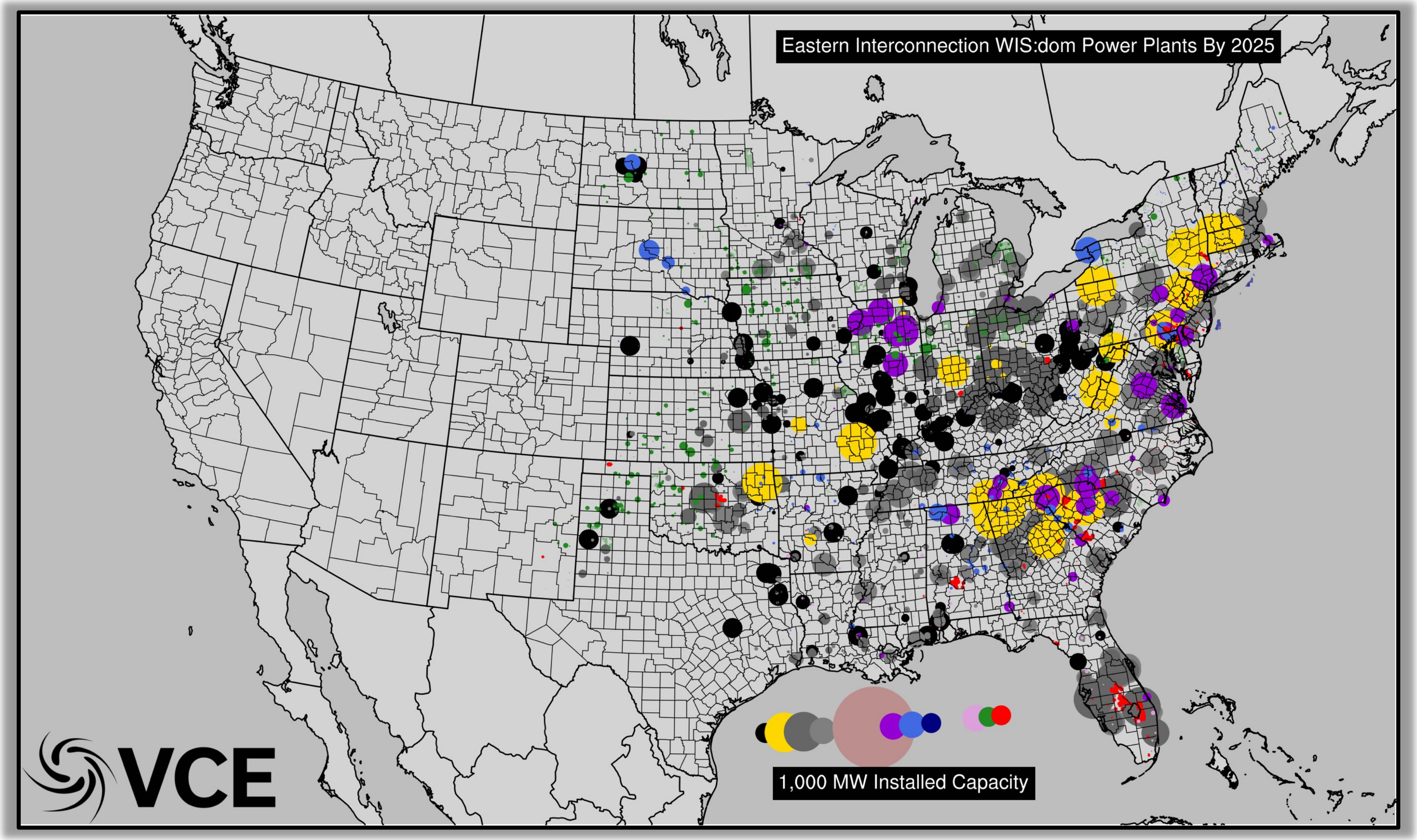

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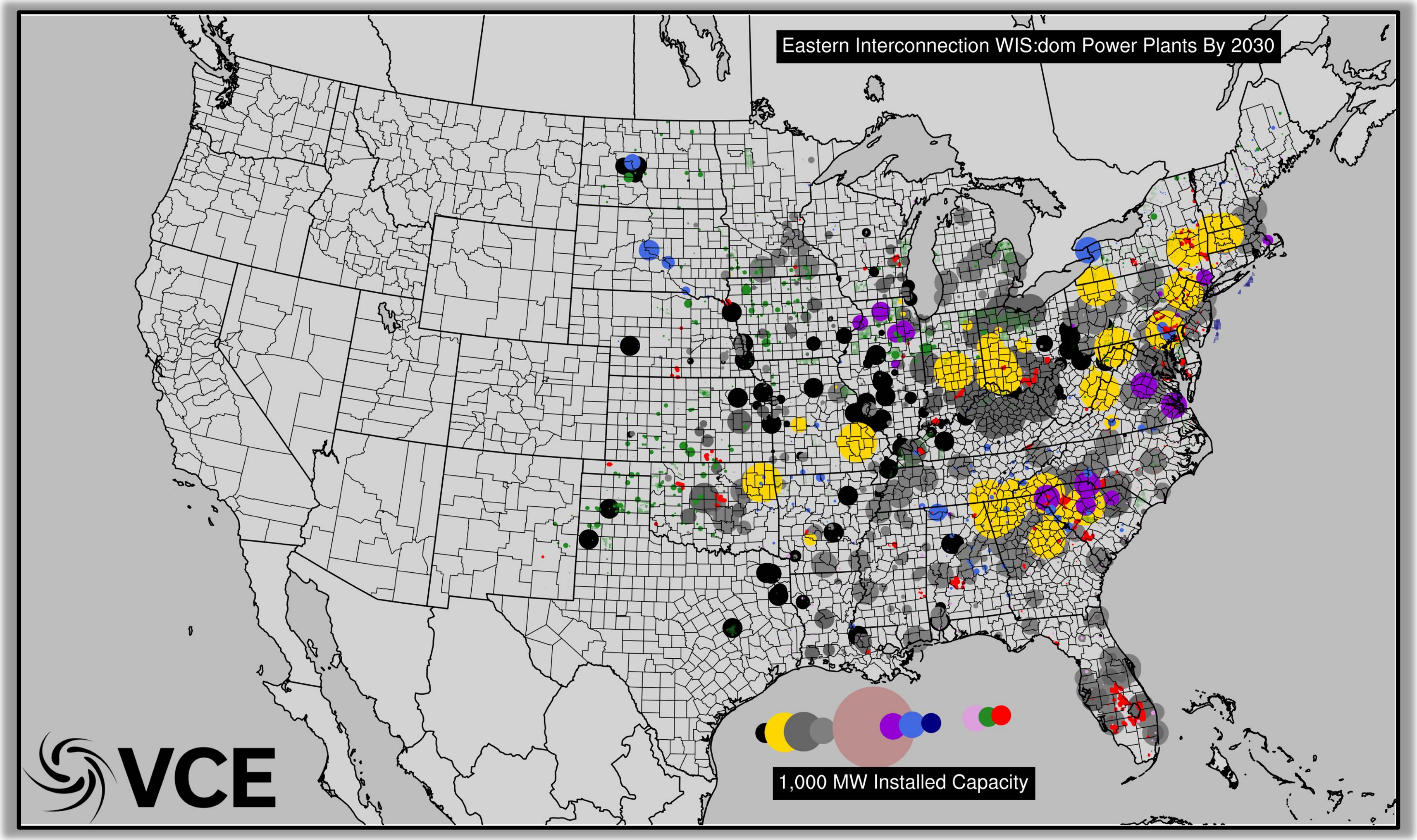

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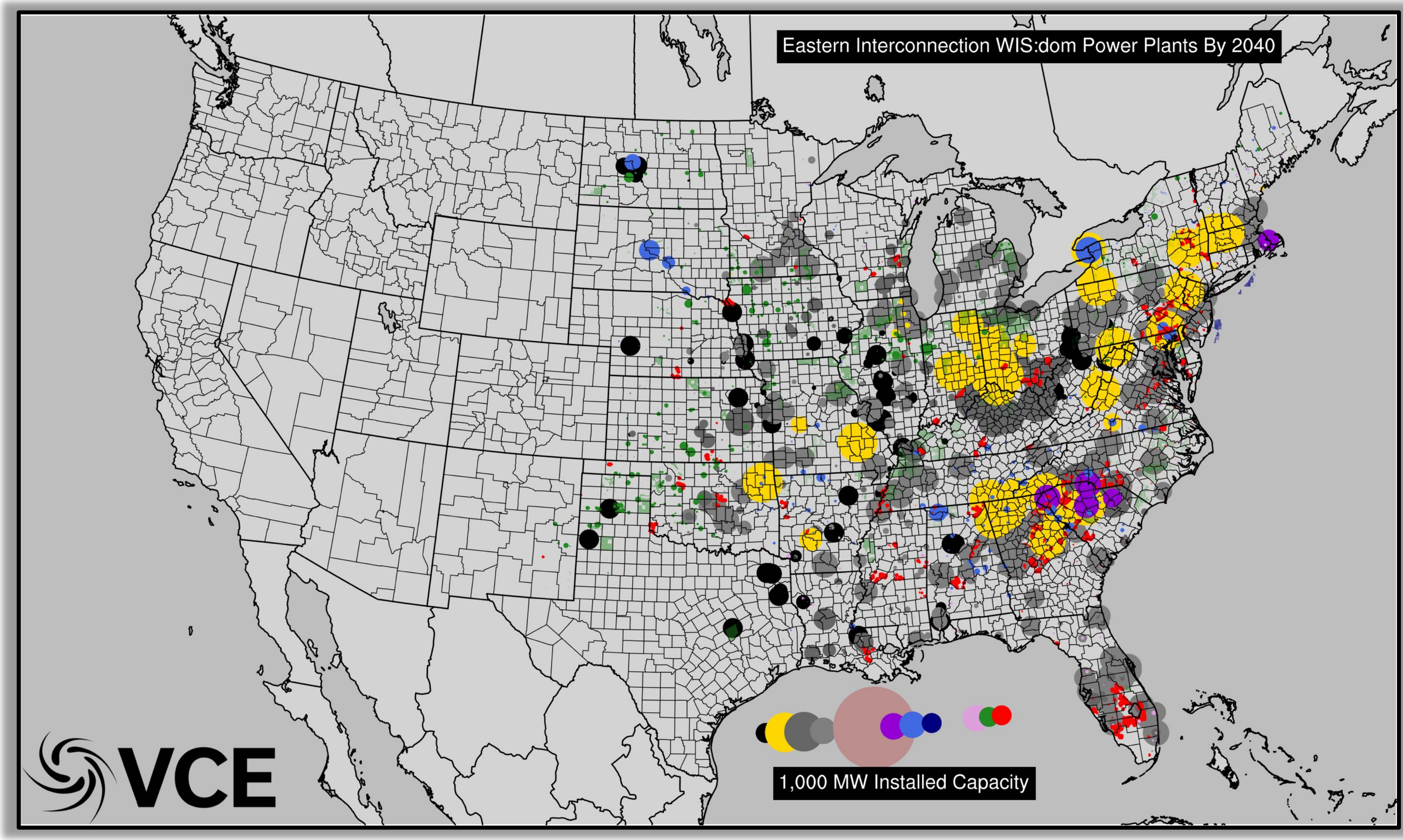

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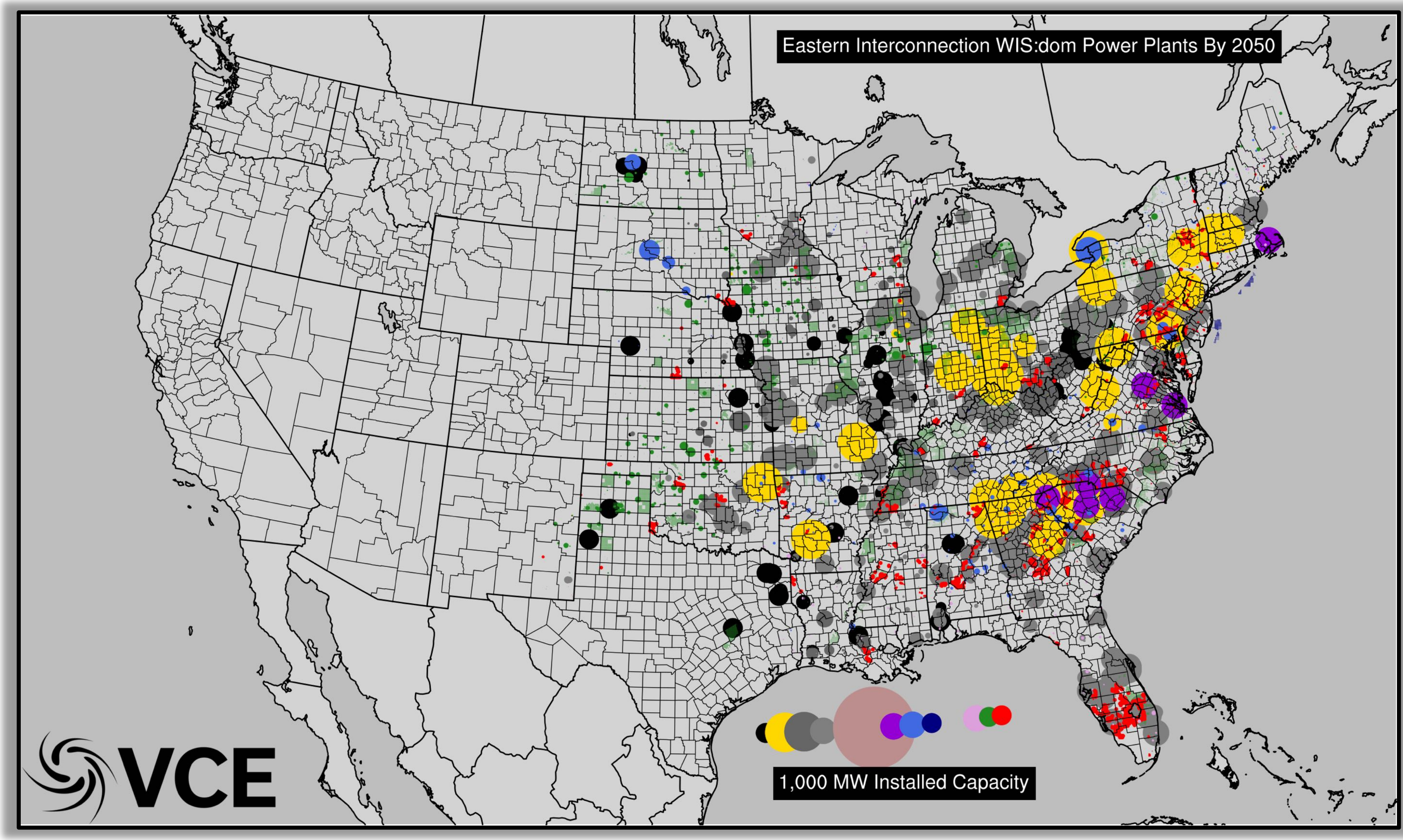
Installed Capacity (Geographic)



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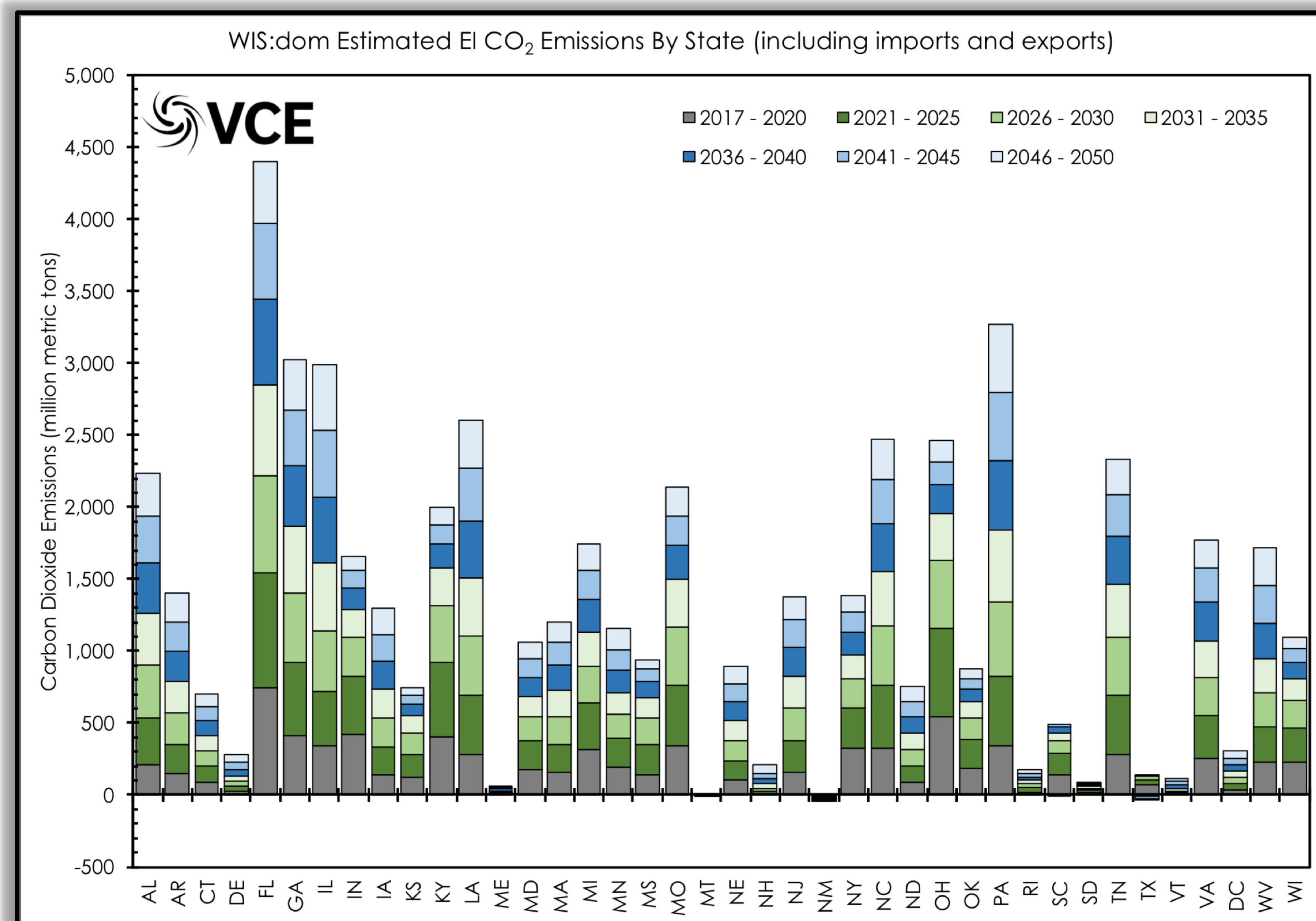
Cumulative Emissions By State



