E4ST Modeling, and Some Suggestions Related to Power Sector Modeling

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Views expressed are those of the individuals. RFF does not take institutional positions on public policies.

Preface

1. We've been asked to talk about our models and about suggestions

2. If you have any suggestions or comments for me, please let me know in person, by phone, or at Shawhan@rff.org. Including about the presentation, which I'll have a chance to improve before it gets posted.

The E4ST Team

- Current active team: Paul Picciano, Daniel Shawhan
- Ray Zimmerman maintains and manages improvements to MATPOWER
- Top reservists: Ray Zimmerman, Bill Schulze, Daniel Tylavsky

Special Thanks To

- Important past contributors including Biao Mao, Carlos Murillo-Sanchez, John Taber, Jubo Yan, Charles Marquet, Di Shi, Yujia Zhu, Doug Mitarotonda, Yingying Qi, Nan Li, Richard Schuler, Bob Thomas, Zamiyad Dar, and Andrew Kindle
- Joe Eto, Phil Overholt, Bob Thomas, Rana Mukerji, DOE CERTS R&M program, NYISO, CURENT, PSERC, and NSF for funding & advice
- Energy Visuals, Inc. for data from its Transmission Atlas and FirstRate products
- Gurobi for the use of its solver software
- Various colleagues in various organizations for advice

