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Multi-stage stochastic optimization of a simple energy system

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http://temoaproject.org

Tools for Energy Model Optimization and Analysis (Temoa)

Goals:

Repeatable Analysis
- Data and code stored in a publicly accessible web repository
- A version control system

Rigorous treatment of uncertainty
- Framework designed to operate in a high performance computing environment

Flexibility
- Programming environment with links to linear, mixed integer, and non-linear solvers
- Drawn on rich existing open source ecosystem

The TEMOA Model

A **technology rich model with perfect foresight**, similar to the TIMES model generator.

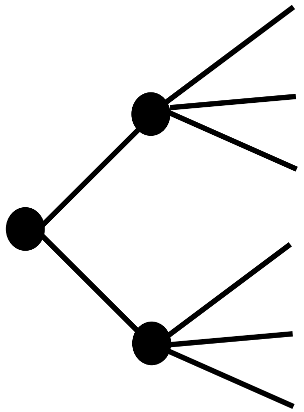
- Flexible time slicing by season and time-of-day
- Variable length model time periods
- Technology vintaging
- Separate technology loan periods and lifetimes
- Global and technology-specific discount rates
- Capacity determined by commodity flows at the timeslice level

Stochastic Optimization

Decision-makers need to make choices before uncertainty is resolved → requires an “act then learn” approach

Need to make short-term choices that hedge against future risk

→ Sequential decision-making process that allows recourse



Stochastic optimization

- Build a scenario tree
- Assign probabilities to future outcomes
- Optimize over all possibilities

Stochastic optimization with PySP

Python-based Stochastic Programming (PySP) is part of the Common Optimization Python Repository (Coopr) package, developed at Sandia National Lab.

To perform stochastic optimization, specify a Pyomo reference model and a scenario tree

PySP offers two options:

1. **`runef`**: builds and solves the extensive form of the model.
   "Curse of dimensionality" → memory problems
2. **`runph`**: builds and solves using a scenario-based decomposition solver (i.e., "Progressive Hedging) based on Rockafellar and Wets (1991).
   Can be implemented in a compute cluster environment; more complex scenario trees possible.

R.T. Rockafellar and R. J-B. Wets. Scenarios and policy aggregation in optimization under uncertainty. *Mathematics of Operations Research*, pages 119–147, 1991.

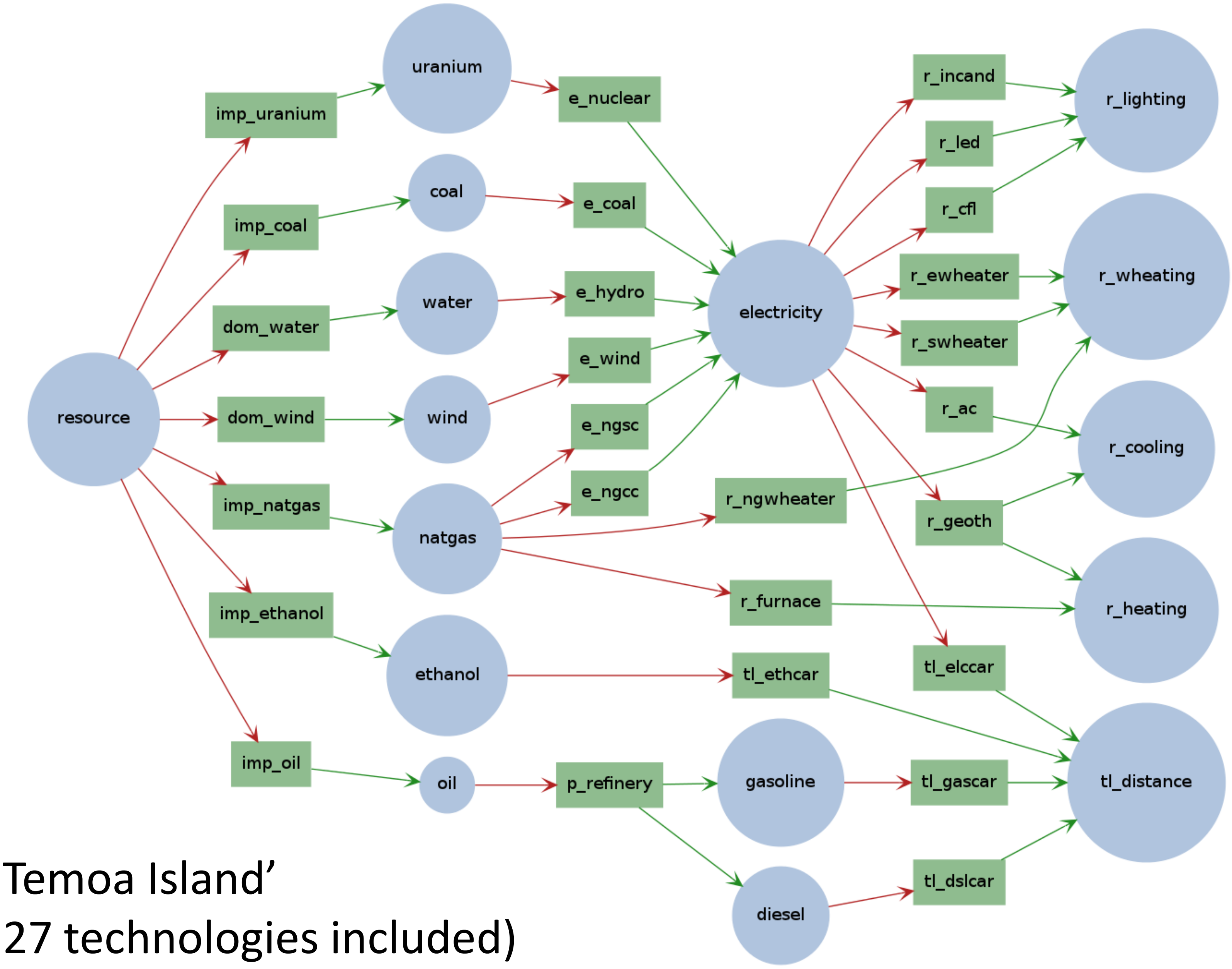
Thought experiment

Suppose that historical coal, oil, and natural gas prices are used to characterize future fuel price uncertainty (conditional probabilities and growth rates)

