Weather-**I**nformed **S**ystems:

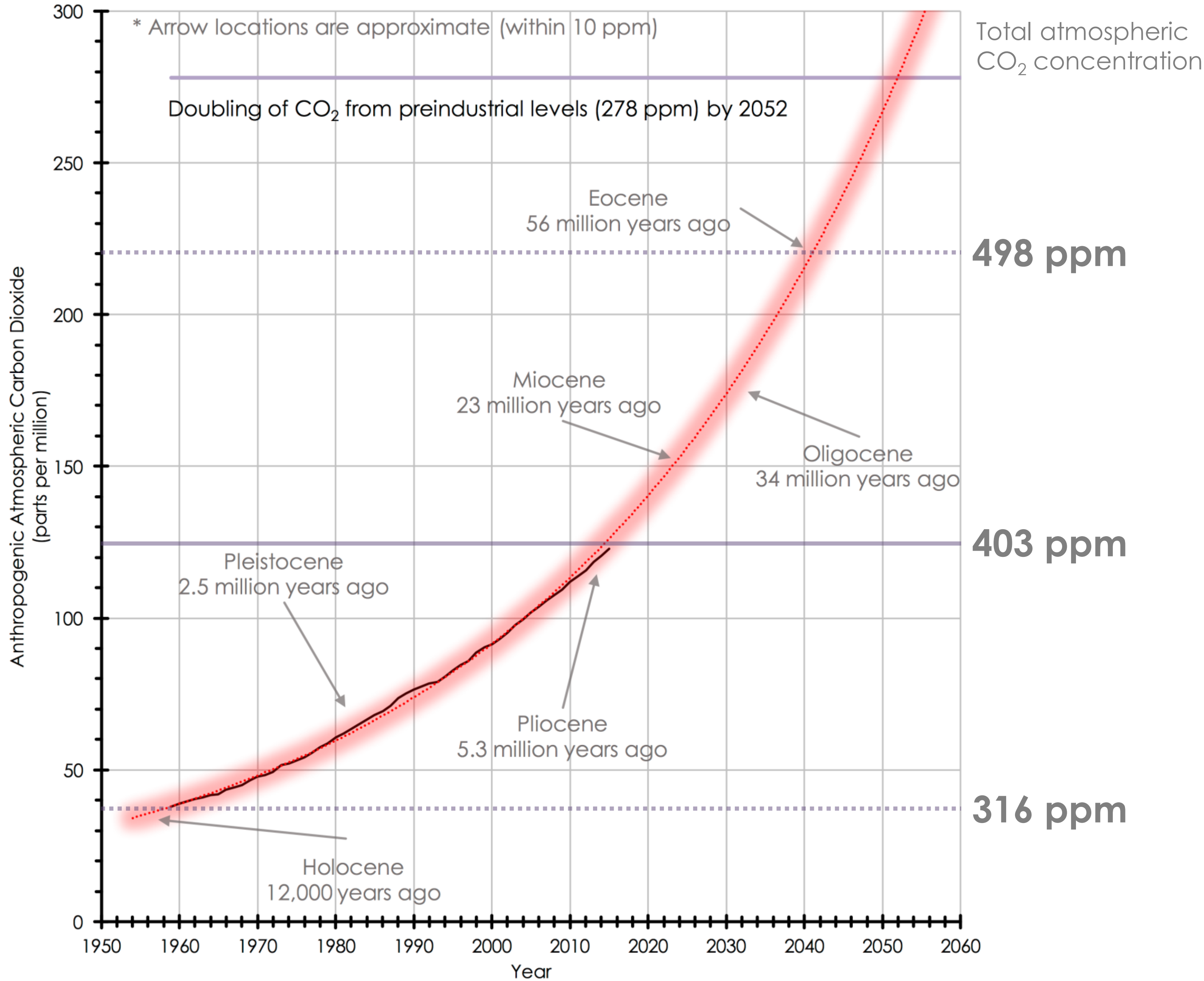
Future Cost-Competitive Electricity Systems and Their Impacts on US CO_2 Emissions

Dr Christopher T M Clack

Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado

Department of Energy; Electricity Advisory Committee, Wednesday September 28th 2016

Pandora's Box: Fossil Carbon



Weather is Key to Decarbonization

- A **fundamental** transformation of the electric power system is underway.

- **D**esign, **O**peration and **M**arkets are currently constructed around "fuels" that are burned.

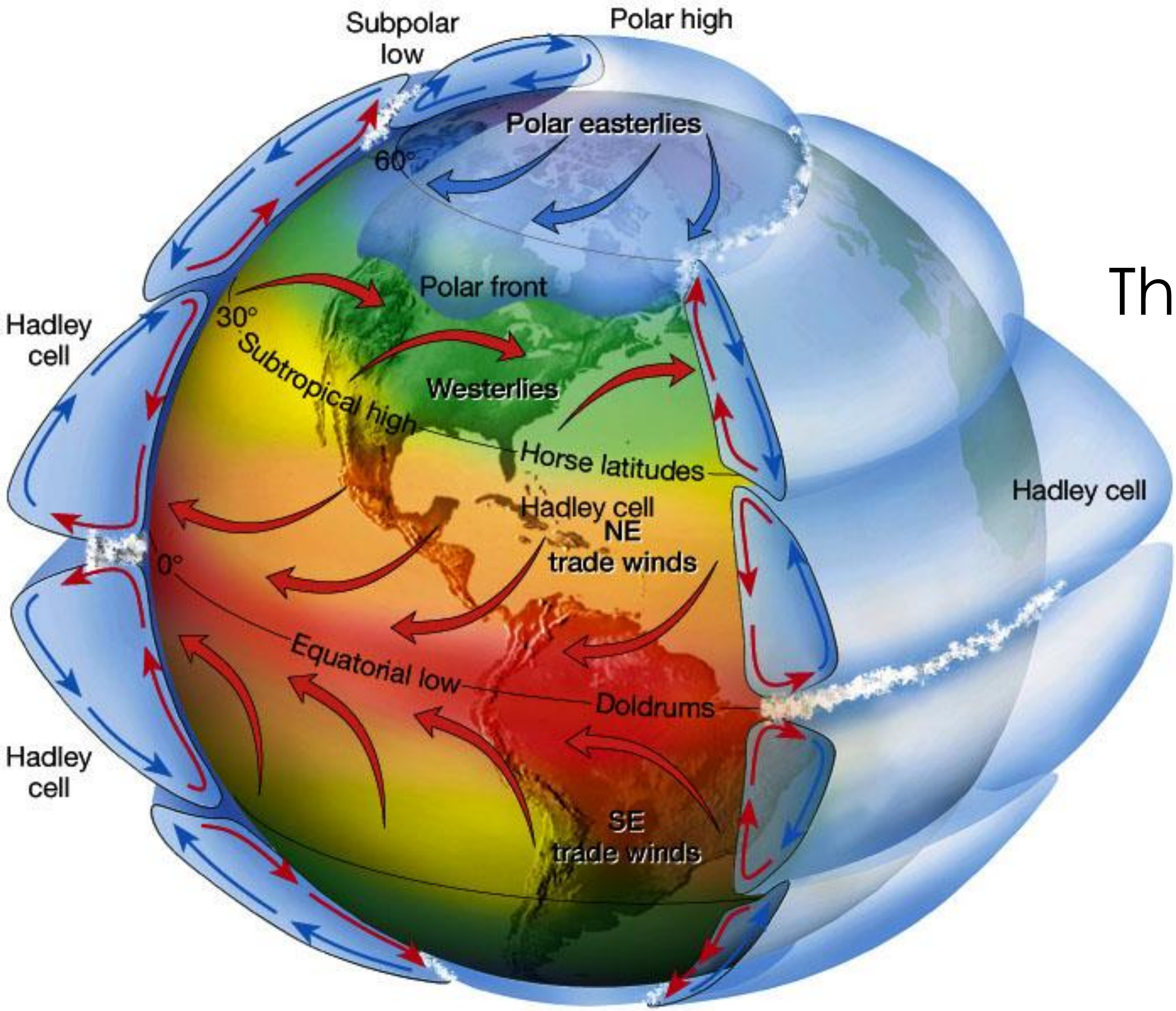
- Solar and wind resources will **power the future**. They are weather-driven.

- **Atmospheric science** should be incorporated at all phases of **D**esign, **O**perations, and **M**arkets.

Critical Components

- **Weather**
- Electricity Infrastructure
- Electric Demand
- Cost of Technologies

Wind and Solar are Variable Generation

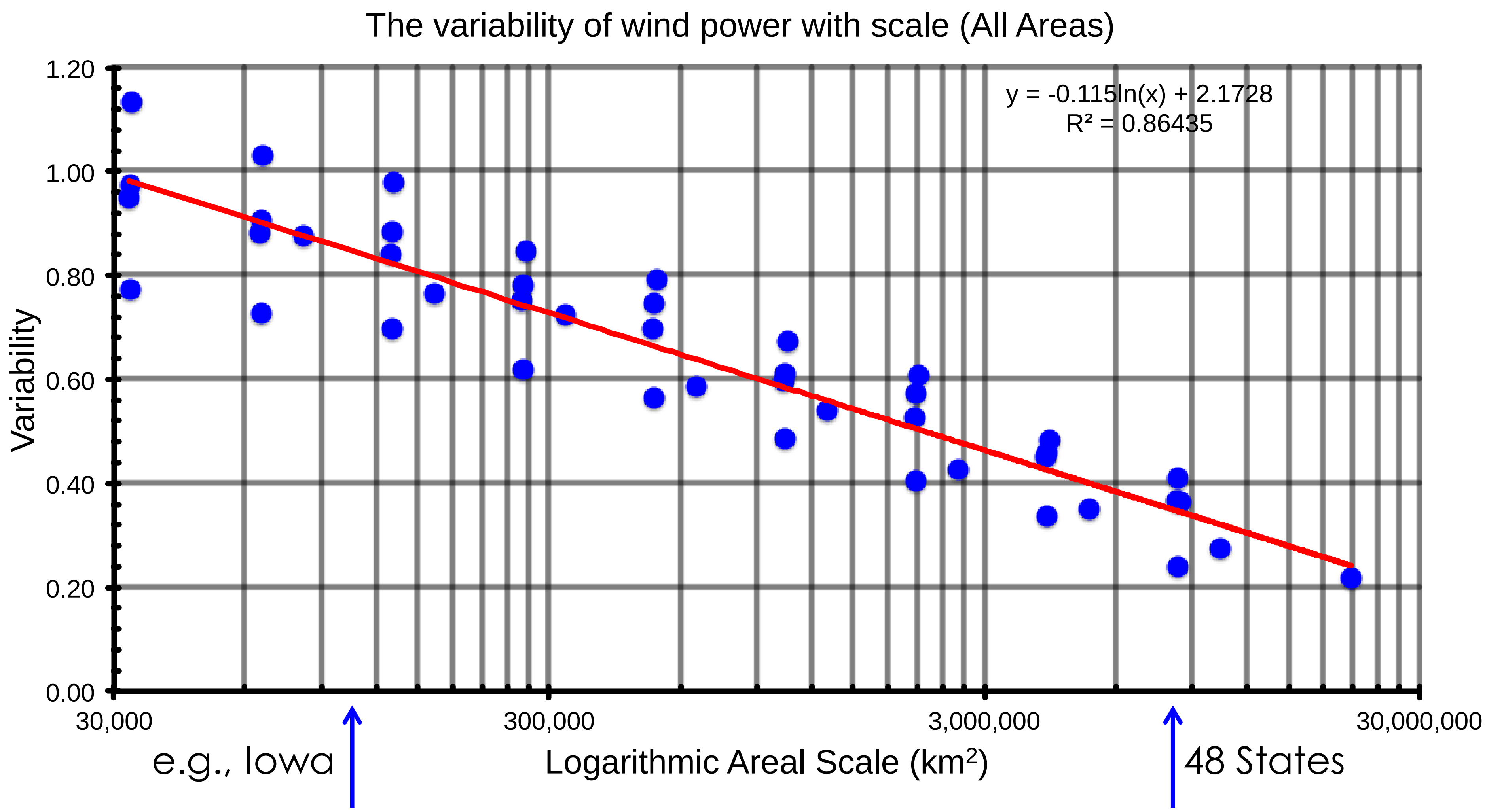


This global heat engine runs **constantly**.

Making "variability" a **local effect**.

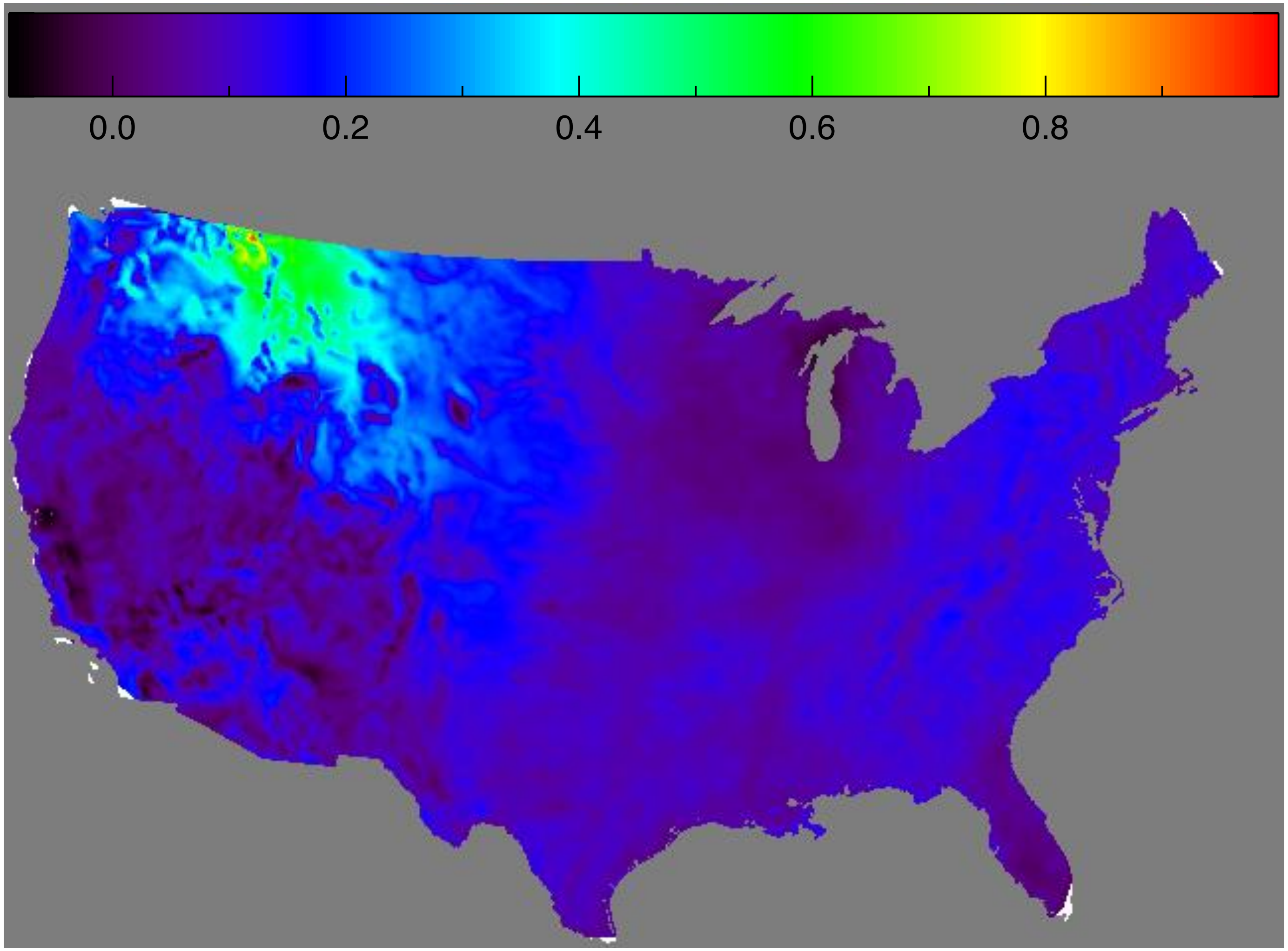
Image Credit: Figure 7.5 in *The Atmosphere, 8th edition*, Lutgens and Tarbuck, 8th edition, 2001

The variability of wind drops by 5 times when area is increased by three orders of magnitude



