Cost–competitive Reduction of Carbon Emissions of up to 80% from the US Electric Sector by 2030

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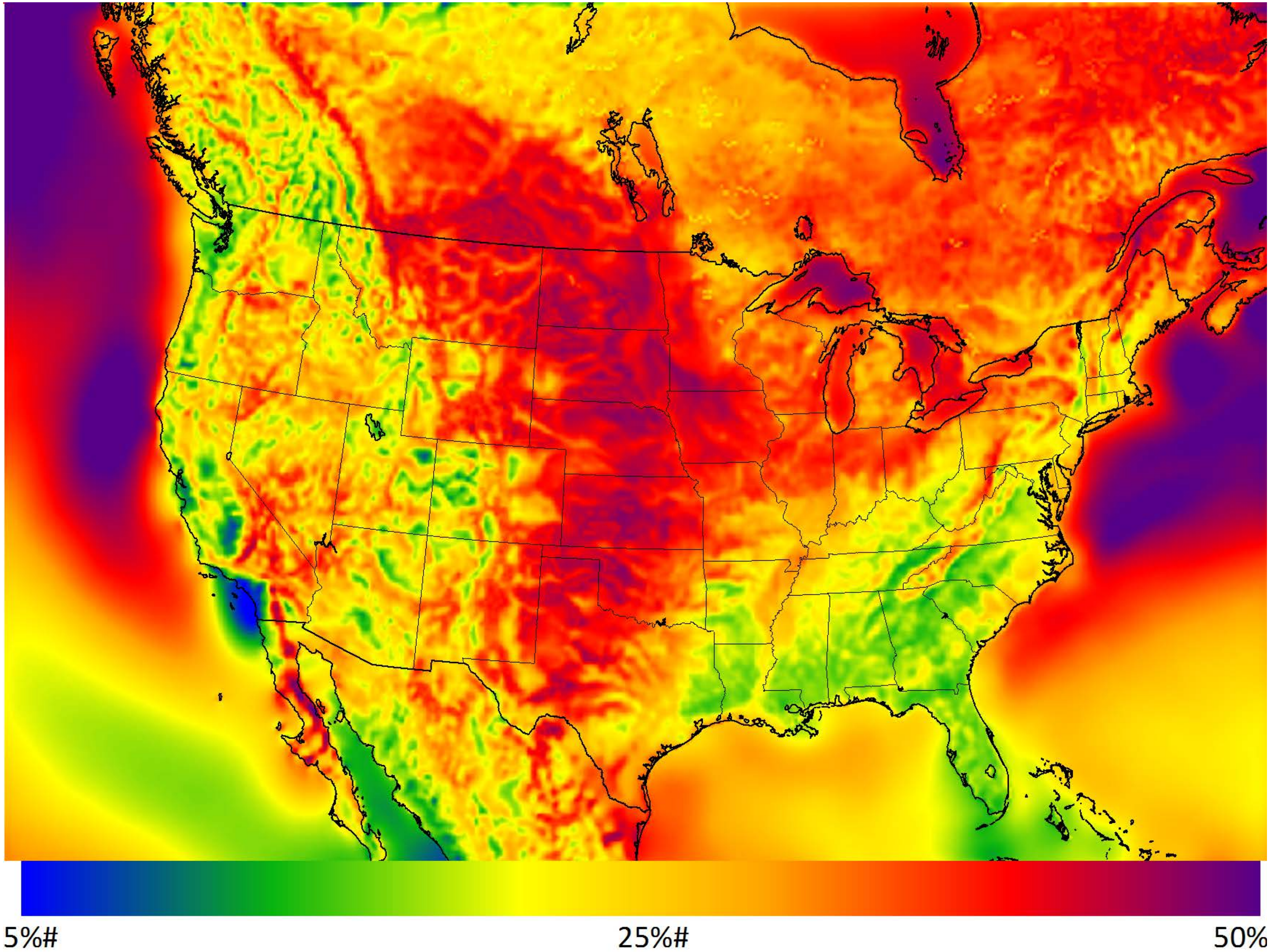
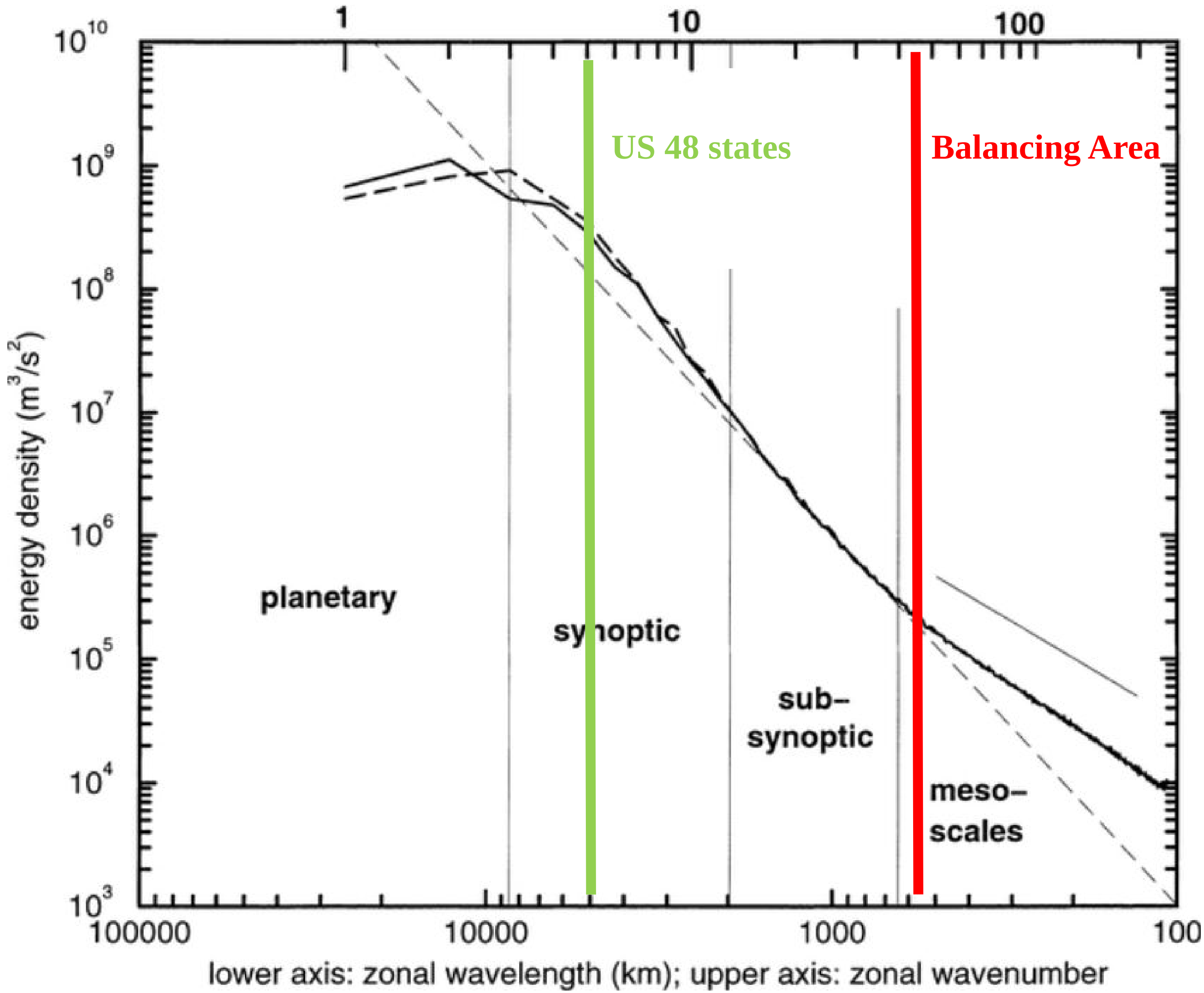
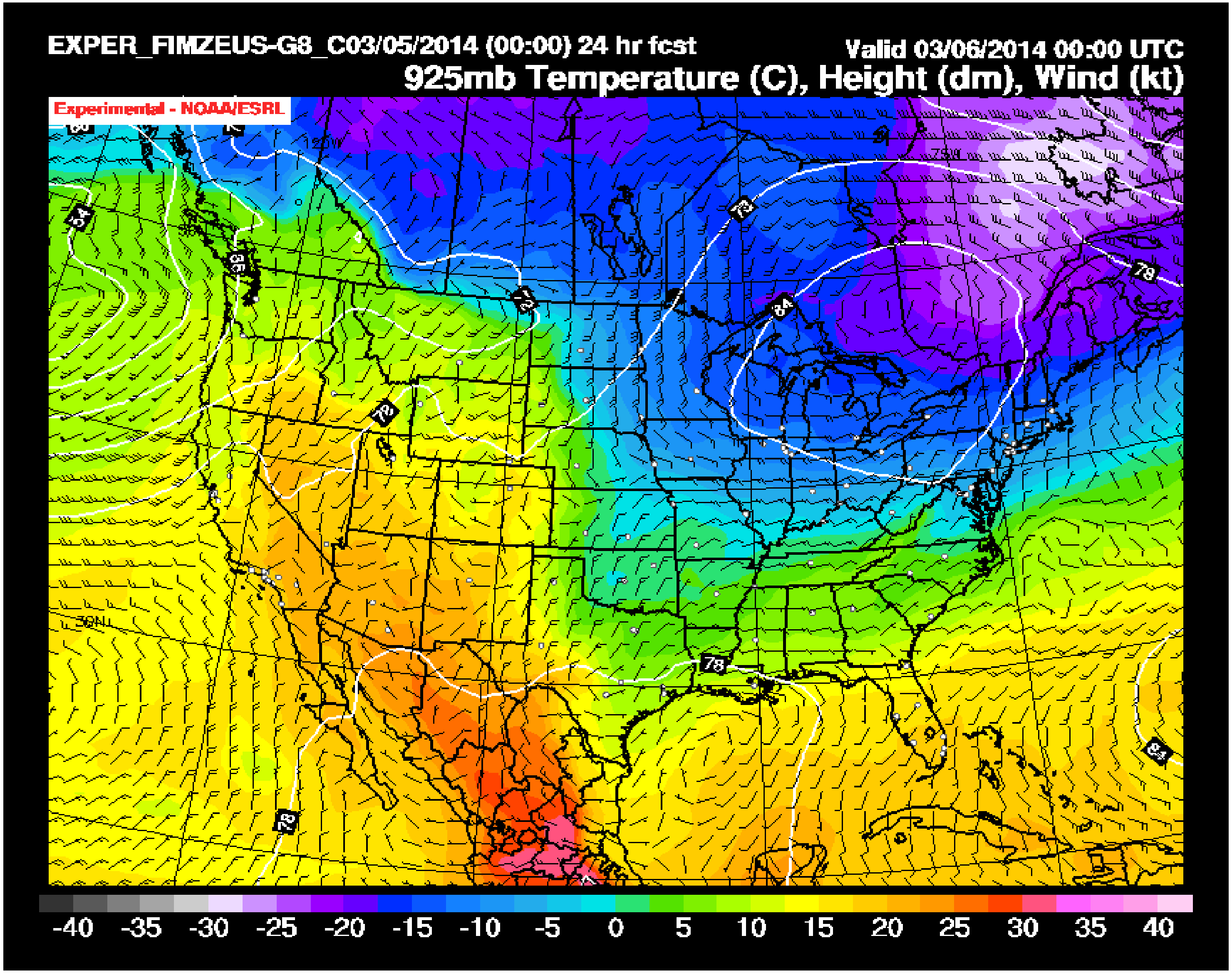
Wind capacity factor: Power costs 3 to 4 cents in red areas.