How might a centralized planner hedge their bets over the next 15 years if exposed to this historical price risk over the next 40 years?

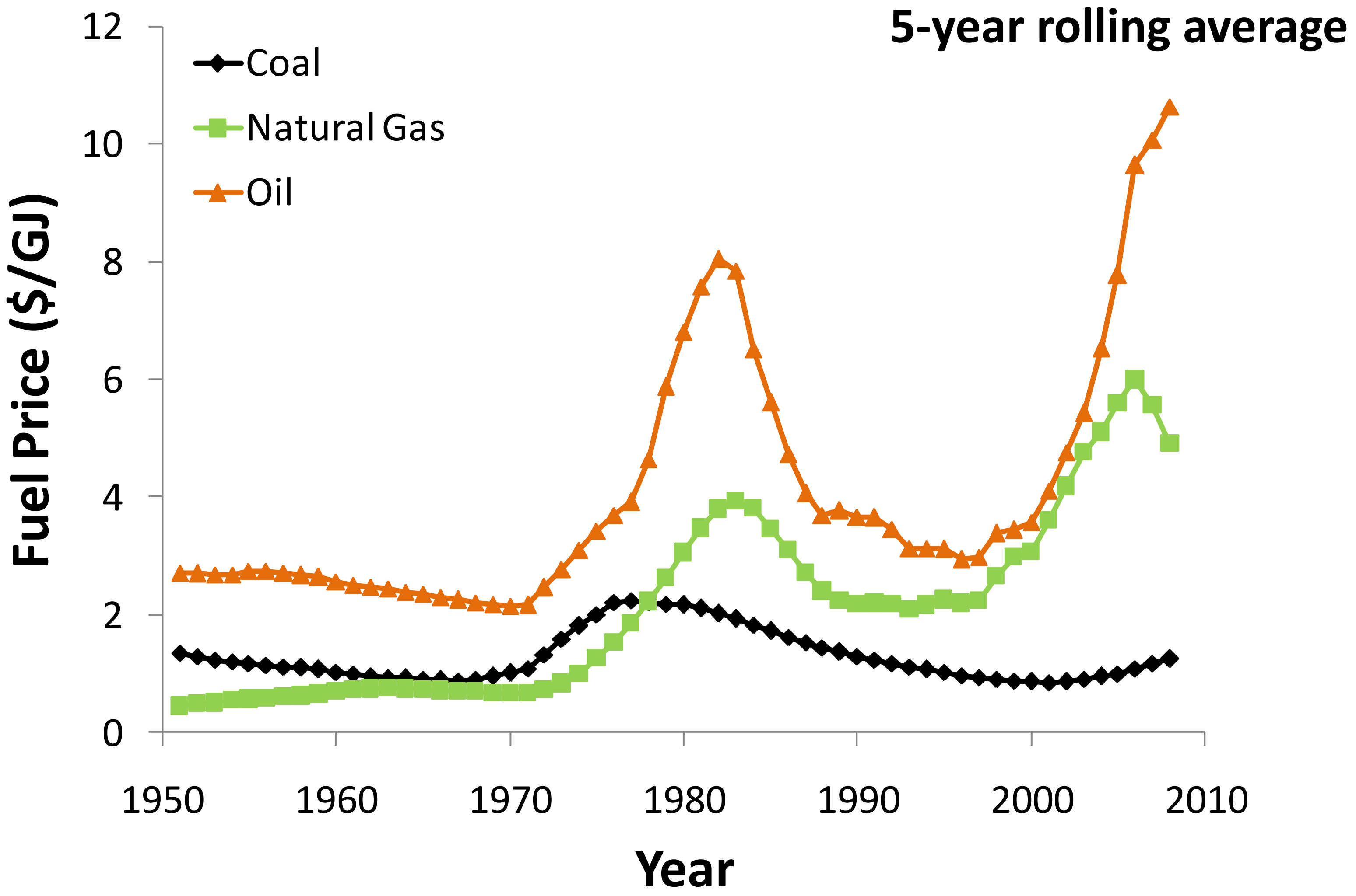
Utilize a simple system with some key technologies to exercise the modeling framework

A stochastic application with ‘Temoa Island’



‘Temoa Island’
(27 technologies included)