E4ST

ENGINEERING, ECONOMIC, AND ENVIRONMENTAL ELECTRICITY SIMULATION TOOL

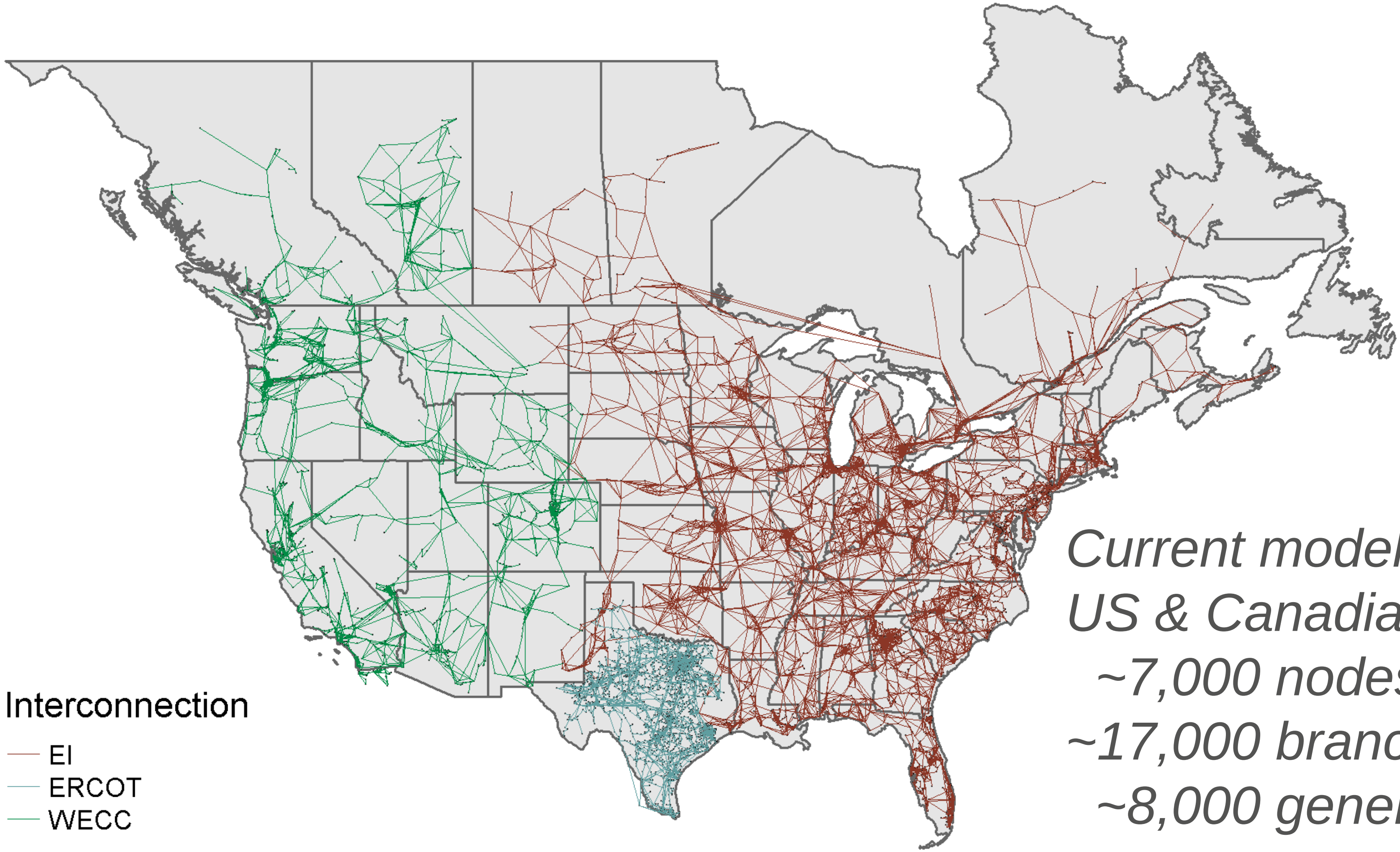
Cornell University

ASU Arizona State University

RESOURCES FOR THE FUTURE

E4ST US & Canada Model Physical Detail

Data Source: Energy Visuals, Inc.



Current models of the three US & Canadian grids.
~7,000 nodes,
~17,000 branches,
~8,000 generators.

Brief Model Description

***E**ngineering, **E**conomic, and **E**nvironmental **E**lectricity Simulation Tool*

e4st.com

- E4ST is designed to project the effects of policies, generator and transmission investments, and other power sector changes.

- E4ST is built on top of MATPOWER, an open-source optimal power flow simulation software package in MATLAB (physics-based flows).

- E4ST added features include:

  (1) Simultaneous optimization of generator investment, retirement, and dispatch;

  (2) Detailed representation of generation, transmission, and demand;

  (3) Price-responsive demand at each node;

  (4) Linked air pollution transport, fate and health effects model;

  (5) Benefit-cost analysis calculations.

The Simulation Tool (E4ST)

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

subject to

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

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

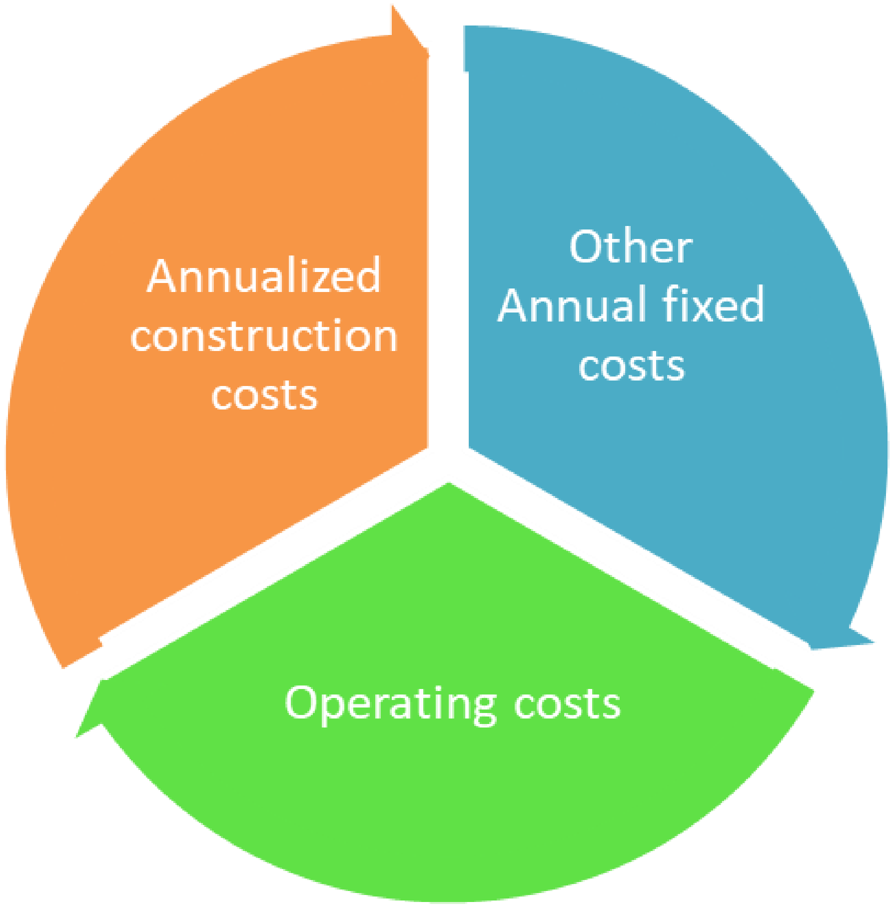
$$K_{ij} > I_{ij}$$

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

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

More information at E4ST.org.

