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A Call for Greater Transparency in Energy Modeling and Analysis

Les Houches, France
7 February 2014

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Talk outline

Introduction to energy economy optimization models

Problems with the status quo; recommendations to fix

Introduction to Tools for Energy Model Optimization and Analysis (Temoa)

Driving questions

How does the world balance the costs of greenhouse gas mitigation in the near-term versus long-term?

What are the anticipated economic and environmental impacts associated with future environmental policies and energy technology deployments?

How do decision makers craft energy planning strategies that are robust to future uncertainties?

How do decision makers incorporate broader environmental sustainability considerations — beyond simply limits to greenhouse gas emissions — into their strategies?

Energy-economy optimization (EEO) models

Large uncertainties combined with a mix of technical, economic, and moral considerations preclude definitive answers to the questions above.

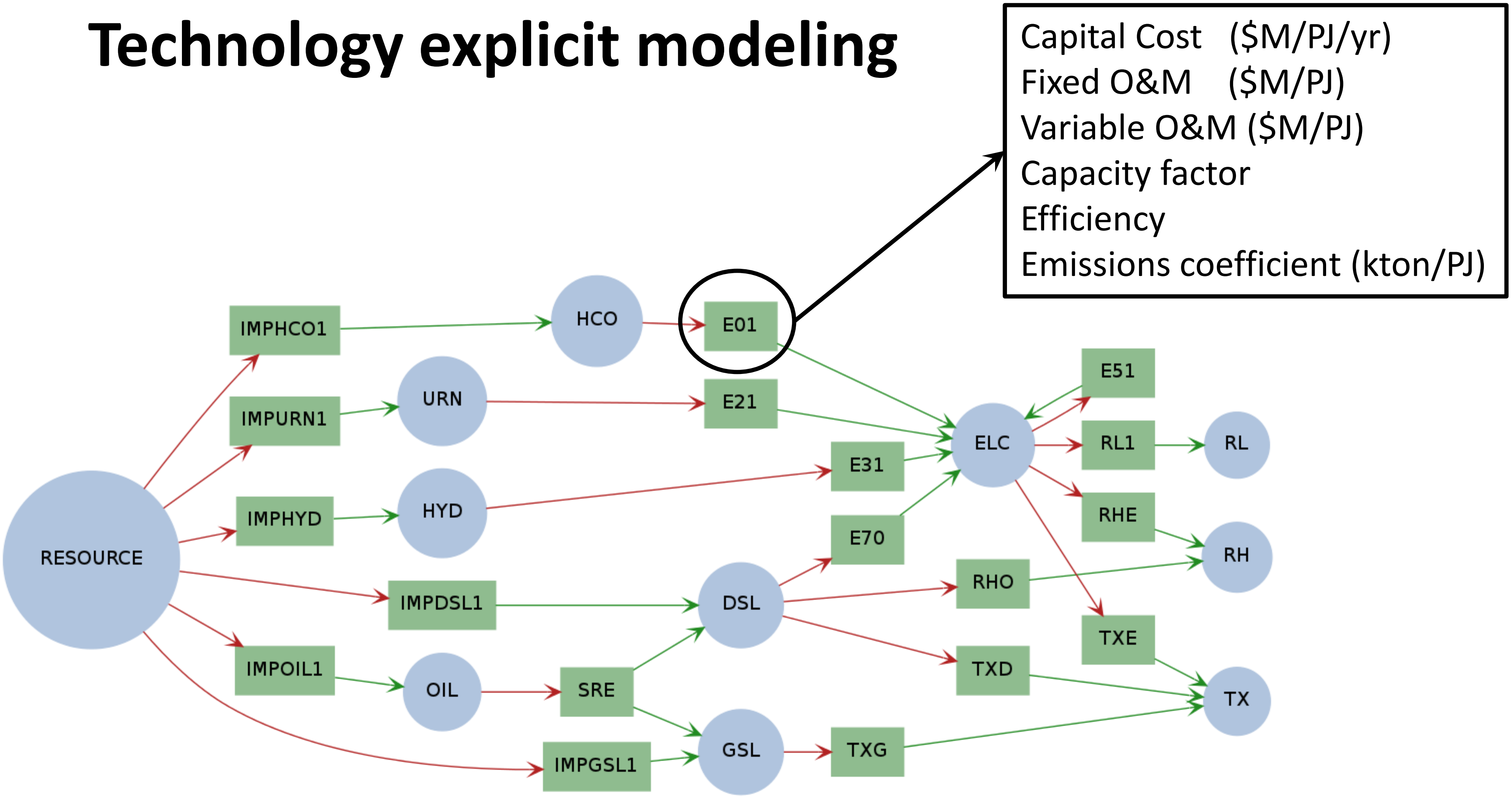
Model-based analysis can deliver crucial insight that informs key decisions.

Energy-economy optimization (EEO) models refer to partial or general equilibrium models that **minimize cost or maximize utility** by, at least in part, optimizing the energy system over multiple decades

- Self-consistent framework for evaluation
- Explore how effects may propagate through a system
- Expansive system boundaries and multi-decadal timescales

What can we usefully conclude from modeling exercises where uncertainty is rigorously quantified?