Stochastic parameters



Historical data drawn from the U.S. EIA *Annual Energy Review 2011*

Source: http://www.eia.gov/totalenergy/data/annual/

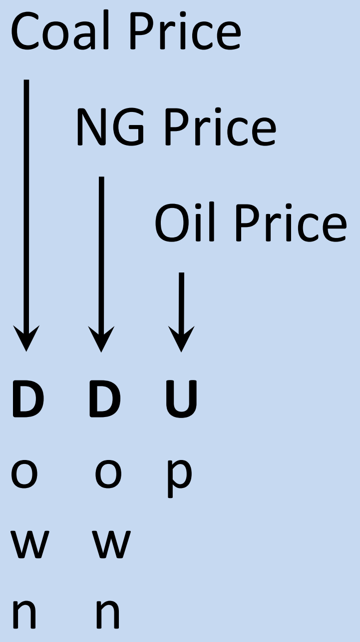
Create Event Tree Using a Markov Chain

1. To define event tree branches, characterize **joint** fuel price outcomes from one period to the next as moving “Up” (U) or “Down” (D)

2. Using the rolling average data, calculate the joint probability and growth rates from one period to the next

3. Calculate the conditional joint probabilities and growth rates based on results from each pair of successive periods

Example:



Coal Price

NG Price

Oil Price

D D U
o o p
w w
n n

The Resultant Contingency Table

Coal
NG
Oil

Probabilities:

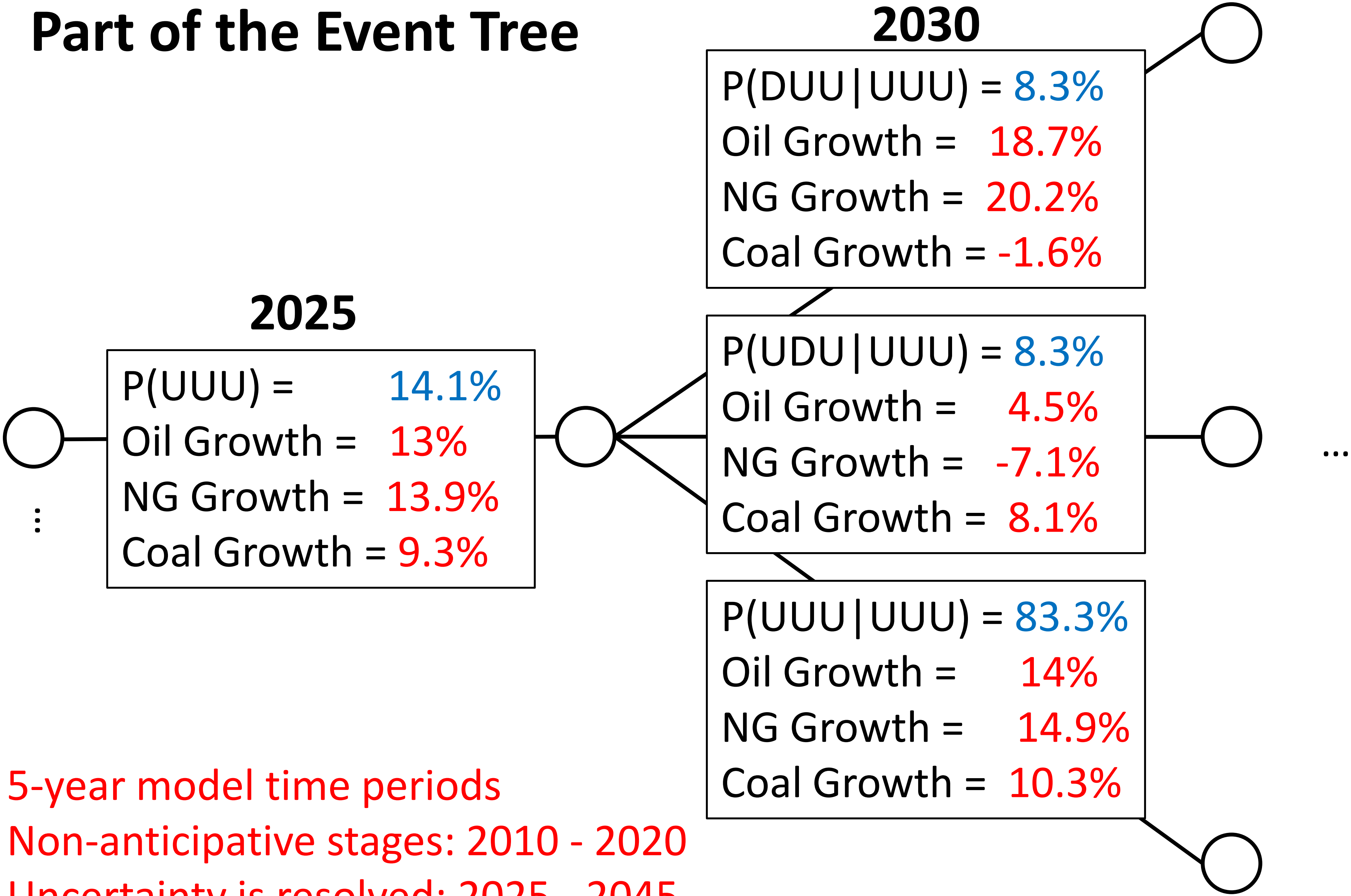
TO

FROM

	DDD	DDU	DUD	DUU	UDD	UDU	UUD	UUU
DDD	61.5%	7.7%	7.7%	15.4%	7.7%			
DDU	100%							
DUD	33.3%		58.3%	8.3%				
DUU			21.4%	71.4%				7.1%
UDD					66.7%			33.3%
UDU						100%		
UUD								
UUU				8.3%		8.3%		83.3%

Historical data drawn from the U.S. EIA *Annual Energy Review 2011*
Source: http://www.eia.gov/totalenergy/data/annual/