To project market outcomes, E4ST finds the combination of electricity consumption, and plant construction, retirement, & operation, that maximizes consumer benefits minus



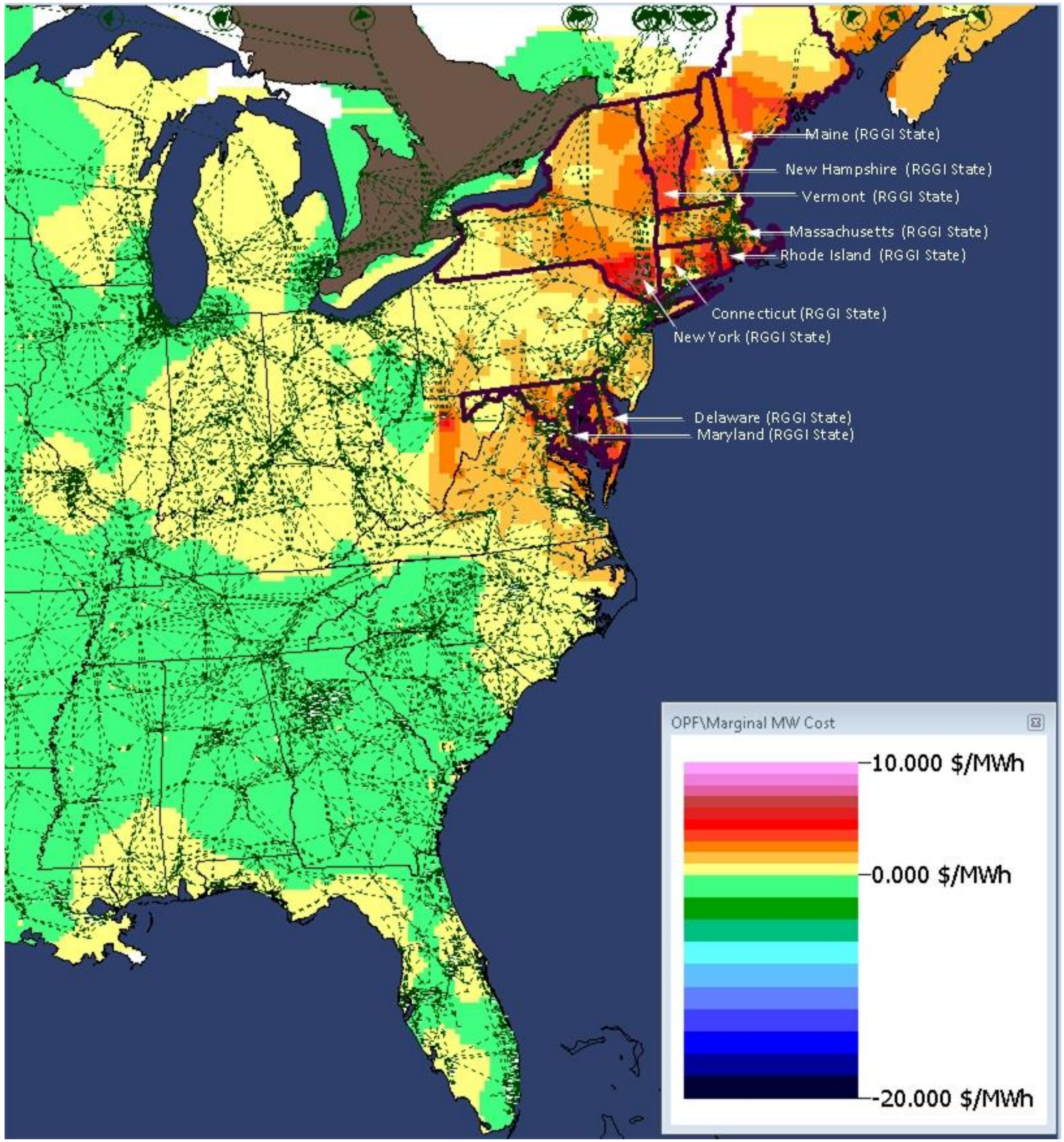
subject to respecting network constraints.

