Project 2E

Mapping Energy Futures: The SuperOPF Planning Tool

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OUTLINE

1. Review of the E4 Simulation tool (E4ST)
2. Inputs used for modeling
3. Validation
4. The first E4ST Fast Predictor
5. Real Options Analysis of a New Line (w/ Saamrat Kasina and Ben Hobbs)
6. Analysis of more stringent RGGI and NY RPS
7. Some accomplishments this year

1. THE SIMULATION TOOL

E4ST

ENGINEERING, ECONOMIC, AND ENVIRONMENTAL ELECTRICITY SIMULATION TOOL

The Simulation Tool

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

subject to

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

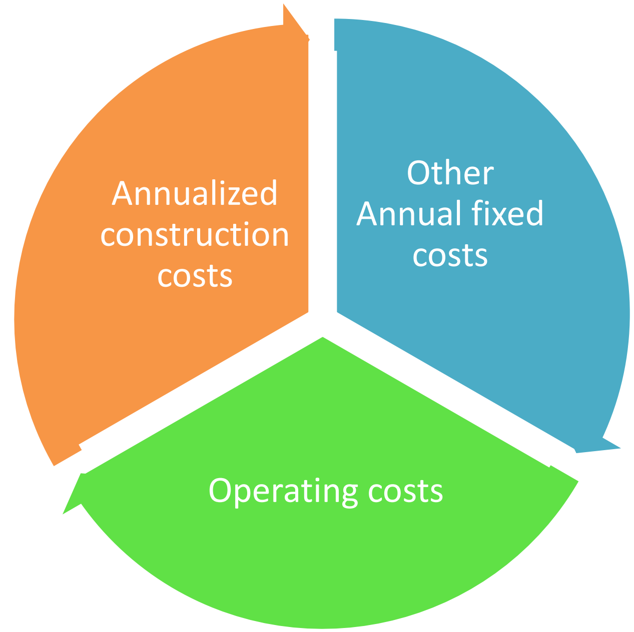
$$p_{ijk} \geq \alpha_i^{\min} (p_{ij}^0 + I_{ij} - R_{ij})$$

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

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

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

It finds the combination of plant construction, retirement, and operation that maximizes **consumer benefits** minus



subject to meeting load and respecting network constraints

Uses of E4 Simulation Tool

Project effects of

- Policies (various types)
- Investments
- Fuel prices
- Technology costs
- Demand changes
- Etc.

Optimize

- Investments
- Policies

Why the E4 Simulation Tool?

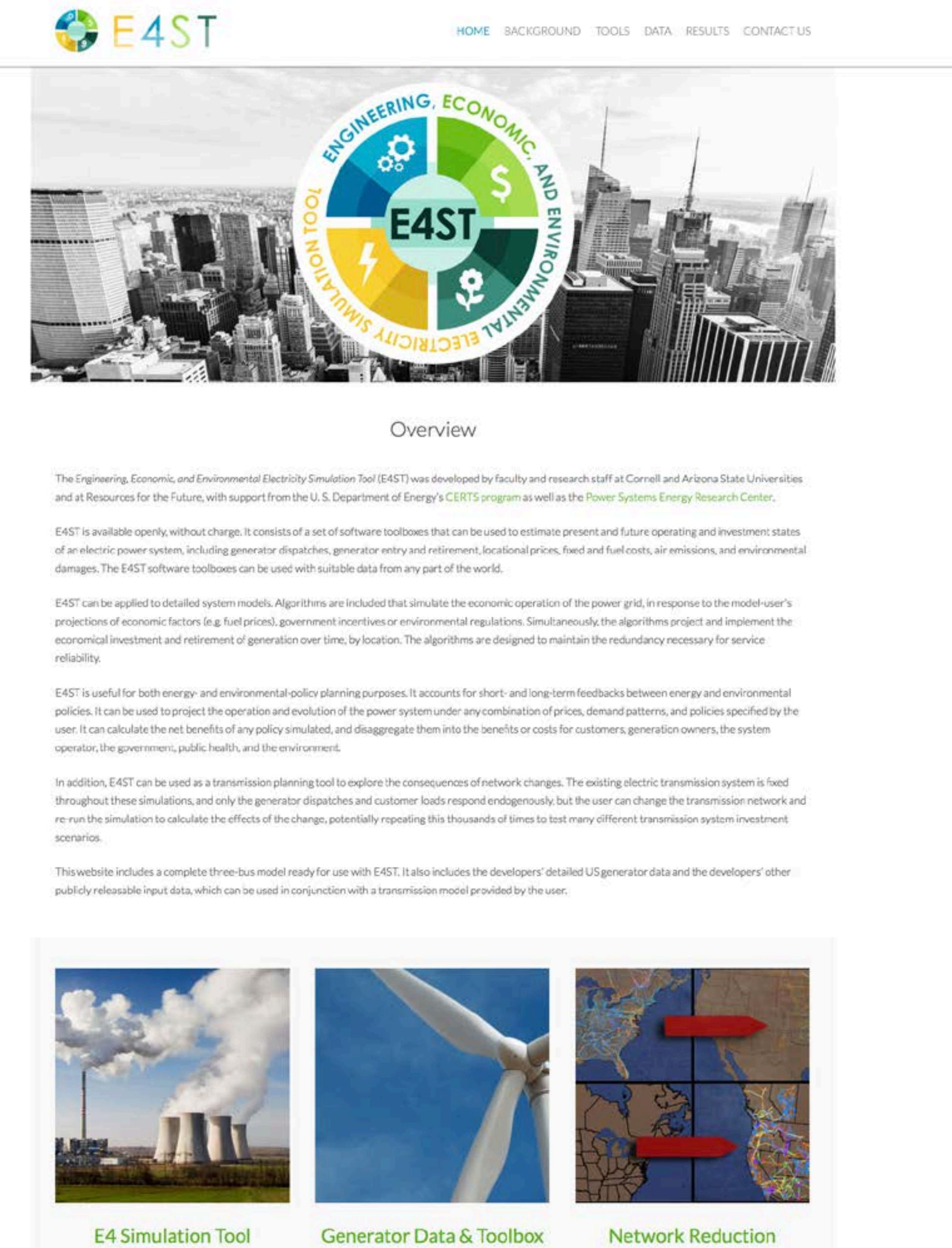
Proper projection or optimization often requires prediction of *system-wide*, *society-wide*, and *long-term* effects.