Part of the Event Tree



2025

P(UUU) = 14.1%
Oil Growth = 13%
NG Growth = 13.9%
Coal Growth = 9.3%

2030

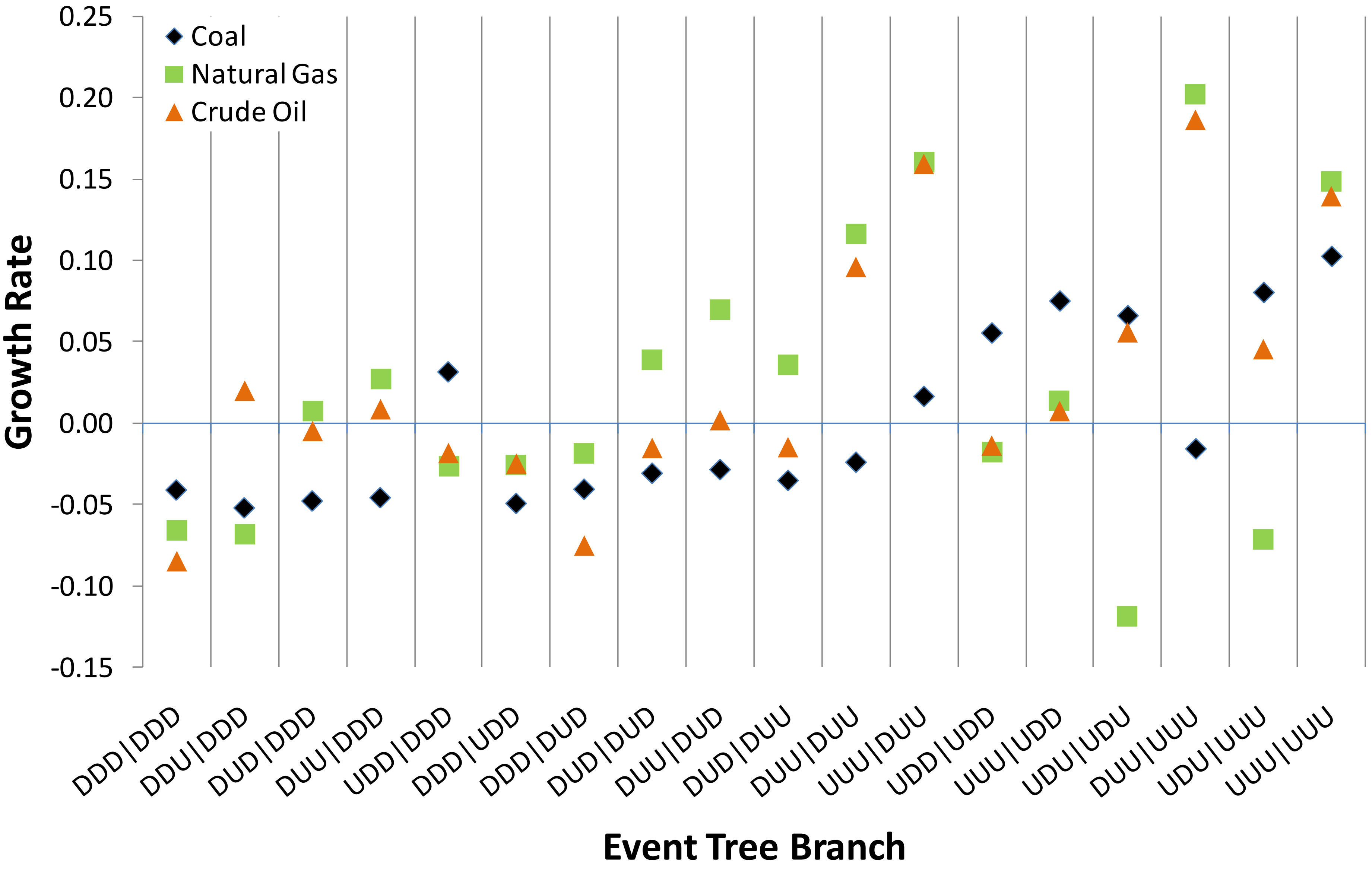
P(DUU|UUU) = 8.3%
Oil Growth = 18.7%
NG Growth = 20.2%
Coal Growth = -1.6%

P(UDU|UUU) = 8.3%
Oil Growth = 4.5%
NG Growth = -7.1%
Coal Growth = 8.1%

P(UUU|UUU) = 83.3%
Oil Growth = 14%
NG Growth = 14.9%
Coal Growth = 10.3%

5-year model time periods
Non-anticipative stages: 2010 - 2020
Uncertainty is resolved: 2025 - 2045
Resulted in a total of 433 scenarios

