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Agent-Based Infrastructure Modeling

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Abstract: Complex Adaptive Systems (CAS) can be applied to investigate complex infrastructures and infrastructure interdependencies. The CAS model agents within the Spot Market Agent Research Tool (SMART) and Flexible Agent Simulation Toolkit (FAST) allow investigation of the electric power infrastructure, the natural gas infrastructure and their interdependencies.

Keywords: Complex adaptive systems (CAS), Agent-based modeling (ABM), Electric power system modeling, Natural gas system modeling, Infrastructure interdependency, Swarm, RePast, CAVE, Virtual reality (VR).

I. Introduction

Many insights can be gained by viewing energy analysis from a Complex Adaptive Systems (CAS) agent-based modeling perspective. Argonne has taken such a perspective to produce integrated models of the electric power and natural gas markets. The agents within the present Spot Market Agent Research Tool (SMART) and the future Flexible Agent Simulation Toolkit (FAST) allow investigation of the electric power infrastructure, the natural gas infrastructure and their interdependency.

II. The Present and Future

Several tools presently exist:

- SMART Version 2.0 (SMART II) is a Swarm model with an integrated set of agents and interconnections representing the electric power marketing and transmission infrastructure.
- SMART II VR is a virtual reality (VR) interface for SMART II.
- SMART II+ is an extension to SMART II that includes an integrated set of agents and interconnections representing the electric power infrastructure, the natural gas infrastructure and connections between them in the form of natural gas-fired electric generators.

FAST is currently under construction. FAST is a complete redesign of SMART II+ that includes improvements in the modeling environment, model detail and representational fidelity.

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III. SMART II

SMART II is a Swarm-based [1] model that uses a set of agents and interconnections to represent electric power systems. SMART II is the Swarm Development Group 2000 Conference (SwarmFest 2000) Best Presentation winner. SMART II itself builds on several other models [2-3]. The SMART II interface is shown in Figure 1. SMART II includes three different kinds of components as follows:

- Generation agents produce electric power.
- Consumer agents use electric power.
- Interconnections represent the transmission grid.

SMART II considers important economic issues such as production costs, investment capital, demand growth for successful consumers, new generation capacity for profitable producers, and bankruptcy for noncompetitive organizations.