System-wide	Society-wide	Long-term
• Determines flows according to laws of physics	• Emissions, their transport, and health effects	• Simultaneously predicts operation, investment, and retirement

Other Characteristics of E4 Simulation Tool

- Adaptable. E.g. can represent ac and dc lines, hydro dispatch, sequential hours, storage, varied state & national mass and rate based emission policies, and RPSes.
- Can account for uncertainty and can stochastically optimize
- Adjustable demand function at each node (and growth)
- Can be used with a model of any grid
- Open-source: transparent, publicly available, & modifiable

E4ST.com/E4ST.org Website



E4ST

HOME BACKGROUND TOOLS DATA RESULTS CONTACT US

ENGINEERING, ECONOMIC, AND ENVIRONMENTAL ELECTRICITY SIMULATION TOOL

E4ST

Overview

The *Engineering, Economic, and Environmental Electricity Simulation Tool* (E4ST) was developed by faculty and research staff at Cornell and Arizona State Universities and at Resources for the Future, with support from the U. S. Department of Energy's CERTS program as well as the Power Systems Energy Research Center.

E4ST is available openly, without charge. It consists of a set of software toolboxes that can be used to estimate present and future operating and investment states of an electric power system, including generator dispatches, generator entry and retirement, locational prices, fixed and fuel costs, air emissions, and environmental damages. The E4ST software toolboxes can be used with suitable data from any part of the world.

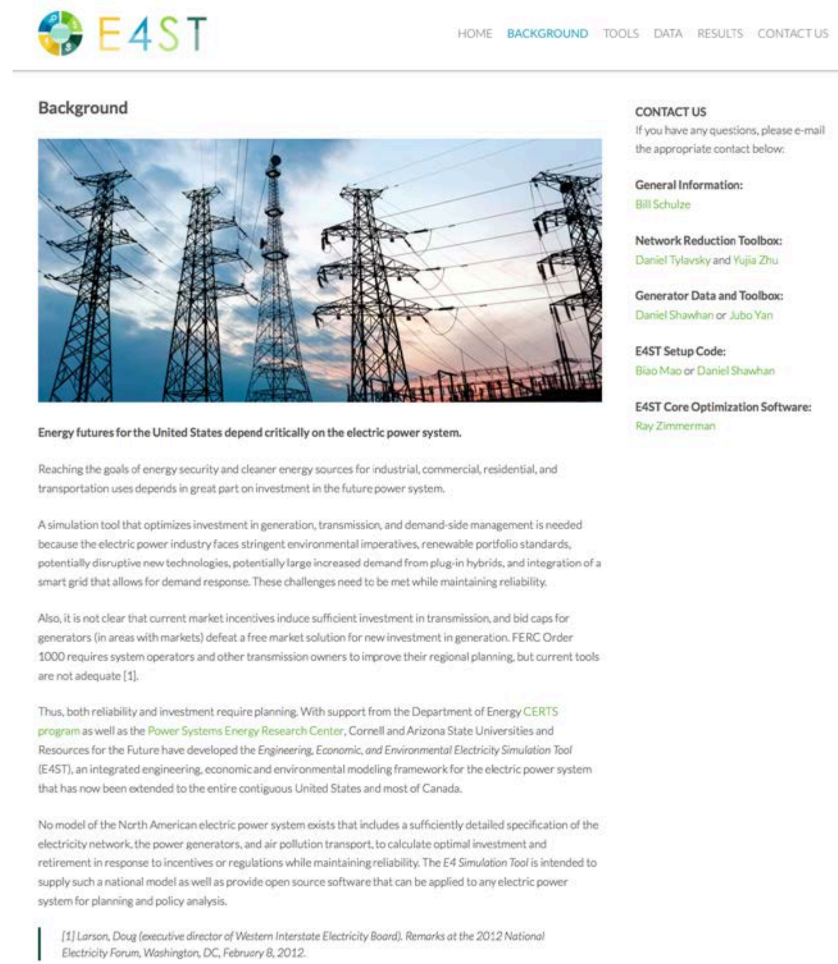
E4ST can be applied to detailed system models. Algorithms are included that simulate the economic operation of the power grid, in response to the model-user's projections of economic factors (e.g. fuel prices), government incentives or environmental regulations. Simultaneously, the algorithms project and implement the economical investment and retirement of generation over time, by location. The algorithms are designed to maintain the redundancy necessary for service reliability.

E4ST is useful for both energy- and environmental-policy planning purposes. It accounts for short- and long-term feedbacks between energy and environmental policies. It can be used to project the operation and evolution of the power system under any combination of prices, demand patterns, and policies specified by the user. It can calculate the net benefits of any policy simulated, and disaggregate them into the benefits or costs for customers, generation owners, the system operator, the government, public health, and the environment.

In addition, E4ST can be used as a transmission planning tool to explore the consequences of network changes. The existing electric transmission system is fixed throughout these simulations, and only the generator dispatches and customer loads respond endogenously, but the user can change the transmission network and re-run the simulation to calculate the effects of the change, potentially repeating this thousands of times to test many different transmission system investment scenarios.

This website includes a complete three-bus model ready for use with E4ST. It also includes the developers' detailed US generator data and the developers' other publicly releasable input data, which can be used in conjunction with a transmission model provided by the user.