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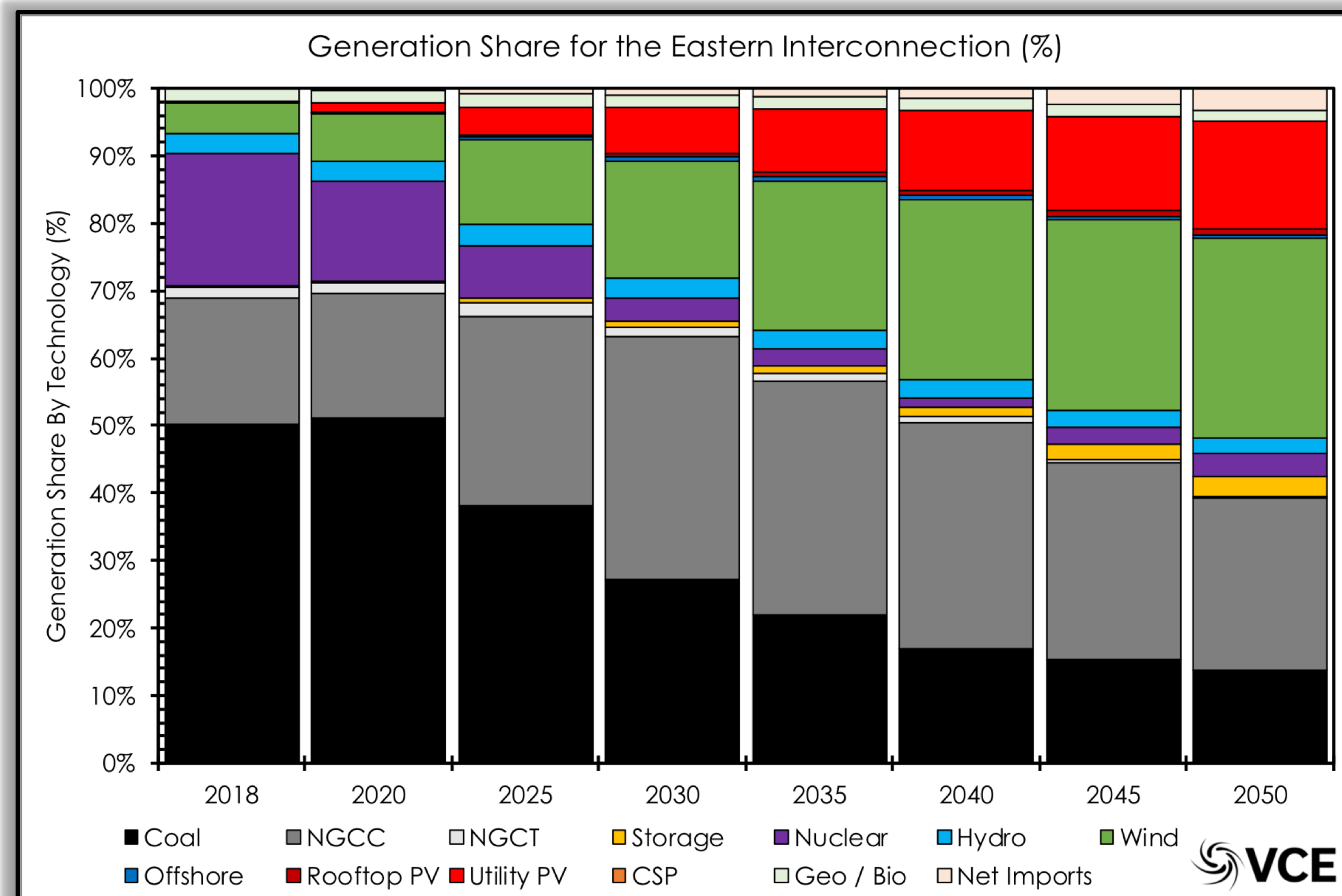
Generation Share For Eastern Interconnection



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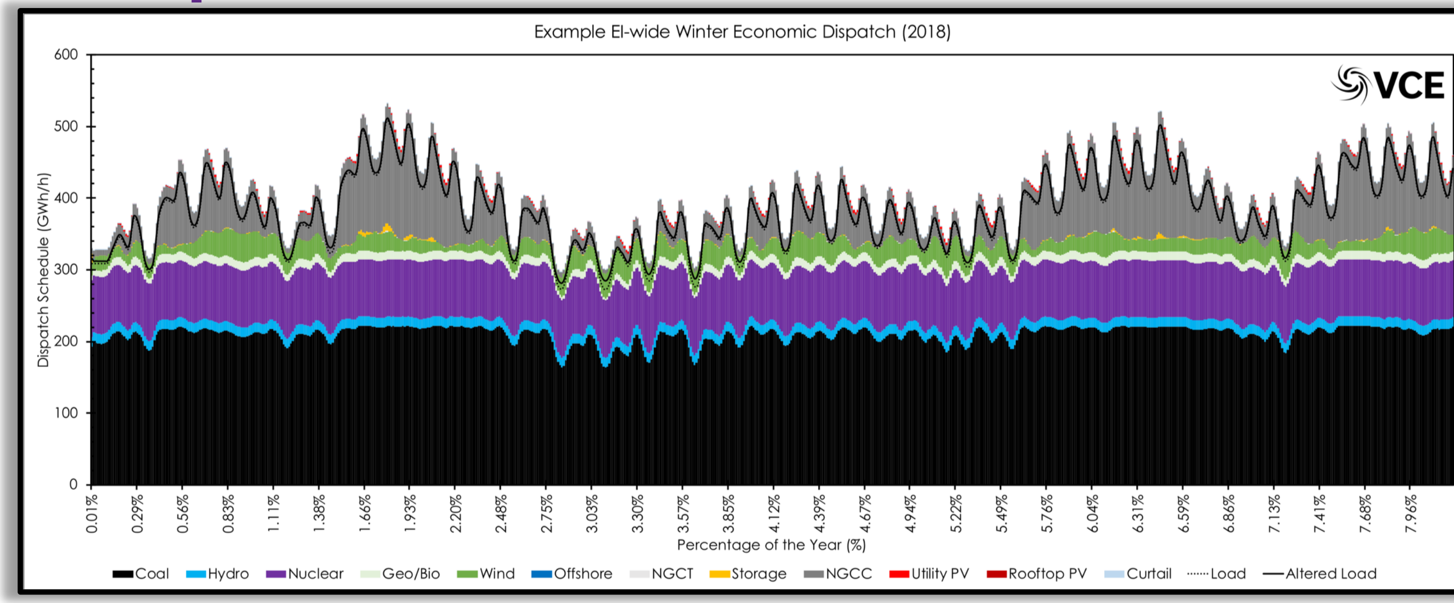
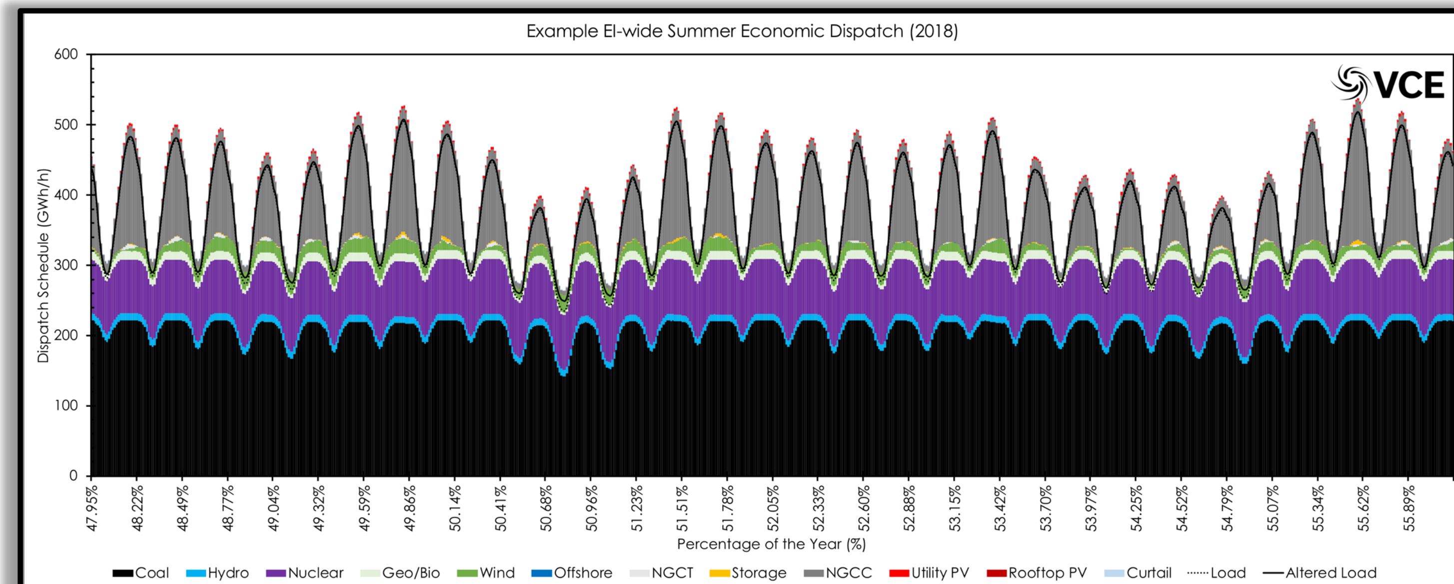
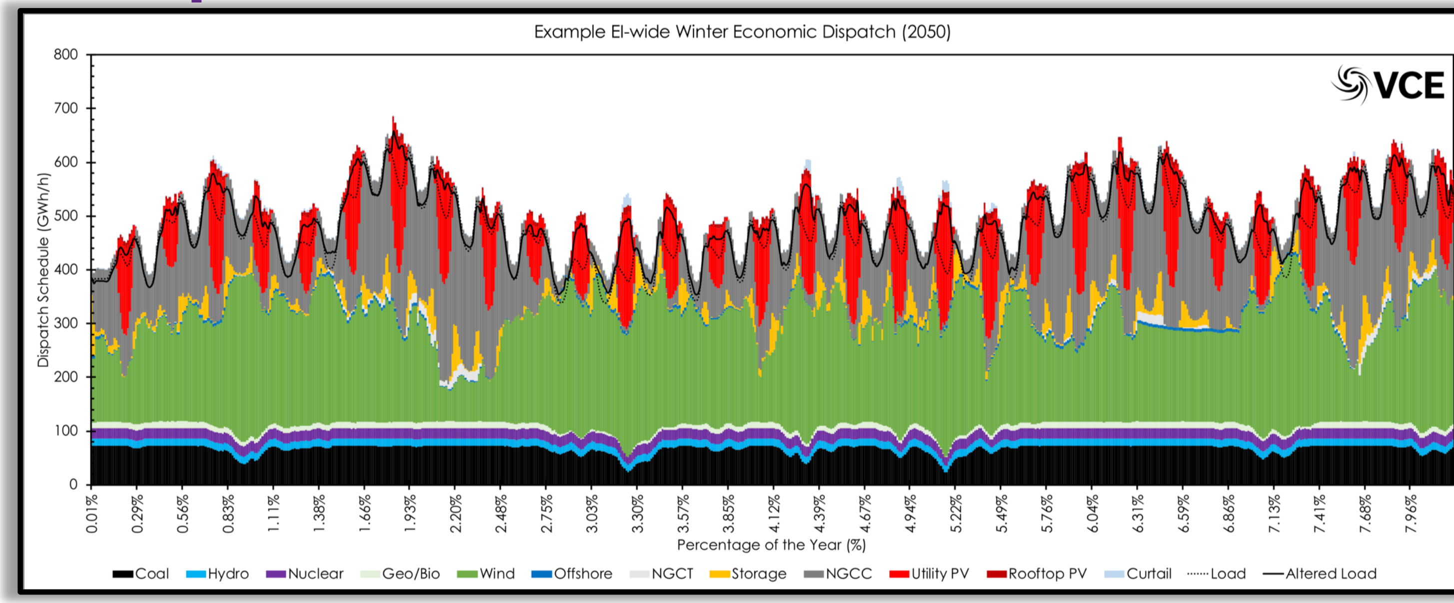
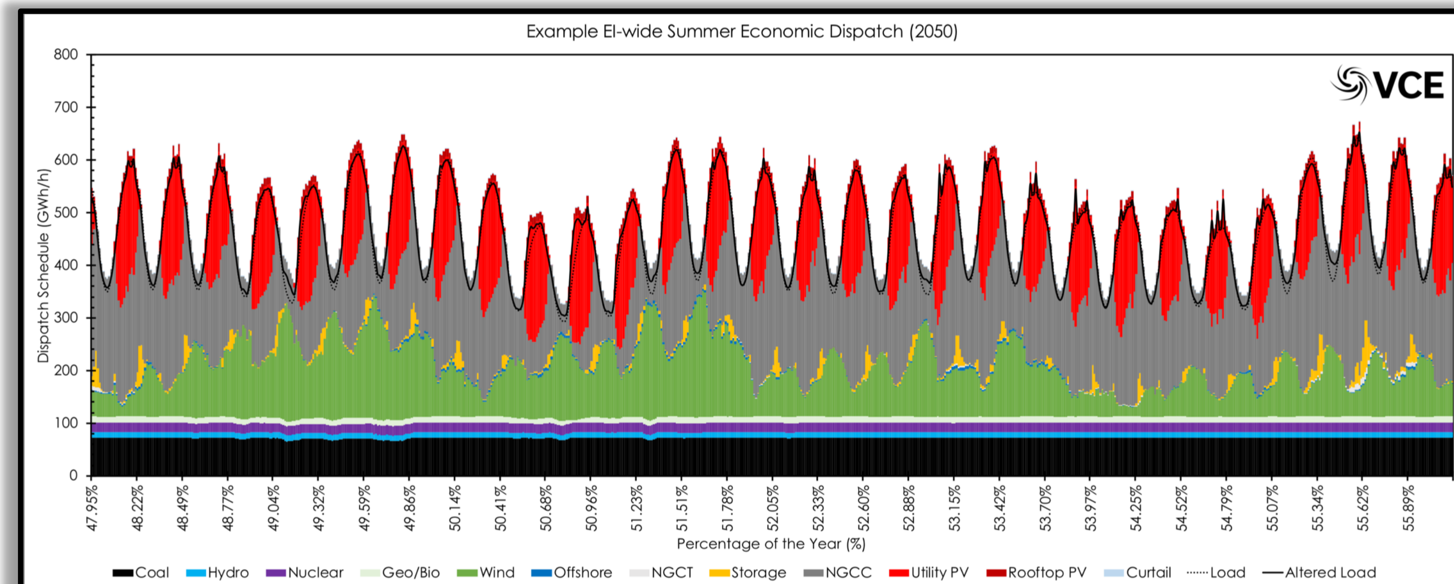
Dispatch For Eastern Interconnection





Dispatch For Eastern Interconnection





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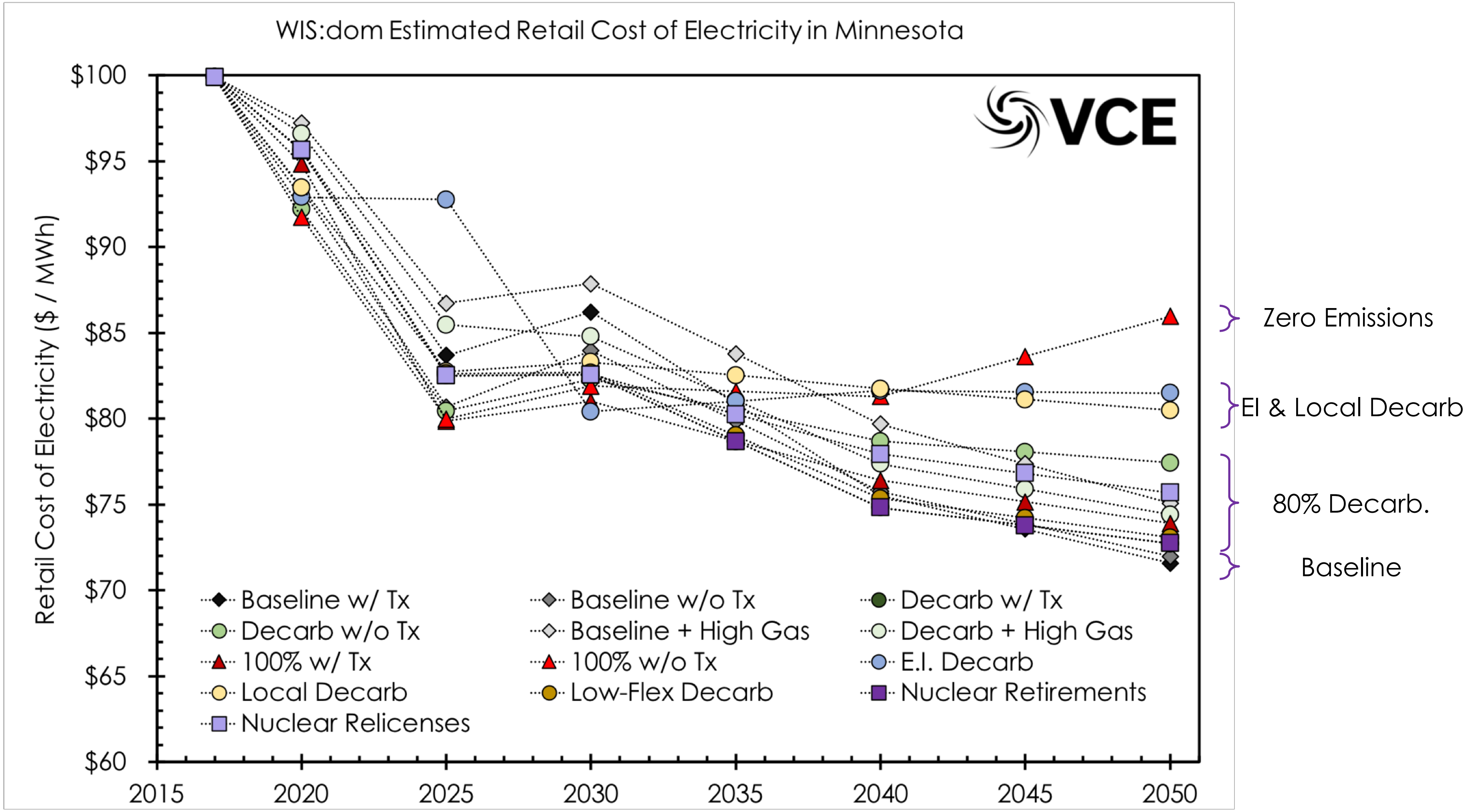
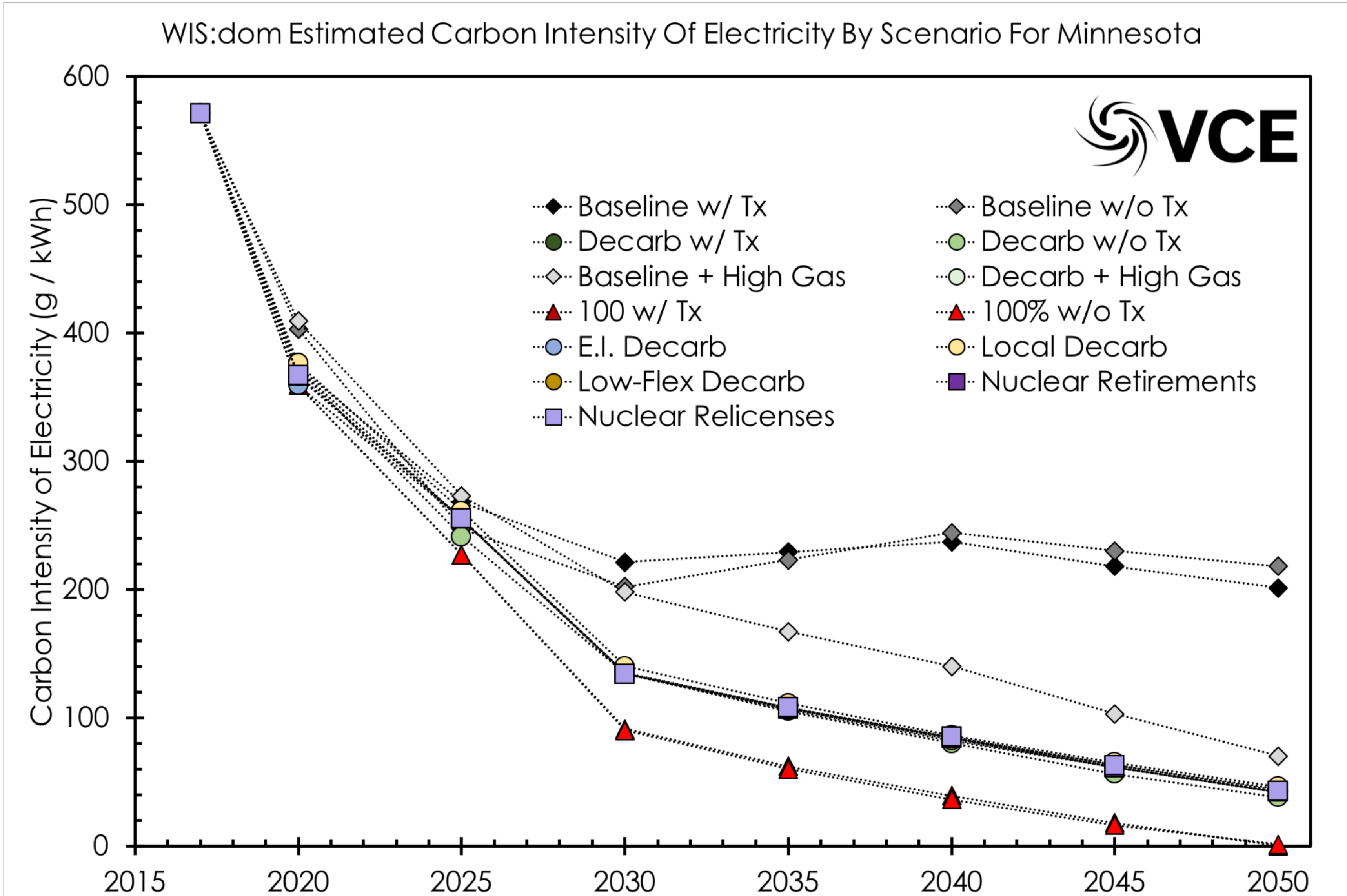
Minnesota's Smarter Grid

