Agent-Based Modeling Tools for Electric Power Market Design

Implications for Macro/Financial Policy?

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Heterogeneous Agents and Agent-Based Modeling Conference
U.S. Treasury, Washington, D.C.
21-22 September 2017
Latest Revision: 18 September 2017
Presentation Outline

- U.S. electric power markets in transition
- What is Agent-based Comp Economics (ACE)?
- ACE support for electric power market design
- Implications for macro/financial policy?
Key References


U.S. Electric Power Industry

- Large numbers of heterogenous participants
- Complex mix of economic, operational, and physical processes
- Originally based on vertically integrated utilities
  - Each utility handled production, transmission, and distribution for an assigned retail region, at administratively set prices
- Restructured 1996-2005 into centrally managed wholesale power markets
The Nine North American Regions with Restructured Centrally-Managed Wholesale Power Markets

- California ISO (CAISO): 1998
- Southwest Power Pool (SPP): 2004
- Electric Reliability Council of Texas (ERCOT): 1996
- Midcontinent ISO (MISO): 1998
- New York ISO (NYISO): 1999
- PJM: 1997
- Regional Transmission Organizations

Added to MISO: 2013

THIS MAP WAS CREATED USING ENERGY VELOCITY, NOVEMBER 2015
U.S. Electric Power Industry in Transition

- **2006-Present:** Increasing focus on *Transactive Energy System (TES) designs*

- **TES Design:** Decentralized architecture based more fully on economic bid/offer-based transactions
  - **Goal:** Achieve greater system efficiency, consistent with system reliability
  - **Initial TES design focus:** Retail distribution
  - **Extended TES design focus:** End-to-end power systems (entire wholesale-retail circular flow)
Example: TES design currently under development at ISU using agent-based modeling tools.
Agent-based Computational Economics (ACE)
http://www2.econ.iastate.edu/tesfatsi/ace.htm

- Computational modeling of economic processes (including whole economies) as open-ended dynamic systems of interacting agents

**Basic Modeling Goals for Scientific Purposes:**

- Match agents to real-world counterparts
- Let agents interact as freely within their virtual worlds as their empirical counterparts interact in real world

System equilibrium/optimality then become *testable hypotheses* rather than modeler-imposed constraints
A More Careful Description of ACE Modeling Principles: (MP1) – (MP7)

(MP1) Agent Definition: An agent is a software entity within a computationally constructed world capable of acting over time on the basis of its own state (data, attributes, and/or methods)

(MP2) Agent Scope: Agents can represent humans, social groups, institutions, biological entities, and/or physical entities

(MP3) Agent Local Constructivity: The action of an agent at any given time is determined as a function of the agent’s own state at that time.
ACE Modeling Principles...Continued

(MP4) **Agent Autonomy:** Coordination of agent interactions cannot be externally imposed by means of free-floating restrictions, i.e., restrictions not embodied within agent states.

(MP5) **System Constructivity:** The state of the modeled system at any given time is determined by the ensemble of agent states at that time.

(MP6) **System Historicity:** Given initial agent states, all subsequent events are determined solely by agent interactions.

(MP7) **Modeler as Culture-Dish Experimenter:** The role of the modeler is limited to the setting of initial agent states and to the non-perturbational observation, analysis, and reporting of model outcomes.
Example: Partial Agent Taxonomy for a Macro Model

- denotes “has a” relationship;
- denotes “is a” relationship
Example: Process Flow Diagram $t \rightarrow t+1$ for an ACE Macro Model

ACE Modeling Principles: Summary Overview

- Together, (MP1) through (MP7) imply that an ACE model is a computational laboratory.

- An ACE model permits a user to explore how changes in initial conditions affect outcomes in open-ended dynamic systems over successive time periods.

- Exploration process is analogous to biological experimentation with cultures in petri dishes.
ACE Permits Researchers to Strive for Comprehensive Empirical Validation: Four Different Aspects (EV1-EV4)

**EV1. Input Validation:** Are the exogenous inputs for the model empirically meaningful and appropriate for the purpose at hand?

