A Strategy To Decarbonize The US

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What is the problem?

- Humans are releasing gigantic amounts of carbon dioxide, and other greenhouse gases, into the atmosphere.
- The greenhouse gases are causing the planet to heat up, beyond normal climate variations.

Credit: Comment on Ocean heat content and Earth's radiation imbalance: D. Nuccitelli, R. Way, R. Painting, J. Church & J. Cook; March 31, 2012
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 Components

• Weather
• Electricity Infrastructure
• Electric Demand
• Cost of Technologies
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.
The variability of wind drops by 5 times when area is increased by three orders of magnitude.

$$y = -0.115 \ln(x) + 2.1728$$

$$R^2 = 0.86435$$

Variability here is defined as the average coefficient of variation over a geographic region when divided up into isolated regions, e.g., Iowa vs. 48 States.
Power output behavior compared with its neighbors of variable resources depends on its location.
Models Need High Resolution Weather Data

Solar PV Potential
Models Need High Resolution Weather Data
Critical Components

• Weather

• **Electricity Infrastructure**

• Electric Demand

• Cost of Technologies
The US Does Not Have A Single Electric Grid

With separate systems

NERC Balancing Authorities
As of October 1, 2015

Dynamically controlled generation
Back-to-Back DC Converter
Submit changes to balancing@nerc.com
Power plants that existed at the end of 2012

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

Models Need Locations of Power Plants
Models Need To Know Where Sites Exist

Image credit - Nature Climate Change – Supplement Figure - http://rdcu.be/f2Dg
Allow Models A Possible Transmission Overlay

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
Models Need Electricity Demand
* Load expanded by GDP, and then by 0.7% per annum to 2030

Reminder: The model is \textit{infinitely adaptable}, and so demands can be altered depending on region.
Critical Components

• Weather

• Electricity Infrastructure

• Electric Demand

• Cost of Technologies
In order to account for curtailment, capacity factors, sunk costs, and other factors, the mathematical optimization utilizes an annual cost-per-unit generation capacity for each generating unit. Since there is no fuel cost for the wind and solar projects, the total cost per project can be separated into capital and Operations and Maintenance (O&M) costs. The natural gas plants, however, have capital, O&M, and fuel costs to consider. For the present studies, the O&M costs and amortized capital costs are combined into a single cost per year.

A review of the literature for capital costs was carried out [1, 2, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61]. The capital and O&M costs selected for the present study are displayed in Fig. 11 and Table 3. The plot shows the projected 2030 capital and O&M costs in 2013$ per watt installed. The best available current price is taken to be the high price for each technology, while the low cost estimate is based upon the optimistic prices in the studies reviewed. The mid range values are the mean of the high and low prices.

Figure 11: The projected 2030 overnight capital costs including fixed O&M in 2013$ used in the present study.

The natural gas power plants are assumed to be a more mature technology. Therefore, we only use a single cost for the natural gas power plants in all three of the price scenarios, namely $1.24 / W (see Fig. 11 and Table 3). However, since natural gas prices have fluctuated wildly in the past we take three cases from the Annual Energy Outlook [1] as our low, mid, and high natural gas fuel prices. The three prices are shown in Table 3 and in Fig. 12 in 2013$ / MMBtu.

Other key factors affecting the cost of natural gas generation are the heat rate (measure of efficiency of the plant), and cost of variable O&M. In order to limit the degrees of freedom in the present studies, these values were kept constant across the scenarios run. The values used were 6.430 MMBtu / MWh for the heat rate and $3.31 / MWh for the variable O&M (2013$) [60, 61].

The final key cost used in the US study is the cost of high-voltage transmission. The handling of transmission in the US study only addresses the cost of erecting new HVDC lines.
Solutions
The Models Solve To Find The “Best” System

Minimize:

\[ \text{ALL OTHER EQUATIONS CONSTRAIN THE MAGNITUDE OF ANY OF THE TERMS} \]

Electric Grid Design
A cost-optimal National Electric System

Retail: 10.1¢ / kWh
0.38¢ / kWh for transmission
8% curtailment of var. gen.

Image credit - Nature Climate Change – Figure 3 - http://rdcu.be/f2Dg

Onshore Wind
Hydroelectric
Offshore Wind
Natural Gas
Solar PV
Nuclear
3 GW Transmission
A cost-optimal National Electric System

Retail: 10.1¢ / kWh
0.39¢ / kWh for transmission
8% curtailment of var. gen.
Electric Grid Operation
Dispatching the optimal system in the 2030s
Dispatching the optimal system in the 2030s
Cost of Electricity
Levelized Cost of Electricity for a National System

Image credit - Nature Climate Change – Figure 2 - http://rdcu.be/f2Dg
How the national system impacts my state?

Electricity Costs in 2014

Electricity Costs in 2030 (NEWS)
CO₂ Emissions
How the national system impacts my state?

Carbon Dioxide Emissions from Electricity Production

National Level

Tons of Carbon Dioxide Released

Millions

Tons of Carbon Dioxide per State Released

Carbon Dioxide Emissions 2014

Carbon Dioxide Emissions 2030 (NEWS)

2014

2030

2,156

295

Millions
SO$_2$ Emissions
How the national system impacts my state?

Sulphur Dioxide Emissions from Electricity Production

- Sulphur Dioxide Emissions 2014
- Sulphur Dioxide Emissions 2030 (NEWS)

Tons of Sulphur Dioxide Released

Thousands

- National Level

Tons of Sulphur Dioxide per State

- 2014
- 2030

AL AR AZ CA CO CT DE FL GA IA ID IL IN KS KY LA MA MD ME MI MN MO MS MT NC ND NE NH NJ NM NV NY OH OK OR PA RI SC SD TN TX UT VA VT WA WI WV WY
NO\textsubscript{x} Emissions
How the national system impacts my state?

Nitrogen Oxides Emissions from Electricity Production

- Nitrogen Oxides Emissions 2014
- Nitrogen Oxides Emissions 2030 (NEWS)

Tons of Nitrogen Oxides Released

Thousands

National Level

Tons of Nitrogen Oxides Per State

0 50 100 150 200 250

2014 2030

2,136 232
H$_2$O Consumption
How the national system impacts my state?

US Thermal Generation Water Consumption

Water Evaporation from Thermal Electricity Generation

Litres of water put into the atmosphere

Water Consumption in 2003

Litres of water released into the atmosphere

Water Consumption by 2030

National Level

Litres of water put into the atmosphere

2003

2030

Litres of water released into the atmosphere

2003

2030

National Level
Employment
How the national system impacts my state?

**Megawatts of Installed Capacity per State**

- **US Total Electricity Employment**
- **Installed Capacity 2010 in MW**
- **Installed Capacity 2030 in MW (NEWS)**

**National Level**

- 2,373

- 1,605

**2015**

- **Thousands**

**2030**

- **Thousands**
Summary
Critical Key Findings My Studies

• 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

Utility Scale Solar PV Plant
Near Golden, CO

Wind Turbine Blades
Leaving Broomfield, CO

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