Retail Cost of Electricity By Scenario



Decarbonization Becomes Clear After 2020



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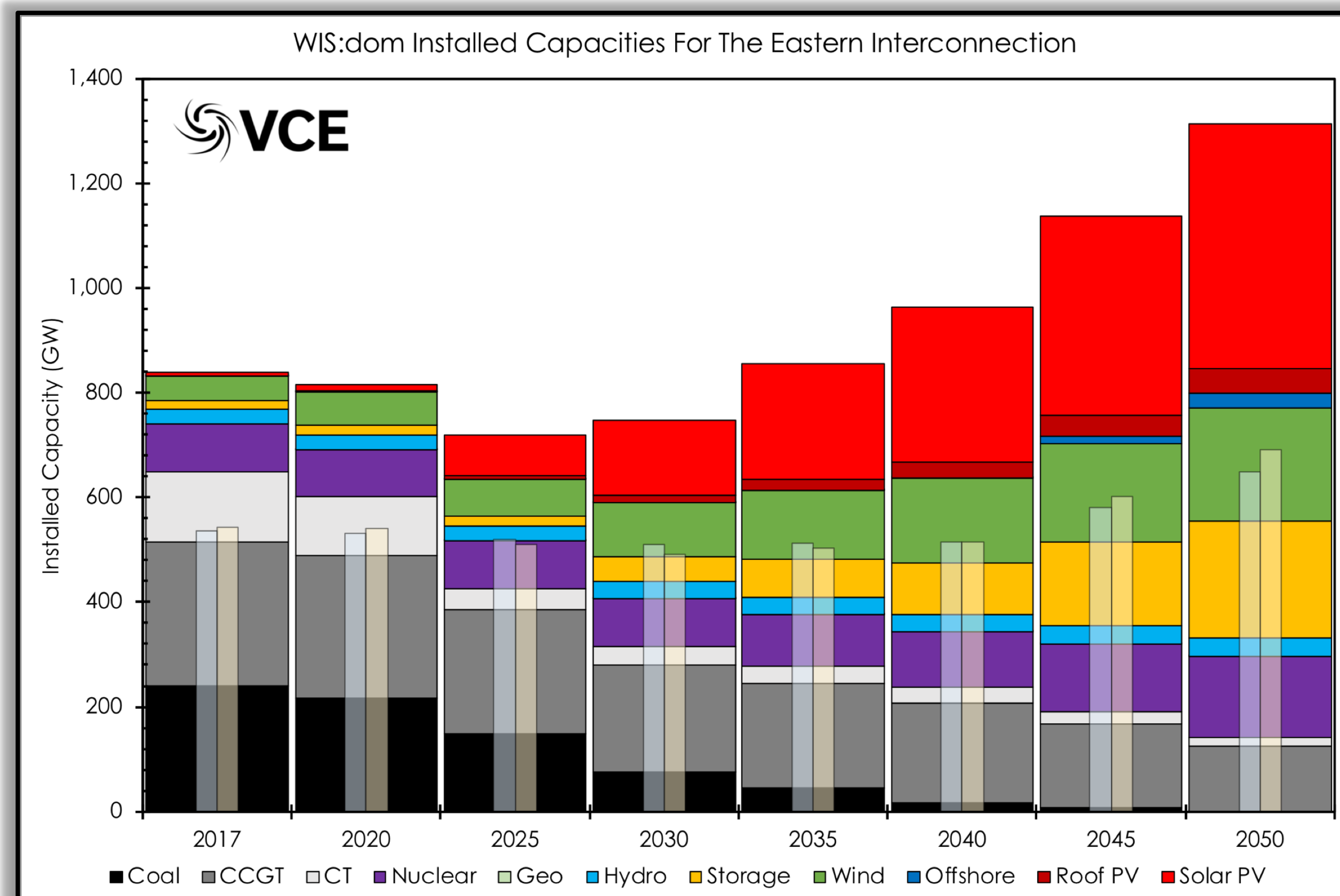
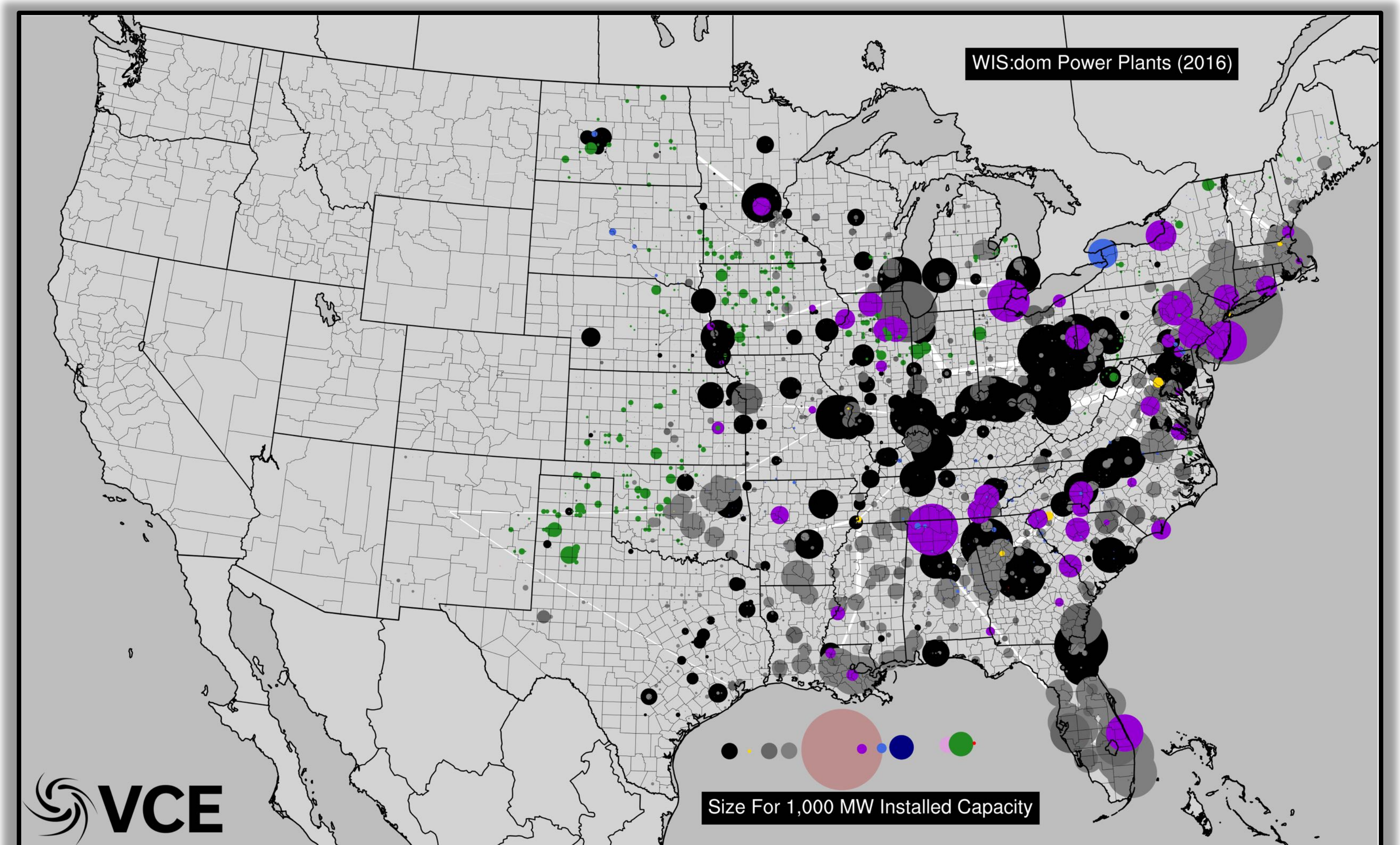
Eastern Interconnection Installed Capacity



Installed Capacity (Geographic)



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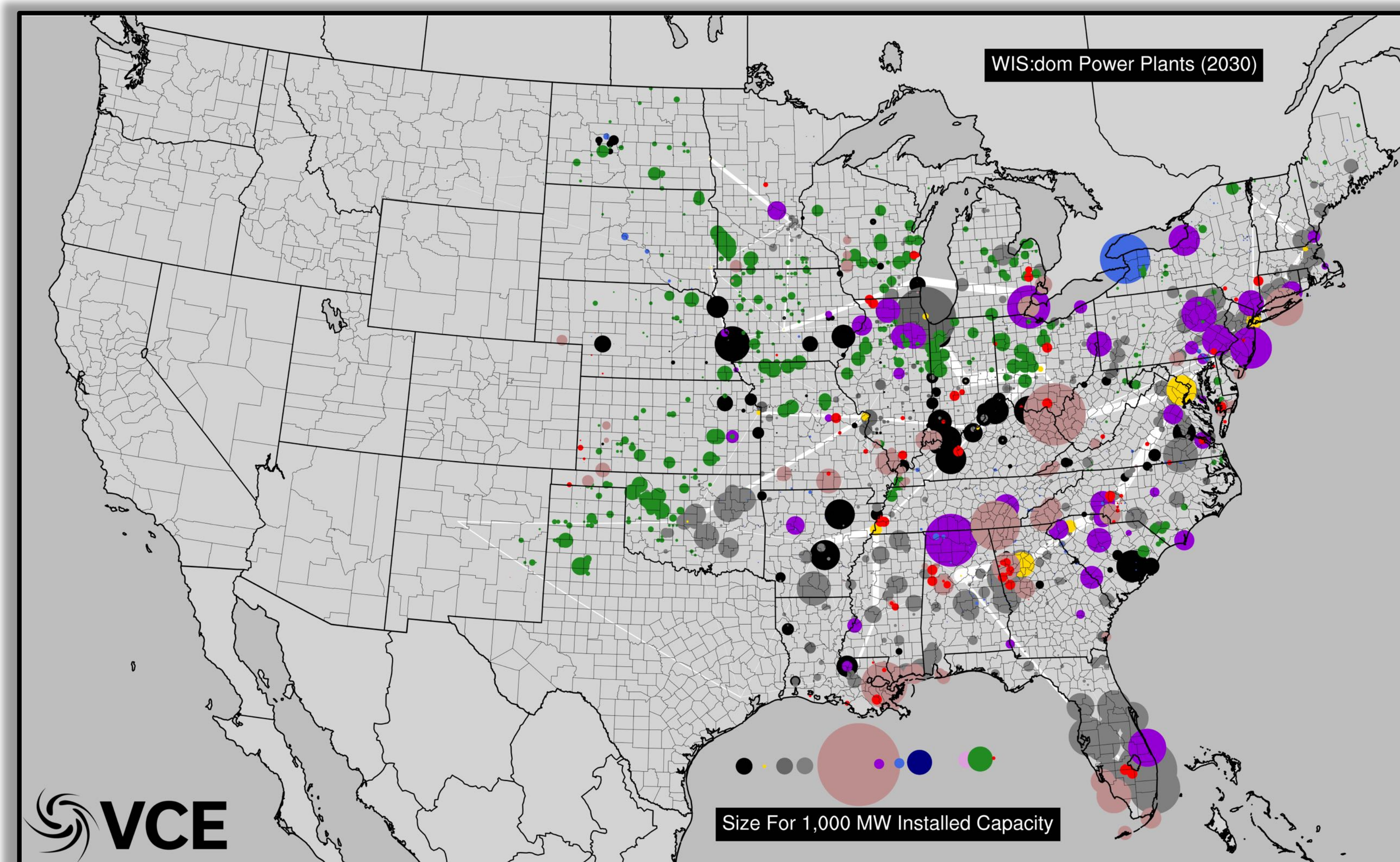
Installed Capacity (Geographic)