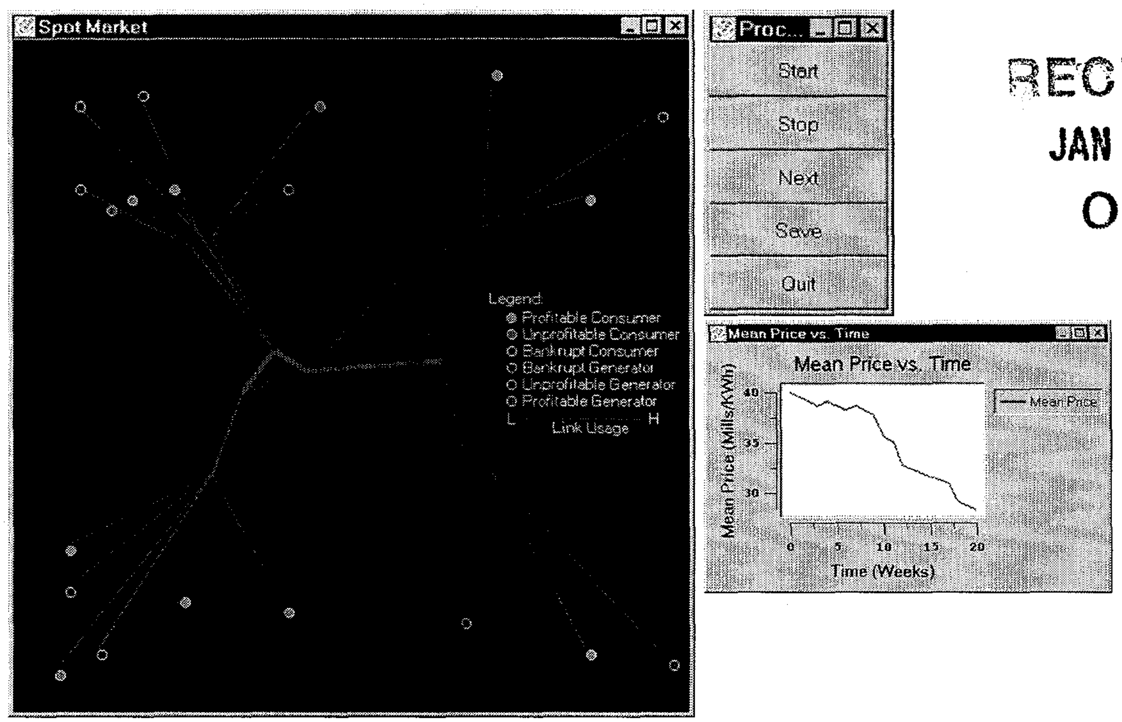

Figure 1: The SMART II Interface

SMART II has undergone initial qualitative validation by matching its outputs to the following basic analytic predictions:

- Markets with a single superior producer among a large number of higher cost competitors have been tested.
- Markets with many identical participants have been tested.

Much more work is clearly required to quantitatively validate and calibrate SMART II therefore only limited qualitative insights are currently being derived.

As originally presented at SwarmFest 2000, qualitative insights from SMART II indicate that certain transmission line configurations may encourage price spikes. Soon after SwarmFest 2000, this insight was borne out.

As was specifically noted at SwarmFest 2000, the California electrical grid has a configuration of a type that may cause price spikes. Substantial price spikes of the kind predicted by SMARTII were recently observed in this market.

Further qualitative insights suggest that greater electrical market price stability may be gained by consciously avoiding specific configurations that encourage instabilities. In other words, qualitative insights from SMART II can help us make things better by not making things worse.

IV. SMART II VR

SMART II VR is a prototype agent visualization tool. SMART II VR is intended to explore the use of advanced interactive three-dimensional visualization in agent-based modeling.

SMART II is a CAVE Automatic Virtual Environment (CAVE)-based virtual reality interface for SMART II. The CAVE is a virtual reality library co-developed by the University of Illinois at Chicago and Argonne. From the CAVE User's Guide [4]:

> The CAVE is a projection-based VR system that surrounds the viewer with four screens. The screens are arranged in a cube made up of three rear-projection screens for walls and a down-projection screen for the floor; that is, a projector overhead points to a mirror, which reflects the images onto the floor. A viewer wears stereo shutter glasses and a six-degrees-of-freedom head-tracking device. As the viewer moves inside the CAVE, the correct stereoscopic perspective projections are calculated for each wall. A second sensor and buttons in a wand held by the viewer provide interaction with the virtual environment.

SMART II VR includes an interactive multifunction wand and two rendering modes.

Detail rendering mode focuses on rendering quality. Directional lighting is included. Agents are rendered as lighted spheres. A texture-mapped floor with shadows and first order reflections is included. This mode allows SMART II VR to take advantage of computers with high graphics performance. An example is shown in Figure 2.

Speed rendering mode focuses on rendering time. Agents are rendered as flat shaded cubes. This mode allows SMART II VR to be used on low performance personal computers. An example is shown in Figure 3.

In SMART II VR, generation agents are shown as green spheres or cubes. Spheres are shown in detailed rendering mode and cubes are shown in speed rendering mode. The size of each object represents its total normalized investment capital level. Size can be interactively changed with the CAVE wand. Each object's color intensity represents its hourly profit level.

Figure 2: SMART II VR Detail Mode

Figure 3: SMART II VR Speed Mode

In SMART II VR, consumer agents are shown as blue spheres or cubes. Spheres are shown in detailed rendering mode and cubes are shown in speed rendering mode. The size of each object represents its total normalized investment capital level. Sizes can be interactively changed with the CAVE wand. Each object's color intensity represents its hourly profit level.

In SMART II VR, interconnections are displayed as red tubes. The size of each tube represents its normalized transmission capacity level. Sizes can be interactively changed with the CAVE wand. Each tube's color intensity represents its hourly utilization level.

V. SMART II+

SMART II+ is a Swarm-based [1] extension to SMART II. SMART II itself builds on several other models [2-3].

SMART II+ includes an integrated set of agents and interconnections representing each of the following:

- The electric power marketing and transmission infrastructure.
- The natural gas marketing and distribution infrastructure.
- The interconnections between the two infrastructures in the form of natural gas fired electric generators.

Both of the infrastructures modeled in SMART II+ include many features:

- Two different kinds of agents, producers and consumers, represent the market participants.
- Interconnections represent transmission or distribution systems with capacities on each line or pipe and complex routing.
- Important economic issues are considered such as investment capital, demand growth for successful consumers, new generation capacity for profitable producers, and bankruptcy for noncompetitive organizations.
- Components can be disabled in real time to simulate failures.