Technology explicit modeling



Objective function: minimize present cost of energy supply over a defined time horizon

Decision variables: activity (PJ) and capacity (PJ/yr) for each technology

High Visibility Model-Based Analyses

IPCC Special Report on Emissions Scenarios

http://www.ipcc.ch/ipccreports/sres/emission/index.htm

IEA Energy Technology Perspectives

http://www.iea.org/techno/etp/index.asp

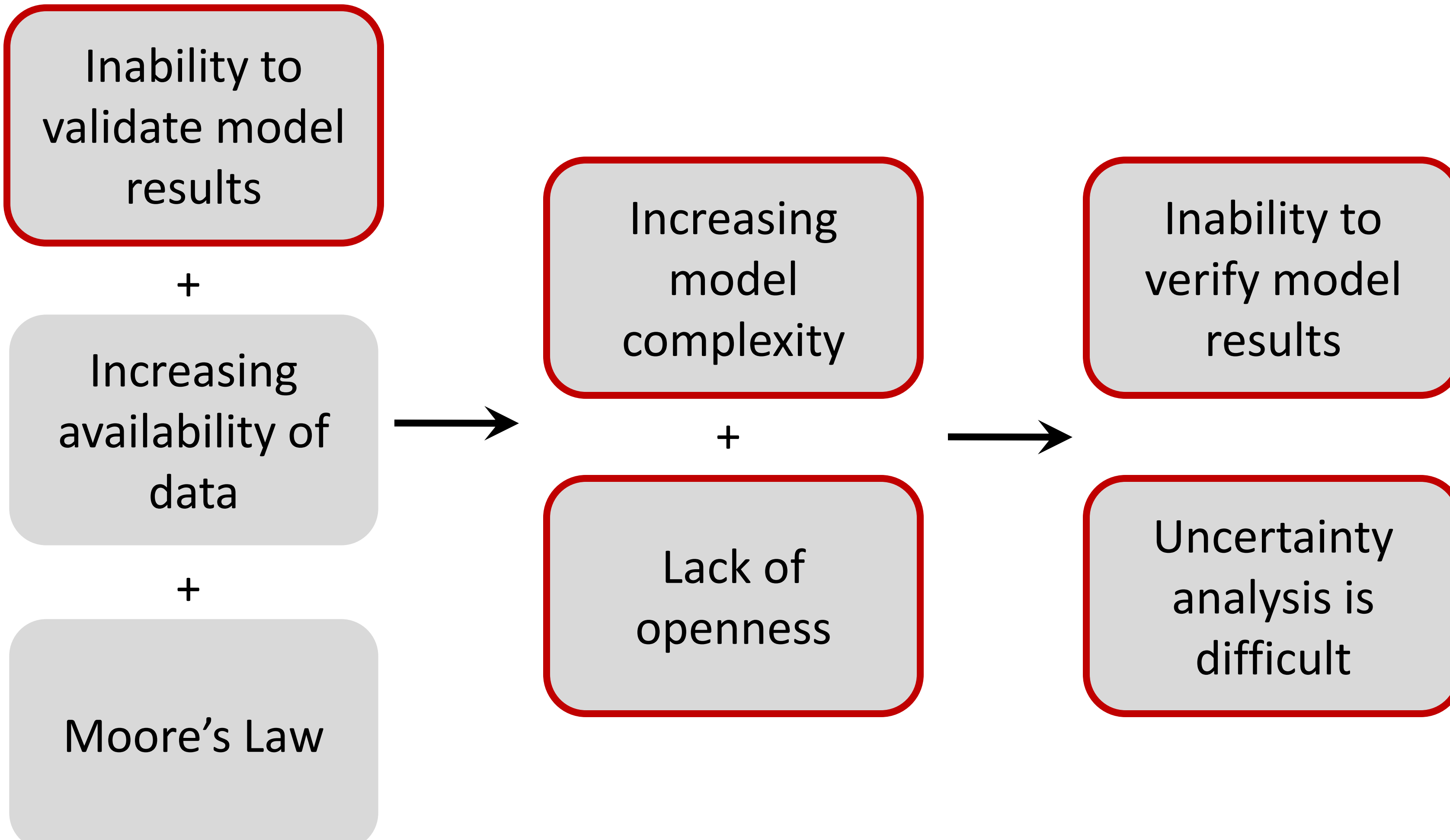
Annual Energy Outlook

http://www.eia.gov/forecasts/aeo/er/

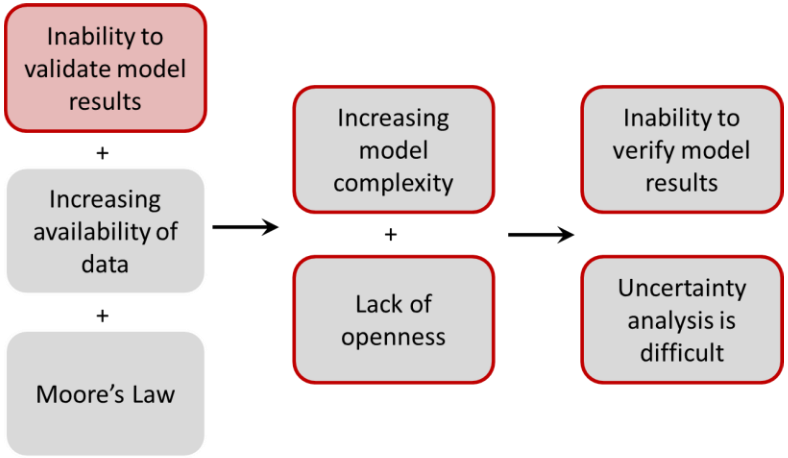
EPA Legislative Analyses

http://epa.gov/climatechange/economics/economicanalyses.html

Problems with the status quo



Inability to validate model results



Four conditions for validatable models according to Hodges and Dewar (1992) :

- It must be possible to observe and measure the situation being modeled.
- The situation being modeled must exhibit a constancy of structure in time.
- The situation being modeled must exhibit constancy across variations in conditions not specified in the model.
- It must be possible to collect ample data with which to make predictive tests of the model.