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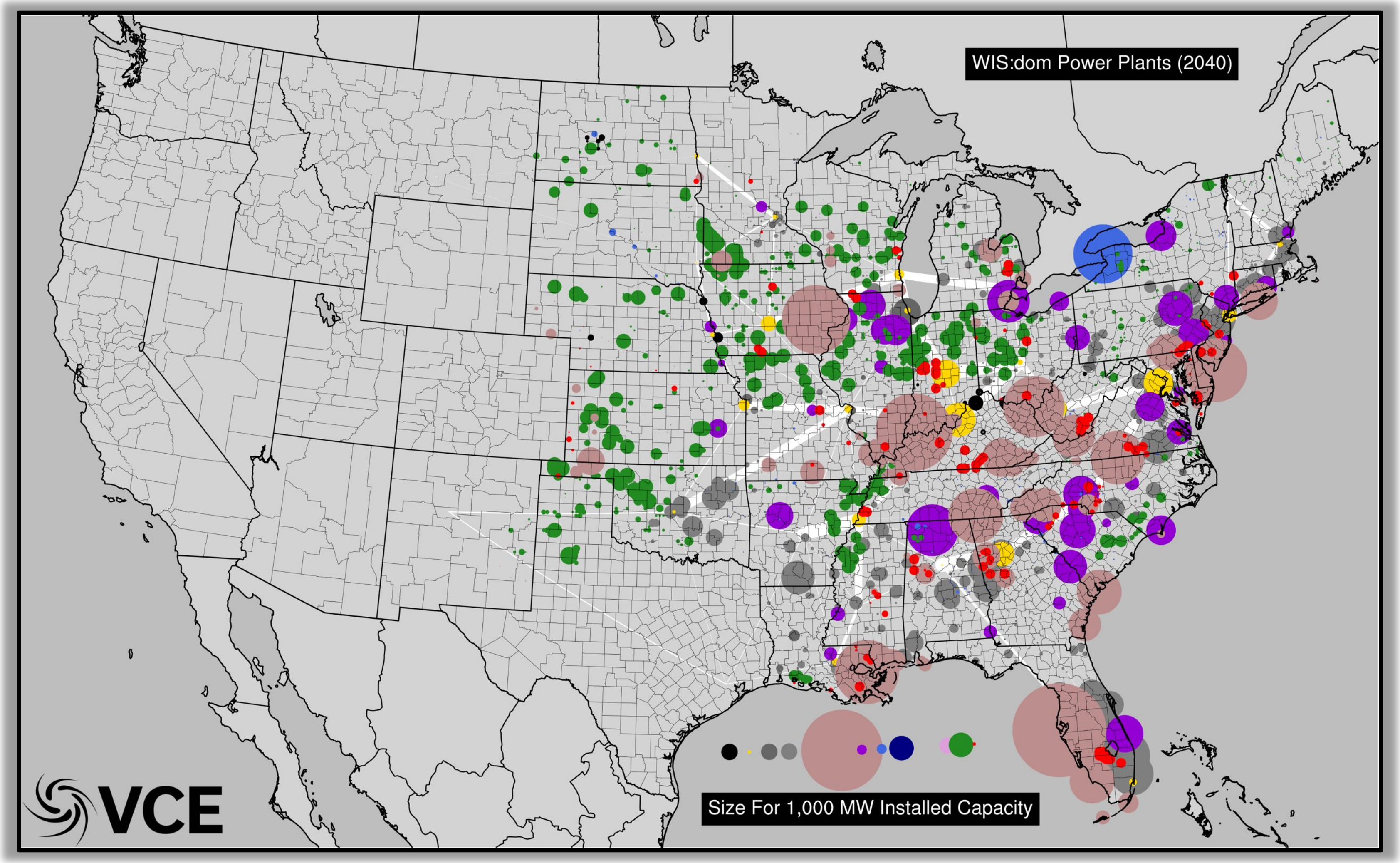
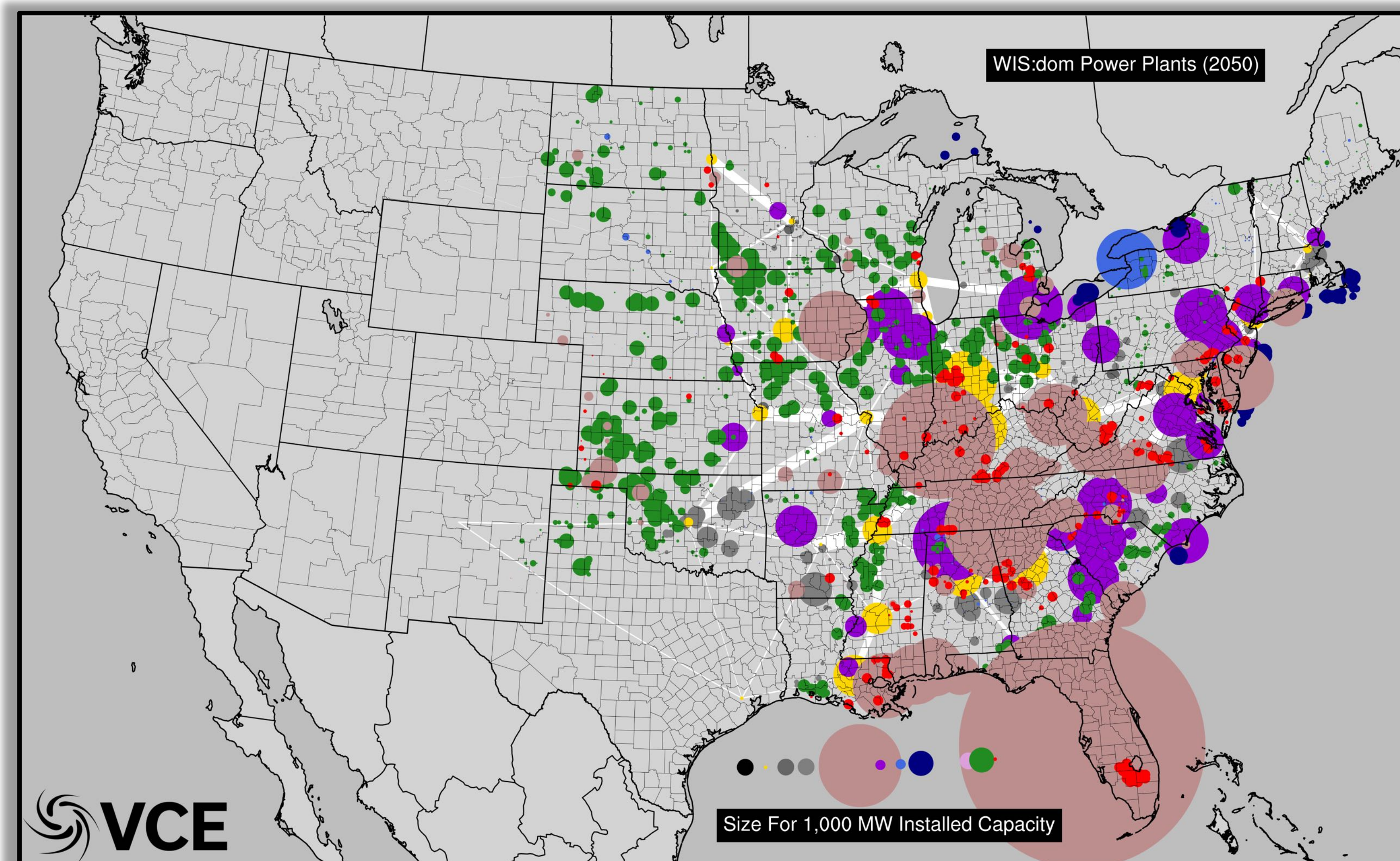
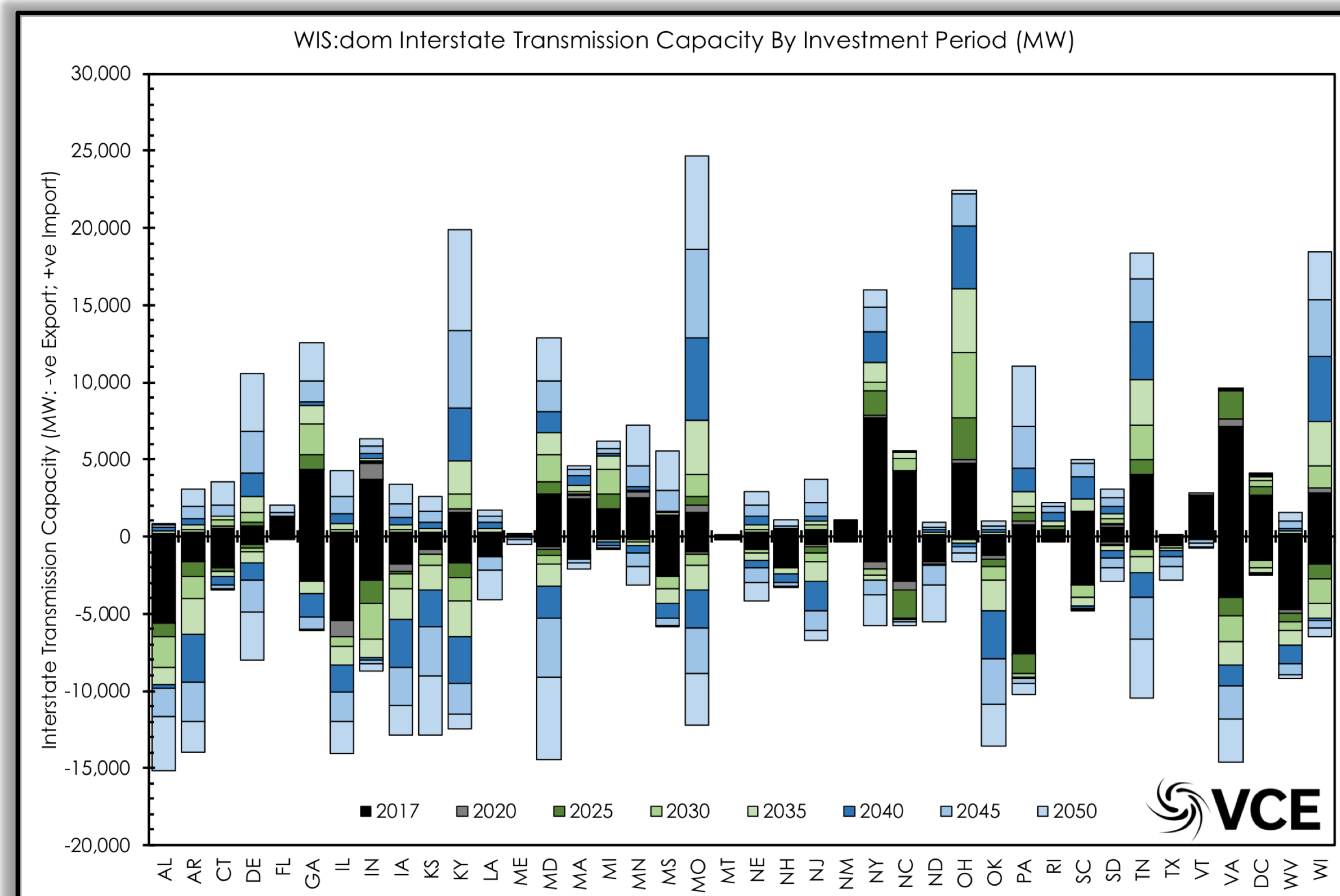
Installed Capacity (Geographic)



Installed Capacity (Geographic)



Installed Interstate Transmission Capacity



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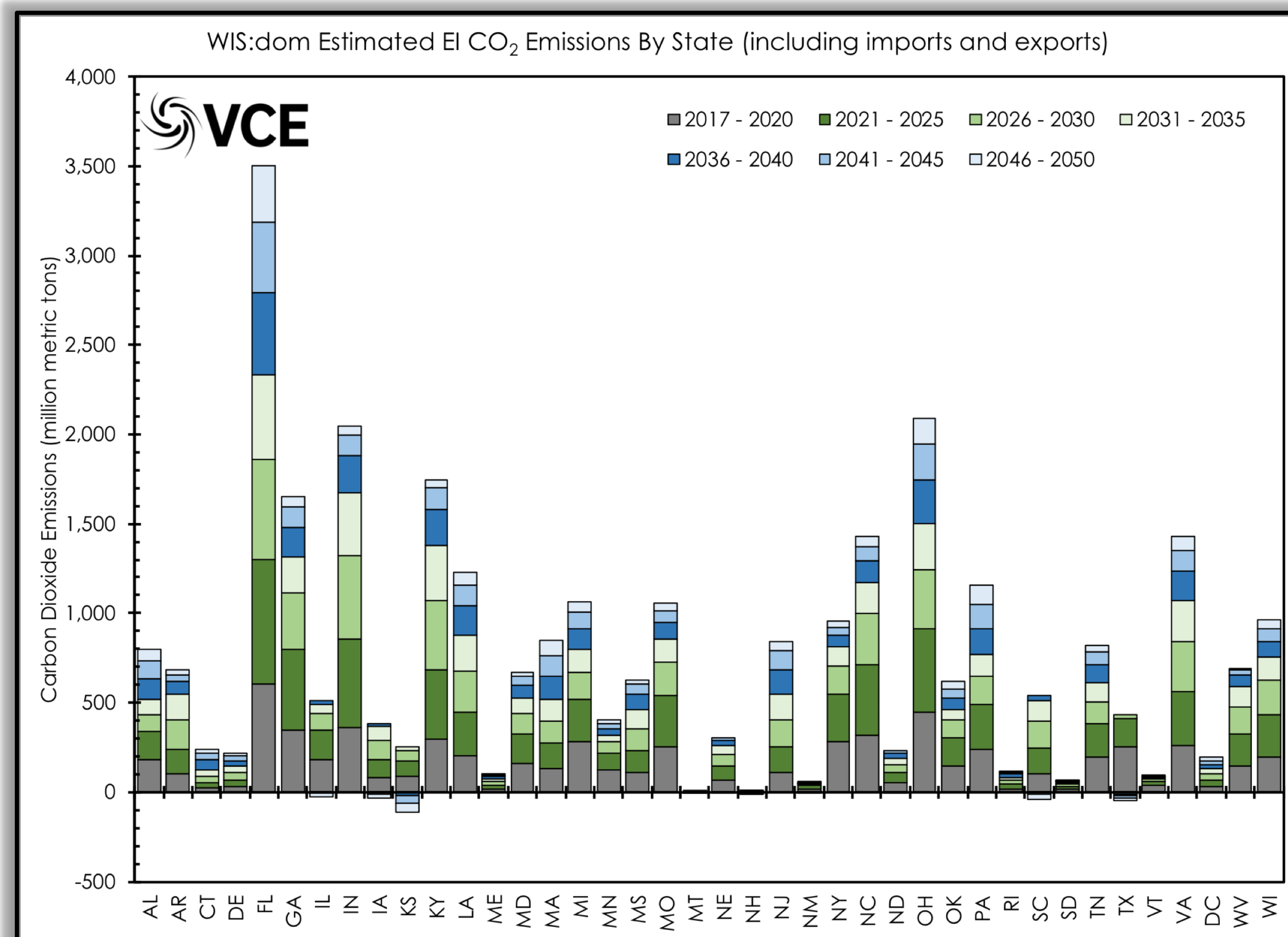
Cumulative Emissions By State



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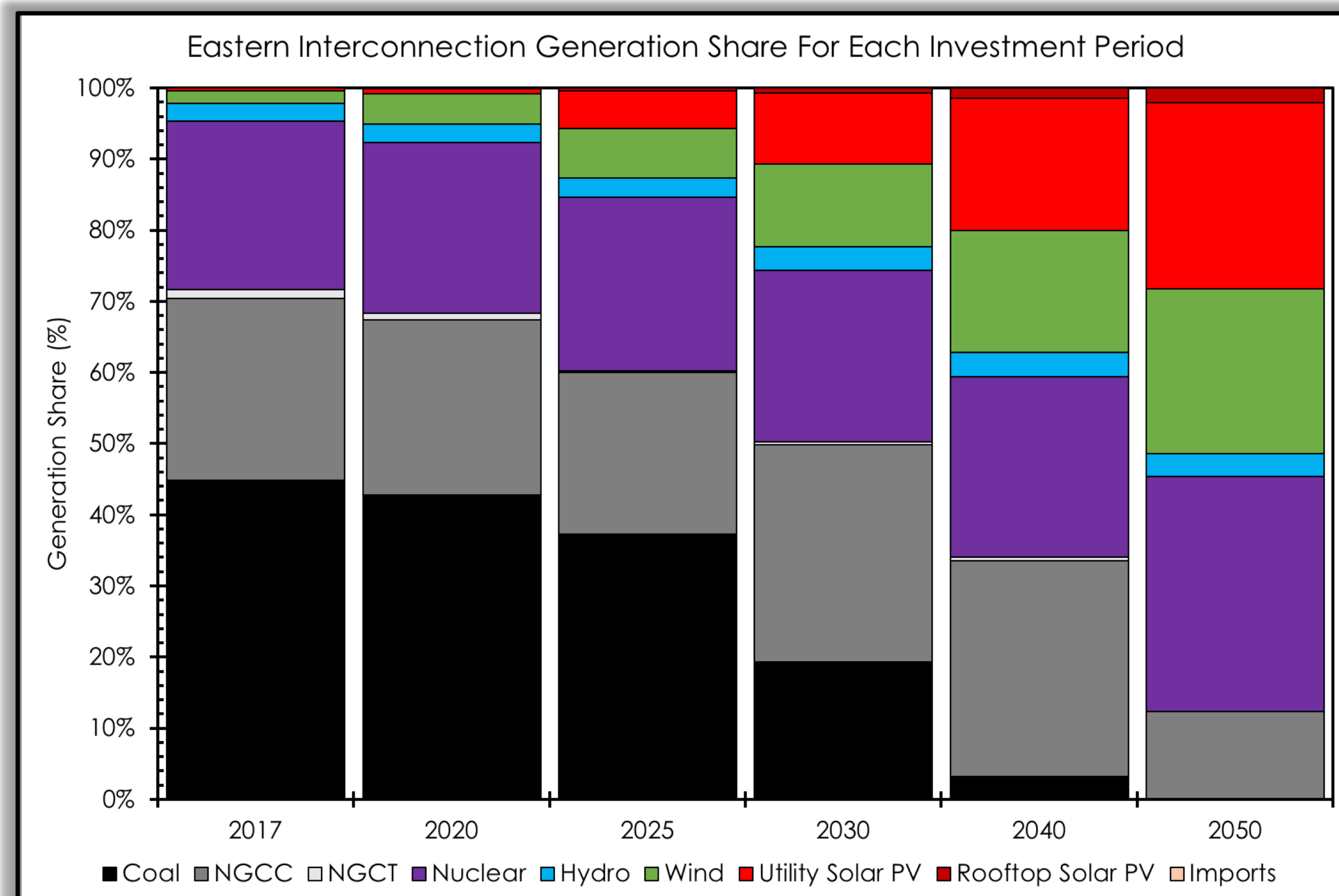
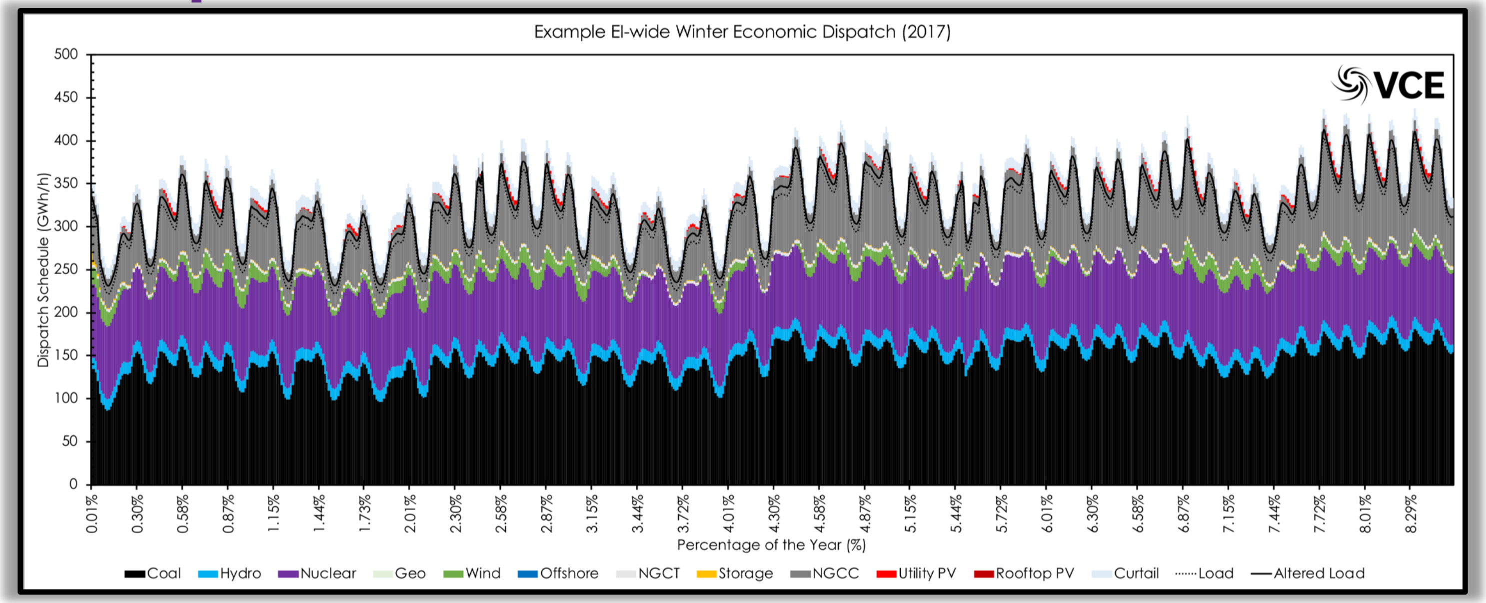
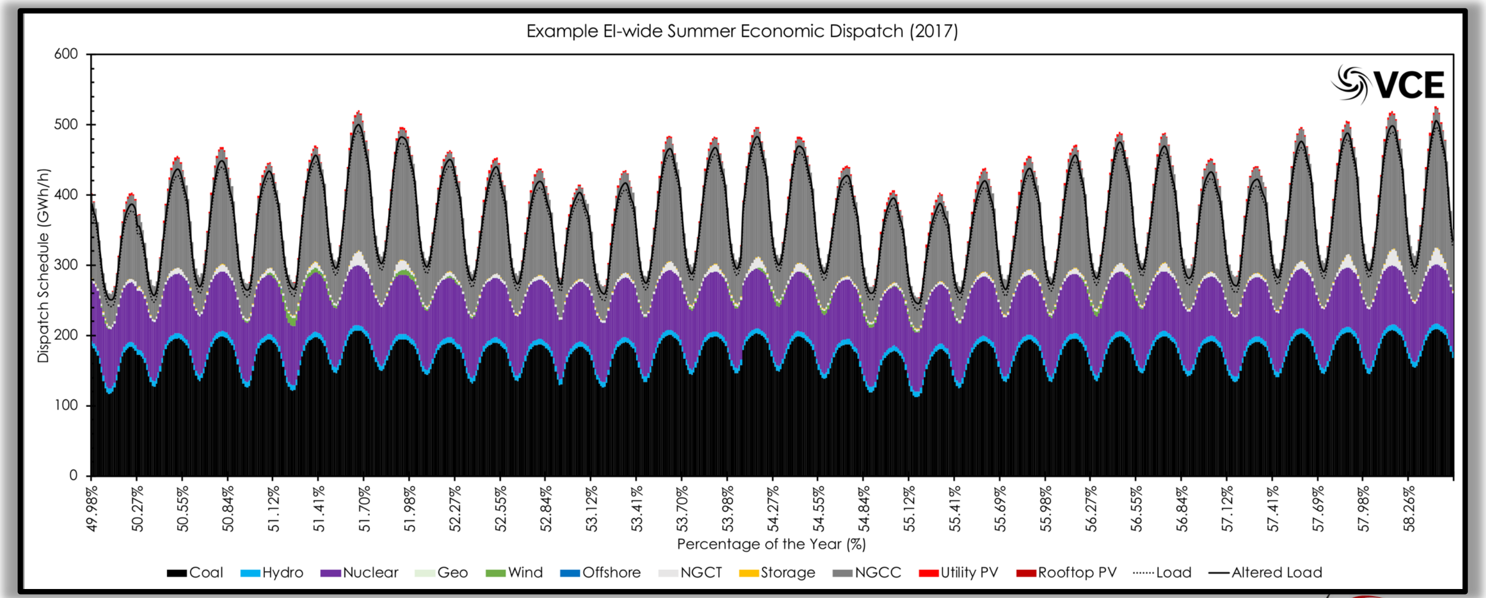
Generation Share For Eastern Interconnection



