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Integrated retail and wholesale power system operation with smart-grid functionality

Dionysios C. Aliprantis
Iowa State University, dionysis@purdue.edu

Scott Penick
Iowa State University

Leigh Tesfatsion
Iowa State University, tesfatsi@iastate.edu

Integrated Retail and Wholesale Power System Operation with Smart-Grid Functionality

Dionysios Aliprantis, *Senior Member, IEEE,*, Scott Penick, *Student Member, IEEE,*,
Leigh Tesfatsion, *Member, IEEE*, and Huan Zhao

Abstract—Our research team is developing an agent-based test bed for the integrated study of retail and wholesale power markets operating over transmission and distribution networks with smart-grid functionality. This test bed seams together two existing test beds, the AMES Wholesale Power Market Test Bed and the GridLAB-D distribution platform. As a first step, we have designed an integrated retail/wholesale market module specifically based on the ERCOT (Texas) energy region, and we are using simplified versions of this module to study potential retail consumer response to real-time-pricing contracts supported by advanced metering. This study reports on the latter work.

Index Terms—Restructured power markets, smart grid, retail competition, real-time pricing, demand response, agent-based test bed

I. INTRODUCTION

RETAIL and wholesale power market operations are intrinsically interdependent. Moreover, these market operations are constrained by transmission and distribution networks supporting underlying power flows. Power systems thus entail complicated dynamic couplings of market and physical system operations [1].

The main goal of the project reported in this study is to develop an agent-based test bed that permits the comprehensive study of power systems from both economic and engineering points of view. Our particular focus is the integrated study of retail and wholesale power markets operating over transmission and distribution grids with "smart-grid functionality."

By *smart-grid functionality* we mean service-oriented grid enhancements permitting more responsiveness to retail customer needs and preferences. An example of such an enhancement would be the installation of residential meters that can be read automatically and that support two-way communication between retail consumers and their suppliers, thus permitting a flexible array of contracts ranging from flat-rate to real-time pricing.

The specific context for the wholesale power market portion of our test bed is the design recommended in a 2003 White Paper [2] by the U.S. Federal Energy Regulatory Commission (FERC) for common adoption by North American wholesale power markets, referred to below as the *Wholesale Power Market Platform (WPMP)*. As depicted in Fig. 1, versions of the WPMP design have been implemented (or adopted for implementation) in energy regions encompassing over 50% of U.S. generating capacity. These energy regions include the Midwest (MISO), New England (ISONE), New York
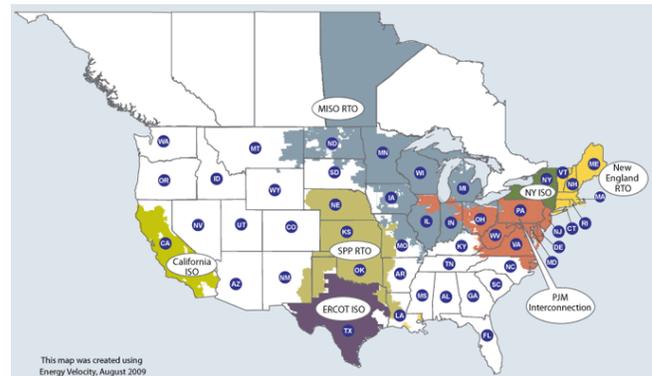
Fig. 1. North American energy regions that have adopted FERC's wholesale power market design. Source: www.ferc.gov/industries/electric/indus-act/rto/rto-map.asp

(NYISO), the Mid-Atlantic States (PJM), California (CAISO), the Southwest (SPP), and Texas (ERCOT).

The core design element of the WPMP is a two-settlement system to be managed by an *Independent System Operator (ISO)* or *Regional Transmission Organization (RTO)*. Roughly, a *two-settlement system* refers to the combined workings of a day-ahead energy market and a real-time energy market that are separately settled each day by means of *Locational Marginal Pricing (LMP)*. Under LMP, a separate price for power is determined at each point of the transmission grid at which power is injected or withdrawn.

As envisioned in the WPMP, and implemented in practice, the wholesale day-ahead market is structured as a double auction. *Load-Serving Entities (LSEs)* are permitted to submit hourly demand bids consisting of both fixed and price-sensitive hourly demands, and *Generation Companies (GenCos)* are permitted to submit hourly supply offers consisting of price-sensitive hourly supplies.