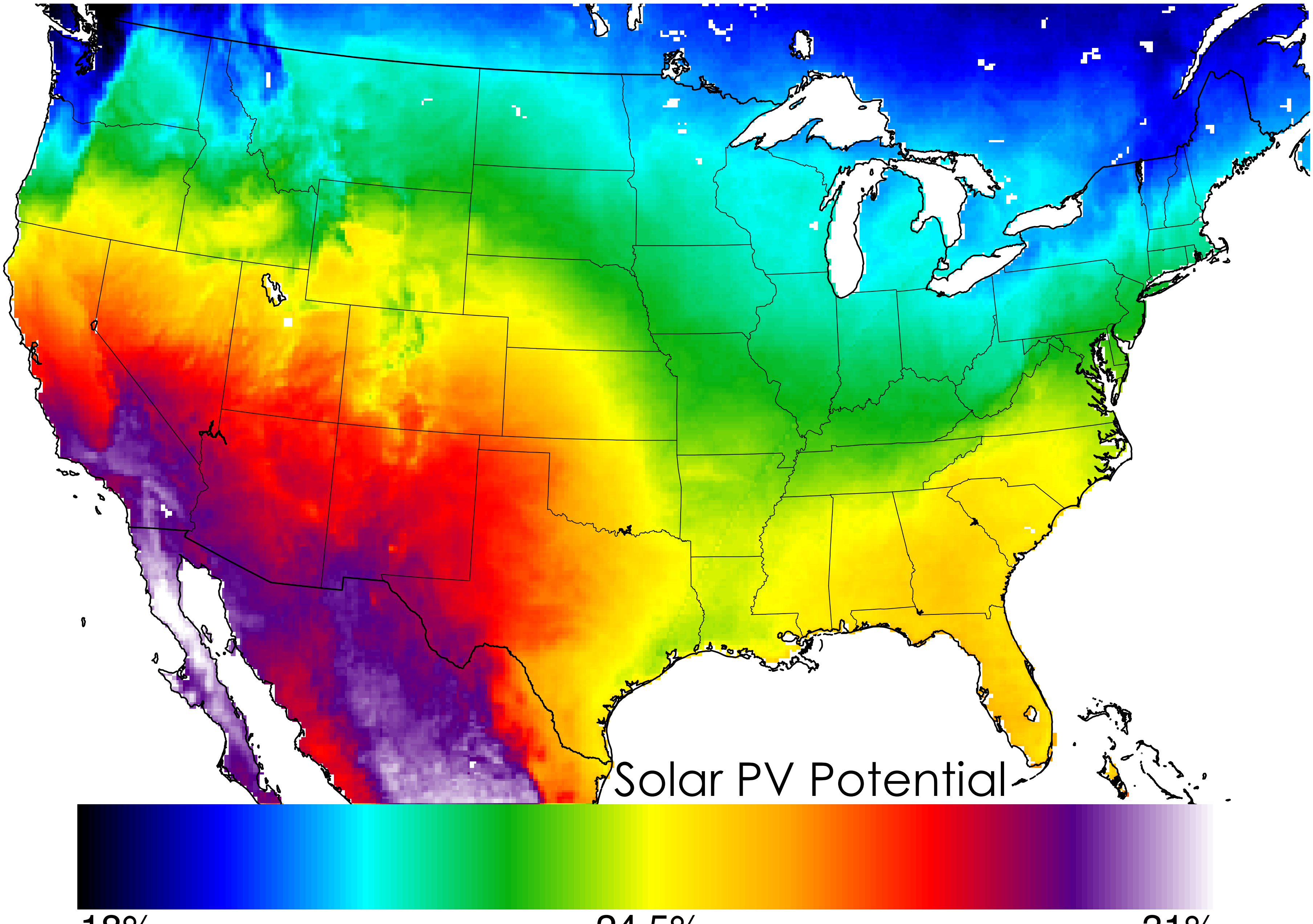
Variability here is defined as the average coefficient of variation over a geographic region when divided up into isolated regions

Local Wind Sites Behave The Same Way



Power output behavior compared with its neighbors of variable resources **depends** on its location

NEWS Uses High Resolution Weather Data



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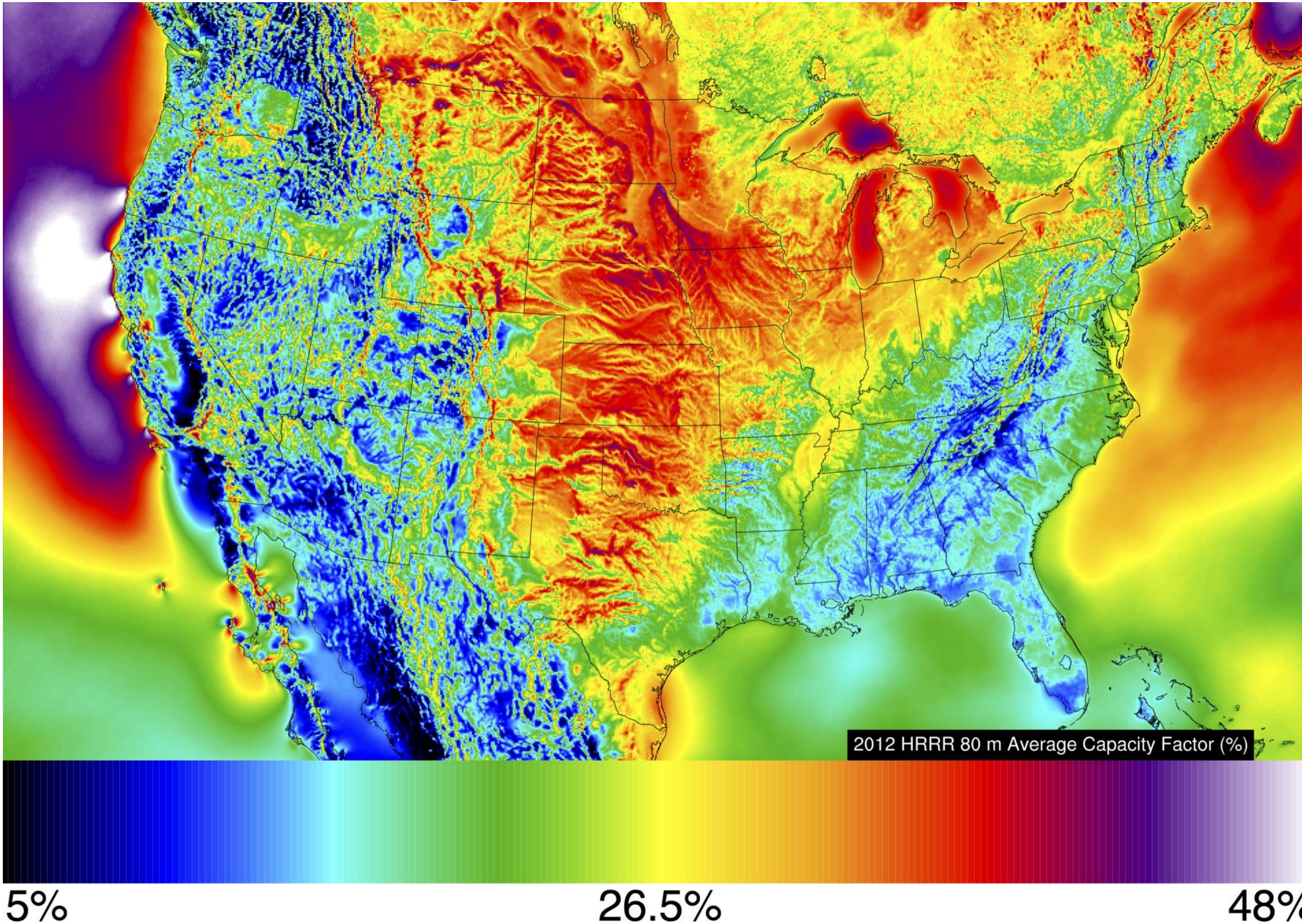
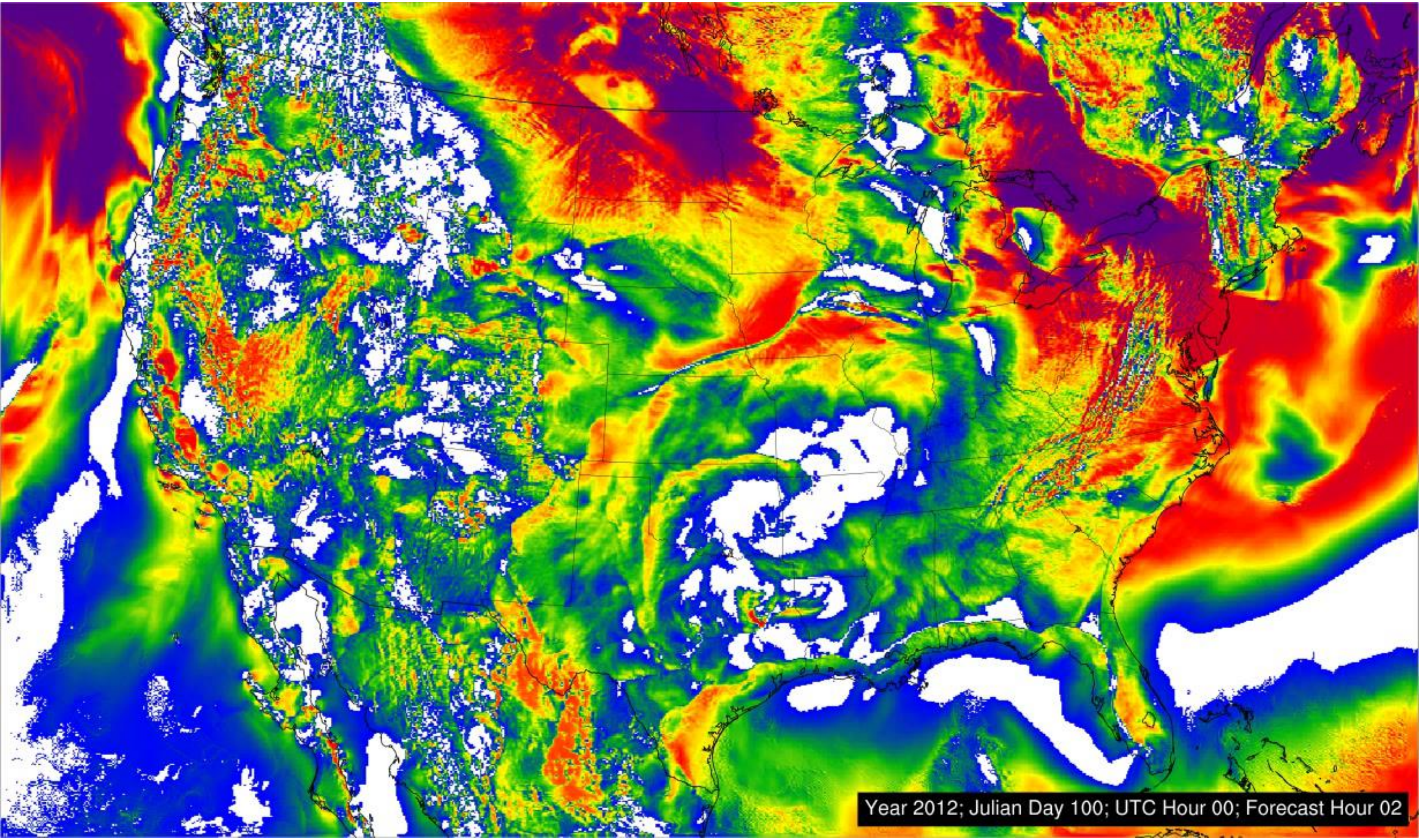


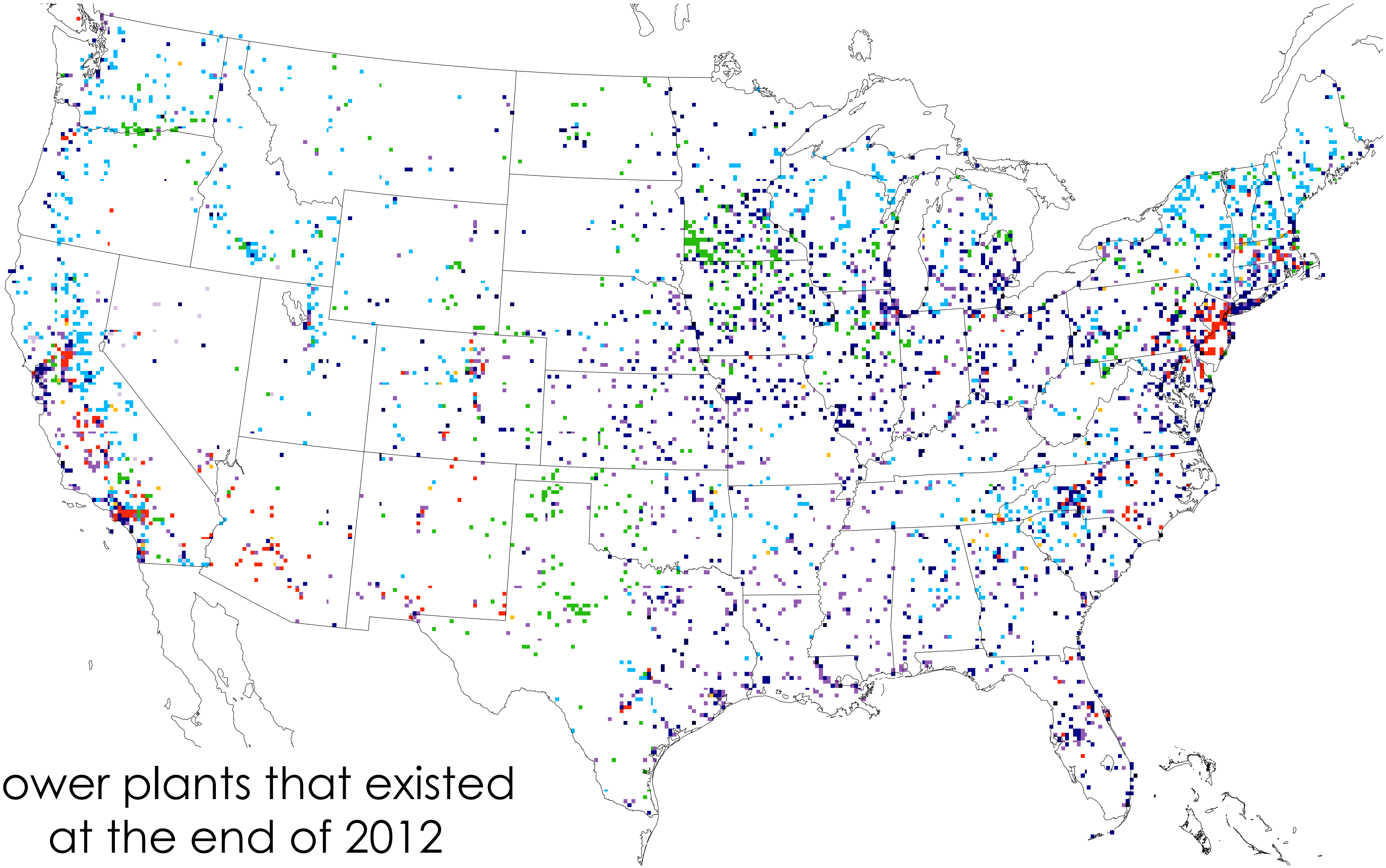
NEWS Uses High Resolution Weather Data



Critical Components

- Weather
- **Electricity Infrastructure**
- Electric Demand
- Cost of Technologies