Dispatch For Eastern Interconnection





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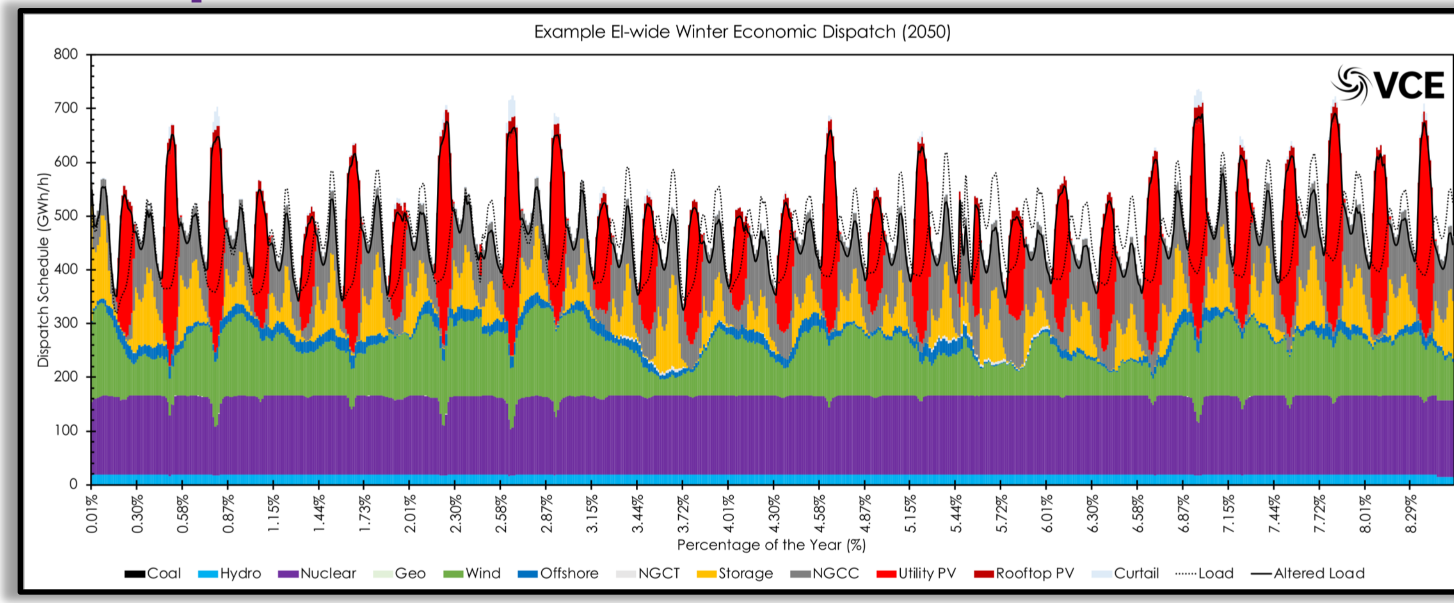
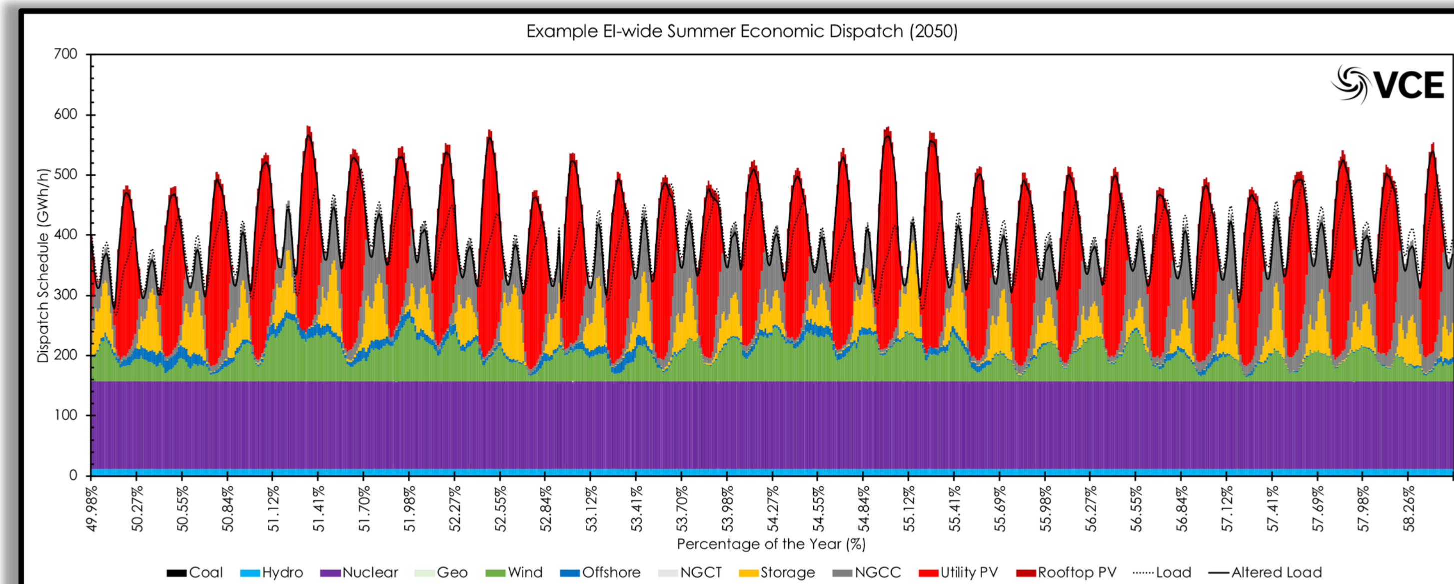
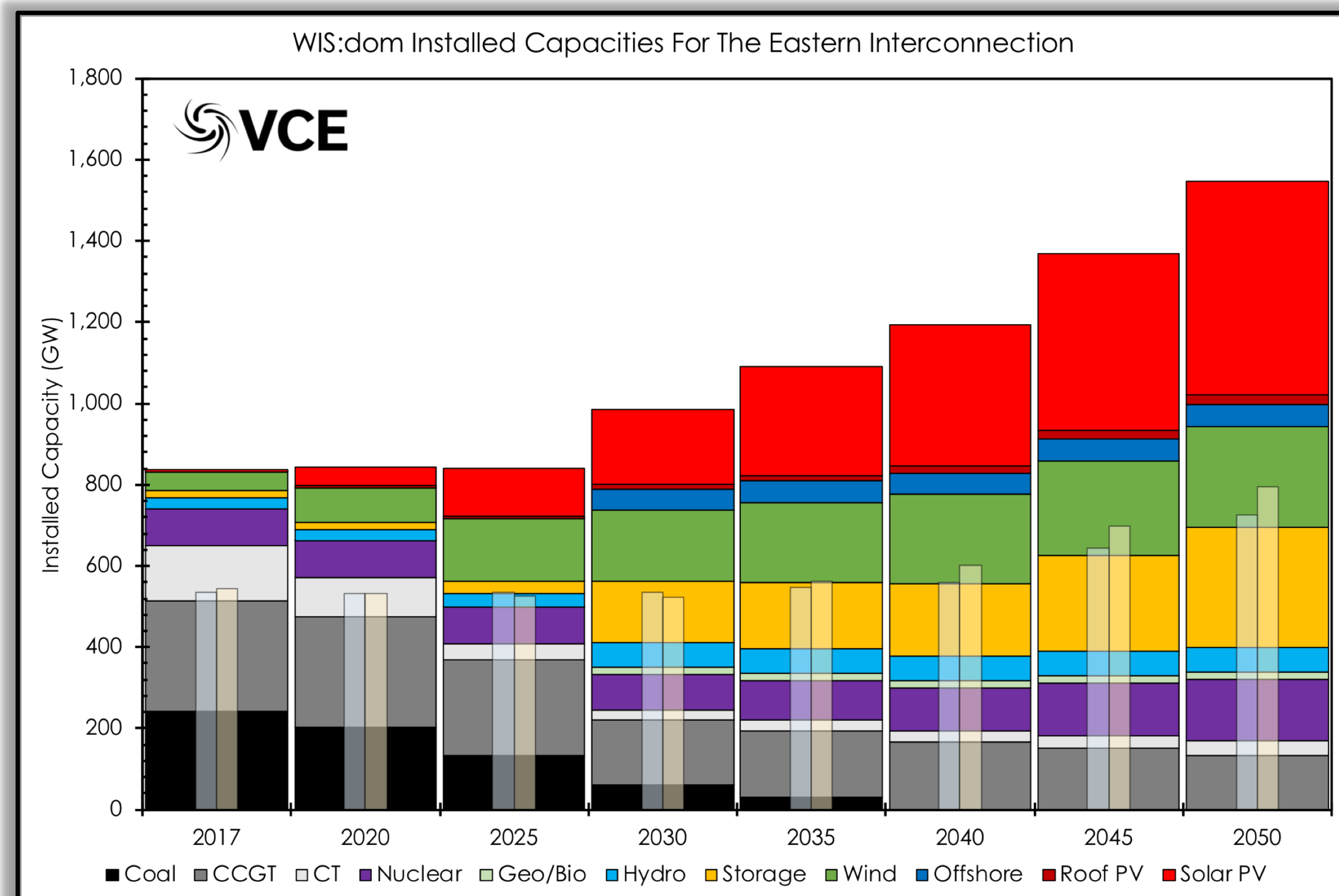
Dispatch For Eastern Interconnection





Eastern Interconnect Low-Carbon Grid

Eastern Interconnection Installed Capacity



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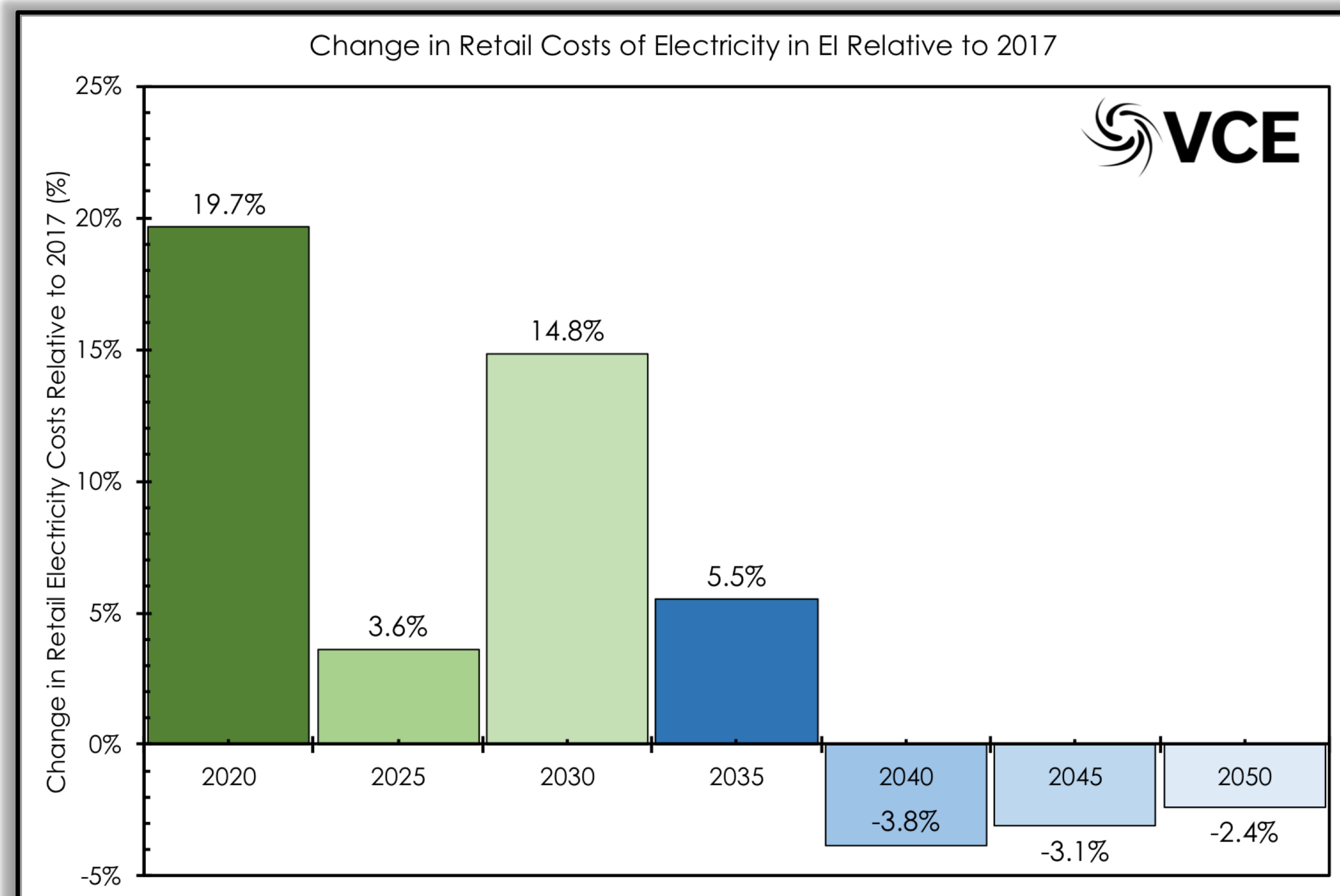
Eastern Interconnection Cost of Electricity



