Simulation Modeling of Power Plant Emission Regulations: Why a Detailed Economic-Engineering-Environmental Model is Needed

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Why a SuperOPF Planning Tool?

- Proper assessment of electricity policies, potential new generation units, and potential expansions of the power transmission system requires prediction of their system-wide, society-wide, and long-term effects.
- System-wide → Transmission flows & detail
- Society-wide → Air pollution externalities
- Long-term → Predicts entry and retirement

OUTLINE

1. SuperOPF Planning Tool description
2. Dataset description
3. Description of 5,000-node and 300-node models of the Eastern Interconnection
4. Comparison of their predictions for leakage in RGGI

SuperOPF Planning Tool: Some Highlights

Determines flows according to laws of physics

Predicts or optimizes system operation, investments, retirements, and effects.

Includes emissions and estimated health damage.

Can be used with model of any grid. We are finishing US-Canadian models.

Will be publicly available and modifiable.

The Model

$$\max_{p_{ijk}, I_{ij}, R_{ij}} \left\{ \sum_i \sum_j \left[\begin{array}{c} \left(\sum_k H_k \left(B_{jk} - \left(c_i^F + a_{jk} e_i \right) p_{ijk} \right) \right) \\ - \left(c_i^T \left(p_{ij}^0 + I_{ij} - R_{ij} \right) + c_i^I I_{ij} \right) \end{array} \right] \right\}$$

subject to

$$p_{ij}^0 + I_{ij} - R_{ij} \geq p_{ijk}$$

$$p_{ijk} \geq \alpha_i^{\min} (p_{ij}^0 + I_{ij} - R_{ij})$$

$$K_{ij} > I_{ij}$$

$$\sum_i p_{ijk} - L_{jk} - \sum_{j'} S_{jj'} (\Theta_{jk} - \Theta_{j'k}) = 0$$

$$F_{jj'} > \left| S_{jj'} (\Theta_{jk} - \Theta_{j'k}) \right|$$

How the Model Makes Its Predictions

It finds the combination of plant construction, retirement, and operation that maximizes

Consumer benefits
- Annualized construction costs
- Other Annual fixed costs
- Operating costs

over each decade, subject to meeting load and respecting network constraints.

More Detail on Features of SuperOPF Planning Tool

- Representative hours with demand, wind, solar, hydro, and availability combinations (currently 38).
- Demand function at each node (and growth)
- AC or linear ("DC") modeling. Here, DC.
- Emission rates and transfer coefficients allow calculation of air pollution damage (currently secondary fine particulate mortality) in each county of US (and soon Canada).

Dataset of Existing Generators

- Capacities, heat rates, emission rates, fuel cost adders, locations, smokestack heights, marginal emission damage, etc.
- Required matching 12 datasets
- Transmission Atlas and FirstRate datasets from Energy Visuals provided some of the most difficult to obtain portions of the data. Our thanks.

Generator and Load Data Overview

- Information about existing units combined from 12 sources
- Investment costs from EIA
- Fuel cost projections from EIA
- Pollution transfer coefficients from EPA-funded model
- Fine PM mortality effects and valuation from NRC
- 12-40 hour types represent the year. Vary in terms of unit availability (from NERC) and load (from ISOs and NERC).
- Load grows (before long run demand response) per ISO projections

http://www.nyiso.com/public/webdocs/newsroom/press_releases/2009/NYISO_2009_Summer_Outlook__05212009_(2).pdf

Converting Pollution into Estimated Mortality Cost

- Seventy million county-to-county transfer coefficients from EPA-funded model
- Population per county, and percentage over 30, from US and Canadian censuses
- Dose-response functions from NRC
- Valuation per premature death from US EPA standard value

Typical Run

- Adjust input parameters to reflect a policy, investment, behavior, etc.
- Sequential optimization of three periods
  1. Year 0 current fleet
  2. Decade 1 allowing retirement and new investment
  3. Decade 2 allowing retirement and new investment

Assumed Fuel Prices

$/mmBtu	Year 0	Decade 1	Decade 2
Natural Gas	$2.50	$4.77	$5.86

These natural gas prices are from recent projections of US Energy Information Administration

Costs of other fuels are assumed to remain at 2012 levels.