NEWS Needs The Locations of Power Plants



Power plants that existed
at the end of 2012

NEWS Needs To Know Where Sites Exist

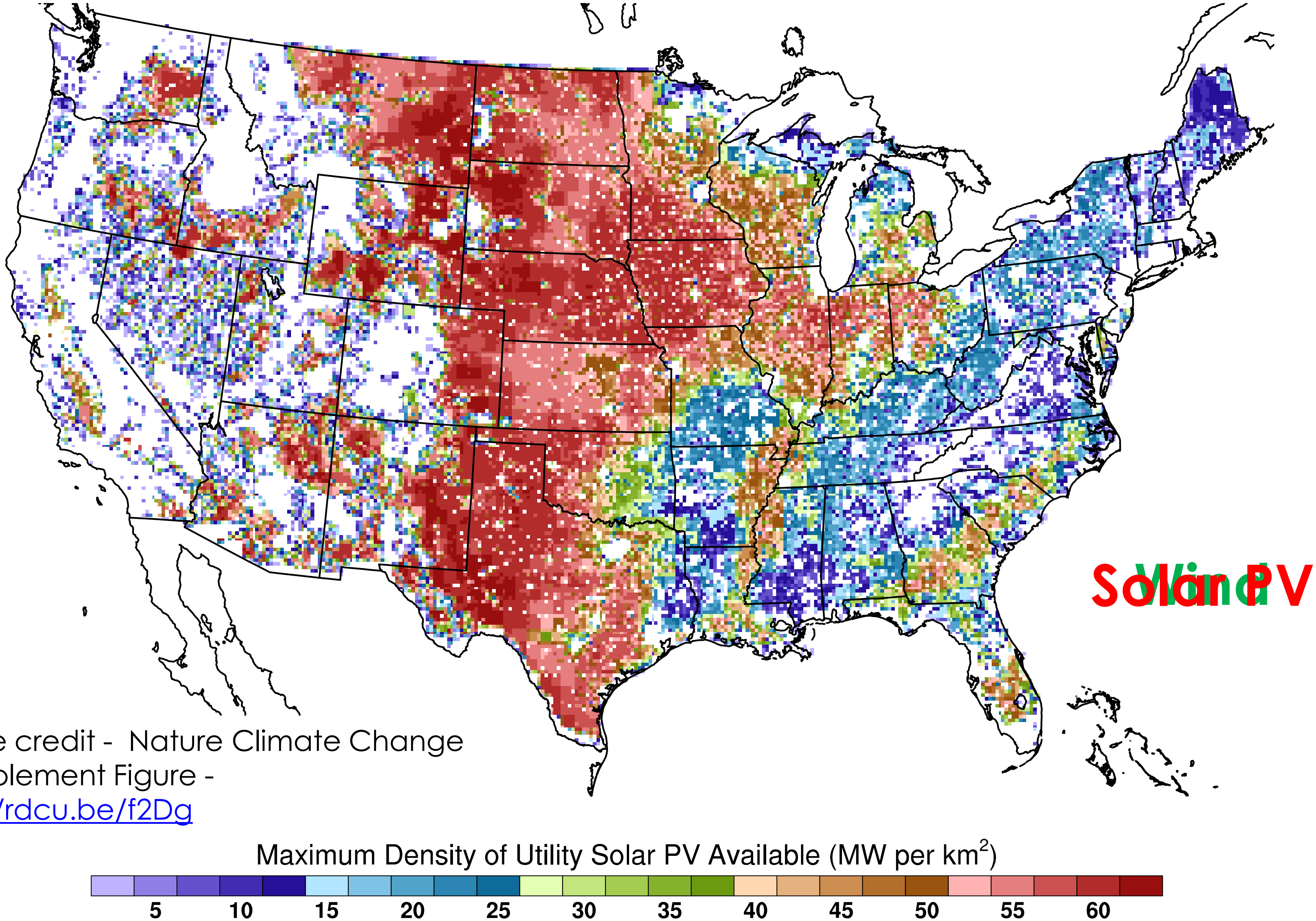
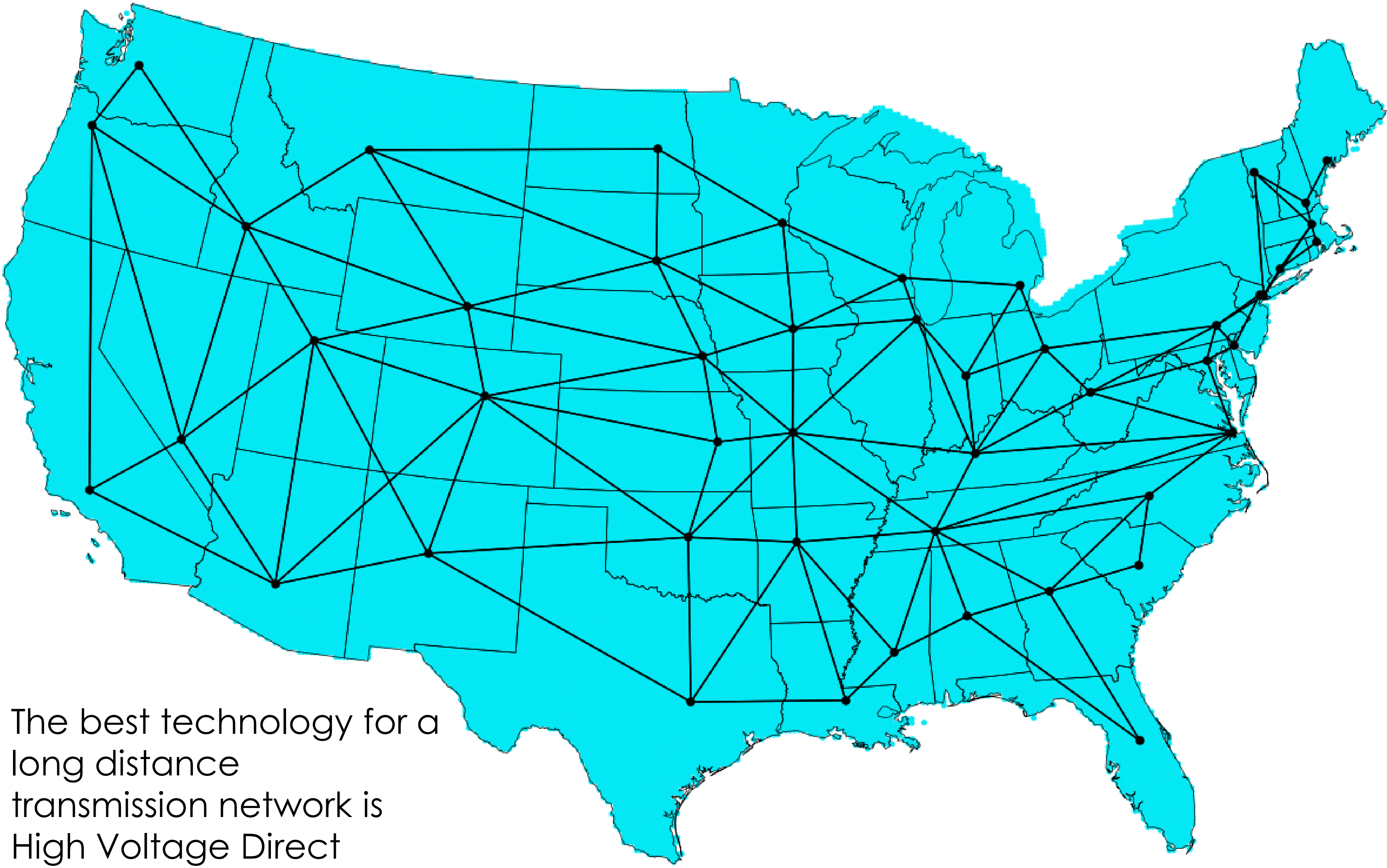


Image credit - Nature Climate Change – Supplement Figure - http://rdcu.be/f2Dg

NEWS Selects Transmission Options

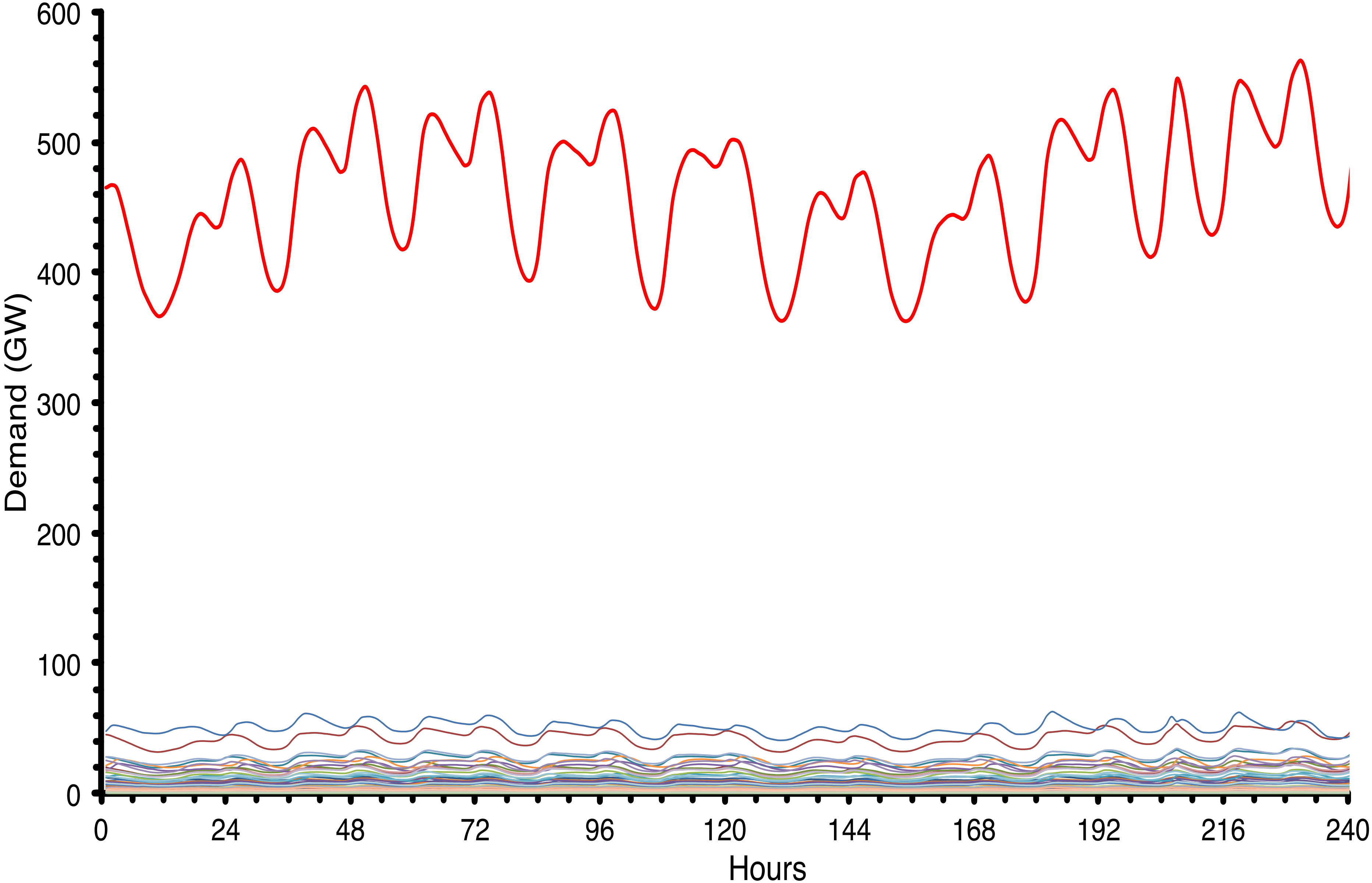


The best technology for a long distance transmission network is High Voltage Direct Current (HVDC).

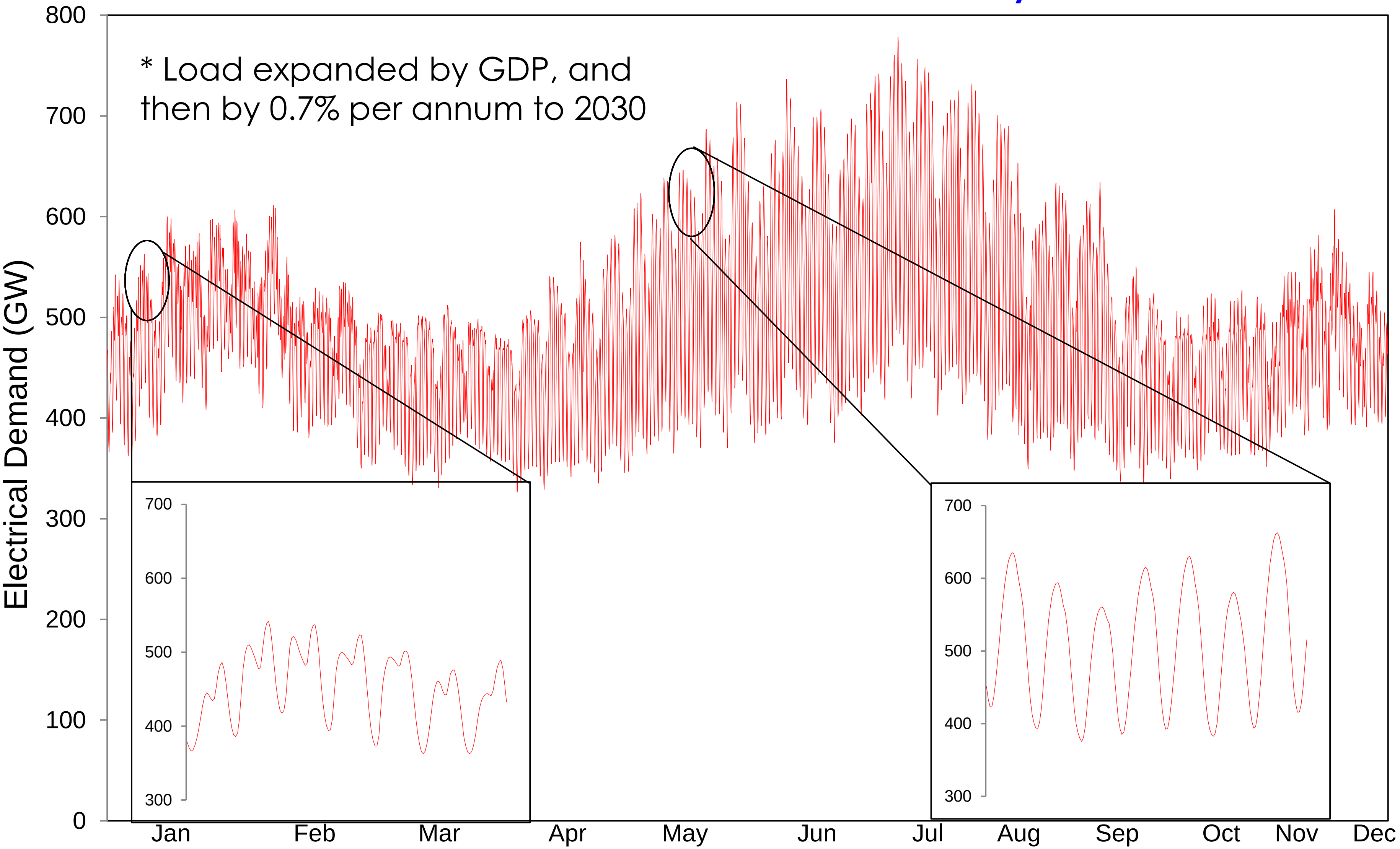
Critical Components

- Weather
- Electricity Infrastructure
- **Electric Demand**
- Cost of Technologies

NEWS Uses Detailed Electricity Demand



NEWS Uses Detailed Electricity Demand



Reminder: The model is *infinitely adaptable*, and so demands can be altered depending on region

Critical Components

- Weather
- Electricity Infrastructure
- Electric Demand
- **Cost of Technologies**