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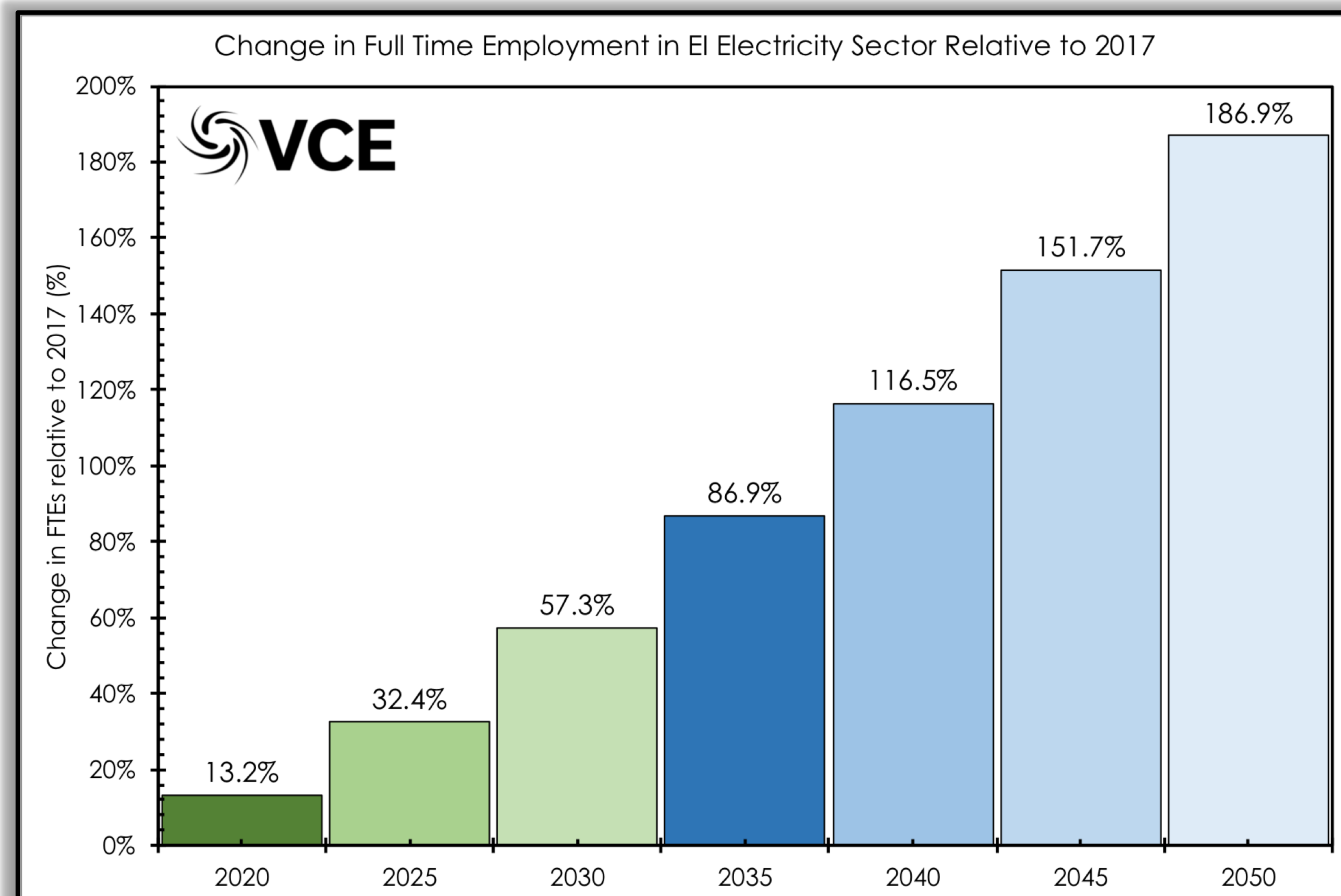
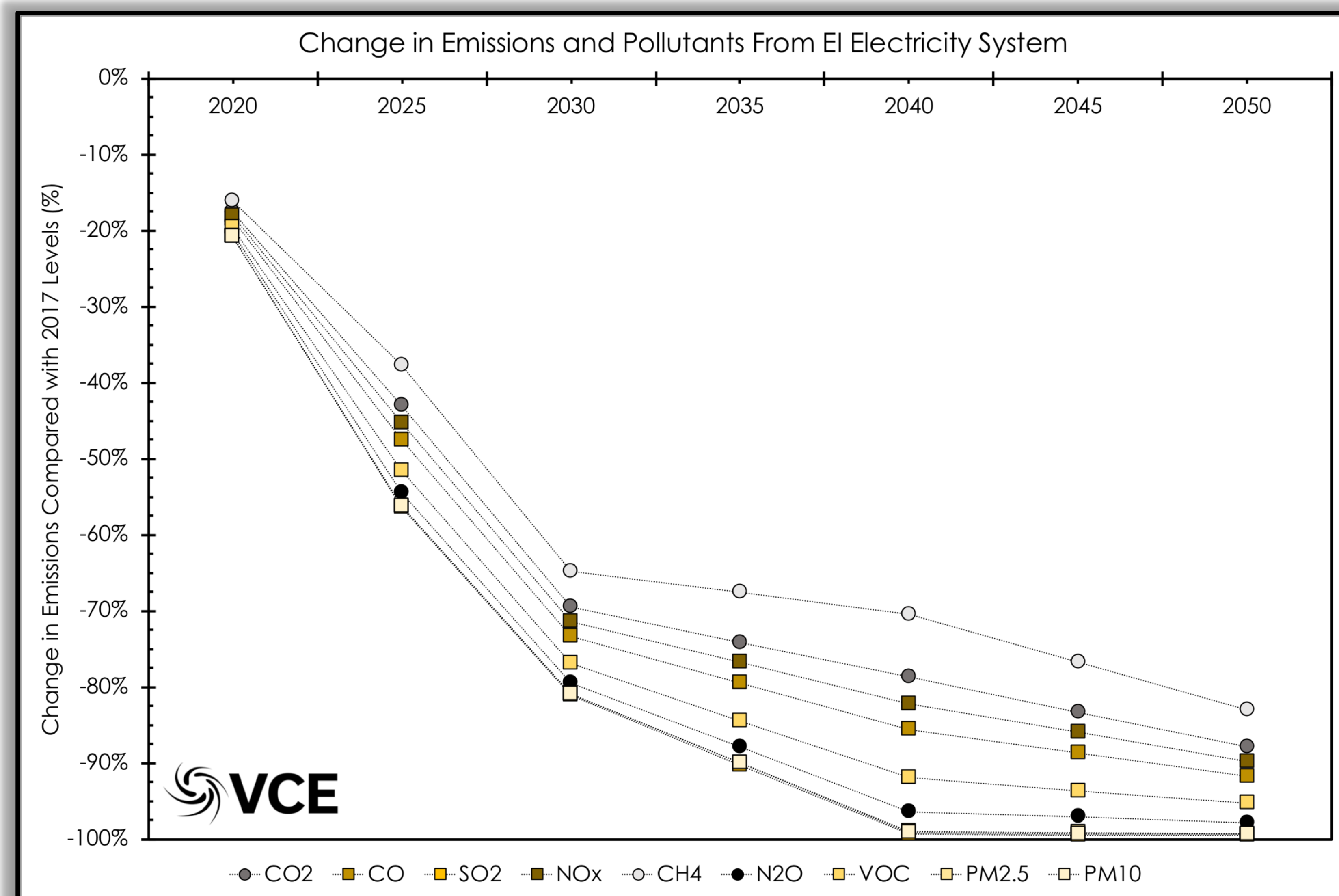
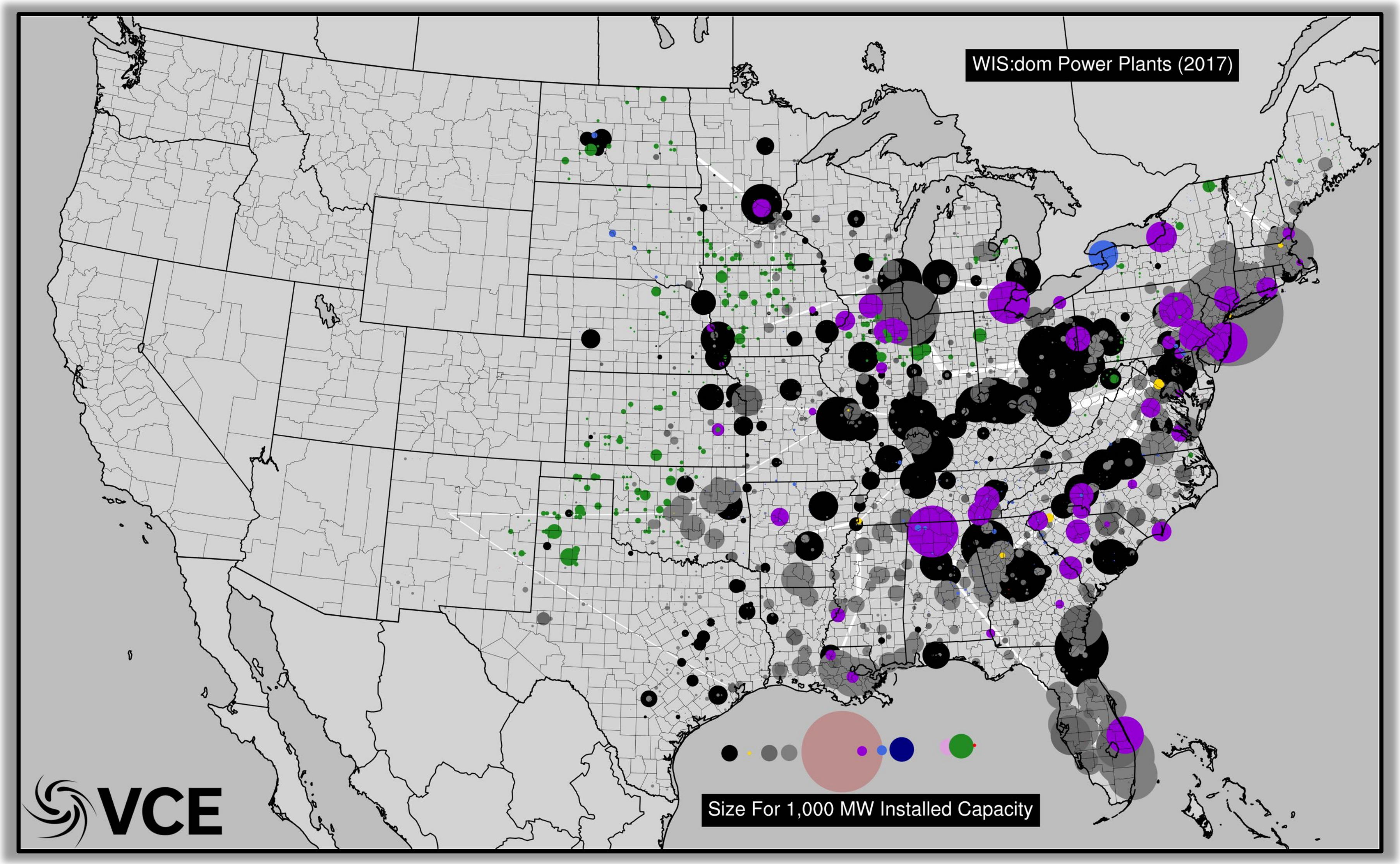
Eastern Interconnection Increased Jobs



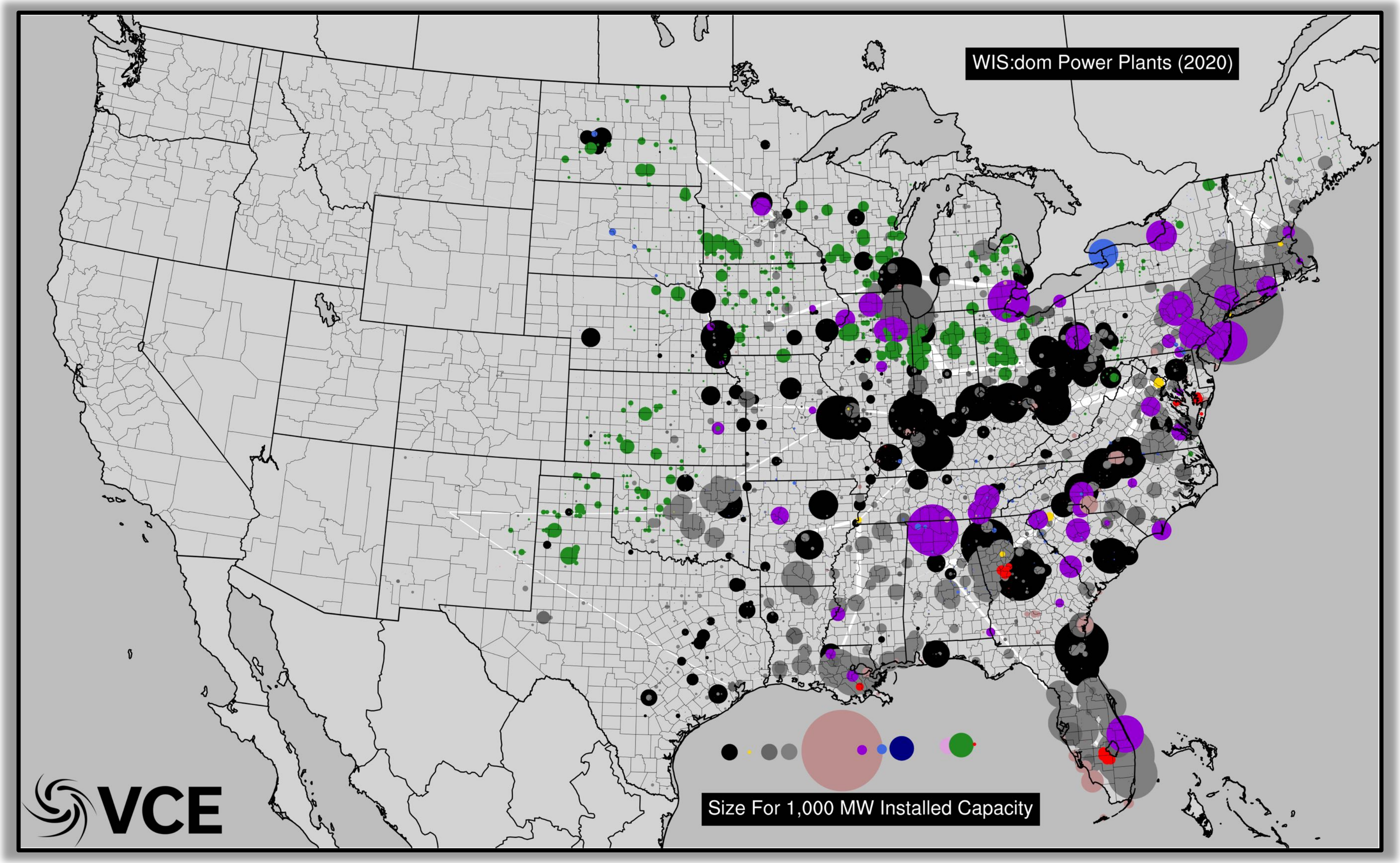
Eastern Interconnection Emissions Change



Installed Capacity (Geographic)



Installed Capacity (Geographic)



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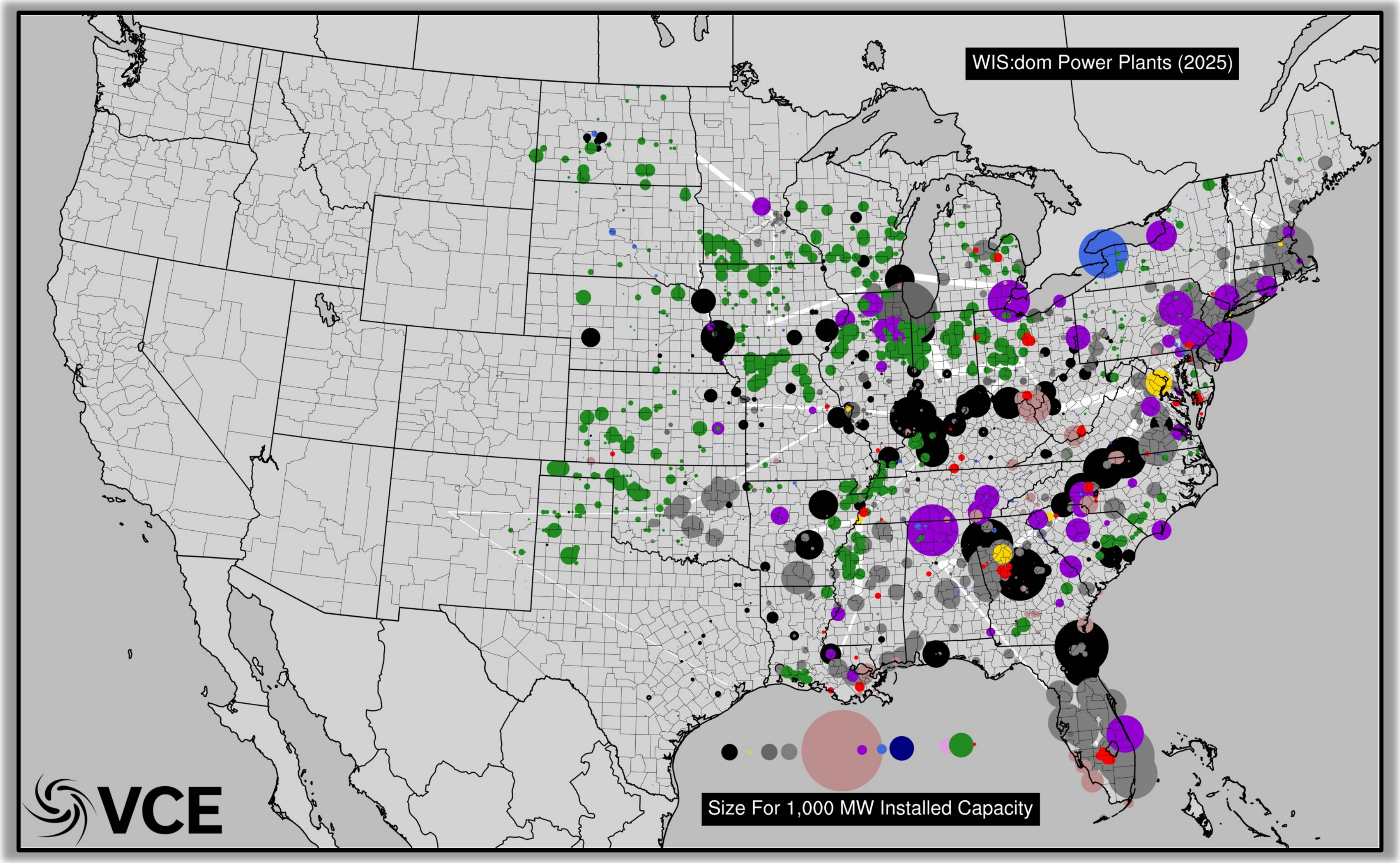
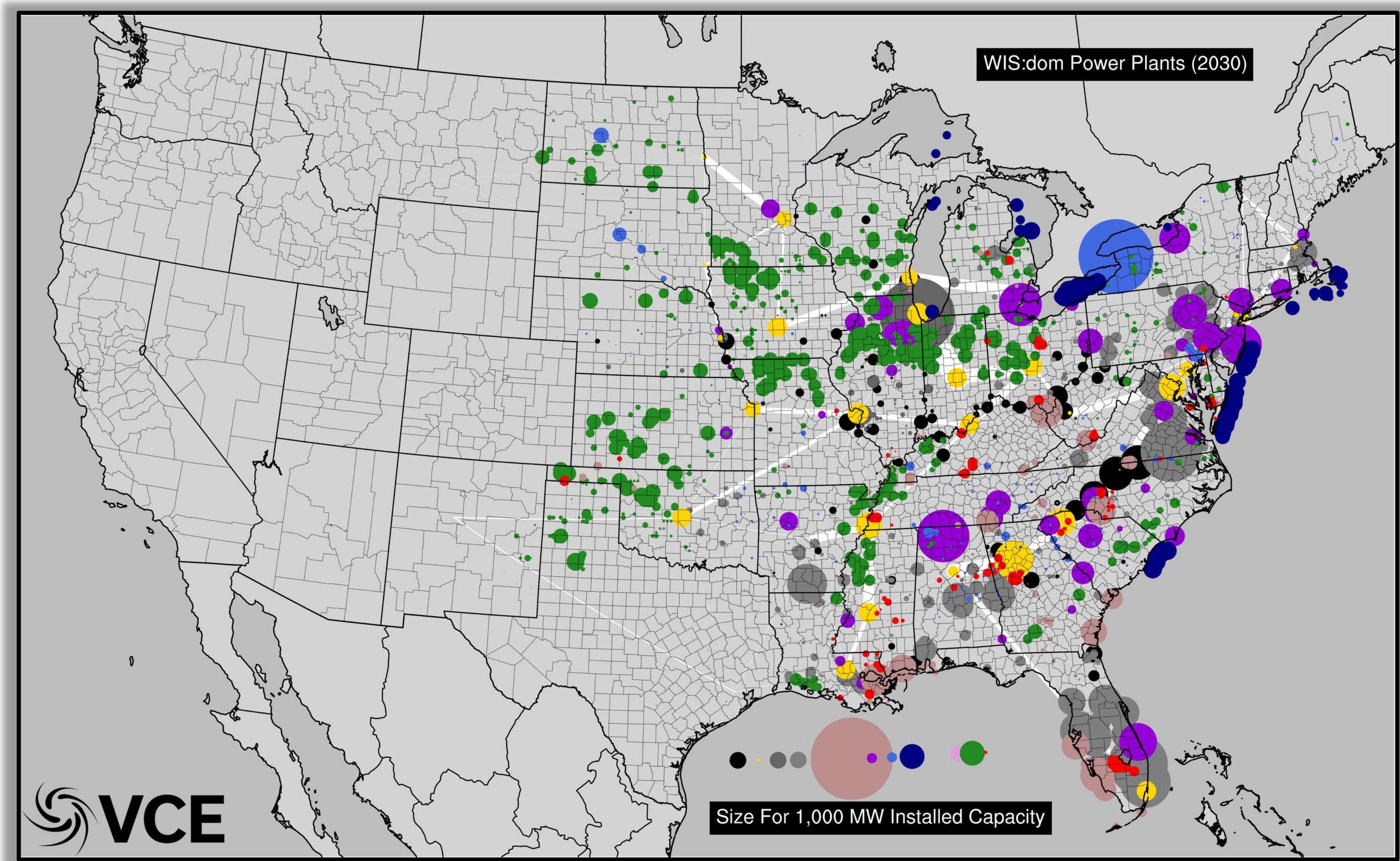
Installed Capacity (Geographic)