In actuality, however, the day-ahead market effectively functions as a single-sided seller auction because the bulk of the demand takes the form of fixed hourly loads (i.e., load profiles) implying essentially vertical hourly demand curves. As elaborated in [3], a key difficulty is that downstream retail power markets in the U.S. are still largely regulated with cost-based pricing, so that LSEs in fact have little incentive to submit price-sensitive demand bids.

Even in states that have nominally introduced retail competition, the use of extended default service contracts and long-term wholesale procurement contracts reduces market entry and contributes to the persistence of vertical demand curves

in wholesale day-ahead markets. As experimentally shown in [4], under this scenario energy sellers are easily able to learn to implicitly collude on reported supply offers involving higher-than-true marginal costs that result in much higher market operating costs.

These adverse market performance characteristics suggest the need for an integrated restructuring of both retail and wholesale power markets. Rather than use actual systems as test beds, however, we are developing an agent-based test bed that seams together two previously developed agent-based test beds:

- AMES [5], an open-source software platform developed by a team of researchers at Iowa State University for the study of strategic trading in ISO-operated restructured wholesale power markets with congestion managed by LMP.
- GridLAB-D [6], an open-source software platform developed by the U.S. Department of Energy at Pacific Northwest National Laboratory (PNNL) for the study of power distribution systems for end-use customers with power loads arising from a variety of modeled appliances and equipment.

The resulting seamed test bed will permit us to pre-test, through intensive systematic experimentation, how an integrated restructuring of retail and wholesale power markets might best be implemented. Of particular interest will be the systematic experimental exploration of recent "smart grid" proposals for improving supply adequacy and the efficiency of overall power system operations, where "efficiency" refers to the non-wastage of current and future resources.

Specifically, four closely-related research topics will be pursued under this project by means of systematic experiments conducted within this seamed test bed, in combination with analytical and empirical studies. Refs. [7]–[12] provide important background materials for these topics.

The first research topic concerns the potential effectiveness of bottom-up *demand response (DR)* initiatives. What are the potential impacts of increased price-responsiveness of demand (e.g., through advanced metering infrastructure or demand response programs) on supply adequacy and the efficiency of market operations? In particular, what are the most appropriate designs for pricing contracts and financial risk-management tools under alternative mixtures of real-time and flat-rate pricing?

The second research topic will focus on *distributed energy resources (DER)*, including both distributed generation and distributed storage facilities. What are the desirable types, sizes, and sitings of DER from a social efficiency viewpoint? Examples of possible consumer-owned DER are depicted in Fig. 2.

The third research topic will focus on grid architecture issues. Will proposed restructurings of the distribution and/or transmission networks to incorporate *microgrid*[1] and other transformations of grid architecture help to improve both supply adequacy and system efficiency? Could market operations

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[1]By a *microgrid* we mean an integrated electrical energy system composed of interconnected energy sinks and sources that can operate in parallel with the distribution grid or in an intentional island mode.
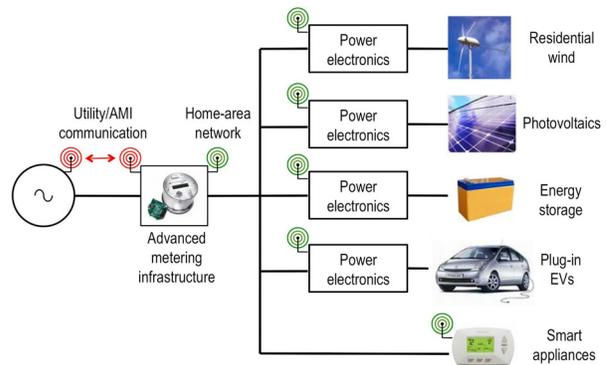

Fig. 2.   Consumer-owned distributed energy resource possibilities.

be used to control local grids in "islanded" mode (under grid contingencies) with increased penetration of distributed generation? How can the market "sense" a disturbance (i.e., blackout), and re-dispatch itself to supply critical local load based on available generation?

The fourth research topic will focus on smart-grid devices and "agent intelligence." What kind of software should be preferably embedded in a smart device? How much computational complexity is required for implementation, and how does it affect cost? What learning algorithm(s) should the agents use? Do some algorithms outperform others, and in what ways? Which ones benefit the users more?

