National Energy with Weather System (NEWS) Simulator Results

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Post Industrial Carbon Dioxide Rise

When (years ago):
- 30,000: Pleistocene
- 3M: Pliocene
- 20 M: Eocene

Equilibrium climate:
- Pleistocene
- Pliocene
- Eocene

Anthropogenic Atmospheric Carbon Dioxide (parts per million)

Observations (278 ppm pre-industrial subtracted)

Exponential Increase:
- Doubling Time = 32 years

$2 \times \text{CO}_2 = 2 \times 278 \text{ ppm} = 556 \text{ ppm}$
- Year at 556 ppm ~ 2052

Image update and adapted from PNAS paper, Hofmann, et al; Solomon et al, Irreversible Climate Change, February 2009; Beerling & Royer, Convergent Cenozoic CO2, Nature Geoscience, July 2011
Take Away Messages

- The US can produce up to **80% of its electricity** from carbon free sources by 2030 at costs similar to those today.

- The US **needs a national high-voltage direct-current transmission system** and it should be co-optimized with generation.

- The US should move away from a localized systems to a large-scale system.

- Current technologies **without storage** can do the job if HVDC is expanded, reducing overall costs of the system.

- Other technologies **can incorporate** into a national electric system.

- HVDC **improves the efficiency of the electric sector**, regardless of generation mix (although the biggest impact is with variable generation).

- If a national HVDC system is introduced other sectors **can be shifted** to electrical energy. For example; water heaters, heat pumps, electric vehicles, power-to-gas, etc.
Solar Irradiance Video (W/m²)
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…)

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**Land Use Constraints**

**Wind**

**Solar PV**
HVDC Transmission Overlay
Mathematical Optimization

Minimize:

\[ \text{Subject to:} \]

ALL OTHER EQUATIONS CONSTRAIN THE MAGNITUDE OF ANY OF THE TERMS
Linear programming techniques for developing an optimal electrical system including high-voltage direct-current transmission and storage

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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 scale and computational resources. The first is an optimization that minimizes the deviation from the electric load requirements. The procedure includes variable generators, conventional generation, 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 electric 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 electronic 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-
NEWS Result: Single US 48 States Electric Power System
(Low Cost Renewables, High Cost Natural Gas)

- Uses Low Cost Renewables and High Cost Natural Gas Fuel
NEWS Result: 128 Independent Electric Power Systems
(Low Cost Renewables, High Cost Natural Gas)

- Uses Low Cost Renewables and High Cost Natural Gas Fuel
Dispatch of wind and solar PV within the simulation
(Low Cost Renewables, High Cost Natural Gas)
NEWS Result: Geographic Scale and Cost of Technology

Figure 14: The installed capacity in GW (a,c,e) and generation share (b,d,f) by technology. Each panel shows different geographic scales of electric power systems for the 2007 data year optimization. (a,b) is for the Low-cost Renewable High-cost Natural Gas (LRHG) scenario. (c,d) is for the MRMG scenario. (e,f) is for the HRLG scenario.
NEWS Result: Geographic Scale and Cost of Technology

**Figure 16:** Summarized picture of the geographic scaling study. All three cost scenarios are shown. Four of the nine geographic scales investigated are shown. (a) Displays the CO$_2$ emissions from the electric sector as a percentage of the emissions from 1990 levels. It illustrates that with a decrease in geographic area (increase in number of independent power systems) the CO$_2$ emissions increase. (b) Shows the total cost of the electric power sector compared with the single connected contiguous US system. The panel indicates that cost-optimal systems over smaller geographic areas are more expensive than larger systems. (c) The share of the electricity generated by carbon-emission-free technologies. It can be seen that with smaller geographic areas less carbon-emission-free generation is selected by the optimization.
What can the US achieve and what will it cost?*

*Without storage and with current technologies*
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- If a national HVDC system is introduced other sectors **can be shifted** to electrical energy. For example; water heaters, heat pumps, electric vehicles, power-to-gas, etc.
NEWS Result: Back-ups
Distribution of Levelized Cost of Electricity

