E-LABORATORIES: AGENT-BASED MODELING OF ELECTRICITY MARKETS*

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ABSTRACT

Electricity markets are complex adaptive systems that operate under a wide range of rules that span a variety of time scales. These rules are imposed both from above by society and below by physics. Many electricity markets are undergoing or are about to undergo a transition from centrally regulated systems to decentralized markets. Furthermore, several electricity markets have recently undergone this transition with extremely unsatisfactory results, most notably in California. These high stakes transitions require the introduction of largely untested regulatory structures. Suitable laboratories that can be used to test regulatory structures before they are applied to real systems are needed. Agent-based models can provide such electronic laboratories or “e-laboratories.” To better understand the requirements of an electricity market e-laboratory, a live electricity market simulation was created. This experience helped to shape the development of the Electricity Market Complex Adaptive Systems (EMCAS) model. To explore EMCAS' potential as an e-laboratory, several variations of the live simulation were created. These variations probed the possible effects of changing power plant outages and price setting rules on electricity market prices.

INTRODUCTION

Electric utility systems around the world continue to evolve from regulated, vertically integrated monopoly structures to open markets that promote competition among suppliers and provide consumers with a choice of services. The unbundling of the generation, transmission, and distribution functions that is part of this evolution, creates opportunities for many new players or agents to enter the market. It even creates new types of industries, including power brokers, marketers, and load aggregators or consolidators. As a result, fully functioning markets are distinguished by the presence of a large number of companies and players that are in direct competition. Economic theory holds that this will lead to increased economic efficiency expressed in higher quality services and products at lower retail prices. Each market participant has its own, unique business strategy, risk preference, and decision model. Decentralized decision-making is one of the key features of the new deregulated markets.

Many of the modeling tools for power systems analysis that were developed over the last two decades are based on the implicit assumption of a centralized decision-making process. Although these tools are very detailed and complex and will continue to provide many useful insights into power systems operation (Conzelmann et al., 1999; Koritarov et al., 1999, Harza, 2001), they are limited in their ability to adequately analyze the intricate web of interactions among all the market forces prevalent in the new markets. Driven by these observations, Argonne National Laboratory's Center for Energy, Environmental, and Economic Systems Analysis (CEEESA) has started to develop a new deregulated market analysis tool, the Electricity Market Complex Adaptive Systems (EMCAS) model. Unlike those of conventional electric system models, the EMCAS agent-based modeling (ABM) techniques do not postulate a single decision maker with a single objective for the entire system. Rather, agents are allowed to establish their own objectives and apply their own decision rules. The complex adaptive systems (CAS) approach empowers many agents to learn from their previous experiences and change their behavior when future opportunities arise. That is, as the simulation progresses, agents can adapt their strategies, based on the success or failure of previous efforts. Genetic algorithms are used to provide a learning capability for certain agents. With its agent-based approach, EMCAS is specifically designed to analyze multi-agent markets and allow testing of regulatory structures before they are applied to real systems; that is, EMCAS can be used as an electronic laboratory or "e-laboratory."

The paper first provides some background information on agent-based modeling. It then introduces EMCAS as a new long-term deregulated market simulation tool. Next, it describes two of the central agents in the model, discusses an EMCAS prototyping approach, and finally presents results from an initial EMCAS simulation run.

OVERVIEW OF THE AGENT-BASED MODELING CONCEPT

The complex interactions and interdependencies between electricity market participants are much like those studied in Game Theory (Picker, 1997). Unfortunately, the strategies used by many electricity participants are often too complex to be conveniently modeled using standard Game Theoretic techniques. In particular, the ability of market participants to repeatedly probe markets and rapidly adapt their strategies adds additional complexity. Computational social science offers appealing extensions to traditional Game Theory.

Computational social science involves the use of ABMs to study complex social systems (Epstein and Axtell, 1996). An ABM consists of a set of agents and a framework for simulating their decisions and interactions. ABM is related to a variety of other simulation techniques, including discrete event simulation and distributed artificial intelligence or multi-agent systems (Law and Kelton, 2000; Pritsker, 1986). Although many traits are shared, ABM is differentiated from these approaches by its focus on achieving "clarity through simplicity" as opposed to deprecating "simplicity in favor of inferential and communicative depth and verisimilitude" (Sallach and Macal, 2001).

An agent is a software representation of a decision-making unit. Agents are self-directed objects with specific traits. Agents typically exhibit bounded rationality, meaning that they make decisions using limited internal decision rules that depend only on imperfect local information. Emergent behavior is a key feature of ABM. Emergent behavior occurs when the behavior of a system is more complicated than the simple sum of the behavior of its components (Bonabeau et al., 1999).

A wide variety of ABM implementation approaches exist. Live simulation where people play the role of individual agents is an approach that has been used successfully by economists studying complex market behavior. General-purpose tools such as spreadsheets, mathematics packages, or traditional programming languages can also be used. However, special-purpose tools such as Swarm, the Recursive Agent Simulation Toolkit, StarLogo, and Ascape are among the most widely used options (Burkhart et al., 2000; Collier and Sallach, 2001).

Several electricity market ABMs have been constructed, including those created by Bower and Bunn (2000), Petrov and Sheblé (2000), as well as North (2000a, 2000b, 2001). These models have hinted at the potential of ABMs to act as electronic laboratories or "e-laboratories" suitable for repeated experimentation under controlled conditions.

THE EMCAS CONCEPT

EMCAS is an electricity market model related to several earlier models (VanKuiken, et al., 1994; Veselka, et al., 1994). The underlying structure of EMCAS is that of a time continuum ranging from hours to decades. Modeling over this range of time scales is necessary to understand the complex operation of electricity marketplaces.

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. In EMCAS, time scales equate to decision levels. There are six decision levels implemented in the model, with decision level 1 representing the smallest time resolution, that is, the hourly or real-time dispatch. Decision level 6 on the other side is where agents perform their long-term, multi-year planning.