Model Validation: 2013 average electricity prices in simulation output and in reality

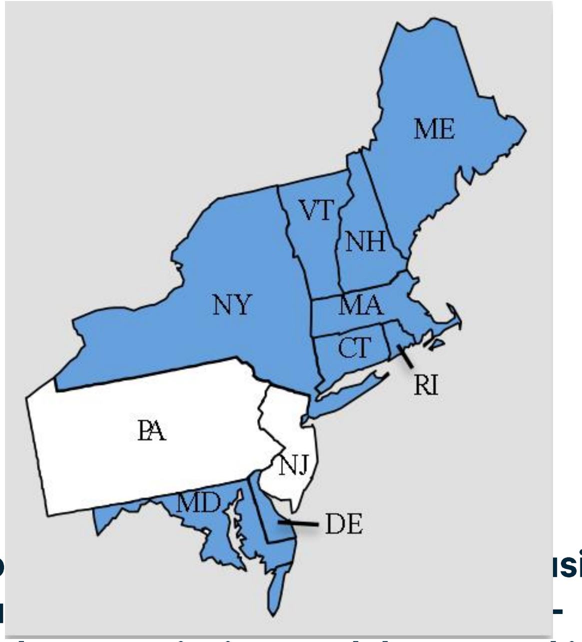
Region	Average LMP from simulation	Actual average LMP	
New England	55.1	56.1	
PJM	37.4	38.0	
State			
west virginia	36.9	35.0	
virginia	40.5	38.6	
pennsylvania	41.9	39.3	
ontario	21.1	26.5	
ohio	34.7	35.1	
north carolina	43.2	38.6	
new jersey	45.4	40.8	
michigan	31.2	35.1	
maryland	42.7	39.6	
kentucky	33.9	35.0	
indiana	33.0	35.1	
illinois	32.0	32.2	
district of columbia	42.3	38.4	
delaware	43.9	40.3	
		Correlation:	**0.97**
NY zone (simple average of LMPs over all hours)			
WNY	37.6	37.8	
NYC	52.6	52.6	
LI	64.1	64.3	
Hudson	53.0	50.1	
Capital	57.5	50.4	
		Correlation:	**0.95**

Sample "Heat" Map: 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)