The electric power infrastructure includes the added feature of natural gas fired electric generators. These generators buy fuel from the natural gas market. The resulting electricity is then sold in the electric power market.

A. SMART II+ Producer Agents

SMART II+ producers determine their production level based on the potential profit to be made. Each producer has investment capital that is increased by profits and reduced by losses. If a producer reaches a predetermined level of investment capital it can purchase additional production capacity in the form of new electric generators or new natural gas sources. New producers are similar to their parent producer and can connect to the distribution network in either the same location or a new one. Producers that run out of investment capital go bankrupt and no longer participate in the market. Producers choose whether or not to sell energy based on either their cost curves or natural gas prices. Standard producers derive their costs and capacities from cost curves with maximum generation limits as shown in Figure 4. Both costs and capacities are exogenous.

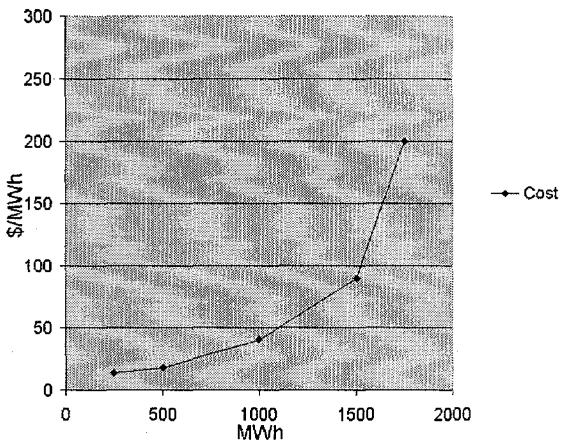

Figure 4: An example producer cost curve

Natural gas fired electric generators derive their costs and capacities from the endogenous natural gas market. These generators are consumers in the natural gas marketplace. Their costs are based on the price they pay for natural gas. Their capacities are based on both the amount of natural gas they can purchase and their design limits.

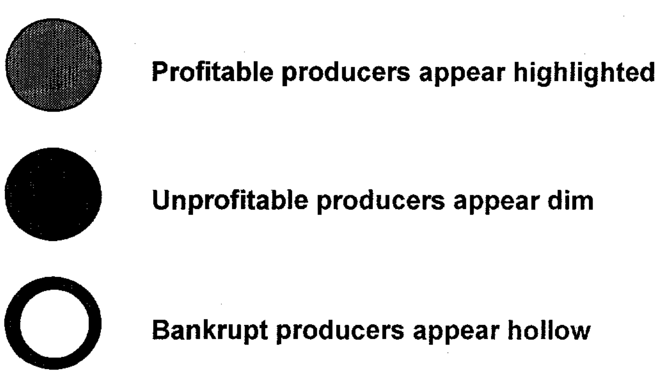

Figure 5: Producer Appearance

Producer simulation display appearance depends on current profit levels (Figure 5).

B. SMART II+ Consumer Agents

SMART II+ consumer agents buy energy for their own use. Businesses buy fixed amounts of energy to remain in business. Populations buy fixed amounts of energy to live their lives. Natural gas fired electric generators buy natural gas to produce salable electric power.

Each consumer has investment capital that is increased by profits and reduced by losses. If a consumer reaches a predetermined level of investment capital it can grow in the form of new consumers. Consumers that run out of investment capital go bankrupt and no longer participate in the market.

Consumer simulation display appearance depends on current profit levels (Figure 6).

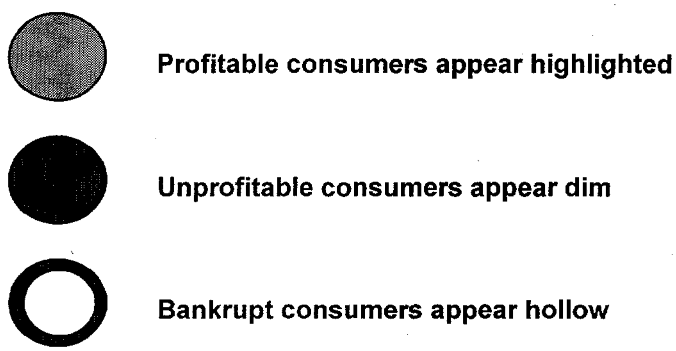

Figure 6: Consumer Appearance

Investment capital represents several things. For industrial users it is their total financial capital. For individuals it is the employment and personal opportunities that keep them in an area or encourage them to leave.