PHOTO: MLADEN ANTONOV/AFP/GETTY IMAGES

Assumed New Power Plant Costs

Fuel Type	Annual Capital Cost, Years 1-10 ($/MW/Year)	Annual Total Fixed Costs ($/MW)	Variable Cost $/MWh (in 2012)
Coal (Dual Unit Advanced PC)	$495,245	$35,255	$29.05
Natural Gas (Advanced NGCC)	$167,859	$20,661	$38.48 (if $5.50 per mmBtu; varies)
Natural Gas (Advanced NGCT)	$107,173	$12,741	$63.50 (if $5.50 per mmBtu; varies)
Wind	$352,720	$10,236	$2*
Nuclear	$959,328	$95,571	$2.04
Solar	$765,175*	$5,849	$2

*Excluding tax credit for wind and solar (included in some runs)

Updated Capital Cost Estimates for Electricity Generation Plants
November 2010, U.S. Energy Information Administration,
Office of Energy Analysis

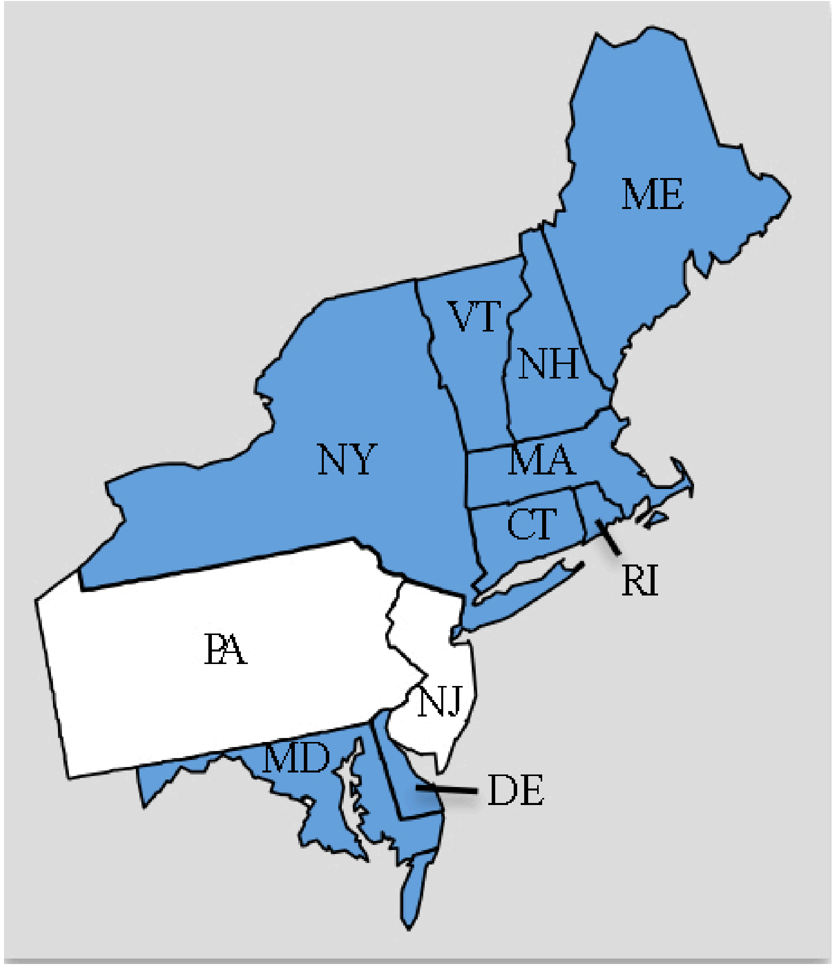
Annual Energy Outlook 2011
April 26, 2011, U.S. Energy Information Administration

