Economy-wide Decarbonization of the United States & Europe

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Colorado School of Mines: Payne Institute for Public Policy
Fall Hybrid Seminar Series
November 9th, 2022

Agenda

1. Introduction & Motivation.
2. Overview of the WIS:dom-P (USA) & WIS:dom-G (Global) modeling suites.
3. Details on & importance of the weather / power datasets.
4. Decarbonization of the United States Economy by 2050 (zero2050usa.com).
5. Decarbonization of Europe by 2050 (forthcoming).
6. Discussion & Questions.

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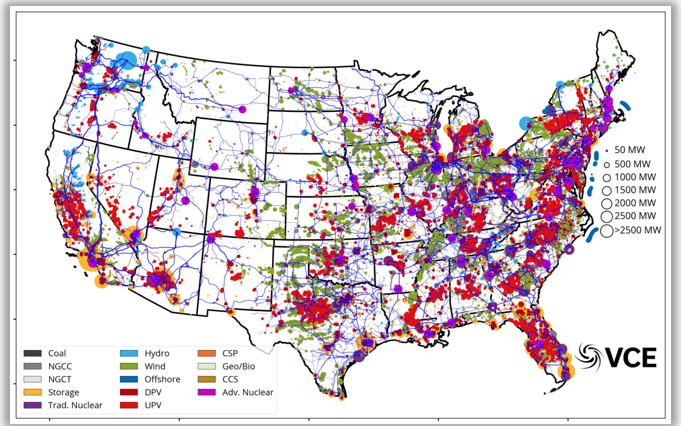

Purpose of Vibrant Clean Energy, LLC:

- 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 & data 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.
- Determine sites for new generation, transmission, distribution and storage assets.

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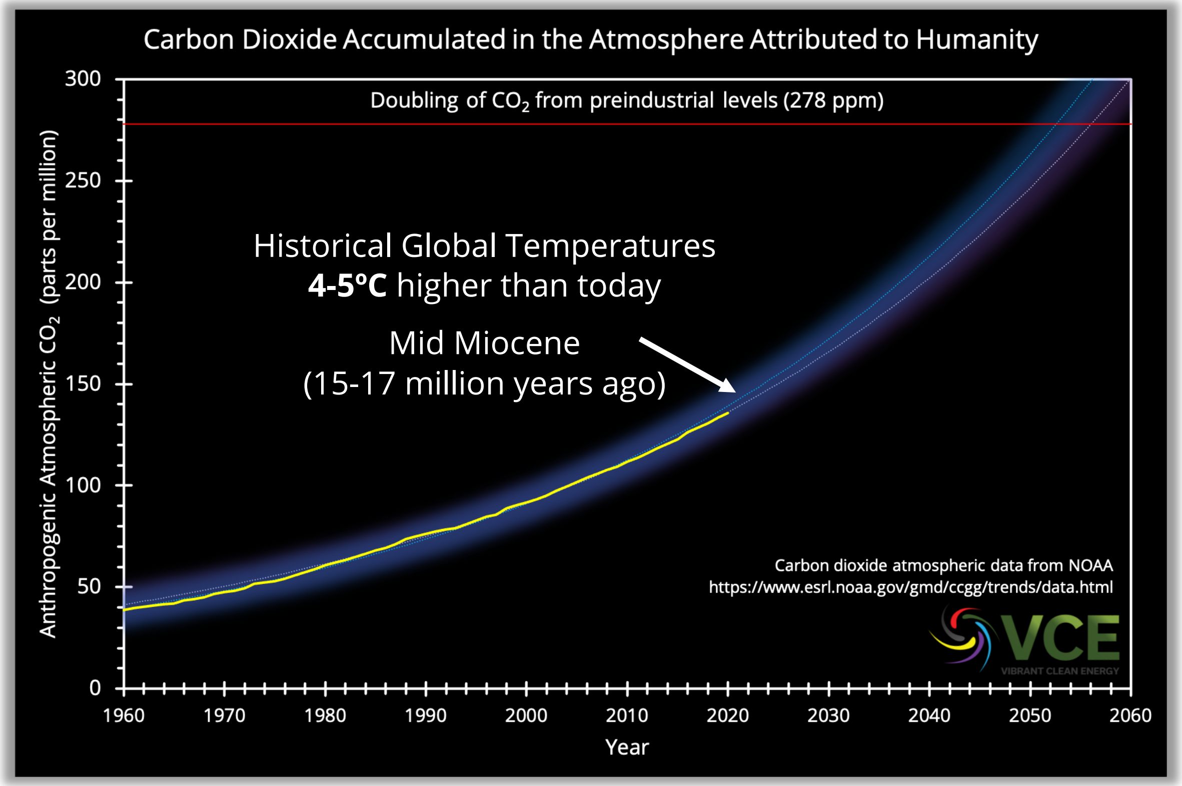
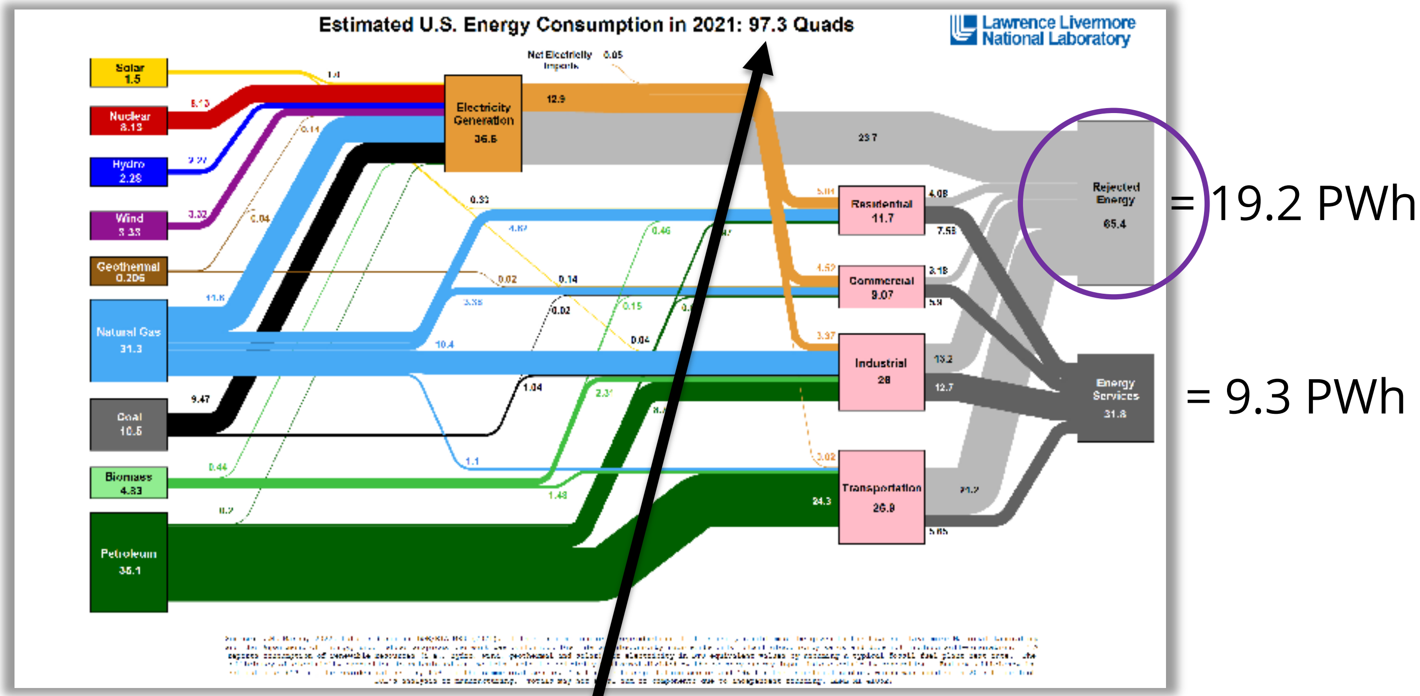
Motivation (Climate Change)



Historical Temperature Analysis:
https://www.nature.com/articles/s41598-020-64743-5

Motivation (USA Energy Demands)



This is equivalent to 28.5 PWh (28,500 TWh)

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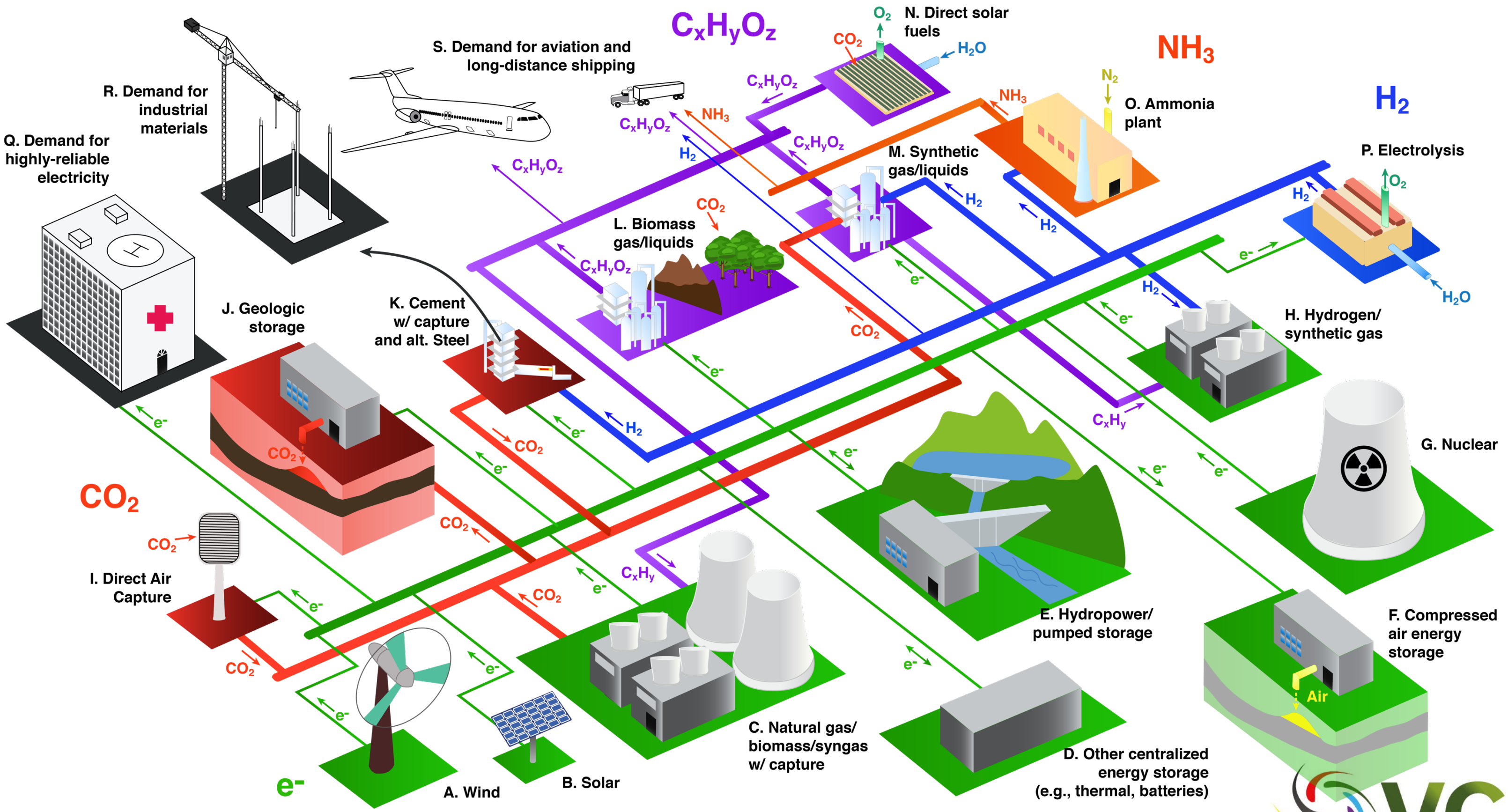
Motivation (Economy Needs Energy)



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Davis et al. *Science*, 2018

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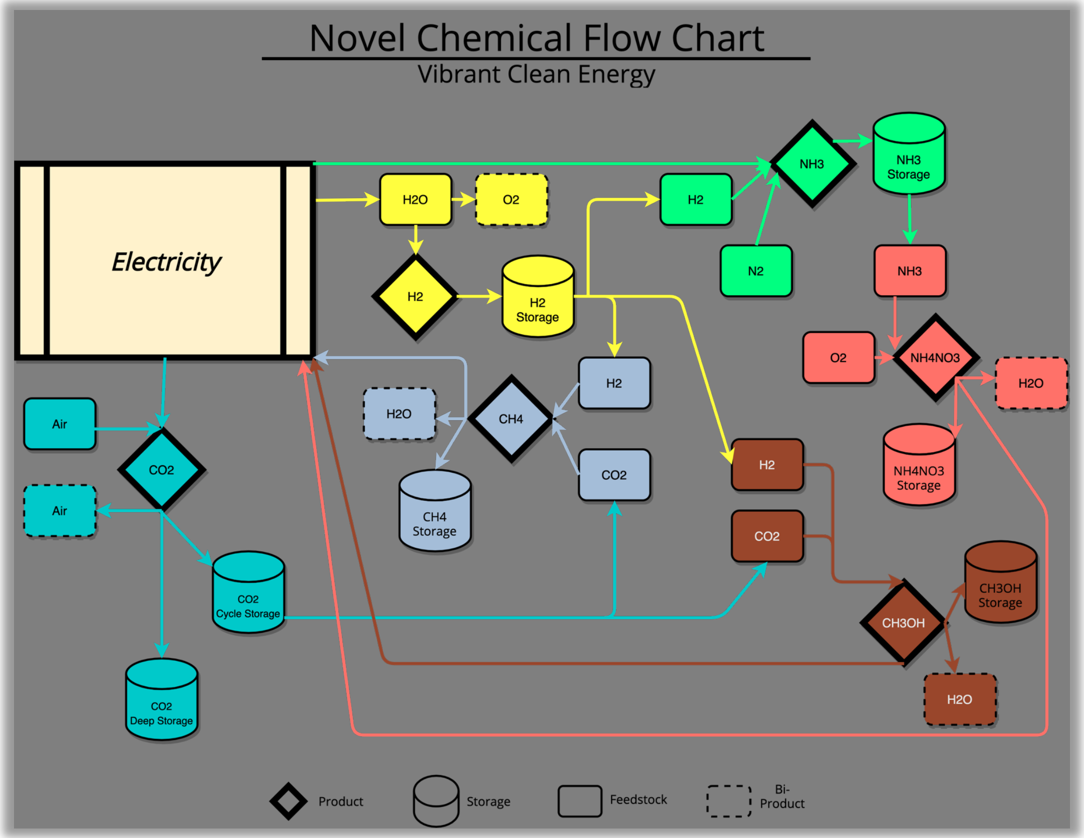
Motivation (Model The Energy System)



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Motivation (Best Clean Energy Sources are Electrical)

Low-marginal Cost Electricity Production Resources (kWh; energy)

- *Wind*
- *Solar*
- *Geothermal*
- *Nuclear*
- *Hydroelectric*

Flexibility Resources (kWh → kW → kWh; capacity)

- *Transmission*
- *Hybrid Resources (wind+solar+storage)*
- *Storage (electricity+heat)*
- *Electrification*
- *Direct Air Capture*
- *Demand-side management*
- *Dispatchable Generation (SMR, EGS, H_2 CC, NGCC+CCS)*
- *Synthetic Fuel/Chemical Production (H_2, CH_4, NH_3)*
- *Peaking Generation (H_2 CT)*

Motivation (Electric Demand Should Increase)

NOTE: In 2021 **28.5 PWh** of primary energy was consumed in the US. Of that **9.3 PWh** was productive for end uses (energy services). Source: LLNL

61% down **18% up**

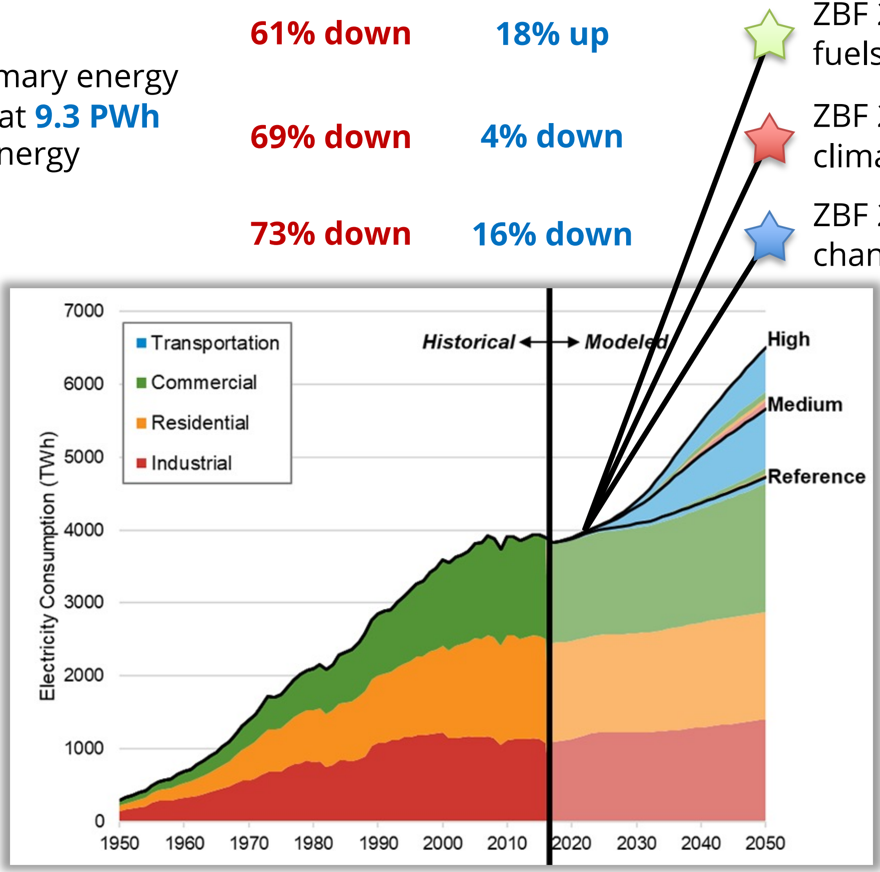
69% down **4% down**

73% down **16% down**

ZBF 2050 TWh with synthetic fuels & products (11 PWh)

ZBF 2050 TWh with RCP4.5 climate change impacts (8.9 PWh)

