Weather Determined Geographic Characteristics of Wind and Solar Energy Generation Systems

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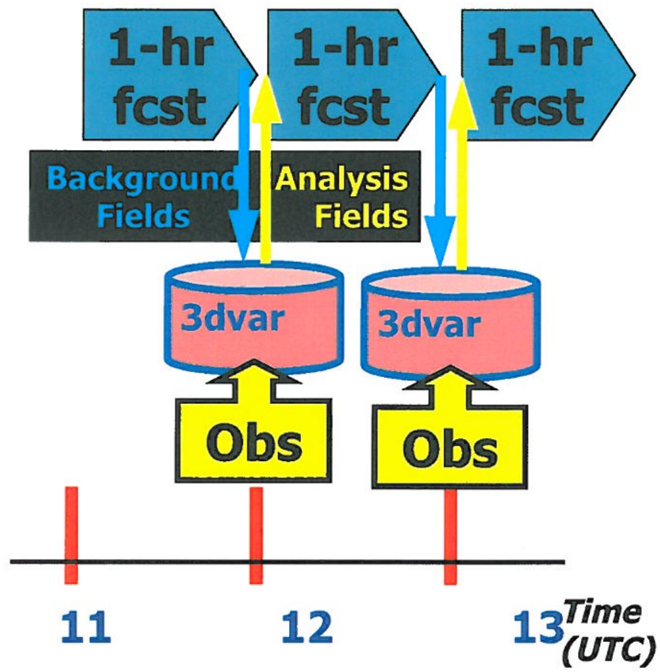
Study Basics

- Weather Assimilation Model to obtain PV Generation and Wind Generation:
  - RUC 13km 0-hour
  - Hourly
  - 2006,2007,2008 (each treated independently)
- Wind and Solar Features
  - Onshore turbines — 3 MW each (90 m)
  - Offshore turbines — 5 MW each (90 m)
  - PV Utility plants — 20 MW each
  - Natural Gas backup — Determined by System
  - Nuclear — 100.4 GW
  - Hydroelectric Dams — 74.4 GW

Rapid Update Cycle (RUC) Hourly Assimilation

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



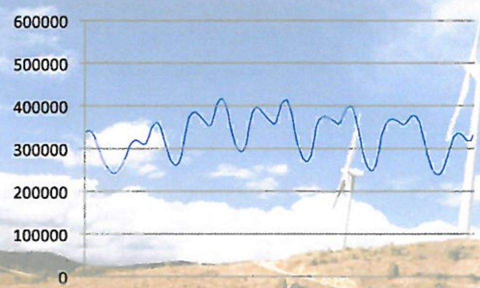
Hourly obs

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

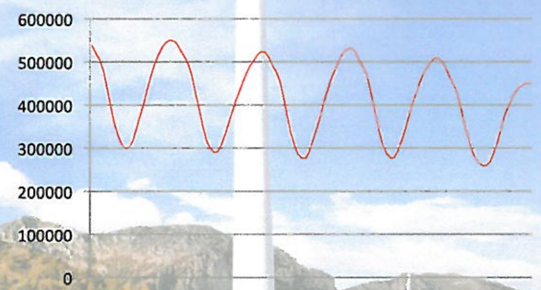
Electrical Load

Electrical Load

- Electricity load from the three years (2006-2008) is grown using GDP until 2011 and then 0.7% per year to obtain 2030 levels.
- Load split into 16 sub-divisions based on largest cities in each balancing authority



2030 Winter Load (MW)



2030 Summer Load (MW)

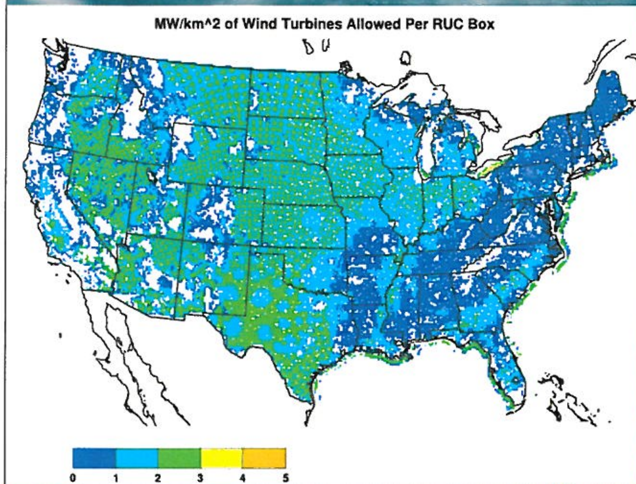
Price Parameter Space

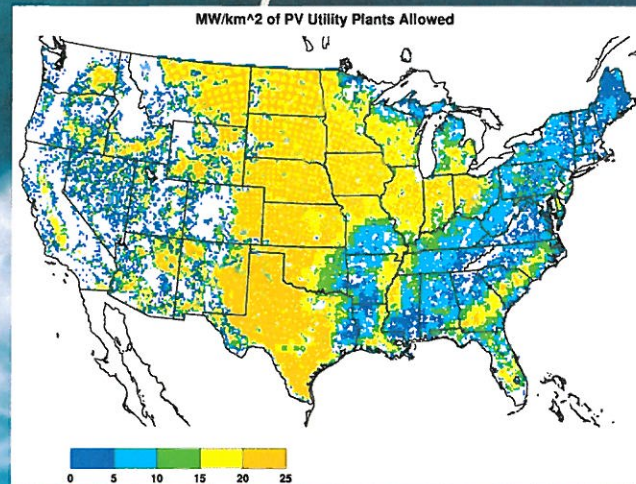
- Costs parameter space:

TECHNOLOGY	LOW	MID	HIGH
ONSHORE WIND	$1.35 / W	$1.61 / W	$1.87 / W
OFFSHORE WIND	$3.50 / W	$4.15 / W	$4.80 / W
PHOTOVOLTAICS	$1.23 / W	$2.13 / W	$3.02 / W
CORRESPONDING NATURAL GAS	$8.63 / mmBtu	$6.60 / mmBtu	$4.56 / mmBtu

- Costs are converted to mortgage costs @ 5% for 30 years. Natural gas capital is $1 / W.
- Transmission costs are $ 1300 / MW-mile.

Classification Maps

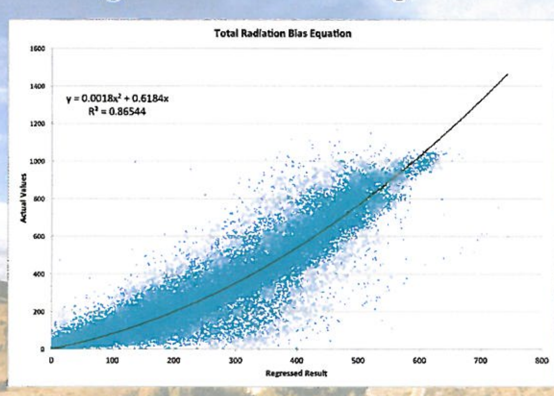




- The type and amount of electricity generation installed in each RUC box is constrained by:
  - Spacing between facilities
  - Topography of the land
  - Land Use (residential, commercial, protected lands, etc...)

Weather Data to Power

- The solar radiation is created by performing a multivariate regression of RUC model data and GOES satellite images.
- The solar realization number is calculated by modeling single axis tracking "standard" PV panels.



- Regression is done on 13 independent variables: 5 satellites, top of atmosphere radiation, zenith angle and the 6 hydrometeors from the RUC assimilation model.
- The regressed data is from the seven SURFRAD sites for 2006 – 8.
- Correlation between the 48,000 data points is 0.9303.