The Three Grid Representations

- 5000-node model retains all high-voltage (>225 kV) lines and aggregates the lower-voltage lines.
  - Matches behavior of original 60,000-node model very closely.
  - With 36 representative hours and investment and retirement optimization/prediction: 2,334,909 variables and 6,382,608 constraints
- 300-node model retains the most often congested lines and aggregates the others.
- 1-node model has no transmission constraints

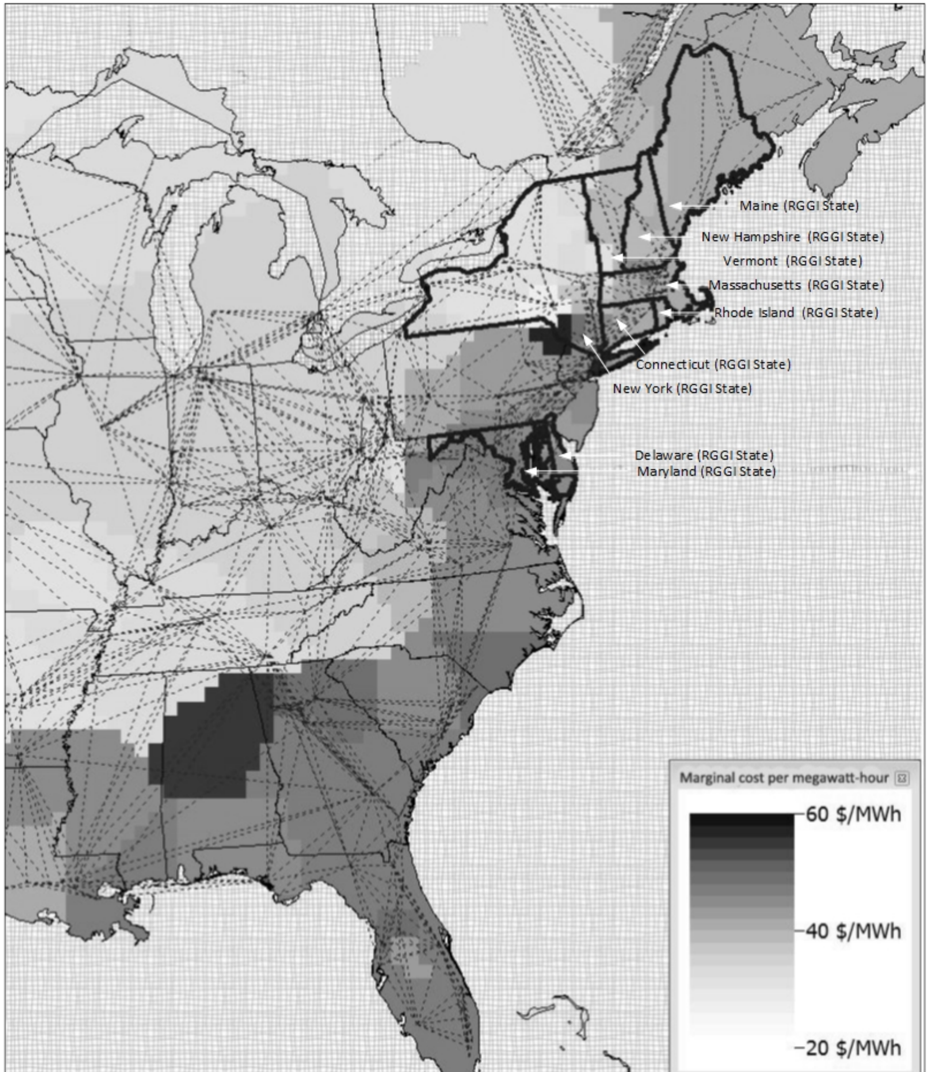
We Compare the Models' Predictions of Effects of New Regional Greenhouse Gas Initiative (RGGI)

- Cap and trade, 9 states in northeastern US
- There is a plan to tighten the cap
- We assume a price of $10 per ton of CO_2
- Concerns over "leakage"