EMCAS includes a large number of different agents to model the full range of time scales (see Figure 1). The focus of agent rules in EMCAS varies to match the time continuum. Over longer time scales, human economic decisions dominate. Over shorter time scales, physical laws dominate. Many EMCAS

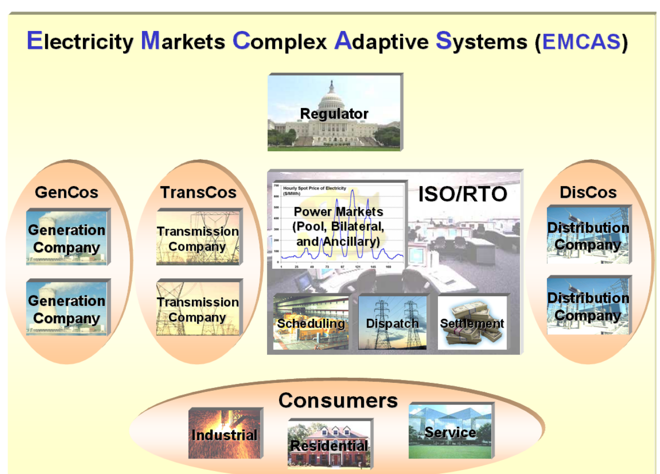

Figure 1: EMCAS Structure and Agents

agents are relatively complex or "thick" compared to typical agents. EMCAS agents are highly specialized to perform diverse tasks ranging from acting as generation companies to modeling transmission lines. To support specialization, EMCAS agents include large numbers of highly specific rules. EMCAS agent strategies are highly programmable. Users can easily define new strategies to be used for EMCAS agents and then examine the marketplace consequences of these strategies. EMCAS and its component agents are currently being subjected to rigorous quantitative validation and calibration.

THE EMCAS ARCHITECTURE

The EMCAS model consists of two components, a simulation server and an interface client, both of which are currently under development. The EMCAS simulation server uses the new ABM approach to simulate deregulated electricity marketplaces. The EMCAS interface client uses a web-based approach to permit shared universal access to the EMCAS model.

The EMCAS simulation server is written in Java. Java directly supports object-oriented implementation, allowing the EMCAS simulation server to be easily extended. Java also supports complex multithreading, allowing the EMCAS simulation server to maximize concurrent execution. The simulation server is designed to use Java Remote Method Invocation (RMI) for distributed computing. Java RMI allows distributed simulation runs across all major platforms, including large computing clusters. The simulation server uses extensible markup language (XML) for data storage. XML is an open, worldwide standard supported by virtually all major software vendors. Because XML is highly portable, EMCAS can be easily interconnected with external data sources, models, and tools.

The EMCAS interface client uses Dynamic Hypertext Markup Language (DHTML) and Scalable Vector Graphics (SVG), allowing it to be displayed in all major web browsers. The interface client can be used anywhere in the world that a server is available via the Internet or on portable computers without a network connection but with a local server. An example of the EMCAS interface client is shown in Figure 2. This simple network illustrates the use of nodes and links. Individual generators, generation companies, and load centers are represented as nodes. Transmission branches are represented as links.

EMCAS AGENT: GENERATION COMPANY

In theory, the decision-making process for a generation company agent (GCA) bidding into a perfectly competitive pool market that pays the clearing price is relatively simple; that is, bid energy at marginal production costs. The realities of today's emerging electricity markets, however, do not always fit this straightforward economic model. Depending on the market rules under which it operates, a GCA can sell its products through various markets, including short- and long-term bilateral contracts, a pool clearinghouse, and as ancillary services. Because electricity markets tend to be highly volatile and uncertain, the decision-making process for GCAs is difficult. This difficulty is compounded by the fact that each GCA does not have perfect

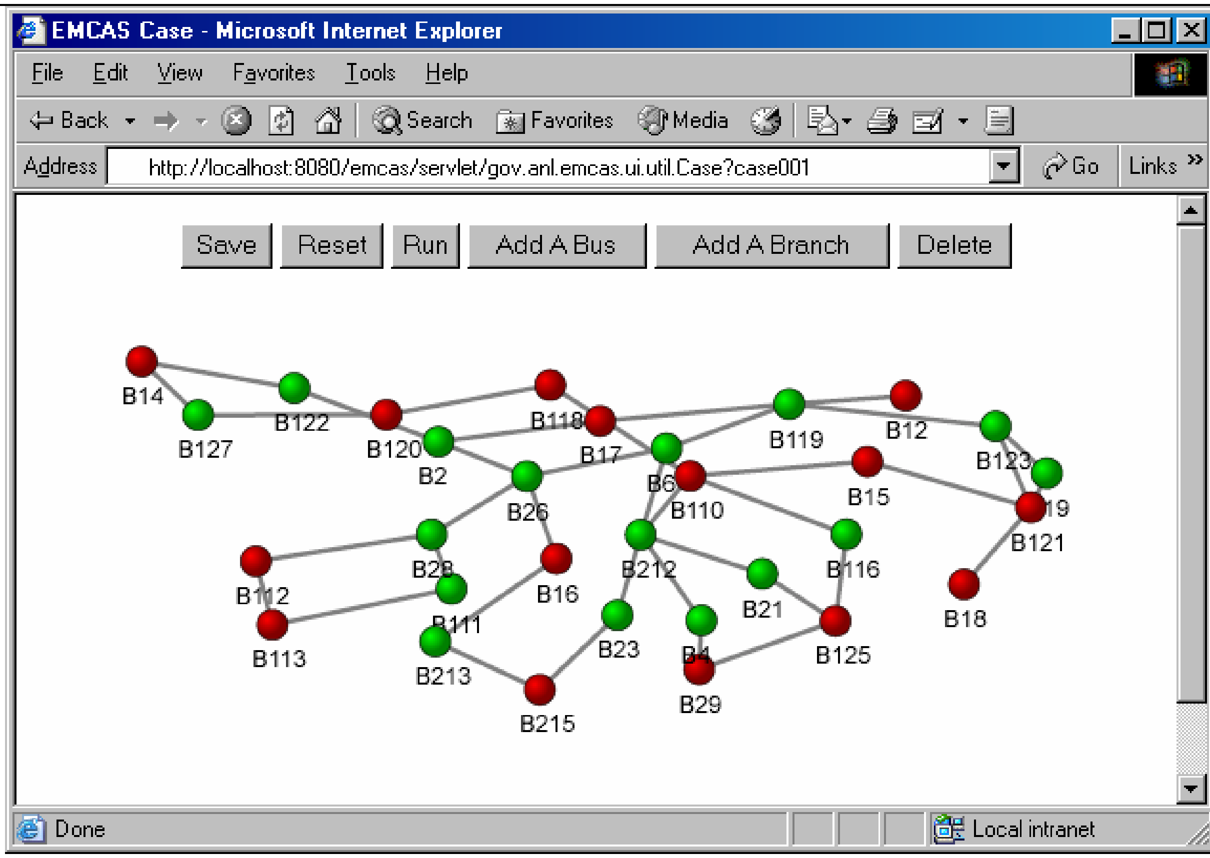

Figure 2: The EMCAS Interface Client

knowledge about other players in the market and how these players have behaved in the past and how they will behave in the future.