E4 Simulation Tool | Generator Data & Toolbox | Network Reduction



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Background

Energy futures for the United States depend critically on the electric power system.

Reaching the goals of energy security and cleaner energy sources for industrial, commercial, residential, and transportation uses depends in great part on investment in the future power system.

A simulation tool that optimizes investment in generation, transmission, and demand-side management is needed because the electric power industry faces stringent environmental imperatives, renewable portfolio standards, potentially disruptive new technologies, potentially large increased demand from plug-in hybrids, and integration of a smart grid that allows for demand response. These challenges need to be met while maintaining reliability.

Also, it is not clear that current market incentives induce sufficient investment in transmission, and bid caps for generators (in areas with markets) defeat a free market solution for new investment in generation. FERC Order 1000 requires system operators and other transmission owners to improve their regional planning, but current tools are not adequate [1].

Thus, both reliability and investment require planning. With support from the Department of Energy CERTS program as well as the Power Systems Energy Research Center, Cornell and Arizona State Universities and Resources for the Future have developed the *Engineering, Economic, and Environmental Electricity Simulation Tool* (E4ST), an integrated engineering, economic and environmental modeling framework for the electric power system that has now been extended to the entire contiguous United States and most of Canada.

No model of the North American electric power system exists that includes a sufficiently detailed specification of the electricity network, the power generators, and air pollution transport, to calculate optimal investment and retirement in response to incentives or regulations while maintaining reliability. The *E4 Simulation Tool* is intended to supply such a national model as well as provide open source software that can be applied to any electric power system for planning and policy analysis.

> *[1] Larson, Doug (executive director of Western Interstate Electricity Board). Remarks at the 2012 National Electricity Forum, Washington, DC, February 8, 2012.*

CONTACT US

If you have any questions, please e-mail the appropriate contact below:

General Information:
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Network Reduction Toolbox:
Daniel Tylavsky and Yujia Zhu

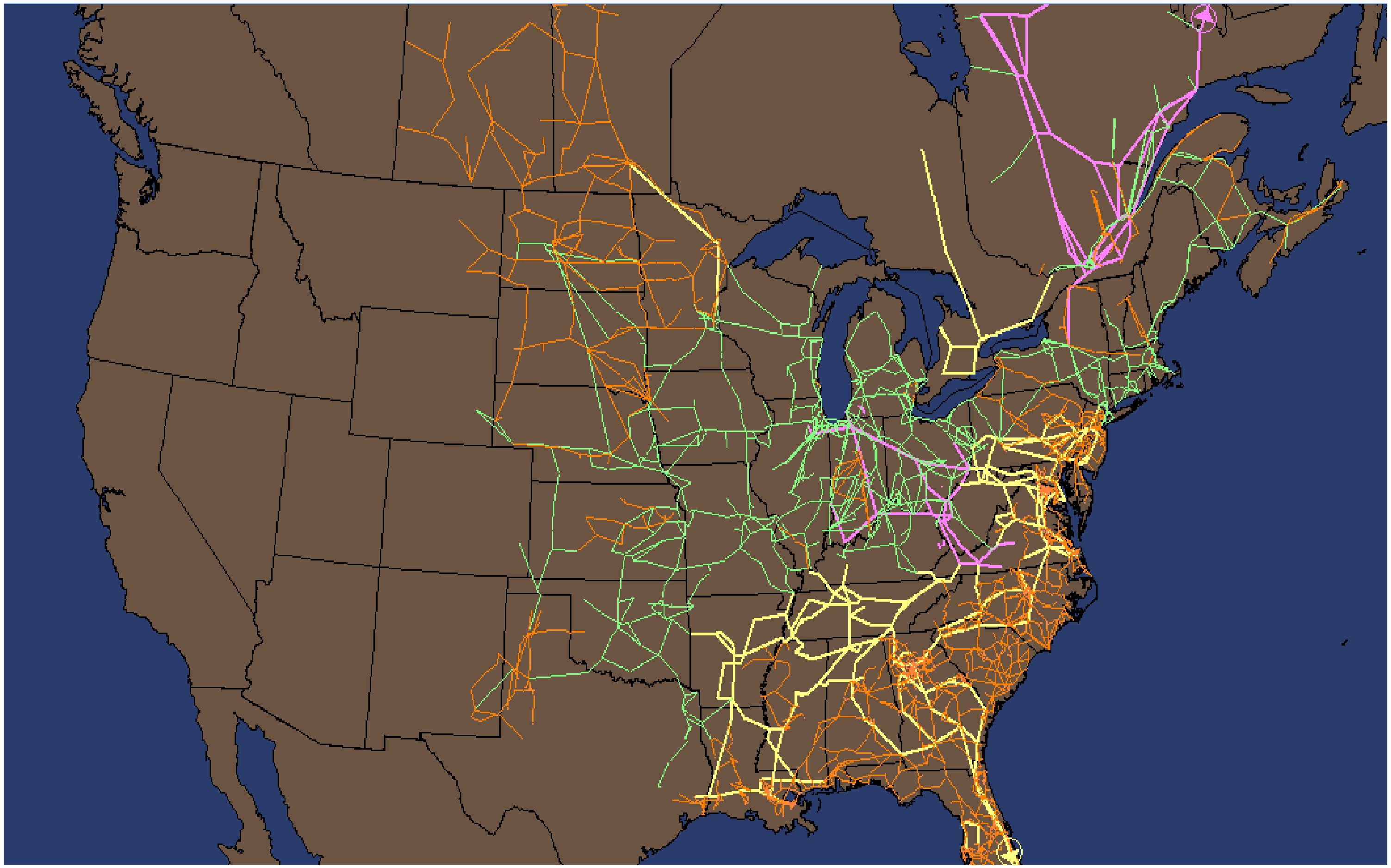
Generator Data and Toolbox:
Daniel Shawhan or Jubo Yan

E4ST Setup Code:
Biao Mao or Daniel Shawhan

E4ST Core Optimization Software:
Ray Zimmerman

2. INPUTS USED FOR MODELING (EI, WECC, and ERCOT)

We Have Built Detailed Models of the West, Texas, and the East (some lines shown here)



Our model of the East: 5222 nodes, 14225 branches, 8190 generators

Have models of the 3 US (& Canadian) grids, plan to build for Mexico, can build for elsewhere.