Branch-specific growth rates



Solve statistics

Solved the extensive form using `runef`

Raw LP

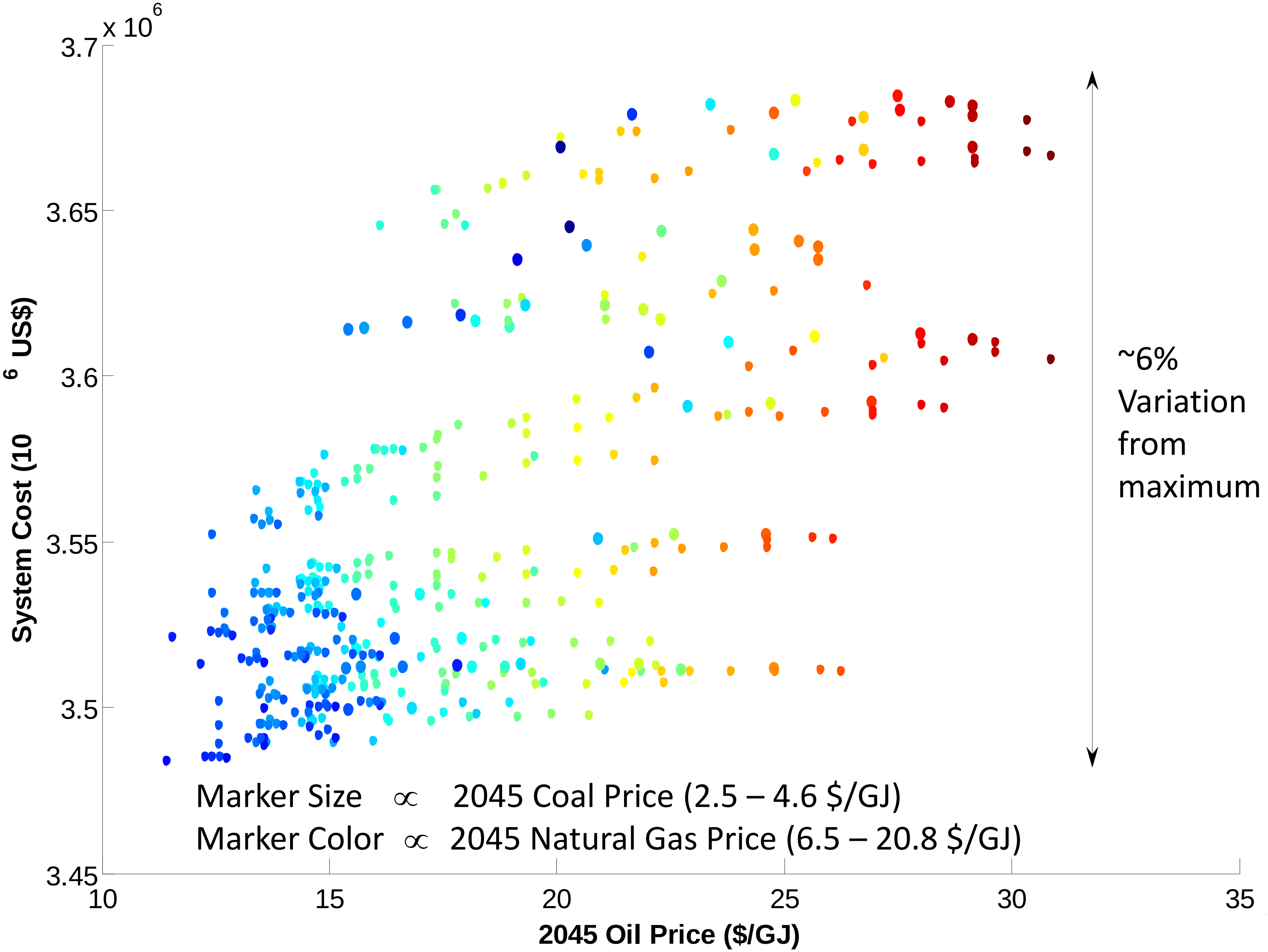
Variables: 5,543,208
Constraints: 7,740,537
Nonzeros: 19,721,671

Presolved LP

Constraints: 914,322
Variables: 257,821
Nonzeros: 2,643,819

It took CPLEX 51,547.88 seconds (14.3 hours) and 709,884 iterations to solve.