Models Need Costs Provided As Inputs

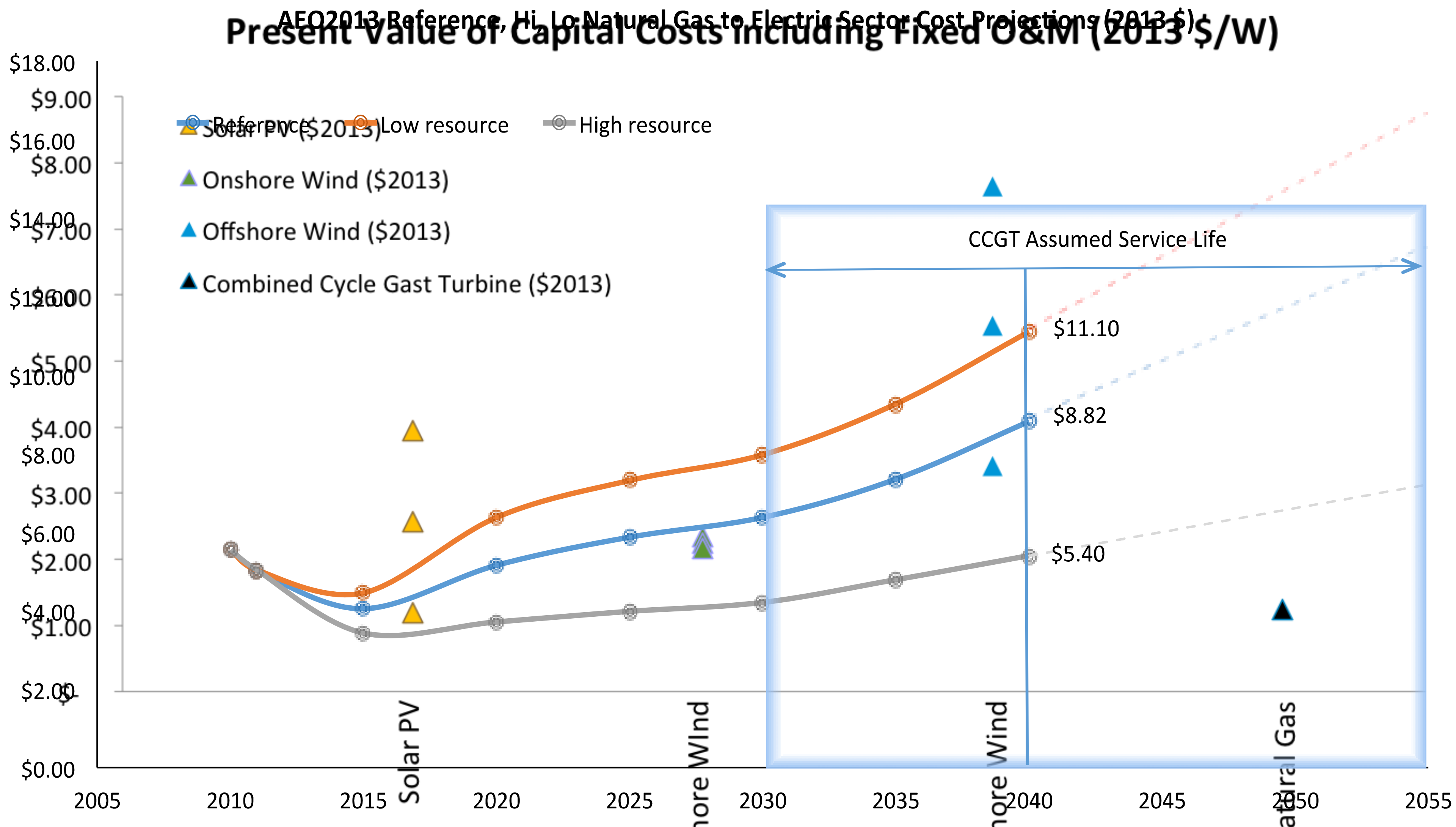


Image credit - Nature Climate Change – Supplement Figure - http://rdcu.be/f2Dg

NEWS Solves To Find The "Best" System

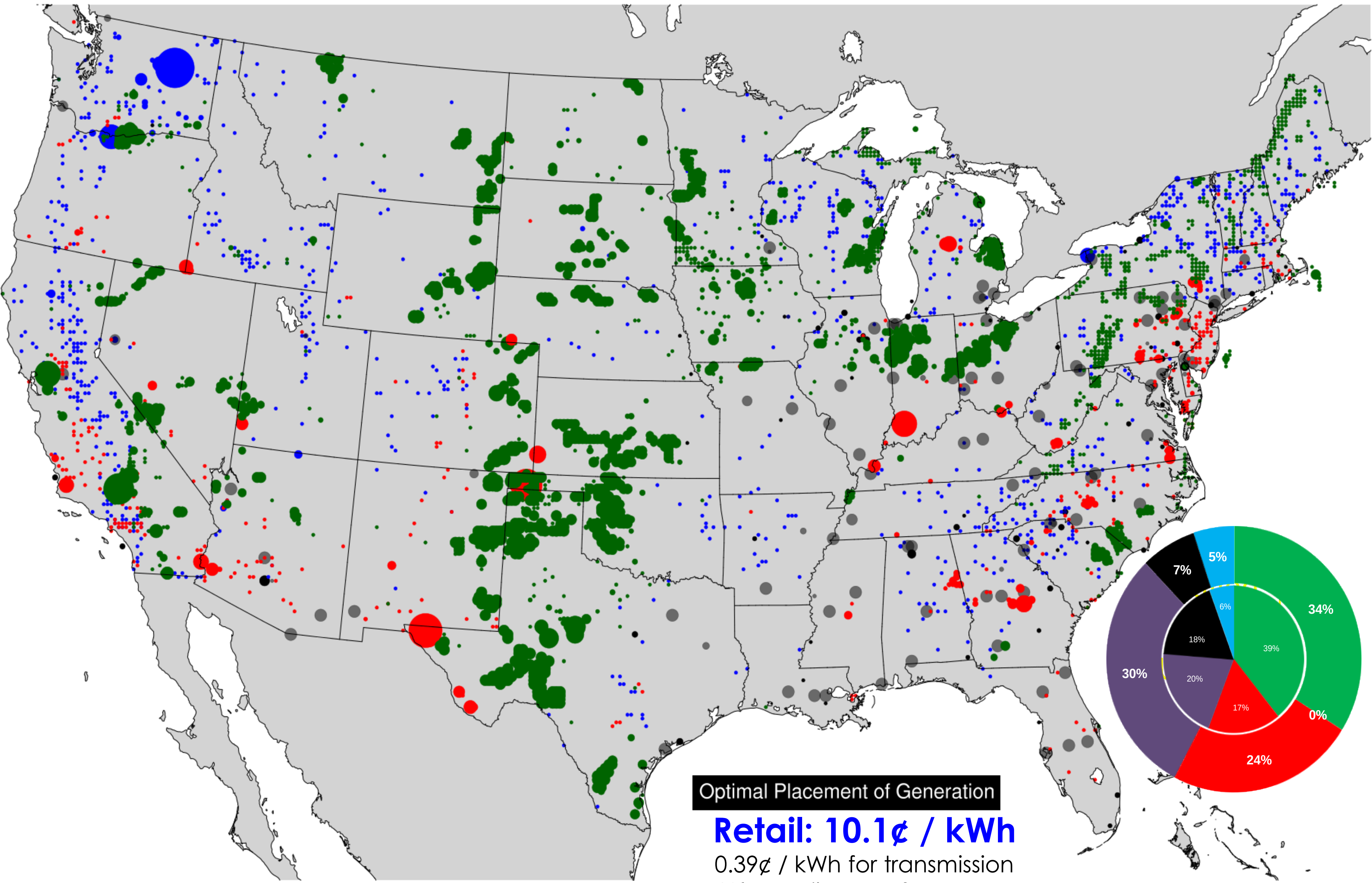
Minimize:

Subject to:

ALL OTHER EQUATIONS CONSTRAIN THE MAGNITUDE OF ANY OF THE TERMS

See, e.g. C. T. M. Clack, Y. Xie, and A. MacDonald: Linear Programming Techniques for Developing an Optimal Electrical System including High-Voltage Direct Current Transmission and Storage, International Journal of Electric Power and Energy Systems, 68, 103-114, (2015).

A cost-optimal National Electric System

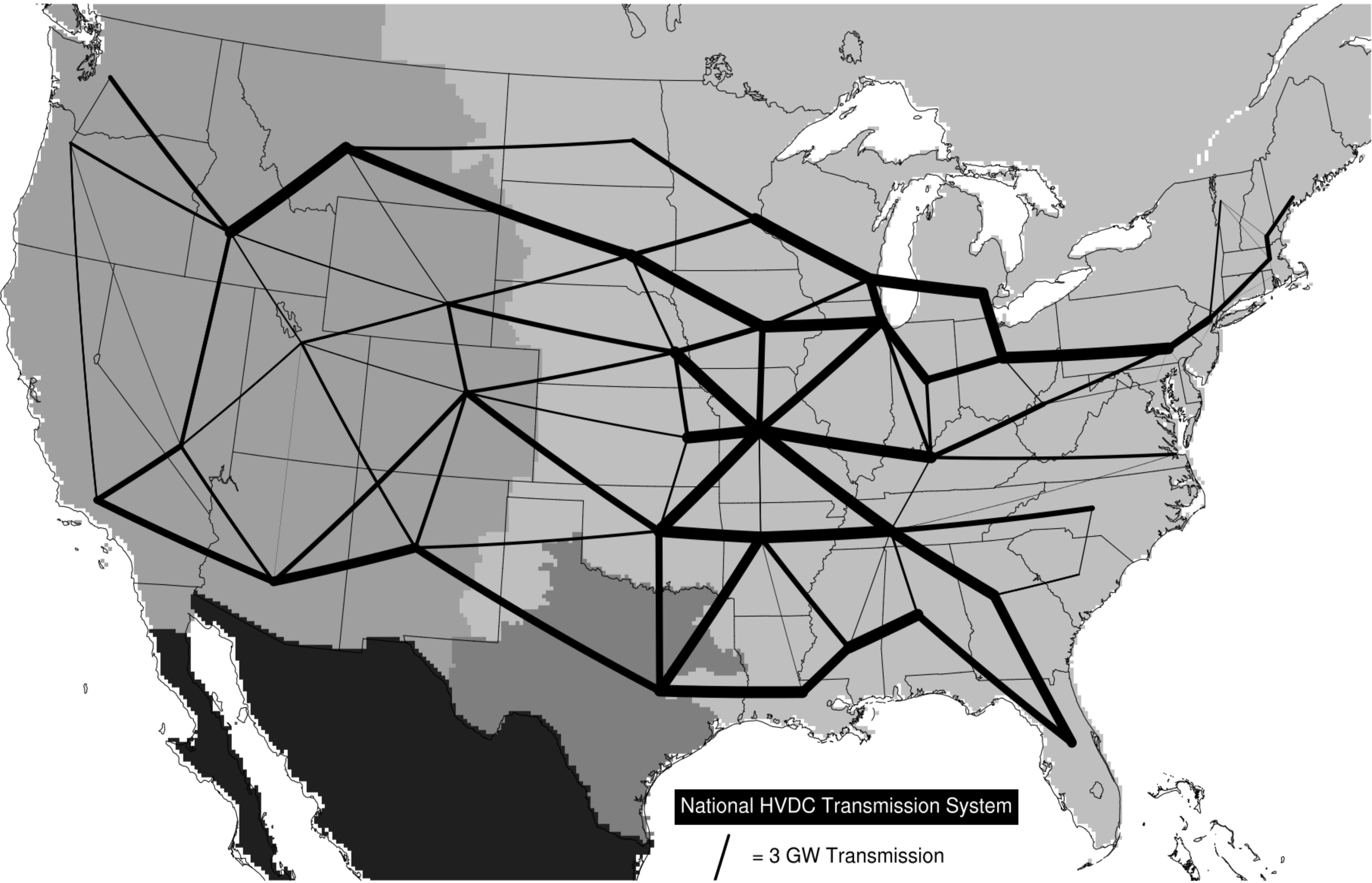


Retail: 10.1¢ / kWh

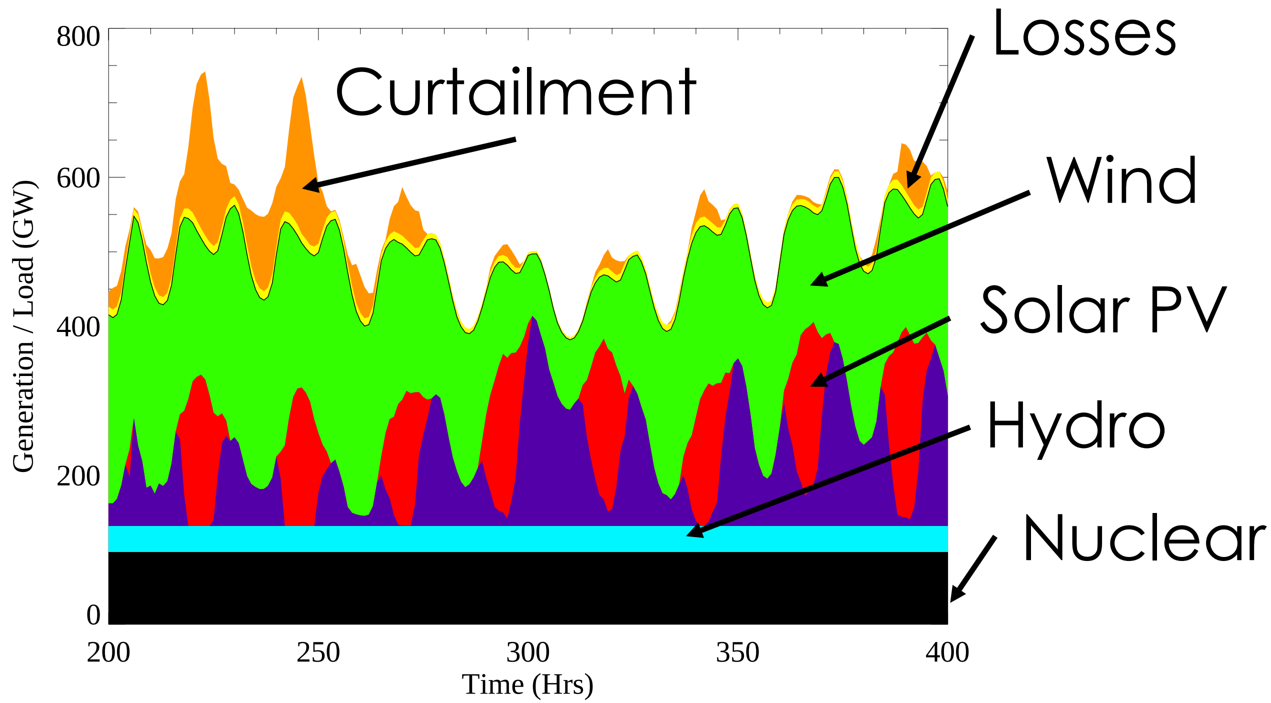
0.39¢ / kWh for transmission

8% curtailment of var. gen.