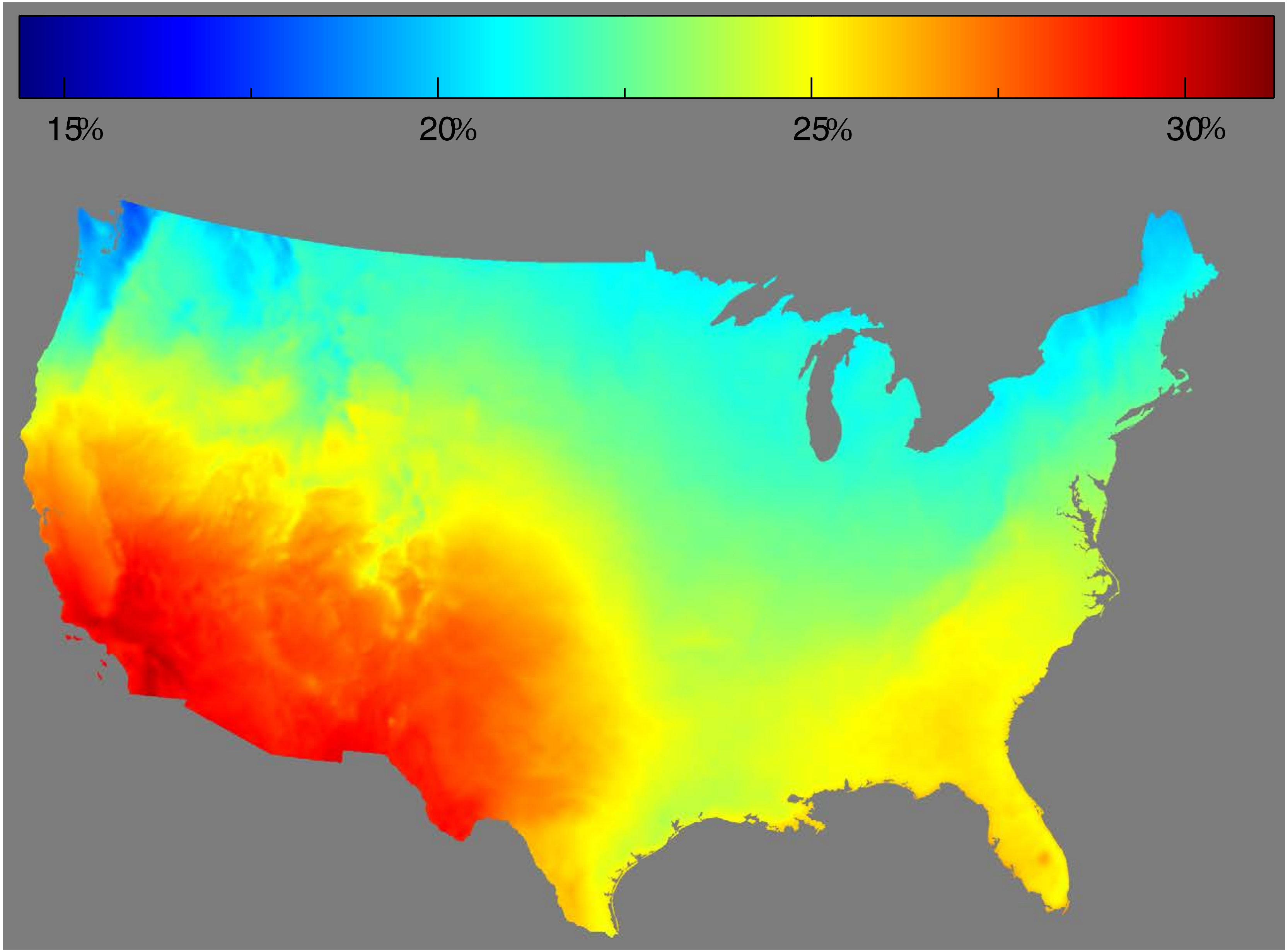
Spectrum of atmospheric kinetic energy density.

Weather energy is concentrated at large scales.



Though wind power may be missing in a small area, it is likely to be available in a larger area.

Solar PV Capacity Factor Map



US Study: National Energy System Designer

Step 1. We collected an extraordinarily detailed and **accurate weather** data set.

Step 2. We collected **electric load data concurrent in time** with the weather data.

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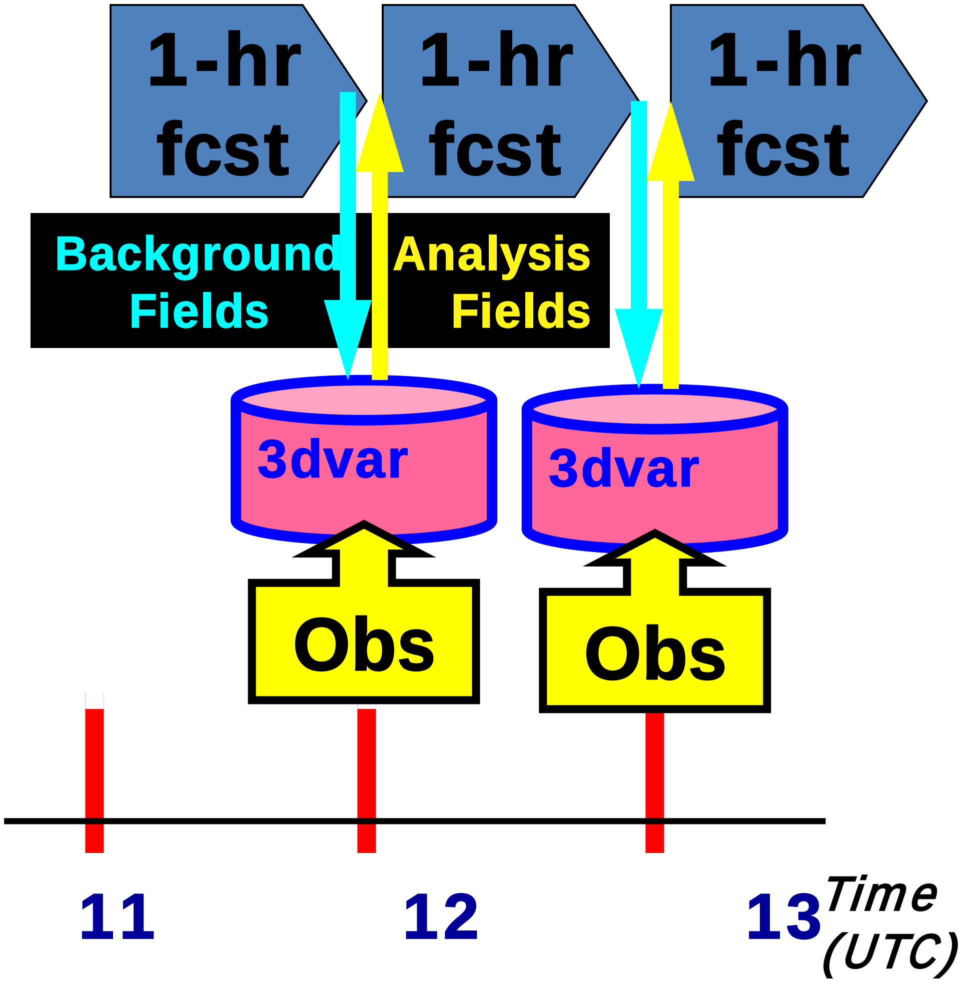
Step 5. The weather and economic simulator was used to study the geographic domain size effects of wind and solar energy generation systems.