Total System Cost versus Oil Price

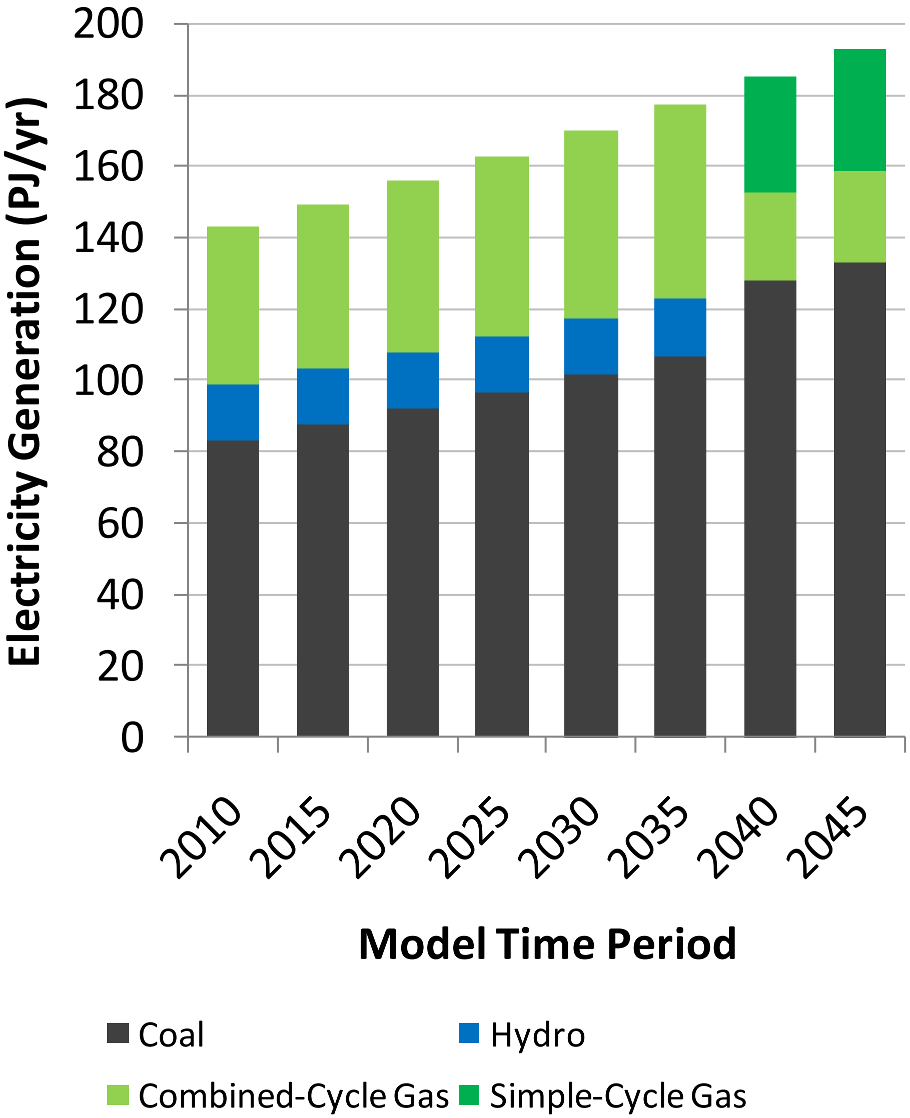


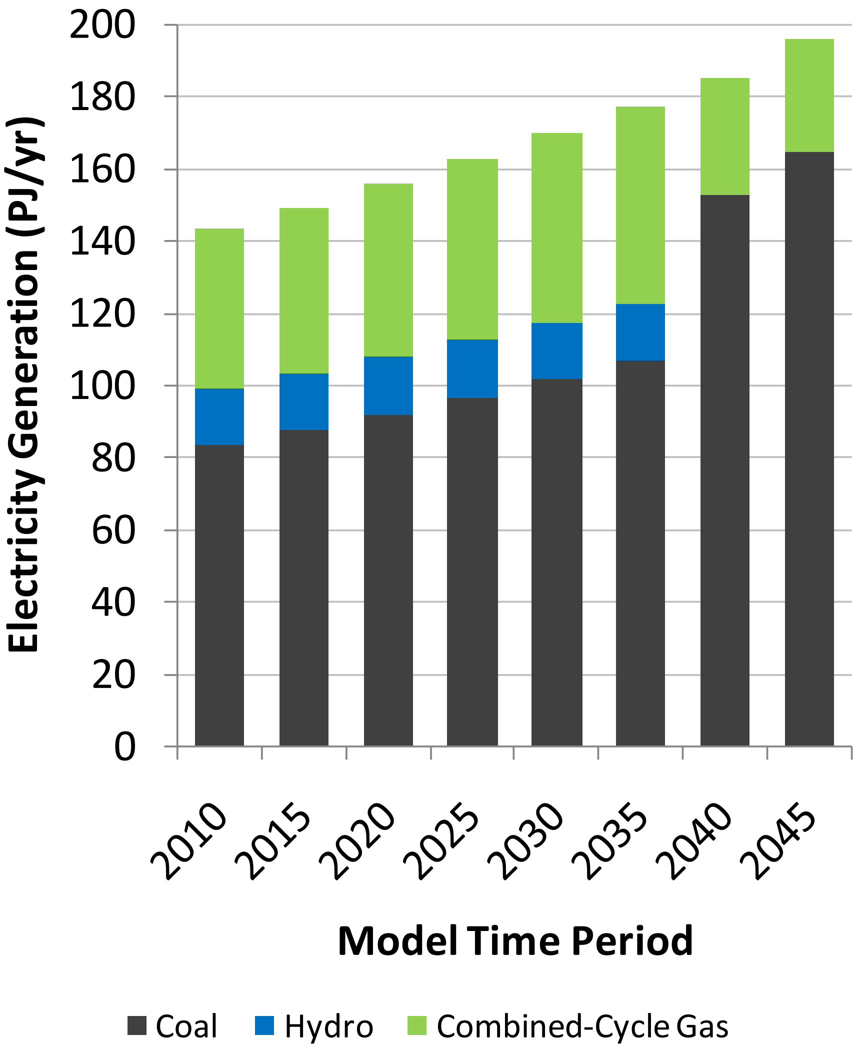
~6% Variation from maximum

Marker Size ∝ 2045 Coal Price (2.5 – 4.6 $/GJ)