Optimization Problem Size

In our 5,222-node Eastern Interconnection model:

~2.5 million variables

~6.5 million constraints

This is necessary to have a realistic electrical model that predicts entry and exit along with operation.

Solves a representative year in approximately an hour if one uses 1 processor and has 12 GB of RAM.

Generator, Network, & Demand Data

- Pre-existing generators: Capacities, marginal costs, fixed costs, locations, emission rates, smokestack specs, more. From combining 12 sources provided by EIA, EPA, & Energy Visuals. Also from Canadian utilities.
- Transmission grids: Reduced from ~10x as many nodes using methods we developed keep generators whole and minimize accuracy loss.
- Representative hours (currently ~40) represent joint frequency distribution of demand, generator availability, wind, and solar.
- Renewable generation data: Hourly generation of *each current and potential wind farm and PV site*.
- Demand magnitude at each node from Energy Visuals, modified with data from EIA and utilities.

3. VALIDATION

Model Validation:

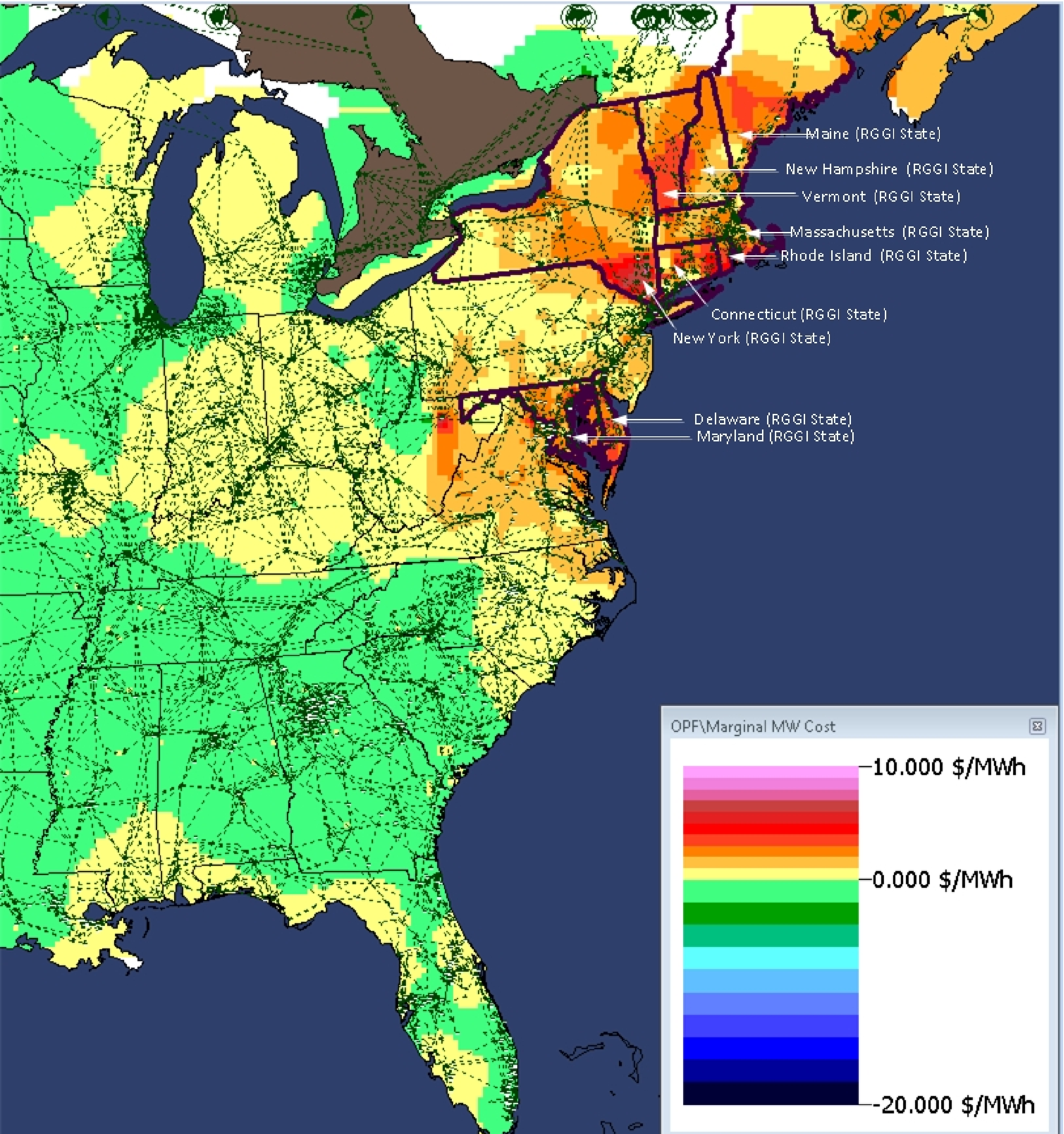
2013 average electricity prices in simulation output and in reality

We added the voltage-based interface constraint between upstate and downstate NY, which varies in reality, and set its value (very close to estimated real average constraint) to get the NYC-WNY price difference right. Otherwise, no "fudge factors."