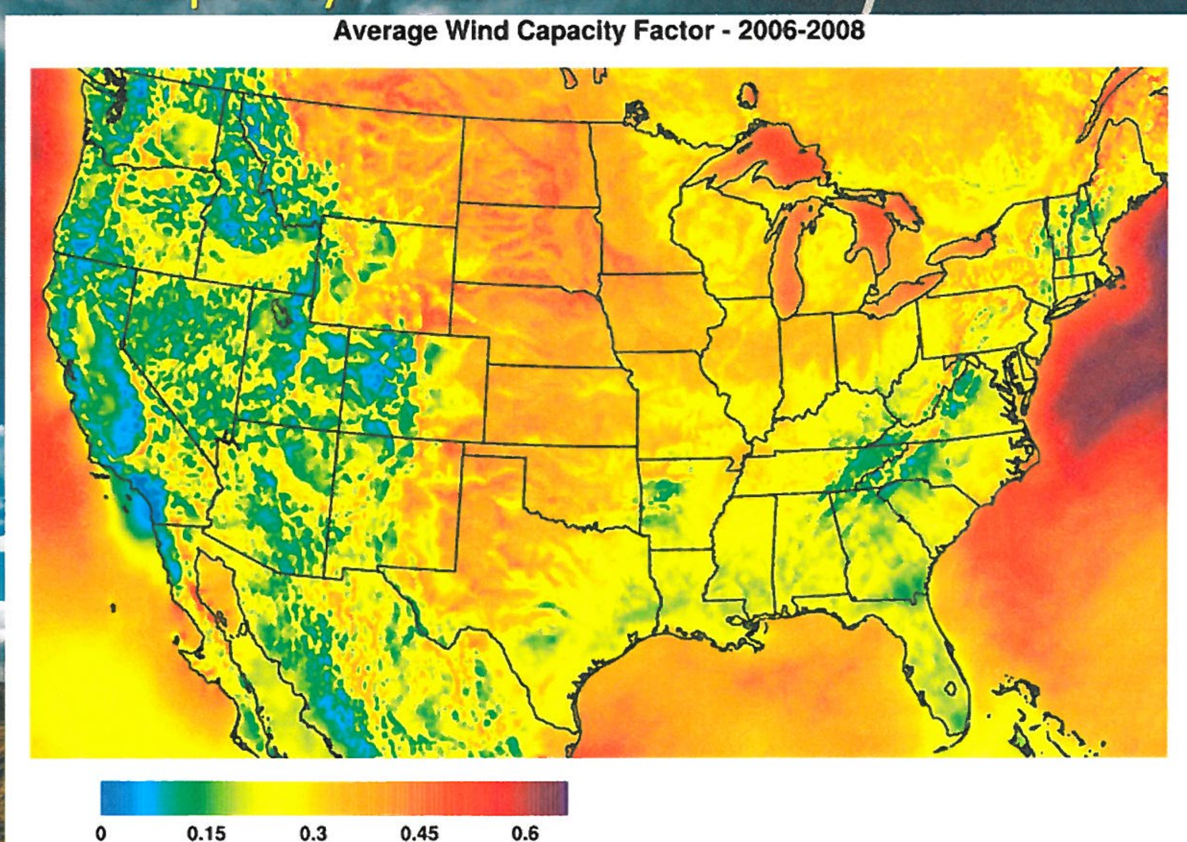
Weather Data to Power

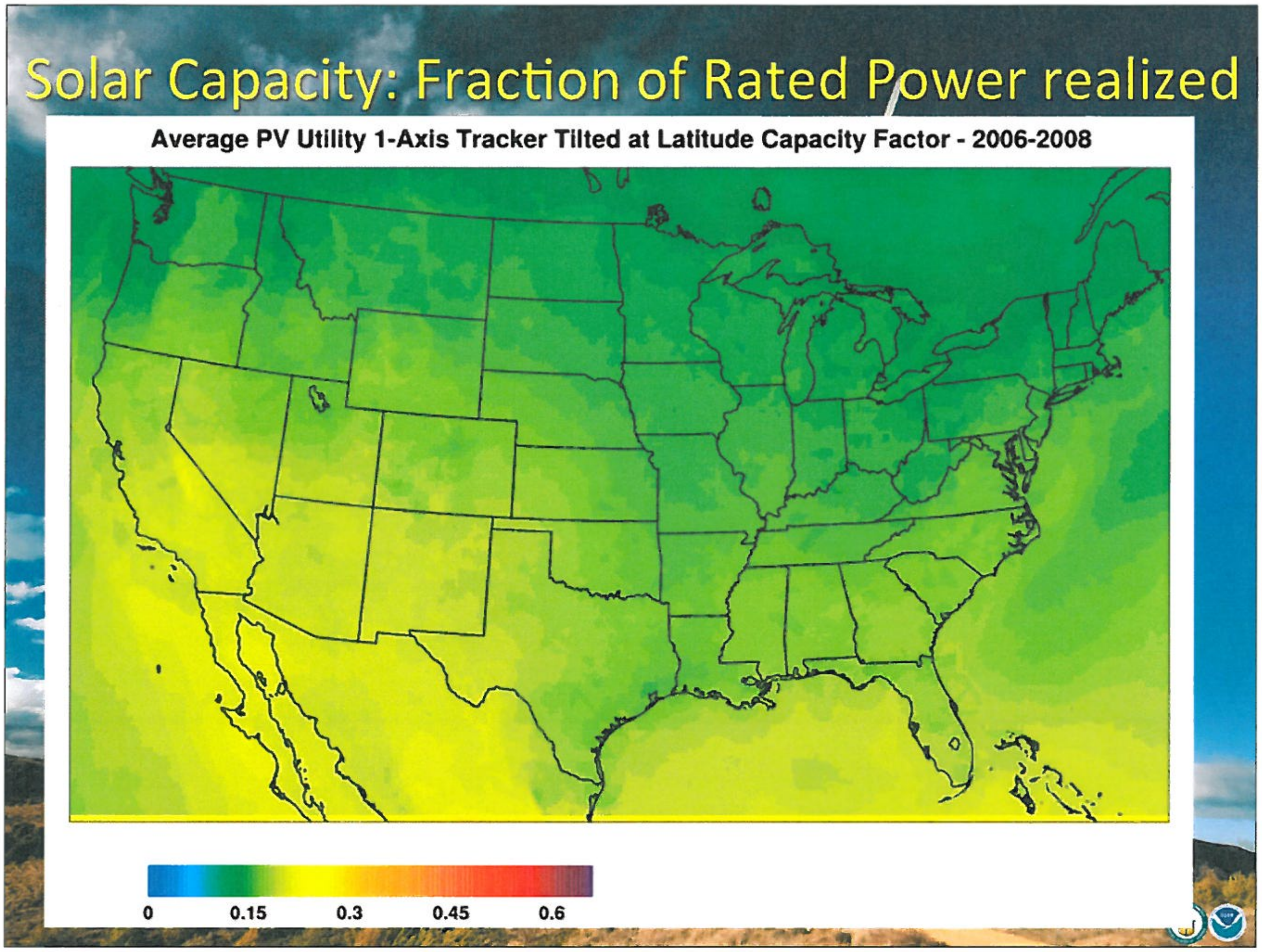
- The wind speed data is interpolated from the RUC assimilation model heights to hub height at 90 m.
- The wind speed is then applied to a generic "power" curve for a 3 MW wind turbine to produce the realization number.