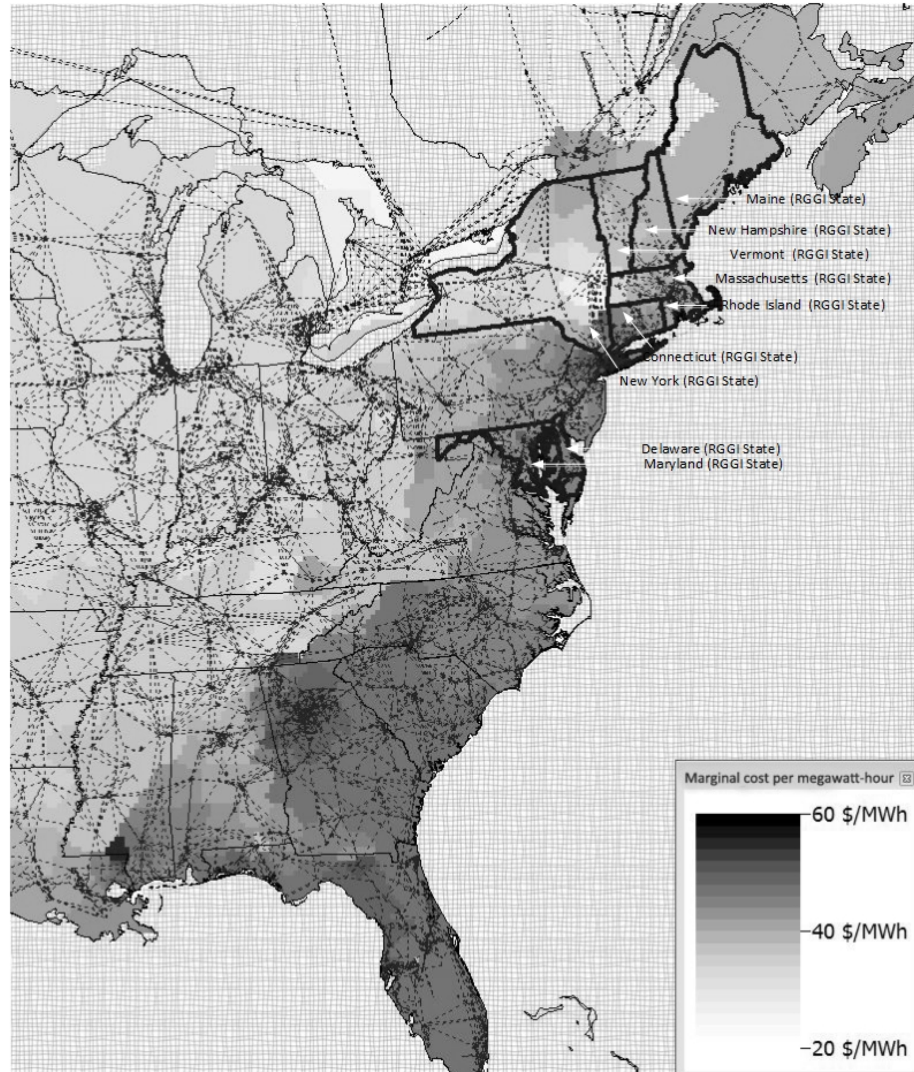


Annual Average Price by Location

300-Node LMP Map



5,000-Node LMP Map



Both maps show prices in year 10 in the scenario with no RGGI policy.

Hypothesis 1

- Because less detailed model has fewer constraints, it will produce results consistent with greater ease of transmission flows between the RGGI and non-RGGI regions:
  - Lower RGGI emissions
  - More emission "leakage" from RGGI to non-RGGI
  - Lower RGGI price increase

300-Node Model Underpredicts RGGI Emissions

Short Tons of CO_2 Emissions in RGGI States with \$10 per ton emission price			
Model Used	Year 0	Year 10	Year 20
1 Node	54,254,639	46,426,309	60,461,374
300 Node	55,439,574	57,964,776	55,006,769
5,000 Node	68,354,796	68,901,179	62,346,980