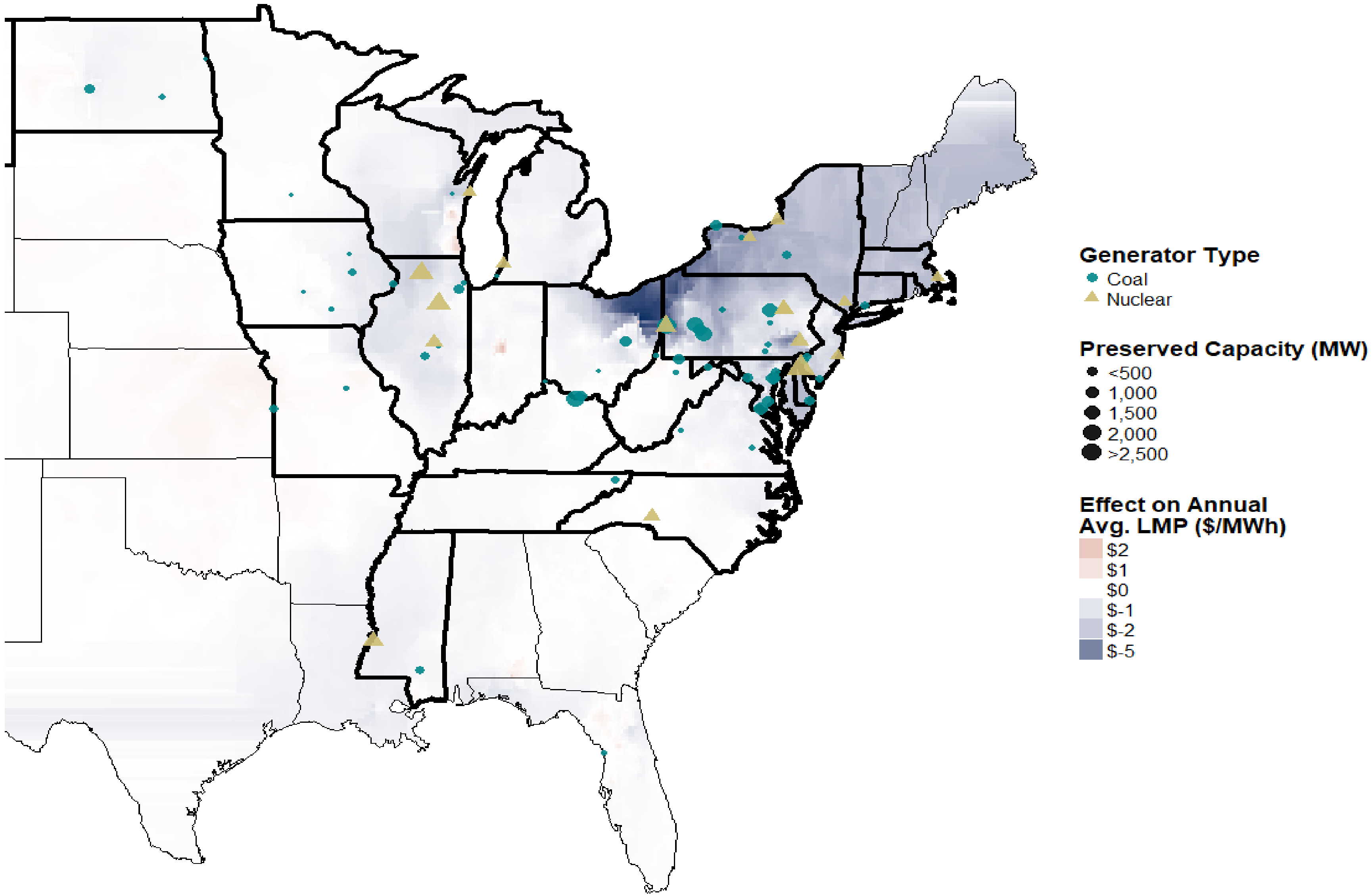
RGGI states are in blue below



So … using Su … - node transmission model, reported in Shawhan et al, *Resource and Energy Economics*, January 2014.

One can make a heat map for any result that varies geographically.

Effects of Profit Guarantee on Average Underlying LMP in 2025 (Change from BAU)



Some Distinctive Features of Our Modeling

1. Relatively accurate model of the transmission **system** (compared to other models that also predict entry and exit of generators)

2. We use an air **pollution** model to estimate health effects

3. We calculate the measure of **welfare** called total social surplus and its five components: consumer, producer, government, transmission, and environmental.

1. Comments about **Model Realism**

E4ST model of US & Canada

- Because we have detailed grid model and >10,000 buildable and existing generators that can be built or retire, we have millions of optimization variables, millions of constraints
- We have to keep the problem linear
- We use step functions or iteration to represent non-linearities

A fully realistic model would be vastly more computationally intensive than any existing model

Some of the features it would need to have:

- Most of the transmission lines
- Alternating-current flows, constraints, and controllability (non-linear)
- Losses (non-linear)
- Security-constrained unit commitment (mixed integer)
- The important contingencies including many not currently included in reliability assessments
- Endogenous ac & dc additions to the transmission system (ac is tricky)
- Good representation of storage and shiftable load
- Imperfect competition in investment decisions (non-linear?)
- Uncertainty and decision-making that takes uncertainty into account
- Load that shifts, increases, and decreases based on prices
- Interactions with other sectors

A fully realistic model would be vastly more computationally intensive than any existing model