Electricity markets do not always meet the criteria of a perfect market. Limited generation capabilities and constraints in the transmission system will under some conditions lead to conditions whereby GCAs have the potential to exercise market power and drive up prices. Power markets are further complicated by the fact that electricity cannot be readily stored, and in some markets, consumers are insulated from market prices by regulated tariffs. Also, expanding generation capacity for both new and existing market players is at times politically difficult, expensive, and takes years from the time that a new project is envisaged to the time that it produces power.

The EMCAS modeling system is designed to simulate the behavior of GCAs and the marketing strategies that emerge as GCAs strive to exploit the physical limitations of the power system and the market rules under which they operate. GCAs can sell products in various markets. In EMCAS, a GCA learns the extent to which local and regional prices are influenced by its marketing strategies. This learning process is based on an “explore and exploit” process. Agents explore various marketing and bidding strategies. Once a strategy is found that performs well, it is exercised (i.e., exploited) and fine-tuned as subtle changes occur in the marketplace. When more dramatic market changes take place and a strategy begins to fail, an agent more frequently explores new strategies in an attempt to adapt to the dynamic and evolving supply and demand forces in the marketplace. Even when a strategy continues to perform well, a GCA periodically explores and evaluates other strategies in its search for one that performs better. However, the exploration rate tends to be significantly lower than under stressful conditions.

A GCA uses a corporate utility function as a yardstick to measure the success of a strategy. This corporate utility includes factors such as company profits and risk factors. Each GCA has its own corporate utility that uniquely characterizes the goals of the company. Over time the corporate utility will evolve as the market changes and as the company redefines its goals. Similar to exploring new market strategies, company goals are more frequently redefined and evaluated under stressful conditions. The characteristics of generation facilities that it owns, the location of its resources, and the unique characteristics of its corporate objects provides for a large degree of diversity among GCAs. Therefore, GCAs do not all follow the same market strategy or make the same decisions under a specific set of circumstances.

In EMCAS, a GCA is comprised of several building blocks that represent different tasks or actions an agent can perform. Each GCA seeks to arrange and parameterize these building blocks in a way that allows the market player to maximize its corporate utility. A building block consists of a set of one or more relatively simple rules. For example, one very simple agent rule may be "if the GCA set the marketing clearing price in the last bidding period then the GCA bid price in the next period will be fractionally higher." One parameter in this building block specifies the rate of change in the bid price.

Although the basic building blocks are available to all GCAs, an exploited strategy may not utilize a building block if it discovers that it is not beneficial. However, if market conditions change or if the GCA discovers a new way to combine the building block with another one, it can be used to develop a new strategy. When a GCA owns and operates more than one generating unit, an integrated strategy is formulated, and the combined affects of unit-level actions are important. This may entail losing money at one facility to gain more profits at another one.

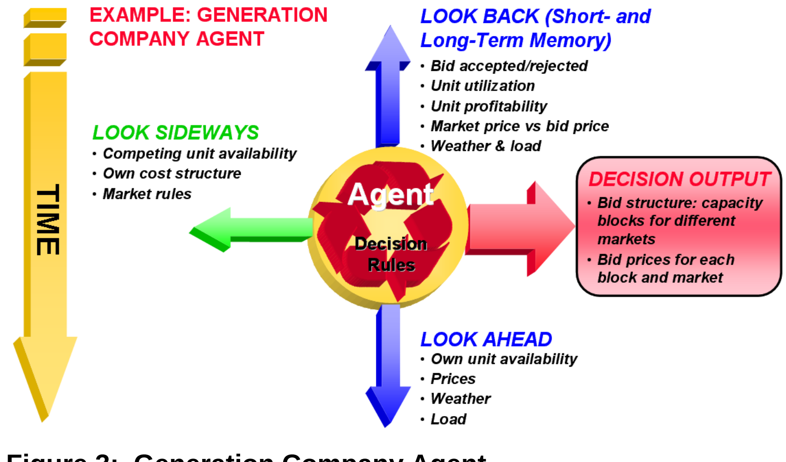

Figure 3: Generation Company Agent

An EMCAS agent makes decisions based on past experiences and anticipated conditions in the future (Figure 3). It also makes its decisions in the context of current market rules and the potential impact that other players will have on markets. A GCA keeps an ongoing record of historical events. These records (i.e., memory) are only available to the GCA and are not made available to other GCAs or the general public. Other information such as system outages, loads, and locational market prices is posted by the independent system operator on a publicly available bulletin board. Both the GCA's own records and public information are used to make projections about the future market-clearing price and the potential influence that its strategy has on prices.

Bidding strategies are a function of the anticipated market conditions. A GCA keeps a history of the strategies employed in the past and how well strategies performed under various supply and demand conditions. After a decision is made and it is acted out in the virtual market, a GCA's history file is updated, and the performance of the decision is evaluated and recorded. This leads to different market behaviors under different conditions. For example, when demand is low and capacity reserve margins are high, a GCA may bid production costs. When demand is high and reserve margins are tight, however, a GCA may exploit a strategy where bids are significantly higher than its production costs.

EMCAS agents also use historical records to fine-tune strategies. A GCA probes the market by pushing or extending a successful strategy a bit further than it had in the past (e.g., increase bilateral price bids). If this action proves successful, it may use this information to continue to extend the strategy further in the future. If the action is not successful, it may lose money, but it has gained information about the market.