This study reports project work to date. Section II reports on the preliminary development of an integrated retail/wholesale power market model based on Texas (ERCOT). Section III presents preliminary research on retail contracting issues using simple analytical models based on this market module. Test bed seaming issues are addressed in Section IV. The final Section V provides concluding remarks.

II. CASE STUDY: ERCOT

As an important initial step towards the development of our seamed AMES/GridLAB-D test bed, we are developing an empirically-grounded integrated retail/wholesale market model specifically based on the market structure implemented by the *Electric Reliability Council of Texas (ERCOT)*.

We have chosen ERCOT as our initial empirical benchmark because ERCOT appears to have moved further than any other U.S. energy region towards the integrated restructuring of its retail and wholesale power market operations [11]. ERCOT is currently in the process of implementing a two-settlement wholesale power market system (separate real-time and day-ahead market settlements) with transmission grid congestion managed by LMP. Moreover, ERCOT is vigorously pursuing implementation of smart-grid initiatives such as smart metering. For example, in December 2009 ERCOT launched a new system of wholesale settlement for its advanced metered customers based on their 15-minute electric energy usage [13].

A. Modeling the ERCOT Distribution System

Of all the issues involved in modeling a distribution system for the study of the implementation of smart-grid technology,
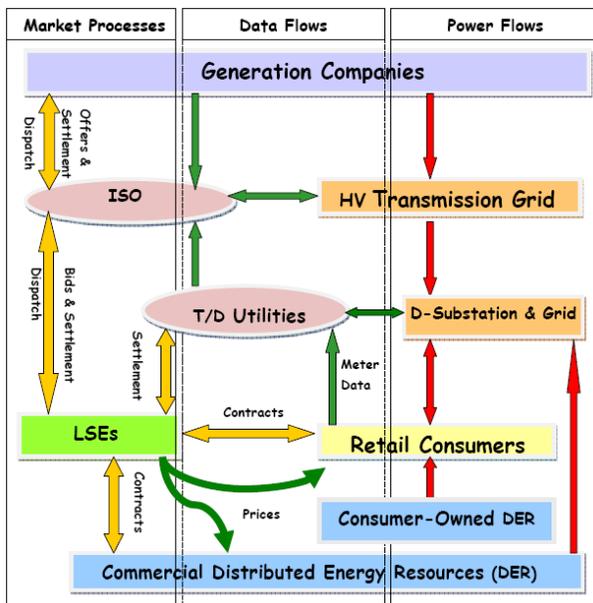
Fig. 3.   Integrated retail and wholesale market structure in ERCOT

Fig. 4.   Principal organizations in ERCOT involved in electric energy retail operations. Source: http://www.ercot.com/services/rq/lse/

finding accurate non-proprietary data for distribution systems is one of the most difficult. Ref. [14] reports compiled data from distribution systems throughout the nation. To compensate for lack of data, the authors propose a statistical method for modeling the distribution systems within a region that are representative of the real system.

Although ERCOT is relatively small compared with the other six restructured U.S. energy regions, it nevertheless spans a large area of land. In particular, ERCOT has significantly different climate regions, which in turn affects retail demand conditions. Consequently, the distribution system modeling method proposed in [14] could potentially be useful for our project.

B. Modeling Retail Competition in ERCOT

One important theme of electricity market reform in ERCOT has been the divestment of traditional utility operations. Specifically, Chapter 25 of the *Public Utility Commission of Texas (PUCT)* now requires that each electric utility shall separate its business activities and related costs into separate units handling generation, transmission, and distribution [15].

The result has been that retail competition in ERCOT is now realized through the separation of physical power flows from the financial contracting for power purchases and sales. As depicted in Fig. 3, power flow operations are managed by *Transmission and/or Distribution Utilities (TDUs)* whereas financial contracts are provided by LSEs.

More precisely, the LSEs purchase bulk power from the wholesale market and resell it to retail customers through various financial contracts. Typically, LSEs are not responsible for infrastructure construction and maintenance. Rather, they compete for retail customers. Customers can switch financial contracts or LSEs without power usage interference.