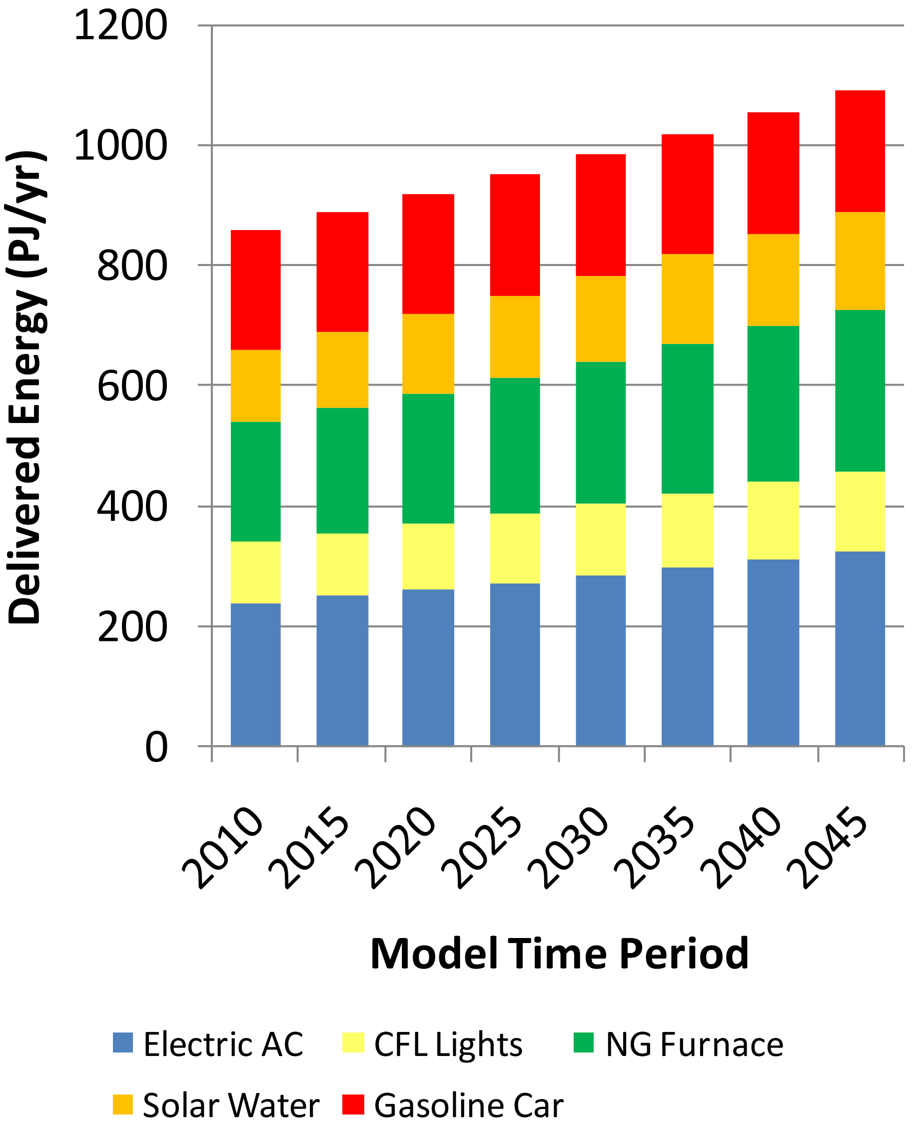
Marker Color ∝ 2045 Natural Gas Price (6.5 – 20.8 $/GJ)

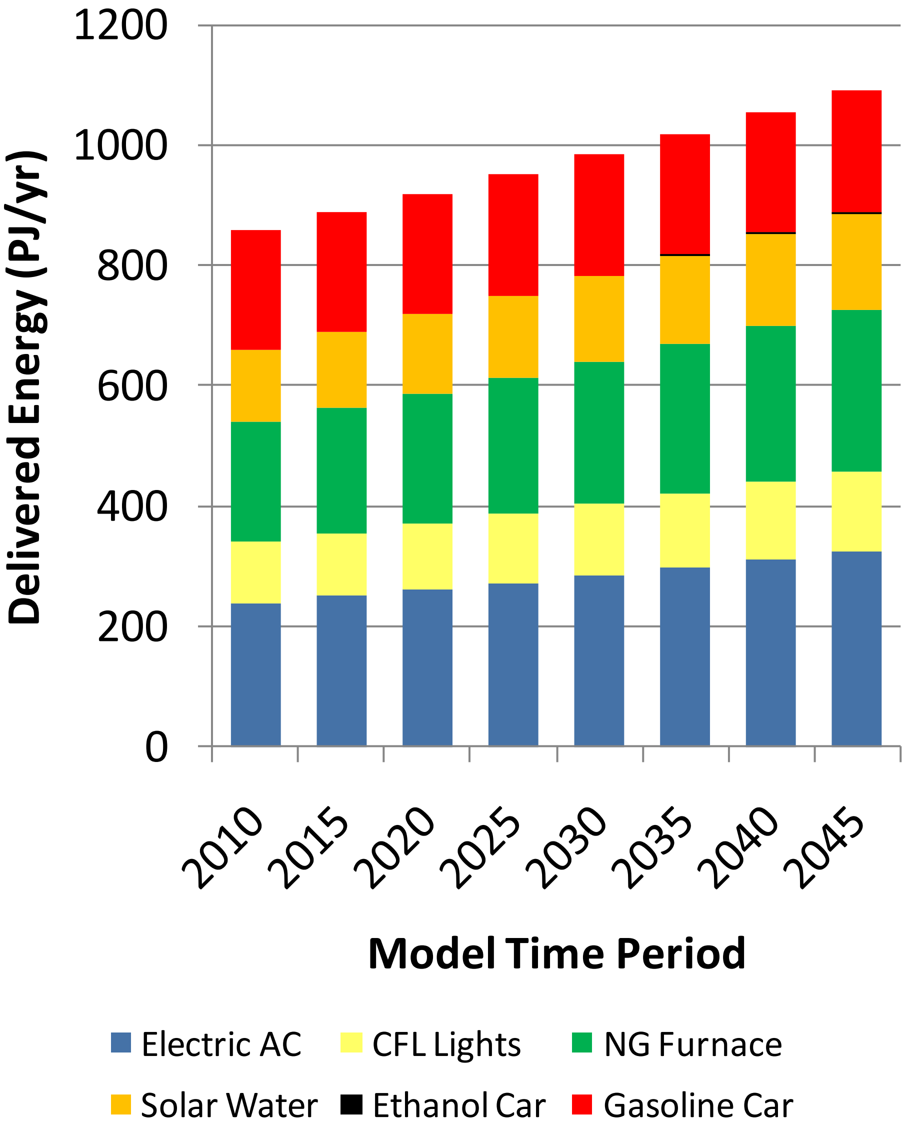
Activity Results: Lowest / Highest Cost Scenario