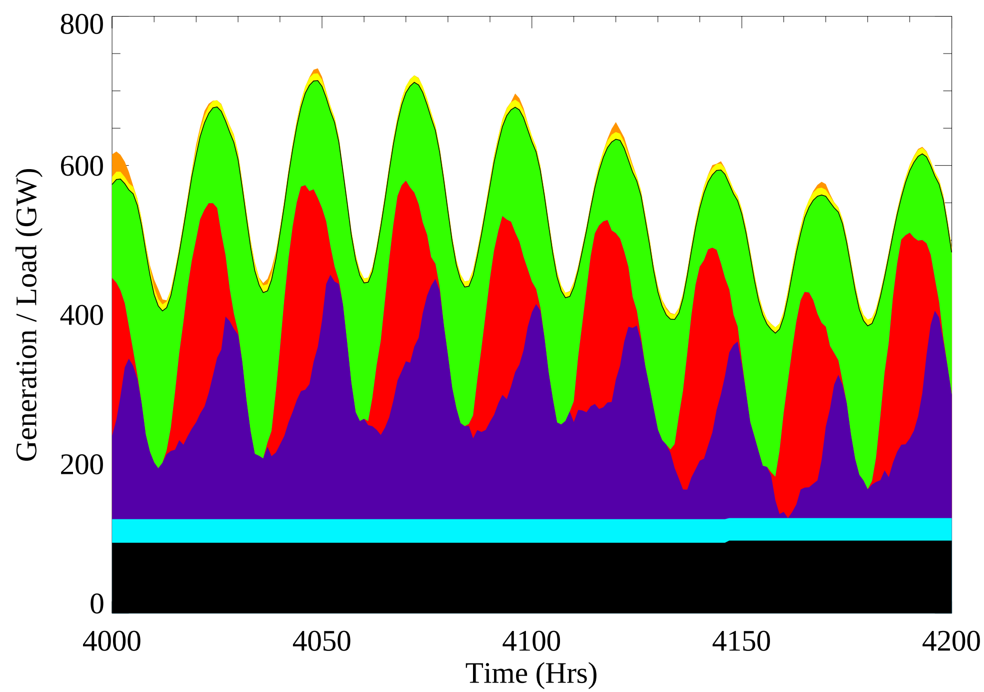
A cost-optimal National Transmission System



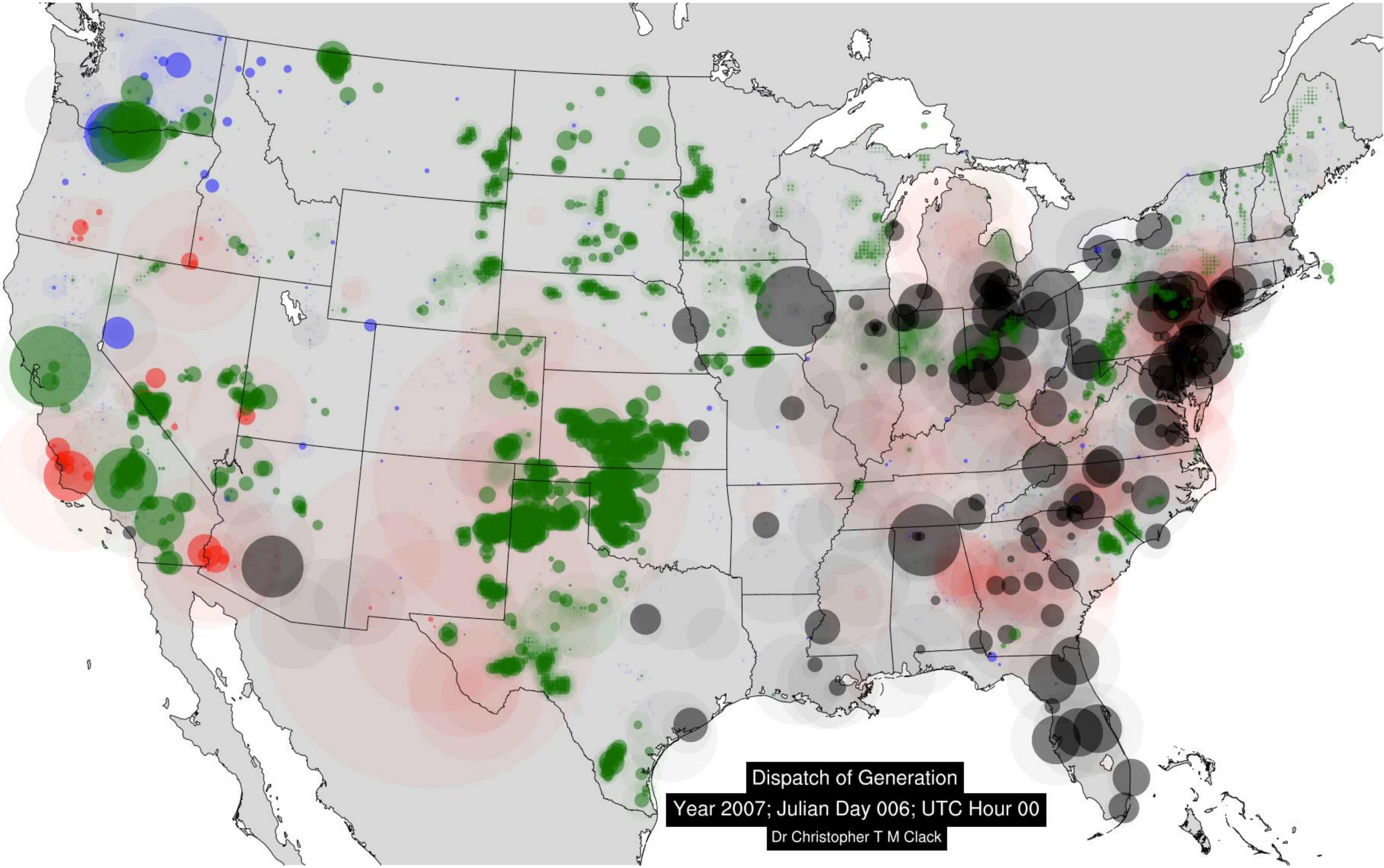
Winter Dispatch Stack



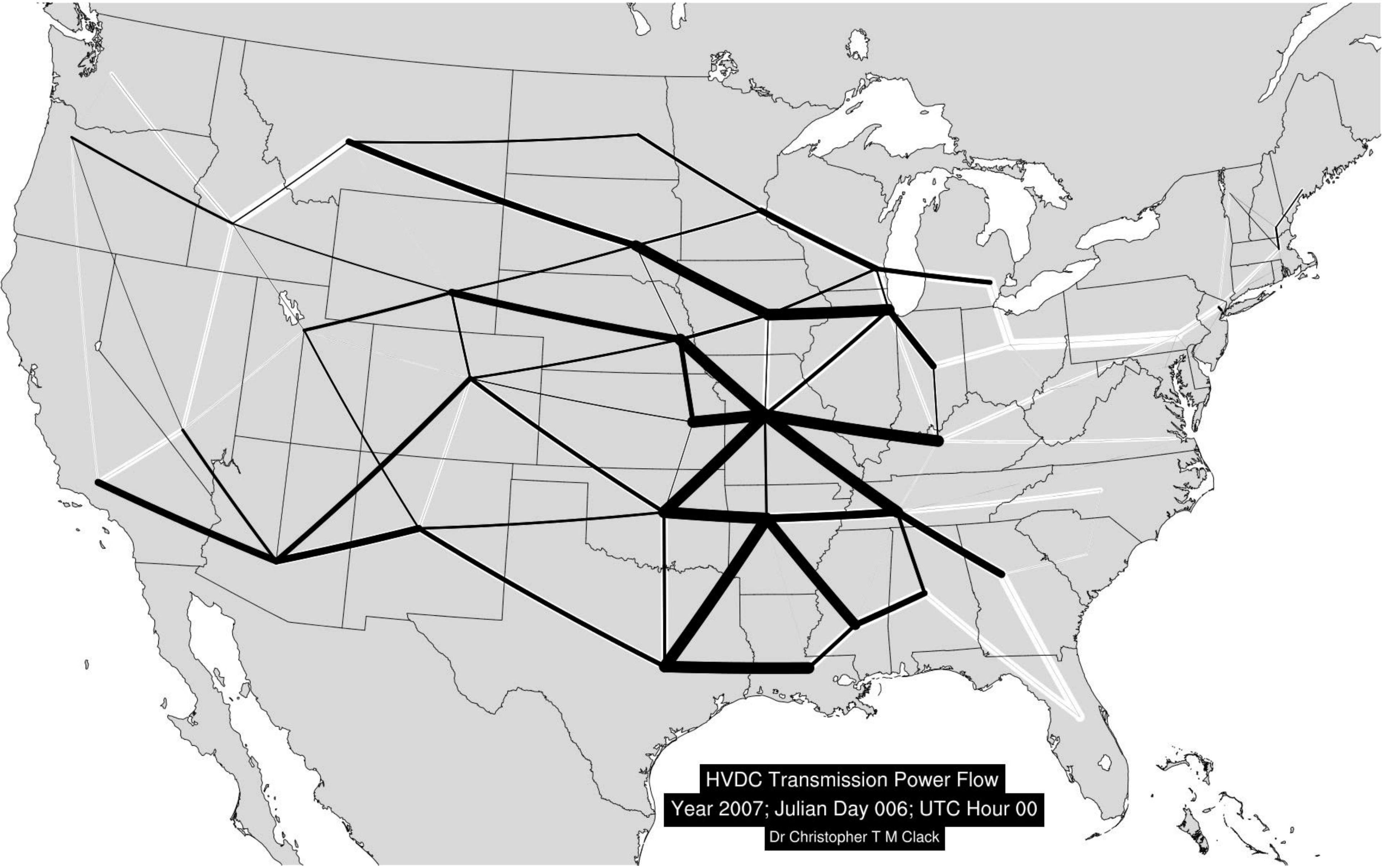
Summer Dispatch Stack



A cost-optimal National Electric System



NEWS Selects Transmission Options



A national electric system could be lower cost

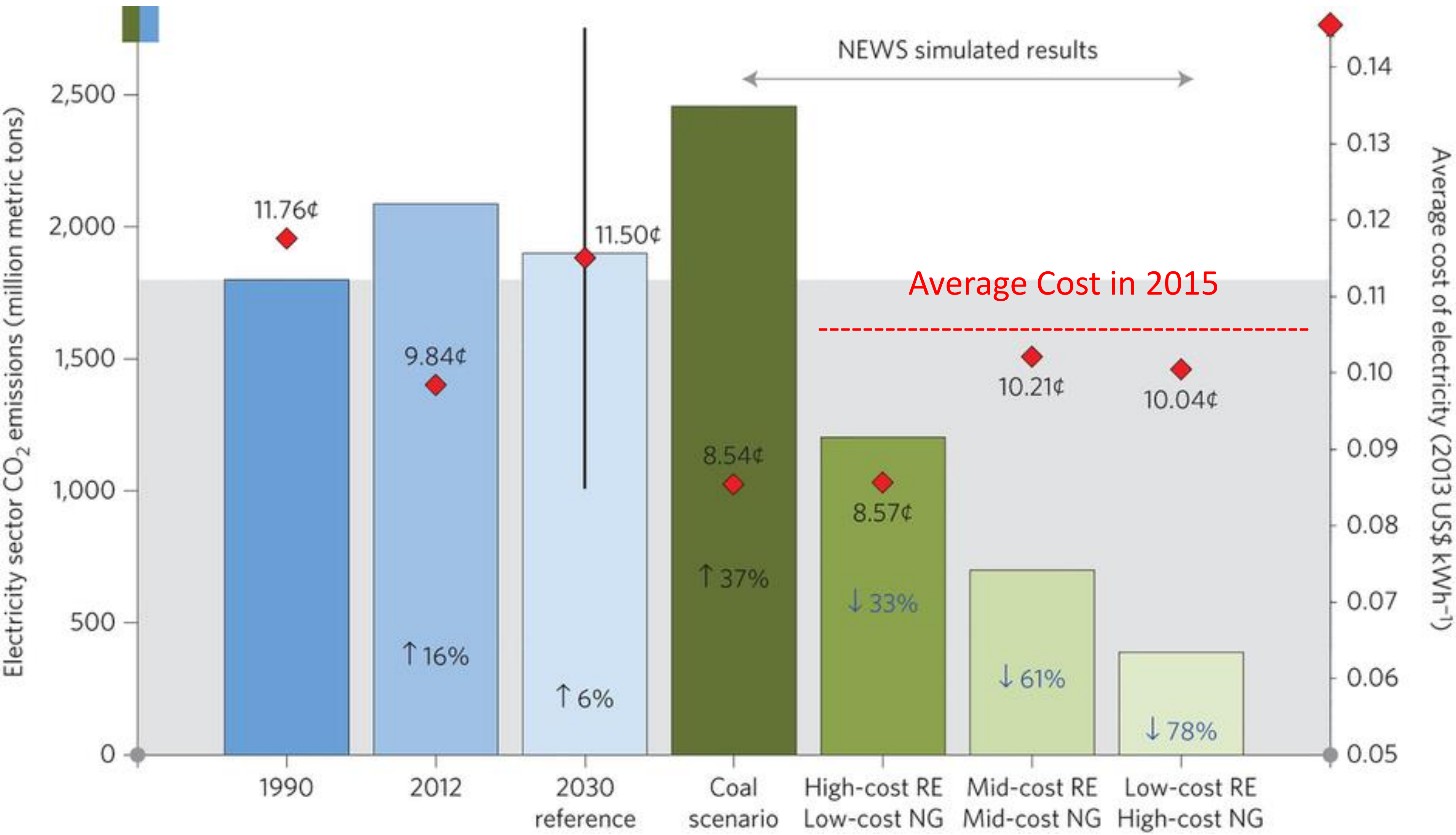
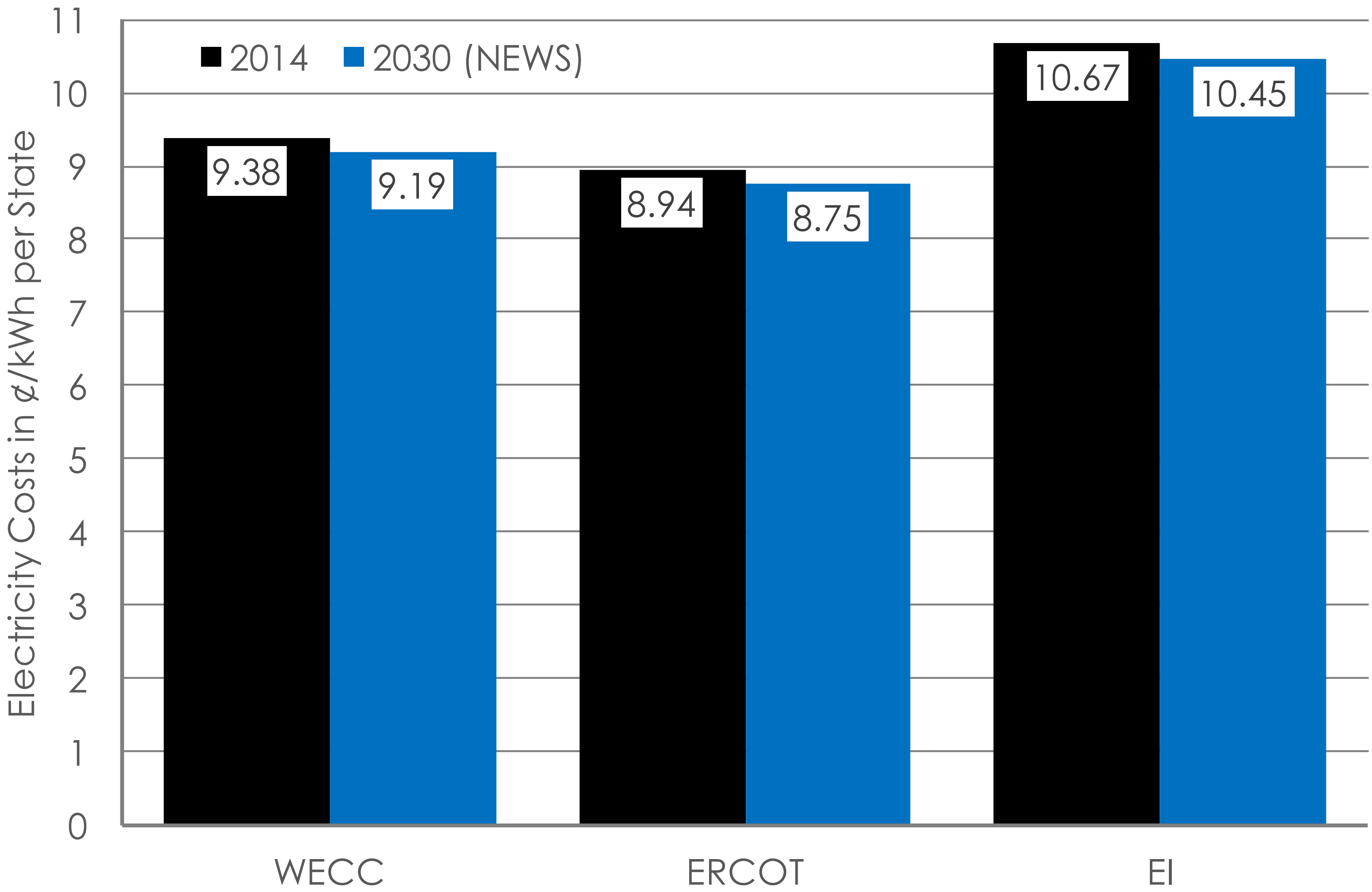
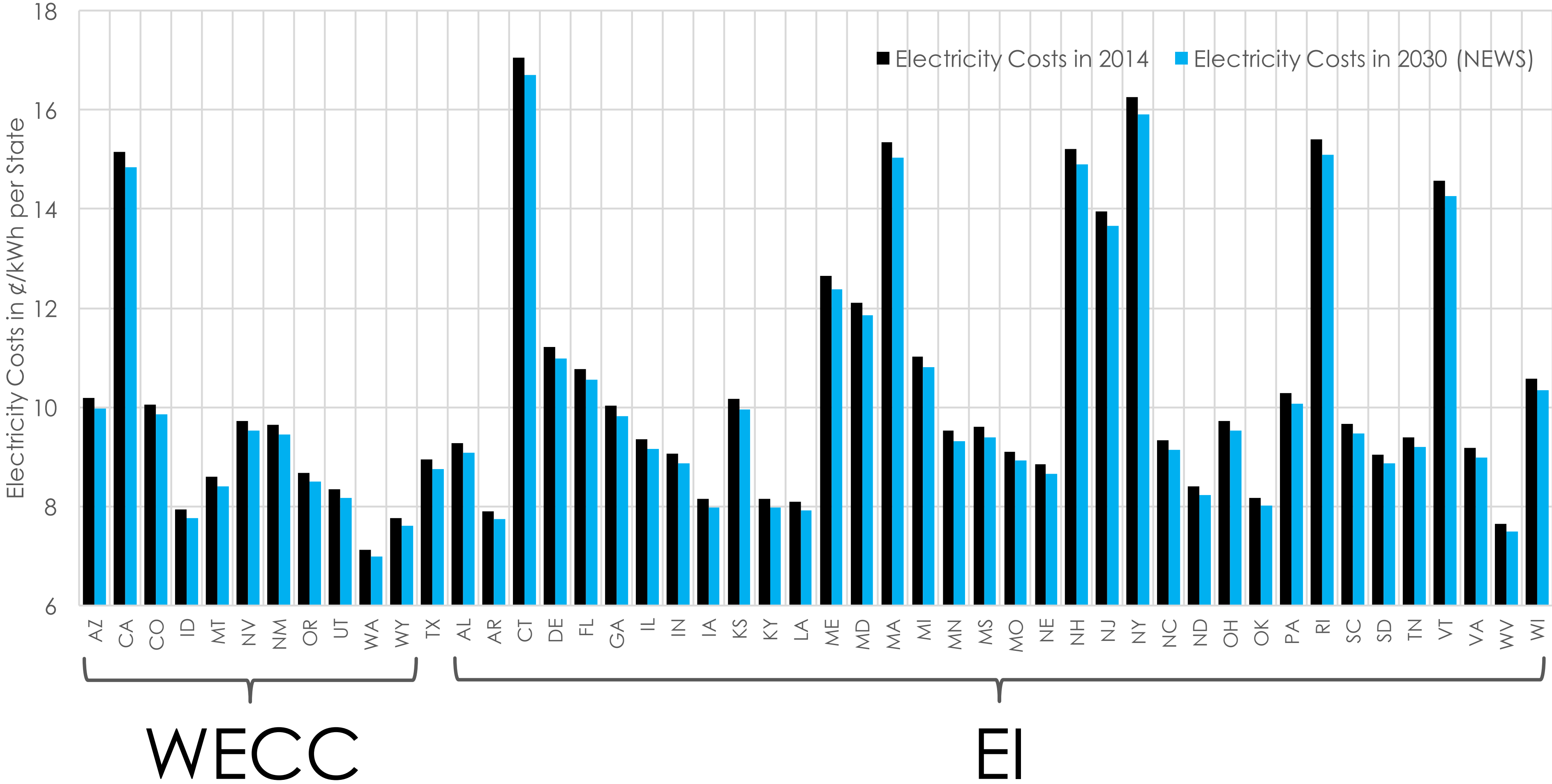