Rapid Update Cycle (RUC) Hourly Assimilation

Cycle hydrometeor, soil temp/moisture/snow plus atmosphere state variables



1-hr fcst

1-hr fcst

1-hr fcst

Background Fields

Analysis Fields

3dvar

3dvar

Obs

Obs

11

12

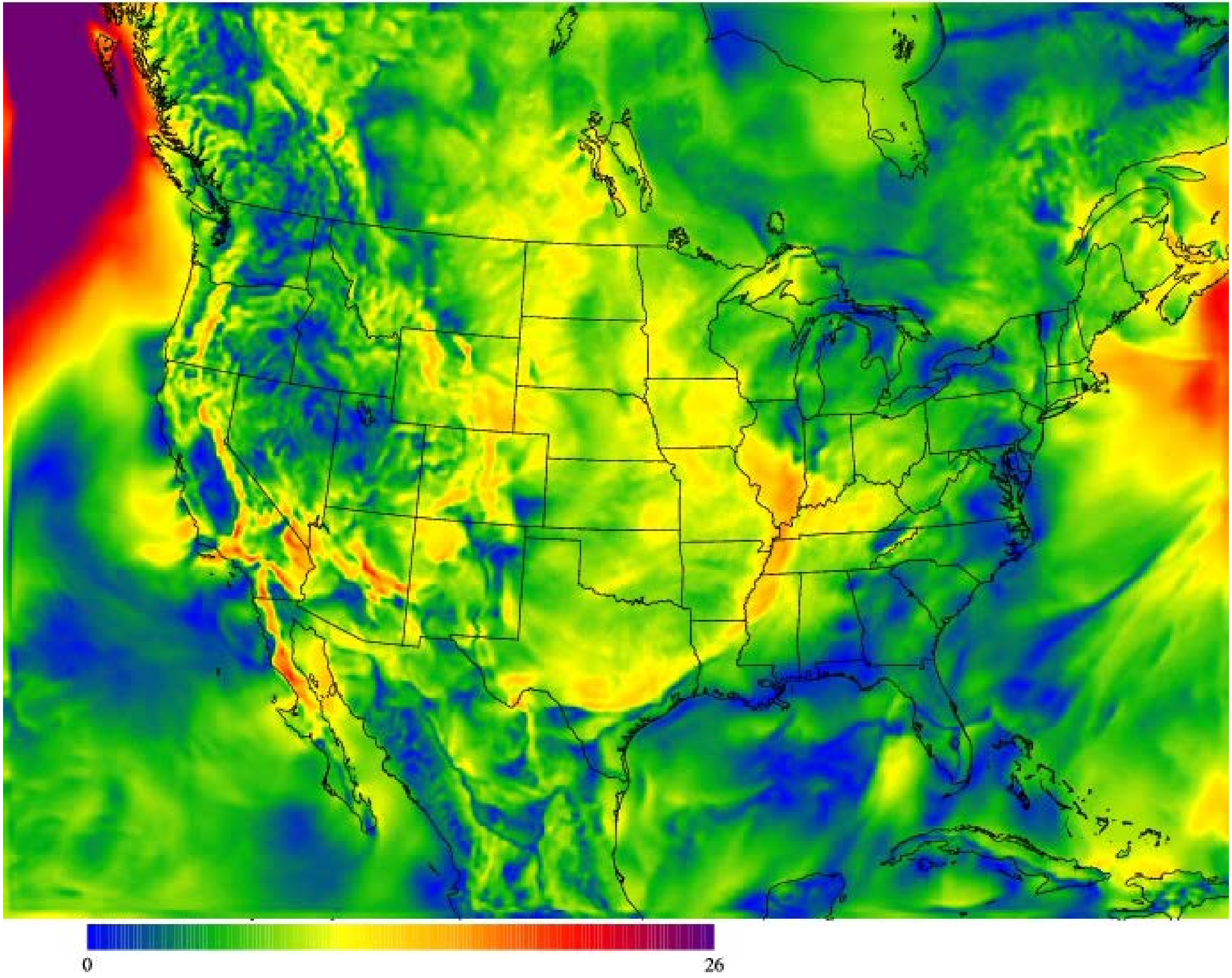
13

Time (UTC)

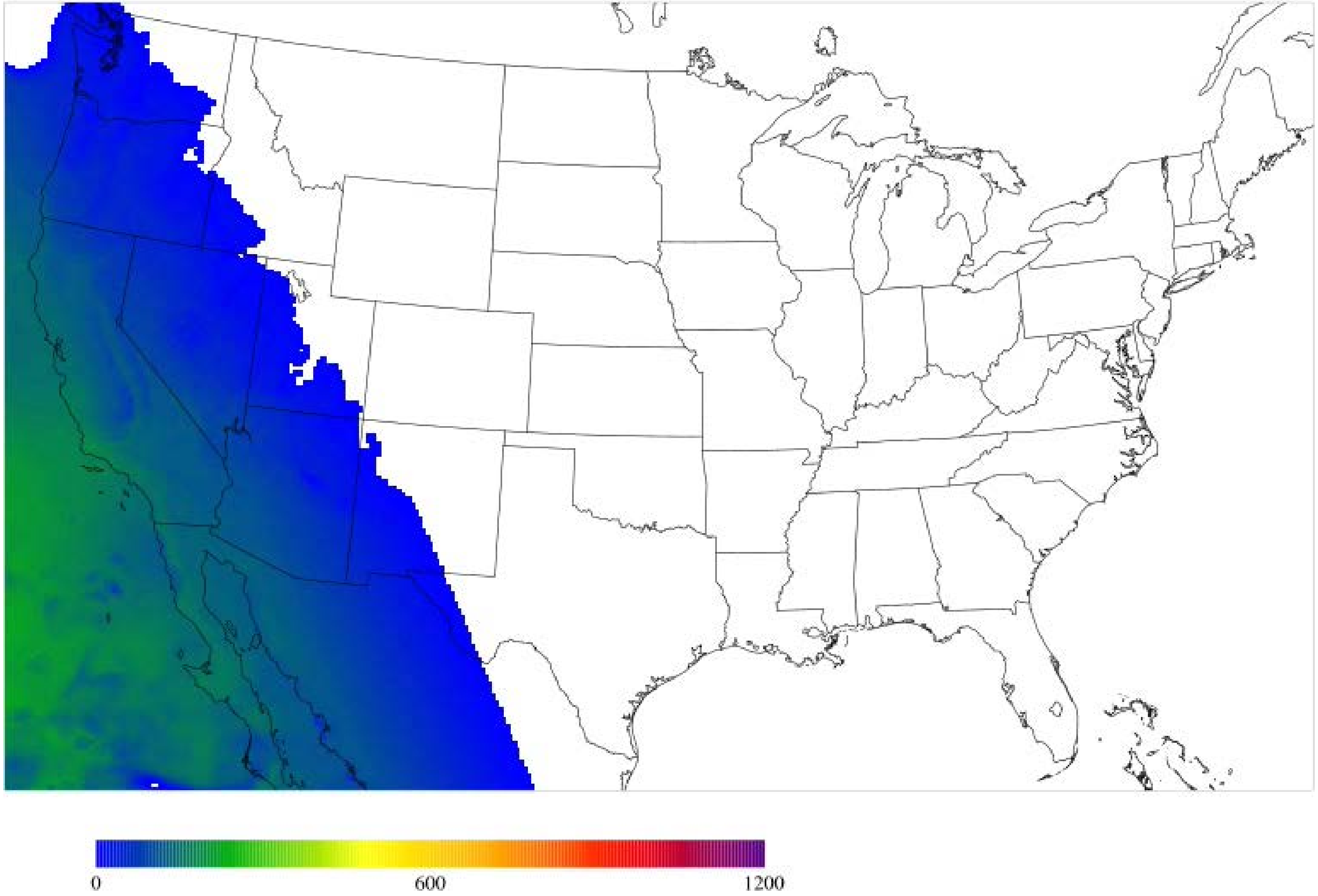
Hourly obs

Data Type	~Number
Rawinsonde (12h)	150
NOAA profilers	35
VAD winds	120-140
PBL – prof/RASS	~25
Aircraft (V,temp)	3500-10000
TAMDAR (V,T,RH) *	200-3000
Surface/METAR	2000-2500
Buoy/ship	200-400
GOES cloud winds	4000-8000
GOES cloud-top pres	10 km res
GPS precip water	~300
Mesonet (temp, dpt)	~8000
Mesonet (wind)	~4000
METAR-cloud-vis-wx	~1800
AMSU-A/B/GOES radiances – *RR only*	
Radar reflectivity/ lightning	1km

Wind Speed Video (m/s)



Solar Irradiance Video (W/m^2)