Uses of unvalidatable models

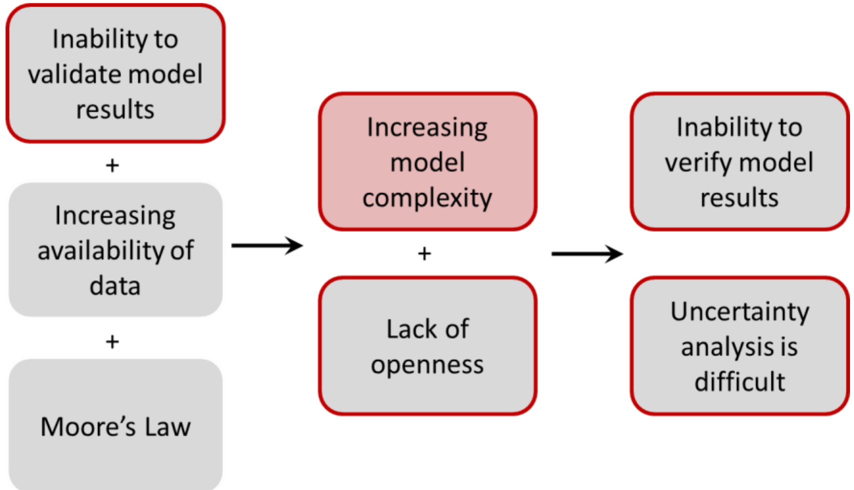
According to Hodges and Dewar (1992):

- As a bookkeeping device, to condense masses of data or to provide a means or incentive to improve data quality;
- As an aid in selling an idea of which the model is but an illustration;
- As an aid in communication, e.g., in teaching or in operating organizations
- As a vehicle to make comparisons
- As an aid in thinking and hypothesizing

To which I add:

- As a tool to identify robust outcomes across a range of tested conditions

Inability to validate leads to increasing model complexity

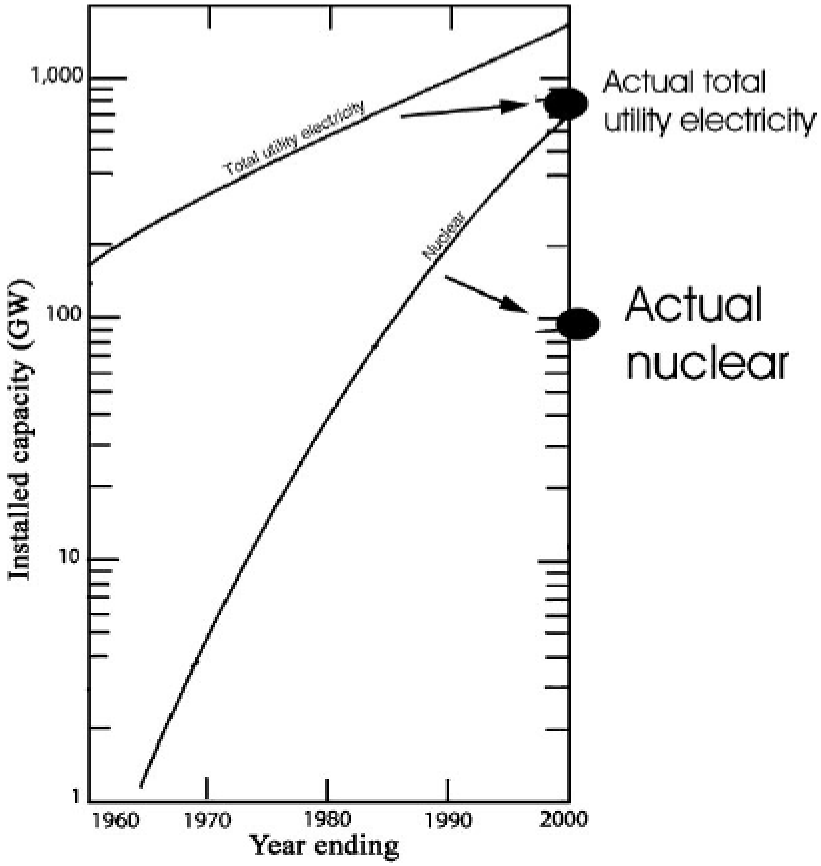


The conventional approach to dealing with structural uncertainty is to build larger and more complex models to account for additional dynamic processes.

Little to guide the modeler and reign in efforts that do not improve model performance

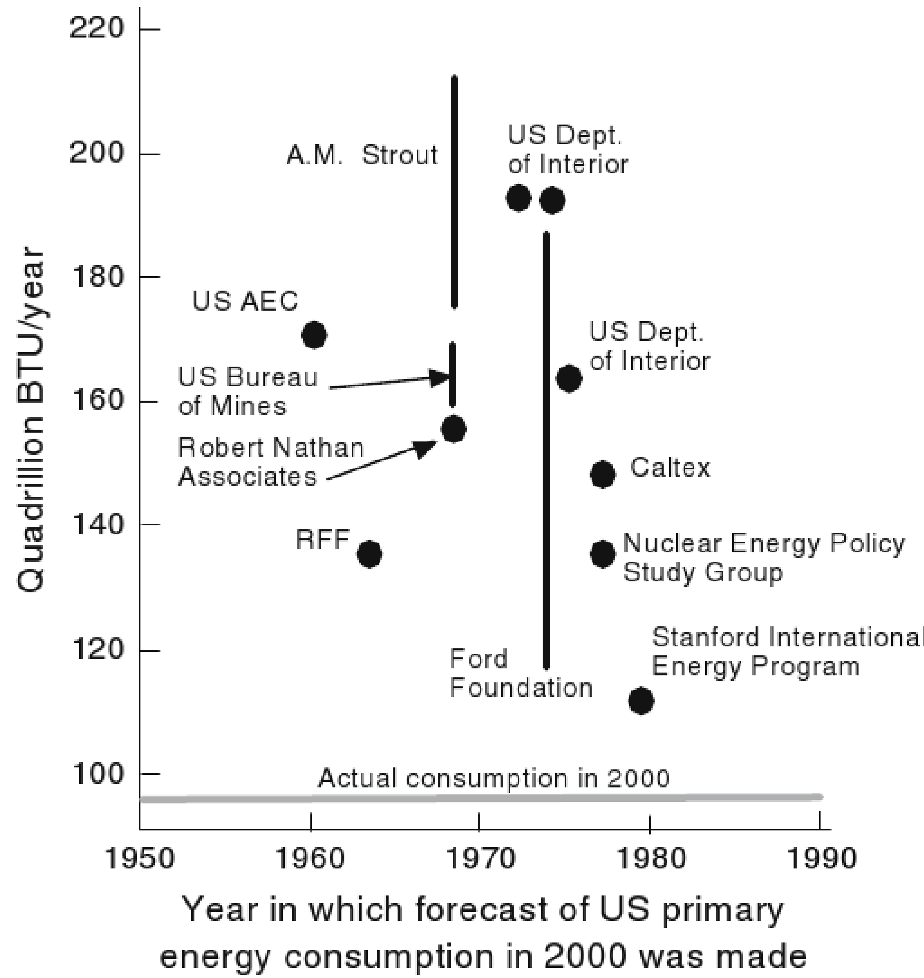
Higher complexity makes it harder to address the parameter uncertainty through sensitivity and uncertainty analysis