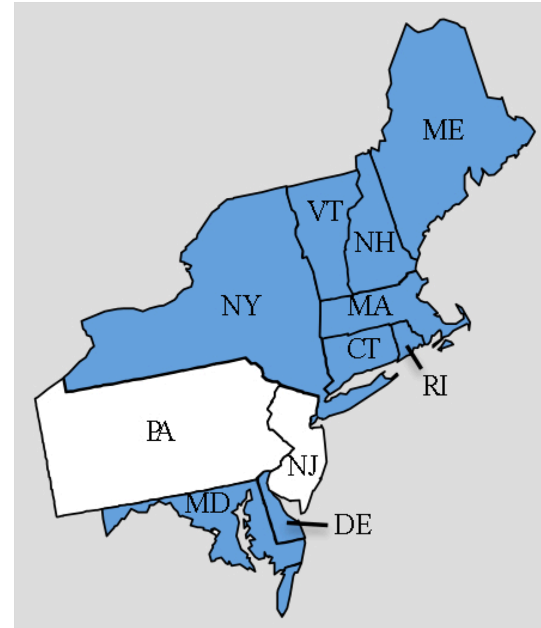
Region	Average LMP from simulation	Actual average LMP	
New England	55.1	56.1	
PJM	37.4	38.0	
State			
west virginia	36.9	35.0	
virginia	40.5	38.6	
pennsylvania	41.9	39.3	
ontario	21.1	26.5	
ohio	34.7	35.1	
north carolina	43.2	38.6	
new jersey	45.4	40.8	
michigan	31.2	35.1	
maryland	42.7	39.6	
kentucky	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



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.

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

4. E4ST *FAST PREDICTOR*

E4ST Fast Predictor
Why?

- Demonstrate capabilities of model
- Provide fast answers to important questions about policies, technologies, and possible futures
- Anyone can use, in minutes

E4ST Fast Predictor Approach

- Run a large number of simulations with different values of input variables
- Use regression analysis to calculate a function that predicts output variable values as a function of any combination of input values

E4ST Fast Predictor Approach

- Regressions use 2nd-order Taylor Series Expansion as their functional form
- R^2 exceeds .95 for many output variables.
- Refining functional form to improving the fit for some (e.g. CO2 emissions and deaths from fine particulates)

E4ST Fast Predictor Approach

- Sliders allow user to set values of input variables
- We have chosen certain ones in this first Fast Predictor
- One can choose others

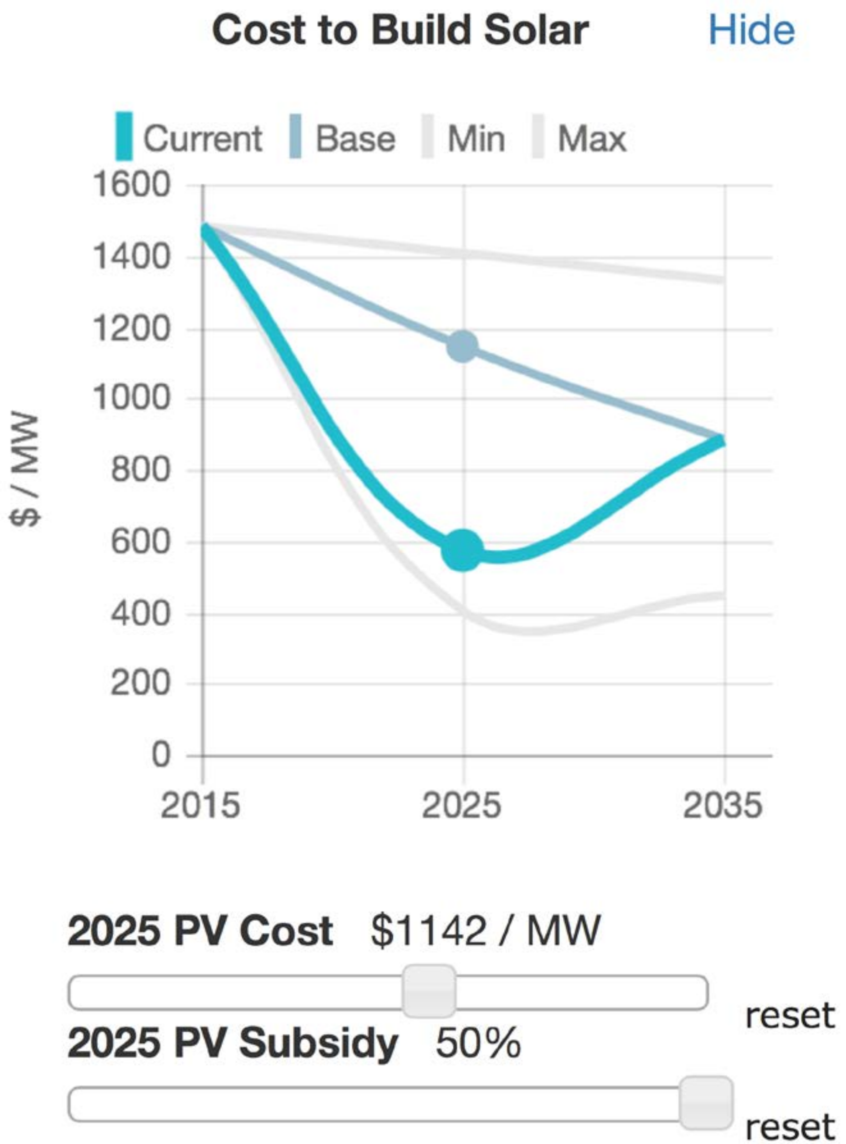
Other Key Inputs & Assumptions of Simulations in this Presentation

- Price elasticity of demand: -0.7 in 2015, -0.8 in 2025, -1 in 2035, where load responds to annual average price (based on H. Fell et al, *Int. Jrnl. of Indus. Org.* 33: 37-47, 2014)
- Grid and generator data are from 2011
- Nuclear fleet held constant: no additions, no retirements
- All dollar values are in real 2013 dollars
- Reported values are net present value in 2013. Discount rate of 2.5% real (~4.5% nominal) per year.