C. SMART II+ Interconnections

Interconnections represent transmission lines or distribution pipes each with an individual capacity limit. Individual capacity limits vary by interconnection type. Central transmission lines or main distribution pipes have high capacity limits and are drawn with thick marks. Outlying transmission lines or secondary distribution pipes have moderate capacity limits and are drawn with medium marks. Feeder lines or pipes have low capacity limits and are drawn with thin marks. Interconnection color represents contents and usage as shown in Figure 7.

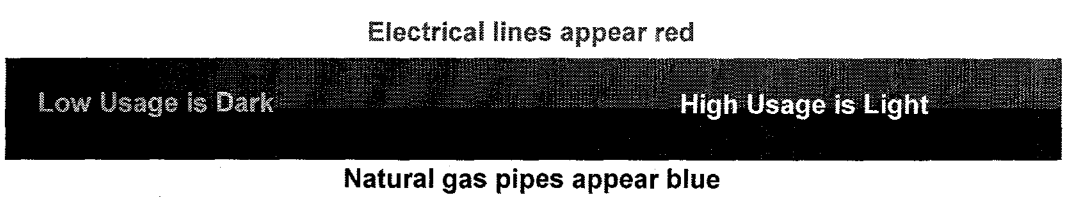

Figure 7: Interconnection Appearance

D. SMART II+ Market Indicators

The key SMART II+ market indicators are market prices, unserved energy and natural gas fired electrical generator market share. All key SMART II+ indicators are represented by graphs updated in real time.

Market price is the per unit purchase price of the given energy resource. Electric power prices are given in tenths of a cent per kilowatt-hour (Mills/KWh). Natural gas prices are given in dollars per thousand cubic feet ($/1,000 cubic feet). The SMART II+ price graphs are shown in Figure 8.

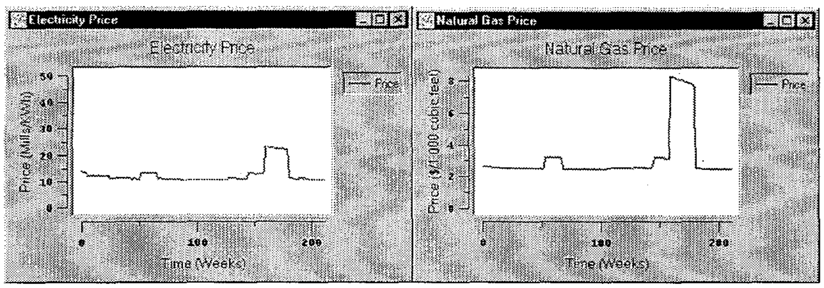

Figure 8: Price Graphs

Unserved energy (UE) is the energy demand that was not met by the market. UE represents a form of market failure. UE is given as a percentage of total energy demand. The SMART II+ UE graph is shown in Figure 9.

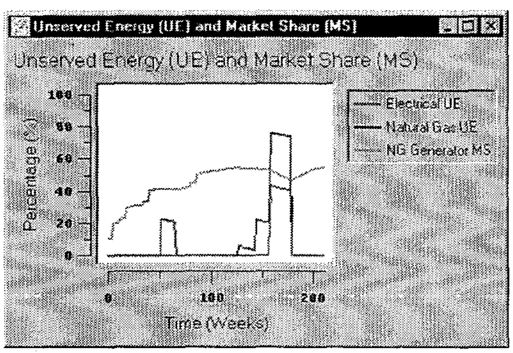

Figure 9: UE and NG Generator MS Graph

Natural gas fired electric generator market share (NG Generator MS) is a measure of the electric generation capacity that is supplied by natural gas units. NG Generator MS is key to infrastructure interdependency. NG Generator MS is given as a percentage of total capacity. The SMART II+ NG Generator MS graph is also shown in Figure 9.

E. SMART II+ Network Display

The geographical SMART II+ display is based on an equivalenced network. An example notional SMART II+ network is shown in Figure 10.