The success of any GCA strategy is not guaranteed. Therefore, the GCA weighs the relative rewards of success against the costs and risks of failure. The anticipated success or failure rate is

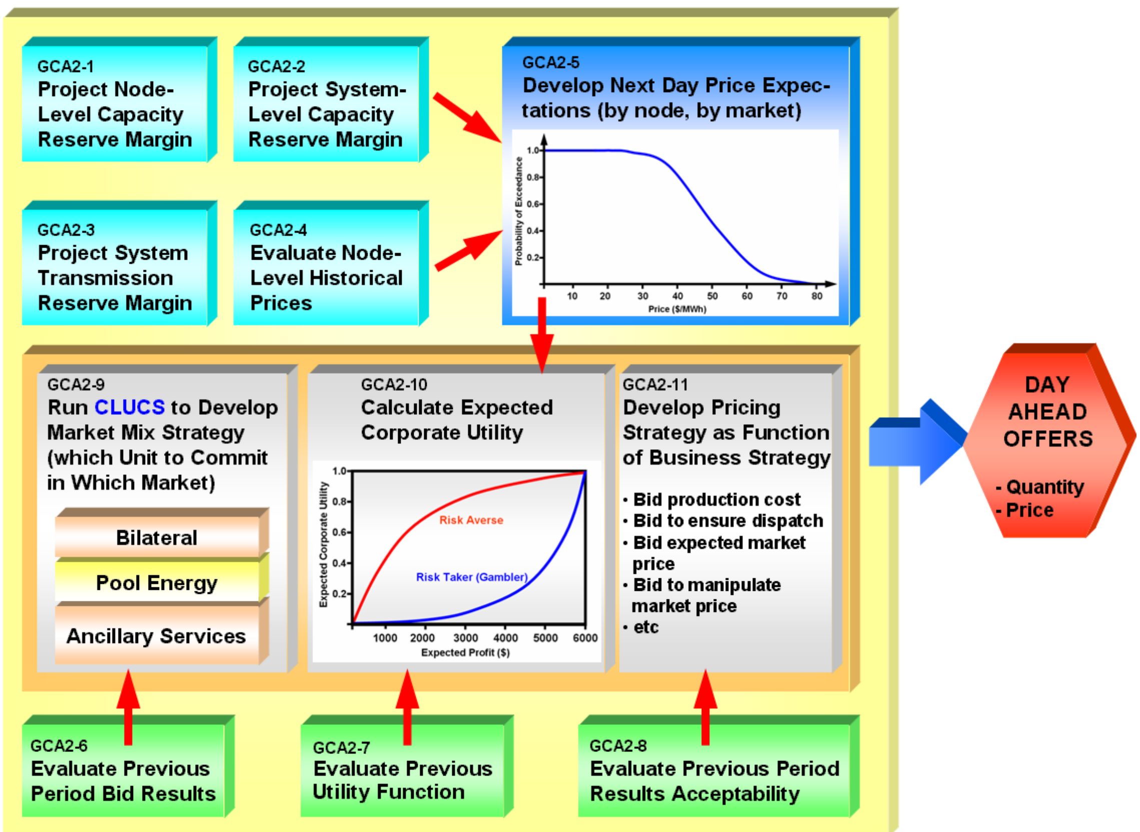

Figure 4: Generation Company Agent Decision Process

based on the GCA's past experiences (i.e., history). The level of risk that a GCA is willing to take is an integral part of its corporate utility. More conservative companies that have a lower tolerance for risk may have lower profits but have a steady stream of income. More aggressive companies may have the potential for higher profits but experience financial failure if anticipated market behaviors do not come into fruition.

Figure 4 shows the decision process used by a GCA in developing its bid portfolio. By using a dynamic set of historical information, which is updated as the simulation moves along, the agent develops price expectations by network location or node for each of the markets (bilateral contracts, energy, and ancillary services). The model accounts for the uncertainty in this process by generating a probability distribution, or a price exceedance probability curve. Together with an evaluation of previous bid portfolio results, the GCA determines the optimal unit commitment strategy by running the Company-Level Unit Commitment and Scheduling (CLUCS) subroutine. CLUCS determines the best market mix and essentially determines which unit (each unit can be split into up to 10 blocks) to commit to which of the available bilateral, energy pool, or ancillary services markets. The expected utility can now be constructed as a function of corporate strategy (risk taker, risk averse) and may account for multiple individual objectives, such as profit, risk preference, etc. A GCA will then develop a pricing strategy for its portfolio of generating assets that maximizes its corporate utility.

The EMCAS modeling system operates at six time scales or decision levels (see Figure 5). At each decision level, generation company agents must make decisions regarding the operation of the generating resources they manage and market strategies:

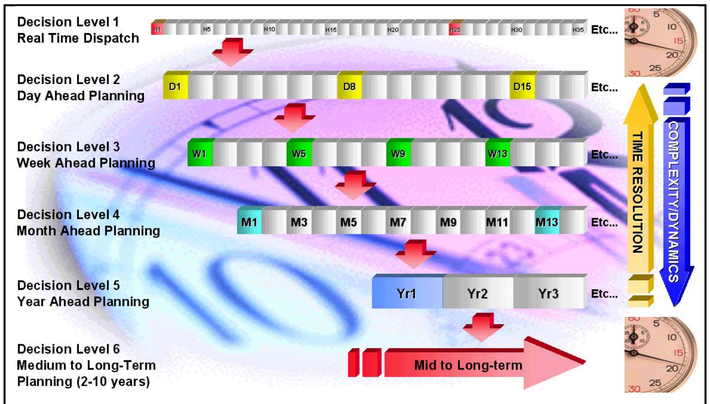

Figure 5: EMCAS Time Scales and Decision Levels

Hourly/Real-Time Dispatch: Power plants are operated as directed by the ISO in accordance with prior market arrangements made under bilateral contracts and in energy/ancillary service markets.

Day-Ahead Planning: Agents determine market allocations (i.e., splits among day-ahead bilateral contracts, energy, and ancillary services) for selling its products. It makes unit commitment schedules for the next day. Deals are made with individual demand agents, and energy bids are sent into the ISO.

Week-Ahead Planning: Weekly bilateral contracts are made with individual demand agents and are sent to the ISO for approval. Day-ahead marketing strategies are adjusted to improve performance during the upcoming week.