Image credit - Nature Climate Change – Figure 2 - http://rdcu.be/f2Dg

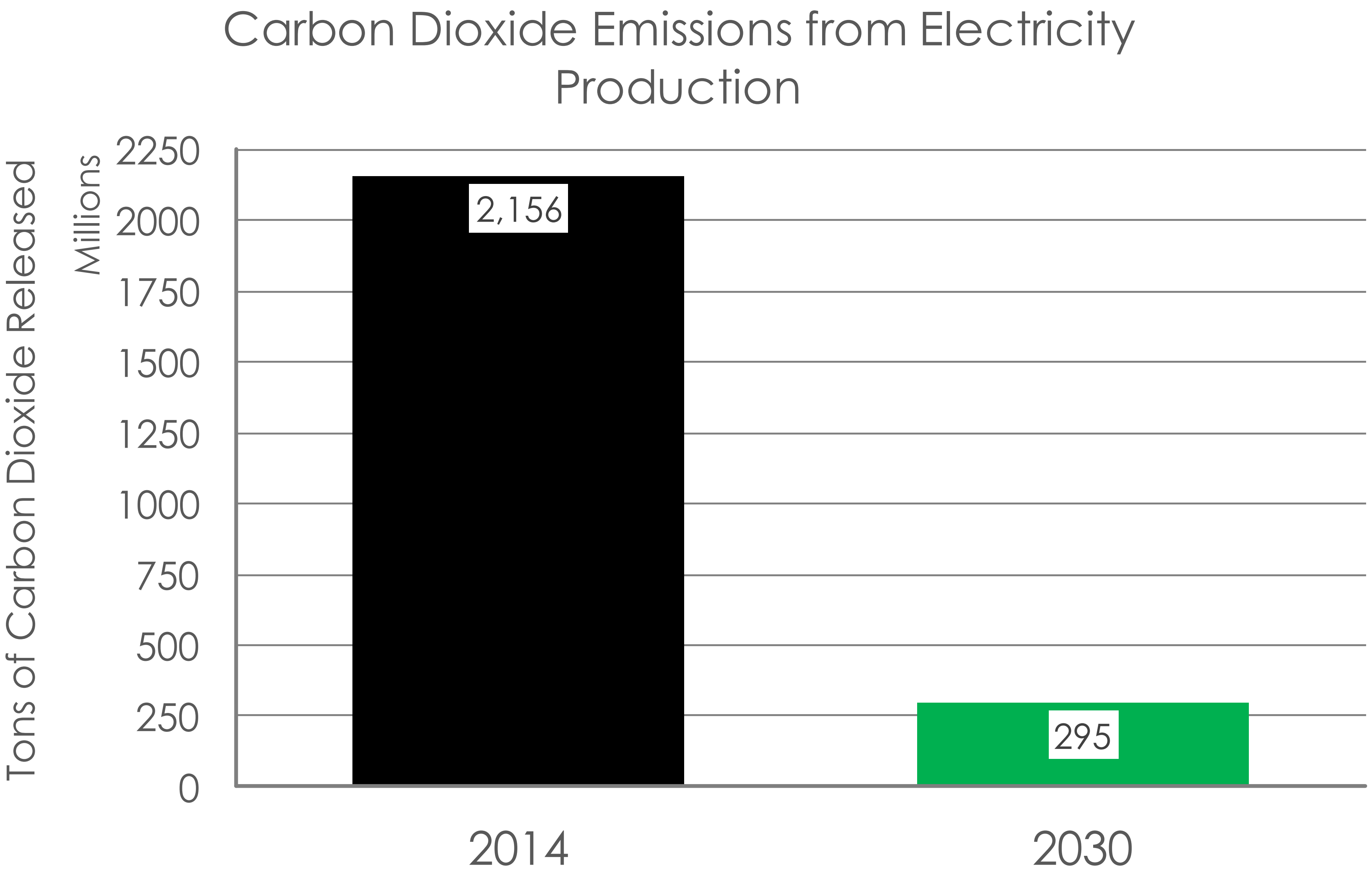
Breaking down a national system by Interconnect



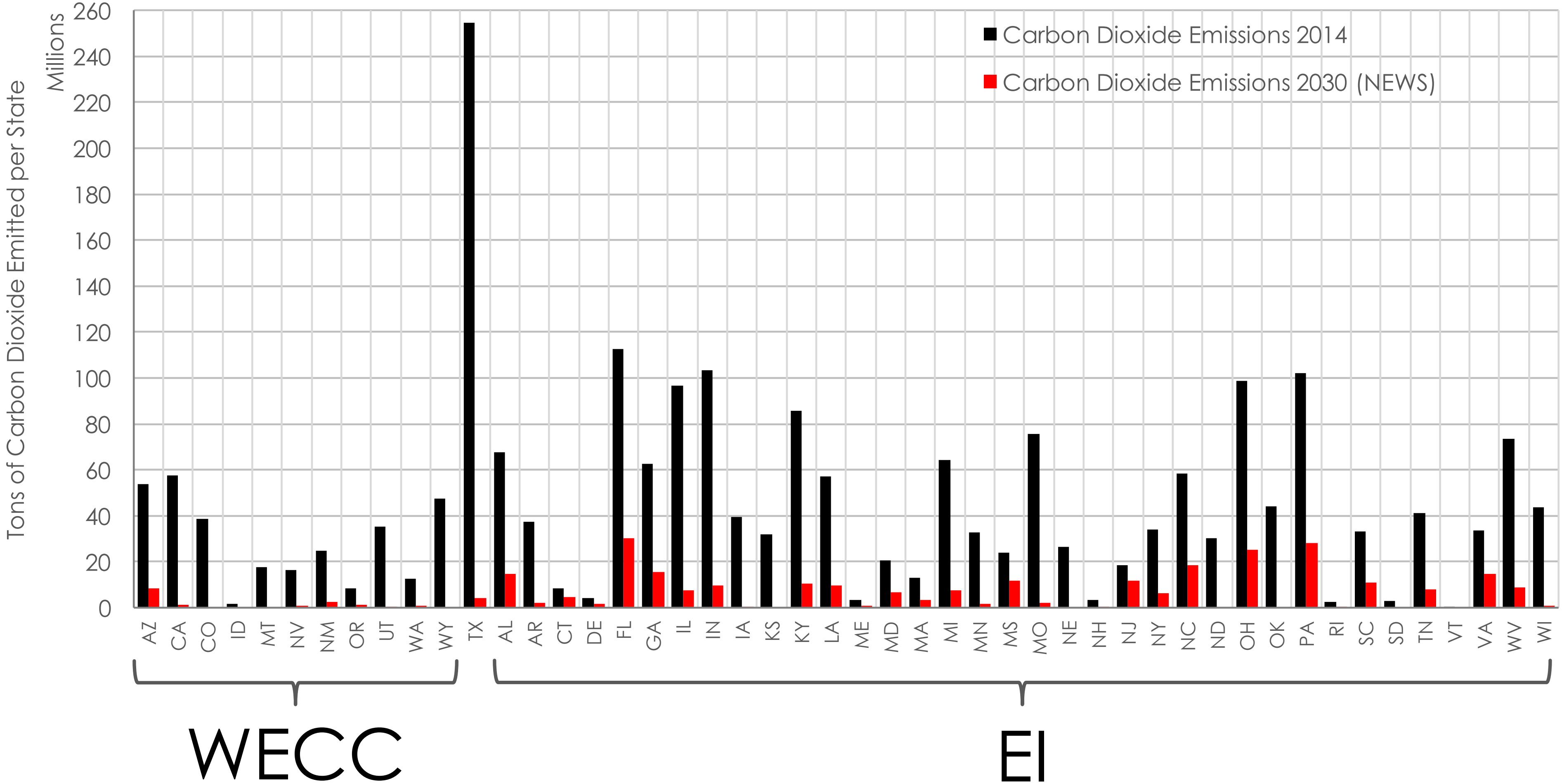
A national system state-by-state



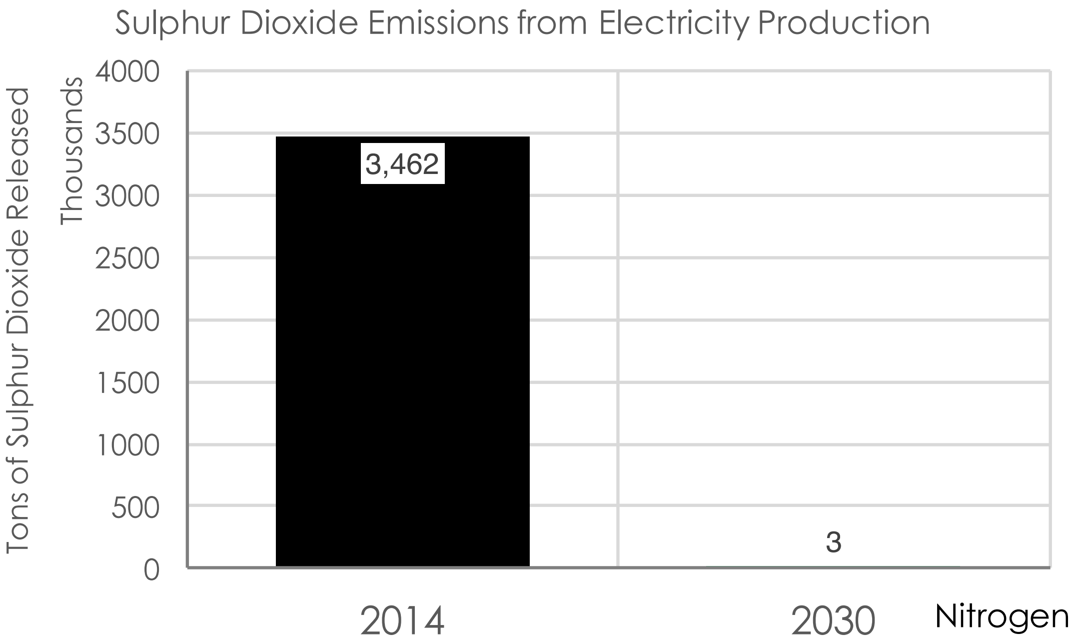
A national system could emit less carbon dioxide