ZBF 2050 TWh without climate change impacts (7.8 PWh)



https://www.nrel.gov/analysis/electrification-futures.html

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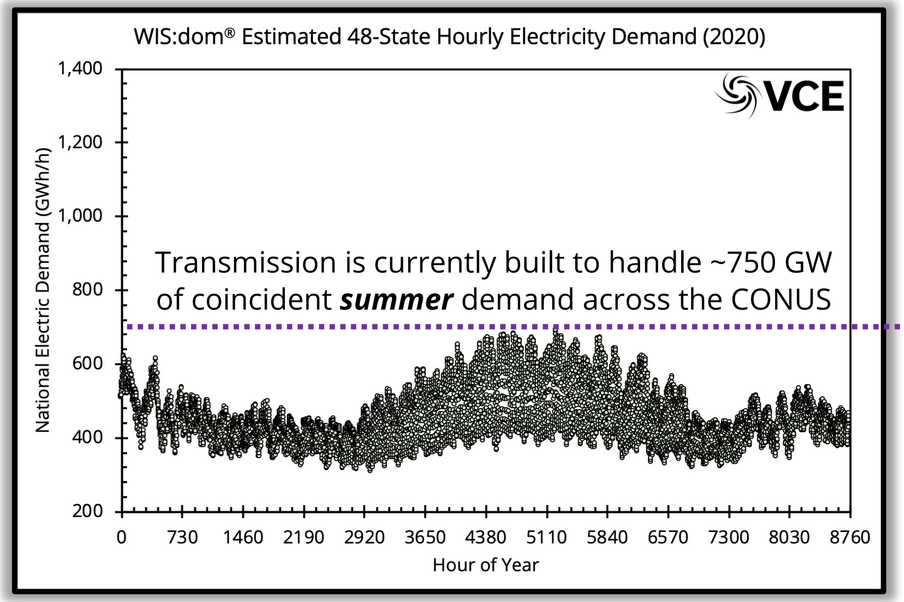
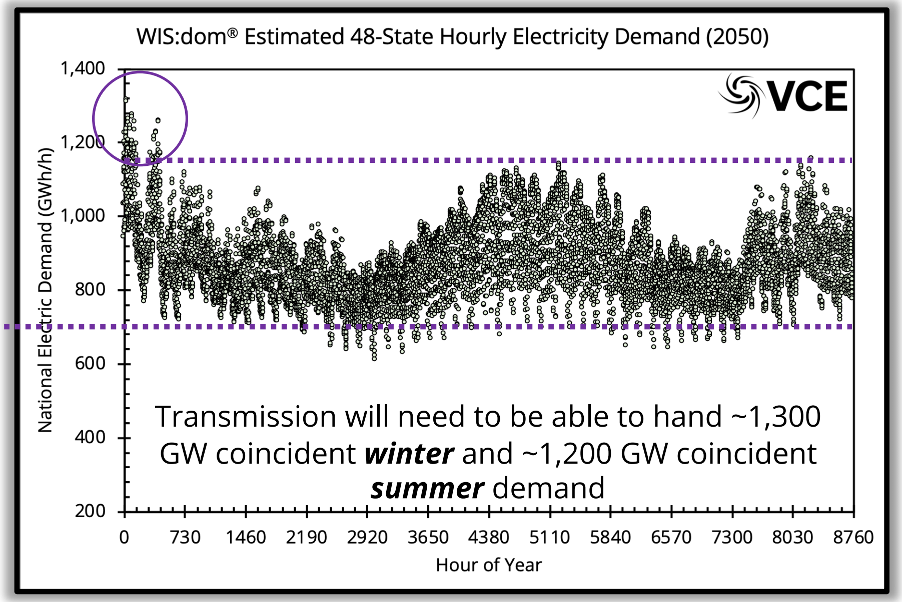
Motivation (Electric Demand Shape will Change)





* Before considering synthetic fuel production

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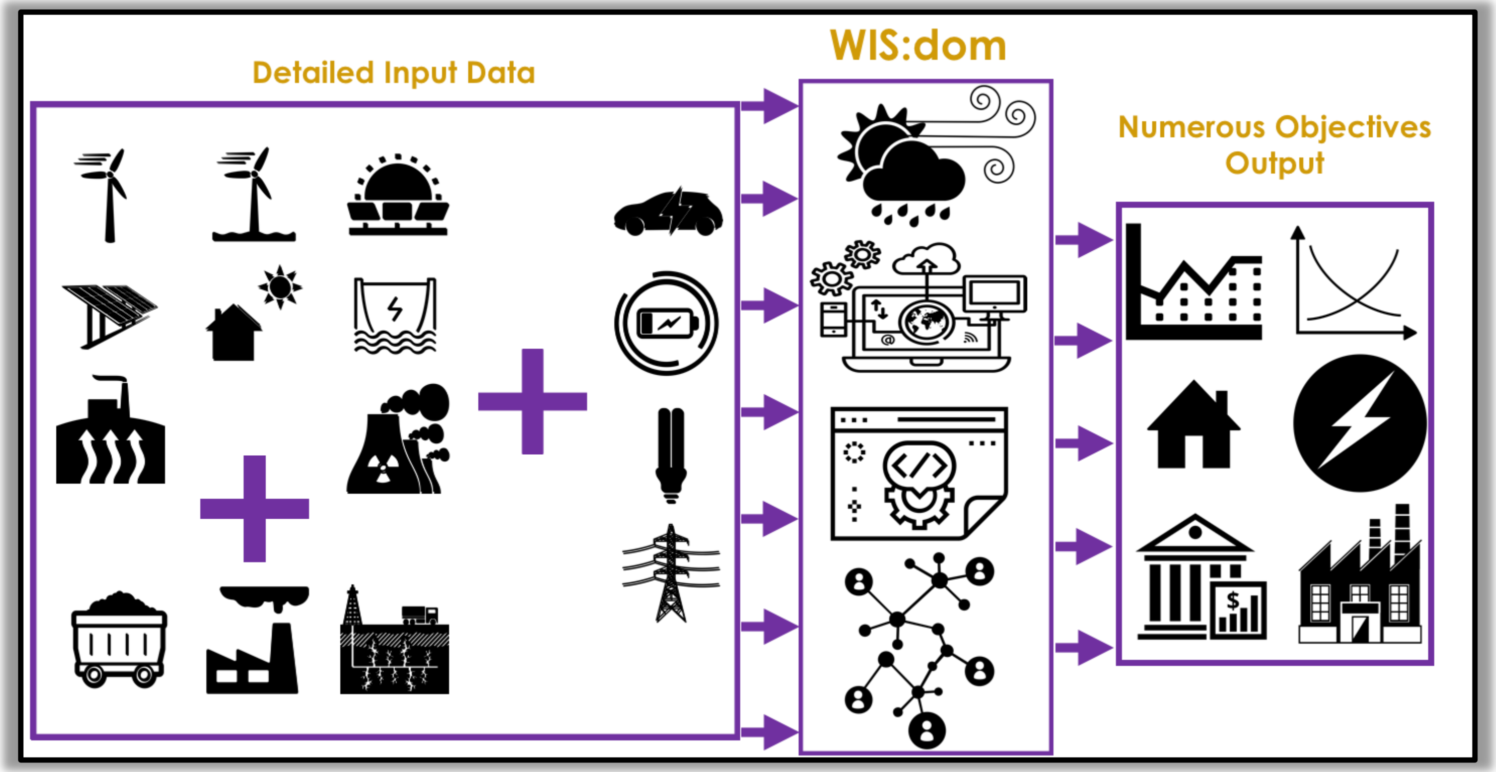
Co-optimization for a Reliable, Robust, and Resilient Grid



WIS:dom Modeling Suite Features

WIS:dom-P & WIS:dom-G are fully combined capacity expansion and production cost model. They combine:

- ✓ Continental-scale, spatially-determined co-optimization of transmission, generation and storage expansion while simultaneously determining the dispatch of these sub systems at 3-km (USA) or 30-km (Global) , 5-minutely or hourly resolution;
- ✓ Includes climate change data from CMIP-5 modeling to climate stress scenarios;
- ✓ Dispatch includes:
  - ➢ Individual unit commitments, start-up, shutdown profiles, and ramp constraints;
  - ➢ Transmission power flow, planning reserves, and operating reserves;
  - ➢ Distribution planning & hybrid optimization;
  - ➢ 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 Generation Technologies

Fossil Fuels:
Coal; Oil; Natural gas steam;
Natural gas combined cycle;
Natural gas combustion turbine;
Natural gas combined cycle with carbon capture and sequestration (pre- & post- combustion);
Coal to ammonia & natural gas to renewable natural gas.

Renewable:
Onshore wind farms (80 m – 200 m hub heights, when applicable);
Offshore wind farms (120 m – 240 m hub heights, when applicable);
Hybrid VRE (wind or solar with battery onsite);
Utility-scale photovoltaic (multiple tracking, angles & types; including bi-facial);
Distributed solar photovoltaic;
Hydroelectric;
Geothermal & enhanced geothermal;
Biomass & biogas;
Hydrogen (created with nuclear or renewable electricity) peaking turbines.

Nuclear:
Legacy (existing) nuclear facilities;
Light-water reactors (PWR & BWR) – limited to conversion sites of retired nuclear, coal, natural gas;
Light-water small modular reactor (SMR);
Molten salts reactor (MSR);
High Temperature Gas-cooled reactor (HTGR).

WIS:dom Transmission, DERs & Other Technologies

Overhead AC transmission lines (down to 69-kV) for bands of voltages;

Spur line transmission for all generation to the nearest transmission substation;

Overhead & Underground (along interstate & railroad ROWs) HVDC transmission lines;

Distribution (69-kV) substations and parameterized distribution spur lines to demand;

Utility-scale electricity storage (traditional batteries, pumped hydro, redox flow batteries);

Distributed electricity storage (traditional batteries, demand flexibility, EVs, demand response);

Hydrogen production facilities;

Direct air capture facilities (combined with H_2 if required for P2X);

Haber process production facilities for ammonia production (typically for agriculture);

Sabatier & Fischer-Tropsch processes facilities for dense, synthetic hydrocarbon fuels.

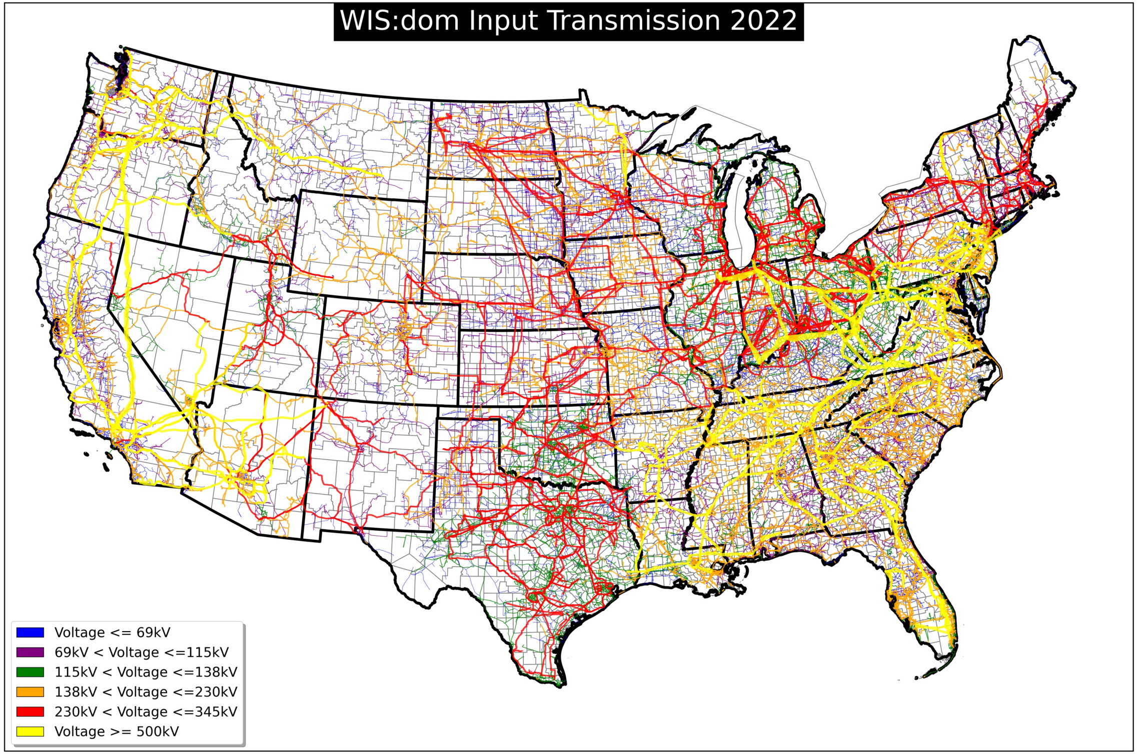
Compactified Objective & Constraint Equations

Equation (3.1) is the mathematical formulation of the objective function:

$$
\Gamma = \min \sum_{\mathcal{L}} \left\{ \begin{array}{c}
\sum_{\mathcal{T}} \left\{ \mathcal{C}^{\mathcal{G}}_{\mathcal{TL}} \cdot x_{\mathcal{TL}} + h \cdot \sum_{t} \left[\left(\mathcal{V}^{\mathcal{G}}_{\mathcal{TL}t} + \left(\mathcal{F}^{\mathcal{G}}_{\mathcal{TL}t} + \mathcal{V}^{c}_{\mathcal{L}} \cdot \mathfrak{F}_{\mathcal{TL}} \right) \cdot \mathcal{H}^{\mathcal{G}}_{\mathcal{TL}t} \right) \cdot p_{\mathcal{TL}t} + \Delta \cdot \left(\mathcal{V}^{\mathcal{O}}_{\mathcal{TL}t} \cdot o_{\mathcal{TL}t} \right) \right] \right\} + h \cdot \sum_{t} \left(\mathcal{V}^{\mathcal{I}}_{\mathcal{L}t} \cdot \mathcal{I}_{\mathcal{L}t} \right) \\
+ \sum_{\eta} \left[\sum_{\alpha} \left(\mathcal{C}^{\mathcal{S}}_{\alpha\eta\mathcal{L}} \cdot y_{\alpha\eta\mathcal{L}} \right) + h \cdot \sum_{t} \left(\mathcal{V}^{\mathcal{S}}_{\eta\mathcal{L}t} \cdot \mathfrak{D}_{\eta\mathcal{L}t} \right) \right] + \sum_{\mathfrak{B}} \left\{ \begin{array}{c} \sum_{\hat{\mathcal{L}}} \left[\frac{\mathcal{C}^{tr}_{\mathfrak{B}\mathcal{L}\hat{\mathcal{L}}} \cdot \mathcal{R}^{tr}_{\mathfrak{B}\mathcal{L}\hat{\mathcal{L}}} \cdot \mathcal{Q}^{tr}_{\mathfrak{B}\mathcal{L}\hat{\mathcal{L}}} \cdot z^{tr}_{\mathfrak{B}\mathcal{L}\hat{\mathcal{L}}}}{2} + h \cdot \sum_{t} \left(\mathcal{V}^{w}_{\mathfrak{B}\mathcal{L}\hat{\mathcal{L}}t} \cdot f_{\mathfrak{B}\mathcal{L}\hat{\mathcal{L}}t} \right) \right] \\ + \sum_{\beta} \left(\mathcal{C}^{\mathcal{N}}_{\mathfrak{B}\mathcal{L}\beta} \cdot n_{\mathfrak{B}\mathcal{L}\beta} \right) + h \cdot \sum_{t} \left(\mathcal{V}^{\mathcal{N}}_{\mathfrak{B}\mathcal{L}t} \cdot u_{\mathfrak{B}\mathcal{L}t} \right) \end{array} \right\} \\
+ h \cdot \sum_{\mathfrak{D}} \sum_{t} \left(\mathcal{V}^{\mathfrak{D}}_{\mathfrak{D}\mathcal{L}t} \cdot r^{-}_{\mathfrak{D}\mathcal{L}t} \right) + \sum_{t} \left(h \cdot \mathcal{V}^{\mathcal{K}}_{\mathcal{L}t} \cdot \mathcal{W}_{\mathcal{L}t} + \mathcal{V}^{\mathcal{R}}_{\mathcal{L}t} \cdot q_{\mathcal{L}t} \right) + \Theta \cdot \left(\sum_{\mathcal{T}} \left(\mathcal{C}^{\mathcal{G}o}_{\mathcal{TL}} \cdot x^{o}_{\mathcal{TL}} + \mathcal{C}^{\mathcal{G}r}_{\mathcal{TL}} \cdot x^{r}_{\mathcal{TL}} \right) + \Re_{\mathcal{L}} \right) \\
+ \Lambda \cdot \left\{ \mathcal{C}^{dp}_{\mathcal{L}} \cdot \left[\mathcal{E}^{p}_{\mathcal{L}} + \lambda_a \cdot \left(\mathcal{E}^{b}_{\mathcal{L}} + \mathcal{E}^{m}_{\mathcal{L}} \right) \right] + h \cdot \mathcal{C}^{de}_{\mathcal{L}} \cdot \sum_{t} \left(\mathcal{E}_{\mathcal{L}t} - \lambda_b \cdot \mathcal{J}_{\mathcal{L}t} \right) \right\}
\end{array} \right\} \qquad (3.1)
$$

Due to scale we model compactifying variables is essential to solve the problem in a reasonable clock time!

WIS:dom Transmission & Generator Input Datasets



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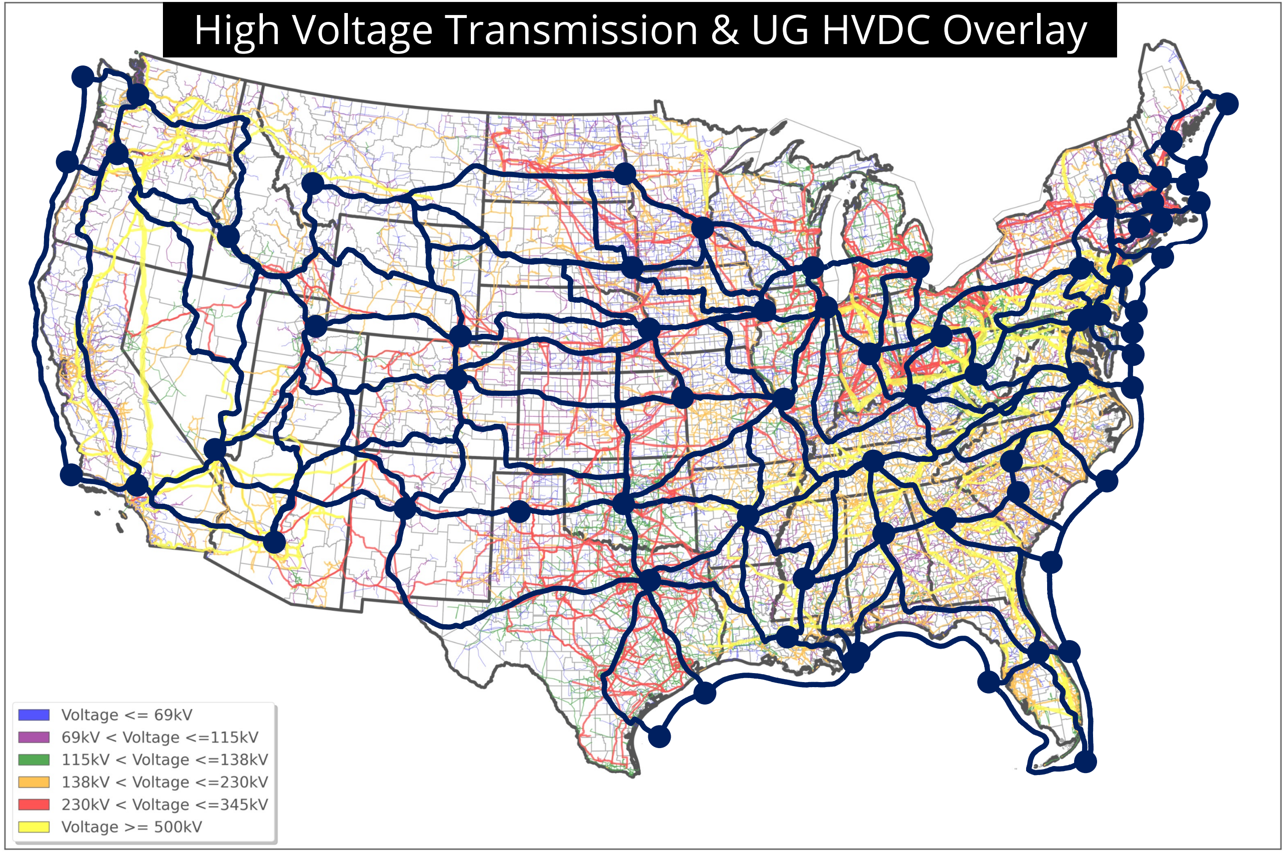