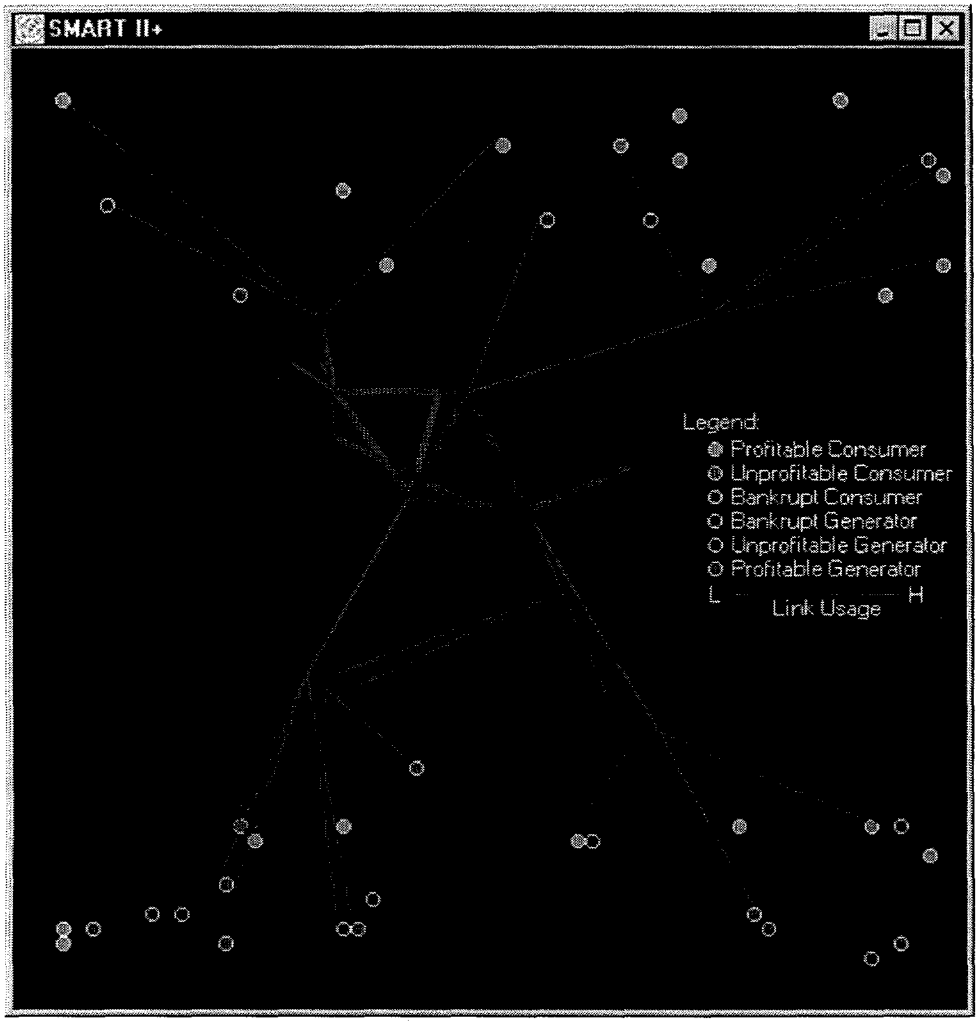

Figure 10: Example Notional SMART II+ Network

F. SMART II+ Validation and Calibration

As with SMART II, SMART II+ has undergone initial qualitative validation by matching its outputs to basic analytic predictions:

- Markets with a single superior producer among a large number of higher cost competitors have been tested.
- Markets with many identical participants have been tested.

SMART II + has undergone initial qualitative calibration by comparing the model's natural gas-fired electric generator market share trends to those found in real systems.

Much more work is clearly required to quantitatively validate and quantitatively calibrate SMART II+ therefore only limited qualitative insights are currently being derived.

G. SMART II+ Insights

As originally presented to our research sponsors in May 2000, preliminary insights from SMART II+ indicate that:

- Rising natural gas-fired electrical generator market share radically increases market interdependence.
- Increasing market interdependence can pit the electric power and natural gas markets against one another during simultaneous failures since both markets are fighting for the same underlying resource, natural gas.

This interdependency insight was borne out in the aftermath of the recent El Paso natural gas pipeline explosion.

What is the state of the world today? Nationwide natural gas-fired electrical generator market share is roughly 15% to 20%. Nationwide natural gas-fired electrical generator market share is expected to radically increase over the next five years. J.P. Morgan analysts predict that there is expected to be a 31% increase in generation capacity [5]. These analysts predict that roughly 95% of new electrical generation capacity will come from natural gas-fired units [5]. An example is the midwestern region dominated by Commonwealth Edison (ComEd).