Installed Capacity (Geographic)



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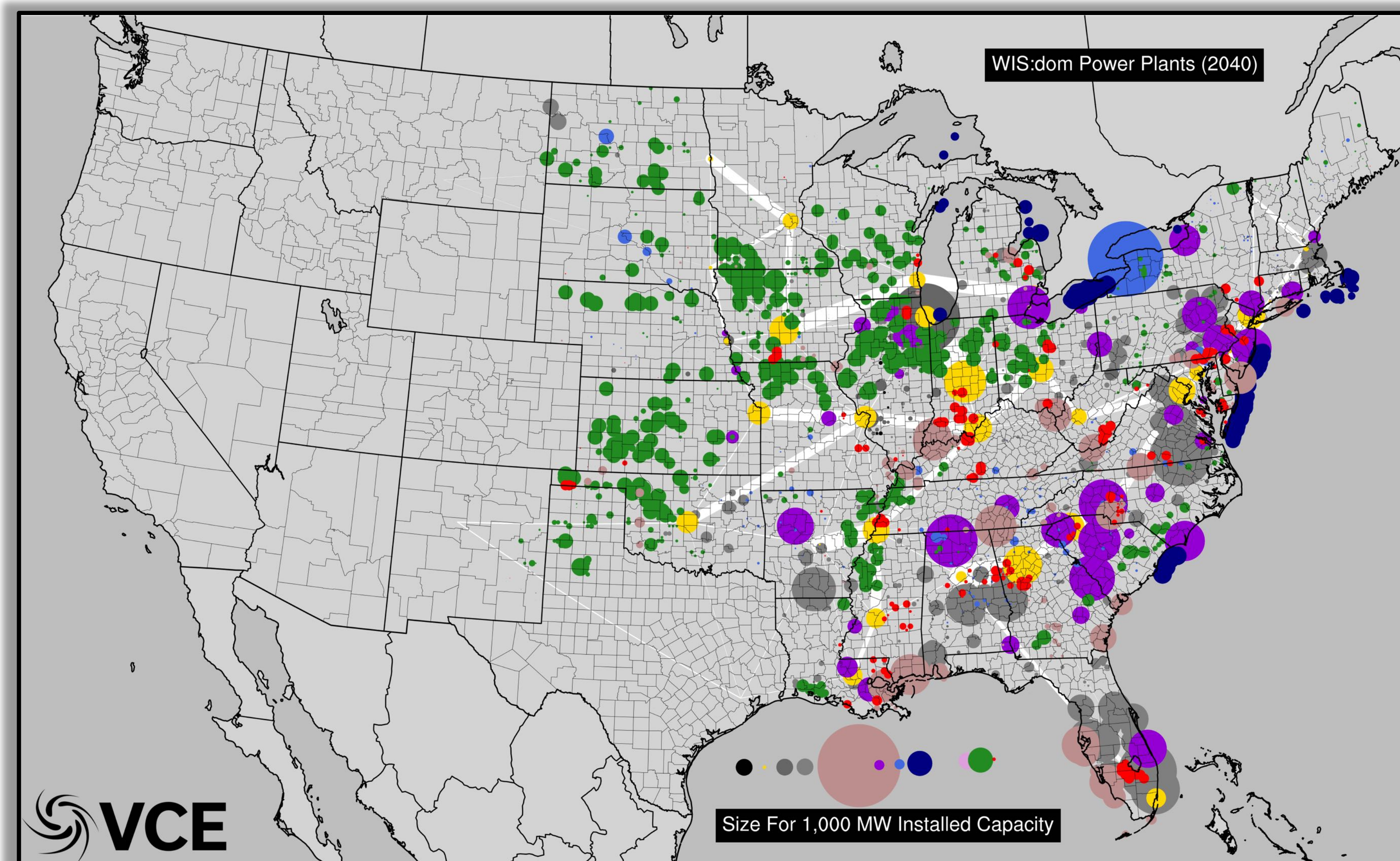
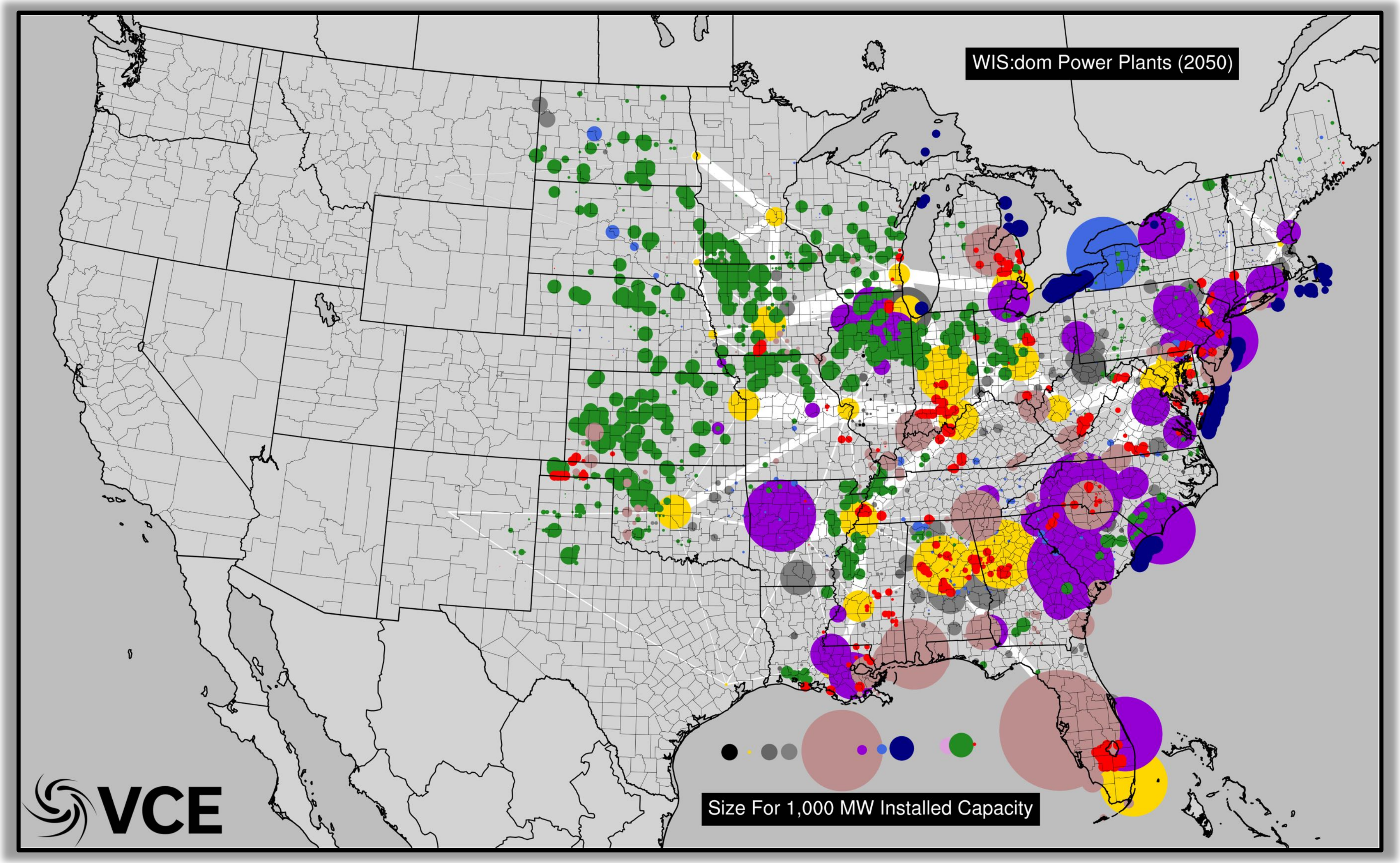
Installed Capacity (Geographic)



Installed Capacity (Geographic)



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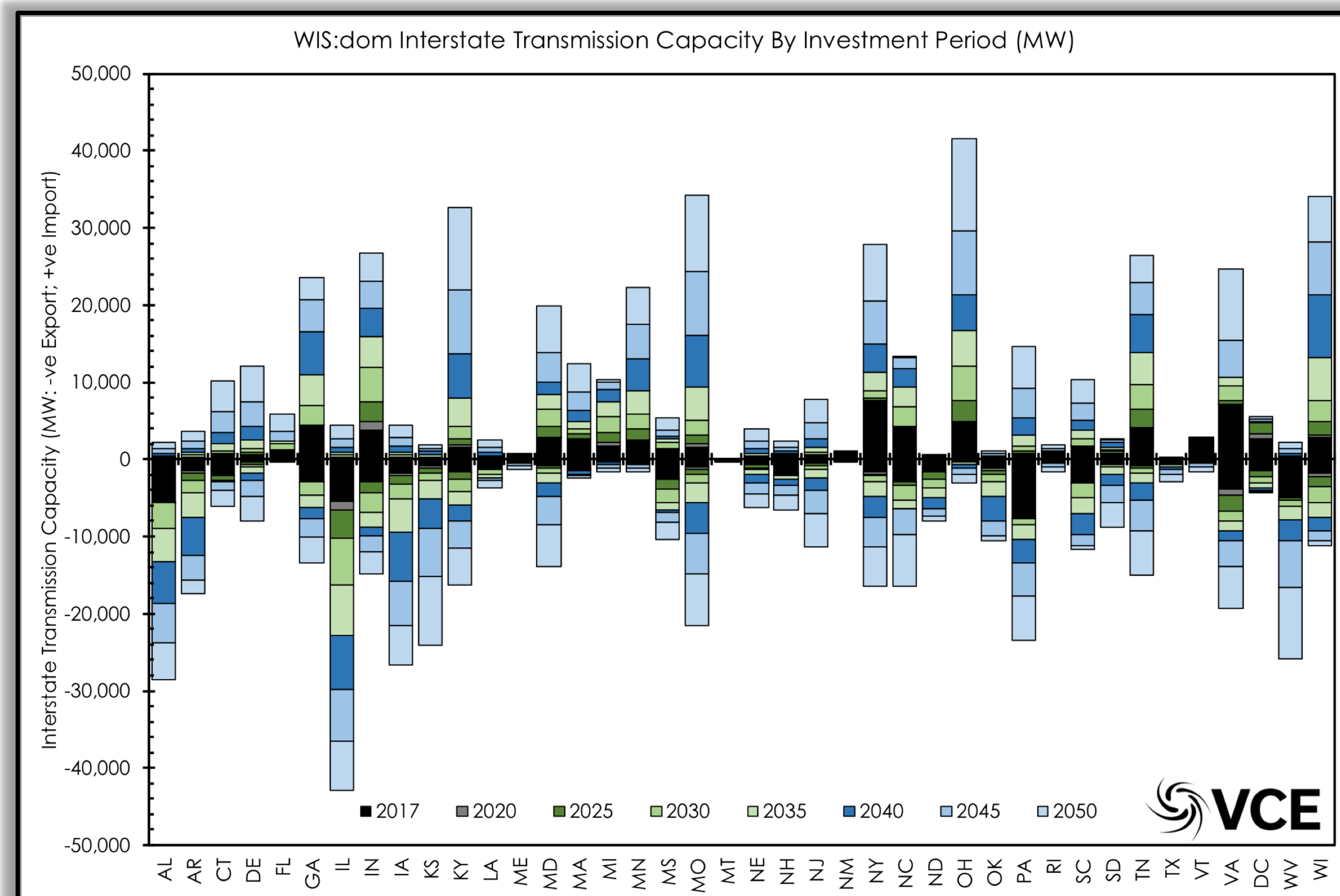
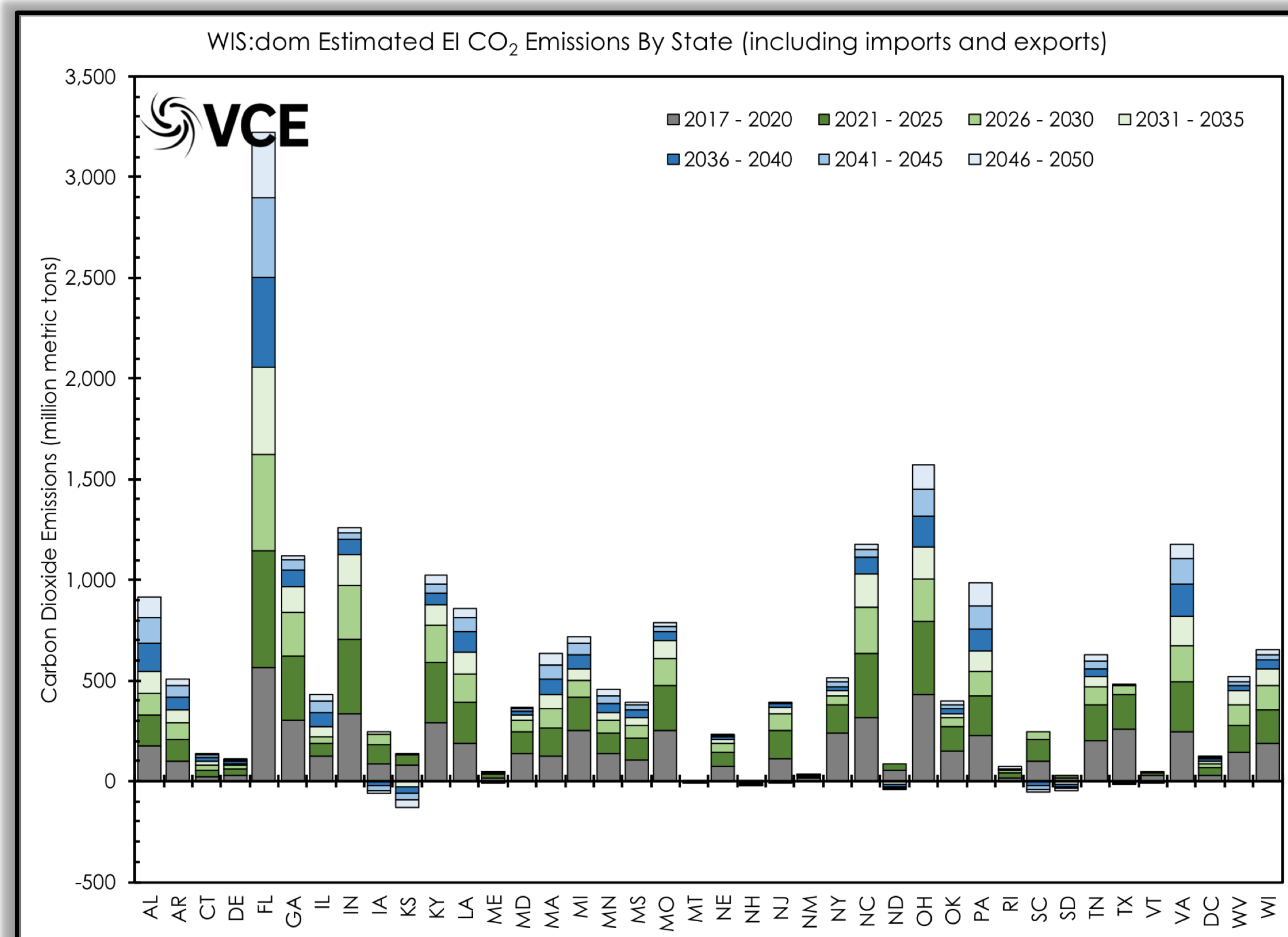
Installed Interstate Transmission Capacity



Cumulative Emissions By State



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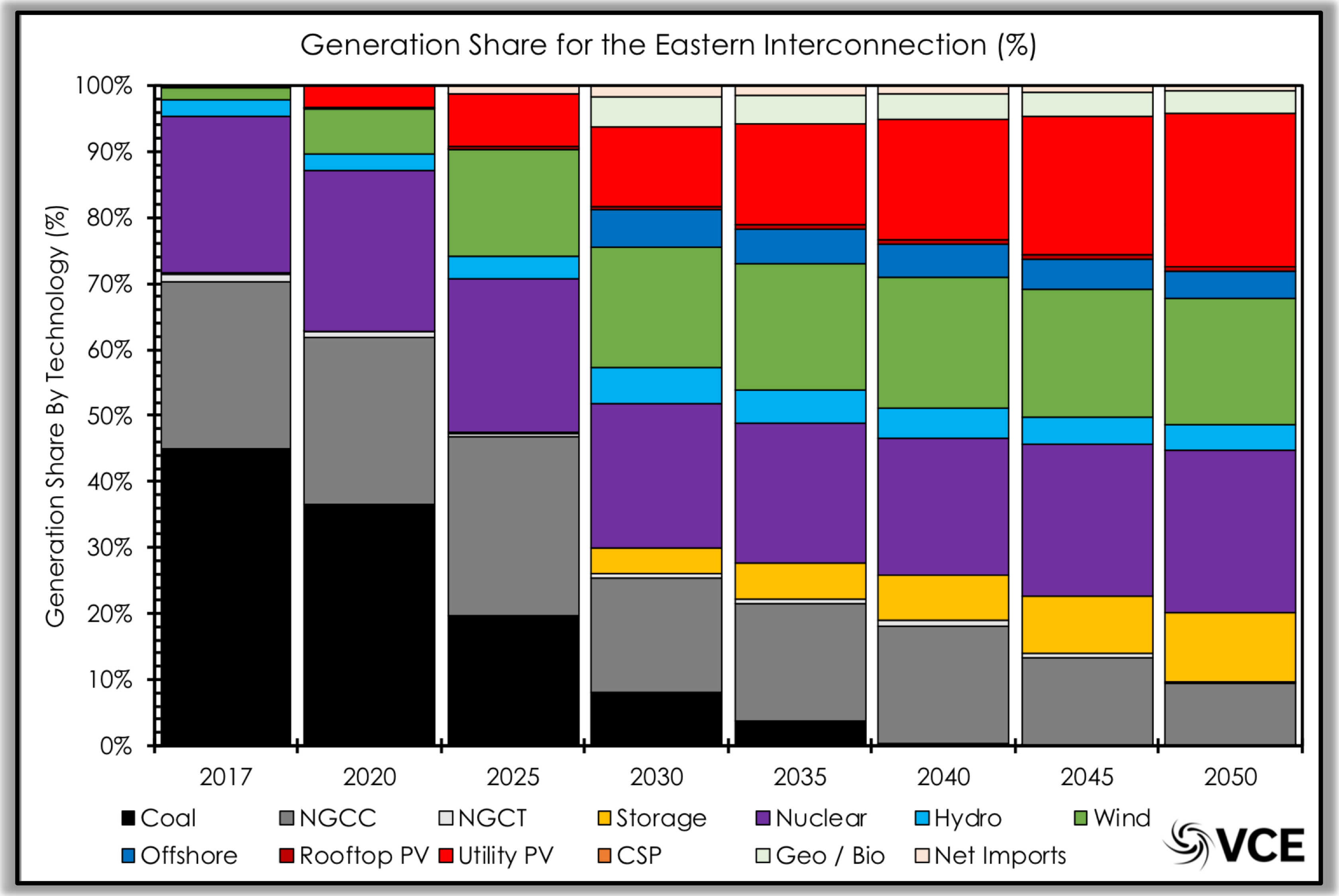
Generation Share For Eastern Interconnection