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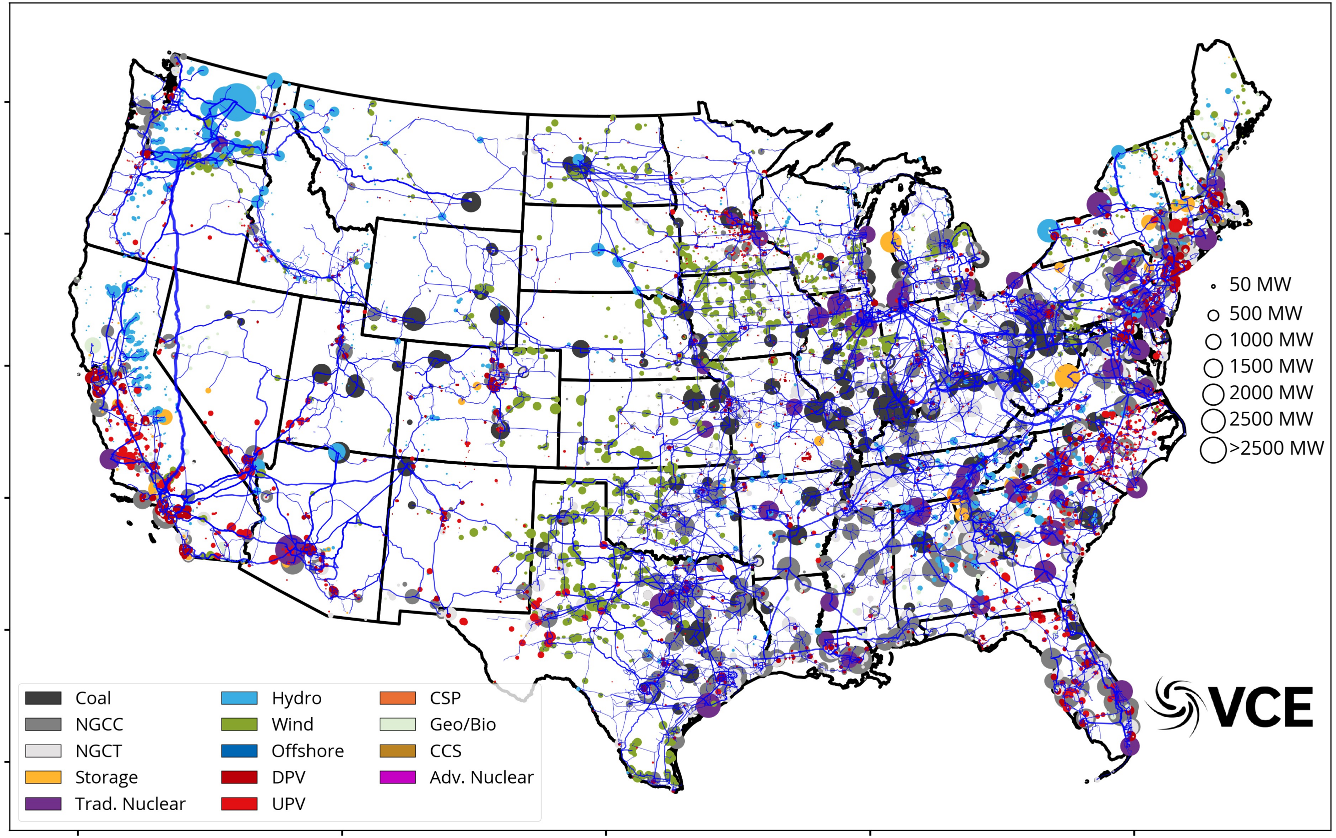

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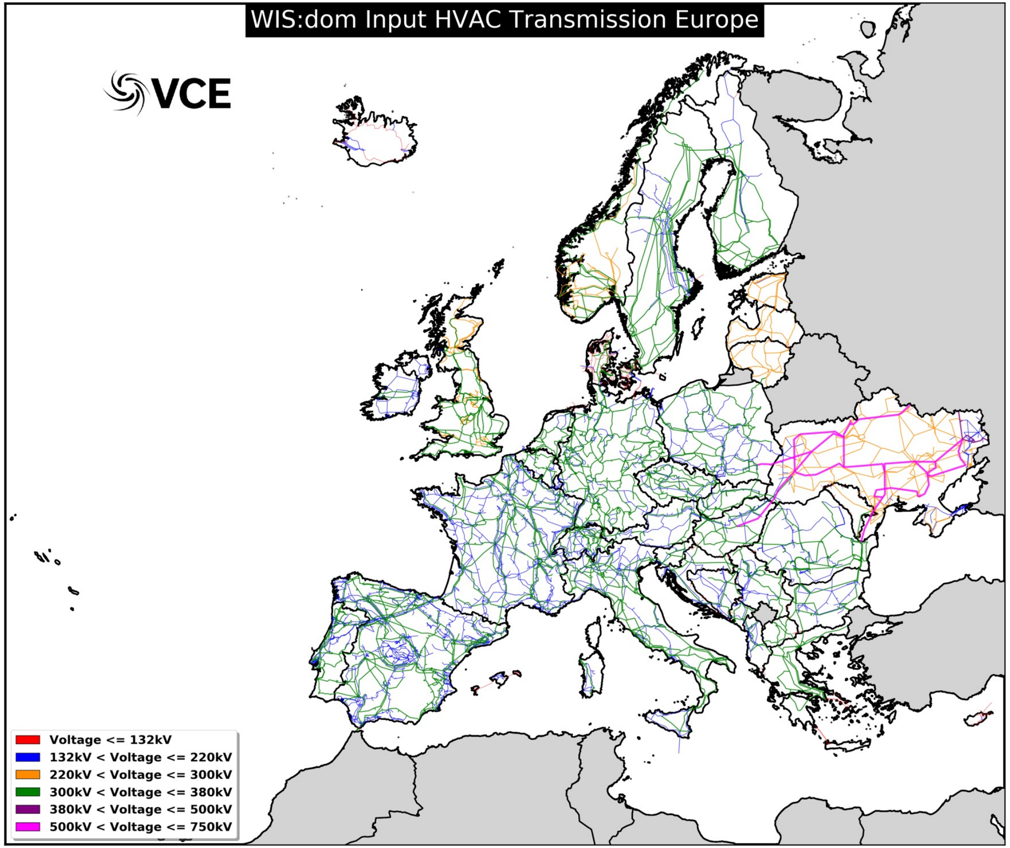

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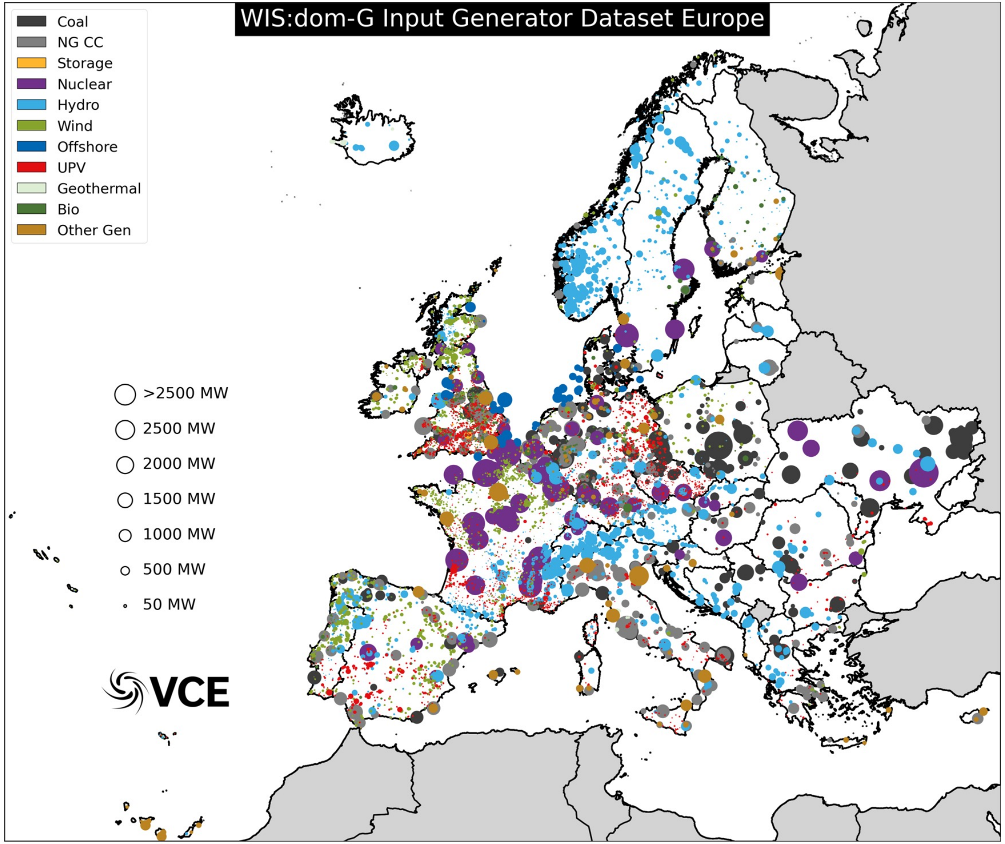

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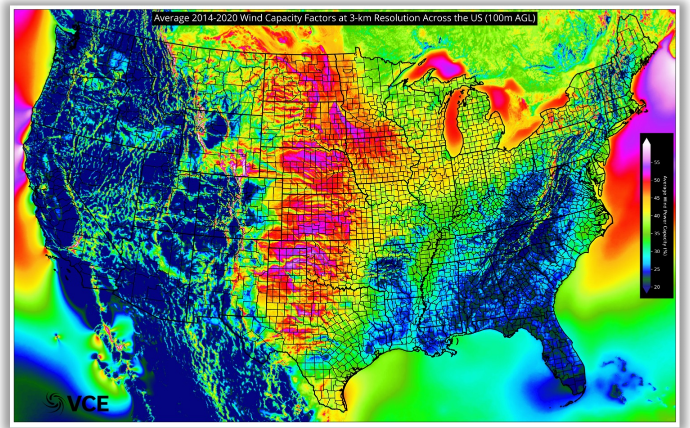
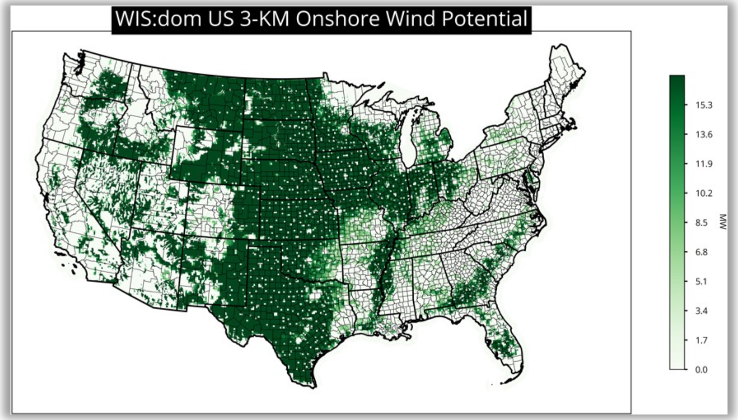
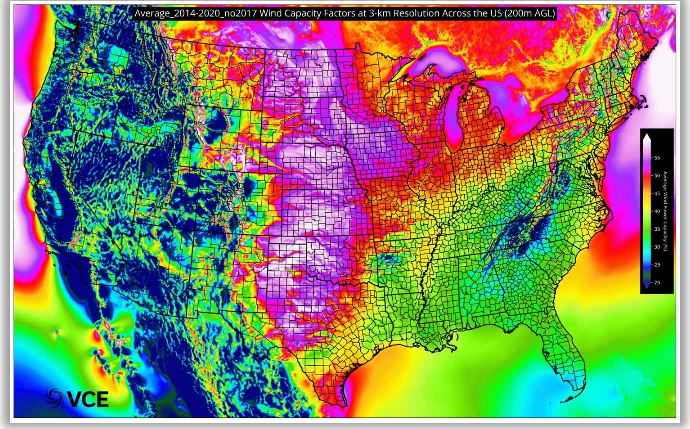
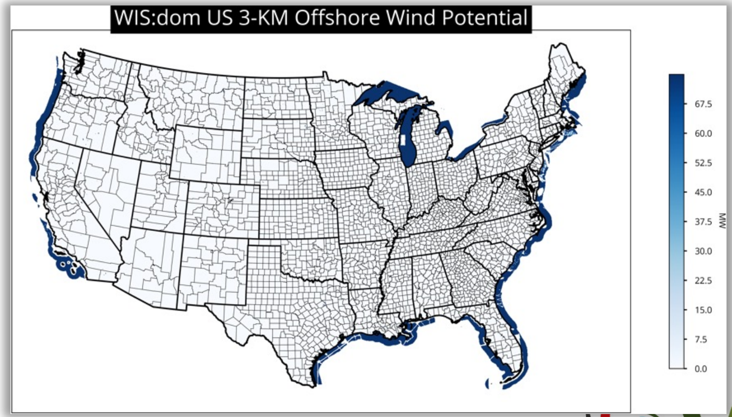
Wind Resource & Potential Siting

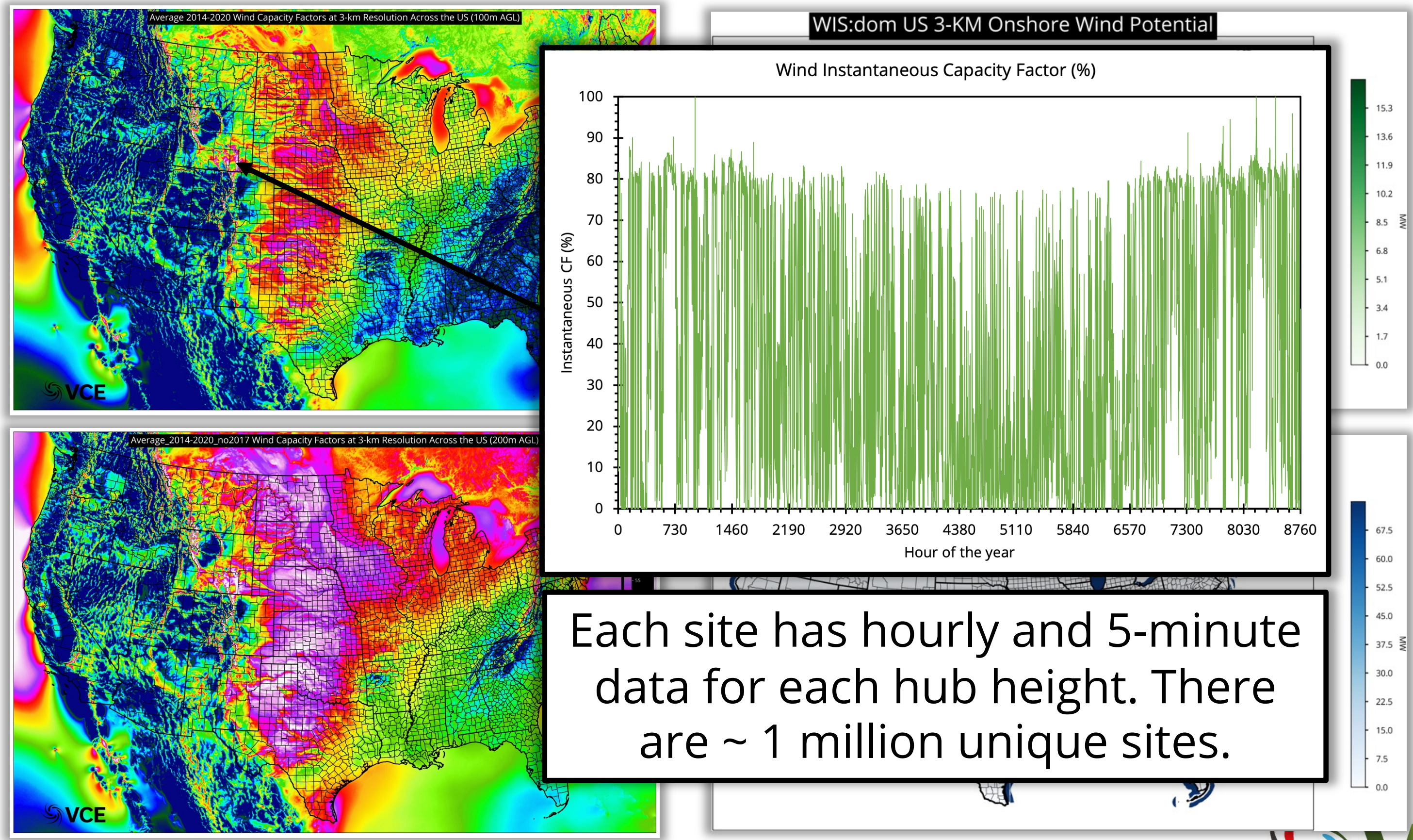






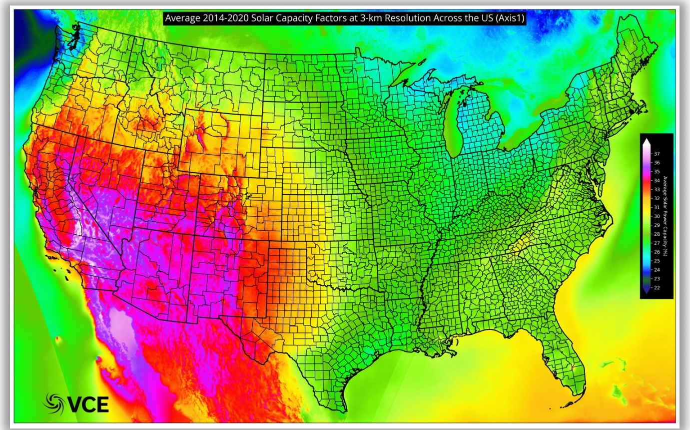


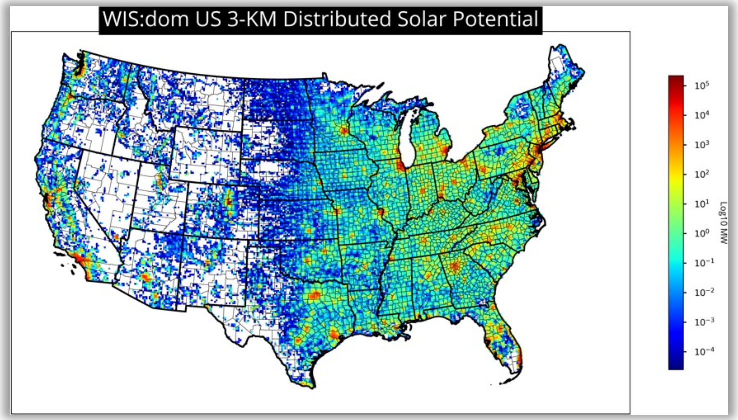
Wind Resource & Potential Siting

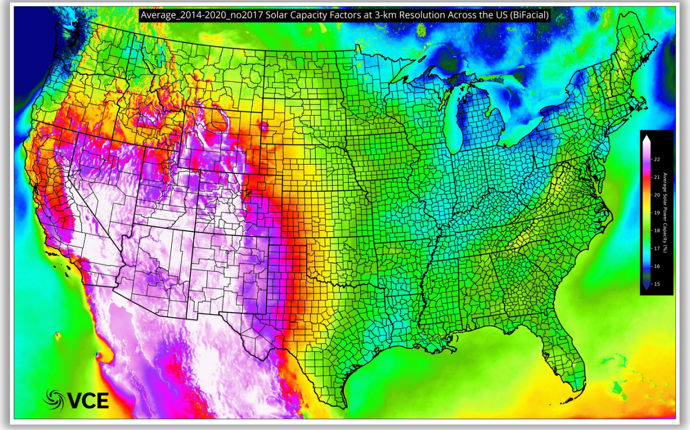


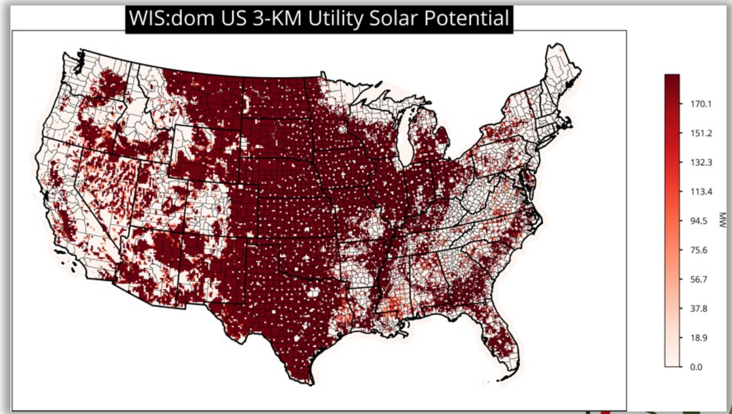
Each site has hourly and 5-minute data for each hub height. There are ~ 1 million unique sites.