Less Detailed Model Overpredicts Emission Leakage

Effect of RGGI on Carbon Dioxide Emissions (Short Tons)				
Model Used		Year 0	Year 10	Year 20
1 Node – Policy Effect	In RGGI	-55,020,247	-48,535,057	-54,408,007
	Outside RGGI	+79,026,267	+54,287,354	+55,735,423
	Net Effect	+24,006,020	+5,752,297	+1,327,416
300 Node – Policy Effect	In RGGI	-25,433,526	-35,510,483	-49,754,186
	Outside RGGI	+36,278,990	+38,155,900	+43,329,451
	Net Effect	+10,845,464	+2,645,417	-6,424,735
5k Node – Policy Effect	In RGGI	-18,282,576	-30,869,475	-61,262,677
	Outside RGGI	+26,208,921	+33,505,346	+43,312,049
	Net Effect	+7,926,345	+2,635,871	-17,950,628

Less Detailed Model Underpredicts Effect of RGGI on Electricity Prices in RGGI States

Effect of RGGI $10 Emission Price on Electricity Price in RGGI States			
Model Used	Year 0	Year 10	Year 20
1 Node	+$0.41	+$0.64	+$0.08
300 Node	+$2.45	+$2.56	+$0.85
5,000 Node	+$4.18	+$3.94	+$1.47

Hypothesis 2

- In a less detailed and consequently less constrained model, one generator can meet more of the needs that occur in different locations at different times.
- As a result, a less detailed model will have less generation capacity (less entry and/or more retirement).

Less Detailed Model Has Less Entry

Results without RGGI (in MW of generation capacity)		
Model Used	Entry	Retirement
1 Node	22,431	142,706
300 Node	32,494	137,706
5K Node	35,341	126,105
Results with $10 RGGI Allowance Price		
1 Node	24,018	143,115
300 Node	34,764	138,702
5K Node	38,892	128,242

Less Detailed Model Has More Retirement

Results without RGGI (in MW of generation capacity)

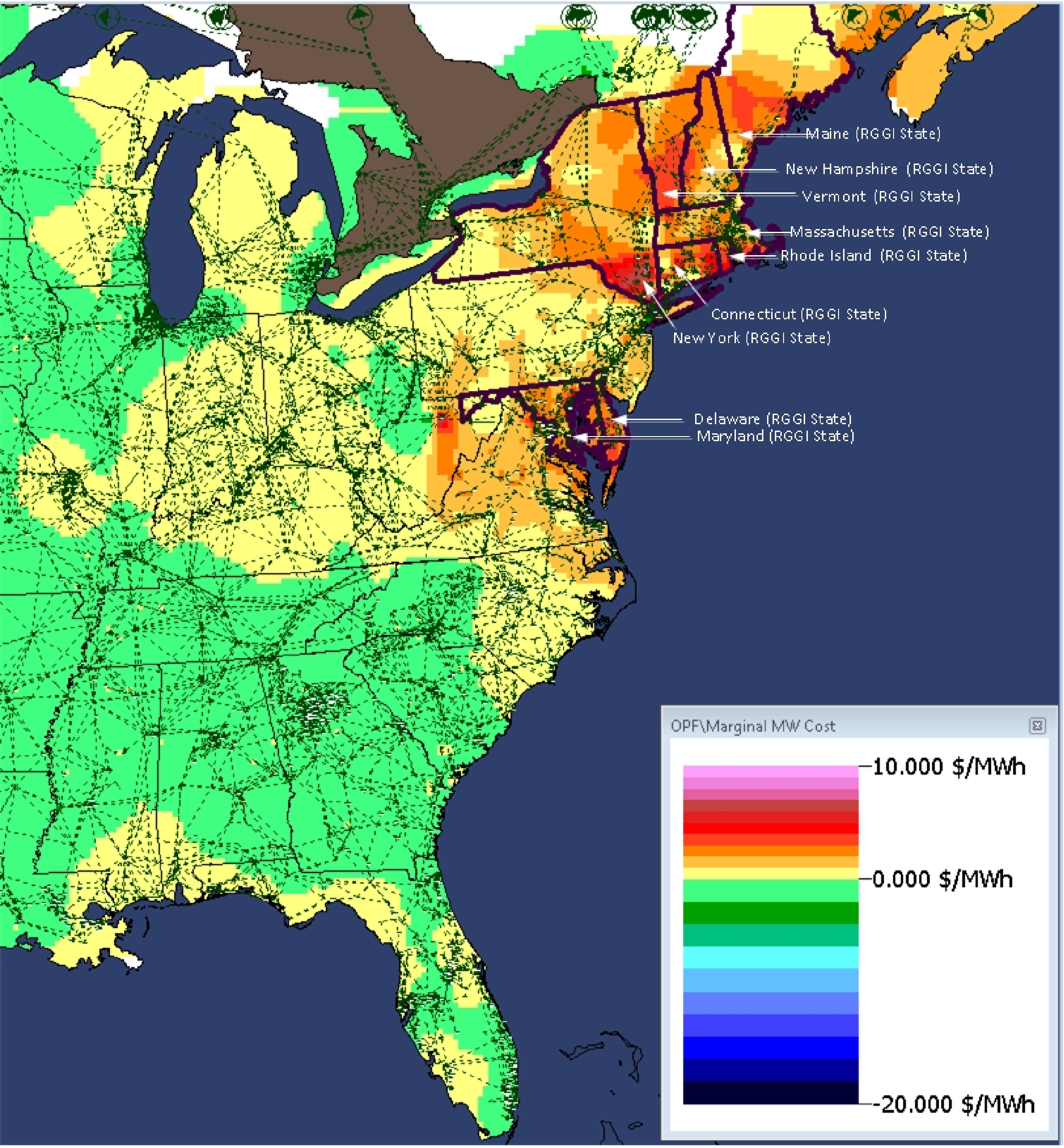
Model Used	Entry	Retirement
1 Node	22,431	142,706
300 Node	32,494	137,706
5K Node	35,341	126,105