Month Ahead Planning: Monthly bilateral contracts are made with individual demand agents and sent to the ISO for approval. Adjustments can be made to unit maintenance schedules.

Month-ahead marketing strategies are adjusted to improve performance during the upcoming month.

Year Ahead Planning: Monthly bilateral contracts are made with individual demand agents and sent to the ISO for approval. Planned maintenance schedules are determined. Month-ahead marketing strategies are adjusted to improve performance during the upcoming year. The corporate utility may also be adjusted. New construction schedules are revised.

Multi-year Ahead Planning: Agents make multi-year bilateral contracts. Capacity expansion plans are formulated. Year-ahead marketing strategies are adjusted to improve performance during the upcoming year.

In EMCAS not all agents make decisions at the same time. For example, only a fraction of the GCAs will make adjustments to day-ahead strategies each Monday of the week. In addition to scheduled decision making, strategies may be adjusted or new strategies may be explored. Adjustment and exploration are done more frequently under stressful conditions.

The EMCAS modeling framework and the methodology used to simulate GCAs serve as an electronic laboratory in which various market rules and systems can be tested.

EMCAS AGENT: INDEPENDENT SYSTEM OPERATOR OR REGIONAL TRANSMISSION ORGANIZATION

The Independent System Operator (ISO) or Regional Transmission Organization (RTO) agent is responsible for operating the transmission grid in order to supply power to loads while maintaining safety and reliability. Through the EMCAS interface, the user can specify a variety of ISO operating rules and study the impact of various policy issues on market performance. Parameters that can be modified include the required levels of regulation, spinning, non-spinning, and replacement reserves. The user can choose among different price setting rules; that is, is it a pay-as-bid market or is the pool market clearing price based on the locational marginal price. Other inputs determine energy market settlement rules as well as ancillary service markets and transmission services.

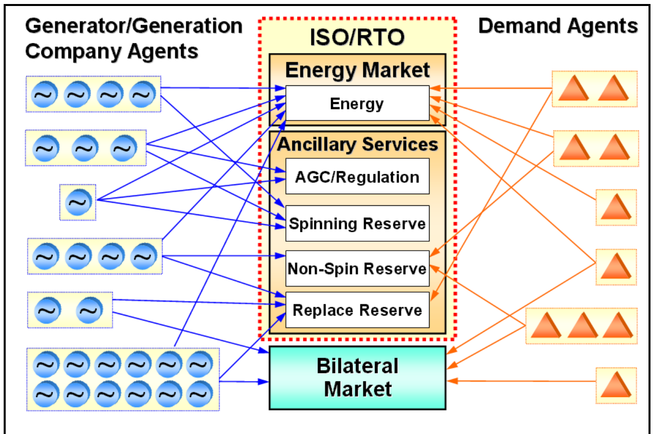

Figure 6: ISO/RTO Pool Market Function

The ISO/RTO has five main functions: (1) projection, (2) pool market operation, (3) generator scheduling, (4) unit dispatching, and (5) market settlement.

Under the *projection function*, the ISO/RTO forecasts for the next day weather (e.g. maximum and minimum temperatures), system demand, and system available generation capacity. This information is available for all market participants as part of a market information system or public bulletin board.

Under the *pool market function*, the ISO/RTO operates a pool market for energy and ancillary services (Figure 6). Generation companies and demand agents can submit their bids into these markets, and the ISO determines the unconstrained market clearing price (MCP). Transmission costs, congestion charges, if any, and other security requirements are added on to compute the locational marginal price (LMP) by node.

Under the *scheduling function*, the ISO/RTO runs the day-ahead System-Level Unit Commitment and Scheduling (SLUCS) subroutine to accept or reject the pool market bids and bilateral contracts (Figure 7). SLUCS optimizes over a 24-hour period, determines the next-day schedule for the generators, and computes the LMP at each network node. As part of the scheduling function, a load flow analysis will be conducted to take into account potential transmission congestion (see next section).

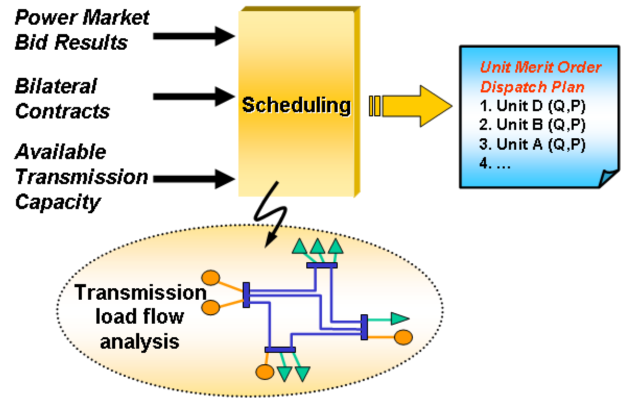

Figure 7: ISO/RTO Scheduling Function

Under the *dispatching function*, the ISO/RTO dispatches the generators in real time to match the demand and maintain the necessary security requirements. In case of sudden loss of generation or transmission, the ISO/RTO will utilize the ancillary service bids to operate the system and supply the demand. Real-time LMPs are calculated, if there is any deviation from the day-ahead schedule.

Under the *settlement function*, the ISO/RTO applies the settlement rules selected by the user to calculate the payments to and receipts from the generating companies, demand agents, and transmission companies. Any difference between the real-time schedule and the day-ahead schedule is settled based on day-ahead LMPs and real-time LMPs.

ISO/RTO LOAD FLOW ANALYSIS

EMCAS simulations are conducted at the bus- and branch level, that is, generators, transmission buses and lines, and customer form the physical system configuration (Figure 8). The Argonne Load Flow (ALF) module of EMCAS simulates the power flows in the transmission network that is operated by the ISO/RTO. ALF is an AC/DC load flow model with capabilities to solve load flow problems of fairly large networks. Transmission networks can have up to 60,000 buses, 100,000 branches, 20,000 transformers, 5,000 shunts, and 1,000 control areas. The module provides users with a variety of convenient ways to manipulate input and output data. ALF also gives a choice of Newton-Raphson and fast decoupled methods for solving the AC power flow problem.