Solar Resource & Potential Siting









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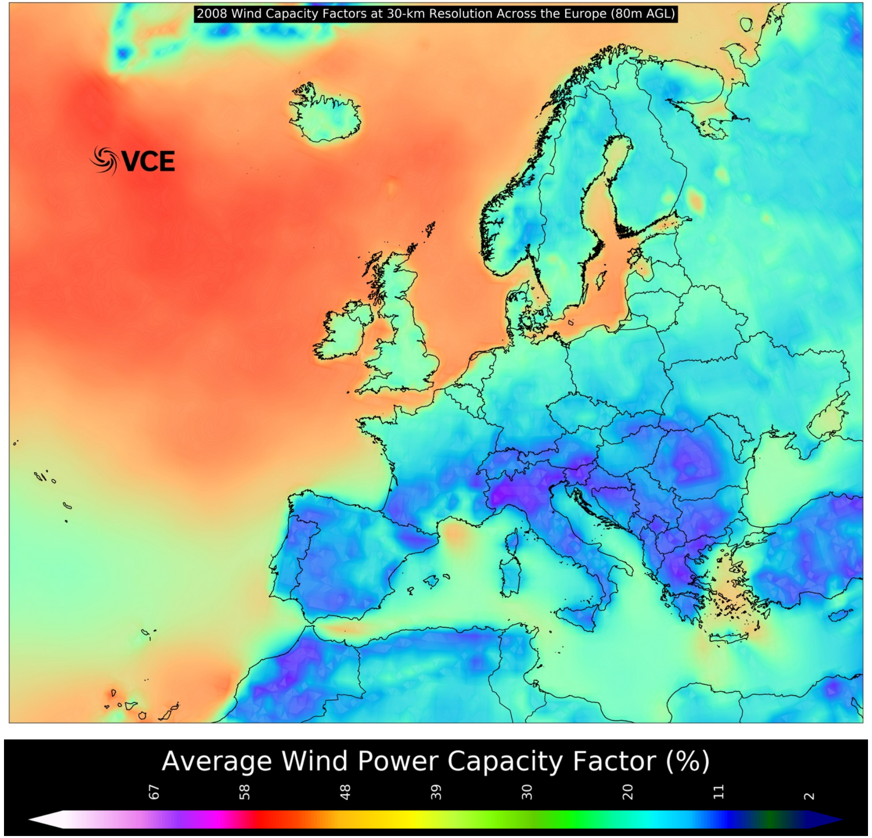
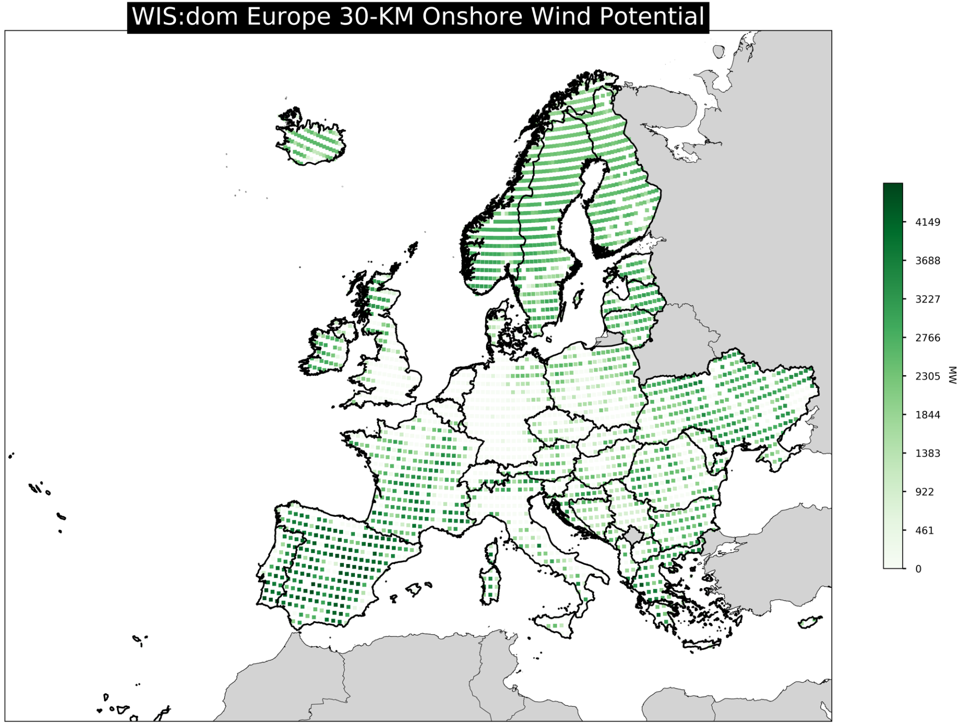
Wind Resource & Potential Siting





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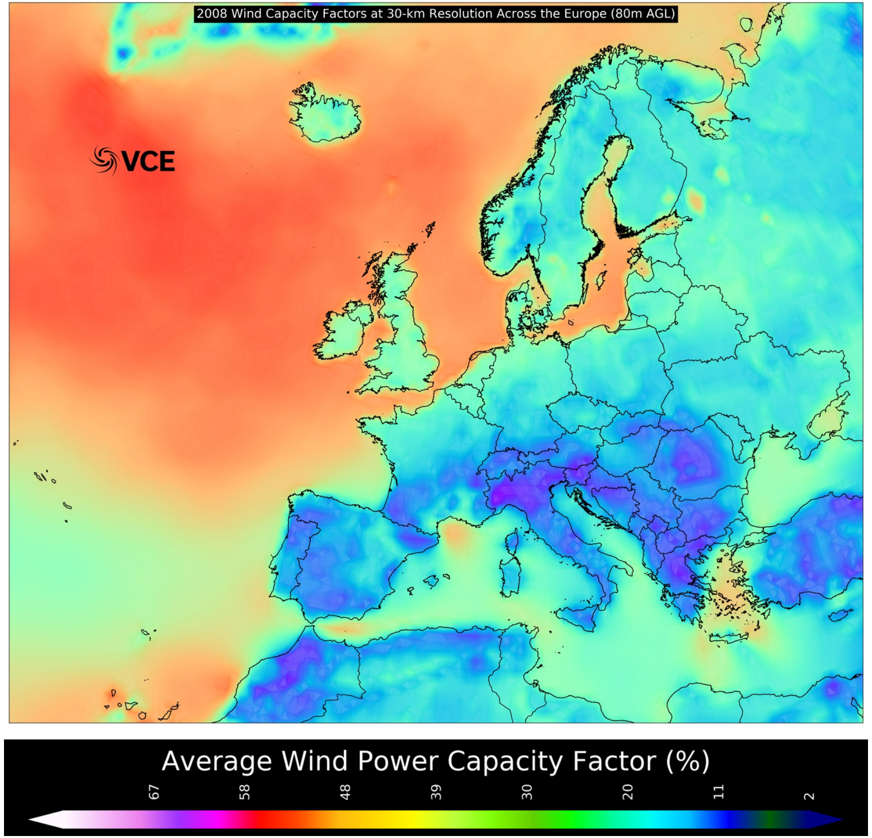

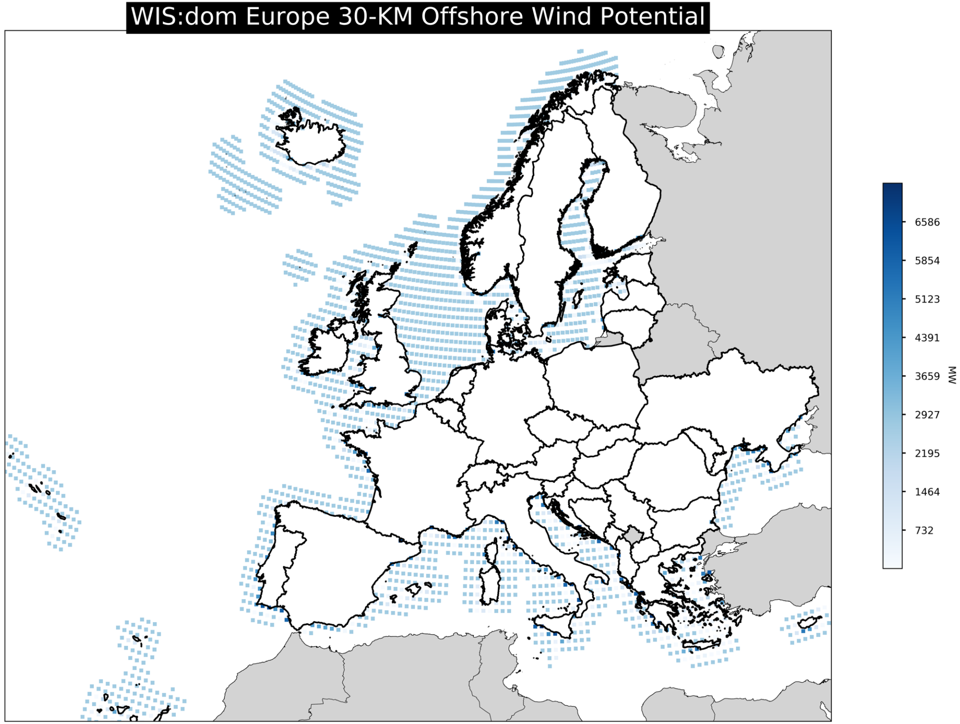

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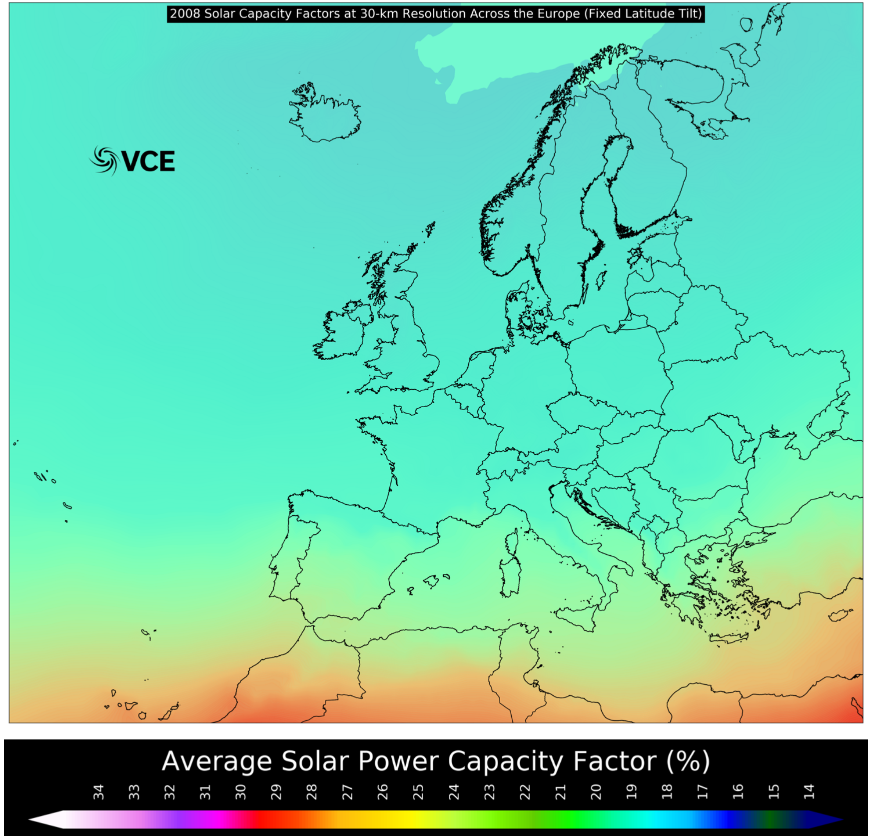

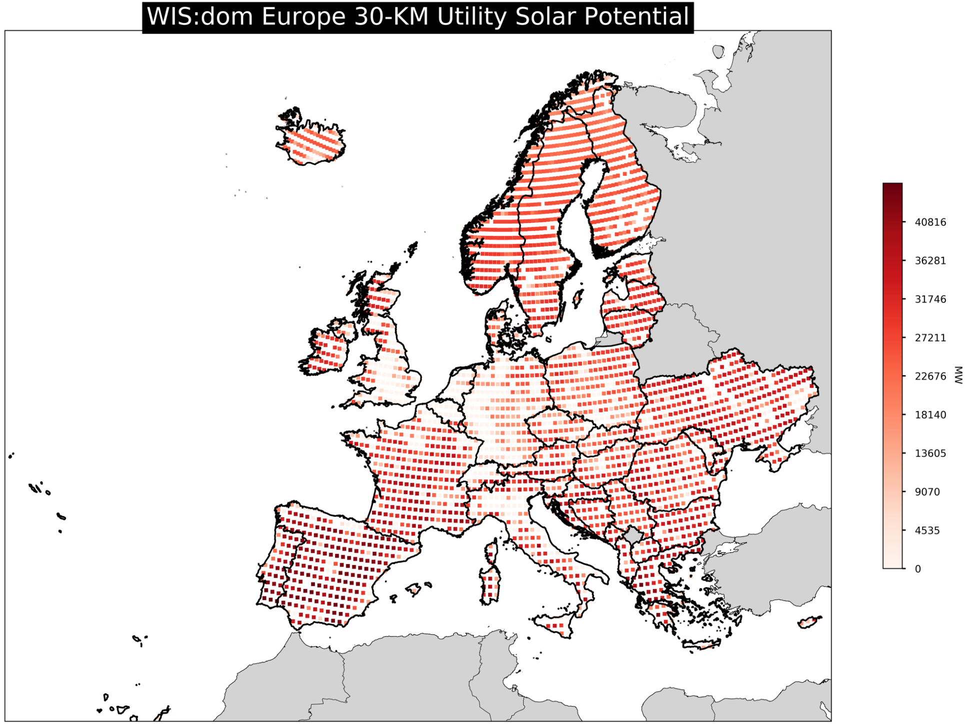

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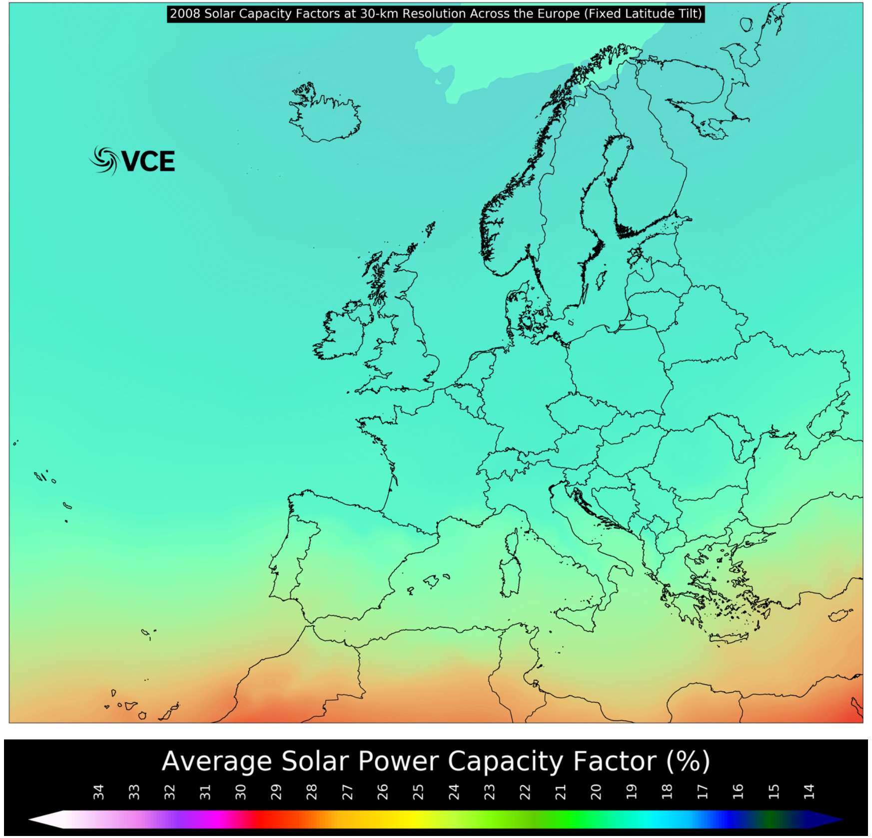

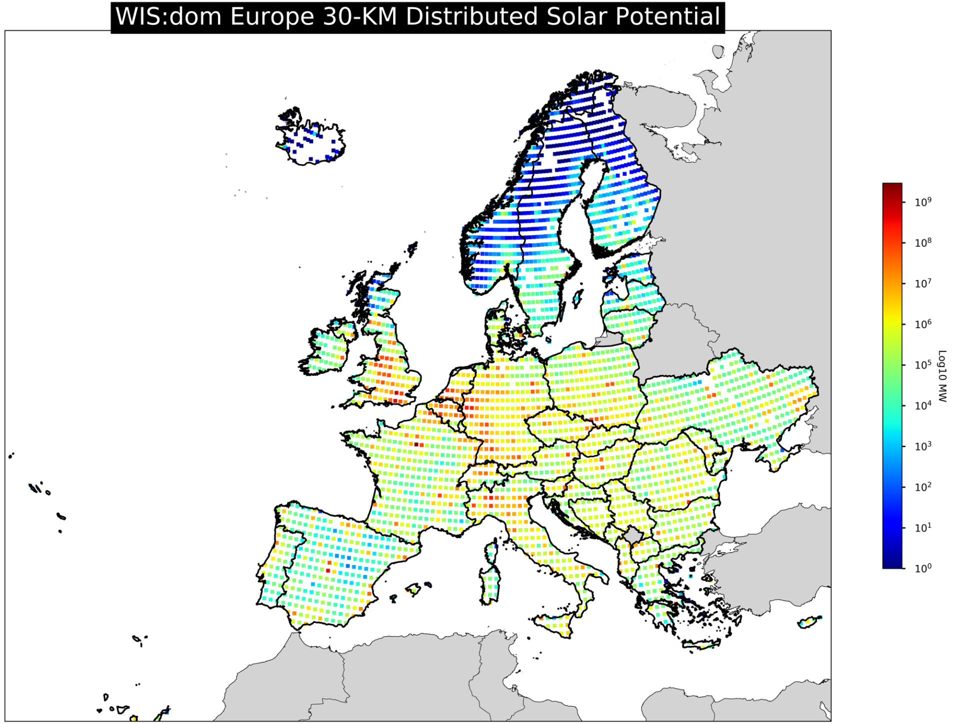

Global Heat Transfer Drives Wind & Solar Constantly

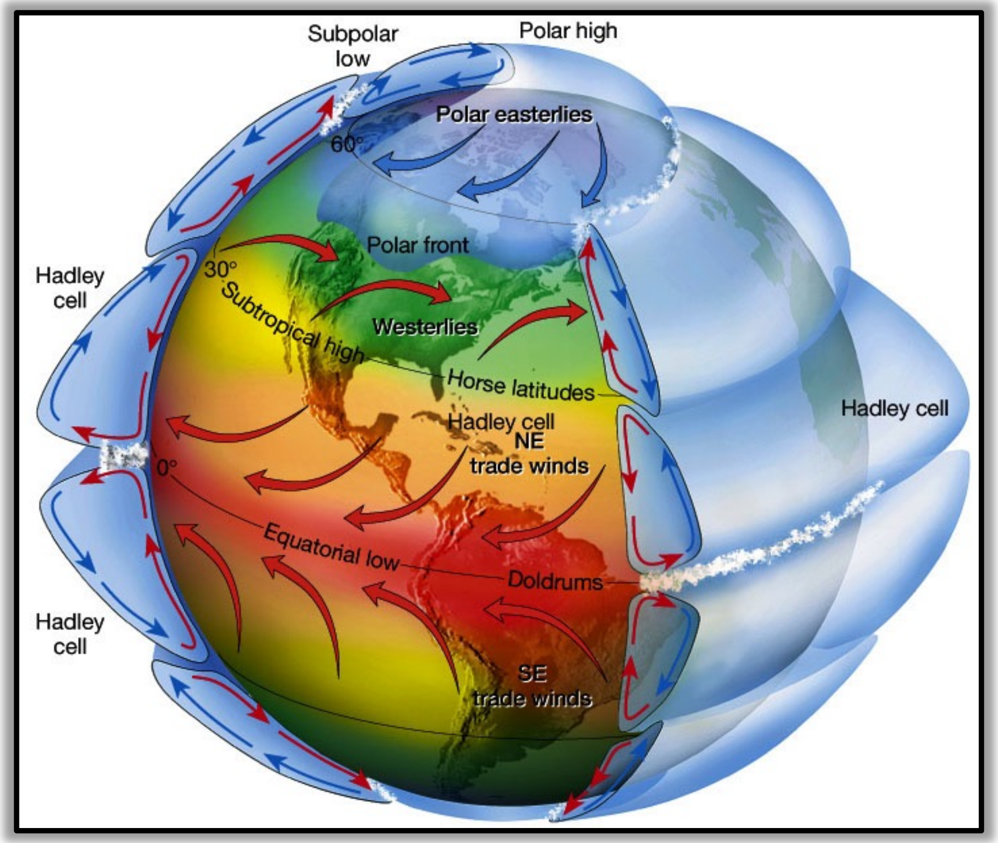

Image Credit: Figure 7.5 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001