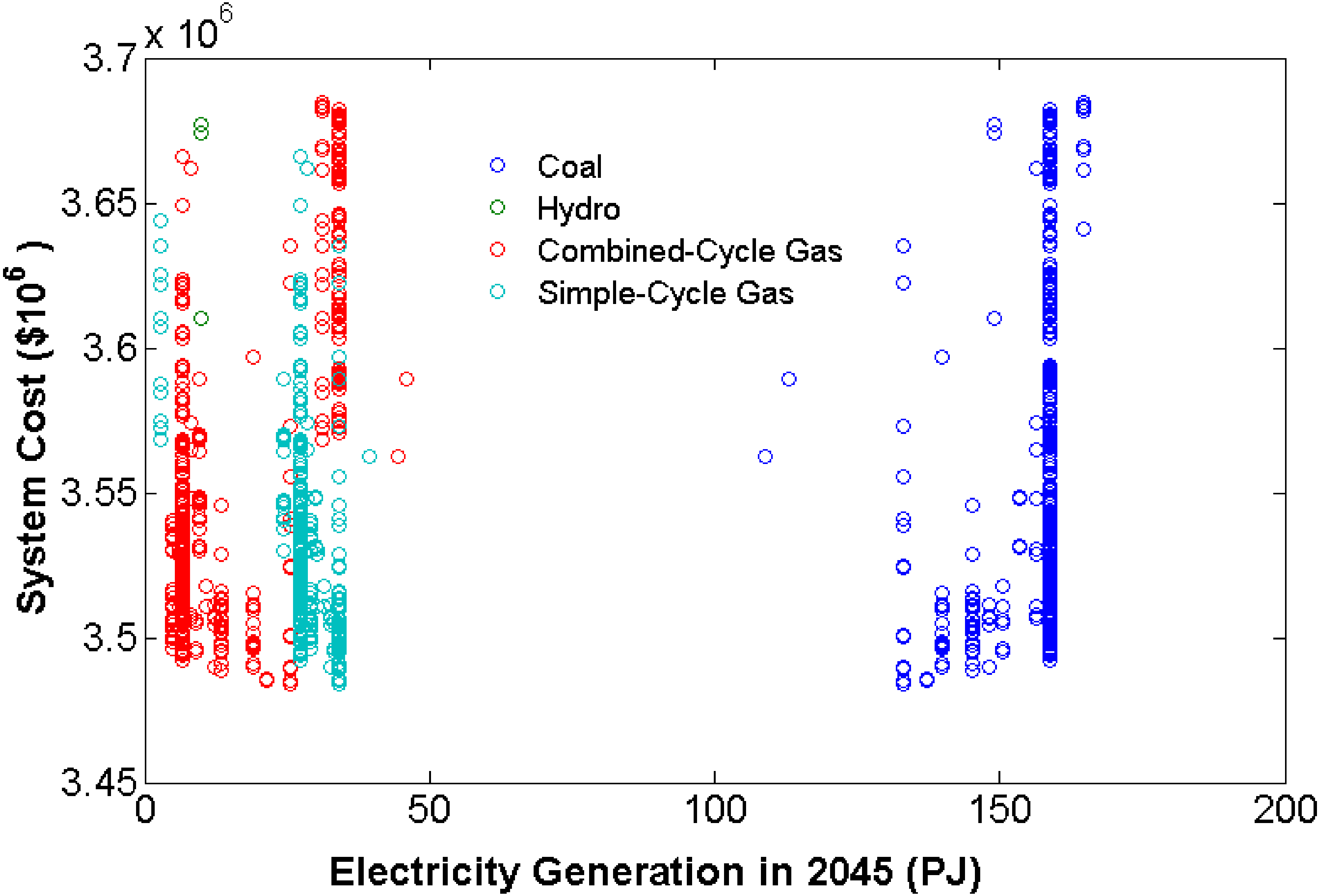


Activity Results: Lowest / Highest Cost Scenario





Process-Level Activity vs. System Cost



Conclusions

Analysis presented here represents a proof-of-principle application of Temoa framework to conduct stochastic optimization

Applying historical fuel price uncertainty to the future with current technology characterization does not result in divergent scenarios
→ hedging is minimal

Switch from combined-cycle to simple-cycle gas turbines if natural gas remains cheap

Vehicles powered by electricity and ethanol generally remain too expensive to justify their deployment in high fuel price scenarios

Temoa Next Steps

Development

- Develop more refined approach to generating stochastic data and branch probabilities (e.g., a semi-parametric approach)
- Find ways to prune the event tree
- Improve ways to analyze outputs from stochastic runs
- Develop a relational database for I/O data
- Adapt single-region US TIMES model to Temoa

Model Access

All model source code and data available for viewing and download through the project website:

http://temoaproject.org

Also, if you'd like a copy of the paper that describes the Temoa formulation, send me an email (jdecarolis@ncsu.edu) :

Hunter K, Sreepathi S, DeCarolis JF, Modeling for Insight Using Tools for Energy Model Optimization and Analysis (Temoa). Energy Economics (under review).

Acknowledgments

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