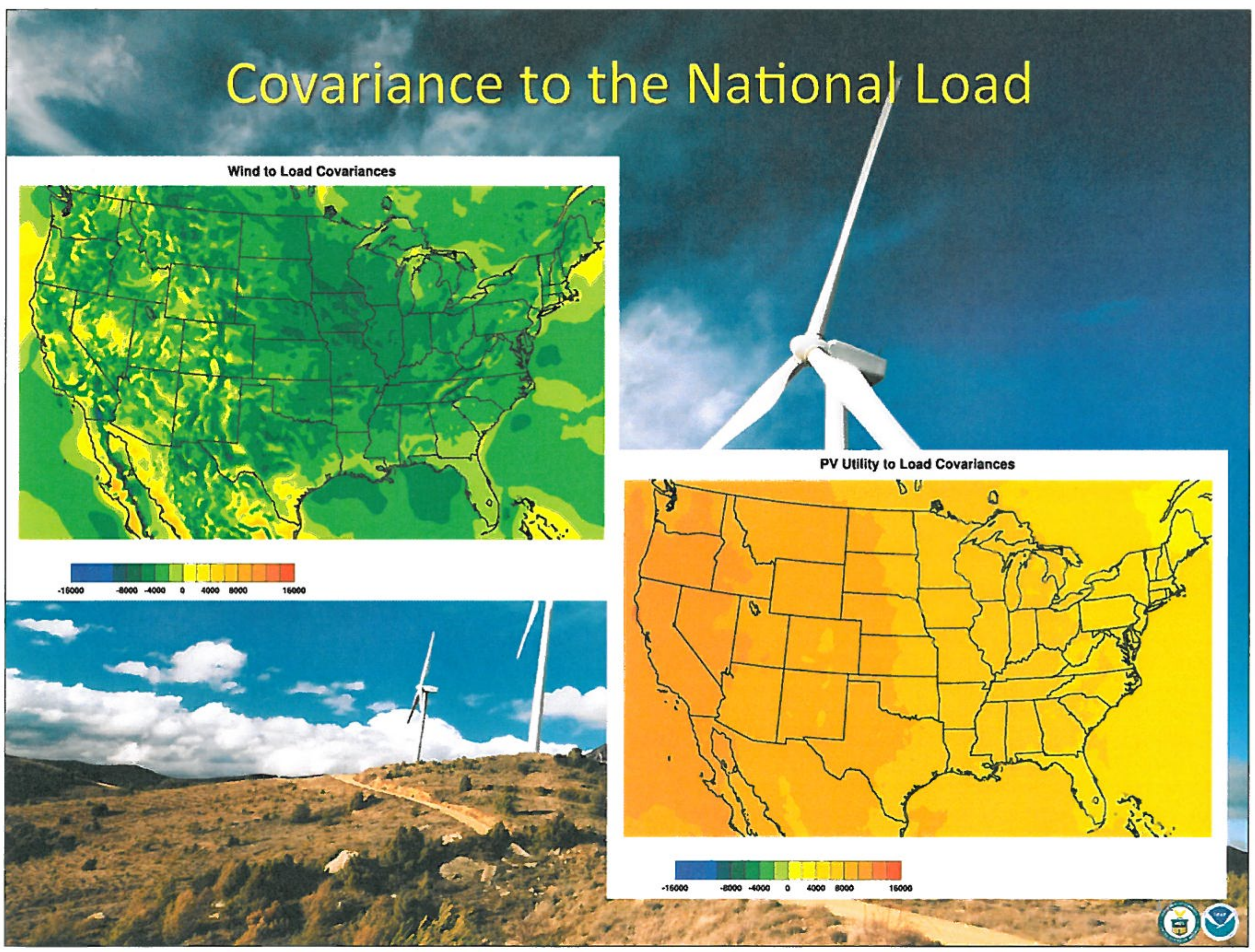
Wind Tower Location	50 m height	70 m height
Tower 1	-1.57 ms^{-1}	-1.30 ms^{-1}
Tower 2	-0.48 ms^{-1}	-0.35 ms^{-1}
Tower 3	-1.38 ms^{-1}	-1.19 ms^{-1}
Tower 4	-1.38 ms^{-1}	-1.12 ms^{-1}
Tower 5	-1.56 ms^{-1}	-0.37 ms^{-1}

- Bias calculations performed at 5 wind tower sites.
- The bias calculations ***suggest*** that the RUC has a low bias, and as such the RUC data will give a lower estimate of the wind power potential.

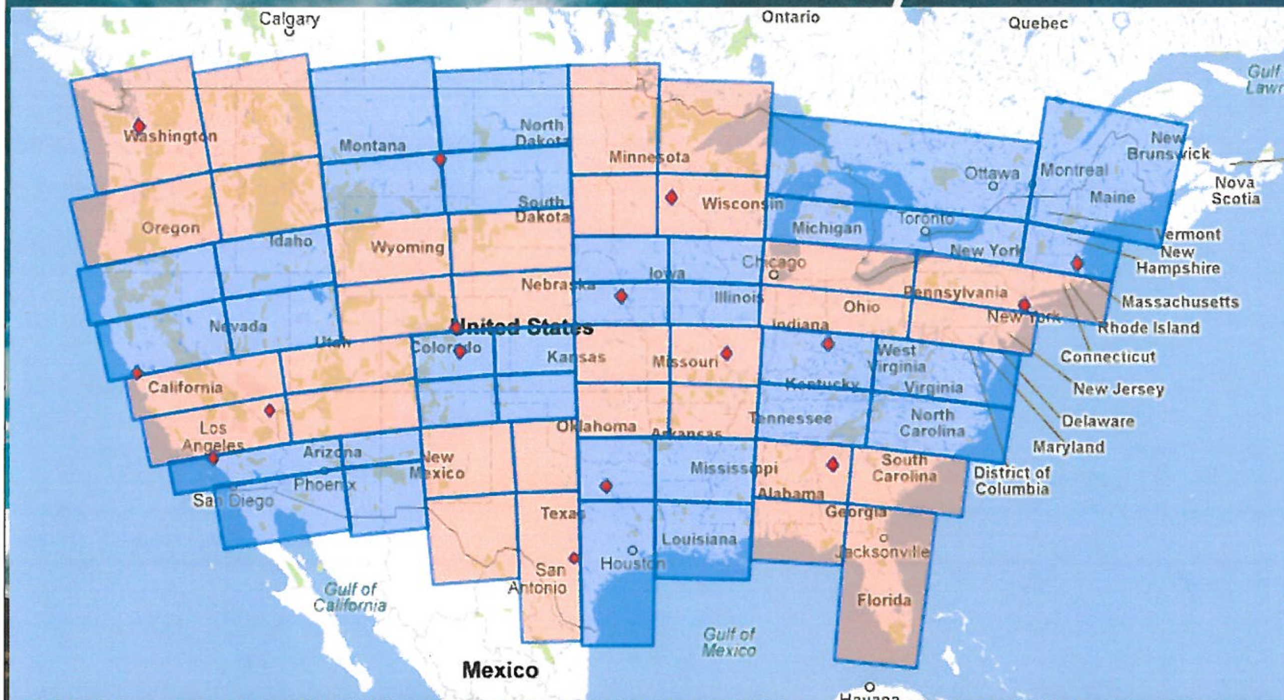
Wind Capacity: Fraction of Rated Power realized




Solar Capacity: Fraction of Rated Power realized
Average PV Utility 1-Axis Tracker Tilted at Latitude Capacity Factor - 2006-2008
0
0.15
0.3
0.45
0.6