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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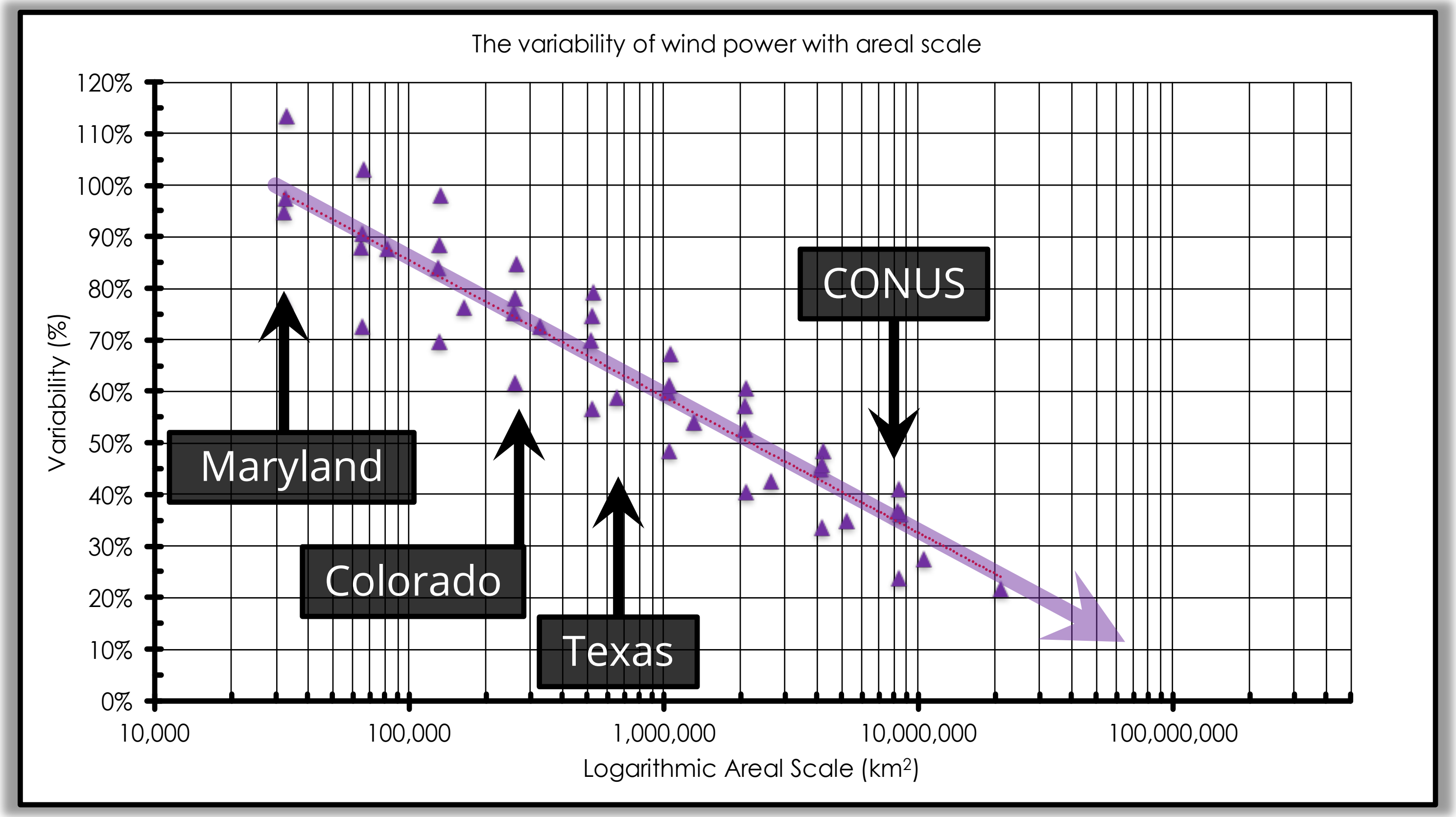
Variability Of Wind & Solar Shrinks With Larger Areas



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

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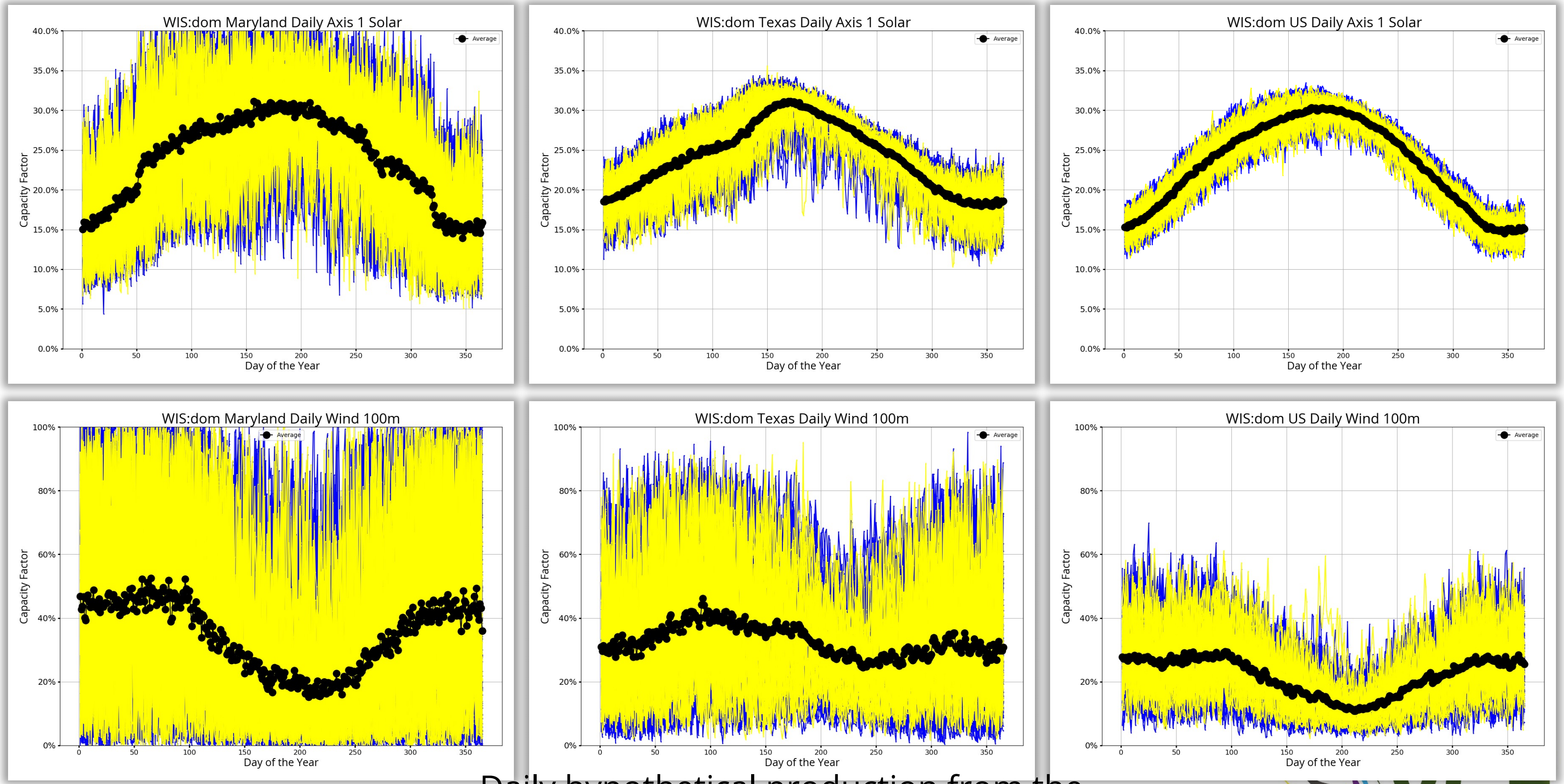

Daily hypothetical production from the VCE long-term dataset (1900-2015)

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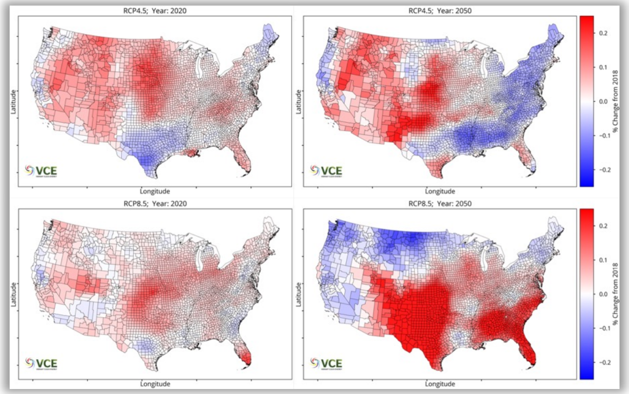
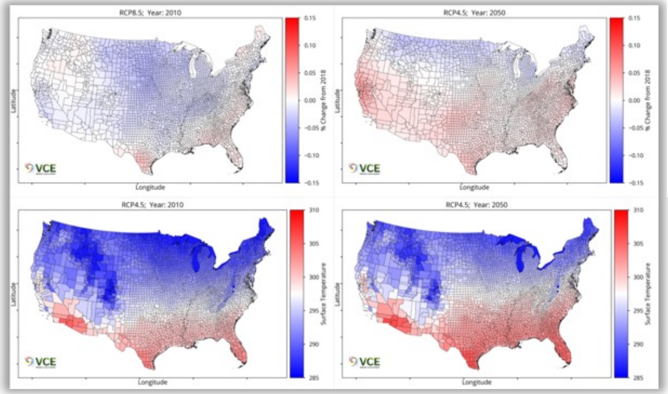
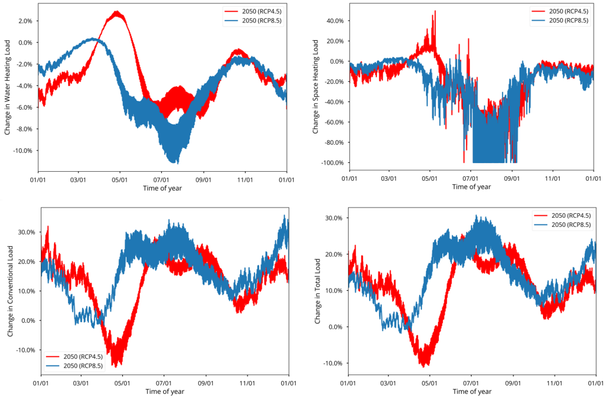
Climate Change Impact All Parts of the Energy System



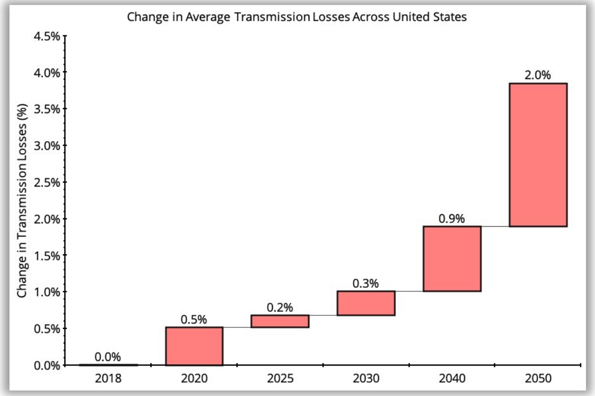
Wind



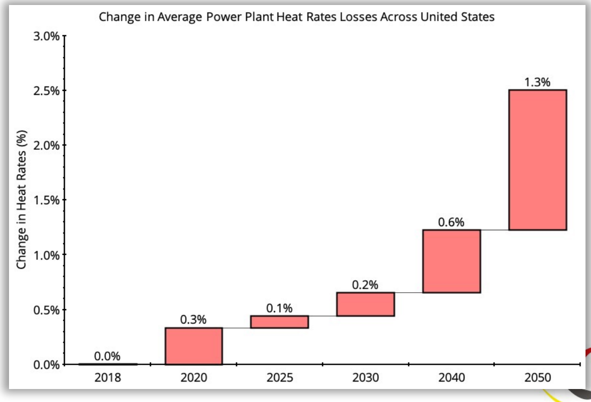
Solar



Demands



Tx Losses



Heat rates

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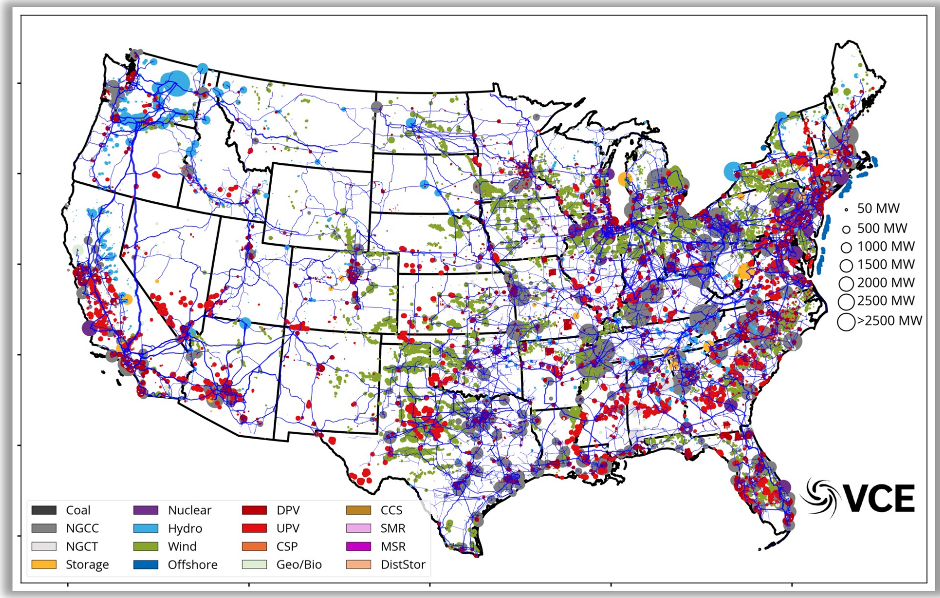
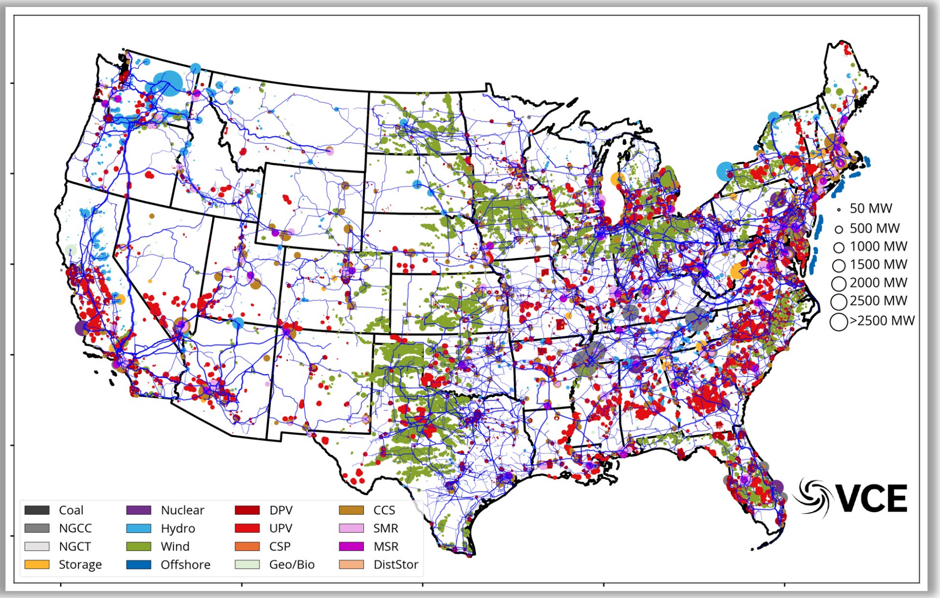
Resource Siting by 2035

