Project 2E

Mapping Energy Futures: The SuperOPF Planning Tool

Dan Shawhan, Biao Mao*, Zamiyad Dar*
(RfF and RPI*)
Bill Schulze, Dick Schuler, Ray Zimmerman, Jubo Yan* (Cornell)
Dan Tylavsky, Di Shi, Yingying Qi*
Yujia Zhu*
(ASU)
John Taber (FERC)
** Graduate Student*

OUTLINE

1. Simulation tool
2. Scope and inputs
3. Sample line investment analysis
4. Does real time pricing increase emissions?
5. Impacts of increased climate variability

1. The Simulation Tool

E4ST

ENGINEERING, ECONOMIC, AND ENVIRONMENTAL ELECTRICITY SIMULATION TOOL

E4ST.com

E4ST

HOME BACKGROUND TOOLS DATA RESULTS CONTACT US

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.

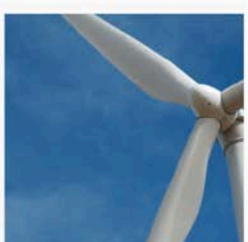
E4ST can be applied to detailed system models. Algorithms are included that simulate the economic operation of the power grid, in response to the model-user's projections of economic factors (e.g. fuel prices), government incentives or environmental regulations. Simultaneously, the algorithms project 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

E4ST

HOME BACKGROUND TOOLS DATA RESULTS CONTACT US

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:
Bill Schulze

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

E4ST.com

E4ST

HOME BACKGROUND TOOLS DATA RESULTS CONTACT US

E4 Simulation Tool

Simulation Tool

The E4 Simulation Tool (E4ST) software can be used to predict or optimize operation, investment, and retirement of generators under different policy, price, demand, and transmission investment circumstances. It can calculate the total costs and benefits, and can disaggregate them into those for customers, generators, system operators, the government, the public's health, and the global climate. The software is based on MATPOWER, giving it access to multiple state-of-the art free and commercial solvers.

The problem is structured as a set of DC optimal power flow sub-problems, one for each of a set of representative hours used to model the range of operating conditions encountered over the course of the planning horizon. The costs of each of the DC OPF sub-problems are weighted by the relative frequency of the corresponding representative hour and can include, in addition to fuel costs, various types of environmental costs, from permit costs for emissions of specific pollutants to aggregate damages from fine particulates. The sub-problems are then linked together into one large optimization problem by generator capacity constraints and costs. These linking costs include capital costs of existing generation as well as investment in capacity.

Users can access the interface of the E4ST by standard Matlab-style commands. For details, see the Usage section in the documentation that is bundled with the code in the downloadable files. Developers can add policies to the input data sets or develop additional features by creating subclasses that inherit from the included interface classes. The design separates the code and the input and output data into the root folder and subfolders named InputData and OutputData, respectively. It also includes a test class to allow the developer to test each class and function hour by hour.

Complete 3-Bus Model

The download below also contains a ready-to-use 3-bus model that contains all of the types of input data. Though E4ST can simulate models with thousands of buses, this user-modifiable 3-bus model is sufficient for testing the various features of E4ST.

Getting Started

To be able to run your own simulations using E4ST, you will need the following:

System Requirements:

- MATLAB
- MATPOWER version 5.0 or later
- High performance LP solver supported by MATPOWER, such as Gurobi or CPLEX.

CONTACT US

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

General Information:
Bill Schulze

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

E4ST

HOME BACKGROUND TOOLS DATA RESULTS CONTACT US

Network Reduction Toolbox

Graphics created using PowerWorld with Energy Visuals data.

The network reduction toolbox performs modified Ward reduction. Two input files are required by the toolbox: the (original) full power-flow base-case model in MATPOWER format and a user-defined list of the external bus indices, i.e., buses to be eliminated.

The output of the toolbox includes three files: a reduced power-flow model file in MATPOWER format; a file providing the new generator-to-bus assignment, which lists to which buses the external generators are moved; and a branch circuit number file indicating which branches are equivalent lines.

For details about the input and output, please refer to the help files of the functions. Every function in the toolbox has a help file that describes its purpose and the format of the input and the output data.

1. **Components**
   The package includes two components:
   a) The reduction software, including all subroutines to generate the reduced model.
   b) An example file which can be used to demonstrating network reduction on a 9 bus system. To run the example, please open and run the file `Example_9bus.m`. This file generates a reduced model of a 9 bus system by eliminating 3 buses. A more detailed description of the reduction process and output files are included in the file.
2. **Installation**
   To install the toolbox please download the package and add the path to the directory to which the toolbox was downloaded.
3. **How to use**
   The basic steps to using this software are:
   a) Read in the input full model data using the `feval` function (a MATLAB built-in function).*
   b) Generate a list of external bus indices.
   c) Call subroutine `MPReduction` to perform the reduction and generate the output files listed above.

CONTACT US

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

General Information:
Bill Schulze

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

E4ST.com

E4ST — HOME BACKGROUND TOOLS DATA RESULTS CONTACT

Generator Data & Toolbox

Toolbox

The generator data toolbox is a set of programs that can be used to combine US data from different sources, combine US and Canadian data, provide imputation for missing data, place generators on a transmission network model, and aggregate similar generators. Users working with data different from that used by the E4ST team, for any part of the world, may still find parts of this code to be useful.

Power grid simulation modeling that includes costs and emissions requires several types of data about the generators on the system. The US federal government collects and publishes a considerable amount of data about generators, but those data are in multiple datasets published by the EIA and the EPA.

Several factors make it difficult to match up those datasets. First, the datasets number the generators differently. Second, sometimes one dataset reports a pair of generators as one, while the other dataset does not. Third, the EPA dataset omits some small generators and all non-emitting generators, and includes some generators that are not in the EIA dataset (perhaps because they are for self-generation but not for supplying the grid).

As part of the generator data toolbox, we have developed methods for identifying which data in each dataset corresponds to which generator in the EIA's annual basic dataset of currently operating generation units, for imputing missing values, and for adding this additional information to that basic dataset.

Generator Data

The result of applying parts of the generator data toolbox to a set of databases from the EIA and EPA is a database with the capacities, heat rates, emission rates, and various other characteristics of the generators in the contiguous United States that supply the wholesale electricity markets.

The data file available here is the 2011 Energy Information Administration (EIA) generation unit dataset (the GeneratorsY2011.xls dataset available at http://www.eia.gov/electricity/data/eia860/index.html) augmented with additional columns from files obtained from the EIA and EPA, as described in the documentation that accompanies the data in the link below. The documentation accompanying the generator data and the associated toolbox summarize how the E4ST team produced this dataset.

CONTACT US

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

General Information:
Bill Schulze

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

E4ST — HOME BACKGROUND TOOLS DATA RESULTS CONTACT US

Results & Publications

Daniel L. Shawhan, John T. Taber, Di Shi, Ray D. Zimmerman, Jubo Yan, Charles M. Marquet, Yingying Qi, Biao Mao, Richard E. Schuler, William D. Schulze, and Daniel J. Tylavsky, "Does a Detailed Model of the Electricity Grid Matter? Estimating the Impacts of the Regional Greenhouse Gas Initiative," Resource and Energy Economics, Volume 36 Issue 1, January 2014, pp. 191–207. http://dx.doi.org/10.1016/j.reseneeco.2013.11.015.

J. Taber, D. Shawhan, R. Zimmerman, C. Marquet, M. Zhang, W. Schulze, R. Schuler, S. Whitley, "Mapping Energy Futures Using The SuperOPF Planning Tool: An Integrated Engineering, Economic and Environmental Model." Proceedings of the 46th Annual Hawaii International Conference on System Sciences, Computer Society Press, January 2013, pages 2020-2029. http://doi.ieeecomputersociety.org/10.1109/HICSS.2013.391. HICSS minitrack peer review information at http://www.hicss.org/components.htm.