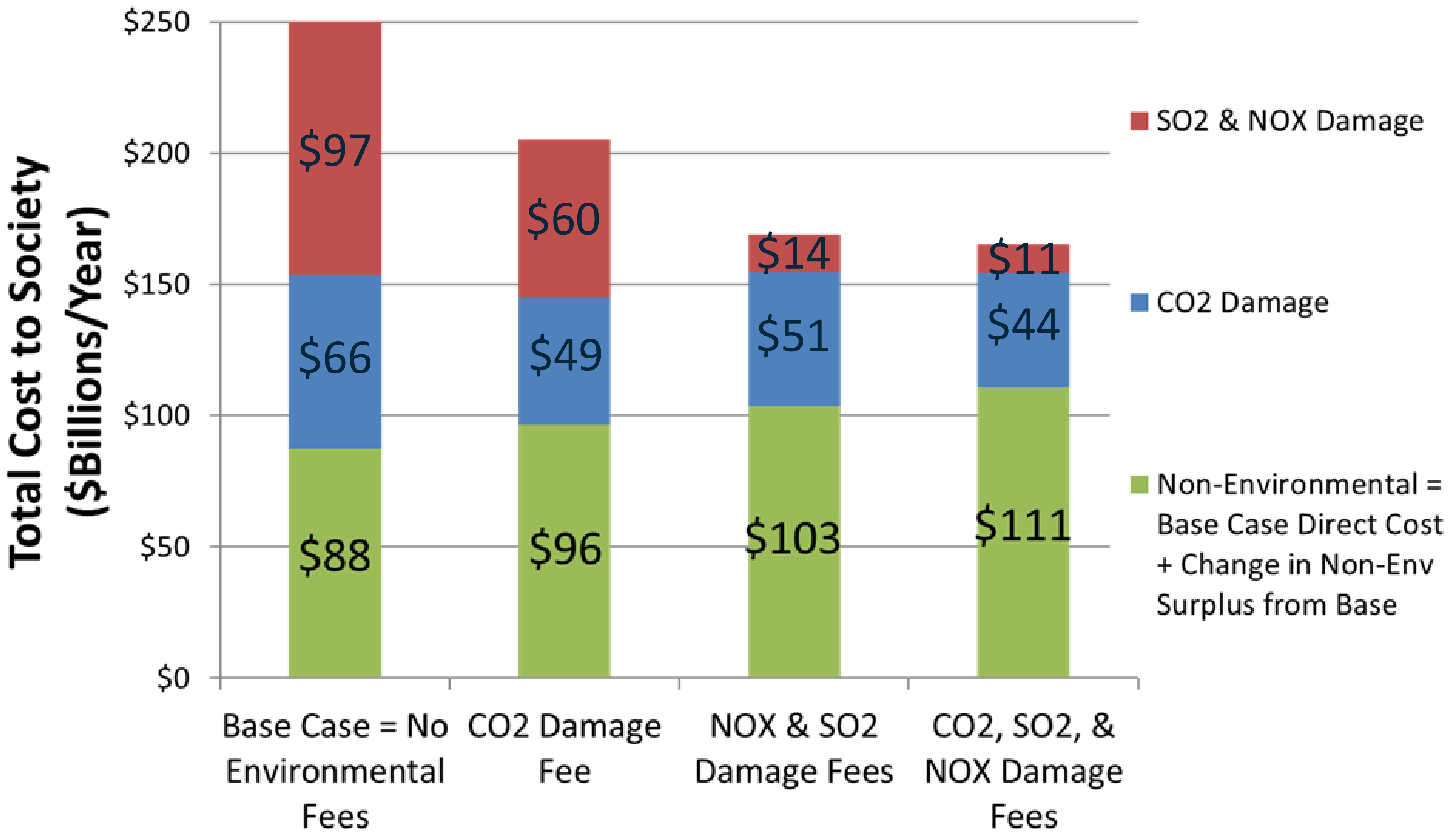
- For many purposes, using simplified models like we do today will continue to be necessary for decades to come
- There is much that can be done to improve the extent to which models can incorporate additional important phenomena
- I think it would be possible to estimate the reliability, resilience, environmental, and internal net benefits of system investments all at the same time.

2. Comments about Environmental Effects

Request from Congress to NASEM committee

…conduct <u>an evaluation of the expected medium- and long-term evolution of the grid</u>. This evaluation shall focus on developments that include the emergence of new technologies, planning and operating techniques, grid architecture, and business models.

Annual Costs to Society of Electricity Under Four Policies, Short-Run Analysis, 2013