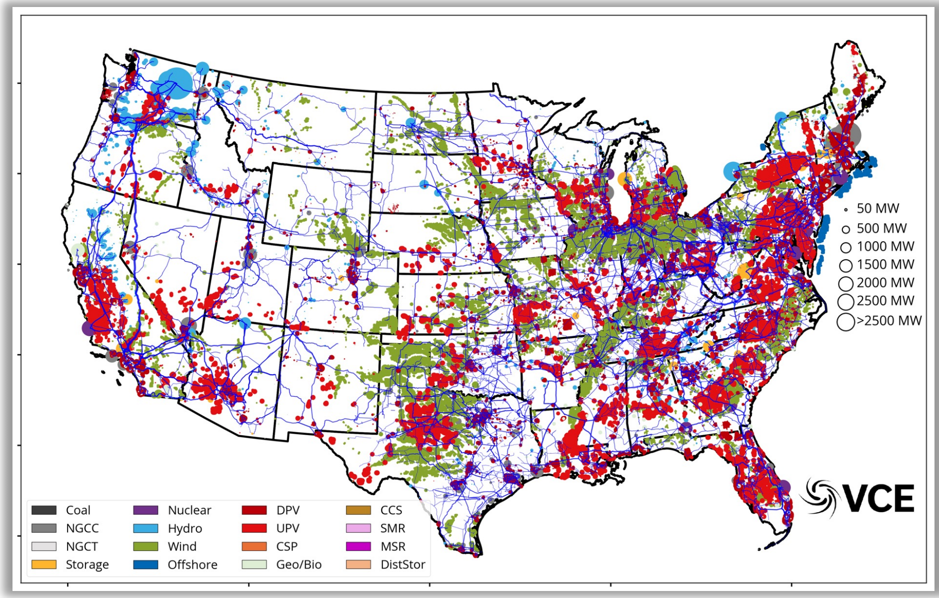


Without HVDC

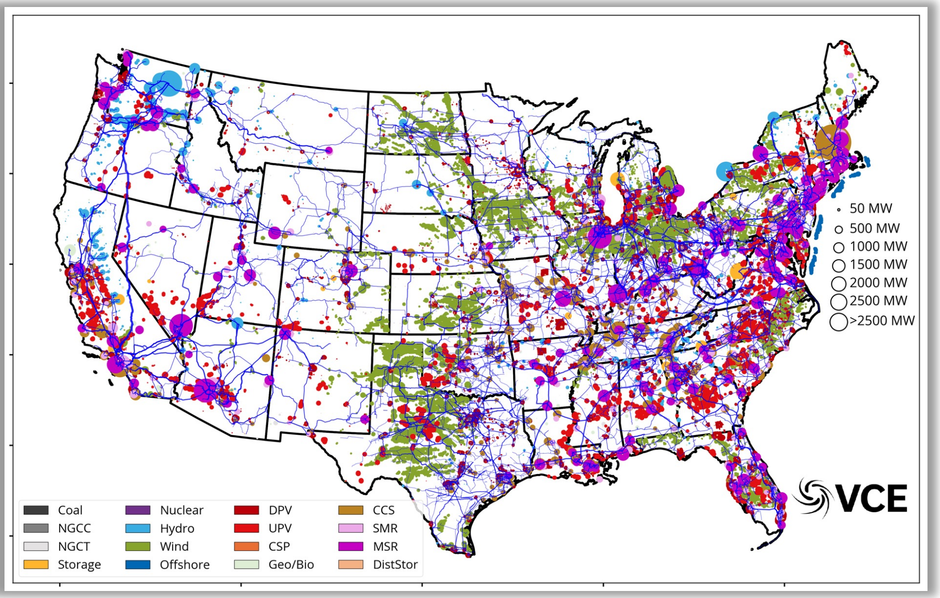


With HVDC

Resource Siting by 2050

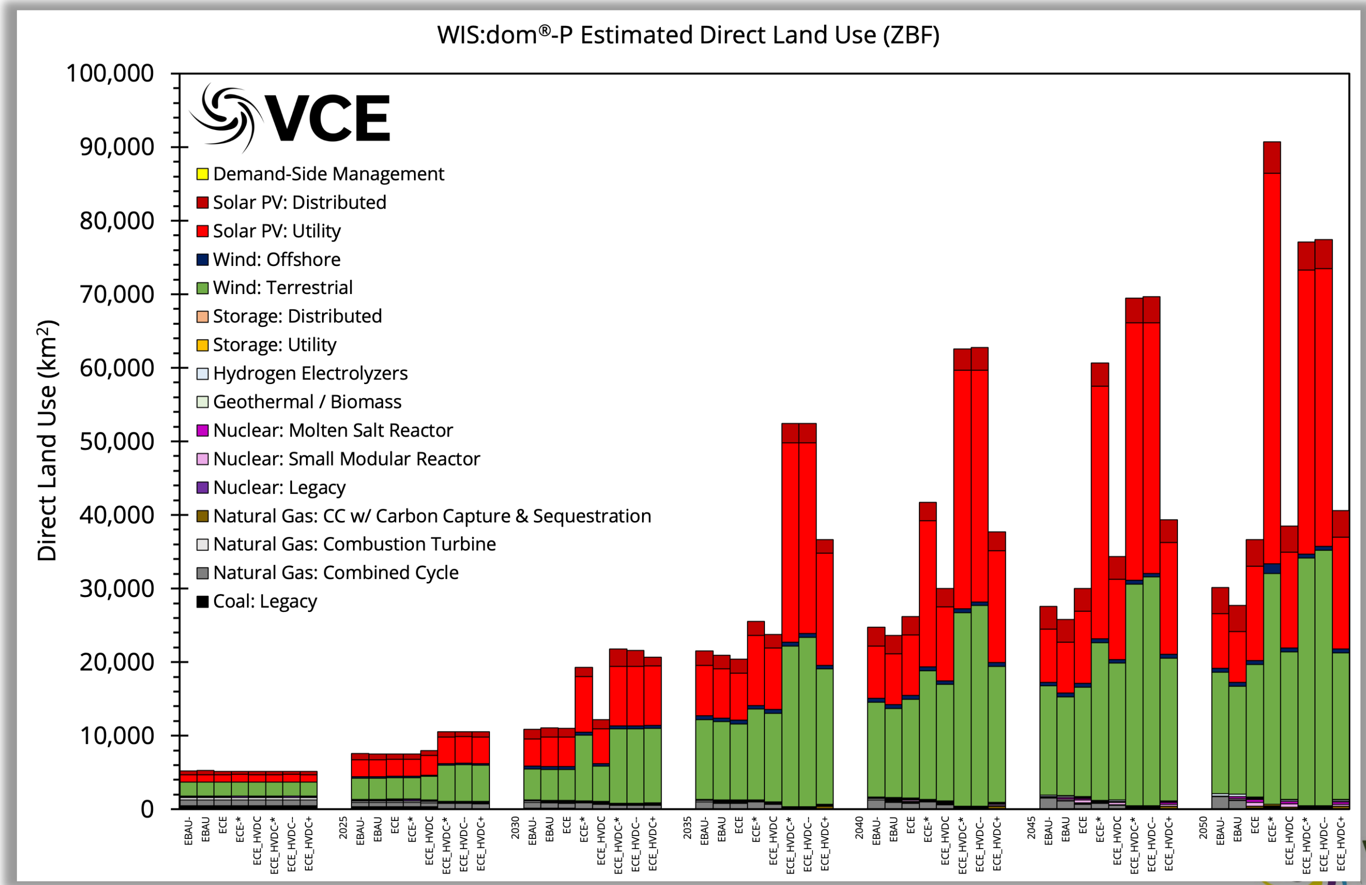


Without HVDC



With HVDC

Comparison of Direct Land Use



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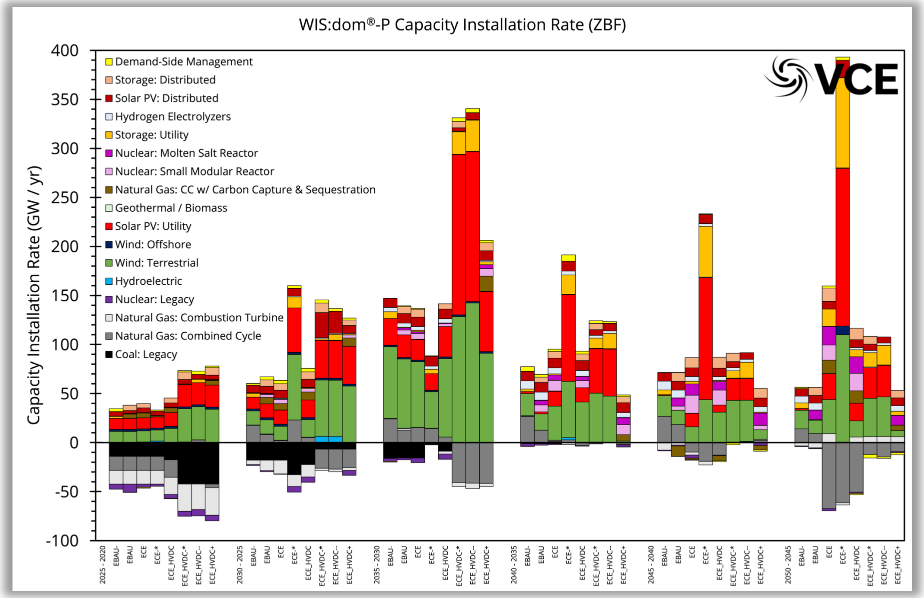
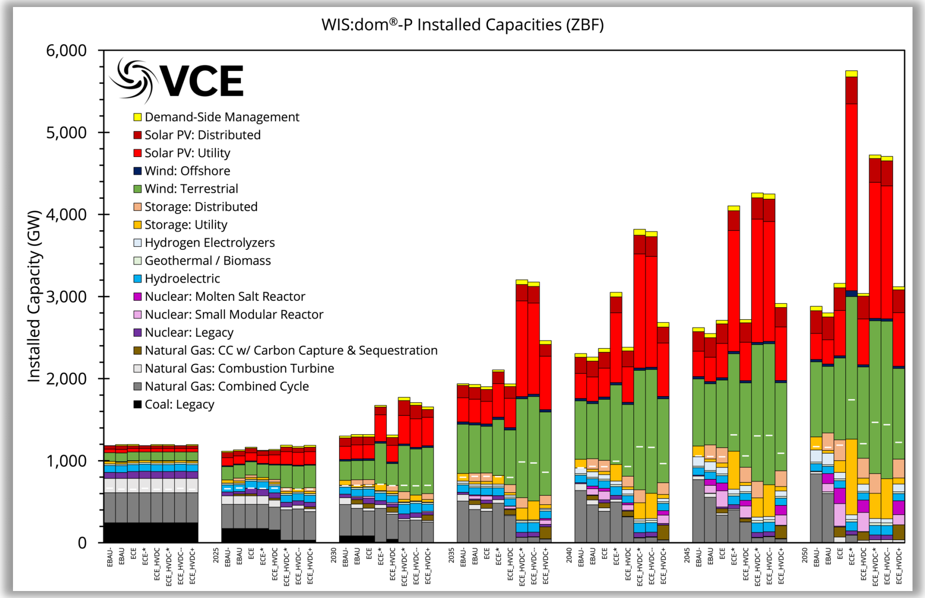
Generation Installation





Historical Average Net Installation Rate is 15.2 GW / yr

There is between ***1,000 & 2,500 GW*** additional installed capacity requirement when HVDC transmission or dense clean generation are omitted

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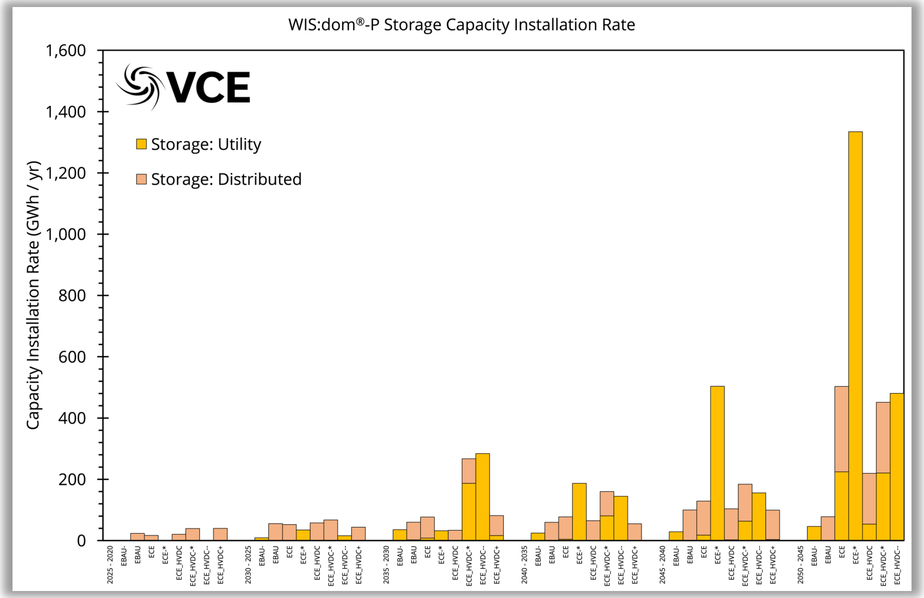
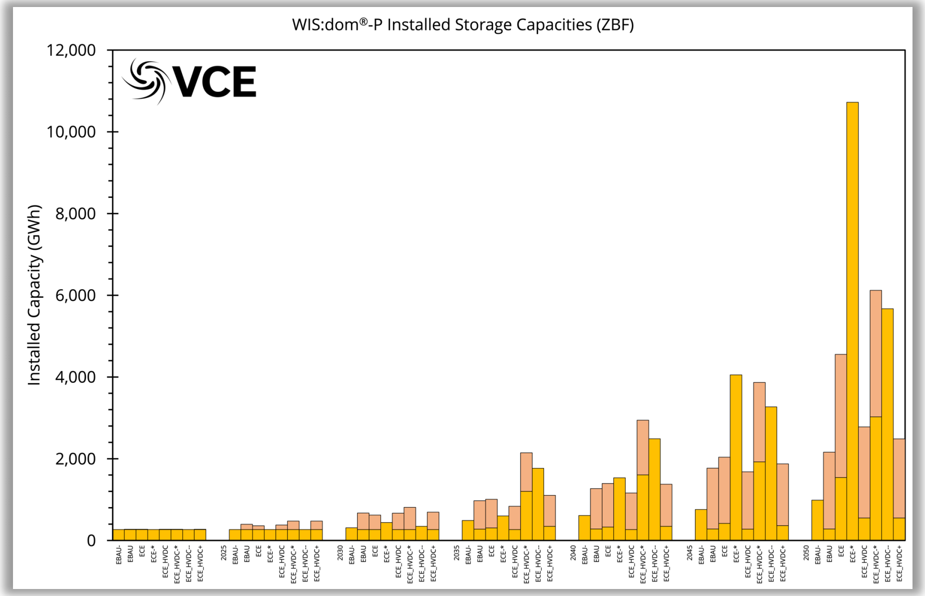
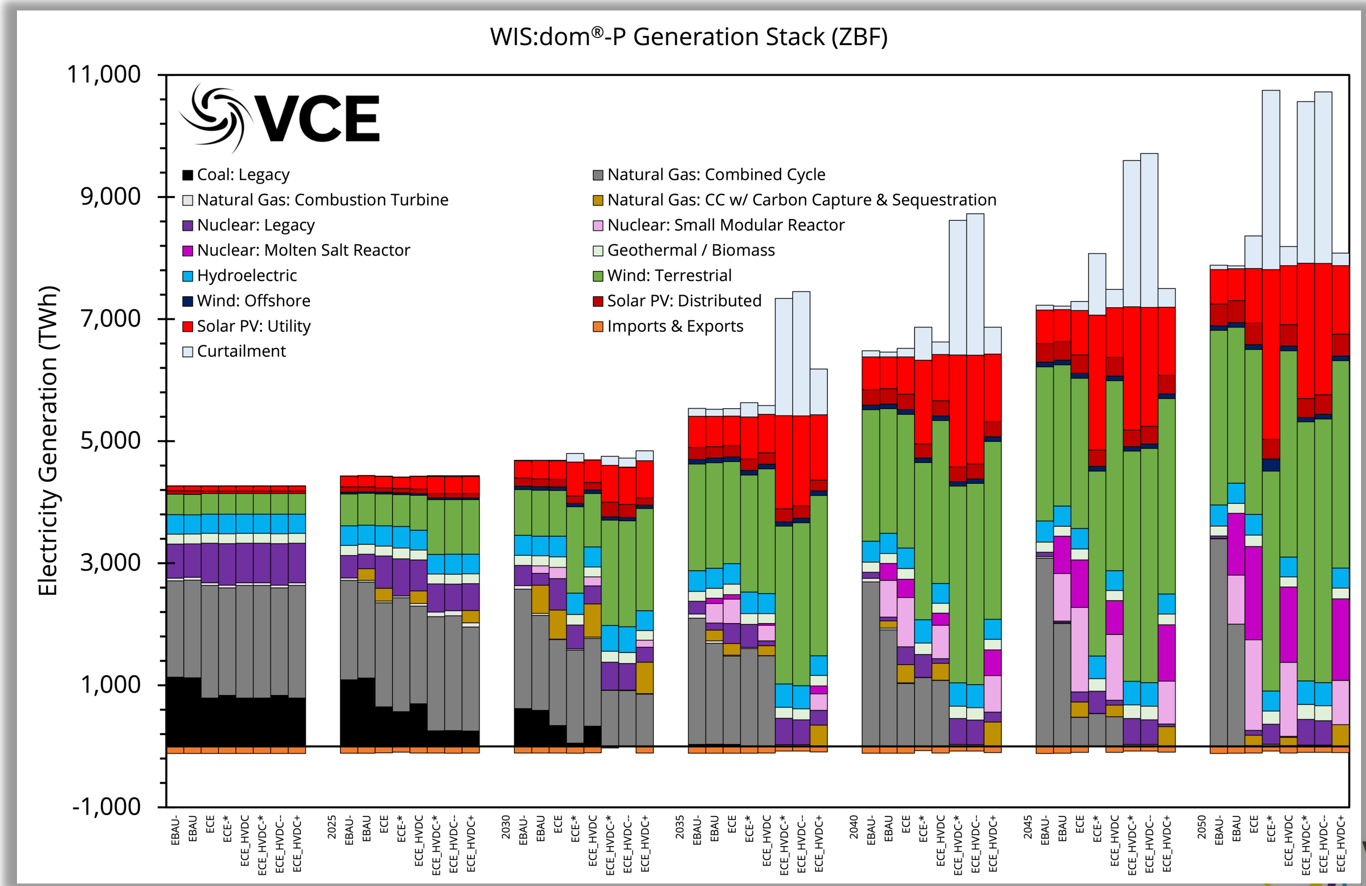
Storage Installation & Rate





With HVDC available the maximum duration of storage required is 8 hours. When it is not available, the maximum storage duration is 12 hours (with much larger peak power requirements as well). Note that hydrogen is used as longer duration storage; but crucially, not as generation fuel supply, but rather as a fungible demand that creates products for other economic sectors.