D. Shi, D. Shawhan, N. Li, D. J. Tylavsky, J. Taber, R. Zimmerman, "Optimal Generation Investment Planning: Part 1: Network Equivalents," North American Power Symposium 2012 (electronic journal), September 2012, pgs. 6. http://dx.doi.org/10.1109/NAPS.2012.6336375

N. Li, D. Shi, D. Shawhan, D. J. Tylavsky, J. Taber, R. Zimmerman, "Optimal Generation Investment Planning: Part 2: Application to the ERCOT System," North American Power Symposium 2012 (electronic journal), September 2012, pgs. 6. http://dx.doi.org/10.1109/NAPS.2012.6336374.

P. Sood, D. J. Tylavsky, Y. Qi, "Improved DC Network Models for Contingency Analysis," North American Power Symposium 2014, Pullman Washington, Sep. 2014, pgs. 6.

Y. Zhu, D. J. Tylavsky, "An Optimization-Based Generator Placement Strategy in Network Reduction," North American Power Symposium 2014, Pullman Washington, Sep. 2014, pgs. 6.

Y. Qi, D. Shi, D. J. Tylavsky, "Impact of Assumptions on DC Power Flow Accuracy," North American Power Symposium 2012, Champaign Illinois, Sep. 2012, pgs. 6.

D. Shi, D. J. Tylavsky, "An Improved Bus Aggregation Technique for Generating Network Equivalents," 2012 IEEE Power Engineering Society General Meeting, San Diego, CA, Jul. 2012, pgs. 8.

C. E. Murillo-Sánchez, R. D. Zimmerman, C. L. Anderson and R. J. Thomas, "A Stochastic, Contingency-Based Security-Constrained Optimal Power Flow for the Procurement of Energy and Distributed Reserve", Decision Support Systems, Volume 56, December 2013, Pages 1-10, ISSN 0167-9236. http://dx.doi.org/10.1016/j.dss.2013.04.006

R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "MATPOWER: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education," Power Systems, IEEE Transactions on, vol. 26, no. 1, pp. 12-19, Feb. 2011. http://dx.doi.org/10.1109/TPWRS.2010.2051168

CONTACT US

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

General Information:
Bill Schulze

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

Uses of E4 Simulation Tool

Project effects of

- Policies
- Investments
- Fuel prices
- Technology cost changes
- 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 Strengths of the E4 Simulation Tool

- Demand function at each node (and growth)
- Can be used with model of any grid.
- Will be open-source: transparent, publicly available & modifiable.

The Simulation Tool

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

subject to

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

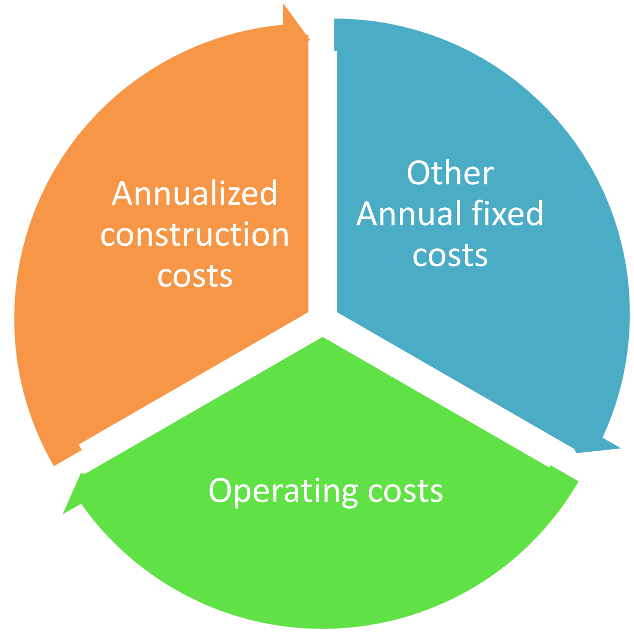
$$p_{ijk} \geq \alpha_i^{\min} (p_{ij}^0 + I_{ij} - R_{ij})$$

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

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

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

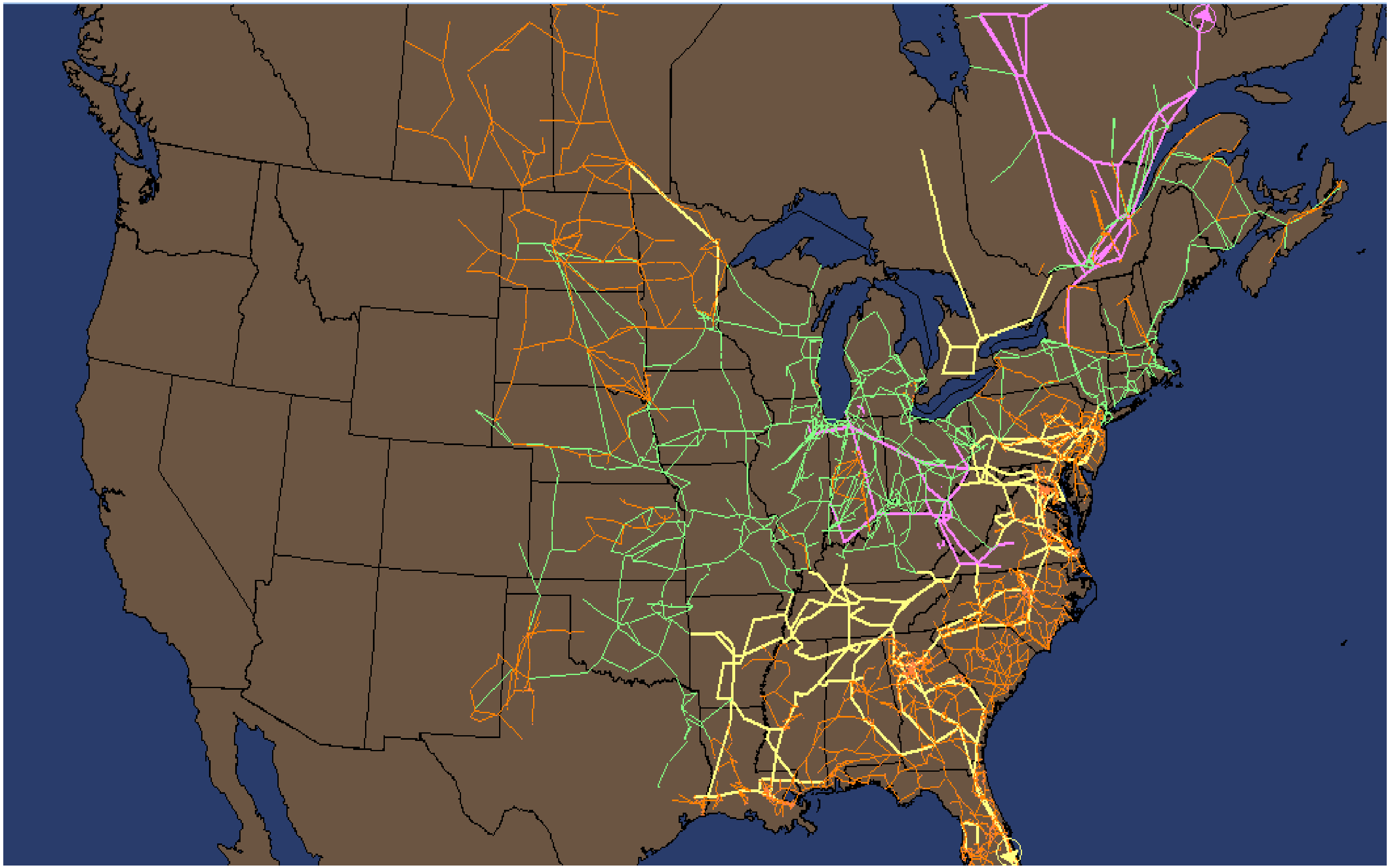
It finds the combination of plant construction, retirement, and operation that maximizes **consumer benefits** minus



subject to meeting load and respecting network constraints

2. SCOPE AND INPUTS

System in Simulation: Eastern 74% of US & Canadian Demand



5222 nodes, 8190 generators, 14225 branches

Input Summary

- 2011 grid and generators. Using eastern model. (Also have western & Texas models.)
- 2013 fuel prices and demand
- We assume that the SO2 & NOX cap-and-trade programs are slack.