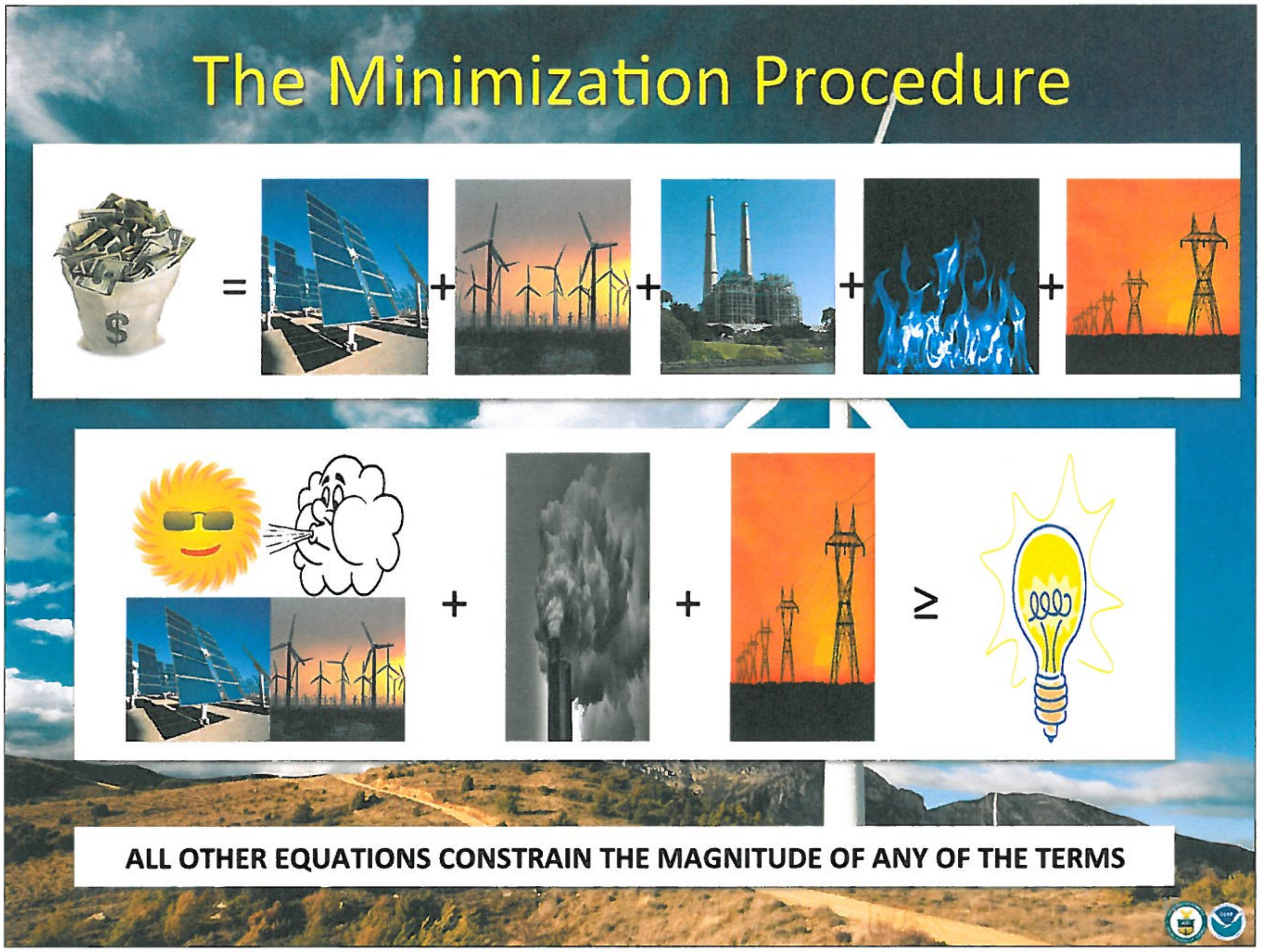

Covariance to the National Load
Wind to Load Covariances
-16000
-8000
-4000
0
4000
8000
16000
PV Utility to Load Covariances
-16000
-8000
-4000
0
4000
8000
16000

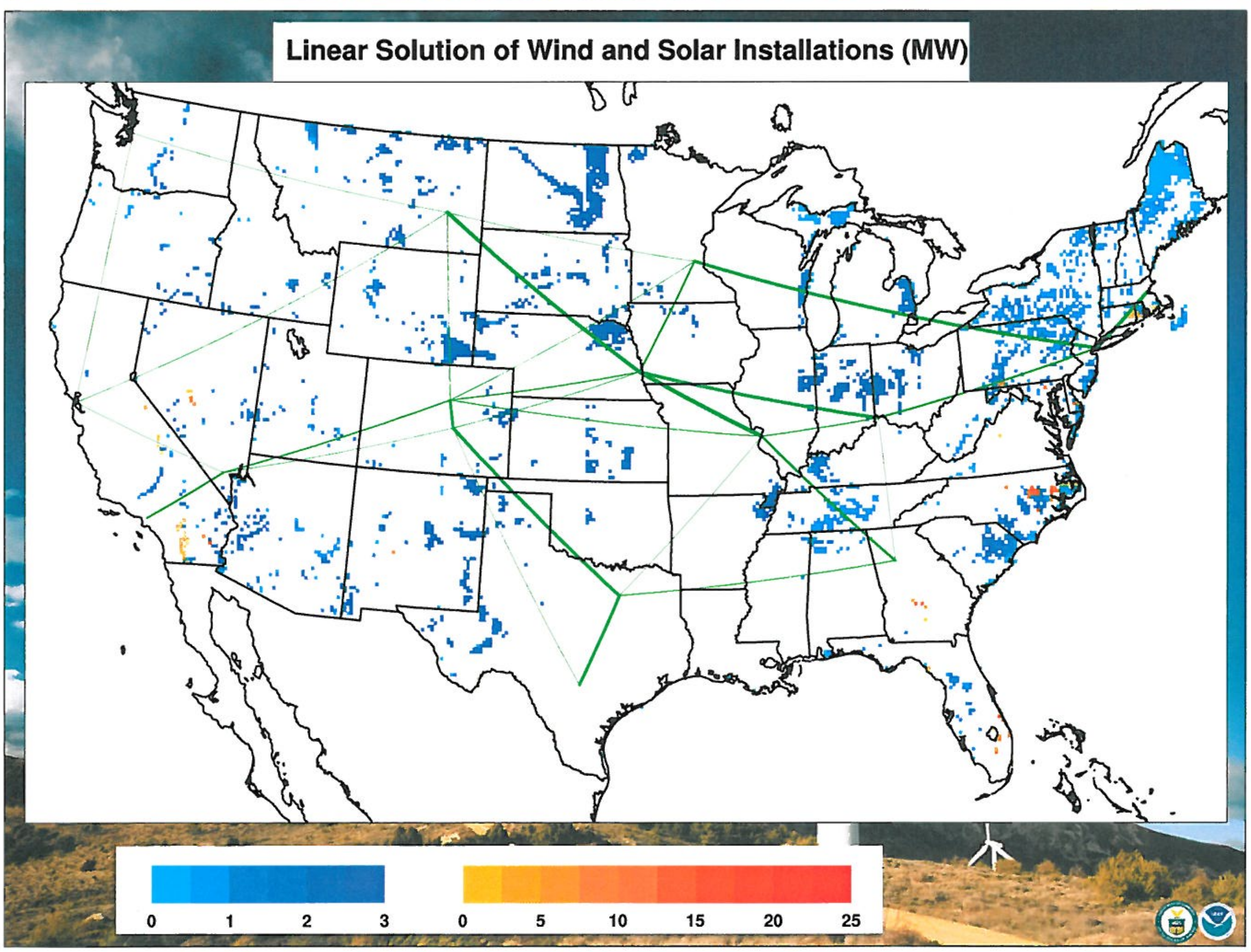
Transmission



Minimization Procedure

- A cost optimization procedure creates a large-scale electricity generation system composed of wind, solar, natural gas backup, with Nuclear and Hydroelectric base load.
- Costs considered:
  - Installing a Wind Farm or Solar PV Utility
  - Natural gas plant installation
  - Natural gas fuel and variable O/M
  - Cost of transmission, both construction and electrical losses
- The cost is subject to:
  - It must meet the load at all times, in all areas
  - The placement of wind and solar must be less than upper bounds
  - Satisfy natural gas reserves requirement
  - Satisfy transmission between nodes