Past projections are generally dismal



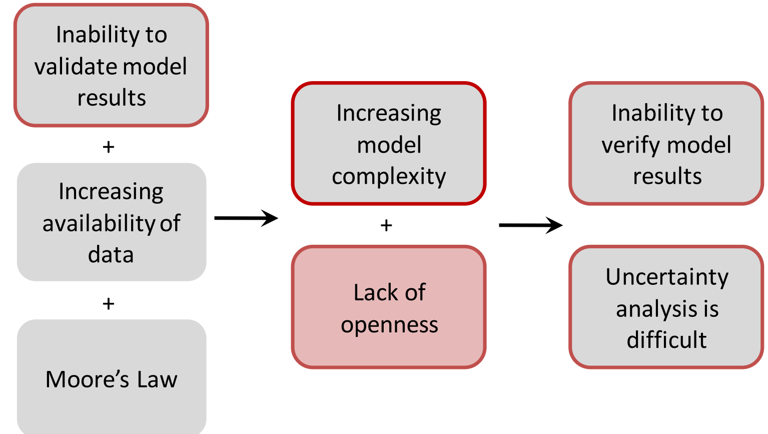
U.S. Atomic Energy Commission forecast from 1962

Source: Craig et al. (2002). “What Can History Teach Us? A Retrospective Examination of Long-Term Energy Forecasts for the United States.” *Ann. Rev. Energy Environ*. 27:83-118.



Source: Morgan G, Keith D. (2008). “Improving the way we think about projecting future energy use and emissions of carbon dioxide.” *Climatic Change*. 90: 189-215.

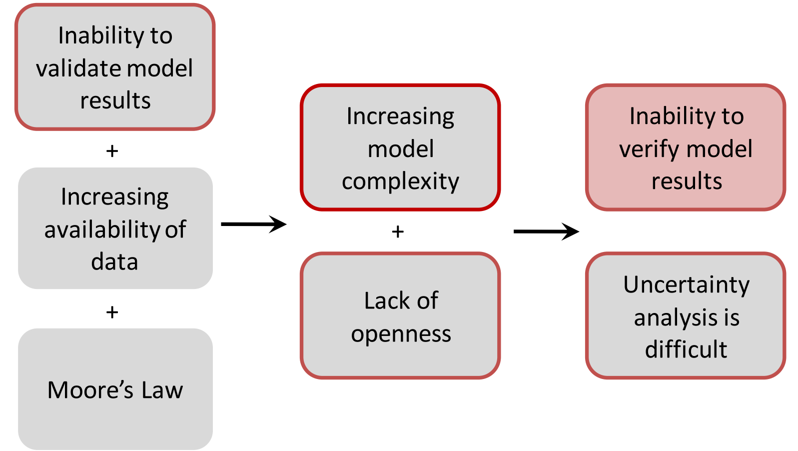
Lack of openness



Most EEO models and datasets remain closed source. Why?

- protection of intellectual property
- fear of misuse; inability to control or limit model analyses
- implicit commitment to provide support to users
- overhead associated with maintenance
- unease about subjecting code and data to public scrutiny

Inability to verify model results



With a few exceptions,

energy-economy models are not open source

Descriptive detail provided in model documentation and peer-reviewed journals is insufficient to reproduce a specific set of published results

Reproducibility of results is fundamental to science

Replication and verification of large scientific models can't be achieved without source code and input data

Why does replication matter?

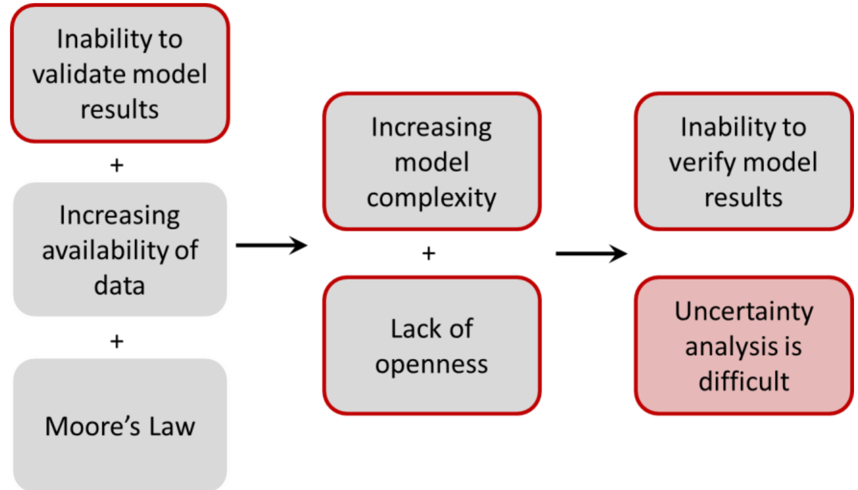
The development of repeatable experiments laid the foundation for reason-based scientific inquiry by allowing independent verification of non-intuitive empirical results

The purpose of describing experiments was to convince skeptics that a counter-intuitive result could be obtained by following a prescribed procedure.

The utility of a repeatability criterion is common to all forms of reason-based inquiry

Particularly relevant to energy- and climate-related policy analysis that could involve the transfer of huge sums of wealth.

Uncertainty analysis is difficult



A common result is false precision

- E.g., EPA analysis of S.2191 (Lieberman-Warner), GDP growth predictions to 0.01%!