Fig. 4 depicts the key entities involved in ERCOT electric energy retail operation in greater detail. LSEs represent either
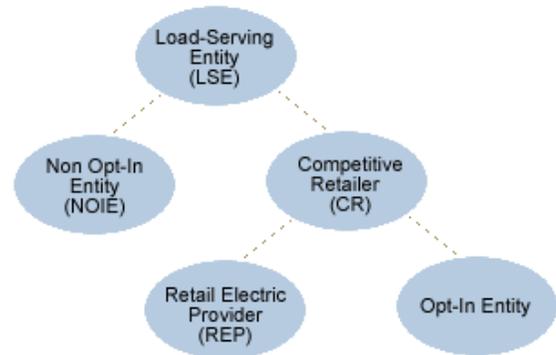
Competitive Retailers (CRs) or *Non Opt-In Entities (NOIEs)*. CRs are the only organizations authorized to sell electric energy to retail customers who have customer choice. NOIEs are electric cooperatives and municipally owned utilities that do not operate as CRs and do not plan to offer customer choice.

The CRs in ERCOT are further subdivided into *Retail Electric Providers (REPs)* and *Opt-In Entities (OIEs)*. A REP is an organization that contracts with qualified scheduling entities to provide scheduling services for their load customers. An opt-in entity is a municipally owned utility or co-operative that opts to offer customer choice.

Entry barriers for REPs in ERCOT are quite low. As reported in [16], by June 2008, 85 REPs were providing electric energy services to customers. These REPs were offering as many as 96 different products in various territories, including 13 REPs which were offering, between them, 23 different renewable energy options.

Electric service switching can be done smoothly with this business separation structure. CRs interact directly with ERCOT when submitting switching requests, where customers choose a new CR. ERCOT processes the switching requests by working with TDUs to obtain the initial and final meter reads, confirming switches with customers, and confirming the switch with the relevant CRs once the switch is approved. The rules for REP operation are evolving to deal with the ripple effects of REP bankruptcies. For example, ERCOT is currently in the process of finalizing its REP rules on disclosure and billing terms.

Various types of customer service contracts flourish in ERCOT's retail market. Indeed, ERCOT provides over 96 different types of contracts for its retail customers. These contracts are primarily differentiated in terms of the type of rate structure that is offered to meet different customer needs. For example, customers can choose among *fixed-price (FP)* contracts, *time-of-use (TOU)* contracts, and *real-time-price (RTP)* contracts.

Many retail customers in ERCOT have been prevented from taking advantage of RTP contracts due to lack of advanced meters, but this situation is changing. Indeed, ERCOT's recent major efforts to promote the spread and use of advance metering [13] could eventually support not only increased

RTP contracting for wholesale power but also contracts for the reverse sale of power from consumer-owned distributed energy resources back to the grid; see Fig. 2.

III. ILLUSTRATIVE ANALYTICAL FINDINGS

The restructuring of retail markets in ERCOT has primarily focused on the introduction of retail competition and RTP contracts. Ideally, retail competition should efficiently transfer price signals from wholesale markets to retail markets, while RTP should provide retail customers the opportunity to respond to fluctuating prices, thus increasing the price-elasticity of their electric energy demands. These two aspects of retail market restructuring are interconnected. Competition should enhance the implementation of RTP contracts, while RTP should provide more choices to the customer, making competition more meaningful.

Our initial studies (under the first research topic) are focused on how to use appropriate smart-grid technology to support retail competition and RTP deployment. These studies are empirically grounded in the real situation in ERCOT, which is in the forefront of retail competition.

The particular issue we consider is the effectiveness of electric energy contract choice from the point of view of the retail consumer. For example, Borenstein and Holland [17] point out that implementing RTP may not be cost-effective in light of the incremental billing and sophisticated metering costs. Also, the study of Faruqui and George [18] suggests that small customers are reluctant to shift energy usage in response to price signals. Using these and other related studies as basic background materials, we plan to explore the extent to which consumers would benefit from the availability of RTP contracts. We are also concerned with obtaining better estimates of the price elasticity of consumer demands for electric energy under different contract availability conditions, making use of detailed empirical data regarding energy requirements of electric appliances and typical weather conditions.

In the following subsections we present findings for a simple analytical model to shed some light on electric energy contract choice from the perspective of the retail consumer. We consider a short-run problem in which a budget-constrained utility-maximizing consumer chooses how much electric energy to consumer in two different periods, on-peak and off-peak, conditional on the terms of his existing electric energy contract. We then show that, under competitive retail conditions, the consumer will always be at least as well off under an RTP contract as under an FP contract, strictly so if wholesale prices differ across the two periods.