Results with $10 RGGI Allowance Price

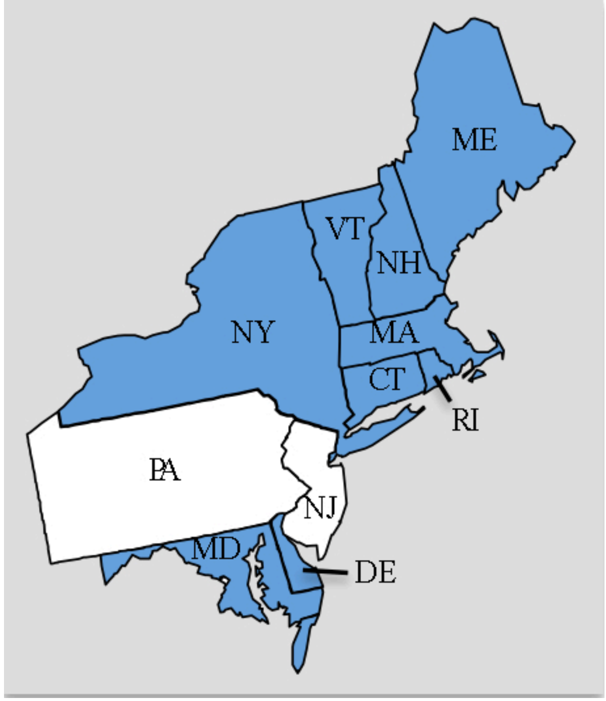
1 Node	24,018	143,115
300 Node	34,764	138,702
5K Node	38,892	128,242

Effect of $10 RGGI Price on Electricity Prices (vs. $0 RGGI price)

Ten Years After Policy Goes Into Effect (Simulation Results with 5,000-Node Model)



RGGI states are in blue below



Source of map at left: Simulation using SuperOPF Planning Tool and 5000-node transmission model, reported in Shawhan et al, *Resource and Energy Economics*, January 2014.

Summary

- We are using electrical model (loop flows) for planning and policy analysis
- Have developed necessary simulation engine, methods, and datasets
- We examine the effect of using fewer nodes and consequently fewer constraints
- Simplification biases results of electrical model
  - Greater flows, and consequences of that
  - Less generation capacity, and consequences of that
  - Implies we need to use detailed electrical model