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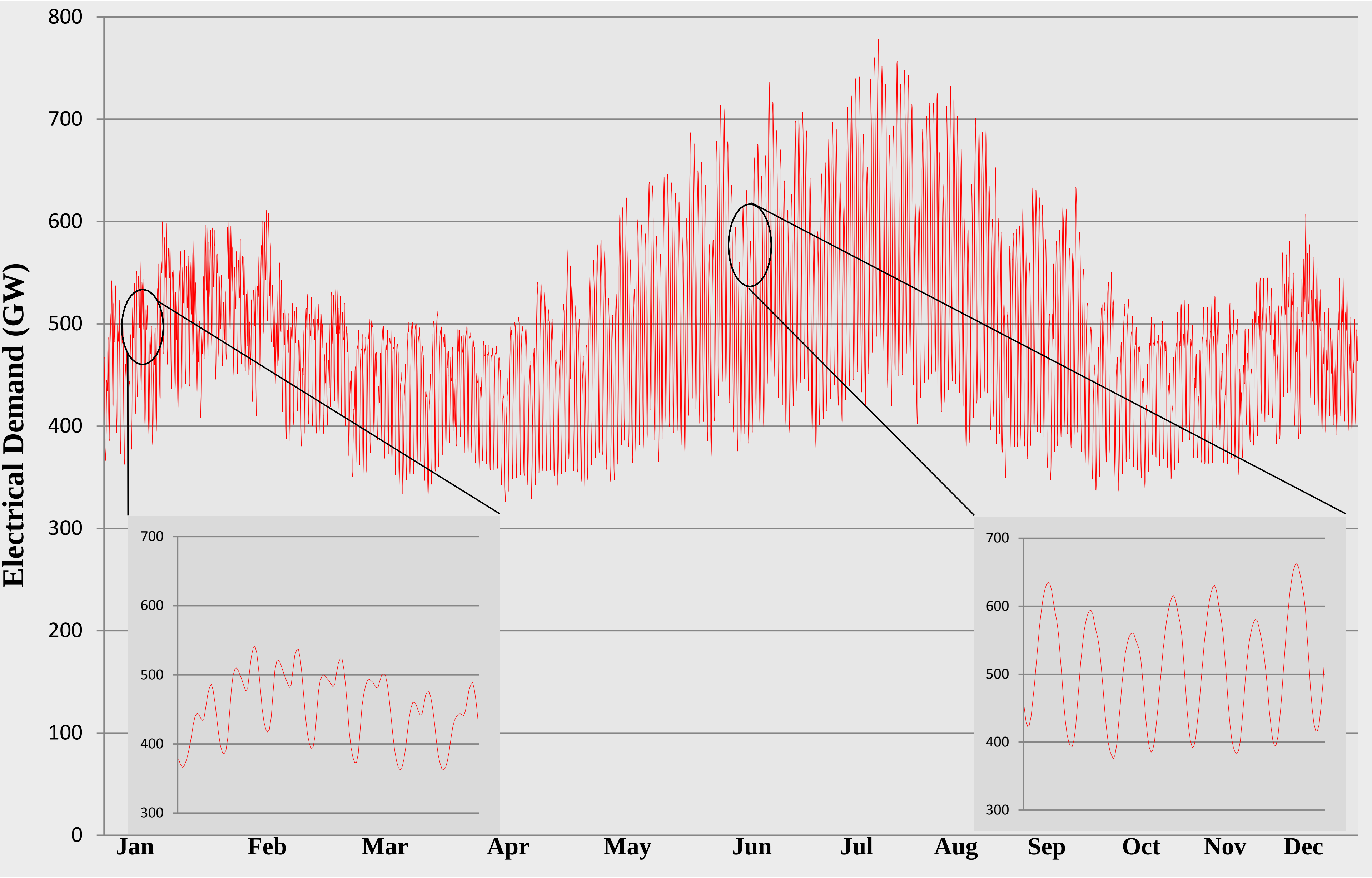
Electric Demand/Load



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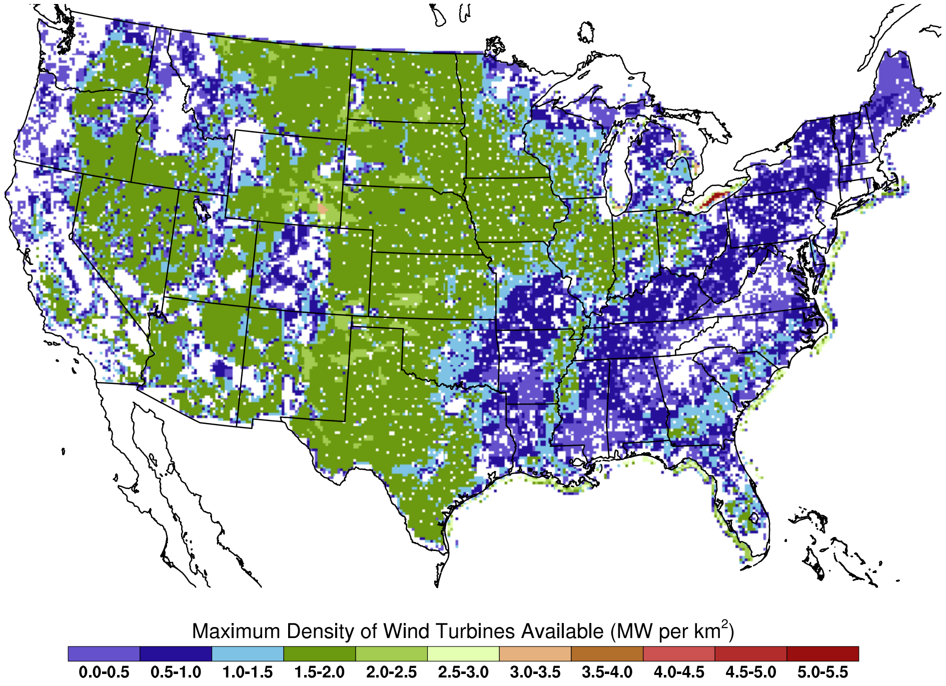
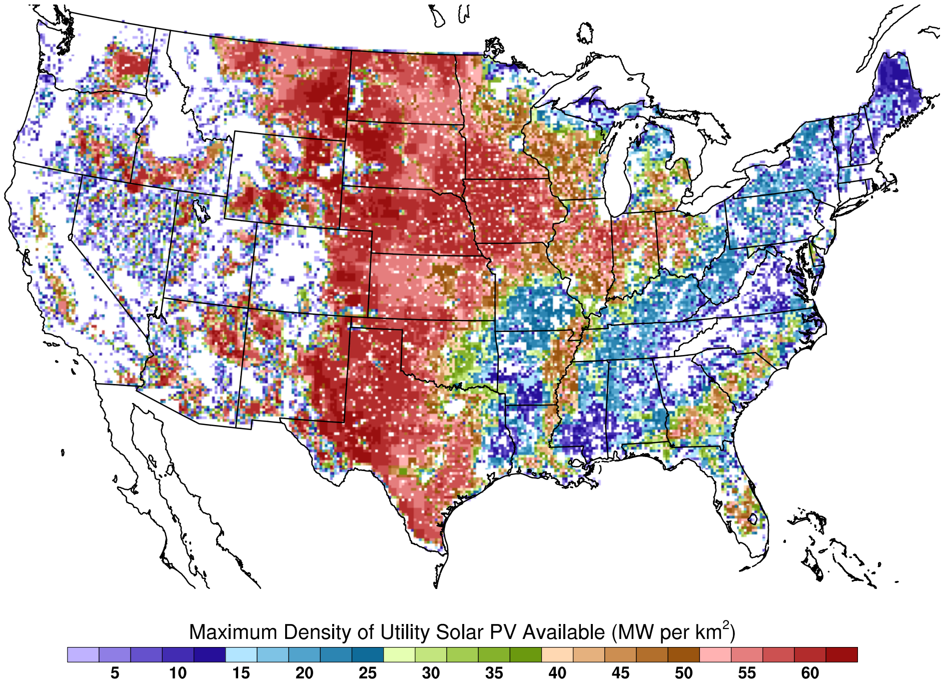
Land Use Constraints



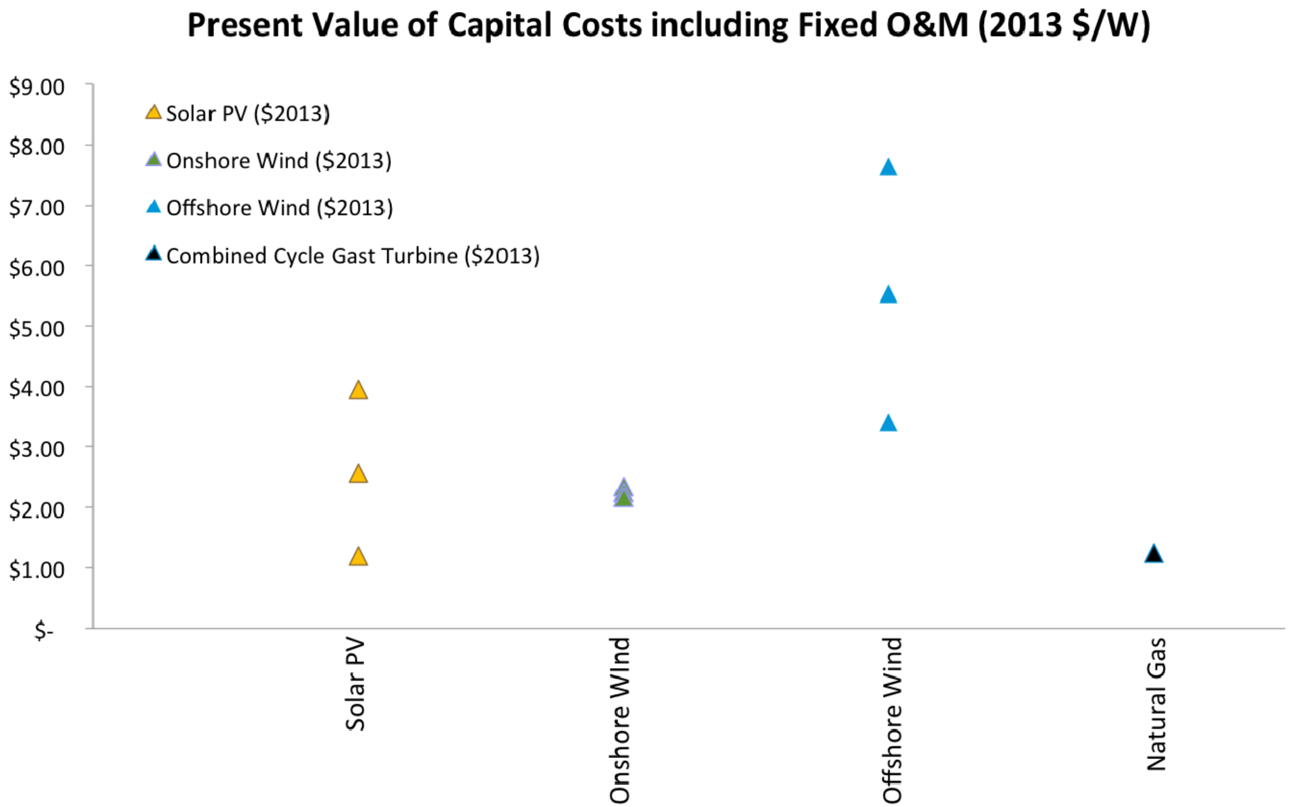
Maximum Density of Wind Turbines Available (MW per km^2)