Large, complex models tuned to look at a few scenarios **by necessity**

Scenario analysis overused

Without subjective probabilities $p(X|e)$, scenarios of little value to decision makers

Problems with scenario analysis

Cognitive heuristics play a role and can lead to misinterpretation of results.

Availability heuristic:

Probabilities of a future event or outcome assessed on the basis of how easily an individual can remember or imagine examples

Anchoring and adjustment:

People start with an initial value or “anchor” and then modify their judgment as they consider factors relevant to the specifics → often insufficient adjustment

→ A few highly detailed scenarios can create cognitively compelling storylines.

Drawn from: Morgan G, Keith D. Improving the way we think about projecting future energy use and emissions of carbon dioxide. *Climatic Change* 2008; 90; 189-215.

Example of the availability heuristic
Drawn from Slovic et al. (1976)

Tom is of high intelligence, although lacking in true creativity. He has a need for order and clarity, and for neat and tidy systems in which every detail finds its appropriate place. His writing is rather dull and mechanical, occasionally enlivened by somewhat corny puns and by flashes of imagination of the scientific type. He has a strong drive for competence. He seems to have little feel and little sympathy for other people and does not enjoy interacting with others.

Which is most probable scenario for Tom?

1. Tom will select journalism as his college major.
2. Tom will select journalism as his college major but become unhappy with his choice
3. Tom will select journalism as his college major but become unhappy with his choice and switch to engineering

So what should we do?

Recommendations drawn from DeCarolis JF, Hunter K, Sreepathi S (2012). “The case for repeatable analysis with energy economy optimization models”, Energy Economics, 34: 1845-1853.

Recommendations

Recommendation 1: Make source code publicly accessible

- Ince et al. (2012): even unambiguous descriptions of computer code are no guarantee of reproducibility.
- Use software configuration management to track and control changes to software
- Utilize revision control to log changes to the codebase

Drawn from DeCarolis et al. (2012)

Recommendations

Recommendation 2: Make model data publicly accessible

- Models cannot be replicated without access to the complete input data set
- Unlike source code, model input data updated frequently
- Archive input data associated with each published analysis
- Publish data in a web-accessible, free, and archived repository

Drawn from DeCarolis et al. (2012)

Recommendations

Recommendation 3: Make transparency a design goal

- Documentation required to interpret model source code and data
- Documentation can come in different forms:
  - A standalone, comprehensive document
  - Comments embedded in the source code
  - Well-designed code with descriptive variable names that provide self-evident meaning

Drawn from DeCarolis et al. (2012)

Recommendations

Recommendation 4: Utilize free software tools

- Use cost-free (gratis) software to minimize the barriers to entry
- Maintain a baseline model that is executable with free tools

Drawn from DeCarolis et al. (2012)

Recommendations

Recommendation 5: Develop test systems for verification exercises

- Create a set of publicly available data files that represent test systems for verification exercises
- Allows modelers to debug changes to model formulation, assess computational performance, and provide a consistent evaluation mechanism for inter-model comparison
- Precedent exists: IEEE Reliability Test System (RTS) to evaluate techniques for assessing electric load reliability

Drawn from DeCarolis et al. (2012)

Recommendations

Recommendation 6: Work toward interoperability of models

- Improve inter-model comparison by ensuring data consistency across models
- Reduce duplication and error in building datasets
- Use a relational database management system (RDMS): data can be queried and mapped efficiently to a project's native input format

Drawn from DeCarolis et al. (2012)

Recommendations

Recommendation 7:

Build models that are as simple as possible to answer the question at hand, and then rigorously exercise it with uncertainty analysis

What we did.

Temoa

Tools for Energy Model Optimization and Analysis

Temoa also means “to seek something” in the Nahuatl (Aztec) language:

TĒMOĀ *vt* to seek something / buscar algo, o inquirir de algún negocio. This contrasts with TEMŌHUA, the nonactive form of TEMŌ ‘to descend.’

Taken from: *An analytical dictionary of Nahuatl*
by Frances E. Karttunen

Temoa goals and approach

Goal: Create an open source, technology explicit EEO model

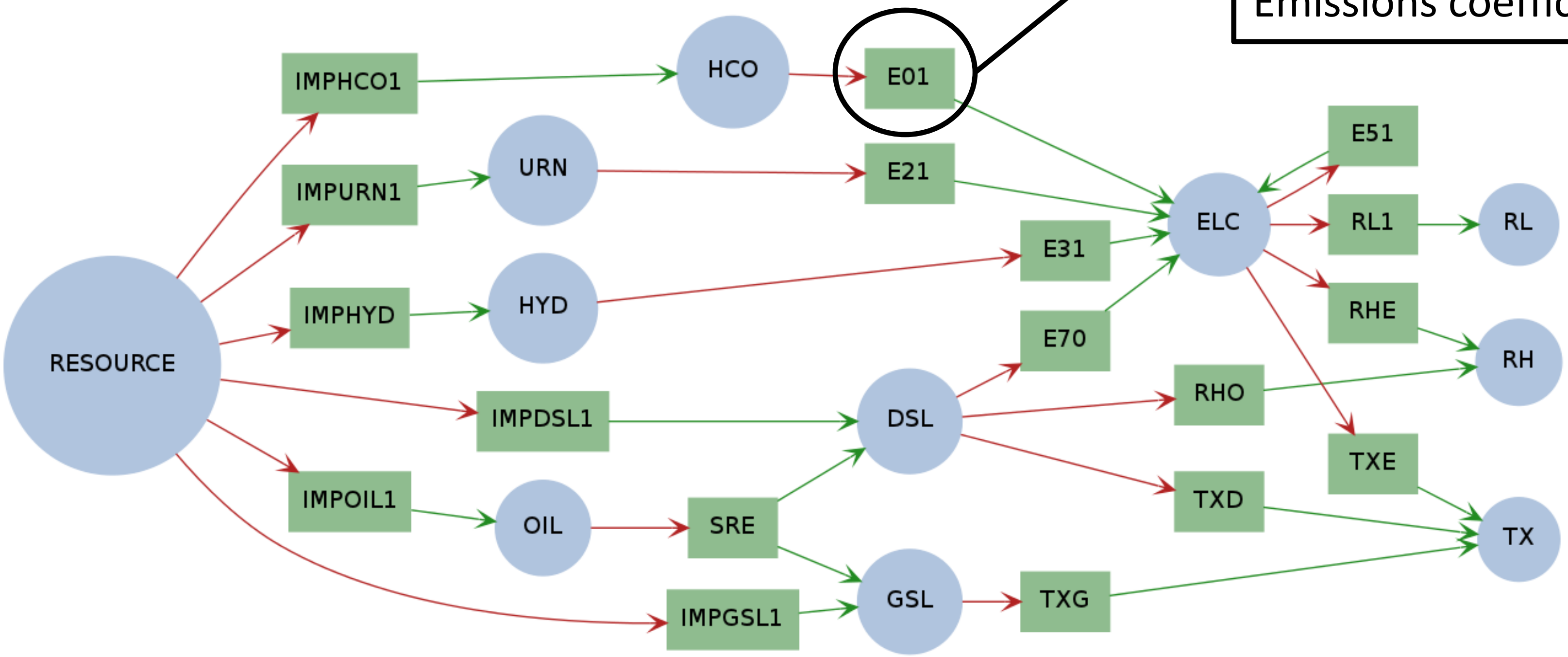
Our Approach:

- Public accessible source code **and data**
- No commercial software dependencies
- Data and code stored in a web accessible electronic repository
- A version control system
- Programming environment with links to linear, mixed integer, and non-linear solvers
- Built-in capability for sensitivity and uncertainty analysis
- Utilize multi-core and compute cluster environments
- Input and output data managed directly with a relational DB*

Technology explicit modeling

Capital Cost ($M/PJ/yr)
Fixed O&M ($M/PJ)
Variable O&M ($M/PJ)
Capacity factor
Efficiency
Emissions coefficient (kton/PJ)

‘Utopia’ (18 technologies included)



Objective function: minimize present cost of energy supply over a defined time horizon

Decision variables: activity (PJ) and capacity (PJ/yr) for each technology

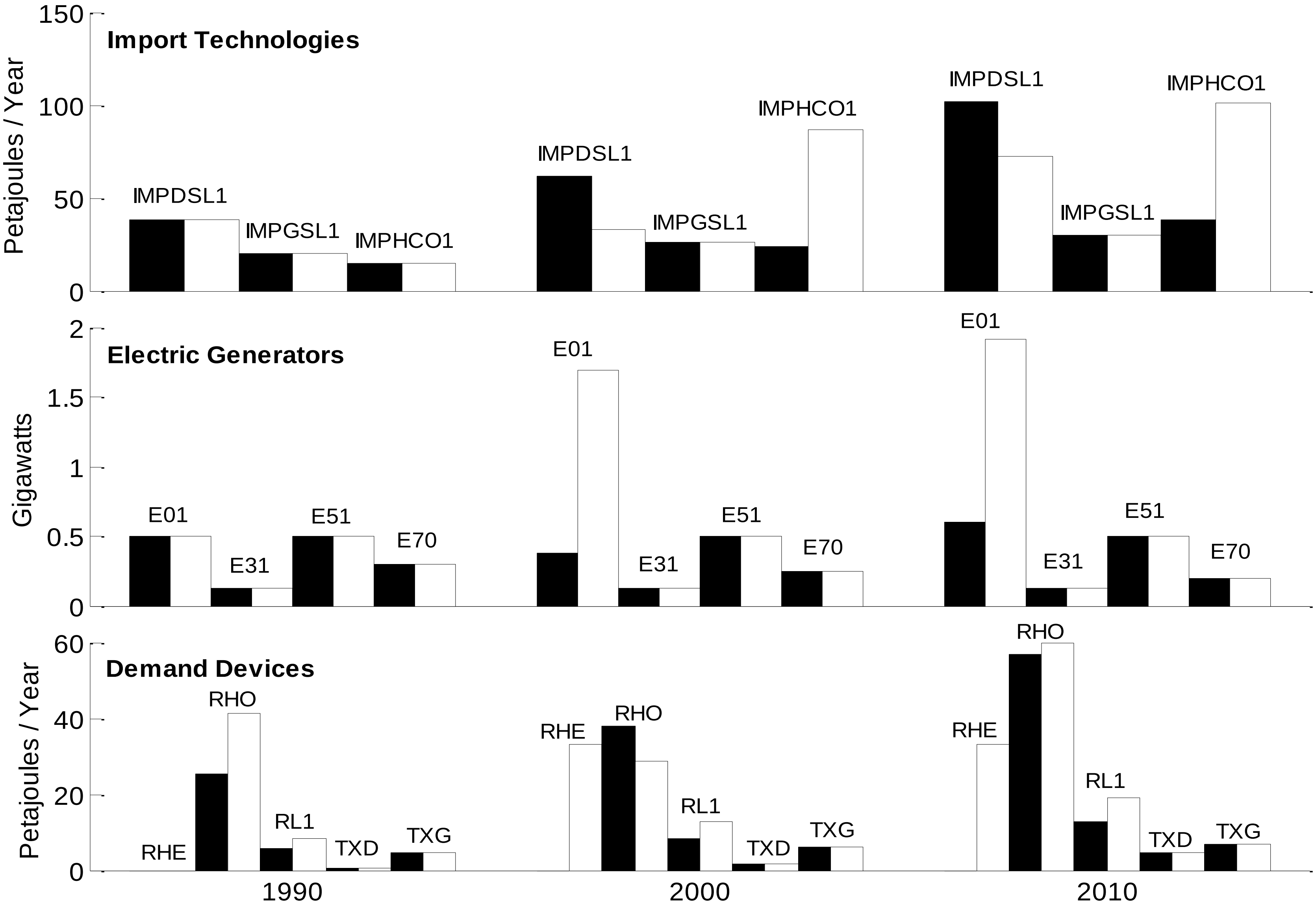
TEMOA Model Features

A **technology explicit 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

‘Utopia’ verification exercise

MARKAL: Black
Temoa: White



Approach to uncertainty analysis.