In addition, ALF has a set of useful network reduction techniques that allow the user to reduce the size of the original transmission network into an equivalent smaller modeling representation. This is a critical step for the power market simulation in EMCAS, as most ISO/RTO-operated transmission grids are quite large; and performing a full-scale AC power flow analysis on an hourly basis would be rather impractical. EMCAS, therefore, is designed to utilize an equivalent reduced transmission network to simulate hourly operation of the power market and determine power flows between different market zones.

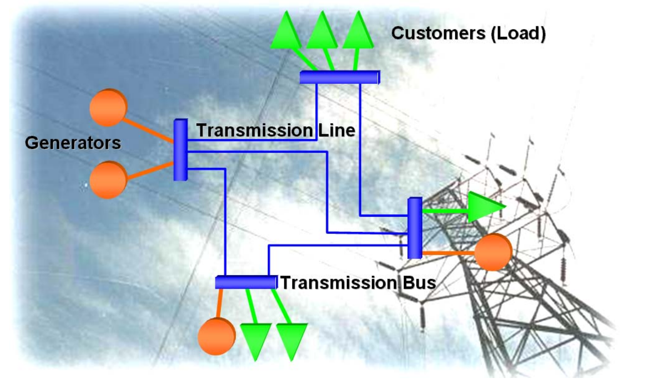

Figure 8: EMCAS Transmission Network Elements

The reduced network provides an equivalent modeling representation of the market zones and interzonal transmission links for the calculation of LMPs. The market zones are frequently referred to as price zones because most electricity markets assume no transmission congestion within a single market zone. Therefore, the equivalent reduced network in EMCAS is designed to reflect the composition of the actual market zones. The power transfer capacities of interzonal transmission links typically correspond to the power transfer capabilities of the actual transmission lines among market zones. ALF employs several network reduction and equivalencing techniques. Depending on the criteria used in the process, network reductions can be performed by:

1. Minimum voltage level,
2. Maximum branch impedance,
3. Bus number, and
4. Control area.

In principle, each of these network reduction techniques can be applied either alone or in combination with other criteria. In addition, all of these network reduction techniques can be applied with or without creating a modeling equivalent of the external network and with or without the optimization of the internal network.

Once established, the reduced transmission network is utilized by EMCAS for hourly simulations of the power market operation. This modeling representation of the transmission system remains in use until some major change in the topology of the transmission grid (e.g., major line outage, etc.) requires a different modeling representation of the equivalent reduced network. In this case, ALF is used again to run the AC load flow analysis of the modified transmission grid and create a new equivalent reduced network that corresponds to the new network topology.

Besides the AC power flow, ALF also has DC load flow modeling capabilities. EMCAS uses the DC load flow algorithm during the hourly market simulations for the modeling of transmission constrained unit scheduling and dispatch and to determine power flows on the interzonal transmission links. Also, for point-to-point power transactions such as bilateral contracts, ALF can calculate the power transfer distribution factors (PTDFs) that determine the corresponding flows on the transmission lines and take into account necessary requirements for the transmission capacity. Also, PTDFs are later used for the billing of transmission use charges associated with this type of power transaction.

EMCAS PROTOTYPING: A POWER MARKET SIMULATION GAME

To better understand the requirements of an electricity market e-laboratory, a live electricity market simulation was created. The market game that was developed used individuals to play the role of generation companies. One additional person played the role of the ISO/RTO.

Each generation company in the market simulation game had three identical generators. The generators included a small natural-gas-fired turbine generator, a medium-sized natural-gas-fired combined cycle unit, and a large coal-fired power plant. Players were allowed up to five bid blocks for each unit. Players submitted bids electronically. The bids were collected and used by the system operator. Players based their bids on public information electronically posted by the system operator. This information included historical and projected prices, demands, supply, and weather.

The system operator collected the players' bids on a periodic basis and used to them to simulate the operation of an electricity spot market. The simulation calculated MCPs and player profits based on internally derived demands, supplies, and weather. The actual simulation demands, supply, and weather differed from the publicly posted projections by small random amounts. Generating units also suffered from unannounced random outages.

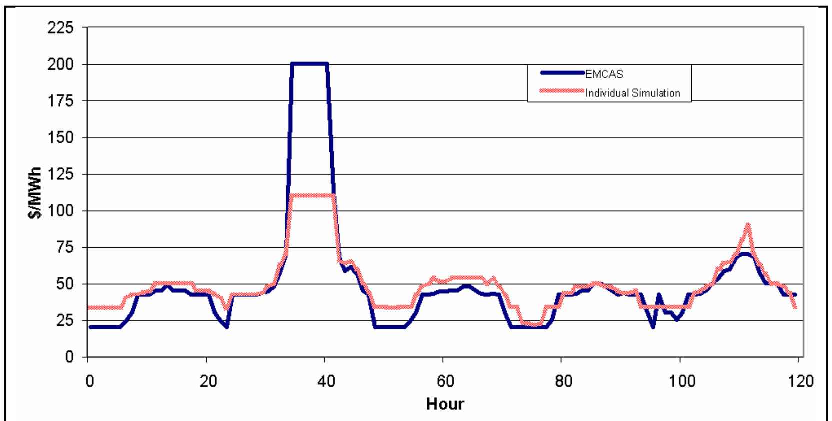

Figure 9: Market Clearing Prices - EMCAS versus Market Game

An initial market simulation game was run with six players. The price results from this run are shown in Figure 9. Subsequently, a second market game with 10 players was run. Experience from these market simulation games suggested that the development of an electricity market ABM might be extremely beneficial. This experience helped to shape the development of EMCAS.

EMCAS AND THE GAME

An EMCAS case has been created based on the previously described market game. Specific agents representing individual market game players were implemented by using EMCAS' agent architecture. The strategies of the individual players were determined by asking them to write short descriptions of their approaches after the completion of the game and then following up the writing with a series of focused interviews. Once the strategies were determined, agents implementing each of the strategies were programmed.