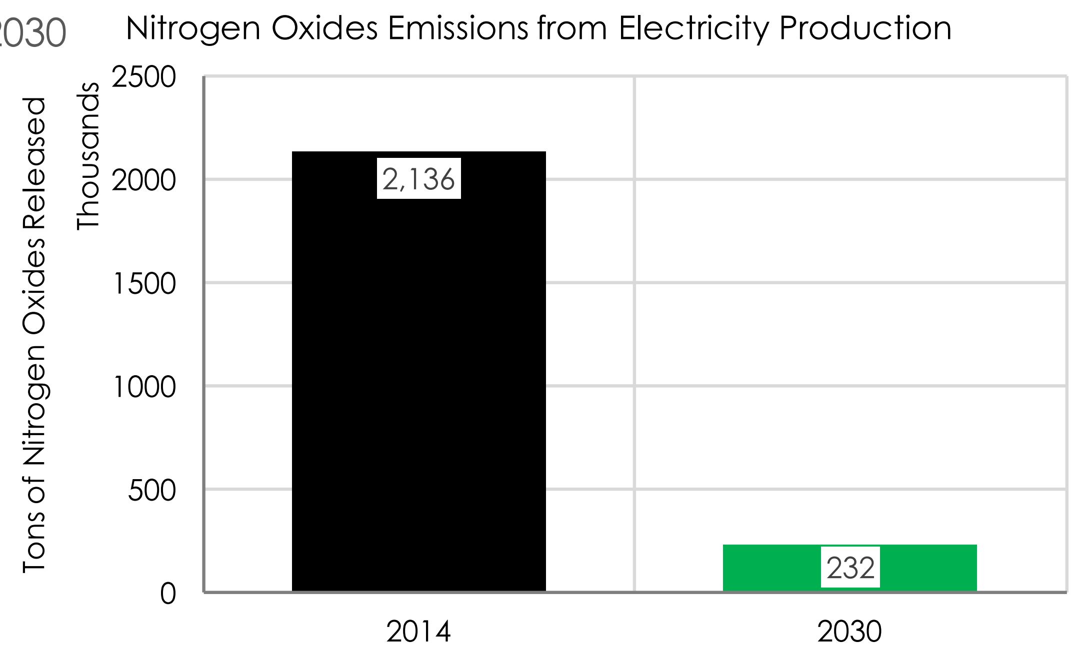


A national system state-by-state

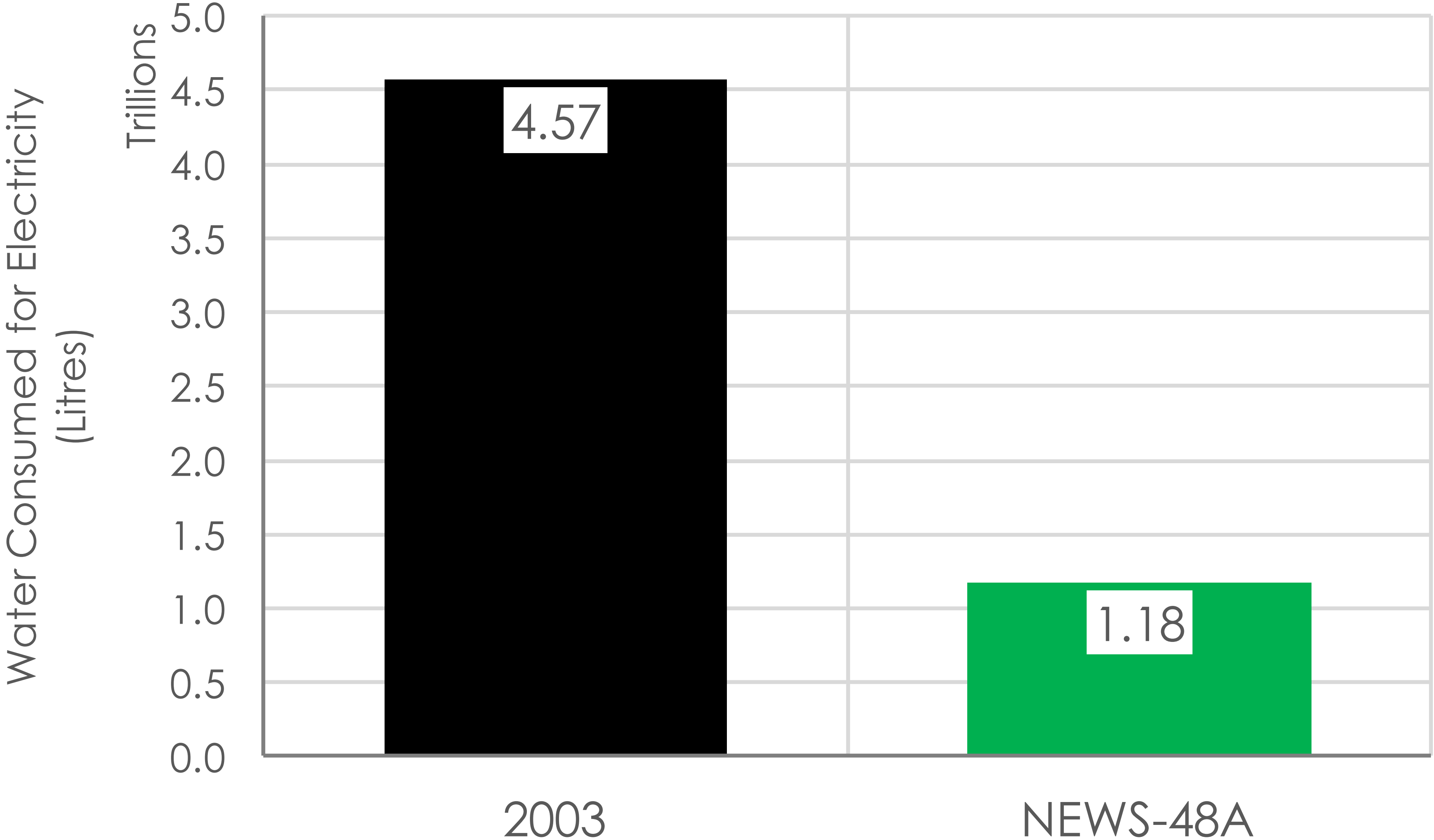


A national system could emit less sulphur dioxide and nitrogen oxides

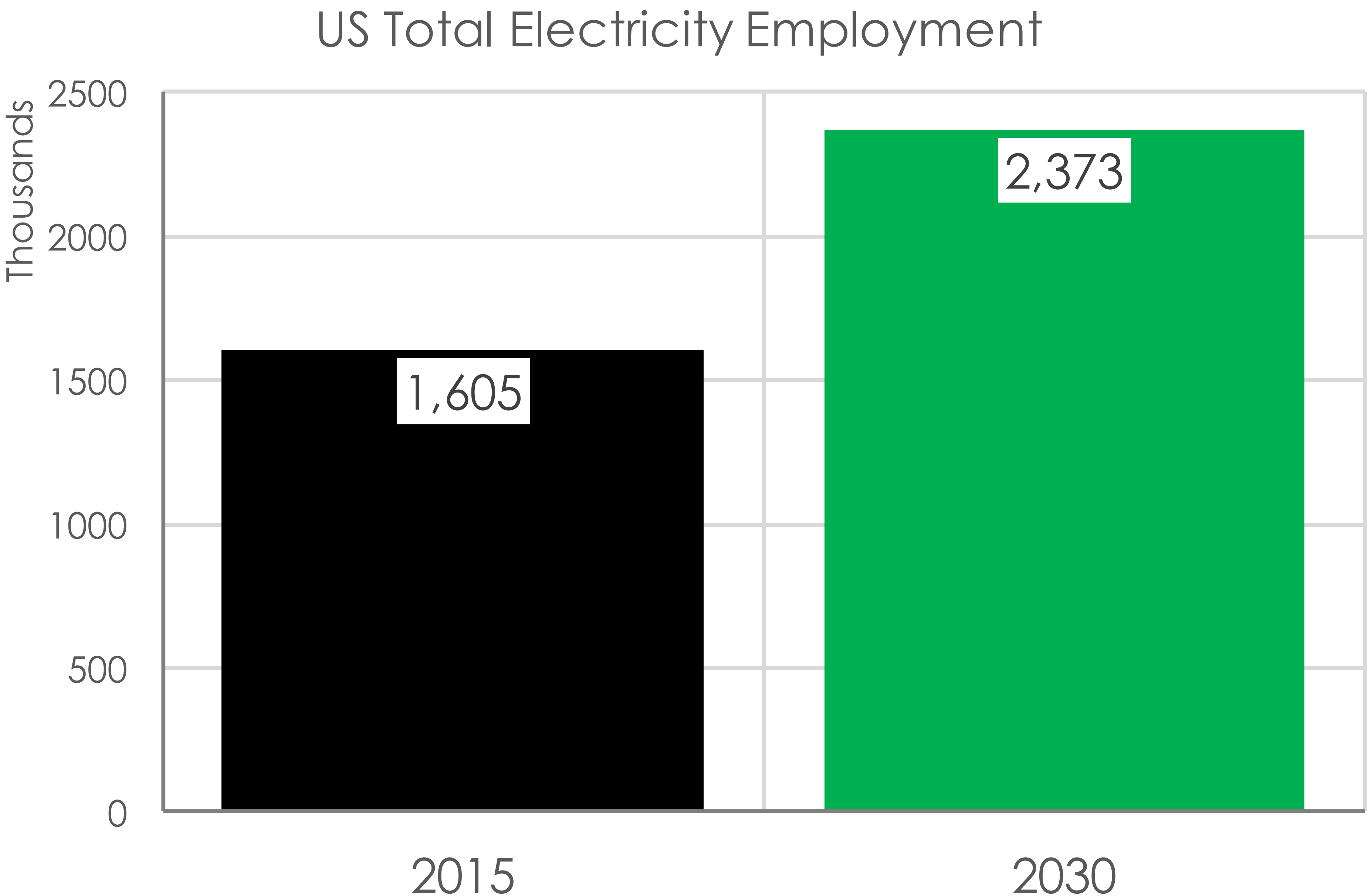




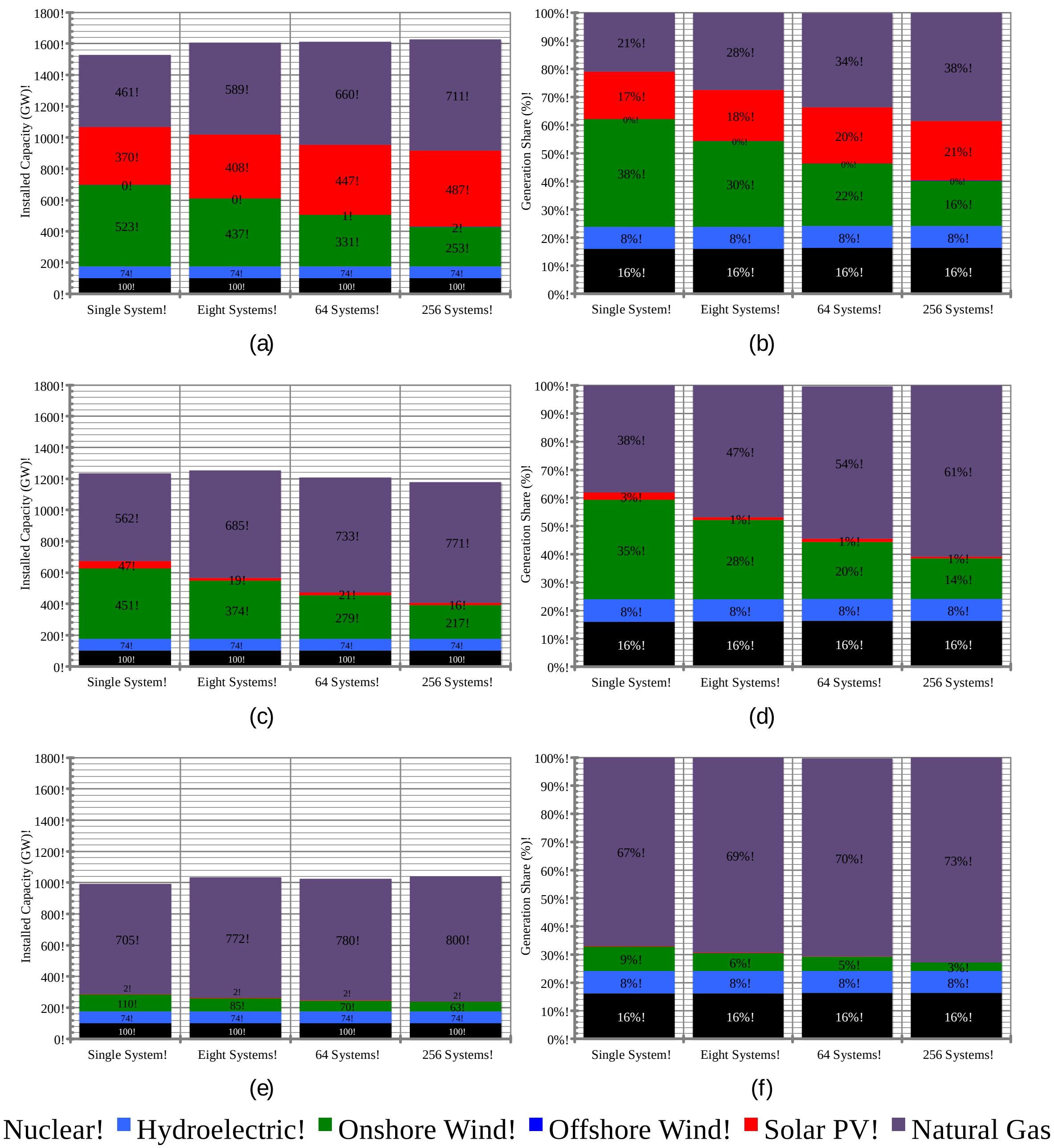
A national system would consume less water



A national system would employ more people



NEWS Result: Geographic Scale and Cost of Technology



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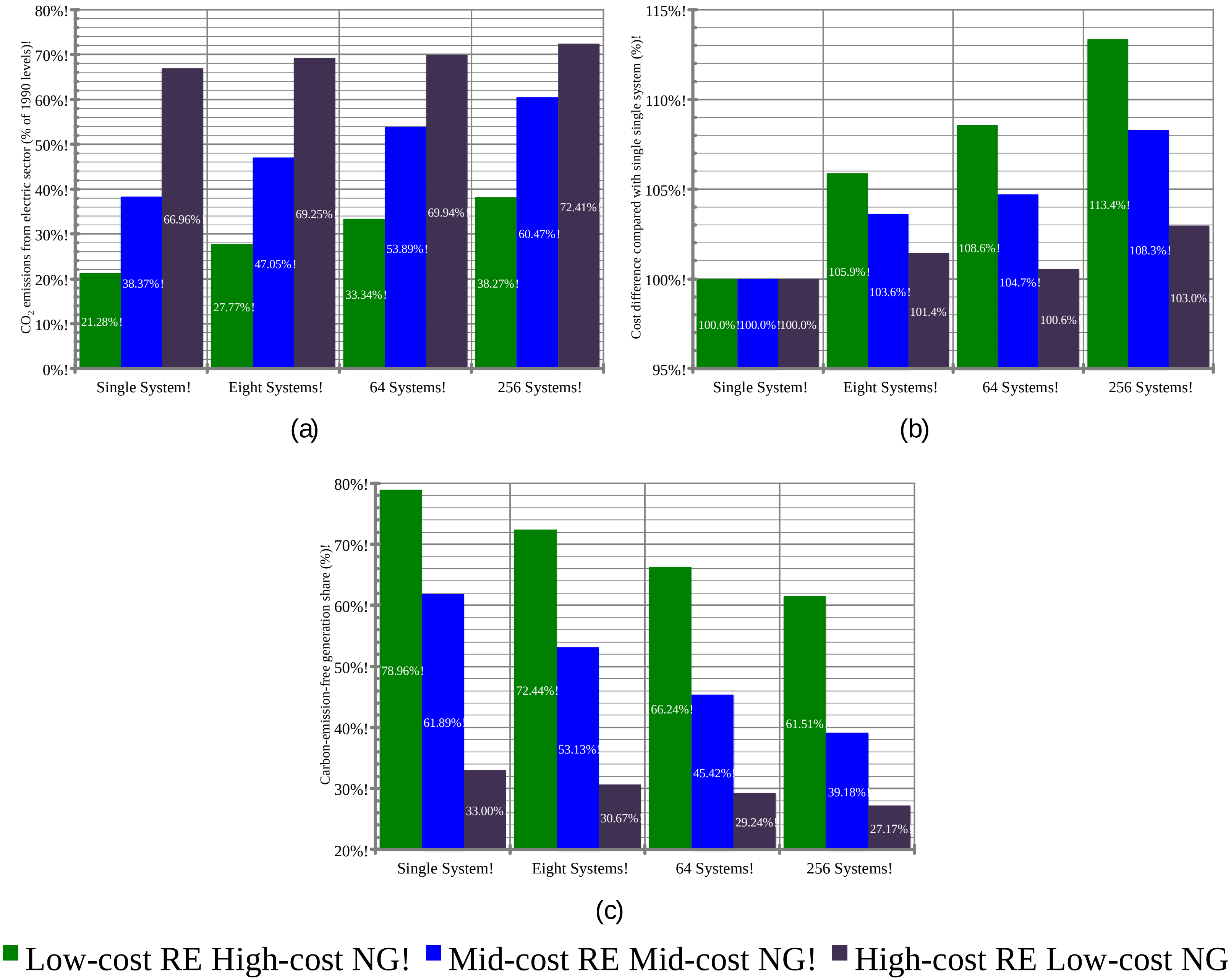
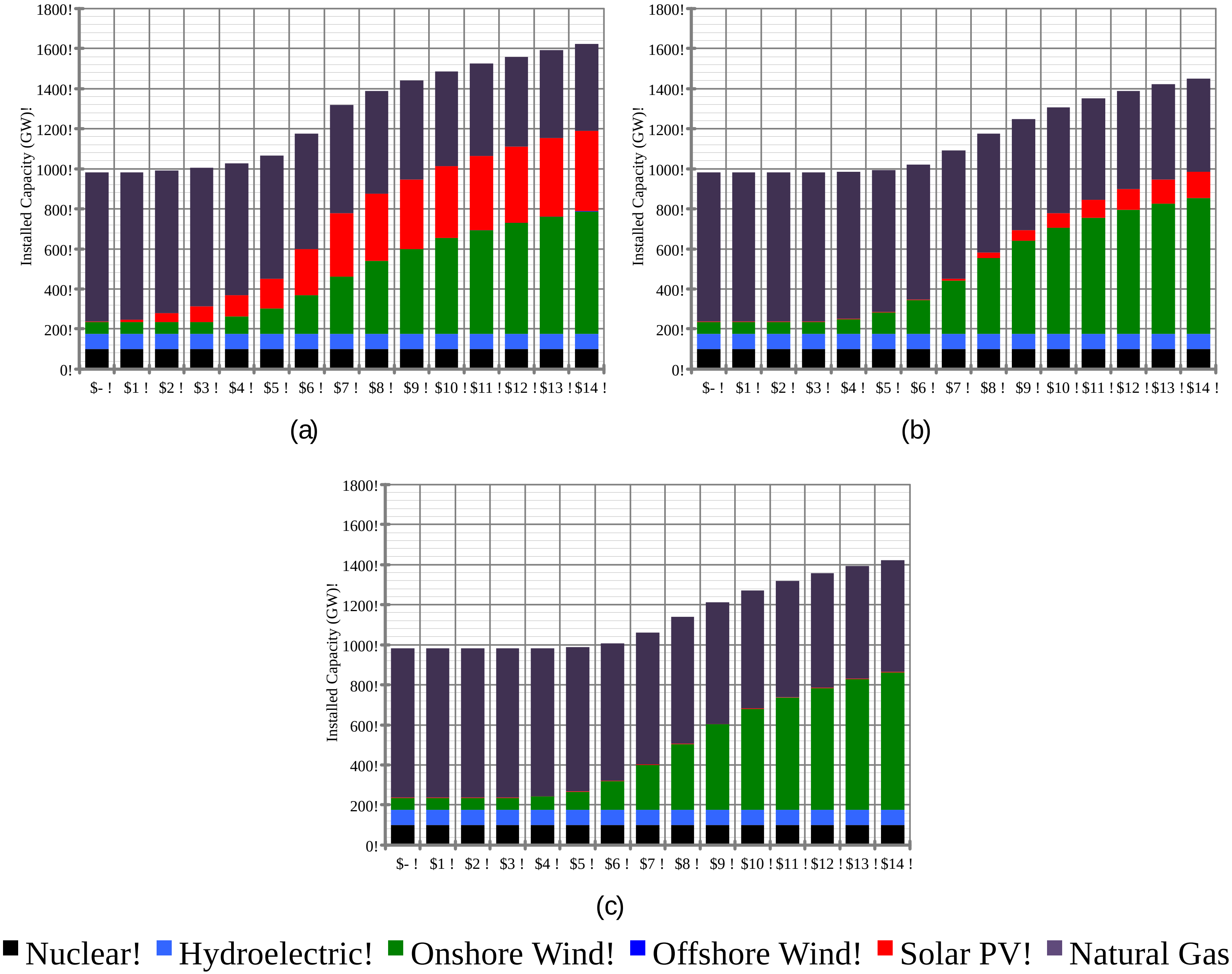