Generation Composition



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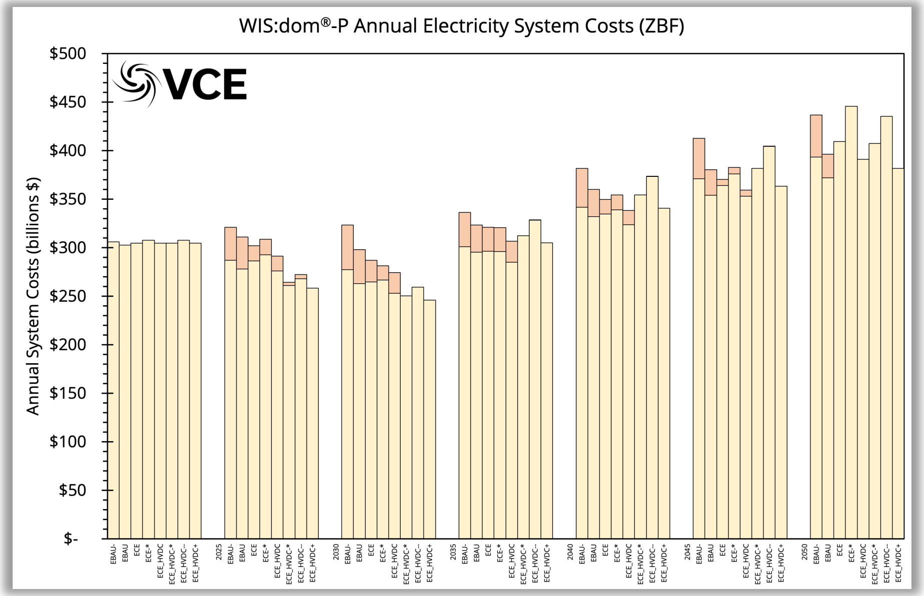
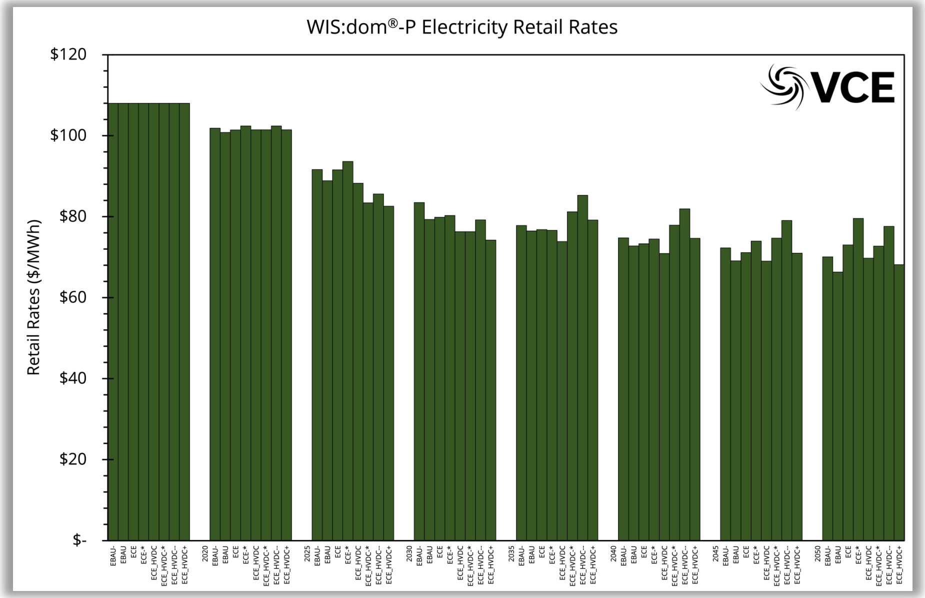
System Costs & Retail Rates





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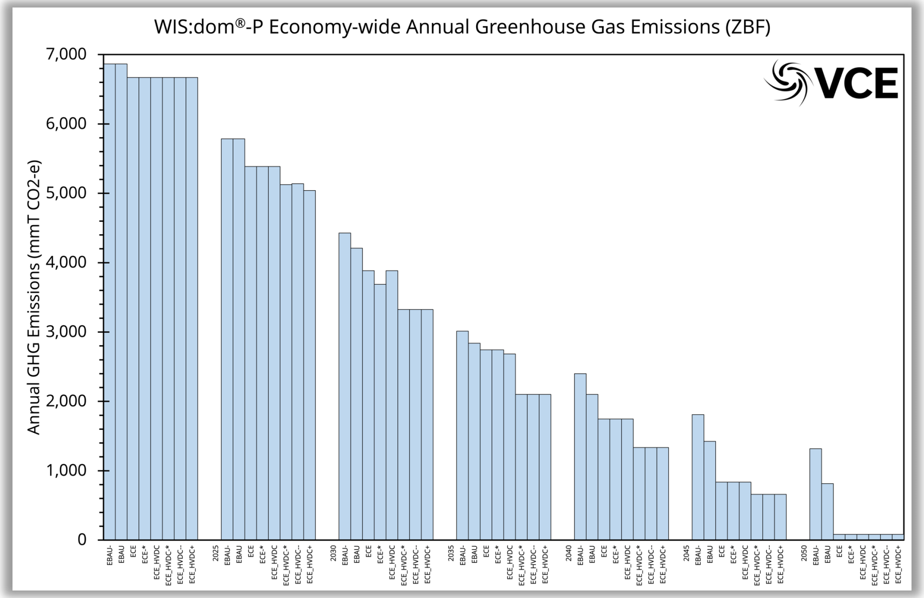
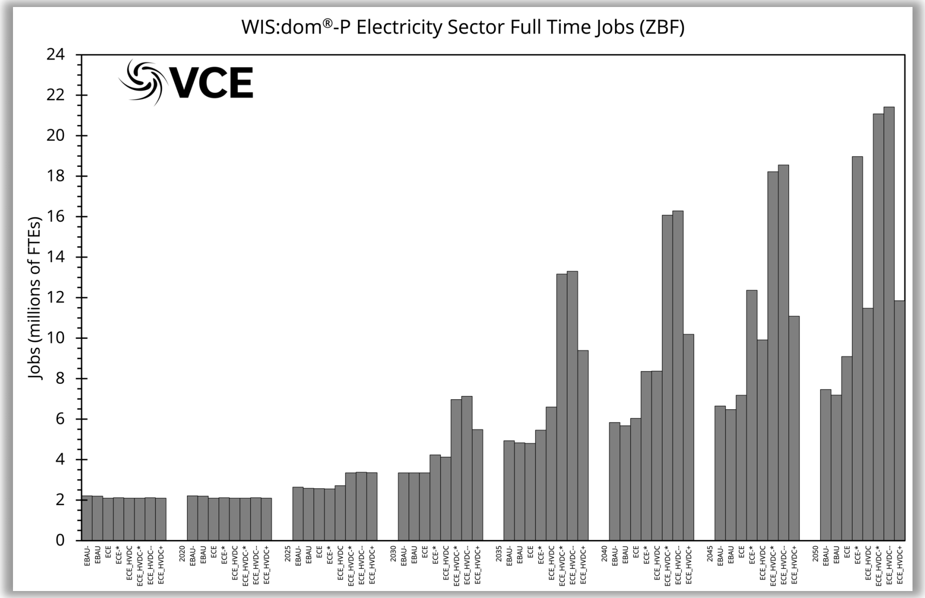
Economy-wide GHG Emissions & Full-time Jobs





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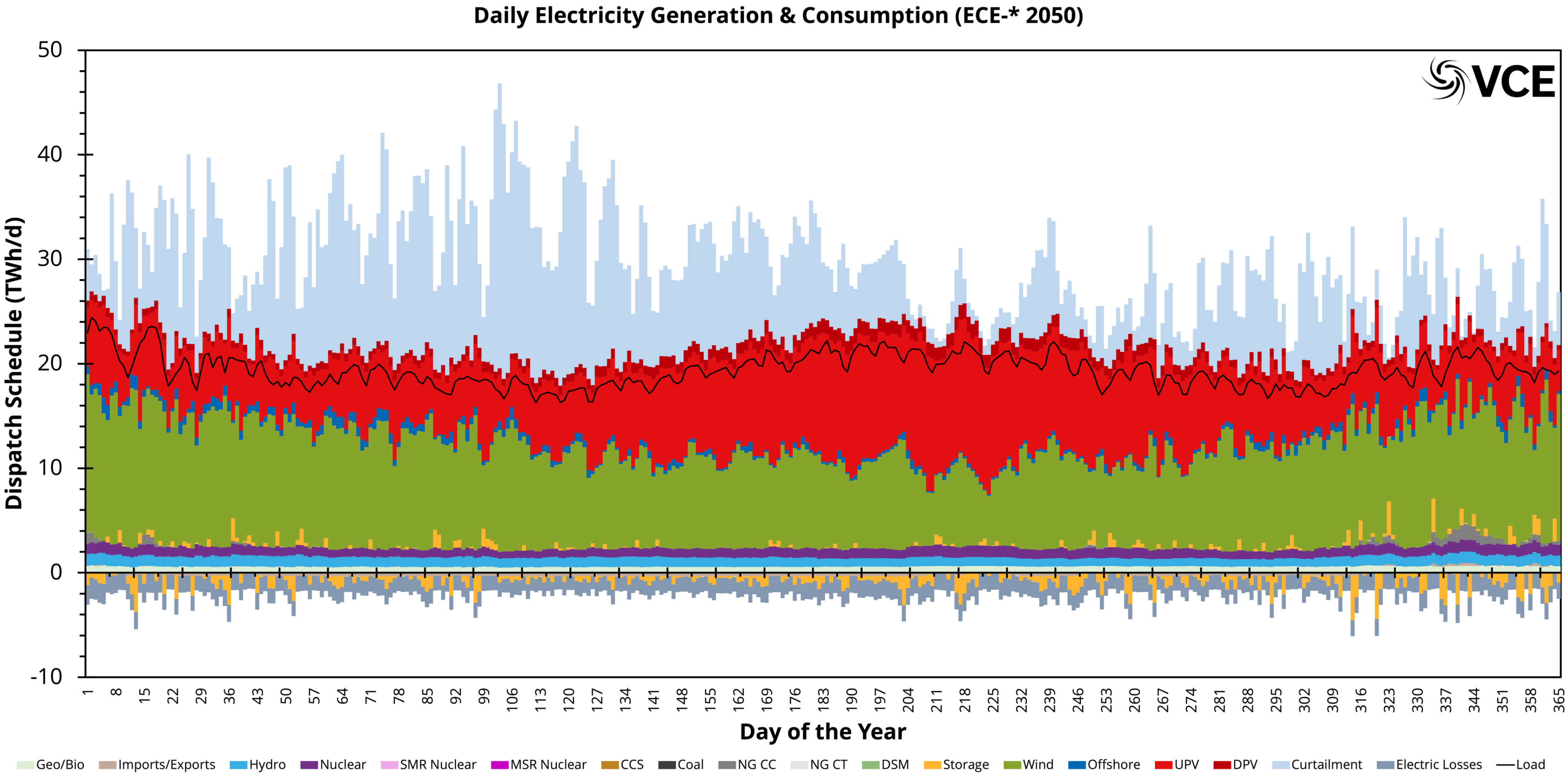
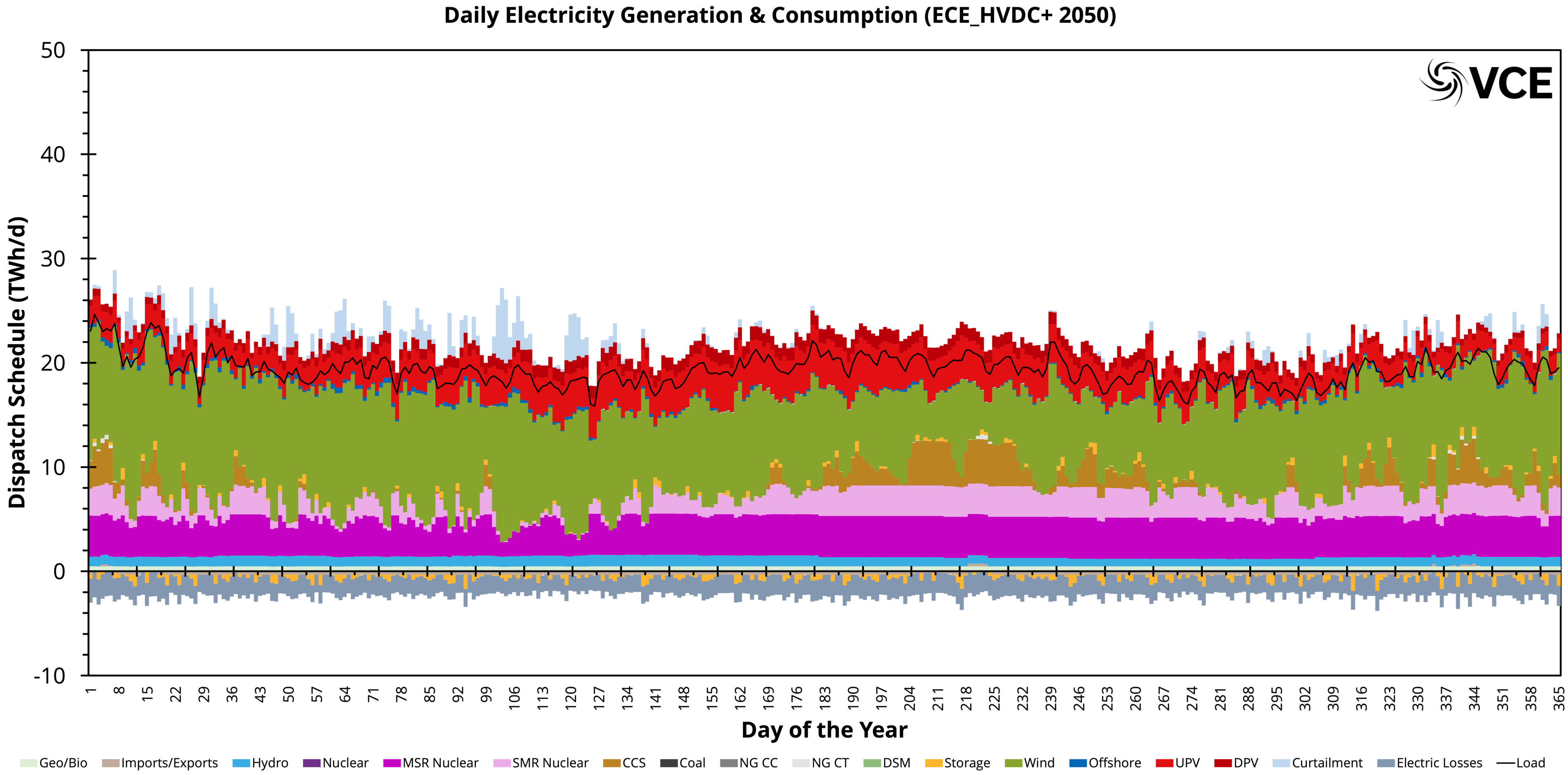
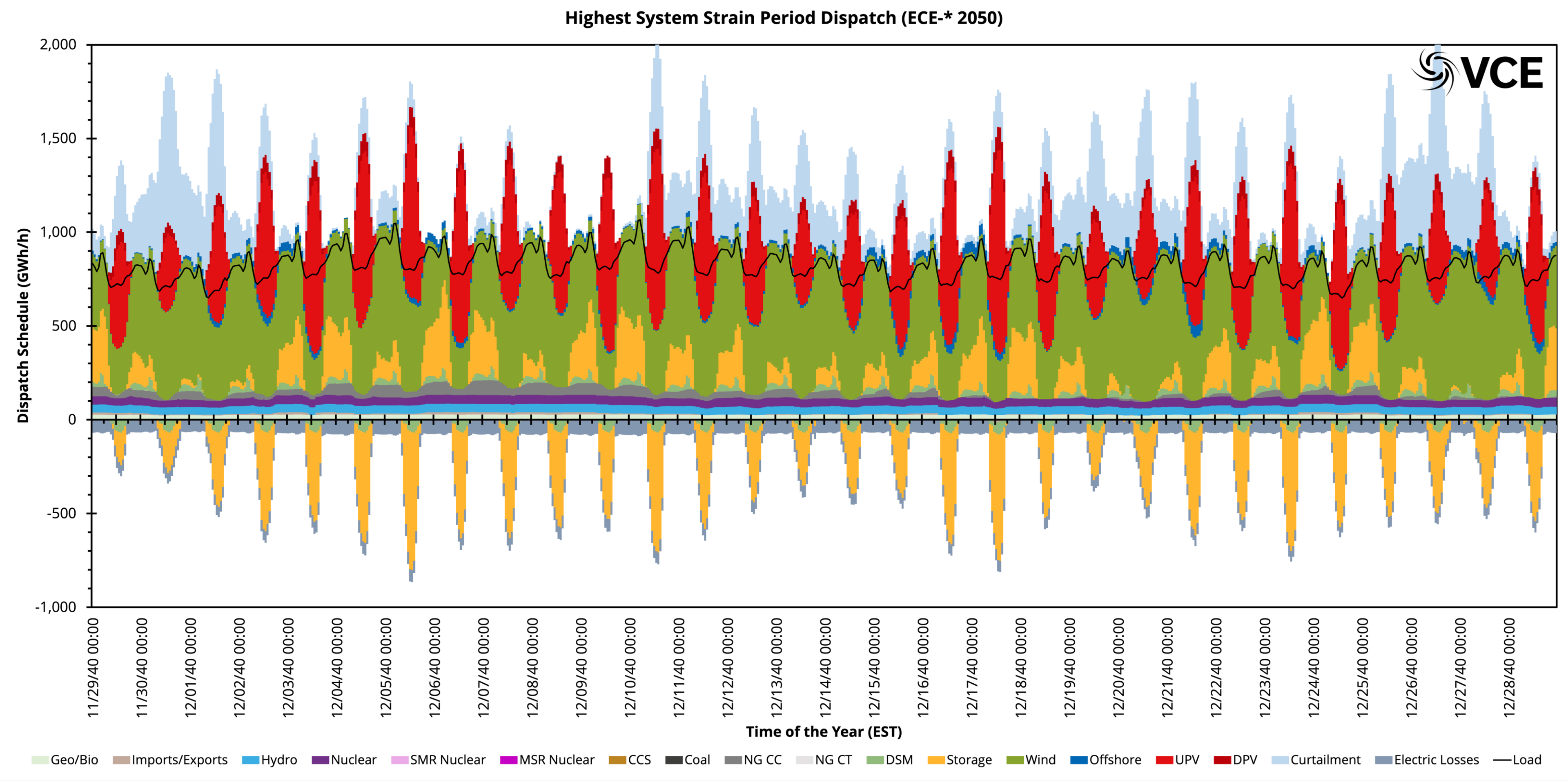
Dispatch of the System (No HVDC or Clean Dense Generation)



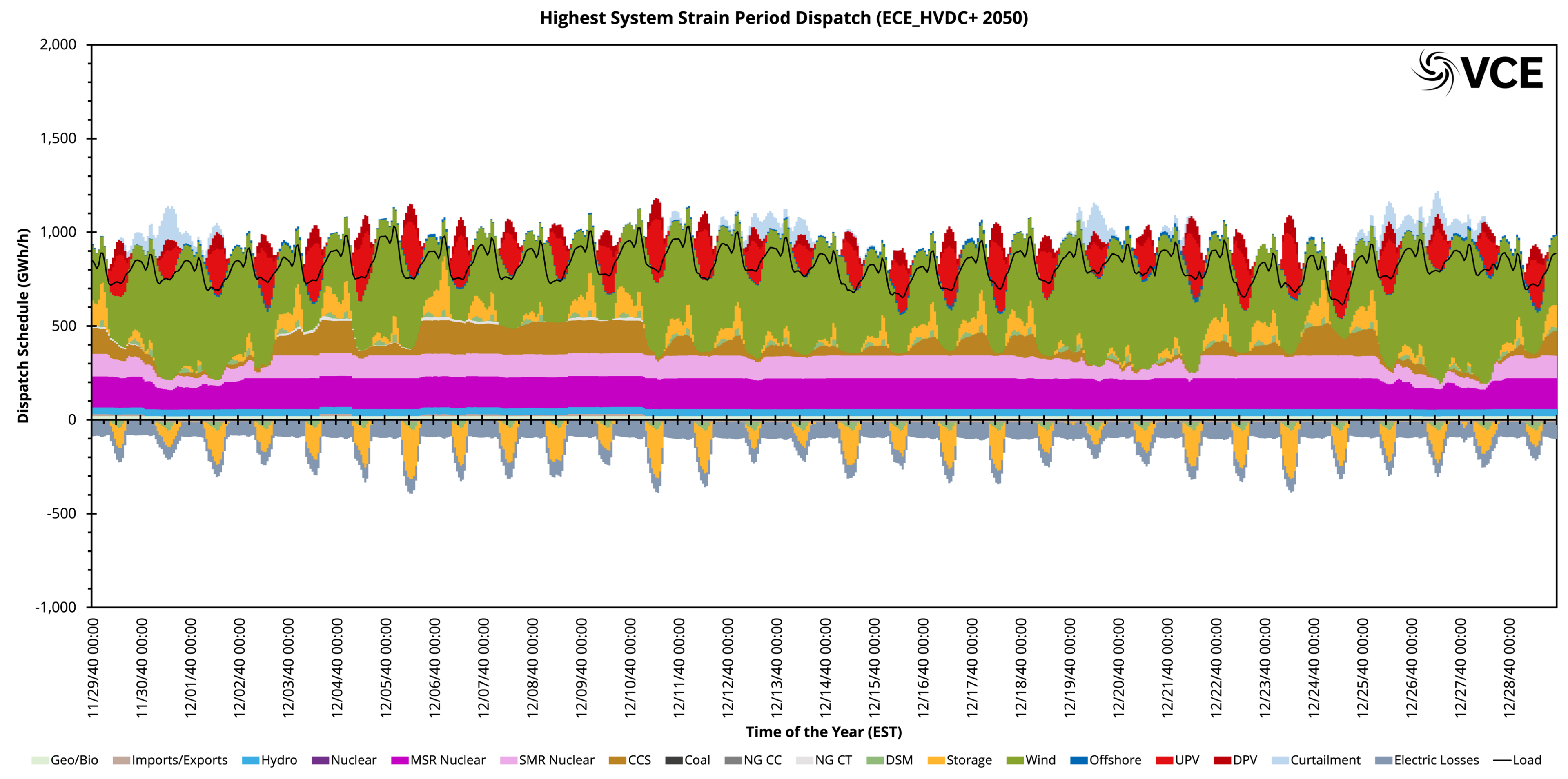
Dispatch of the System (With HVDC & Clean Dense Generation)