- System uses only $\sim 205,000$ 3MW wind turbines
- Approximately $460 \text{ km}^2$ of land taken out of current use
- Wholesale cost of wind power $5.2\text{¢} / \text{kWh}$
- A share of $38.4\%$ of electricity generation

- System uses only $\sim 18,500$ 20MW solar PV plants
- Approximately $6,110 \text{ km}^2$ of land taken out of current use
- Wholesale cost of solar power $4.6\text{¢} / \text{kWh}$
- A share of $16.7\%$ of electricity generation

Wholesale cost of natural gas power $12.3 \text{¢} / \text{kWh}$

Average retail cost of electricity for the entire system $10.7\text{¢} / \text{kWh}$
NEWS Result: Sensitivity to Natural Gas
NEWS Result: Sensitivity to Natural Gas

Figure 22: The installed capacity (GW) by technology for the natural gas sensitivity study over the 2007 data year. Each panel displays the capacity of each technology for the full range of natural gas fuel costs simulated. (a) Shows the Low-cost Renewables scenario, (b) displays the Mid-cost Renewables scenario, and (c) is the High-cost Renewables scenario. In all panels there is a cost of natural gas fuel below which no wind or solar PV is developed. Moreover, the deployment of wind and solar PV with increasing natural gas fuel cost is not linear. As more wind and solar PV are added, the overall installed capacity increases. There is a steep increase in the use of wind and solar PV because high resources are available and curtailment is not an issue because their share of total electricity is still relatively low. Eventually, with continued natural gas fuel cost increases, the highest resource sites are saturated, and when new sites are selected, some of the energy begins to be curtailed further raising costs. An interesting analogy is that of population growth. At first it is very rapid, but at some point the population reaches a turning point where resources and competition become scarce, which acts...
Figure 23: The generation share (%) by technology for the natural gas sensitivity study over the 2007 data year. Each panel displays the share of electricity provided by each technology for the full range of natural gas fuel costs simulated. (a) Shows the Low-cost Renewables scenario, (b) displays the Mid-cost Renewables scenario, and (c) is the High-cost Renewables scenario. The nonlinear behavior of the addition of wind and solar PV is very pronounced. Once all the high-resource, low-correlated wind and solar PV sites are developed, the system moves to less desirable choices, substantially slowing the increase in wind and solar PV generation share. From an economics standpoint, this is understood to be caused by increasing marginal cost for wind and solar PV generators.
NEWS Result: Sensitivity to Natural Gas

(a) Displays the CO$_2$ emissions from the electric sector as a percentage of the emissions from 1990 levels. It illustrates the decrease in emissions with rising natural gas fuel cost, but with diminishing returns at the highest costs; there is a negative logistic relationship.

(b) Shows the relative total system costs compared with the system produced by $4 / MM Btu natural gas fuel cost. The cost differences exhibit a power law relationship.

(c) Highlights the carbon-emission-free generation at the various natural gas fuel costs. It can be represented by a logistic function, suggesting diminishing increases in wind and solar PV generation share with higher natural gas fuel cost.

(d) Represents the curtailment of wind and solar PV as a percentage of total wind and solar PV generation at each natural gas fuel cost. The increase in curtailment is steepest for the Low-renewable scenario, which can be attributed to high penetrations of solar PV.
NEWS Result: The Effect of Coal and EPA CAA 111(d)
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- Nuclear
- Hydroelectric
- Onshore Wind
- Offshore Wind
- Solar PV
- Natural Gas
- Coal

**Figure 27** displays cost-optimal configurations for a single connected contiguous US electric power system. **Figure 28** shows the installed capacity in GW (a) and generation share (b) by technology for each cost scenario. It is clear that in the LRHG scenario, more wind and solar PV is installed compared to the other scenarios. The installed capacity share of coal power plants varies across the scenarios, with the LRHG scenario showing a significant reduction in coal power production. In the LRHG scenario, natural gas power plants are replaced by wind and solar PV, allowing more wind-generated power to be used within the system.