**EV2. Process Validation:**
- How well does the model represent real-world processes important for the purpose at hand?
- Are these representations consistent with essential scaffolding constraints, such as physical laws, stock-flow relationships, and accounting identities?
EV3. Descriptive Output Validation:
How well are model-generated outputs able to capture the salient features of the sample data used for model identification? (in-sample fitting)

EV4. Predictive Output Validation:
How well are model-generated outputs able to forecast distributions, or distribution moments, for sample data withheld from model identification or for data acquired at a later time? (out-of-sample forecasting)
ACE Approach to Policy Design

- What is the purpose of the policy study?
  - Intended application domain?
  - Intended *Policy Readiness Level (PRL)*?
  - Intended audience for study?

- Given this purpose, strive for “right” degree of EV1-EV4 empirical validation for:
  - Agent types and numbers
  - Agent initial state specifications (data, attributes, methods)
  - Agent interactions
  - Performance metrics
  - Performance tests

*Note:* “Right” $\rightarrow$ “simple but not too simple for purpose at hand”
Policy Readiness Levels (PRLs)

- **PRL-1:** Conceptual policy idea
- **PRL-2:** Analytic policy formulation
- **PRL-3:** Low-fidelity policy model *(fidelity measured via EV1-EV4)*
- **PRL-4:** Moderate-fidelity small-scale model
- **PRL-5:** High-fidelity small-scale model
- **PRL-6:** Prototype small-scale model *(expected field conditions apart from scale)*
- **PRL-7:** Prototype large-scale model
- **PRL-8:** Field study
- **PRL-9:** Real-world implementation

Basic research typically done at universities and research institutes

Infamous “Valley of Death”

Industry, government, regulatory agencies
PRLs 4-6: “Valley of Death”

- PRLs 4-6 ➔ “Valley of Death” for good ideas

- ACE test systems can help to bridge this valley.
  - **ACE Test System:** Software framework plus library of software classes permitting plug-and-play building and study of a family of ACE models PRL-3 to PRL-7.

  - **Proof of Concept:** Use of ACE test systems for electric power market research
Example 1: Wholesale Power Market Research at ISU
http://www2.econ.iastate.edu/tesfatsi/AMESMarketHome.htm

- **Goal**: Normative study of U.S. restructured wholesale power markets
  - Series of pubs/reports 2000-present *(PRL-1 to PRL-4)*

- **Key Issues Studied**: Locational marginal pricing, auction & contract design, system operator role, exercise of market power by pivotal suppliers, strategic learning

- **Key Supporting Tool**: **AMES Wholesale Power Market Test Bed** developed in a series of steps *(PRL-3 to PRL-4)*
  - AMES is an ACE test system capturing core features of US centrally-managed wholesale power markets (commitment, pricing, & dispatch operations)
AMES = Agent-based Modeling of Electricity Systems

Latest version 4.0 released 4/13/2017: (PRL-4)

AMES Wholesale Power Market Test Bed

Load
Attributes:
- Location
- Profile

Market Participant
- Dispatchable Generator
Attributes:
- Location
- Capacity
- Min up/down times
- Ramp rate
- UC costs
- Dispatch cost
- Methods:
  - Make offer
  - Update offer (learn)

- Wind/Solar Farm (Non-Dispatchable)
Attributes:
- Gen unit locations
- Gen unit types
- Methods:
  - For each gen unit, an output curve mapping local weather to power output

- Load-Serving Entity
Attributes:
- Location
- Methods:
  - Forecast load
  - Make bid
  - Update bid (learn)

Grid
Attributes:
- Buses/zones
- Line limits
- Reactances

ISO

Market
Attributes:
- Market design
- Methods:
  - Run SCUC
  - Run SCED

DAM
Attributes:
- Market design
- Methods:
  - Run SCED

RTM

AMES V1.0 (2007): Key developer, Dr. Junjie Sun, now at OCC/U.S. Treasury!
Example 2: Integrated Retail and Wholesale (IRW) Power Market Research at ISU
http://www2.econ.iastate.edu/tesfatsi/IRWProjectHome.htm

- **Goal:** Normative study of “demand response” programs designed to encourage more demand-side participation in power system operations
  - Series of pubs/reports 2012-present (*PRL-1 to PRL-4*)