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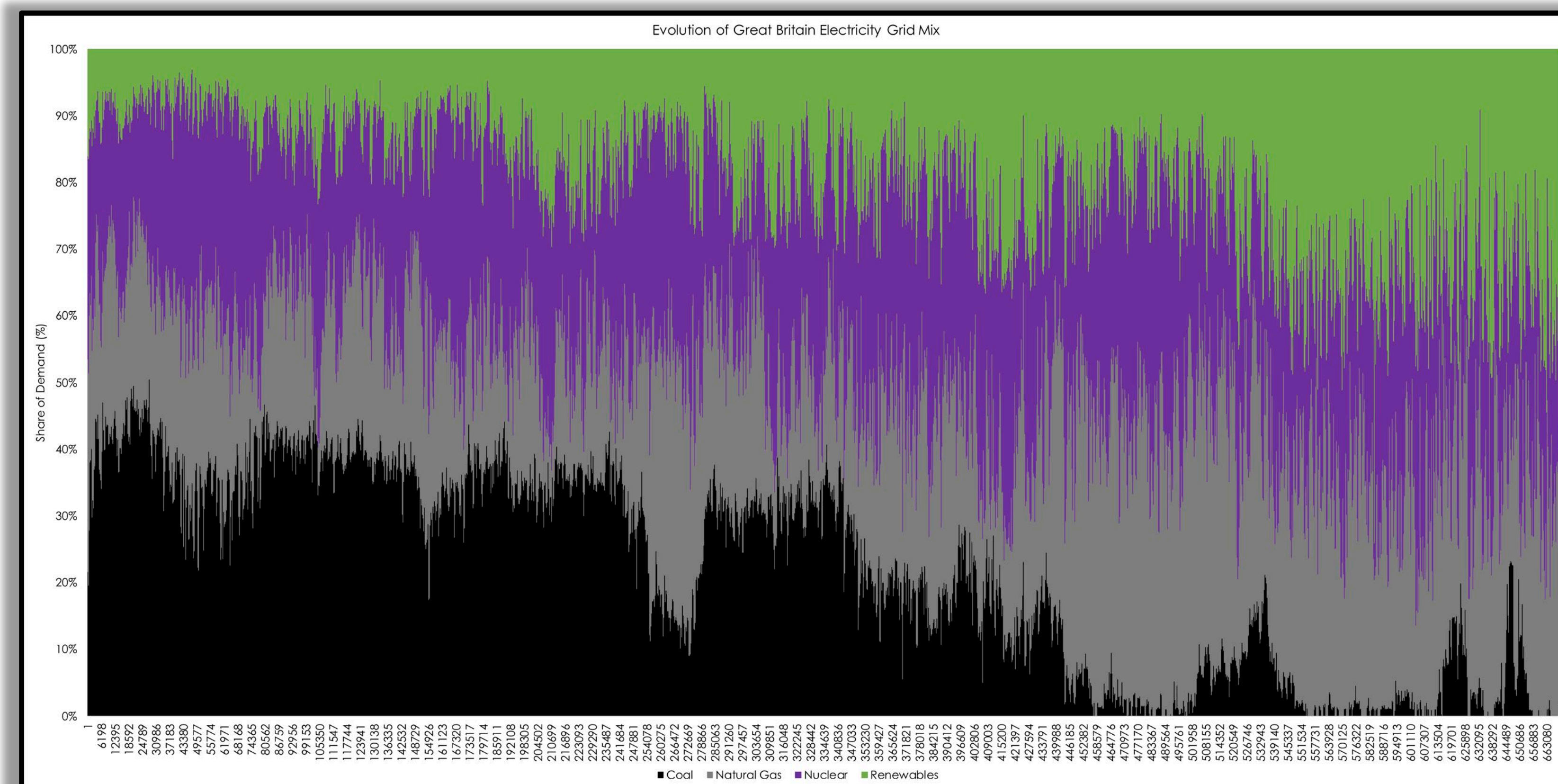
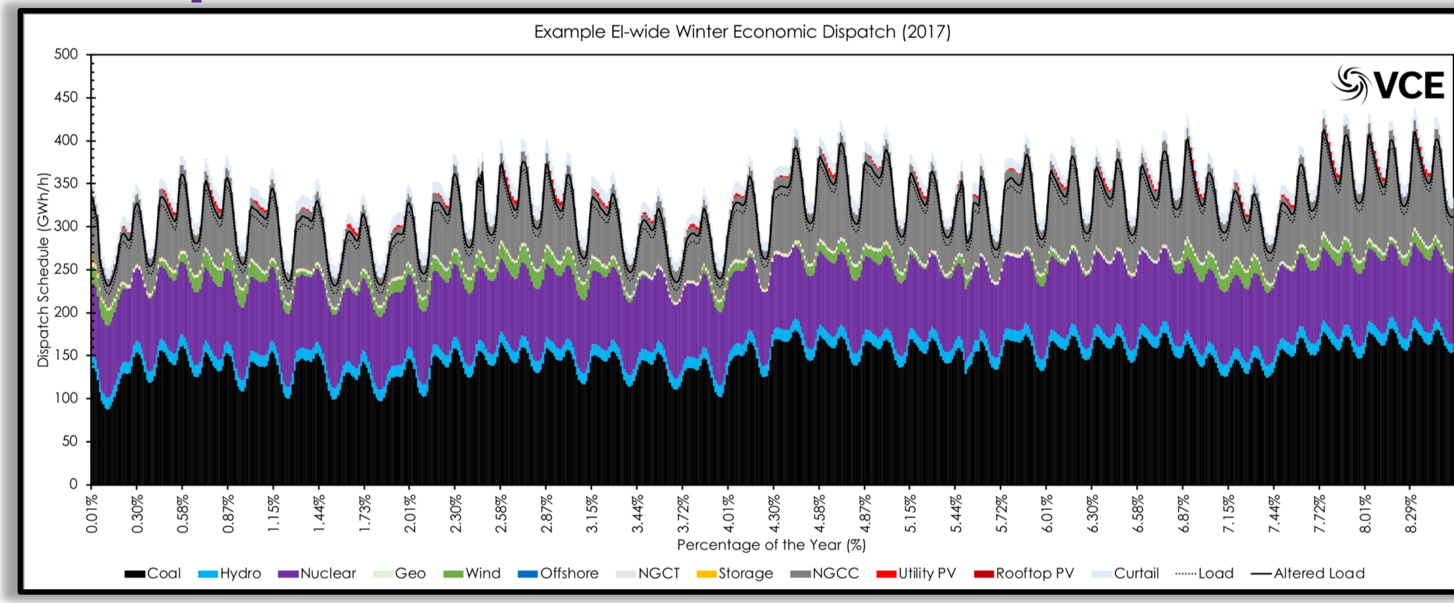
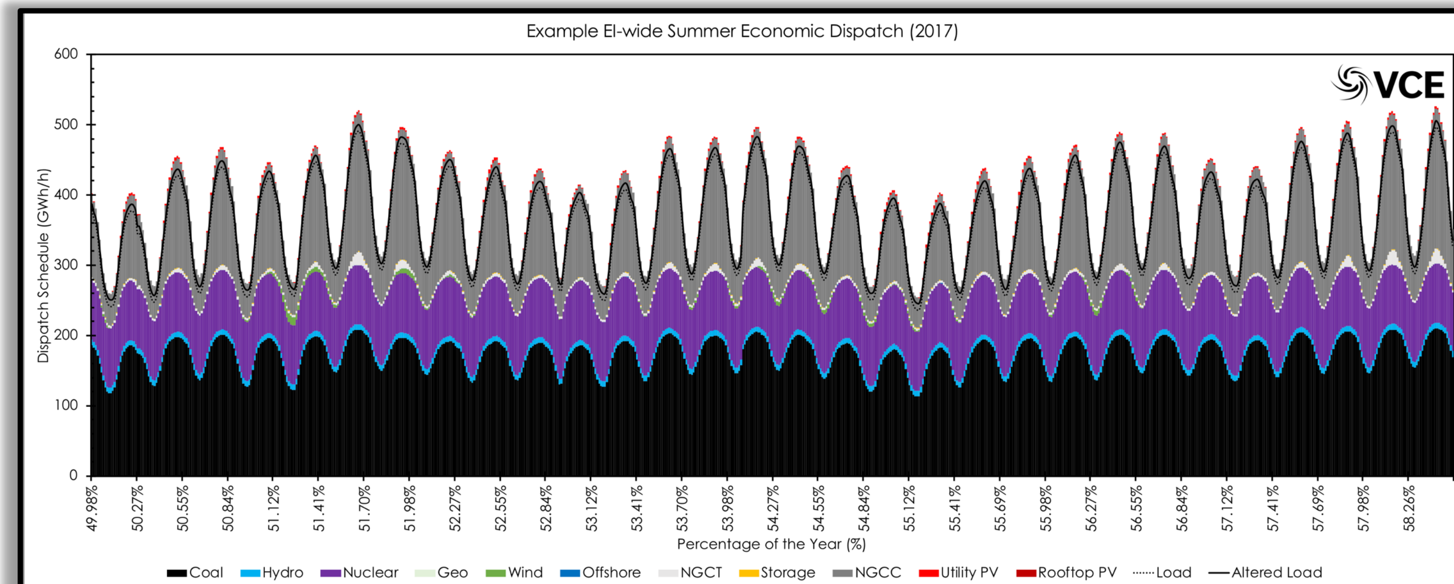
Aside: Generation Share for United Kingdom



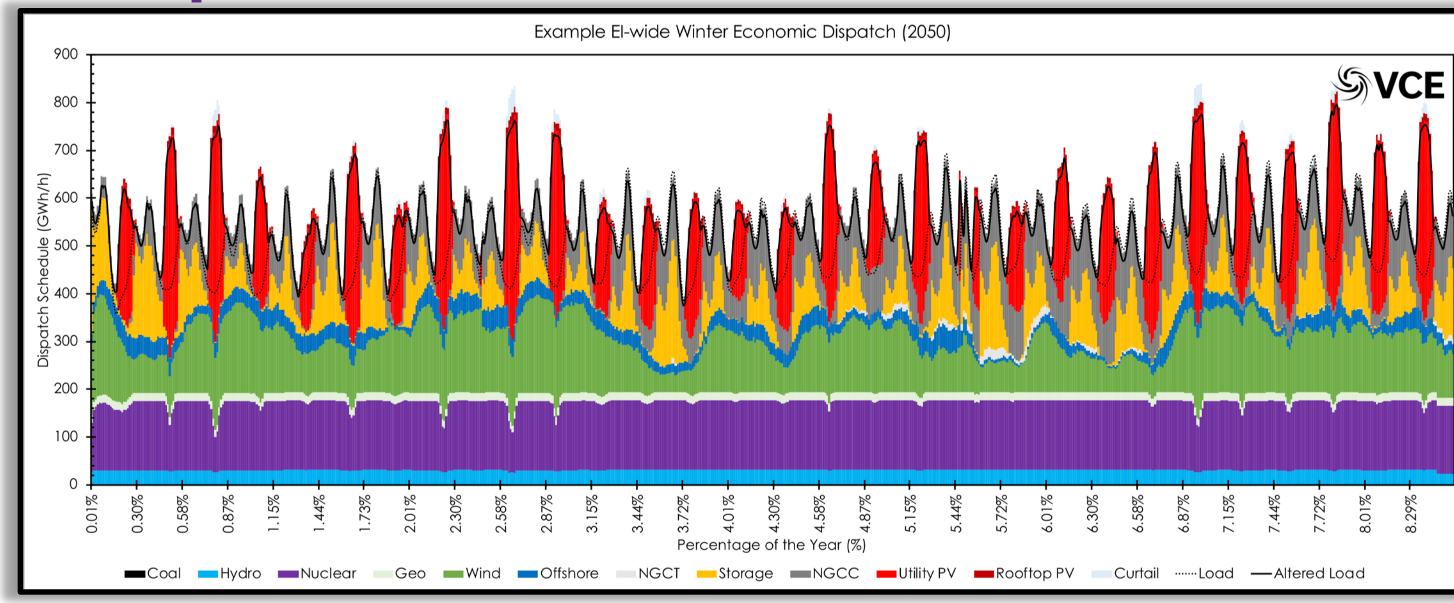
Except this is over only 6 years!

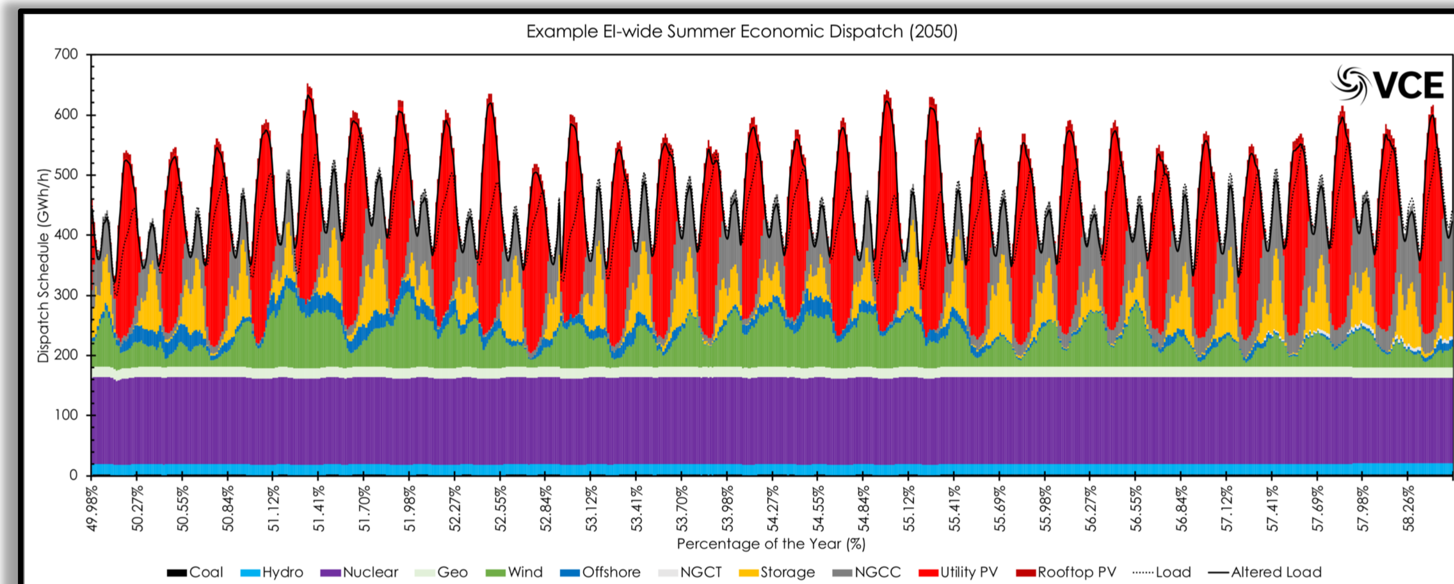
Dispatch For Eastern Interconnection



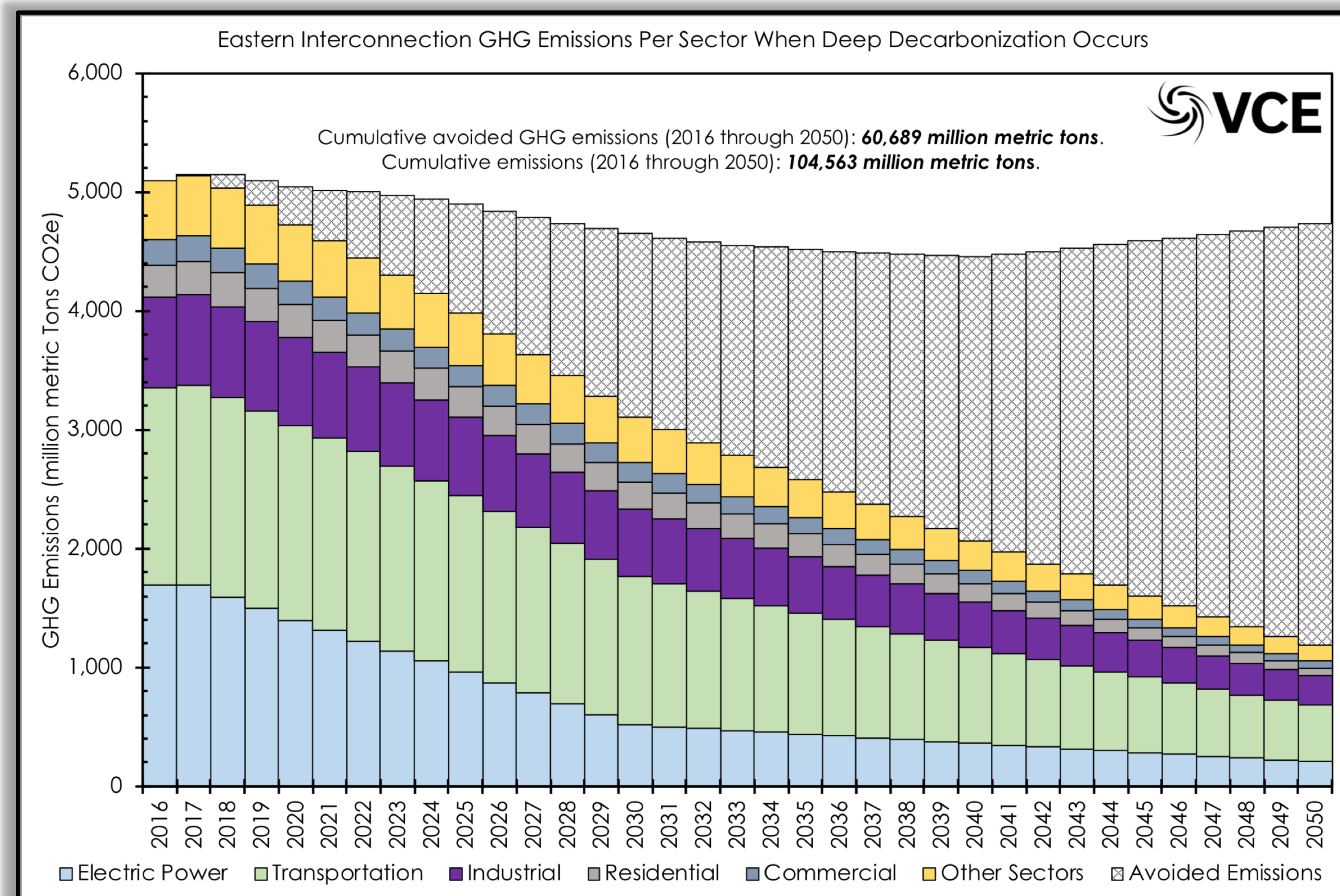


Dispatch For Eastern Interconnection





Avoided Emissions For Eastern Interconnection



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Thank You

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Website: VibrantCleanEnergy.com