Generator and Demand Data Overview

- Generators: Capacities, marginal costs, fixed costs, emission rates, locations, smokestack heights combined from 12 sources. EIA, EPA, and Energy Visuals Inc.
- 38 representative hours represent joint distribution of demand, generator availability, wind, and solar
- Own-price elasticity of demand = -0.2
- Use EIA estimates of generator costs

Hourly Wind & Solar Data by Node

- Using a year of hourly data from thousands of sites, we have close approximations of what wind farm output and PV output was, or would have been, in each hour at each suitable node
- Same year as our hourly load data

Improvements Found Necessary This Year for Proper Line Analysis

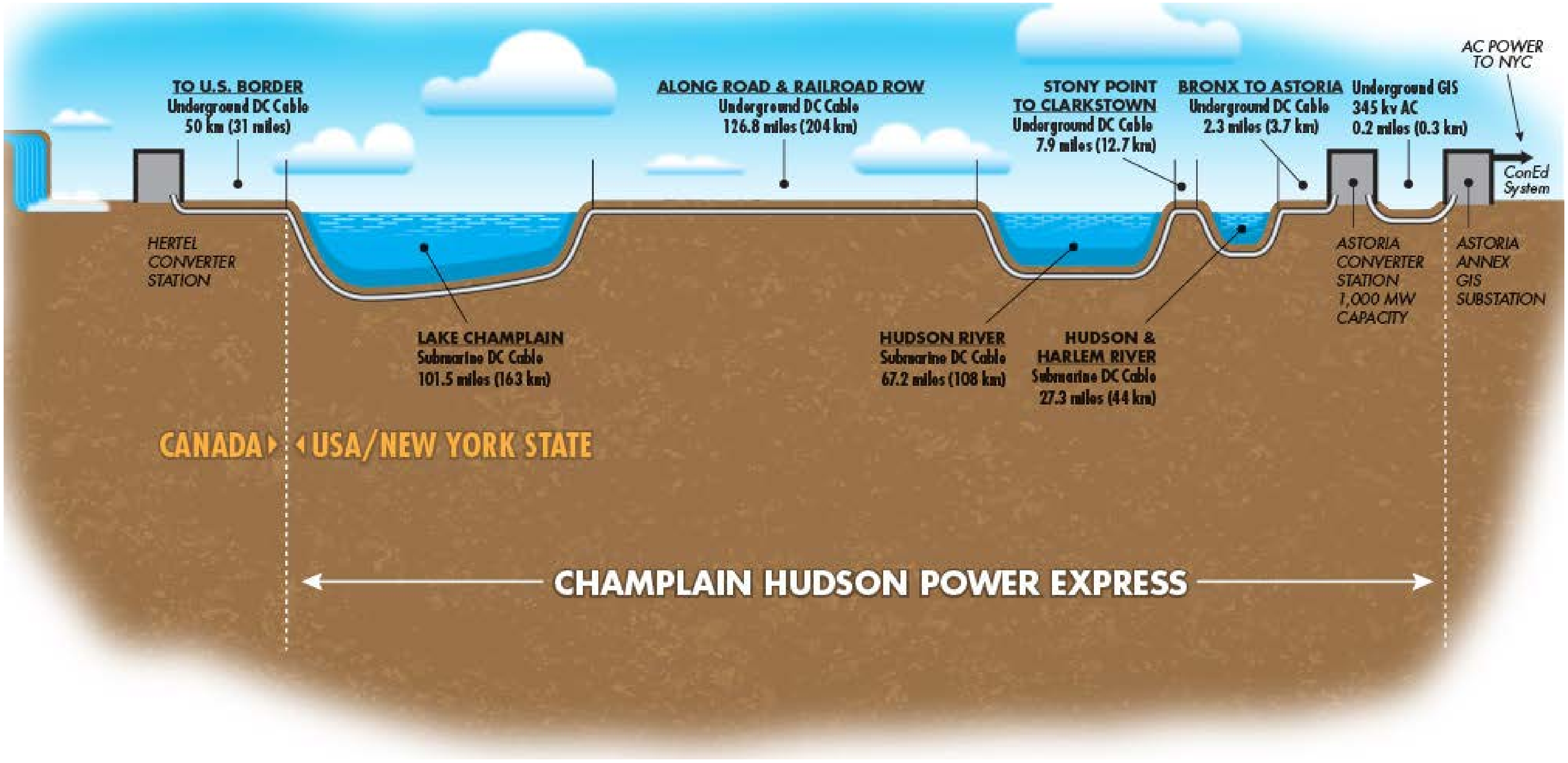
- Add endogenous hydro dispatch
- Add cap and trade capability
- Update geographic NG price differences within NY and in New England
- Vary construction costs by location (using NEMS assumptions)
- Correct demands and capacities in Canada
- Correct water amounts by province