NEWS Result: Sensitivity to Natural Gas



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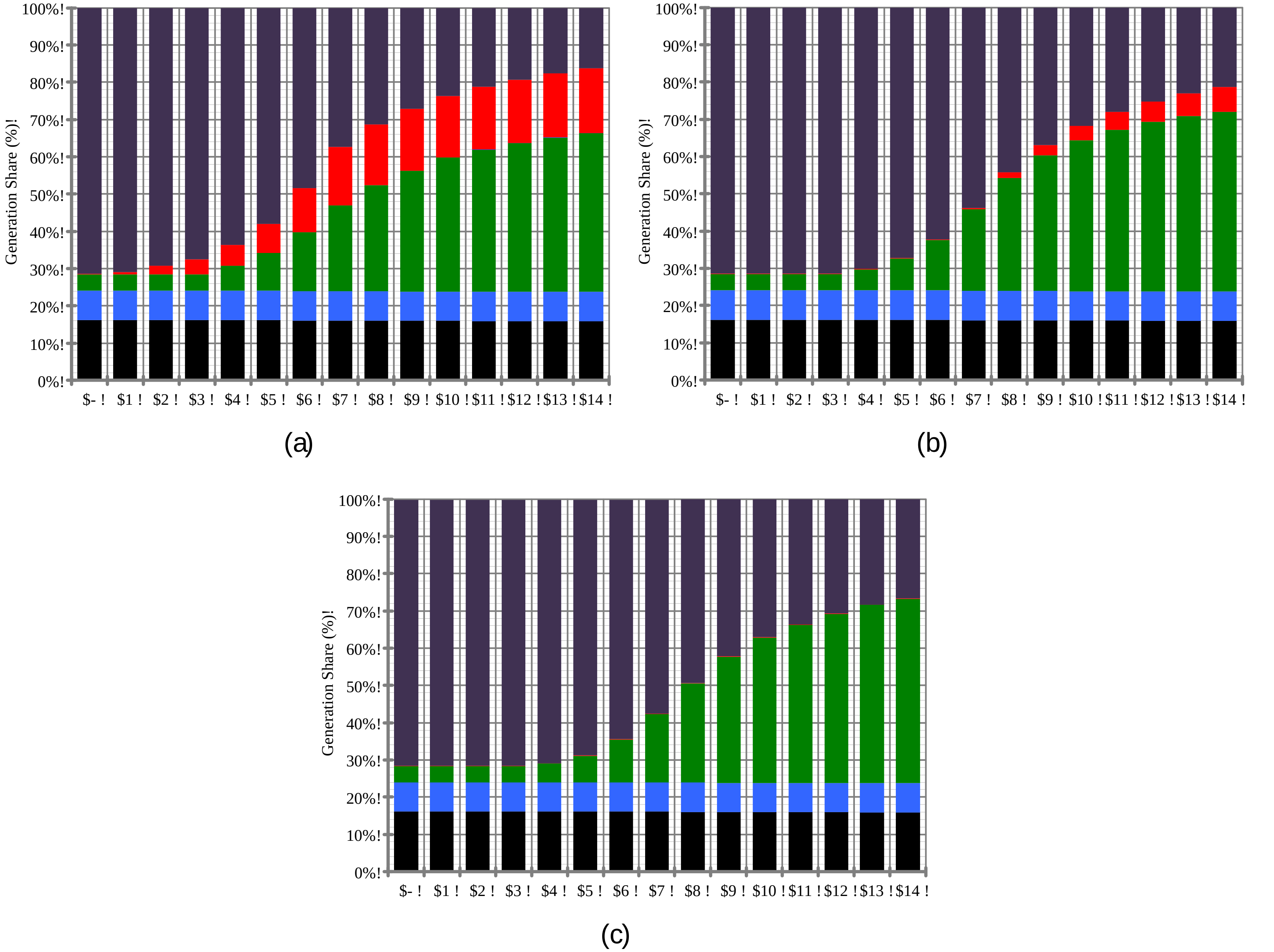
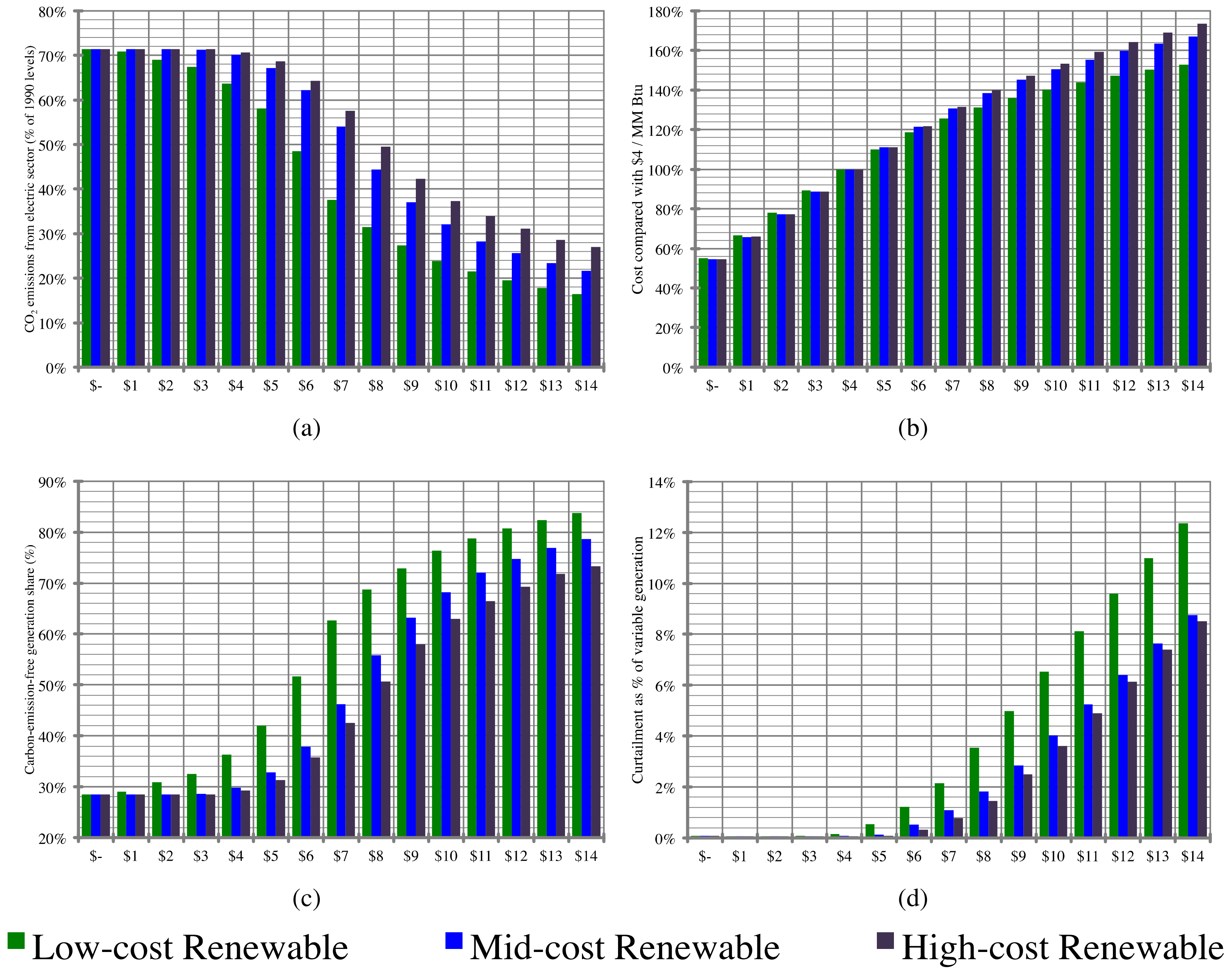


Nuclear! Hydroelectric! Onshore Wind! Offshore Wind! Solar PV! Natural Gas

NEWS Result: Sensitivity to Natural Gas



Realistic Solutions Do Exist

- The US can ***reduce*** carbon dioxide emissions by ***80%*** compared with ***1990 levels***:
  - ✓ While **decreasing** the cost of electricity
  - ✓ With a large share of **wind** and **solar**
  - ✓ By deploying a **national transmission system**
  - ✓ By using **existing** technologies **only**
  - ✓ **Without** using storage, biomass or CCS.

Critical Key Findings

- It is ***not*** always best practice to place variable generators ***where the most power*** potential is.

- **A large area system** is beneficial for numerous reasons, but particularly to find ***more valuable*** sites for variable generation.

- Coordinated planning **is** more efficient than competition.

- The least cost paths are, at most, **80% variable** generation. The **last 20%** is more appropriately dealt with by ***another*** method / technology.

Questions?

NEWS Webpage:
esrl.noaa.gov/gsd/renewable/news-simulator.html

NEWS Results Webpage:
esrl.noaa.gov/gsd/renewable/news-results/#usstudy-2007-lrhg-1

NEWS Results Data:
esrl.noaa.gov/gsd/renewable/news-results/usstudy/

Free Copy of the Nature Climate Change Paper:
http://rdcu.be/f2Dg


Wind Turbine Blades
Leaving Broomfield, CO


Utility Scale Solar PV Plant
Near Golden, CO

Photos by Will von Dauster, 2015

Dr Christopher T M Clack
Christopher.Clack-1@colorado.edu
chrisclack@hotmail.com

colorado.academia.edu/ChristopherClack
researchgate.net/profile/Christopher_Clack2
linkedin.com/in/clacky007
twitter.com/clacky007

Simplified Optimization Procedure

$$\text{Minimize} \quad \psi = \sum_{\phi} \sum_{\kappa} \mathcal{C}^{v}_{\phi\kappa} \cdot V_{\phi\kappa} + \sum_{\mu} \left(\mathcal{C}^{g}_{\mu} \cdot G_{\mu} + \mathcal{C}^{f}_{\mu} \cdot \sum_{\tau} D_{\mu\tau} \right) + \sum_{\hat{\alpha}} \sum_{\hat{\beta}} T_{\hat{\alpha}\hat{\beta}} \cdot \left(\mathcal{C}^{ts} + \mathcal{C}^{tl}_{\hat{\alpha}\hat{\beta}} \cdot \delta_{\hat{\alpha}\hat{\beta}} \right)$$

- Yearly cost of variable generation ($/MW)
- Installed capacity of variable generation (MW)
- Yearly cost of conventional generation ($/MW)
- Installed capacity of conventional generation (MW)
- Cost of conventional fuels ($/MWh)
- Amount of fuel burned converted to MWh
- Yearly cost of transmission stations ($/MW)
- Installed capacity of transmission (MW)
- Yearly cost of transmission lines ($/MW-mile)
- Length of transmission lines (mile)

Simplified Optimization Procedure

Load constraint

VARIABLE GENERATION

CONVENTIONAL GENERATION

NET ELECTRIC DEMAND

Subject to:

$$\sum_{\phi} \left(b^{v}_{\phi\omega} \cdot \sum_{\kappa} V_{\phi\kappa} \cdot \mathcal{W}_{\phi\kappa\tau} \right) + \sum_{\mu} b^{c}_{\mu\omega} \cdot (D_{\mu\tau} + N_{\mu\tau} + H_{\mu\tau}) = \mathcal{L}_{\omega\tau} - F_{\omega\tau} + E_{\omega\tau}, \quad \forall\, \omega, \tau$$

Variable generator Filter

Installed capacity of variable generation (MW)

Weather Component (h)

Conventional generator filter

Conventional Generation (MWh)

Nuclear generation (MWh)

Hydroelectric generation (MWh)

Electric demand (MWh)

Transmission power flux (MWh)

Excess generation (MWh)

Simplified Optimization Procedure

VERY IMPORTANT CONSTRAINT AND EXTREMELY COMPUTATIONALLY EXPENSIVE

HVDC transmission flux constraint

Transmission power flux (MWh)

Transmission power flow (MWh)

Transmission power flow (MWh)

$$F_{\omega\tau} = \sum_{\alpha} T_{\alpha\beta\tau} \cdot (1 - \lambda_{\alpha\beta} \cdot \delta_{\alpha\beta})\Big|_{\beta=\omega} - \sum_{\beta} T_{\alpha\beta\tau}\Big|_{\alpha=\omega}, \quad \forall\, \omega, \tau \ (\alpha \neq \beta)$$

Length of transmission lines (mile)

Electric loss factor (%/mile)

Simplified Optimization Procedure

Transmission Capacity Bound (MW)

Transmission capacity constraint

Transmission Capacity (MW)

Transmission power flow (MWh)

$$\mathcal{T}_{\hat{\alpha}\hat{\beta}} \geq T_{\hat{\alpha}\hat{\beta}} \geq T_{\alpha\beta\tau}\big|_{\alpha,\beta=\hat{\alpha},\hat{\beta}} \geq 0, \quad \forall\, \hat{\alpha}, \hat{\beta}, \tau \; (\hat{\alpha} > \hat{\beta})$$

Simplified Optimization Procedure

Planning reserve requirement constraint

Installed capacity of conventional generation (MW)

Conventional generator filter

Conventional generator filter

Planning reserve (%)

Conventional generation (MWh)

$$\sum_{\mu} b^{c}_{\mu\omega} \cdot G_{\mu} \geq (1 + \mathcal{R}^{g}_{\mu}) \cdot \sum_{\mu} b^{c}_{\mu\omega} \cdot D_{\mu\tau} \geq 0, \quad \forall\, \omega, \tau$$

Simplified Optimization Procedure

$$\mathcal{B}^{n-}_{\omega} \cdot \sum_{\mu} \left(b^{c}_{\mu\omega} \cdot \mathcal{N}_{\mu\tau} \right) \leq \sum_{\mu} b^{c}_{\mu\omega} \cdot N_{\mu\tau} \leq \mathcal{B}^{n+}_{\omega} \cdot \sum_{\mu} \left(b^{c}_{\mu\omega} \cdot \mathcal{N}_{\mu\tau} \right)$$

$$\mathcal{B}^{h-}_{\omega} \cdot \sum_{\mu} \left(b^{c}_{\mu\omega} \cdot \mathcal{H}_{\mu\tau} \right) \leq \sum_{\mu} b^{c}_{\mu\omega} \cdot H_{\mu\tau} \leq \mathcal{B}^{h+}_{\omega} \cdot \sum_{\mu} \left(b^{c}_{\mu\omega} \cdot \mathcal{H}_{\mu\tau} \right)$$

Nuclear and hydroelectric dispatch constraints

$$\mathcal{B}^{v-}_{\phi\kappa} \leq V_{\phi\kappa} \leq \mathcal{B}^{v+}_{\phi\kappa}, \quad \forall\ \phi, \kappa$$

Wind and solar siting constraint

$$0 \leq G_{\mu} \leq \mathcal{B}^{g}_{\mu}, \quad \forall\ \mu$$

Conventional Generation siting constraint