Approach to uncertainty analysis

Use the following techniques in series:

Sensitivity analysis and Monte Carlo simulation
→ Determine key sensitivities

Multi-stage stochastic optimization
→ Develop a hedging strategy

Explore near-optimal, feasible region
(Modeling-to-Generate-Alternatives)
→ Test robustness of hedging strategy

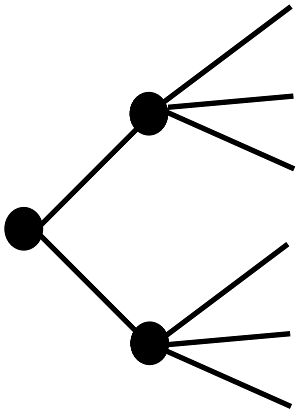
Stochastic Optimization

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

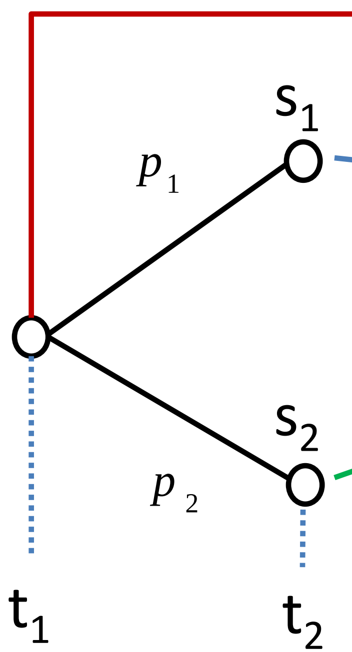


Simple example of stochastic optimization

Suppose we have two technologies, A and B. Let *x* and *y* represent the installed capacity in Stages 1 and 2, respectively.

Stage 1 Decision Variables:

x_A, x_B



Stage 2 Decision Variables:

y_{A,s_1}, y_{B,s_1} Scenario 1: s_1

y_{A,s_2}, y_{B,s_2} Scenario 2: s_2

$$\text{Minimize: } c^T x + \sum_{s=1}^{N} p_s \cdot d_s^T \cdot y_s$$

Subject To:

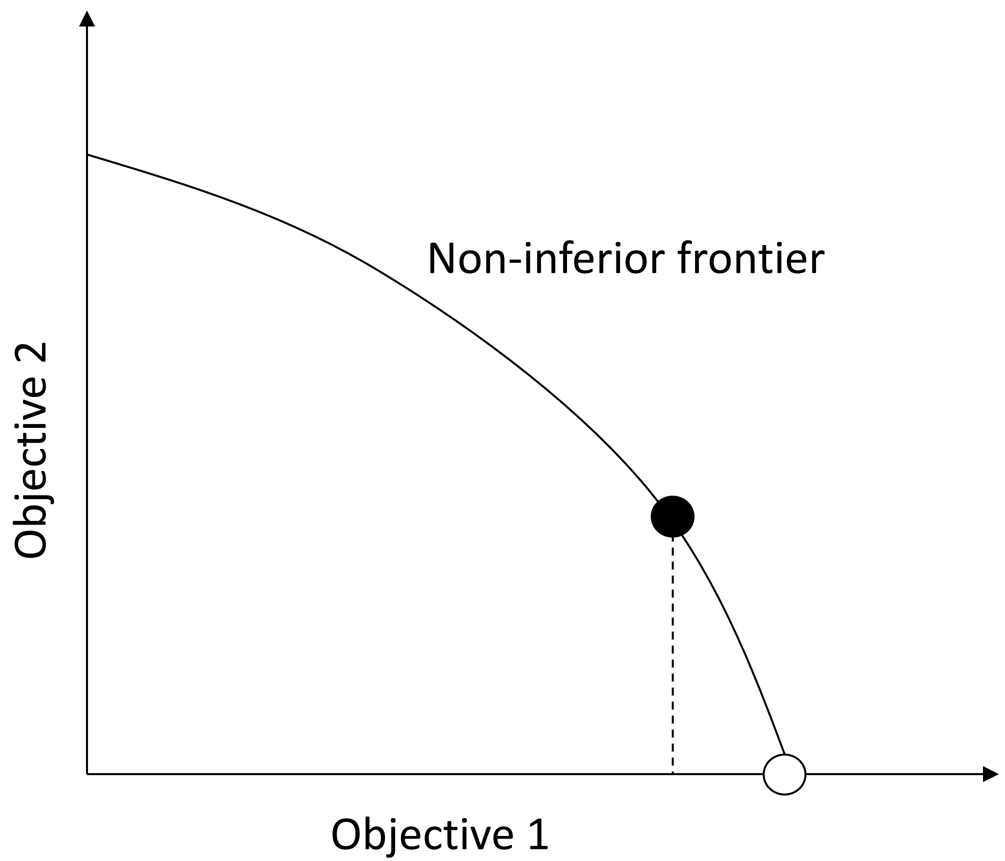
$$Ax = b$$

$$T_s x + W_s y_s = h_s \quad for \quad s = 1, \ldots, N$$

$$x \geq 0$$

$$y_s \geq 0 \qquad for \quad s = 1, \ldots, N$$

What about structural uncertainty?



Consider an optimization model that only includes **Objective 1** and leaves **Objective 2** unmodeled. The true optimum is within the feasible, suboptimal region of the model's solution space.

Viable alterative solutions exist within the model's feasible region.

Example adopted from Brill et al. (1990).