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**

3. INVESTMENT EVALUATION SAMPLE RESULTS

Economic Feasibility of a New Line: The Champlain-Hudson Power Express

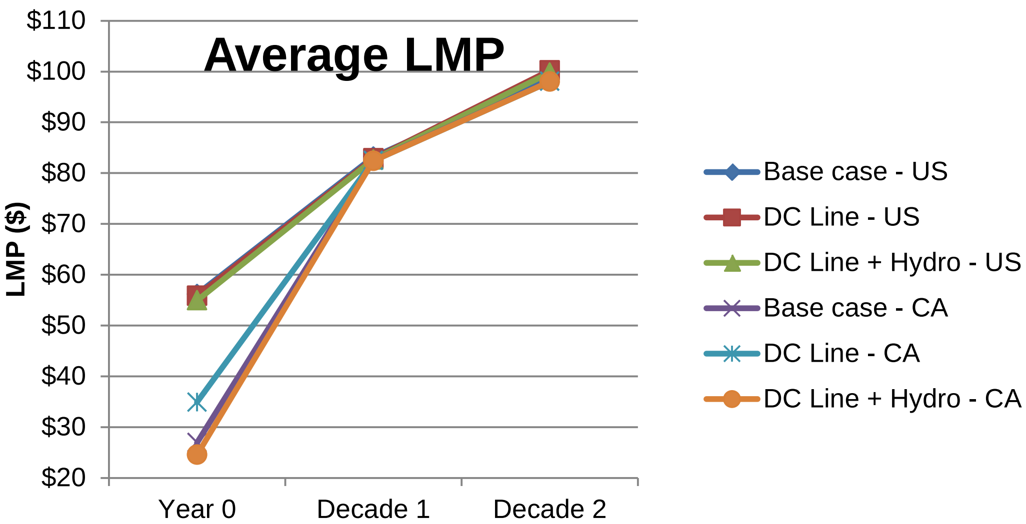


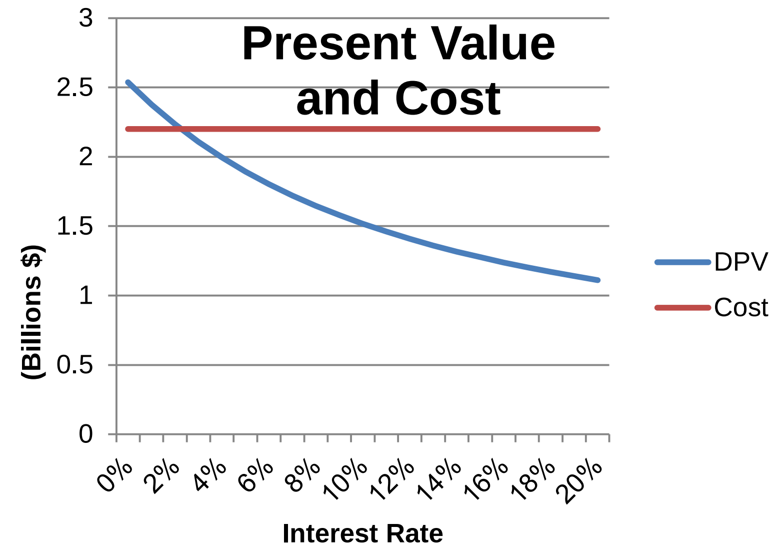
The Champlain-Hudson Power Express

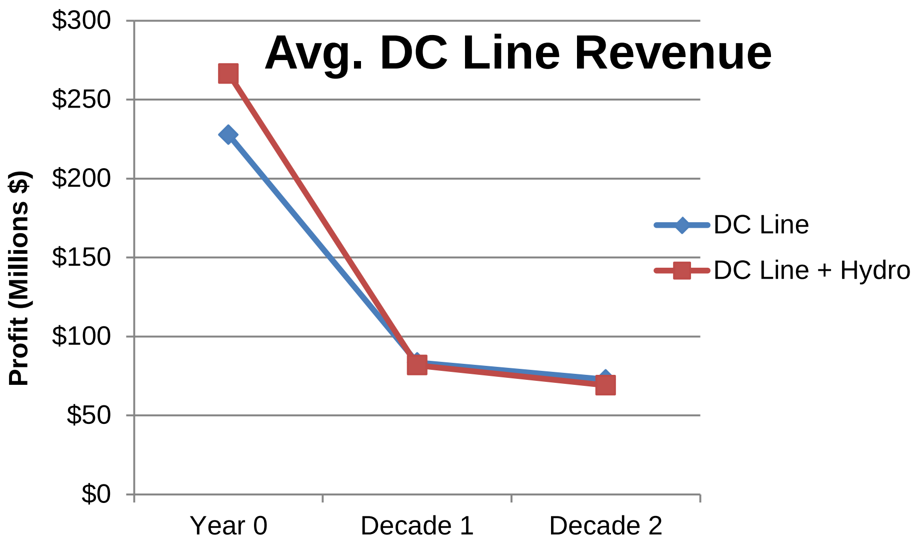
- The line starts at the Hertel Substation in LaPrairie, Canada, where a converter will be built to allow power to flow from the Hydro Quebec system through a 1000 MW 320-kV DC line to New York City.
- A 36 mile section of underground line will be built to the US border to connect to a 333 mile line that will be constructed from the the US border to Astoria where a second converter will be constructed to provide power to the Astoria Annex GIS Substation.
- The line will be placed under Lake Champlain and under the Hudson River for most of the distance.
- The cost is about 2.2 Billion Dollars.
- Assume Clean Power Plan in place and similar limits in Canada.

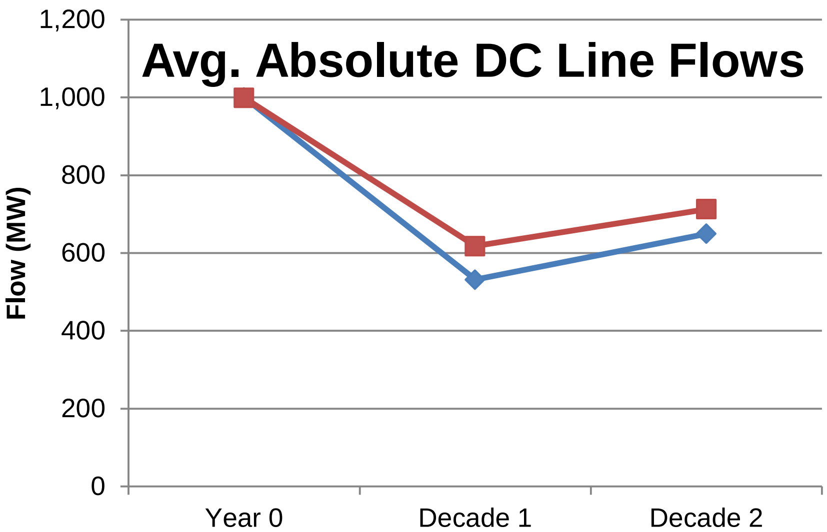
The Champlain-Hudson Power Express

with CO_2 price in US & Canada, SO_2 and NOX prices of 0, load growth, low hydro construction, and low NG prices in parts of US from fracking