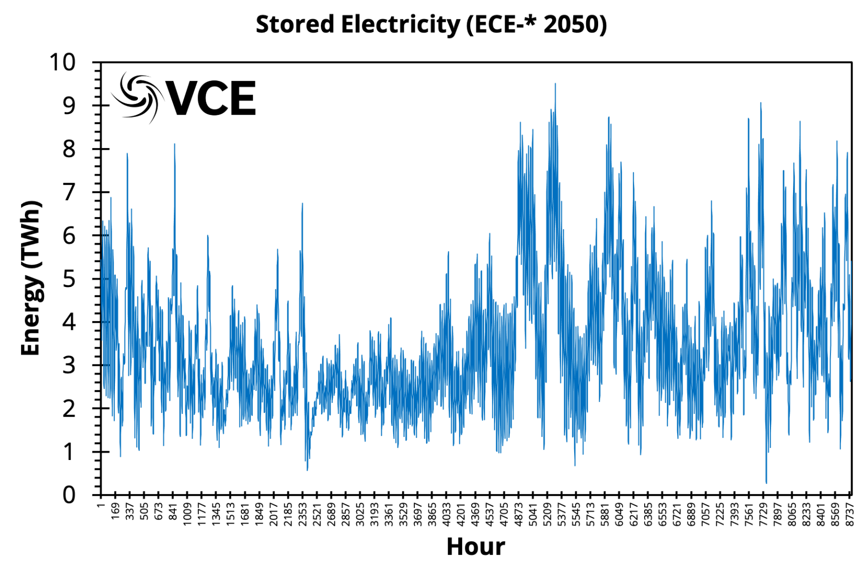
Dealing with Worst Weather & Demand Combinations (No HVDC or Clean Dense Generation)



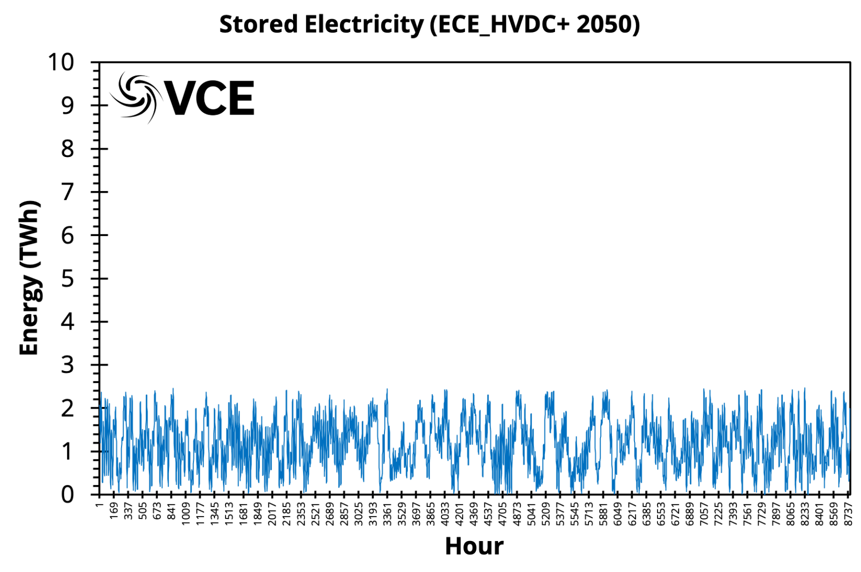
Dealing with Worst Weather & Demand Combinations (With HVDC & Clean Dense Generation)



Behavior of Electric Storage



Without HVDC



With HVDC

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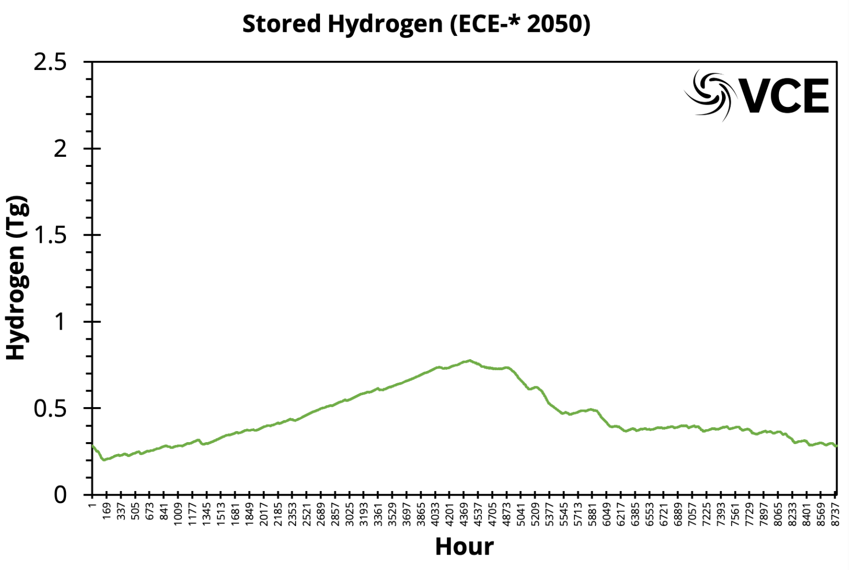
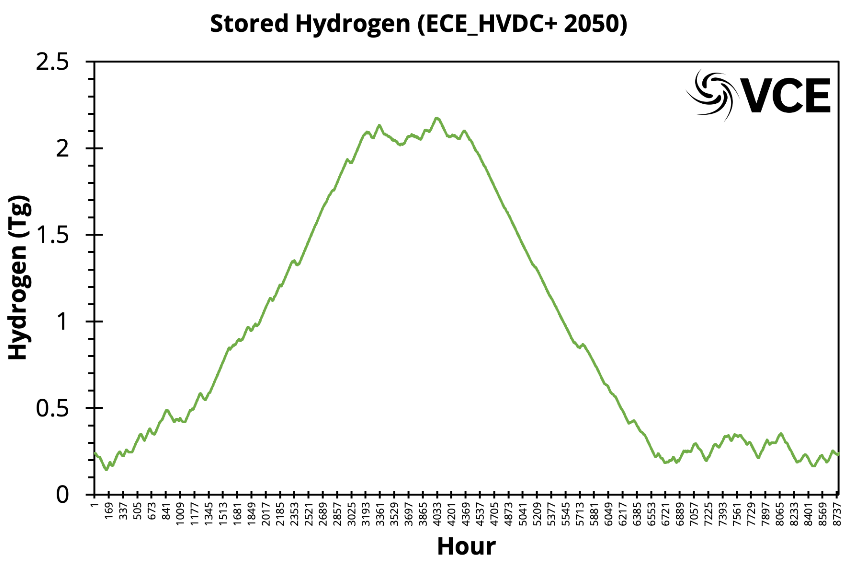
Behavior of Hydrogen Storage



Without HVDC



With HVDC

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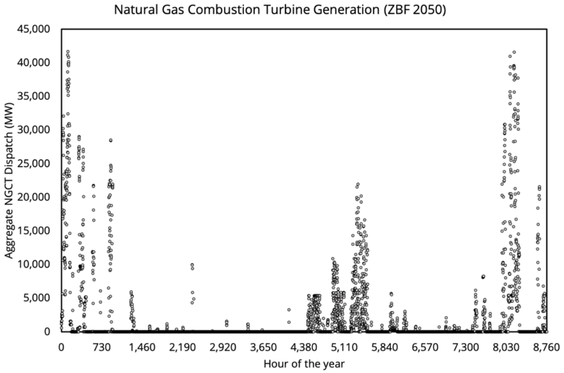
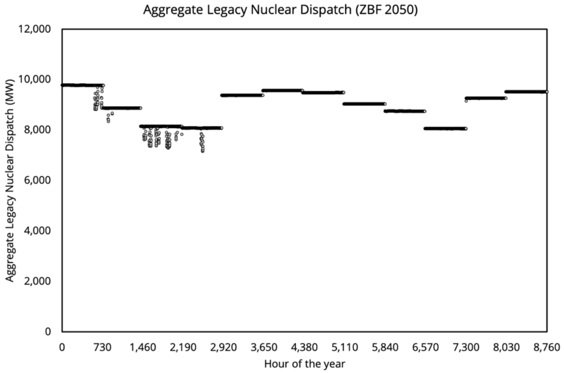
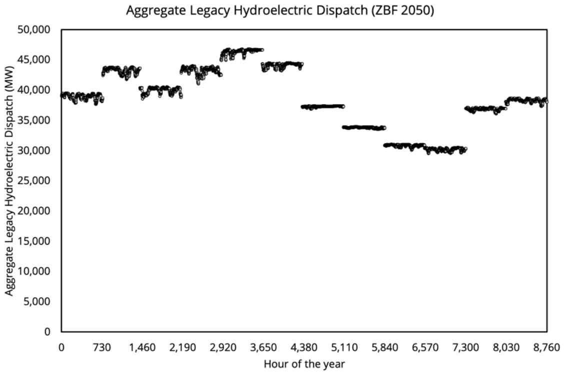
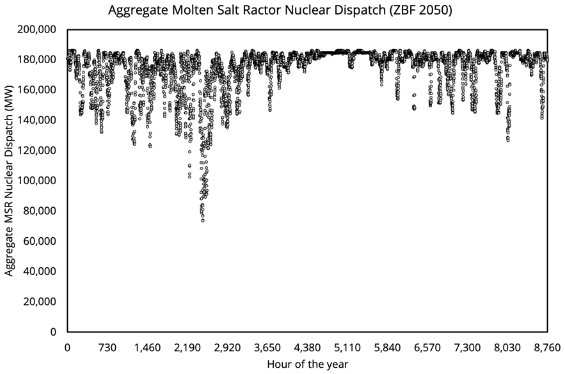
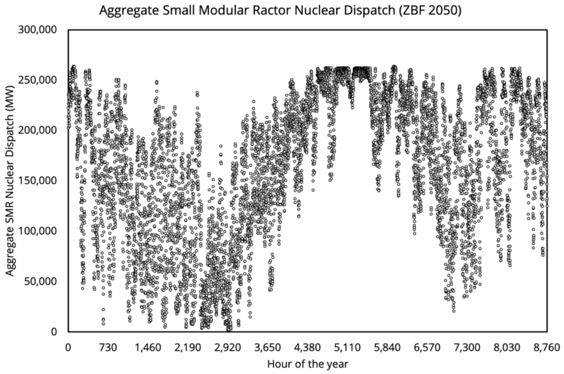
Example Dispatch of Generation (2050)

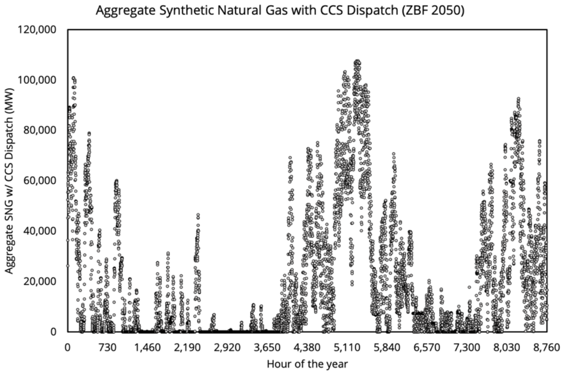












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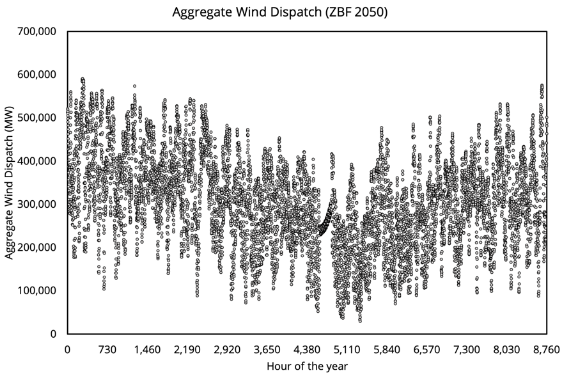

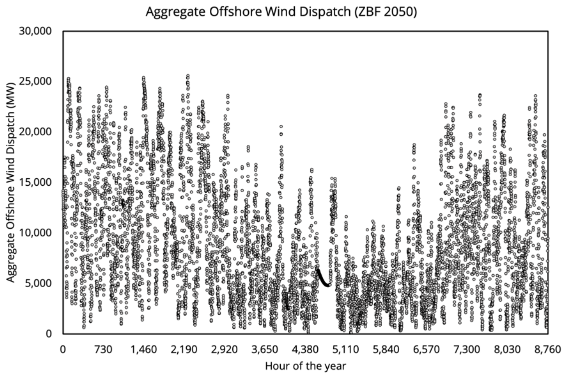

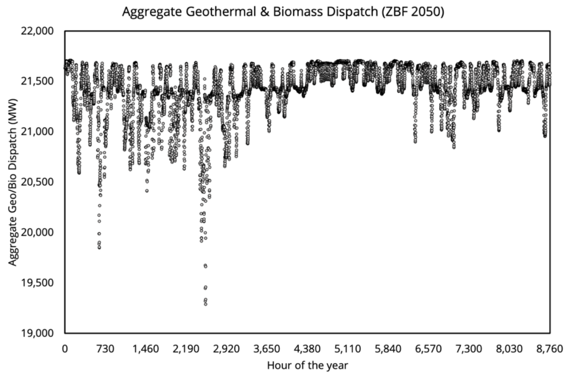

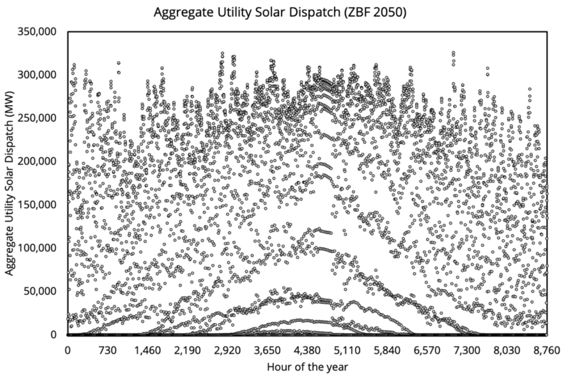

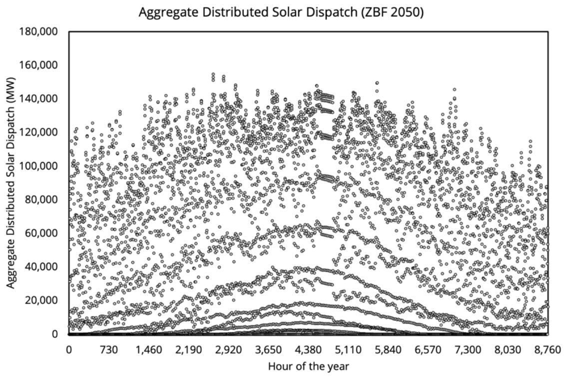

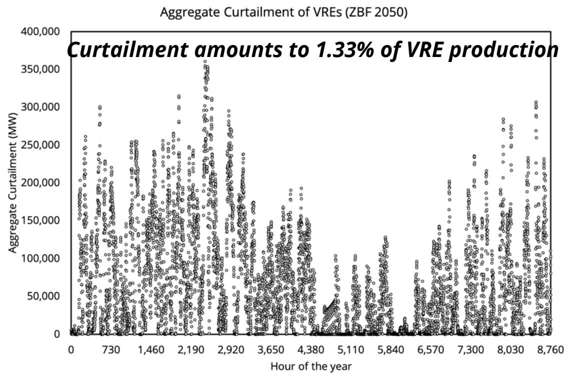

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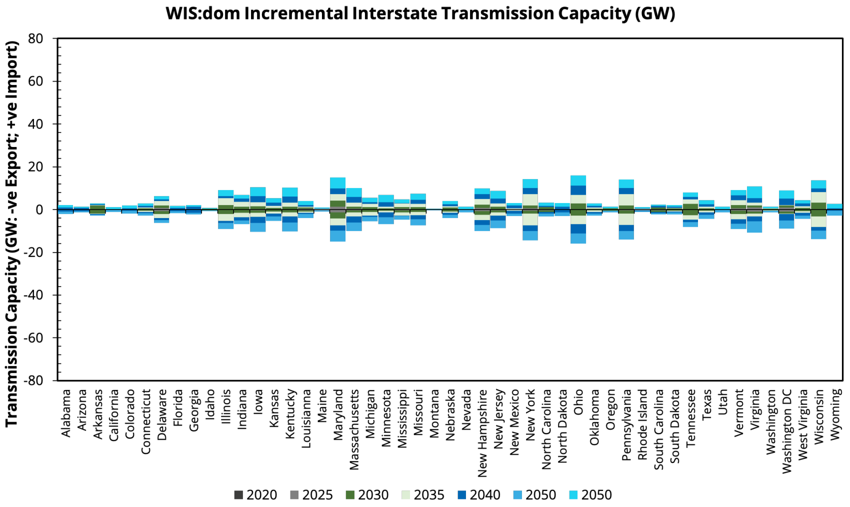
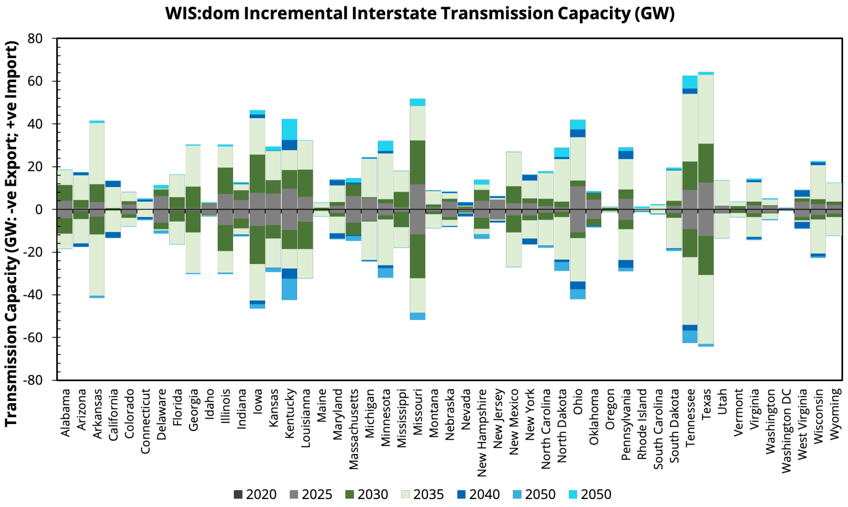
Behavior of Hydrogen Storage



Without HVDC



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Agenda

1. Introduction & Motivation.
2. Overview of the WIS:dom-P (USA) & WIS:dom-G (Global) modeling suites.
3. Details on & importance of the weather / power datasets.
4. Decarbonization of the United States Economy by 2050 (zero2050usa.com).
5. Decarbonization of Europe by 2050 (forthcoming).
6. Discussion & Questions.

Broad Results (Full Results Not Ready Yet: Sorry!)

Modeling has shown that Europe can reduce economy-wide GHG emissions to near-zero by 2050 by installing:

1. 800 GW of onshore wind;
2. 210 GW of offshore wind;
3. 1,150 GW of utility- and distributed-scale solar photovoltaic;
4. Retain the approximately 120 GW of nuclear (if not, then another 800 GW of solar PV is required);
5. Storage with capacity of 170 GW and 14 hours of energy;
6. Retire all coal- and natural gas- fired power plants;
7. Include an HVDC overlay (or at least increase all cross-border transfers to be able to handle 4x of 2020 levels;
8. Heavily invest in hydrogen for feedstock of fertilizer, steel, and some hard to decarbonize heating applications.

The slope from 2020 through 2050 is generally smooth, but the Russian invasion of Ukraine accelerated adoption of fuel switching (heat pumps and EVs) and clean generation. Costs will be comparable with 2020 for electricity, but energy burden costs will be substantially reduced.

Agenda

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Thank You

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