Try it on your device

[e4st.com/fp](e4st.com/fp)

Input Screens: Solar Build Cost

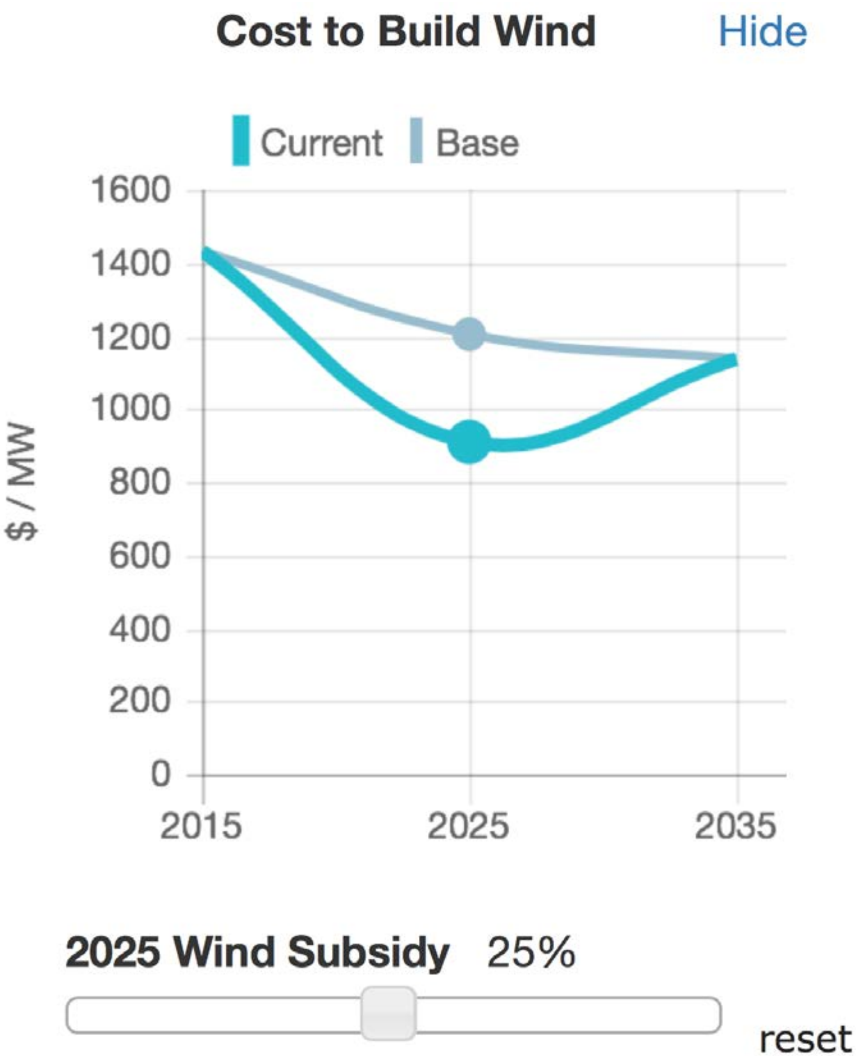


This screen allows the user to adjust both the capital cost of utility scale solar power and the 2025 subsidy level. The capital cost without subsidy can be adjusted by the top slider from the base case estimate shown in light blue.

The bottom slider selects the subsidy level in 2025 that is assumed to be in place well in advance of 2025 so that the system can respond by 2025. The darker blue line shows the net capital cost after subsidy.

The subsidy is removed by 2035. Note that rapid depreciation is incorporated into the capital cost without subsidy for all years.

Input Screens: Wind Build Cost



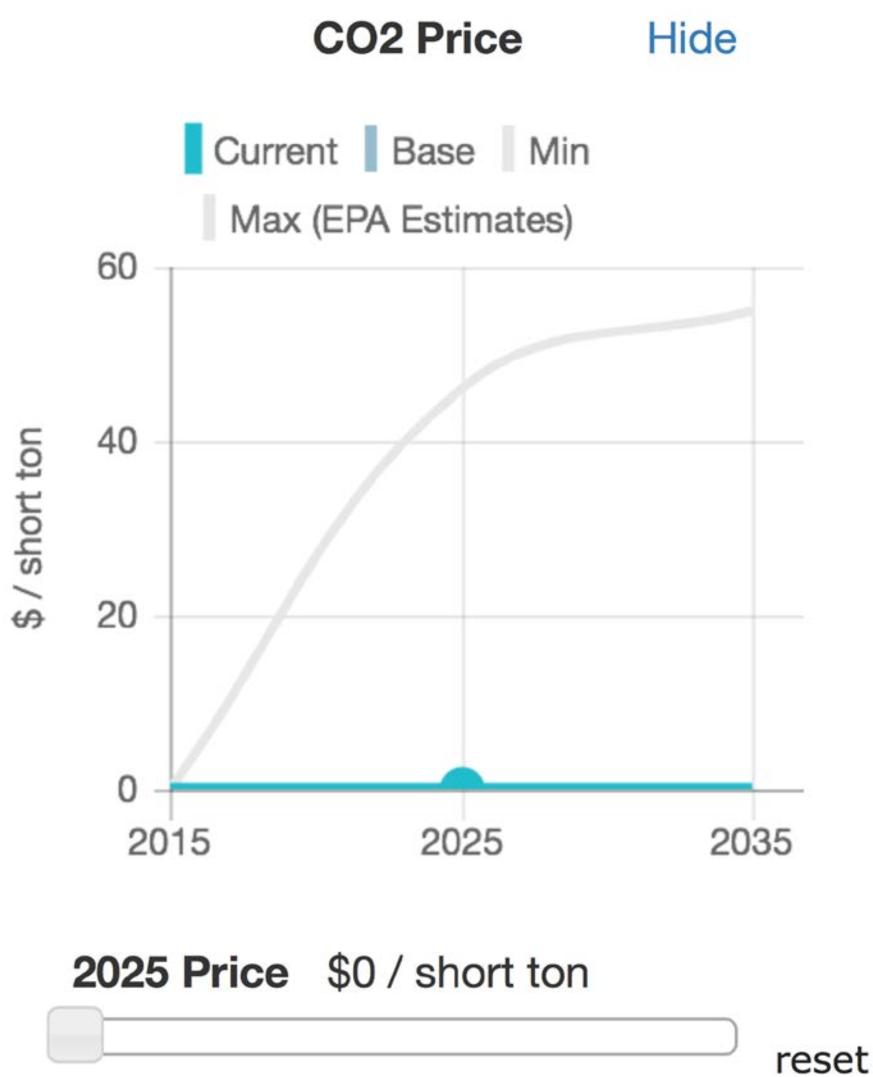
This screen allows the user to adjust the 2025 subsidy level for wind. The darker blue line shows the net capital cost after subsidy. The capital cost without subsidy is shown in light blue and corresponds to the base case.