Pollution Modeling is Important for Power Sector Decisions

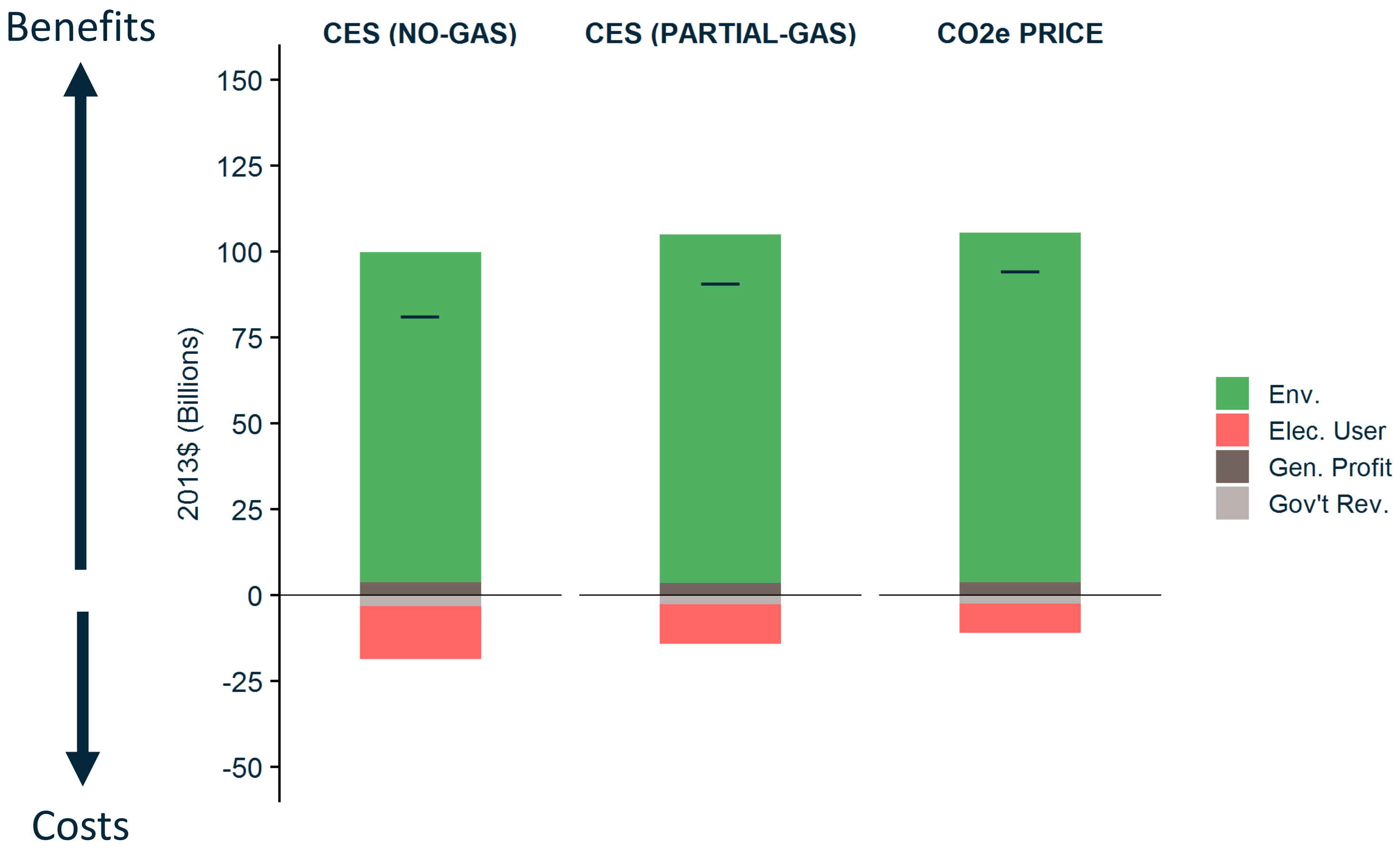
- ~10,000 estimated US deaths per year from US power plant SO2, NOX, PM2.5
- For the majority of the policies and investments we have simulated, |estimated environmental net benefits| > |sum of all other net benefits|
- Some estimates of CO2 damage per ton are much larger than the Obama Administration estimates

Some Suggestions

- Make the most available air models better & the better ones more available
- Require air pollution effects to be fully considered in decisions
- Governments should charge emitters for estimated environmental damages

3. Comments about **Welfare Analysis**

Example of Welfare Analysis: Projected Net Benefits of 2 Clean Energy Standards and Greenhouse Gas Emission Pricing, in 2035



Benefits and Costs

Environment:

Climate: Net damages caused by CO_2 & methane; Health: Estimated value of the mortality from SO_2 and NO_X emissions.

Electricity User:

Non-environmental "consumer" surplus of all electricity end-users.

Generator Profits:

Generator revenues minus production costs.

Gov't Revenue:

Revenues from emission policies, less costs of renewables tax credits.

Note: Transmission revenue is here included in electricity user net benefits.

Potential Additional Elements of Welfare Analysis

- Welfare losses from reliability and resilience failures could be included as well. Represent various contingencies in the modeling.
- Analysis can be further improved by estimating distributional effects (e.g. Burtraw et al work)
- Can include estimated general equilibrium effects (e.g. Hafstead et al. work)

4. Comments about **Distribution Pricing**

A Way to Make the Evolution of the Distribution System and End-User Choices Much More Efficient

- Reduce distribution costs greatly, promote renewables, and reduce inefficient grid defection by making distribution charges match short-run marginal cost more closely.
    - Modeling important for this.
    - Would reduce distribution revenue.
- Charge for environmental damages and use some of the proceeds from the environmental charges to help cover the fixed costs of providing distribution service

This Week: Lining Up Sources of Cost and Location Assumptions for Some Long-Run Grid Evolution Technologies

- We are adding **advanced nuclear, hot dry rock geothermal, direct air capture of CO2**, and a better representations of **short- and long-duration storage** and CCS

- We need good assumptions about costs, how costs will change as a function of learning from deployment, performance, and what are the lower-cost locations

- If you know about the sources of such assumptions for any of these technologies, grateful if you'd let me know today so I can let you know our tentative planned sources and you can comment

- If you know of someone who could come up with even better assumptions, grateful if you'd let me know today. Have some budget for this.

Thank you.