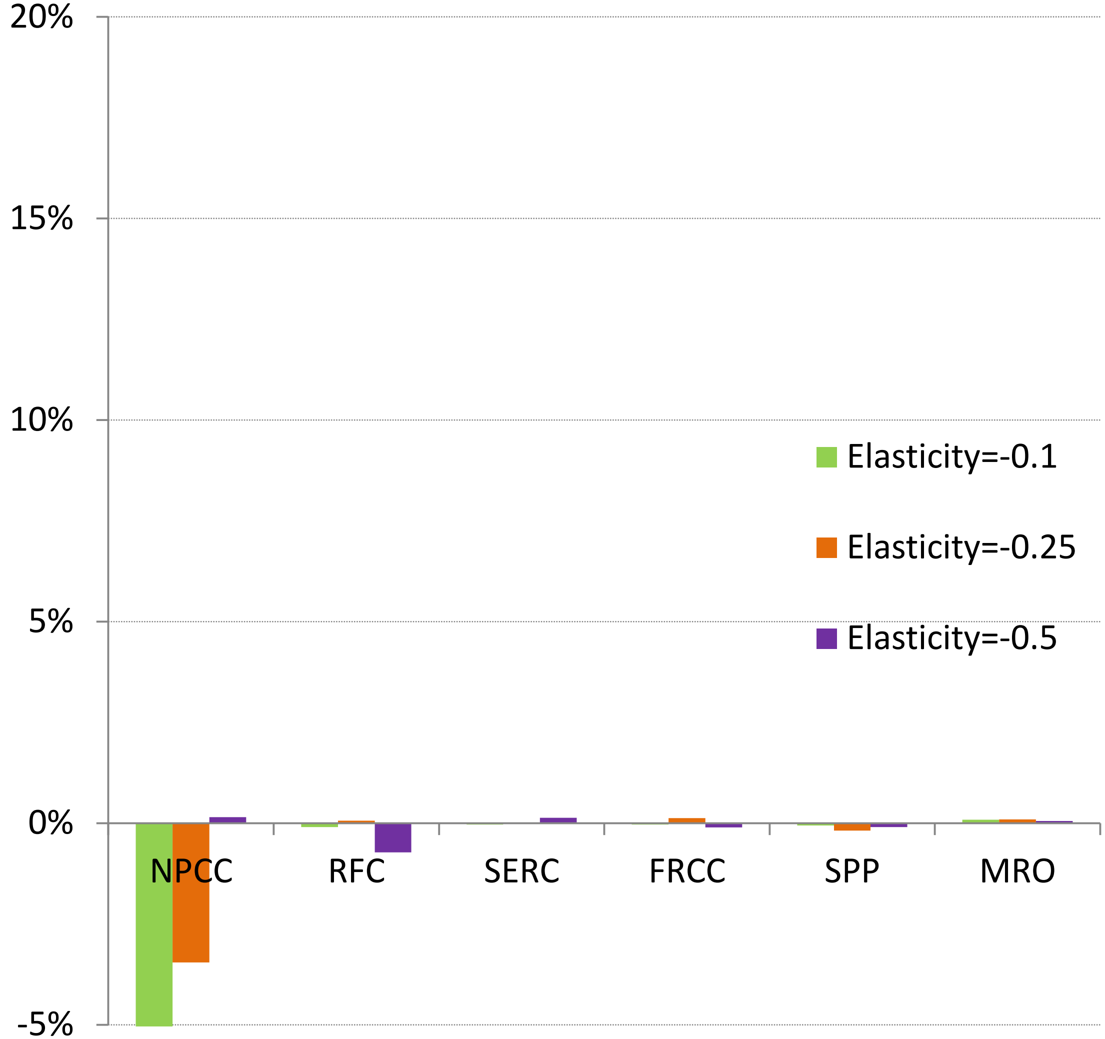


4. EFFECTS OF REAL-TIME PRICING ON EMISSIONS

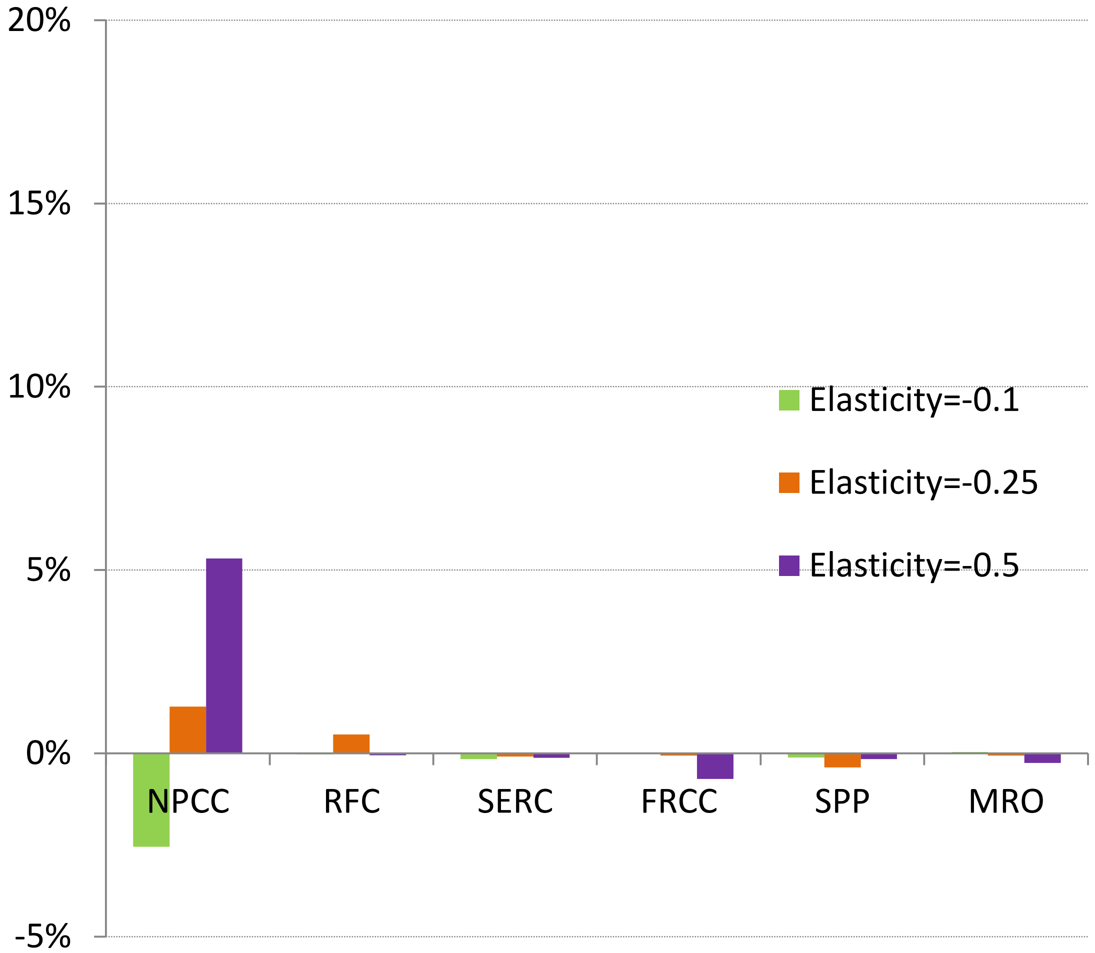
Does real time pricing increase emissions?

- We test what would happen if the current system were switched to real time pricing (RTP) from fixed prices.
- We represent RTP as a change in the hourly elasticity of demand from 0 to -0.1, -0.25, or -0.5.
- Real time pricing experiments suggest that -0.1 is the most realistic of these.
- We make the conservative assumption that RTP does not change load. (Though in fact experiments suggest that it is likely to reduce load.)