Maximum Density of Utility Solar PV Available (MW per km^2)

- The type and amount of electricity generation installed in each RUC cell is constrained by:
  - **Spacing between facilities**
  - **Topography of the land**
  - **Land Use (residential, commercial, protected lands, etc…)**

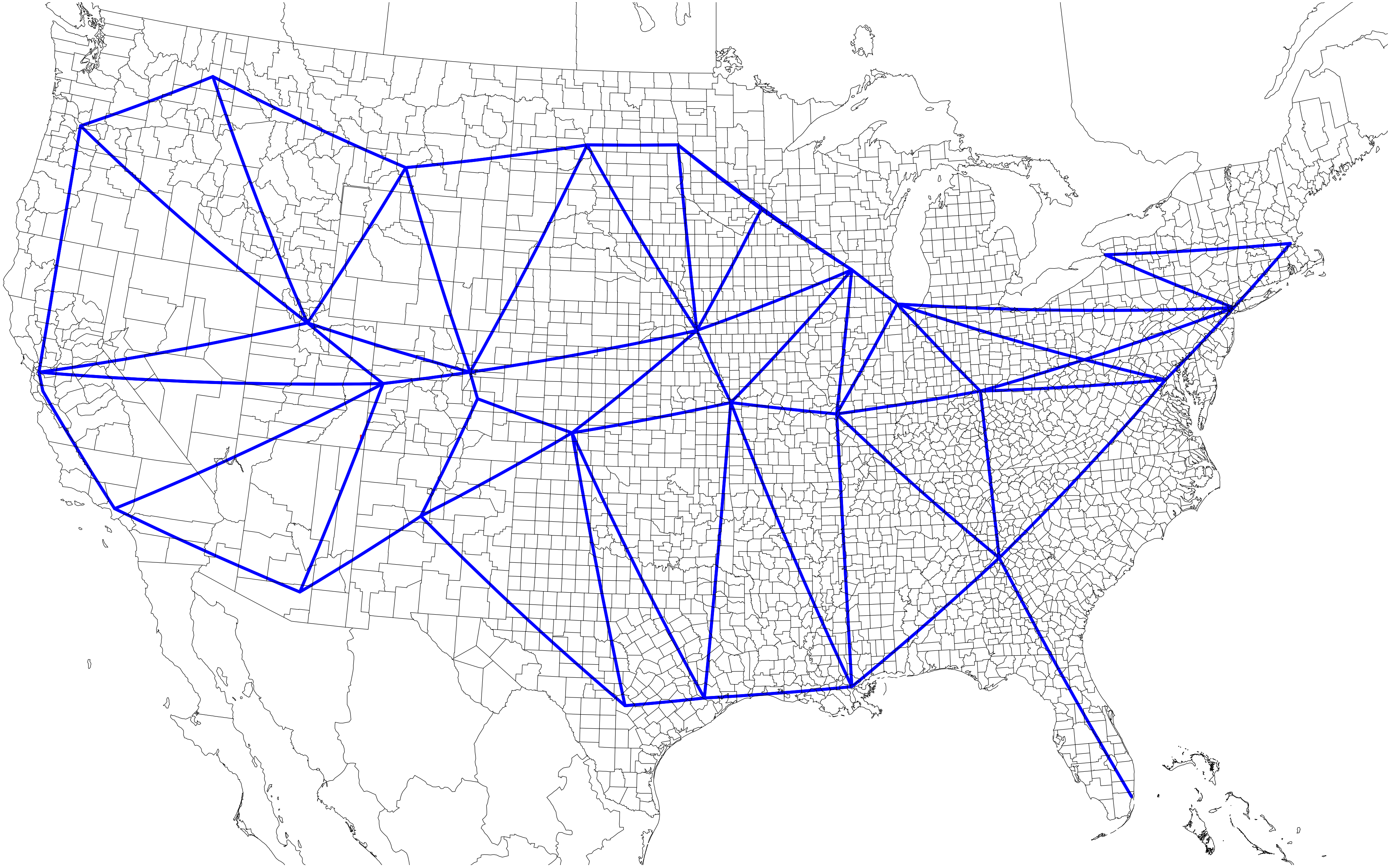
Cost Data/Values



2030 Estimates	Onshore	Offshore	PV	CCGT	NG Fuel	HVDC lines	HVDC Stations
Low W&S High NG	$2.16	$3.41	$1.19	$1.24	$11.10	$701.36	182,856.11
Mid W&S Mid NG	$2.25	$5.53	$2.57	$1.24	$8.82	$701.36	182,856.11
High W&S Low NG	$2.36	$7.64	$3.94	$1.24	$5.40	$701.36	182,856.11

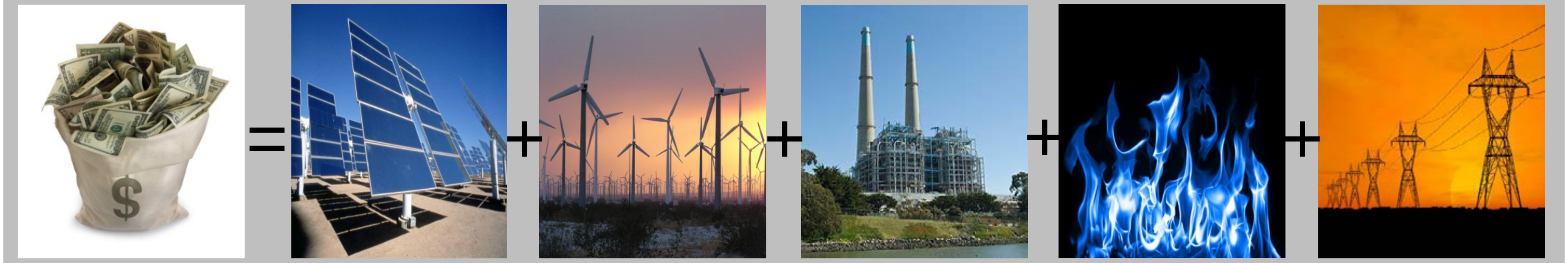
Natural gas has a heat rate of 6,430 Btu / kWh. Variable O&M is $3.11 / MWh

HVDC Transmission Parameterization



Mathematical Optimization

Minimize:

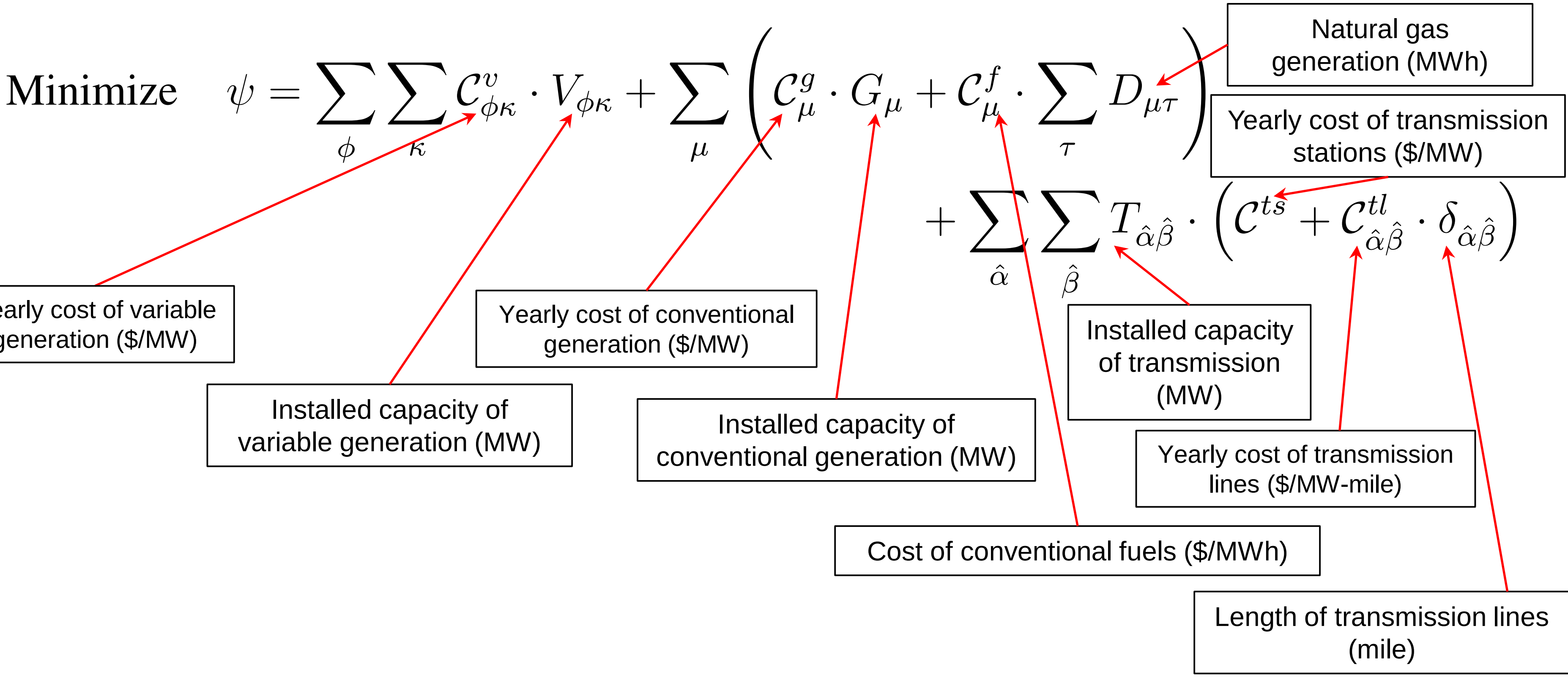


Subject to:

ALL OTHER EQUATIONS CONSTRAIN THE MAGNITUDE OF ANY OF THE TERMS

For details of the NEWS optimization see Clack *et al.*, IJEPES 2015.