Modeling to Generate Alternatives

Still haven't dealt with structural uncertainty in the model

Need a method to explore an optimization model's feasible region → "Modeling to Generate Alternatives"[†]

MGA generates alternative solutions that are **maximally different in decision space** but perform well with respect to modeled objectives

The resultant MGA solutions provide modelers and decision-makers with a set of alternatives for further evaluation

[†]Brill (1979), Brill et al. (1982), Brill et al. (1990)

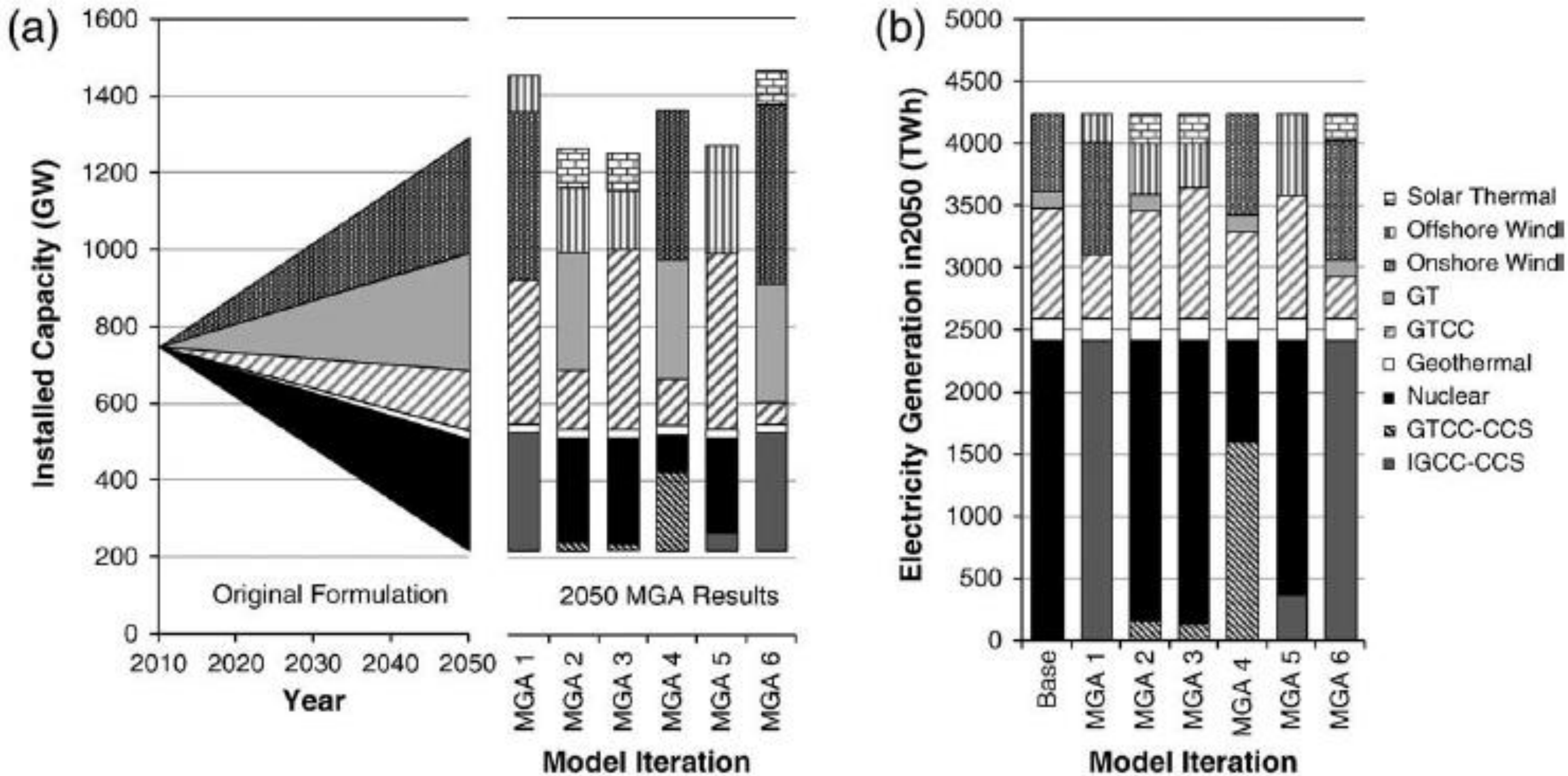
Hop-Skip-Jump (HSJ) MGA

Brill et al. (1982)

Steps:

1. Obtain an initial optimal solution by any method
2. Add a user-specified amount of slack to the value of the objective function
3. Encode the adjusted objection function value as an additional upper bound constraint
4. Formulate a new objective function that minimizes the decision variables that appeared in the previous solutions
5. Iterate the re-formulated optimization
6. Terminate the MGA procedure when no significant changes to decision variables are observed in the solutions

Sample Result



Drawn from DeCarolis (2011)

Conclusions

Most EEO models and model-based analyses are opaque to external parties

A prerequisite for making energy scenarios more scientific is open access to model source code and data
→ enables repeatability

Rigorous uncertainty analysis is necessary to develop useful and actionable insight for policy

Challenge for modeling community to archive model, data and results in a systematic and transparent fashion.

Relevant papers (published or submitted)

DeCarolis J.F. (2011). Using modeling to generate alternatives (MGA) to expand our thinking on energy futures. *Energy Economics*, 33: 145-152.

Howells M., Rogner H., Strachan N., Heaps C., Huntington H., Kypreos S., Hughes A., Silveira S., DeCarolis J., Bazillian M., Roehrl A. (2011). OSeMOSYS: The open source energy modeling system: An introduction to its ethos, structure and development. *Energy Policy*, 39(10), 5850-5870.

DeCarolis J.F., Hunter K., Sreepathi S. (2012). The Case for Repeatable Analysis with Energy Economy Optimization Models. Energy Economics, 34: 1845-1853.

Hunter K., Sreepathi S., DeCarolis J.F. (2013). Tools for Energy Model Optimization and Analysis. Energy Economics, 40: 339-349.

Acknowledgments

- Kevin Hunter, MS student, Civil Engineering, NCSU
- Sarat Sreepathi, PhD student, Computer Science, NCSU
- Jean-Paul Watson and Bill Hart, Sandia National Laboratory

This work would made possible through the generous support of the National Science Foundation. CAREER: *Modeling for Insights with an Open Source Energy Economy Optimization Model*. Award #1055622

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