A. Electric Energy Contract Choice Model: Basic Set-Up

Consider a consumer on a particular day D who has the ability to shift his electric energy consumption between two different periods each day, on-peak and off-peak. Let b denote the consumer's choice of electric energy consumption for the on-peak period, and let b' denote the consumer's choice of electric energy consumption for the off-peak period. Also, let a denote the consumer's choice of consumption for a composite good other than electric energy. Hereafter it will be assumed

that the composite good a is a numeraire good in terms of which all other prices are evaluated, so that the price of the composite good itself is fixed at 1.

Suppose the consumer evaluates the utility of his electric energy consumption on day D by means of the following log-linear utility function:

$$U(b, b', a) = a + \alpha \ln b + \beta \ln b' \quad , \qquad (1)$$

where $\alpha > \beta > 0$. The latter assumption implies that the on-peak period is the more preferred consumption period in the following sense: starting from a common level of electric energy consumption in each period, the consumer could increase his utility by switching some amount of consumption from the off-peak to the on-peak period.

Suppose, also, that the consumer has available an income m for expenditures on day D, where m is measured in terms of the numeraire good a. His objective for day D is to maximize $U(b, b', a)$ with respect to selection of b, b', and a subject to the budget constraint

$$a \; + \; p^o \cdot b \; + \; p^f \cdot b' \; = \; m \quad , \qquad (2)$$

where p^o denotes the price paid by the consumer for on-peak electric energy and p^f denotes the price paid by the consumer for off-peak electric energy.

Solving the consumer's budget-constrained utility maximization problem, the consumer's optimal solution values for electric energy consumption during on-peak and off-peak periods are as follows:

$$b^*(p^o) \; = \; \frac{\alpha}{p^o} \quad \text{and} \quad b'^*(p^f) \; = \; \frac{\beta}{p^f} \quad . \qquad (3)$$

Plugging these solution values into the budget constraint (2) gives the consumer's optimal solution value

$$a^* \; = \; (m - \alpha - \beta) \qquad (4)$$

for consumption of the composite good a.

For later purposes, it is important to keep in mind that the electric energy prices p^o and p^f in (3) denote the electric energy prices that are *charged* to the retail consumer for electric energy consumption in the on-peak and off-peak periods. These prices might differ from the actual wholesale prices for electric energy in the on-peak and off-peak periods.

Hereafter the actual wholesale prices for electric energy in the on-peak and off-peak periods will be denoted by p and p', respectively. Note that any LSE contracting with the consumer for delivery of electric energy in the on-peak and off-peak periods must pay these actual wholesale prices, regardless of the prices it charges to the consumer.

B. Contract Prices and Consumer Welfare

We now need to consider the possible price configurations and the welfare of the consumer under different forms of electric energy contracts. For an FP contract, the price of electric energy is fixed at some level $\overline{p}$ regardless whether usage occurs in the on-peak or off-peak periods: $p^o = p^f = \overline{p}$. In contrast, under a RTP contract the price of electric energy

in each usage period is set at the level of the actual wholesale electric energy price: $p^o = p$ and $p^f = p'$.[2]

If the price for a good increases relative to the prices of other goods, a budget-constrained consumer will benefit (gain more utility) if he substitutes consumption of the lower-priced goods for consumption of the higher-priced good. Consequently, in the present example, an RTP contract should induce the consumer to shift his consumption towards the period with the lowest electric energy price, all else equal. The question still arises, however, whether the consumer is better off under an RTP contract than under an FP contract under all circumstances.

Making use of these solution values (3) and (4), the utility levels attained by the consumer conditional on either an RTP or an FP electric energy contract, given arbitrary positive values for the RTP contract prices (p, p') and the FTP contract price $\bar{p}$, are as follows:

$$U^{\text{RTP}} = (m - \alpha - \beta) + \alpha \cdot \ln \frac{\alpha}{p} + \beta \cdot \ln \frac{\beta}{p'} \quad ; \quad (5)$$

$$U^{\text{FP}} = (m - \alpha - \beta) + \alpha \cdot \ln \frac{\alpha}{\bar{p}} + \beta \cdot \ln \frac{\beta}{\bar{p}} \quad . \quad (6)$$