Present Paper Optimization Procedure



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

Natural gas generation (MWh)

Yearly cost of transmission stations ($/MW)

Yearly cost of variable generation ($/MW)

Yearly cost of conventional generation ($/MW)

Installed capacity of transmission (MW)

Installed capacity of variable generation (MW)

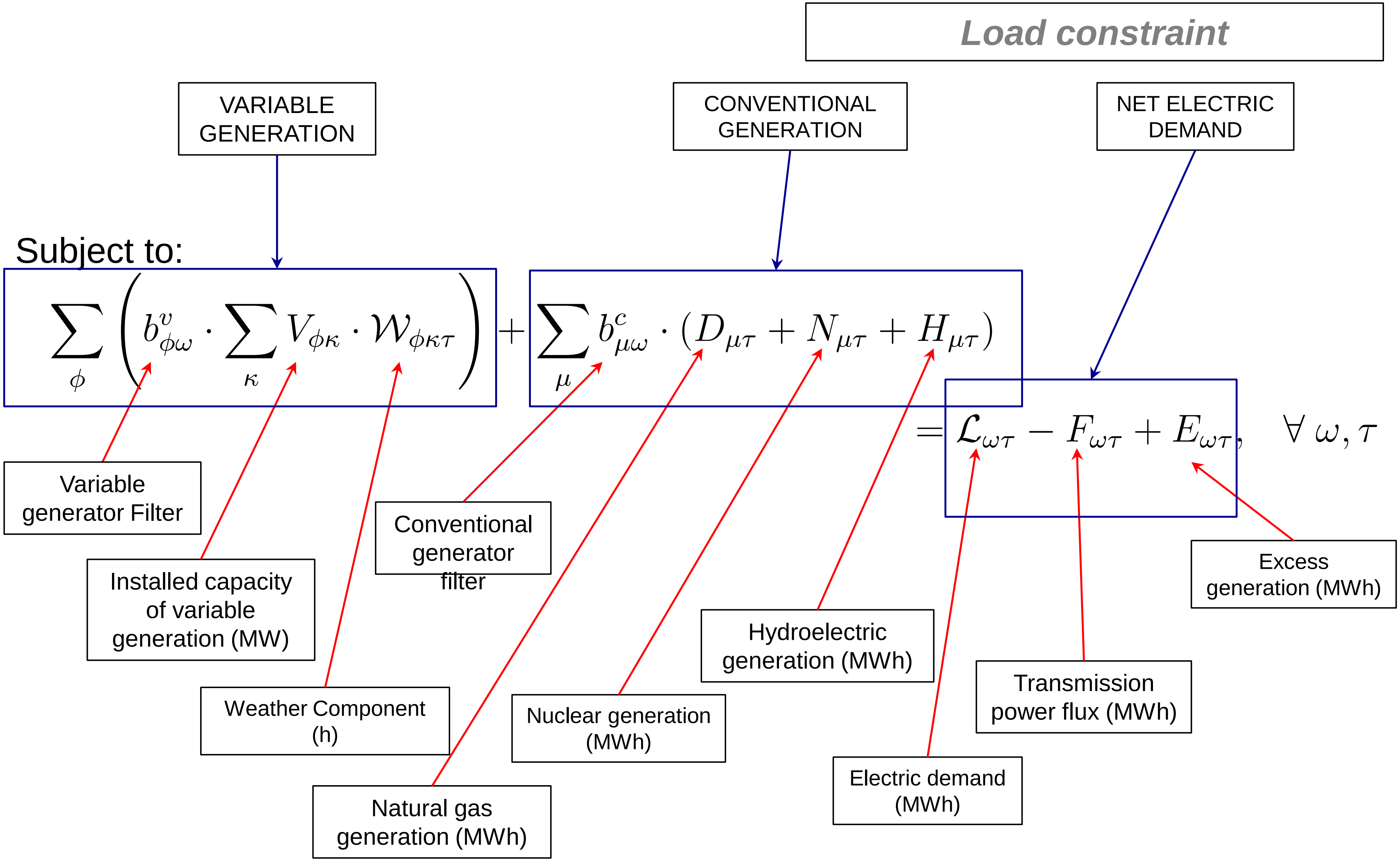
Installed capacity of conventional generation (MW)

Yearly cost of transmission lines ($/MW-mile)

Cost of conventional fuels ($/MWh)

Length of transmission lines (mile)

Present Paper Optimization Procedure



Load constraint

VARIABLE GENERATION

CONVENTIONAL GENERATION

NET ELECTRIC DEMAND

Subject to:

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

Variable generator Filter

Installed capacity of variable generation (MW)

Weather Component (h)

Natural gas generation (MWh)

Conventional generator filter

Nuclear generation (MWh)

Hydroelectric generation (MWh)

Electric demand (MWh)

Transmission power flux (MWh)

Excess generation (MWh)

Present Paper Optimization Procedure

VERY IMPORTANT CONSTRAINT AND EXTREMELY COMPUTATIONALLY EXPENSIVE

HVDC transmission flux constraint

Transmission power flux (MWh)

Transmission power flow (MWh)

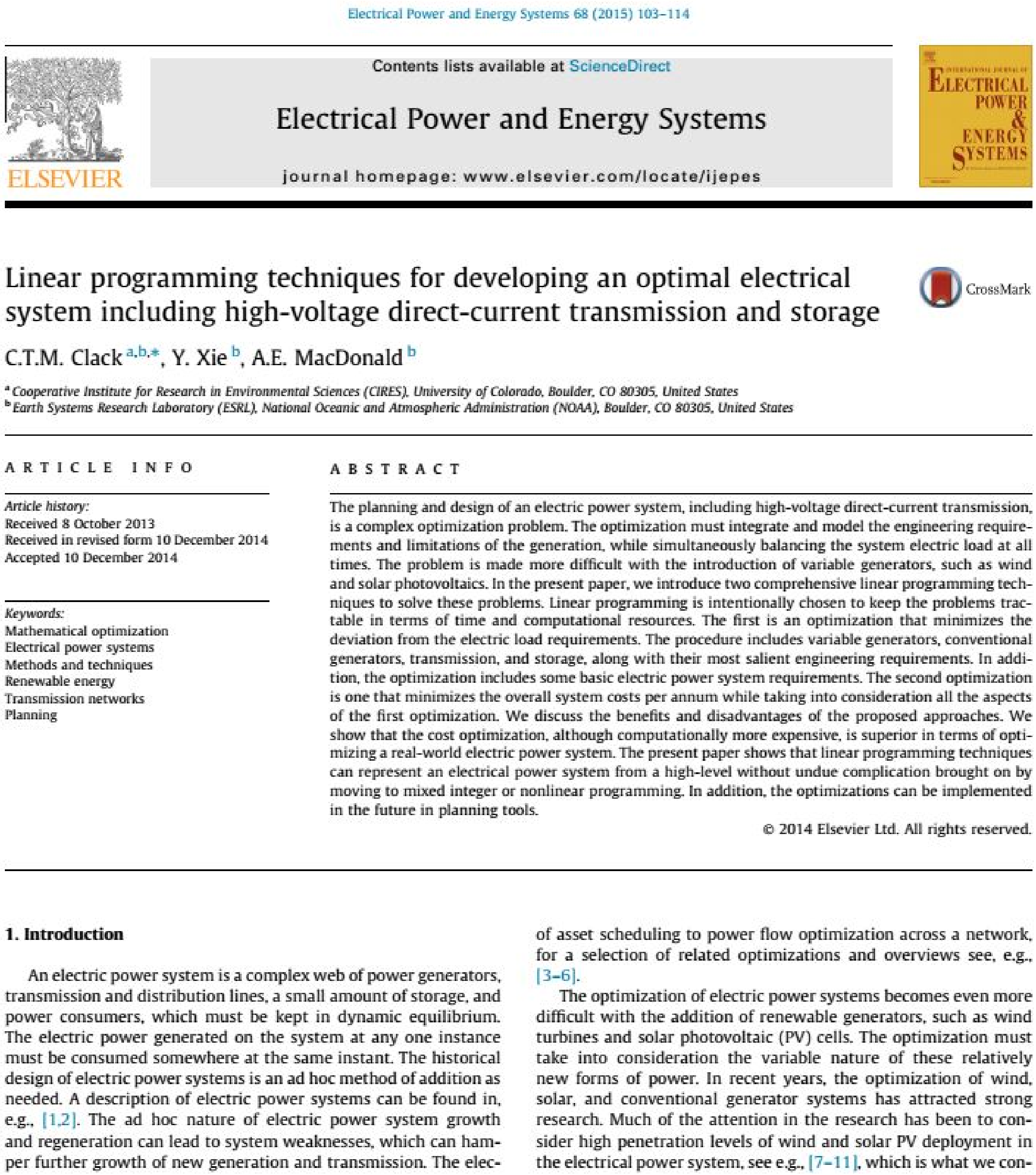
Transmission power flow (MWh)

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

Length of transmission lines (mile)

Electric loss factor (%/mile)

Peer reviewed description of the linear programming optimization techniques used.