The Minimization Procedure
=
+
+
+
+
+
+
≥
ALL OTHER EQUATIONS CONSTRAIN THE MAGNITUDE OF ANY OF THE TERMS


Linear Solution of Wind and Solar Installations (MW)
0 1 2 3
0 5 10 15 20 25

Full CONUS Solution

- Installed capacity:

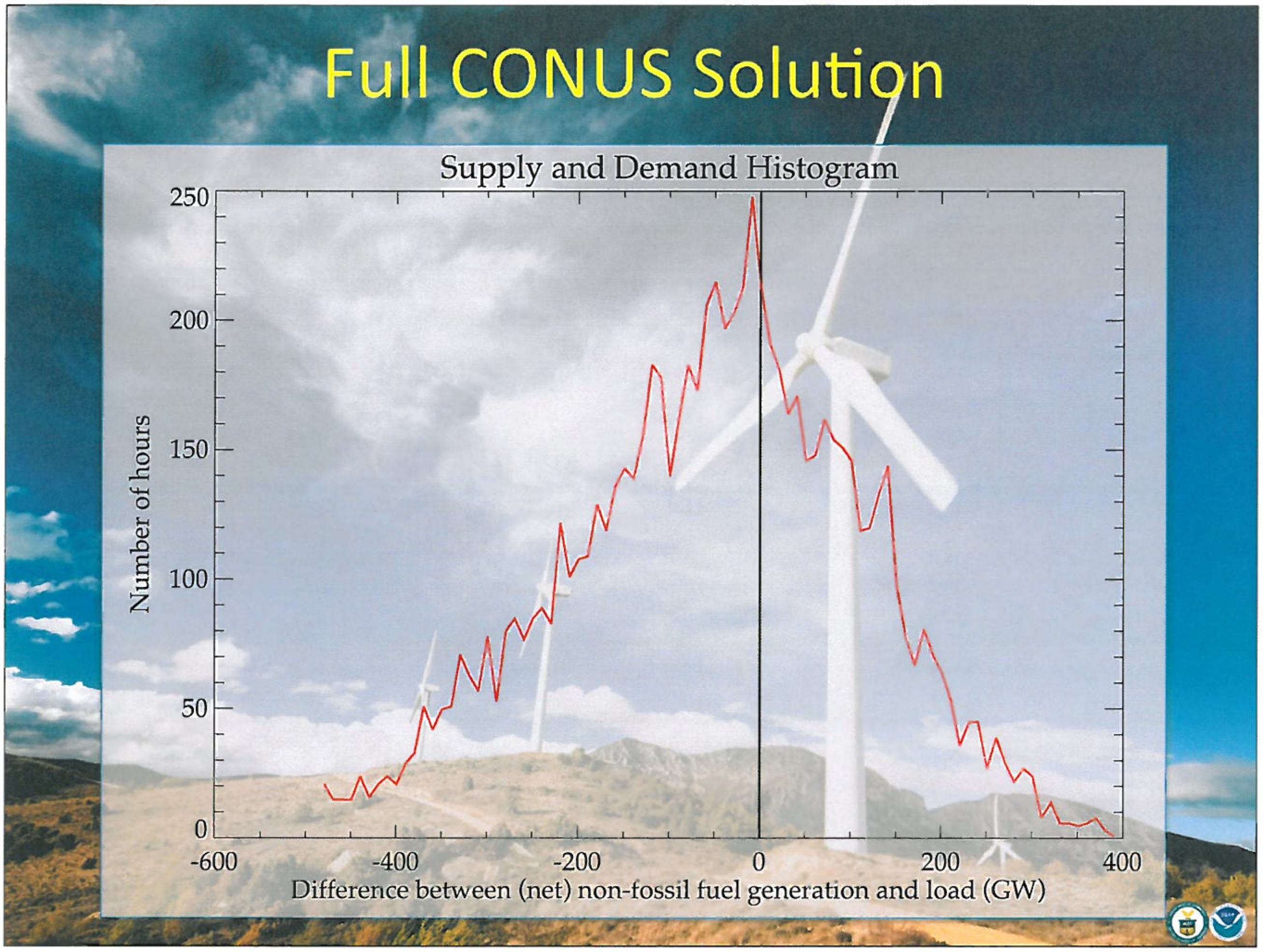
Technology	Capacity (GW)
Onshore Wind	975.63
Offshore Wind	3.21
Photovoltaic	199.53
Natural Gas	503.22

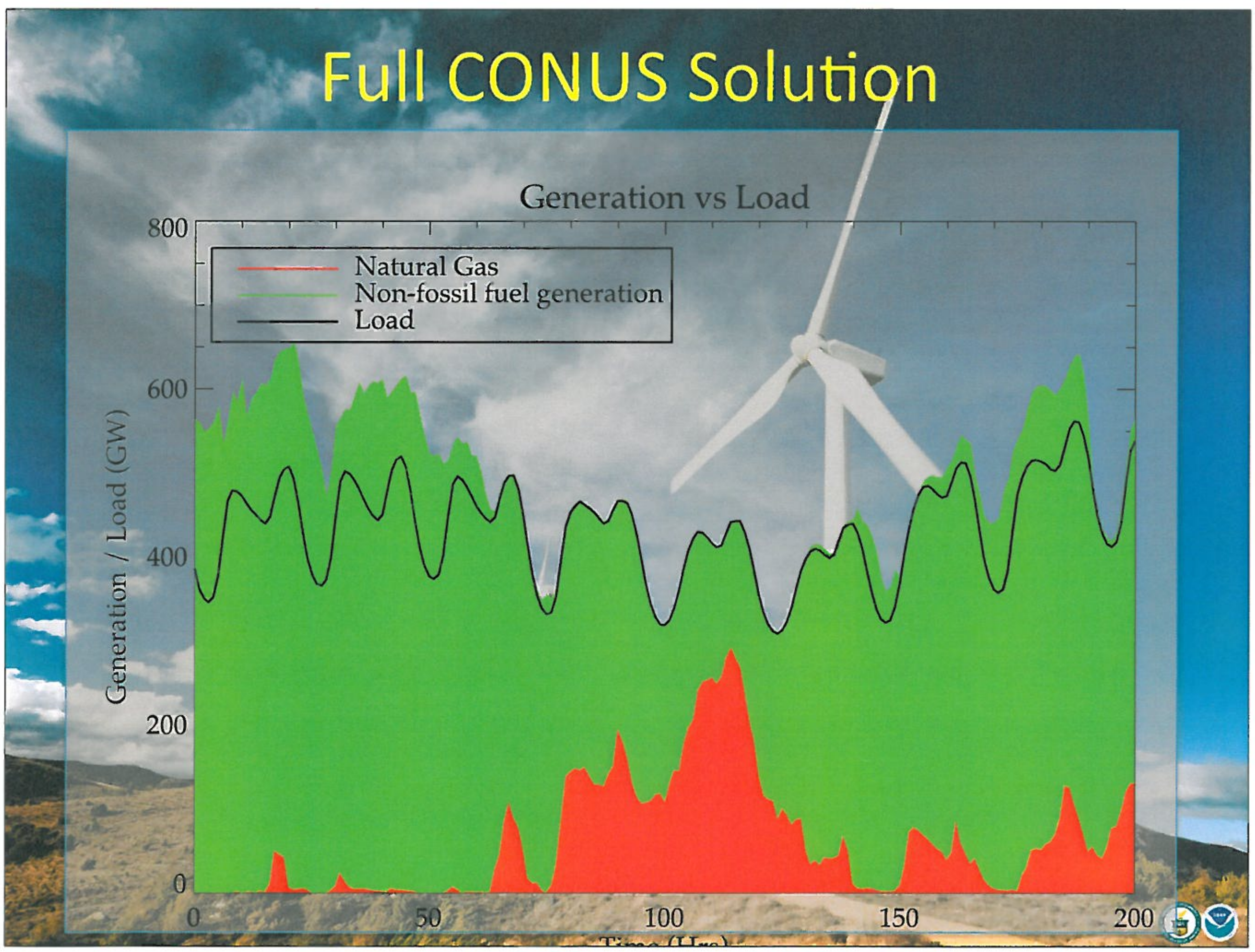
TOTAL CAPACITY (INC NUKE & HYDRO): **1886.992 GW**