The slider selects the subsidy level in 2025 that is assumed to be in place well in advance of 2025 so that the system can respond by 2025

The subsidy is removed by 2035. Note that rapid depreciation is incorporated into the capital cost without subsidy for all years.

Since wind is a more mature technology and less uncertain, the estimated capital cost is not user selectable.

Input Screens: CO2 Price



This screen allows the user to adjust the slider to set the 2025 price for CO2 emissions from power plants that determines the price trajectory shown.

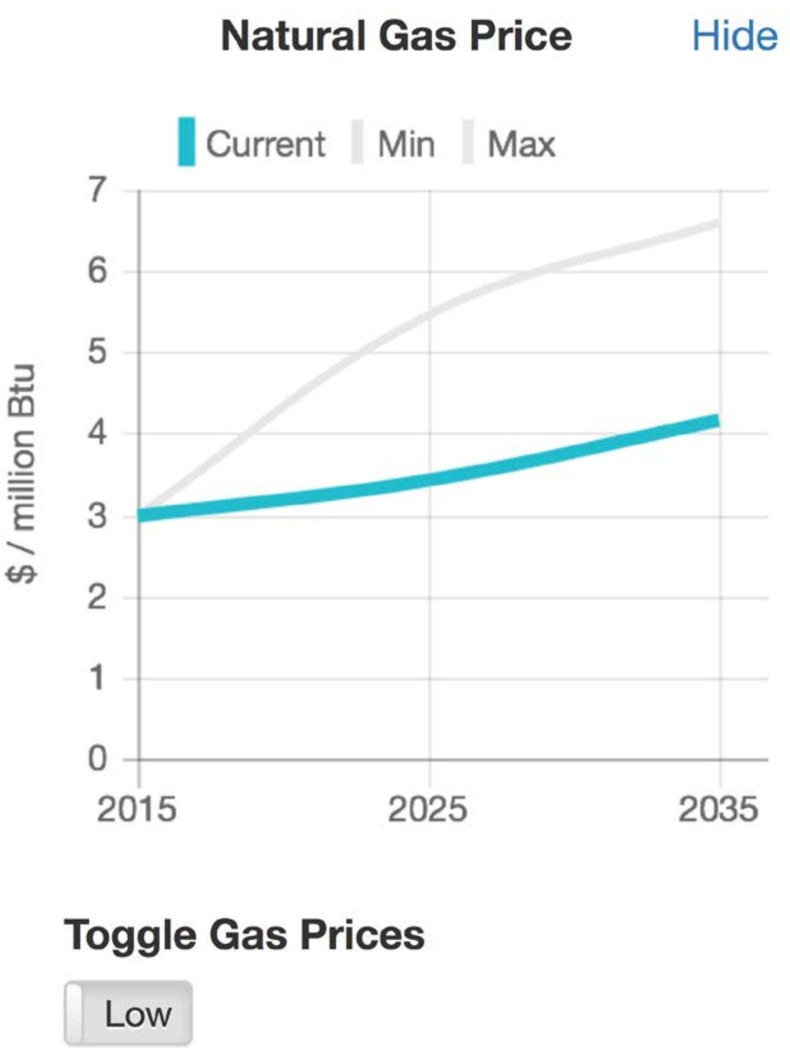
This price could be imposed either by a tax or by cap-and-trade.

The darker blue line shows the chosen price path.

The maximum value for the slider and path shown starts at a zero value for 2015 and corresponds to USEPA estimates of CO2 damages per short ton for 2025 and 2035.

The base case and minimum, assume that no CO2 price is charged to generators.

Input Screens: Natural Gas Price

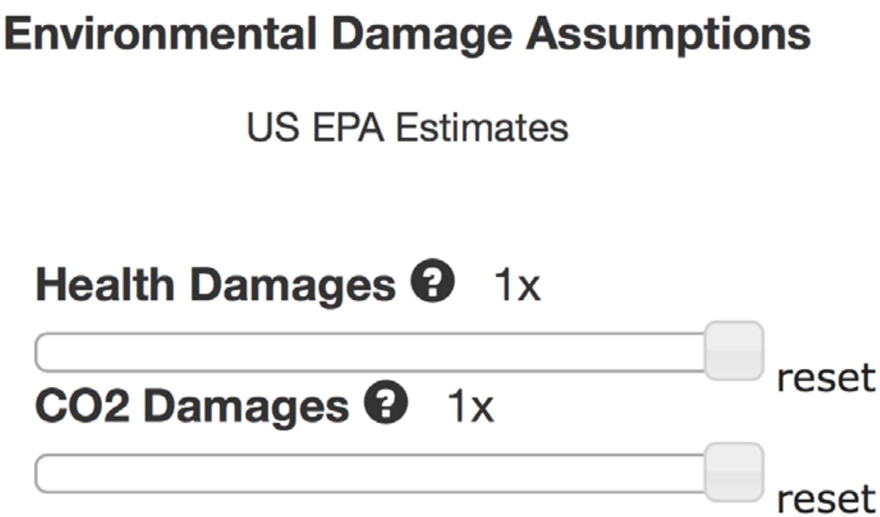


This screen allows the user to toggle between low and high projections for natural gas prices.