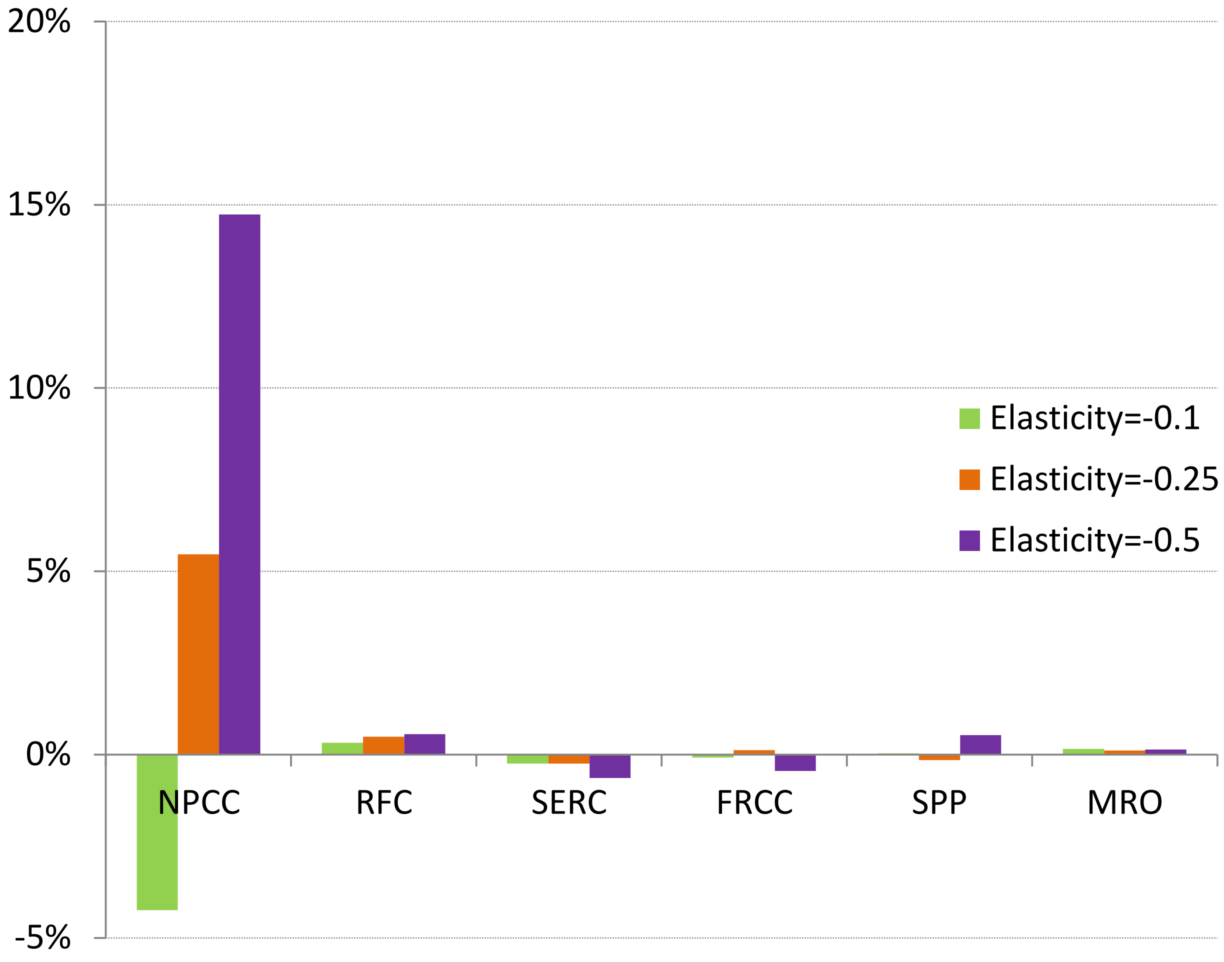
CO_2 Emission Changes



NO_x Emission Changes



SO_2 Emission Changes



Summary

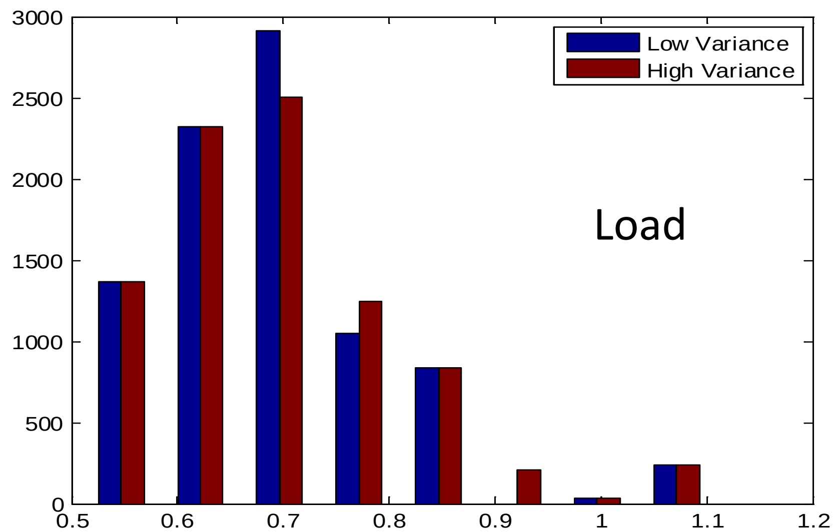
- The most realistic hourly demand elasticity (-0.1) generally leads to no significant change or else lower emissions
- NO_x and SO_2 emissions increase with more elastic demand because more coal is used in NPCC

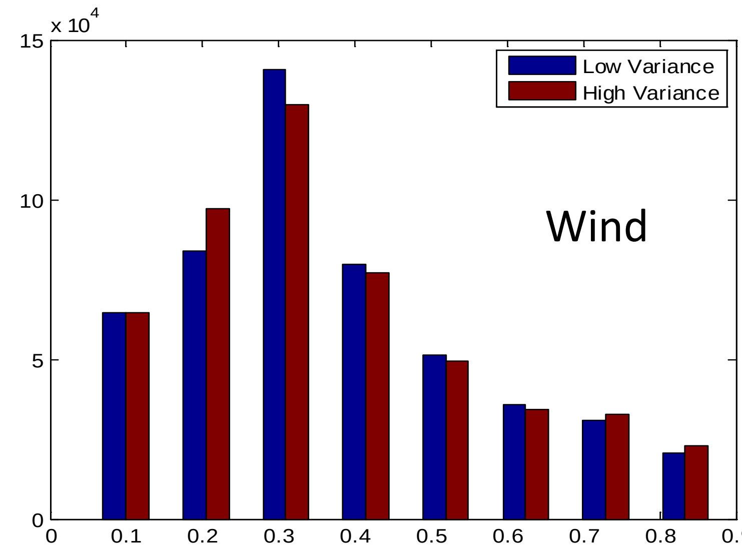
5. IMPACTS OF INCREASED CLIMATE VARIABILITY

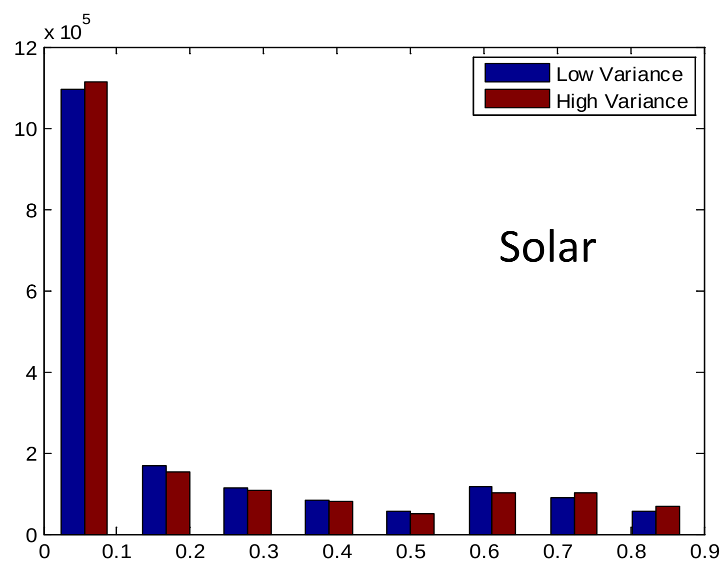
Increased Climate Variability

- This is a methodological study to examine how to model increased variability in loads, and wind and solar availability factors as well as drought using the E4ST
- Wind and solar availability factors range from 0 to 1.
- First, we fitted a beta distribution to each nodal availability factor across the 38 hour types and increased the variance by 5% in the fitted distribution.
- We then used this to shift the availability factor in each hour, in a way that retained covariance among hour types.
- Also did this for nodal load, where we used a fitted log normal distribution to calculate the load shifts for each of the 38 hour types that would result in a 5% increase in variance.

Increased Climate Variability:
Example Hour Type Distributions for the MRO

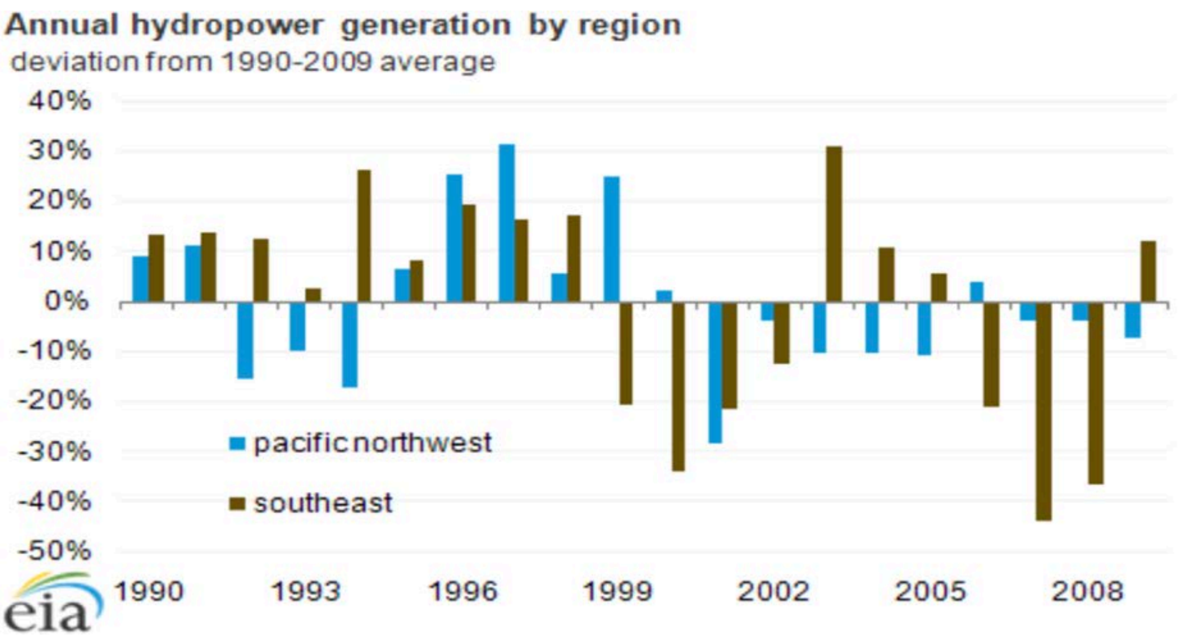






Increased Climate Variability: Drought

- Going back 1000 years or more there have been many extreme droughts especially in the West
  - Some are predicting a Mega Drought for the Western US
- Recently the Southeast has experienced drought as well
  - The chart below shows about a 30% probability of a 30% shortfall over twenty years