The individual agents developed to emulate the market game players were run using the same data originally used for the game. The resulting prices are similar to those found in the individual market game as shown in Figure 9. The main difference is that the prices near hour 40 are higher in the EMCAS case because the EMCAS agents were programmed to use the evolved final strategies of the players. Many of the market game players had begun the game using a relatively cautious approach to bidding. As the game progressed, they learned to become much more aggressive. For example, several players developed "hockey stick" strategies that have low prices for the majority of each generator's capacity followed by extremely high prices for the last few megawatts. This approach can be effective because players have little to risk and much to gain. The risk is minimal because the vast majority of their generation bids are likely to be accepted. The gain is potentially high because MCP pricing will assign the last few megawatts high prices to all generation during times of shortage. The result lends new meaning to the hockey term "high sticking."

The EMCAS agents were programmed with the final, more aggressive strategies of the human players. Thus, EMCAS tended to have higher prices throughout the simulation. Once EMCAS was able to replicate the original market game, it was used to explore its suitability as an e-laboratory.

CHANGING THE RULES

To explore EMCAS' potential as an e-laboratory, several variations of the original market game case were created and simulated. These variations probed the effects of changing power plant outages and price setting rules on electricity market prices. As previously mentioned, EMCAS and its component agents are currently being subjected to rigorous quantitative validation and calibration. All of the EMCAS results presented here are intended to explore EMCAS' potential to be used as an e-laboratory. As such, they are not intended to represent complete analyses of the issues described.

Figure 10 shows the results for the baseline case. This EMCAS run assumes a Pay-MCP market without power plant outages with prices closely following the assumed daily load pattern. The first variation to the base case that was tested was the effect of power plant outages in a Pay-MCP market. The hourly prices are shown in Figure 11. In this example, the overall effect of power plant outages is to greatly increase market prices during periods of peak demand. This suggests that an important concern for regulators setting pricing rules is the relative balance between system supply and demand. In particular, systems that have demands that approach the

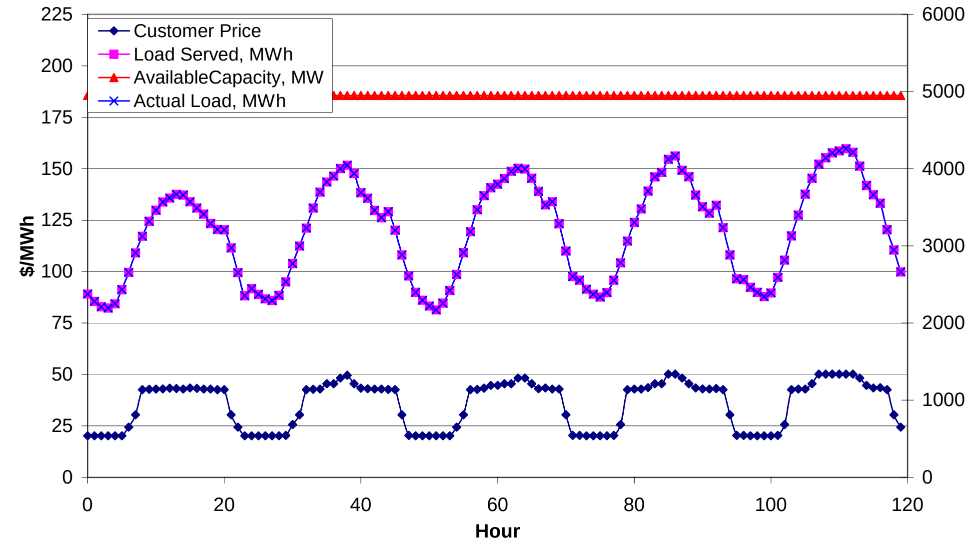

Figure 10: Pay-MCP without Power Plant Outages

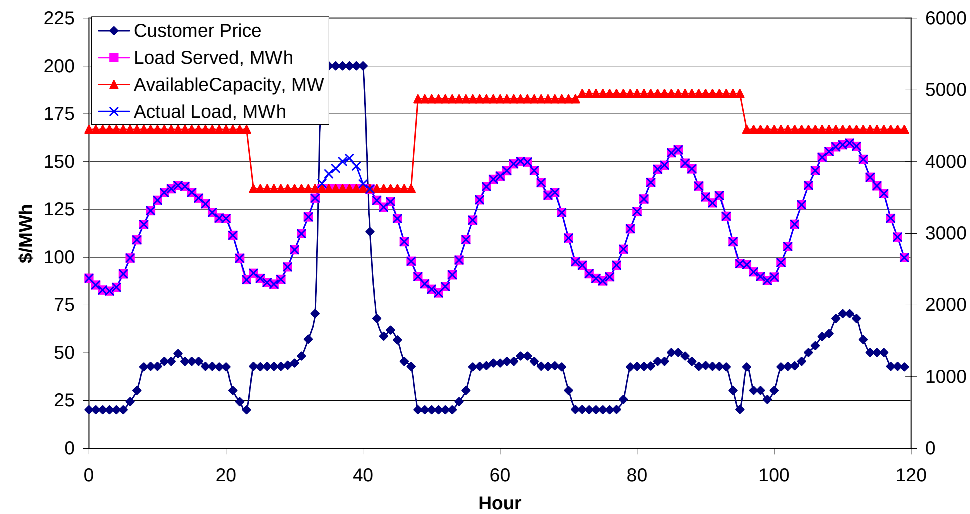

Figure 11: Pay MCP with Power Plant Outages

maximum generation supply may experience significant price spikes under Pay-MCP. Such systems might fare better under Pay-as-Bid because they could potentially be victimized by strategies such as high sticking.

In the second variation, the market was set up as Pay-as-Bid. Agent pricing strategies were suitably modified to reflect the new price setting rule. The actual hourly loads, the hourly loads served, the available generation capacity, and the resulting hourly prices are shown in Figure 12. In this case, all of the loads were served, so the actual hourly loads and the hourly loads served are the same. In this example, the overall effect of Pay-as-Bid is to noticeably reduce price fluctuations. This observation suggested a third experiment.