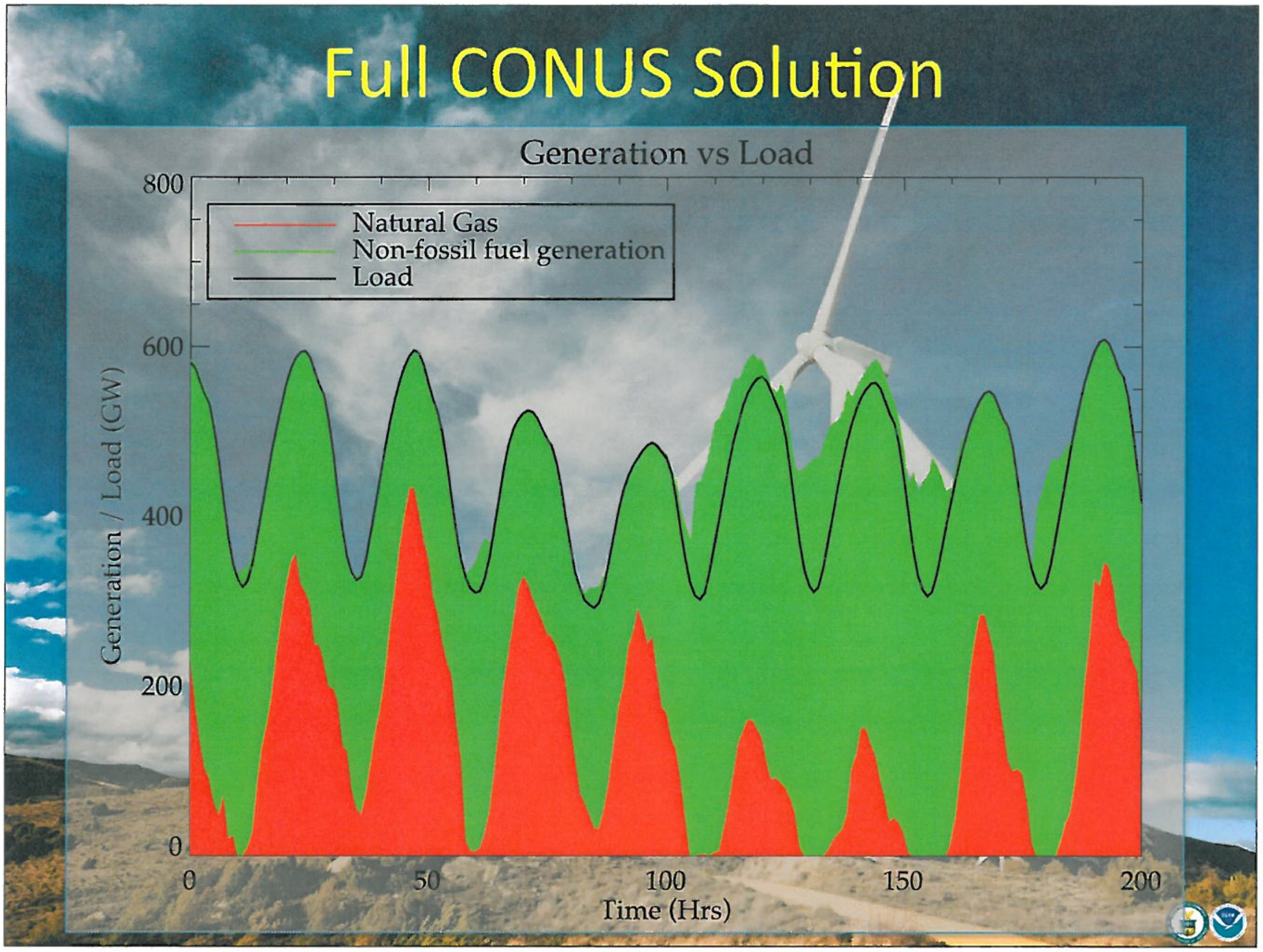
TODAY: 1137.3 GW [**470.3 GW** NATURAL GAS]