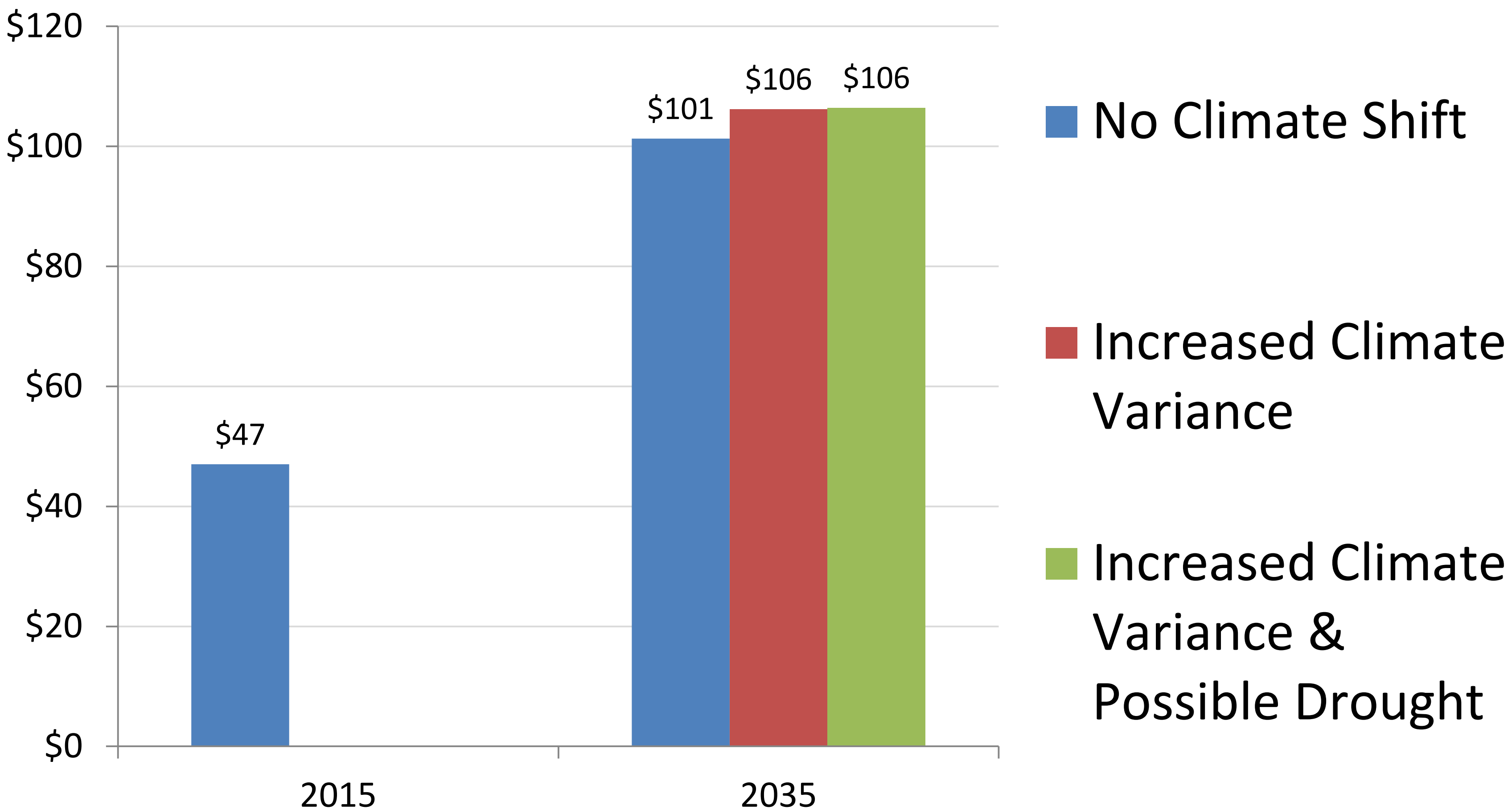
Increased Climate Variability: E4ST Model

Examine two years:

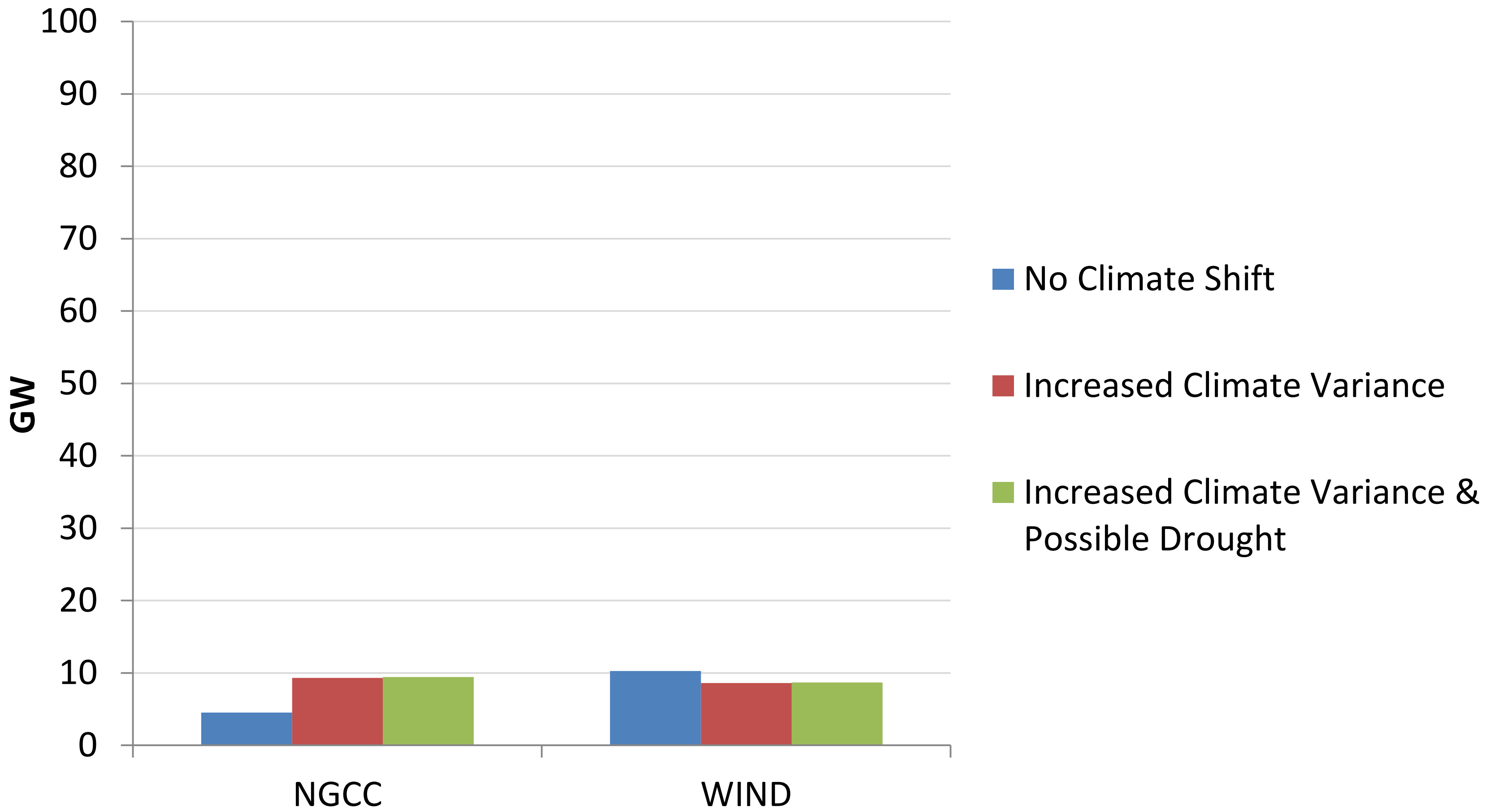
1. 2015 base year with no change in climate
2. 2035 with
   a. no change in climate, or
   b. increased climate (load, wind, solar) variance only, or
   c. increased climate variance and 30% probability of drought (76 hour types)

In all of these cases, in 2035, we cap total (US + Canadian) CO_2 emissions 25% below those of 2015.