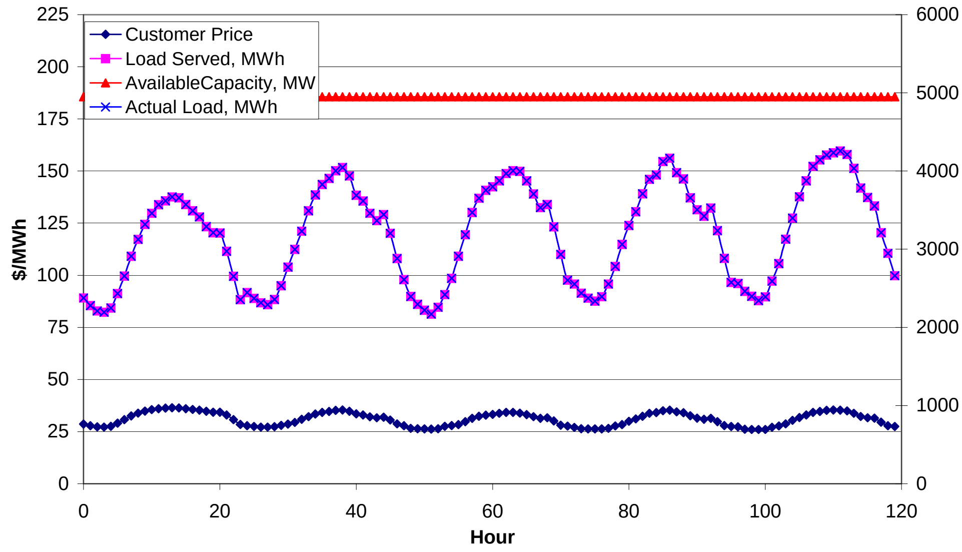

Figure 12: Pay-as-Bid without Power Plant Outages

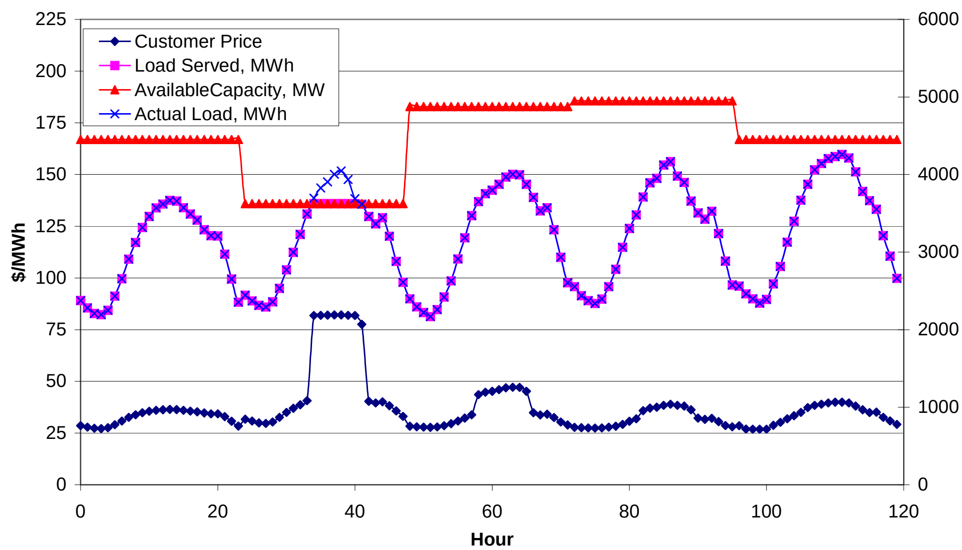

Figure 13: Pay-as-Bid with Power Plant Outages

The third variation looked at the effect of Pay-as-Bid price setting with power plant outages. As before, agent pricing strategies were suitably modified to reflect the price setting rule. The hourly prices are shown in Figure 13. As with the previous Pay-as-Bid example, in this run, the overall effect is to substantially reduce price volatility compared to Pay-MCP, particularly during times when high demands intersect with reduced supplies.

THE PROFIT MOTIVE

Considering the lower and more stable prices found under Pay-as-Bid, it appears that this form of pricing is better for consumers under this simplified model run. Producers, however, may have a different view. While prices are lower and more stable under Pay-as-Bid, producers lose money under this approach, as shown in Figure 14. Naturally, unprofitable markets tend to drive producers out. This can greatly reduce long-term competition and result in cyclical price trends with long periods. Clearly, market rules must balance the interests of producers and consumers in order to preserve long-term market stability.

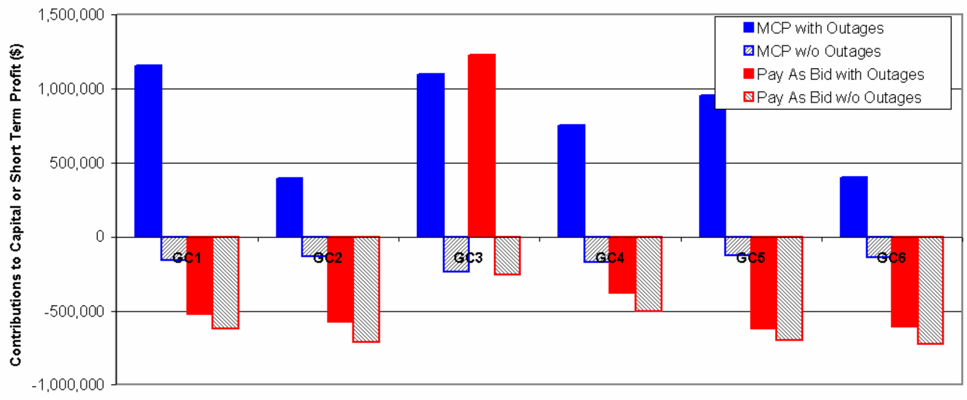

Figure 14: Generation Company Profits under Various Market Rules and Outages Regimes

CONCLUSIONS

As electric utility systems around the world continue to move toward open, competitive markets, the need for new modeling techniques will become more obvious. Although traditional optimization and simulation tools will continue to provide many useful insights into market operations, they are typically limited in their ability to adequately reflect the diversity of agents participating in the new markets, each with unique business strategies, risk preferences, and decision processes. Rather than relying on an implicit single decision maker, ABM techniques, such as EMCAS, make it possible to represent power markets with multiple agents, each with their own objectives and decision rules. The CAS approach allows analysis of the effects of agent learning and adaptation. The simple test runs presented in this paper clearly demonstrate the value of using EMCAS as an e-laboratory, where regulatory structures can be tested before they are applied to real systems.

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