- **Key Issue Studied:** Price-responsive demand initiatives
  - **One-Way Communication:** Households adjust power usage to signalled retail prices that directly reflect wholesale prices

- **Key Supporting Tool:** IRW Test Bed (*PRL-3 to PRL-4*)
  - ACE test system consisting of AMES + distribution feeders
  - Households have “intelligent” (price-responsive) appliances
IRW Test Bed (PRL-4)

(a) Illustrative IRW Test Case
(b) IRW Test Bed Circular Flow
Illustrative IRW Test Case: Key Findings

- 500 households with smart (price-responsive) A/C system controllers;
- Dynamic interplay between wholesale and retail power markets results in “braided cobweb dynamics” that can be unstable;
- Households are typically better off under flat-rate retail contracts than dynamic-price contracts, even for case of convergent cobweb dynamics.

Example 3: New TES Project at ISU
http://www2.econ.iastate.edu/tesfatsi/itdprojecthome.htm

- **DOE/PNNL-Funded Project (2017-2019)**
- **Goal:** Development of a new *Transactive Energy System (TES)* design, based on swing contracts, for flexible service provision in end-to-end power systems
- **Preliminary analysis** (swing contract pubs, PRL-1 to PRL-3)

\[
b = \text{bus } b; \\
t_s = 8:00\text{am}; \quad \text{(service start time)} \\
t_e = 10:00\text{am}; \quad \text{(service end time)} \\
P = [P_{\min}, P_{\max}] = [10\text{MW}, 40\text{MW}]; \\
R = [-R^D, R^U] = [-38\text{MW/h}, 28\text{MW/h}]; \\
\phi = \$35/\text{MWh.}
\]

Illustrative swing contract with swing (flexibility) in offered power and ramp-rate services (PRL-1)
ACE Test System Support for New TES Project

- Conceptual development of a nested sequence of ACE test systems for performance tests of new TES design.
  - These ACE test systems range from PRL-3 to PRL-5
  - Implementation via PNNL’s Framework for Network Co-simulation (FNCS) in collaboration with PNNL
  - FNCS is a high-level architecture supporting run-time coordination among multiple agent-based component subsystems
Agent taxonomy for ACE Test Systems

PNNL’s GridLab-D (PRL-5)

IEEE Distribution Test System (PRL-5)
Wholesale supply contracts:
Dispatchable resources will be permitted to submit these contracts in swing-contract form
Illustrative Test Case: Simulation of a TES distribution design via an ACE Test System

1) **Household Agents:** Have smart (price-responsive) Heating, Ventilation & Cooling (HVAC) systems

2) **Local Intelligent Software Agents (LISAs):** Manage household HVAC systems.

3) **PowerMatcher (TNO, NL):** Commercially available TES design for distribution systems, tested in field studies

   — **Two-way communication** between LISAs and non-profit Distribution System Operator (DSO)
   — LISAs repeatedly send state-conditioned bids (demand schedules) to DSO, which DSO uses to form aggregate demand schedules;
   — DSO sends retail price signals to households to achieve system reliability (load balancing), subject to a break-even constraint.
IEEE 13-Node Distribution System for Test Case: 180 household agents with multiple appliances (PRL-5)

Tests have been run to verify 2-way communication between DSO and 180 households works properly (direct control & PowerMatcher).
Aspects of this Electric Power Market Research of Possible Relevance for Macro/Financial Policy

- As seen, ACE test systems facilitate:
  - study of complex systems with heterogenous agents
  - study of systems composed of coupled processes (human, natural, physical, institutional) as open-ended dynamic systems
  - consideration of strategic learning and game behaviors by human decision-makers with differing objectives
  - tailoring of model fidelity to purpose, subject to data availability
  - carrying out of detailed systematic normative design studies
Two additional points about ACE test systems:

- Financial, physical, and institutional constraints are welcome scaffolding:
  - Help limit the range of outcomes that must be considered
  - Help ensure the credibility of model outcomes

- There is no need to simplify model specifications purely on grounds of analytical tractability.
Conclusion

- Agent-based modeling tools are already being used for descriptive studies of macro/financial systems.

- Conjecture:

  ACE test systems could make a substantial contribution to the normative study of macro/financial policies, regulations, and institutional designs.