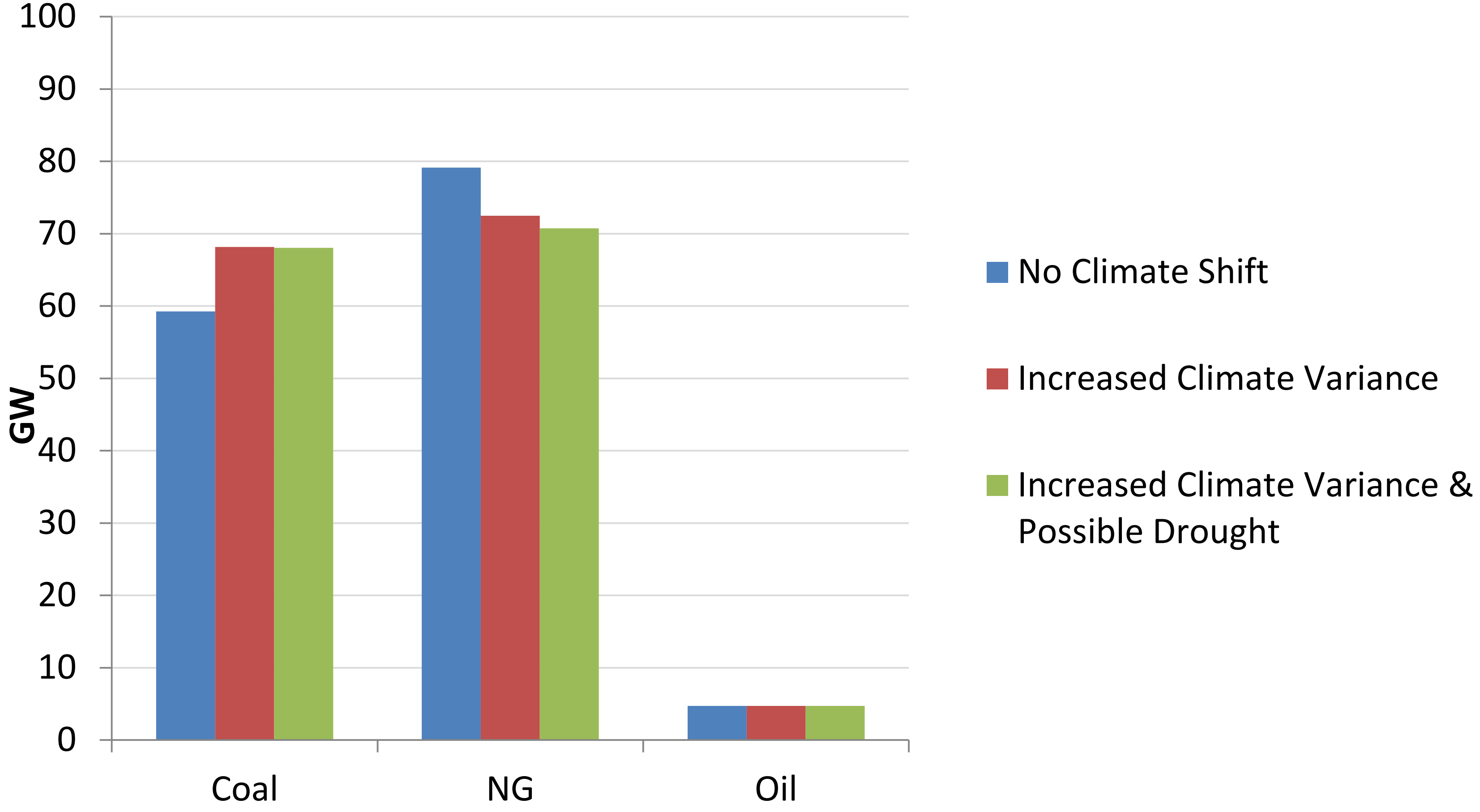
Average LMPs of SERC



Investment in SERC



Retirement in SERC



Climate Variability Results

- Clean Power Plan and higher natural gas prices drive LMPs up by 2035 in all cases
- Results in substantial retirement of old gas generation and coal
- SERC and EI results similar for LMP, retirement and investment in 2035
- Increasing variance of load, wind, and solar causes a decrease in retirements of old gas and an increase in investment in combined cycle gas but a decrease in wind investment
- Drought only slightly magnifies these trends

ACCOMPLISHMENTS IN THE LAST 12 MONTHS

Model Improvements this Year

1. Added endogenous dispatch of hydropower, and data necessary for it
2. Added cap-and-trade simulation capability
3. Added RPS simulation capability
4. Improved demand functions
5. Completely rewrote the set-up and results processing code, with improved efficiency, clarity, and documentation
6. Expanded automatic and semi-automatic output recording and reporting
7. Wrote code to handle large batches of simulations
8. Investigated and pursued computer options for running large batches of simulations

Data Improvements this Year

1. Corrected loads and hydro energy constraints (incorrect in original source data)
2. Updated various inputs including regional natural gas price differences in the northeast (changed from 2011 because of fracking)
3. Varied construction and fixed costs by location in the northeast (using NEMS assumptions)
4. Developed methods and inputs for simulating real-time pricing
5. Developed methods and inputs for representing increased weather variability

Validation this Year

1. From-scratch testing of E4ST simulation code
2. Extensively tested set-up code
3. Debugged additions and modifications
4. Compared model's predictions of locational marginal prices with actual

Outreach this Year

1. Further developed website files and text, for posting
2. Presented at HICSS, NYS Econ Ass'n, Ass'n of Env & Rsc Economists, and Society for BCA conferences
3. Presented to NYISO planning staff, NYSERDA staff, and NYISO Environmental Advisory Committee
4. Scheduled upcoming presentation to EIPC (tomorrow)
5. Met with top Mexican government officials and researchers about creating Mexican E4ST. Ongoing.
6. Met with Canadian utility, industry, NGO, and government officials about E4ST uses. Ongoing.
7. Met with DOE EPSA and State Department officials about E4ST uses and other topics. Ongoing.
8. Made plans with North American Natural Gas Model developers to link E4ST with that model in the future
9. Submitted paper to HICSS on predicting profitability of transmission line. Review in progress.

Applications this Year

- "Stochastically Optimized, Carbon-Reducing Dispatch of Storage, Generation, and Controllable Loads." IEEE Transactions on Power Systems, Vol. 30, Issue 2 (March 2015), pp. 1064–1075.
- Completed draft of "Predicting the Profitability of Energy Storage Using Recent Price Data: A Method and an Approach to Testing Such Methods." Expect to submit in August 2015 to IEEE Transactions on Power Systems.
- Analysis of effects of real-time pricing of electricity
- Simulations for real-options and conventional analyses of a proposed transmission line
- Analysis of increased climate variability