ComEd presently gets less than 10% of its current 20,000 MW generation capacity from natural gas-fired generators. Permits are being issued for the construction of 8,000 MW of new capacity, over 95% of which will be natural gas-fired.

The interdependency between the electric power and natural gas markets implies that when natural gas-fired electrical generator market share becomes high enough a single energy resource, "virtual natural gas," is being traded in both markets. Viewing energy systems from the perspective of virtual natural gas suggests that future electrical system capacity expansion planning should explicitly feature the natural gas distribution infrastructure as a key component. Power Systems Engineers should note that electrical models might be substantially incomplete without explicitly including the natural gas infrastructure. Highly distributed electrical generation plans including local load servicing schemes may especially benefit from this view since they rely heavily on the existence of other energy sources such as natural gas.

VI. FAST

FAST is an integrated infrastructure model based on SMART II+. FAST includes many of the features of SMART II+ along with improvements in modeling infrastructure, detail and fidelity. FAST is currently under construction. FAST has three components:

- FAST:Run is the runtime infrastructure that will be merged with the University of Chicago's RePast open source agent-based modeling framework [6].
- FAST:E is the electric power system model.
- FAST:G is the natural gas system model.

FAST:Run is designed to be a lightweight large-scale system with the following major features:

- FAST:Run is written entirely in Java.
- FAST:Run is fully distributed.
- FAST:Run has a multithreaded scheduler that focuses on maximizing parallel execution.

The underlying design paradigm of FAST is that of a time continuum ranging from decades to seconds:

- On the scale of decades the focus is long term human decisions constrained by economics.
- On the scale of years the focus is short-term human economic decisions constrained by economics.
- On the scale of months, days and hours the focus is short-term human economic decisions constrained by economics and physical laws.
- On the scale of minutes or less the focus is on physical laws that govern energy distribution systems.

Modeling over the full range of time scales is necessary to understand the complex infrastructure interdependency between the electric power and natural gas markets.

FAST includes a large number of different agents to model the full range of time scales. The focus of agent rules in FAST varies to match the time continuum. Over longer time scales human economic decisions dominate. Over shorter time scales physical laws dominate.

Many FAST agents are relatively complex or "thick" compared to typical agents. FAST agents are highly specialized to perform diverse tasks ranging from acting as Independent System Operators to being transmission lines. To support specialization, FAST agents include large numbers of highly specific rules.

The FAST system and its component agents will be subjected to rigorous quantitative validation and calibration.

VII. Conclusion

Developing the initial capability to create CAS models requires substantial organizational investment. Once this initial investment has been made tools can be created that allow many insights.

VIII. Acknowledgement

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IX. References

[1] Burkhart, R., M. Askenazi, and N. Minar. Swarm Release Documentation. Available as http://www.santafe.edu/projects/swarm//swarmdocs/set/set.html.

[2] VanKuiken, J.C., T.D. Veselka, K.A. Guziel, D.W. Blodgett, S. Hamilton, J.A. Kavicky, V.S. Koritarov, M.J. North, A.A. Novickas, K.R. Paprockas, E.C. Portante, and D.L. Willing, APEX User's Guide (Argonne Production, Expansion, and Exchange Model for Electrical Systems) Version 3.0, ANL/DIS/TM-21, Argonne National Laboratory, Argonne, Ill., 485 pages (November 1994).

[3] Veselka, T.D., E.C. Portante, V.S. Koritarov, S. Hamilton, J.C. VanKuiken, K.R. Paprockas, M.J. North, J.A. Kavicky, K.A. Guziel, L.A. Poch, S. Folga, M.M. Tompkins, and A.A. Novickas, Impacts of Western Area Power Administration's Power Marketing Alternatives on Electric Utility Systems, ANL/DIS/TM-10, Argonne National Laboratory, Argonne, Ill., 216 pages (January 1994).

[4] Pape, D., C. Cruz-Neira, M. Czernuszenko CAVE User's Guide. Available as http://www.evl.uic.edu/pape/CAVE/prog/CAVEGuide.html (1997).

[5] Anderson, J.A., "What's Electrifying Natural Gas," Business Week, (September 19, 2000).

[6] Collier, N. and D. Sallach. RePast. Available as http://repast.sourceforge.net/.