Electrical Power and Energy Systems 68 (2015) 103–114

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Linear programming techniques for developing an optimal electrical system including high-voltage direct-current transmission and storage

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ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form 10 December 2014
Accepted 10 December 2014

Keywords:
Mathematical optimization
Electrical power systems
Methods and techniques
Renewable energy
Transmission networks
Planning

ABSTRACT

The planning and design of an electric power system, including high-voltage direct-current transmission, is a complex optimization problem. The optimization must integrate and model the engineering requirements and limitations of the generation, while simultaneously balancing the system electric load at all times. The problem is made more difficult with the introduction of variable generators, such as wind and solar photovoltaics. In the present paper, we introduce two comprehensive linear programming techniques to solve these problems. Linear programming is intentionally chosen to keep the problems tractable in terms of time and computational resources. The first is an optimization that minimizes the deviation from the electric load requirements. The procedure includes variable generators, conventional generators, transmission, and storage, along with their most salient engineering requirements. In addition, the optimization includes some basic electric power system requirements. The second optimization is one that minimizes the overall system costs per annum while taking into consideration all the aspects of the first optimization. We discuss the benefits and disadvantages of the proposed approaches. We show that the cost optimization, although computationally more expensive, is superior in terms of optimizing a real-world electric power system. The present paper shows that linear programming techniques can represent an electrical power system from a high-level without undue complication brought on by moving to mixed integer or nonlinear programming. In addition, the optimizations can be implemented in the future in planning tools.

1. Introduction

An electric power system is a complex web of power generators, transmission and distribution lines, a small amount of storage, and power consumers, which must be kept in dynamic equilibrium. The electric power generated on the system at any one instance must be consumed somewhere at the same instant. The historical design of electric power systems is an ad hoc method of addition as needed. A description of electric power systems can be found in, e.g., [1,2]. The ad hoc nature of electric power system growth and regeneration can lead to system weaknesses, which can hamper further growth of new generation and transmission. The elec- of asset scheduling to power flow optimization across a network, for a selection of related optimizations and overviews see, e.g., [3–6].

The optimization of electric power systems becomes even more difficult with the addition of renewable generators, such as wind turbines and solar photovoltaic (PV) cells. The optimization must take into consideration the variable nature of these relatively new forms of power. In recent years, the optimization of wind, solar, and conventional generator systems has attracted strong research. Much of the attention in the research has been to consider high penetration levels of wind and solar PV deployment in the electrical power system, see e.g., [7–11], which is what we con-

Present Paper Optimization Procedure

- Optimization has O(10^6) equations, O(10^7) variables and O(10^{8-9}) non zeroes

- Solves in O(10^6) iterations or O(10^5) seconds.

- We solve on a dedicated Server with 1 TB of RAM and 32 processors

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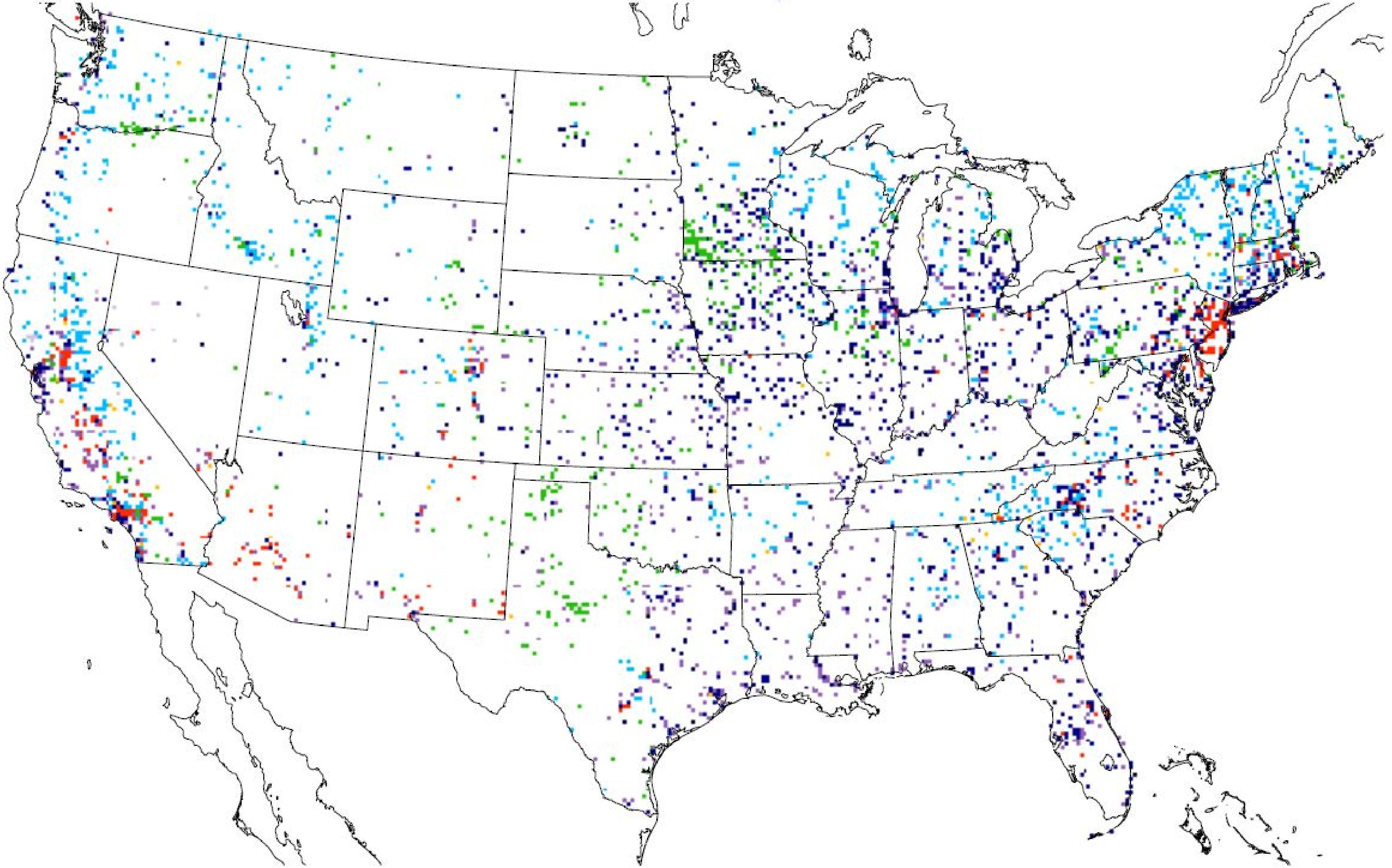
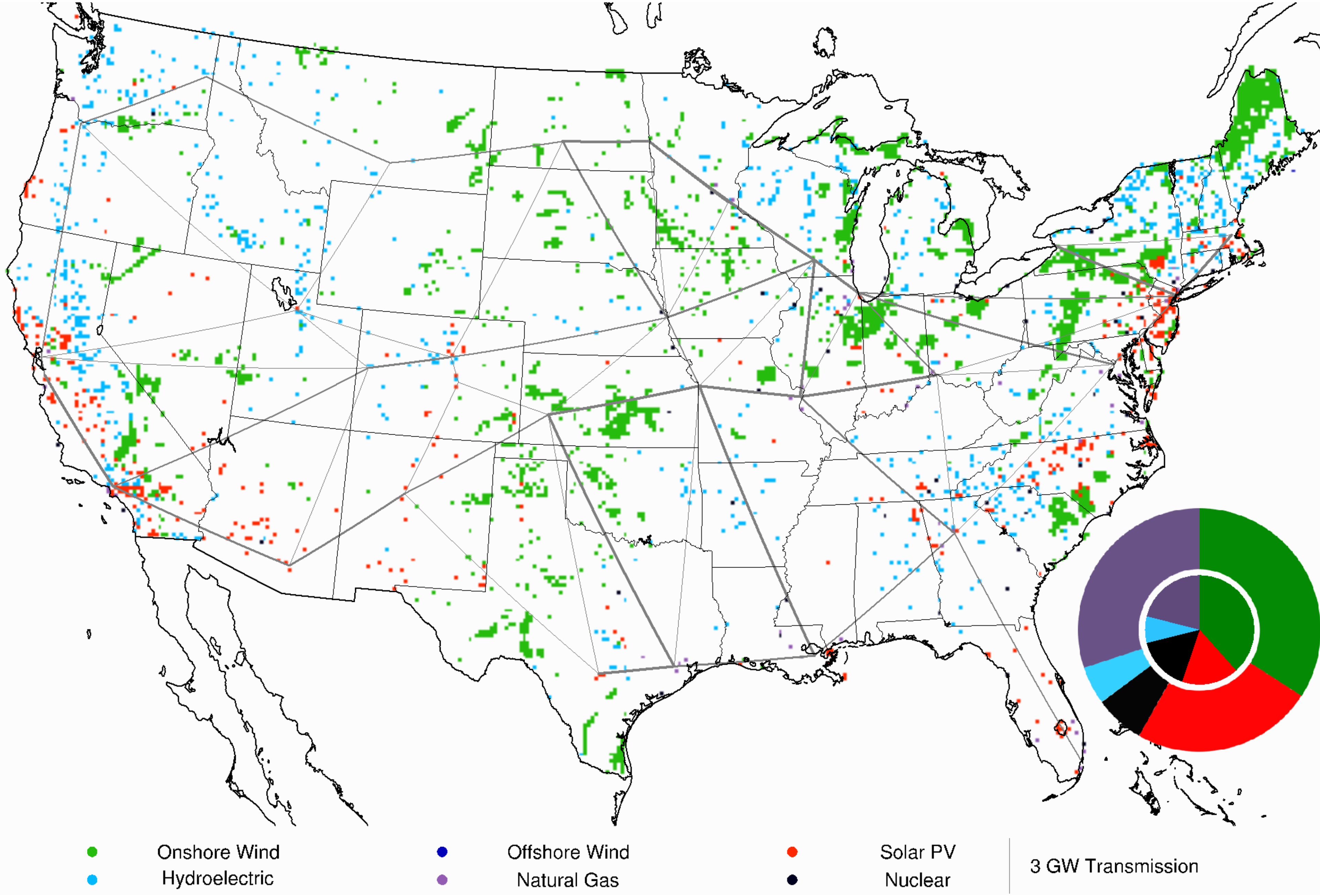
The Electric Power System in 2012