The darker blue line shows the chosen price path.

The base case is assumed to be the lower price path.

Input Screens: Environmental Damages



This screen allows the user to choose what fraction of USEPA estimates of environmental damage to use in calculating net benefits.

Since health damages are based on lives lost from exposure to fine particulates, the health damage fraction between 0X and 1X also proportionately affects lives lost.

CO_2 damages per short ton are also adjustable between 0X and 1X.

4b. Example Applications of the E4ST Fast Predictor

Fast Predictor Sample Results

Fast predictor results went on several slides here. Go to e4st.com/fp to make fast predictor results.

E4ST Fast Predictors Can Allow Anyone to Interactively Learn…

- The **effects and value of policies and investments** of all kinds, including
  - Environmental, technology, and demand response policies
  - Transmission, generation, and distributed energy investments
  - Reductions in the costs of technologies
- The effects of different kinds of **uncertainty**
  - How would a certain policy or investment perform under possible futures?
- Important principles of **good policy design**
  - Pricing emissions and advancing technologies can usually reduce emissions at lowest cost
  - Prices on emissions other than CO_2 greatly increase net benefits
  - Even with full emission pricing, complementary policies can reduce costs

5. Real Options Analysis of a New Line

Mao, Kasina, Shawhan, and Hobbs
of RFF, Hopkins, and RPI

Suitability of Model for Transmission Line Analysis

- Electrical model
- Close replication of actual locational prices
- Calculates total societal benefits
- Endogenous investment
- Can run many cases

Build line by 2025 or wait for uncertainty about CO2 price path and nuclear retirement to be resolved?

Line cost	$0 - $1.2B	$1.3B - $1.4B	$1.5B - $2.4B	Above
Expected profit positive if operational by 2025?	Yes	Yes	No	No
Better to wait until later to decide?	No	Yes	Yes	Yes*
		*Not profitable in any of the cases.		

Two More Observations from Transmission Line Analysis

We also analyze the net benefits to society

- Profitability does not necessarily align with societal net benefits, largely because of emission and health effects
- Difference in emission prices helps line profitability but tends to hurt societal benefits

6. Interaction of Regional Greenhouse Gas Initiative and NY Clean Energy Standard

Incremental benefits of more stringent RGGI ($M/yr in EI)

Potential change in RGGI caps (M short tons)-->	From 80 in '25, 80 in '35 to 70 in '25, 60 in '35	From 70 in '25, 60 in '35 to 60 in '25, 40 in '35
to Customers	-2362	-4000
to Congestion revenues	93	322
to Government revenue	1228	1888
to CO2 damage	838	1314
to NOX damage	491	496
to SO2 damage	1508	2461
to Producers	902	1515
Total	2697	3996

Assumes that NY wind+solar requirements are 10% in 2025, 20% in 2035.
If they were 15% in 2025 and 35% in 2035, then benefits would be about 63% of these.

NY average prices

NY wind+solar requirement (in '25/in '35)	RGGI stringency (in M short tons in '25 and '35): 80/80	70/60	60/40
10%/20%	61.62	62.38	63.91
15%/35%	60.16	60.73	62.07

7. Some Accomplishments in the Last Ten Months

Some Model & Documentation Improvements this Year

1. Added endogenous technology cost reductions
2. Added ability of load to respond to average annual price in addition to real-time price
3. Method for simulating rate-based emission limits
4. Added future Canadian hydro (important for US) after forging relationships with Canadian data experts
5. Generalized code to run on others’ computers with little set-up
6. Improved output processing code
7. Wrote dedicated documentation for external users
8. Developed means of others obtaining the Energy Visuals portion of our input data

E4ST Diffusion this Year

1. Major renewable energy broker **Altenex** has adopted
   a. For forecasting uncertainty in their renewables business
   b. Tried **all commercially available software**, concluded E4ST was better
   c. Worked better out of the box than some software costing $100,000s
   d. Purchased proprietary part of data from Energy Visuals
2. Resources for the Future has adopted
3. Microsoft considering use in renewable energy procurement decisions
4. Brookfield Renewable Energy Group evaluating E4ST for commercial use
4. DOE EPSA is funding Mexico extension
5. Bureau of Ocean Energy Management (BOEM) requested proposal to use
6. Two **consulting firms** has proposed to NYSERDA and BOEM to use E4ST
7. The **Economic Research Institute of the State Grid Company of China**
8. Mexican government has offered data in exchange for a Mexico extension

Presentations and Papers this Year

1. "The Engineering, Economic and Environmental Electricity Simulation Tool (E4ST): Description and an Illustration of its Capability and Use as a Planning/Policy Analysis Tool." *Proceedings of the 49th Annual Hawaii International Conference on System Sciences*, Computer Society Press, January 2016. Winner **best paper award** in the Electric Energy Systems track.
2. "Interplay of RGGI and Clean Energy Standards," Presentation to the Environmental Advisory Council of the NYISO. Troy, NY, May 6, 2016. (Shawhan)
3. EPA air office and NCEE staff
4. DOE Office of Electricity staff
5. DOE EPSA staff
6. Request for presentation at General Electric in Schenectady

Some Applications this Year

- Develop the first Fast Predictor
- Evaluate proposed transmission line under various circumstances, interaction w/ policies
- Real options analysis of transmission line
- Examine interaction of cap and trade programs with clean/renewable energy standards
- Examine effects of new hydro capacity
- Further modeling of the effects of real-time pricing


END