- Let me know any comments or suggestions you have in person, by phone, or at shawhan@rff.org
- If you'd like to go to dinner together tonight, let me know

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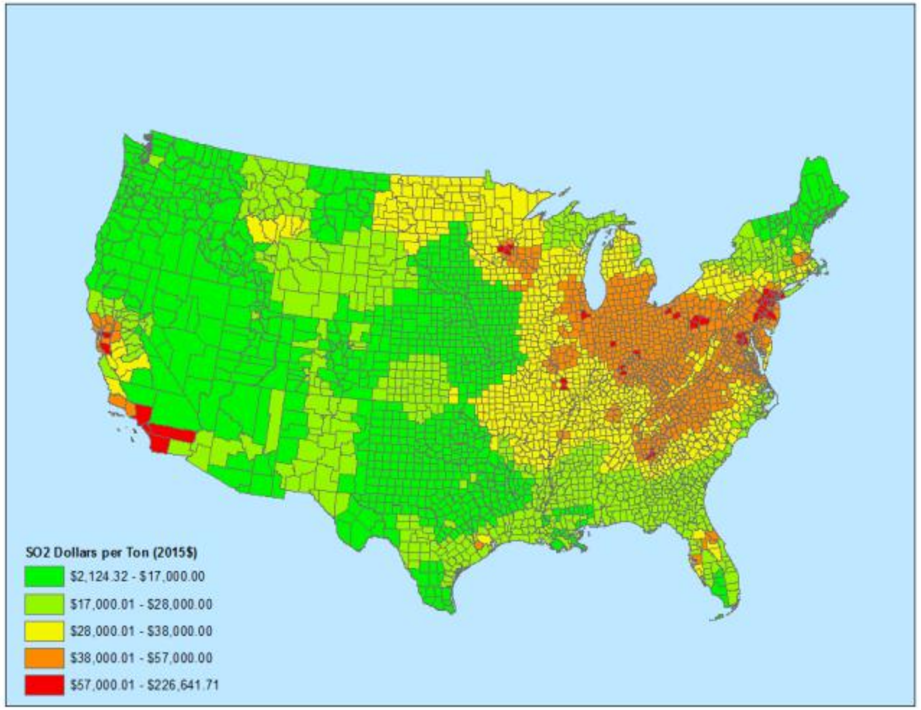
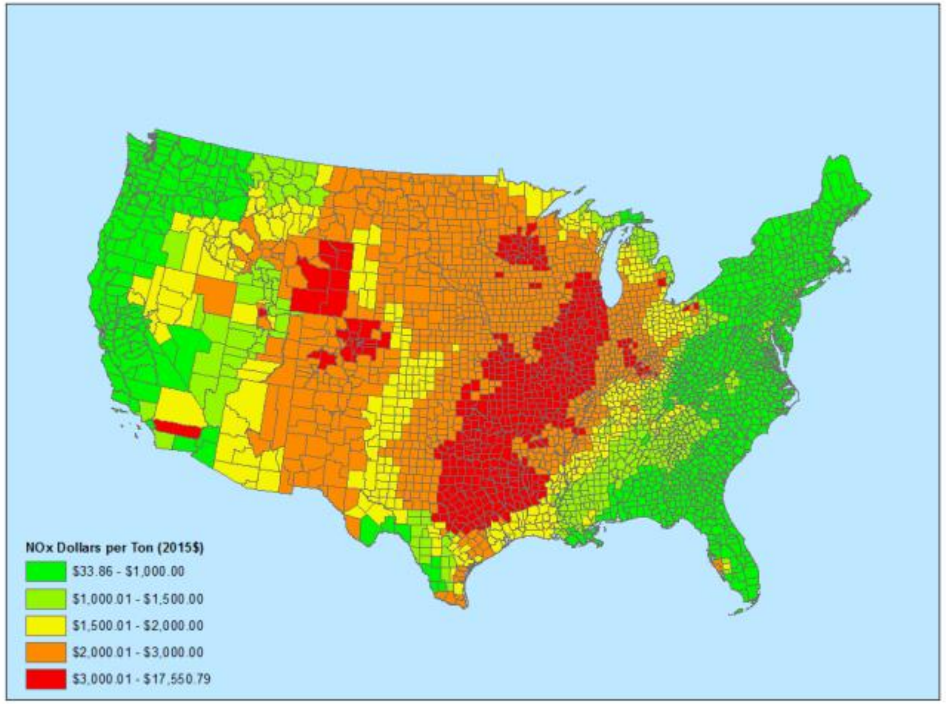
Damage as a Function of Emission Location ($/Ton, from AP2 Model)

SO_2



NO_x



Note: These are the AP2 “low end” values.
Credit: Nicholas Muller and Industrial Economics