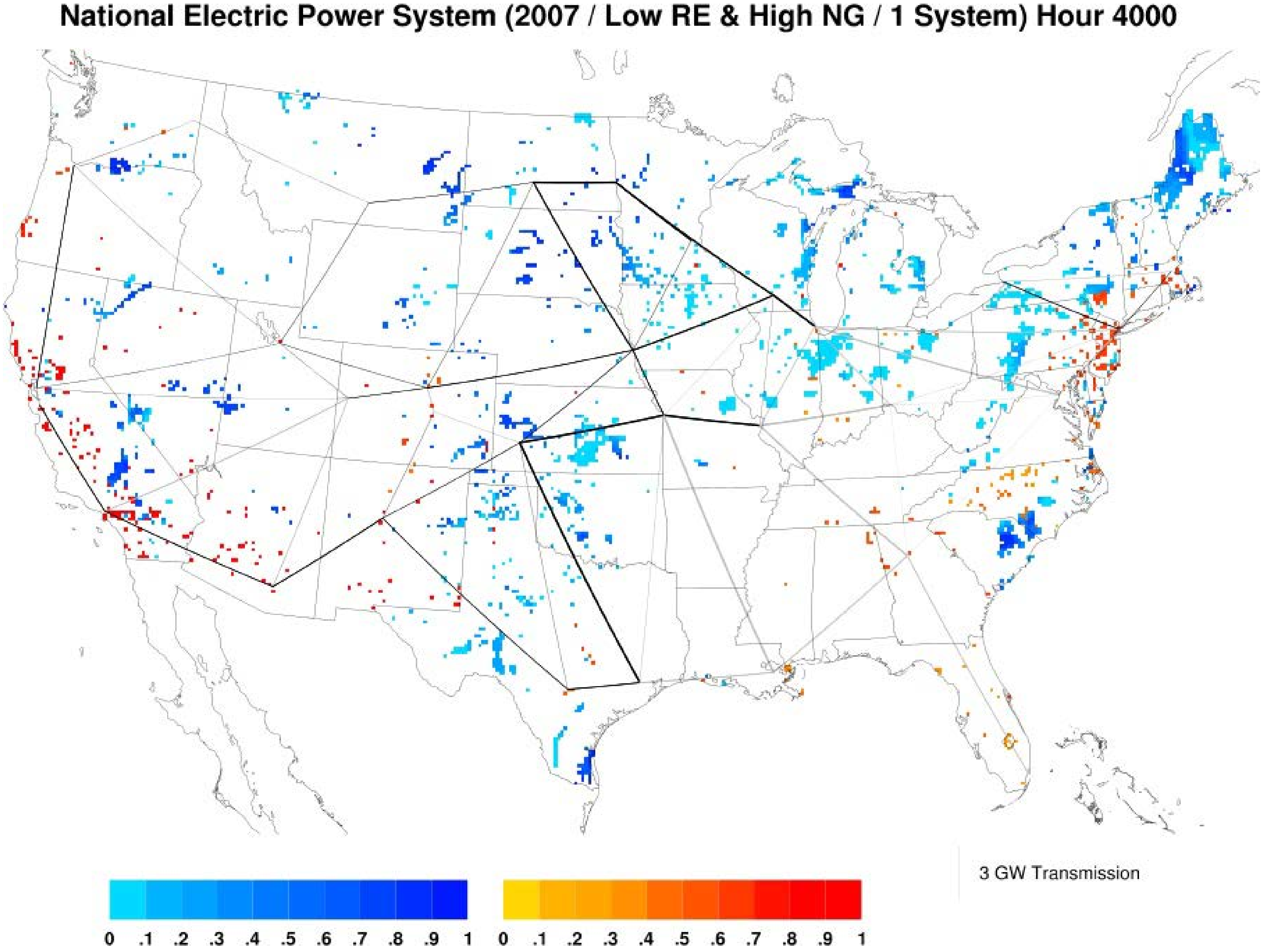


● Storage
● Other
● Coal
● Geothermal
● Natural Gas
● Hydroelectric
● Nuclear
● Offshore Wind
● Onshore Wind
● Solar PV

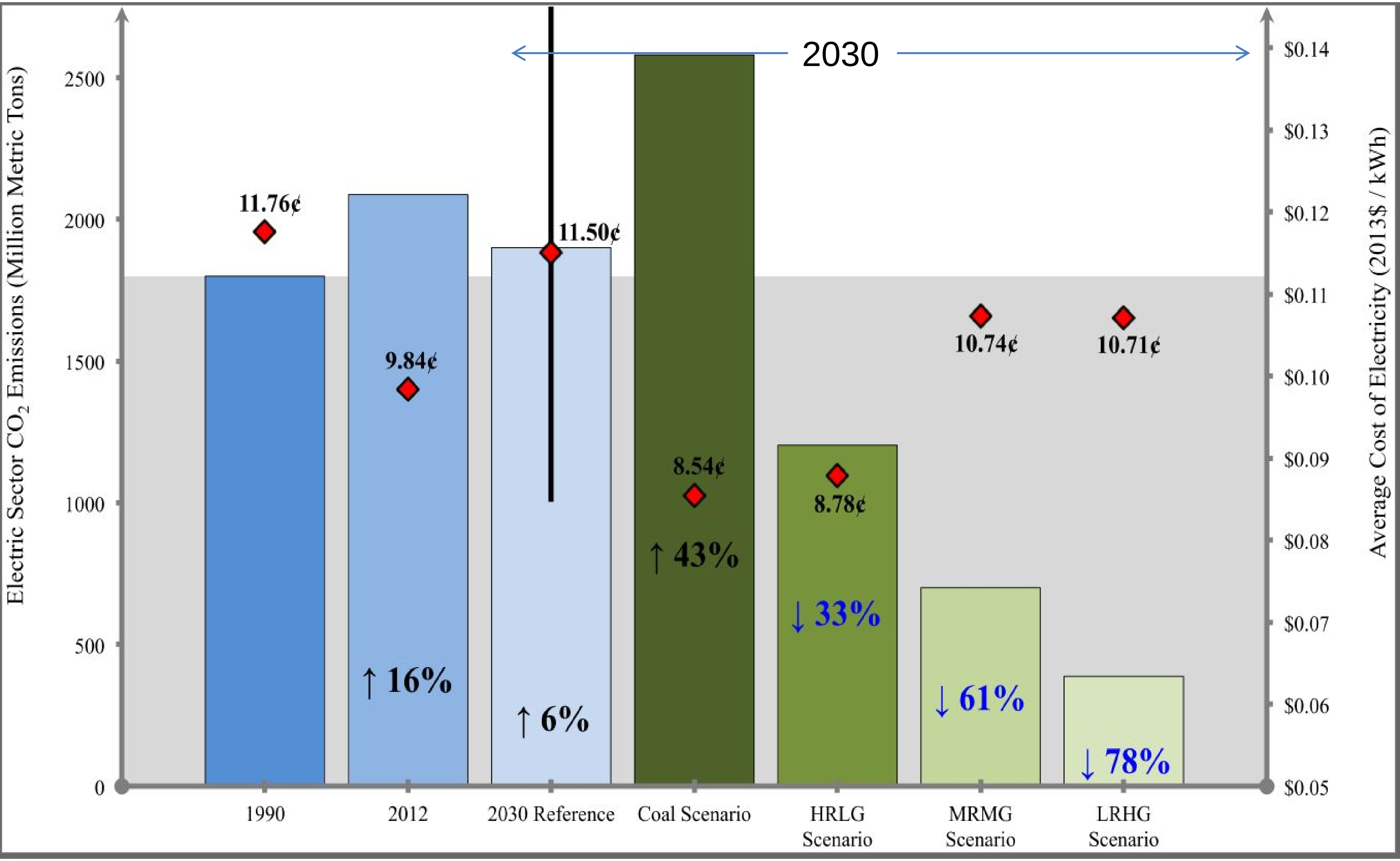
Cost optimized US Electric Power System for 2030



Dispatch of wind and solar PV within the simulation



Cost and Carbon Emission Analysis



Conclusions

- Since weather is variable over large geographic scales, wind and solar generation and use must also encompass large geographic areas to be reliable and cost effective.

- HVDC transmission grids would enable a large domains big enough to make wind and solar work.

- The US could reduce CO2 emissions up to 80% with comparable electric costs to recent decades.

Questions . . . .