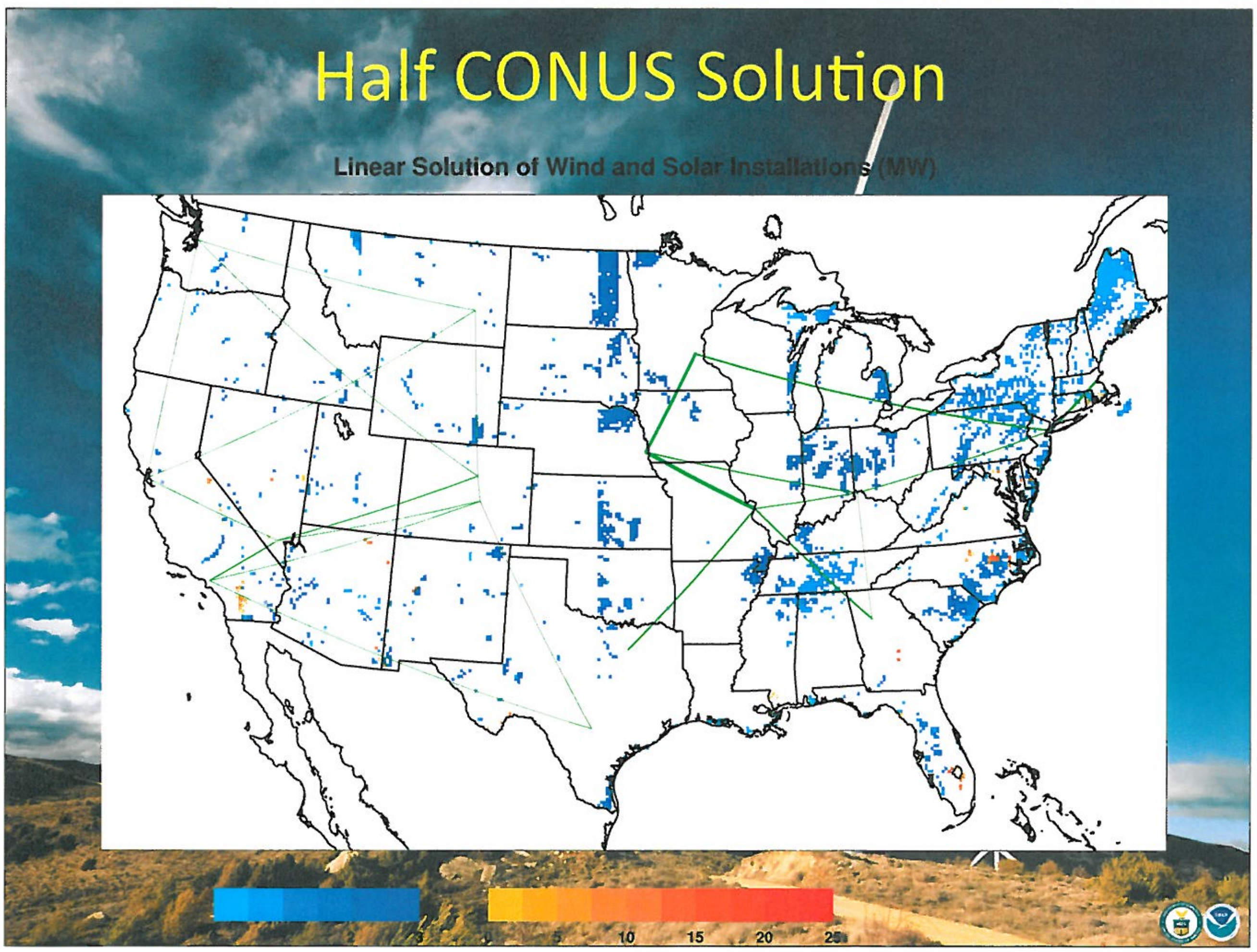
Full CONUS Solution

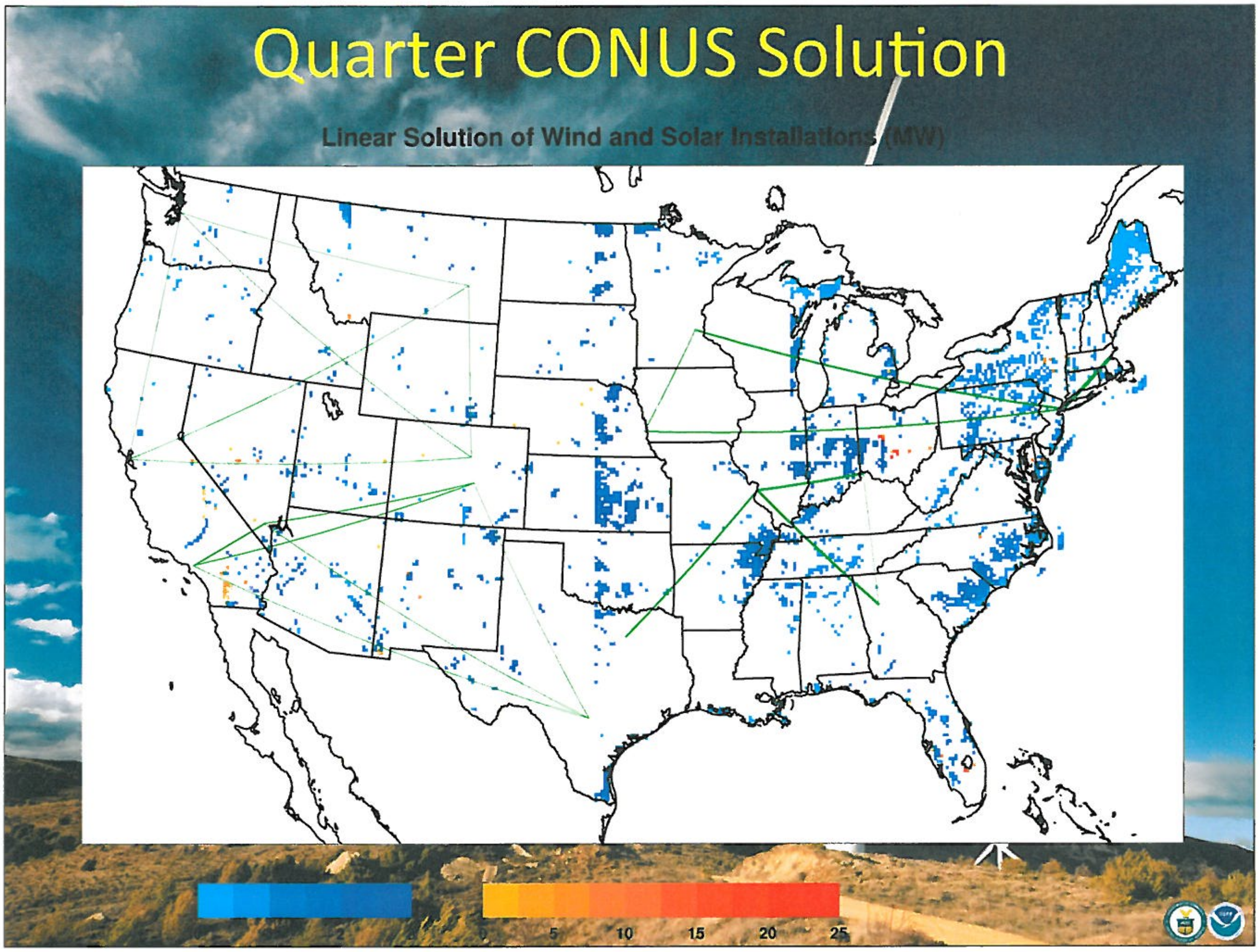
- Mean Capacity factors:
  - Onshore Wind: 33.47%
  - Offshore Wind: 51.33%
  - Photovoltaic: 17.29%
  - Natural Gas: 19.46%
- Transmission losses: 1.15%
- Electricity production curtailed: 9.81%

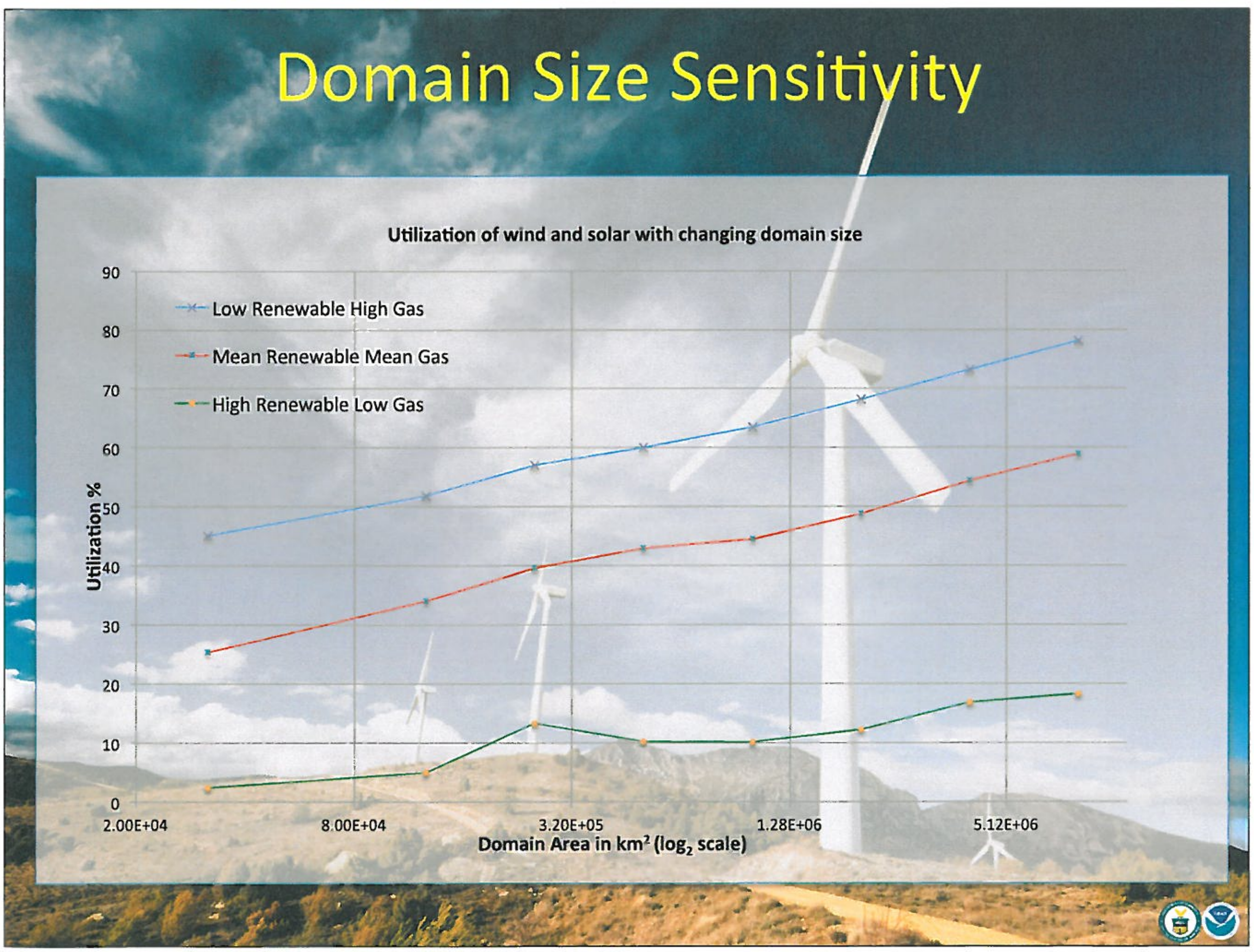

Full CONUS Solution
Supply and Demand Histogram
Number of hours
250
200
150
100
50
0
-600
-400
-200
0
200
400
Difference between (net) non-fossil fuel generation and load (GW)


Full CONUS Solution
Generation vs Load
Natural Gas
Non-fossil fuel generation
Load
Generation / Load (GW)
800
600
400
200
0
0
50
100
150
200

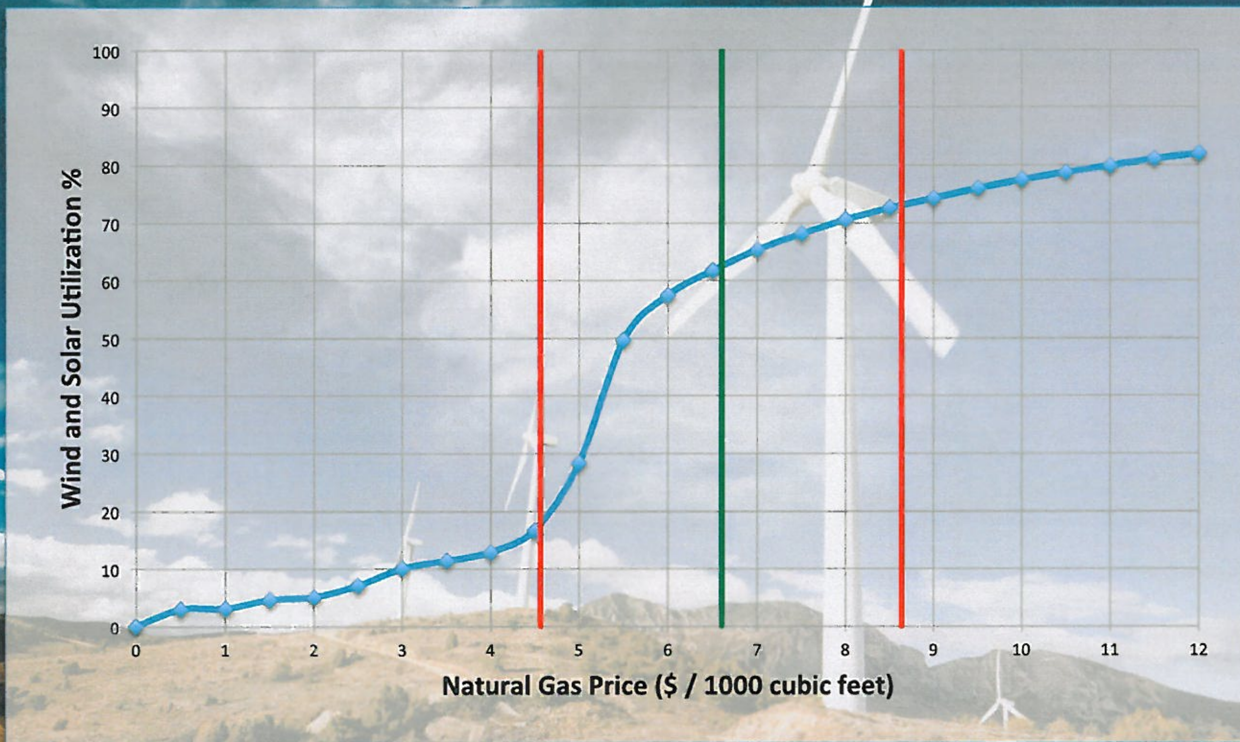

Full CONUS Solution
Generation vs Load
Natural Gas
Non-fossil fuel generation
Load
Generation / Load (GW)
0
200
400
600
800
0
50
100
150
200
Time (Hrs)


Half CONUS Solution
Linear Solution of Wind and Solar Installations (MW)
5
10
15
20
25


Quarter CONUS Solution
Linear Solution of Wind and Solar Installations (MW)
0
5
10
15
20
25


Domain Size Sensitivity
Utilization of wind and solar with changing domain size
Low Renewable High Gas
Mean Renewable Mean Gas
High Renewable Low Gas
Utilization %
90
80
70
60
50
40
30
20
10
0
2.00E+04
8.00E+04
3.20E+05
1.28E+06
5.12E+06
Domain Area in km² (log₂ scale)

Natural Gas Price Sensitivity



What the study demonstrates

- The utilization and cost effectiveness of combined wind and solar power generation is optimized for larger geographic (*this scaling is more critical for low gas prices*).
- The location of optimal wind and solar generating capacity far from demand would require a upgraded power transmission systems.
- Placement of wind in solar generation in an optimal national system is very different than the current ad hoc bottom-up approach.
- A national wind-solar generation system could supply a large percentage of US power (this is sensitive to costs).
- Such a system would result in large CO2 emission reductions.

What the study does not demonstrate

- Does not show exact locations of wind and solar placement. The resolution of the model is 13 km by 13 km.
- Grid integration is not included in the model.
- Local transmission and distribution is not in the model.
- The cost optimization, by definition, only outputs the most economical system. Other systems with higher and lower utilization can occur in reality.
- The transmission from the model is only a proxy.