Consider, now, the possible settings for the FP contract price $\bar{p}$ in relation to the utility of the consumer. Suppose that an LSE only provides an FP contract to the consumer at a fixed price $\bar{p}$ if this fixed price is high enough to ensure the LSE covers its electric energy purchase costs in the wholesale market. The following restriction on $\bar{p}$ ensures that the LSE just "breaks even" in terms of covering its purchase costs, hence it determines the minimum fixed price that the LSE would be willing to set for its FP contract:

$$\bar{p} = \frac{[p \cdot b^*(\bar{p}) + p' \cdot b'^*(\bar{p})]}{[b^*(\bar{p}) + b'^*(\bar{p})]} \quad . \quad (7)$$

Assume that a large number of LSEs are competing for retail consumers in the particular region including the consumer at hand, so that the LSEs are all paying the same wholesale prices for servicing these consumers. Suppose that the fixed prices offered by these LSEs in their FP contracts are then driven down by competition to the level $\bar{p}$ satisfying (7).

Substituting into (7) the consumer's optimal electric energy consumption levels $b^*(\bar{p}) = \alpha/\bar{p}$ and $b'^*(\bar{p}) = \beta/\bar{p}$ under an FP contract with a fixed price $\bar{p}$, as determined from (3), one can solve for the *competitive fixed price* as follows:

$$\bar{p}^c = \frac{\alpha \cdot p + \beta \cdot p'}{\alpha + \beta} \quad . \quad (8)$$

Substituting the competitive fixed price (8) into the utility level (6) attained by the consumer under an FP contract, and comparing the results against the utility level (5) attained by the consumer under an RTP contract, the result is:

$$U^{\text{RTP}} = (m - \alpha - \beta) + \alpha \ln \alpha + \beta \ln \beta$$
$$- \alpha \ln p - \beta \ln p' \quad ; \quad (9)$$

$$U^{\text{FP}} = (m - \alpha - \beta) + \alpha \ln \alpha + \beta \ln \beta$$
$$- (\alpha + \beta) \cdot \ln(\frac{\alpha \cdot p + \beta \cdot p'}{\alpha + \beta}) \quad . \quad (10)$$

Using Jensen's inequality,[3] it is seen that that $U^{\text{RTP}} \geq U^{\text{FP}}$, and $U^{\text{RTP}} > U^{\text{FP}}$ when $p \neq p'$. Consequently, the utility attained by the consumer is at least as high under the RTP contract as under the FP contract, and strictly higher if the wholesale prices for on-peak and off-peak electric energy differ.

Note that the total electric energy amounts consumed under the two contract types are ambiguous. Moreover, it follows from the form of the consumer's budget constraint (2) and the consumer's optimal electric energy consumption solution (3) that the total expenditure on electric energy under each type of contract is the same: namely, $\alpha + \beta$. These findings are consistent with the findings in the U.S. Department of Energy's Pacific Northwest Testbed Demonstration on the Olympic Peninsula [7].

In some commentaries on retail restructuring, the benefits of restructuring are motivated in terms of lower electric energy usage or expenditures. Overall energy savings might be an appropriate concern from a social welfare point of view. However, from the point of view of individual consumers, the appropriate measure of welfare is their attained utility levels, since this is what will incentivize their behavior.

IV. TEST BED SEAMING ISSUES

We plan to investigate the interaction of retail and wholesale market by seaming AMES [5] with GridLAB-D [6]. A short introduction to the two test beds and the intended seaming work are outlined in this section.

A. The AMES Test Bed

As detailed in [19], AMES(V2.05) is an open-source Java package that simulates the operations of an ISO-administered wholesale power market with grid congestion managed by LMP. The AMES wholesale power market operates over an AC transmission grid starting with hour H00 of day 1 and continuing through hour H23 of a user-specified maximum day. AMES includes an ISO together with a collection of LSEs and GenCos distributed across the buses of the transmission grid.

The objective of the not-for-profit ISO is the maximization of *Total Net Surplus (TNS)*[4] subject to transmission constraints and GenCo operating capacity limits. In an attempt to attain this objective, the ISO operates a day-ahead energy market settled by means of LMP.

The welfare of each LSE j is measured by the net earnings it secures each day through the purchase of power in the day-ahead market and the resale of this power to retail customers.

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[2] In reality, a mark-up would presumably be included to cover servicing costs and provide a "normal" rate of profit for the LSE. These complications are not relevant for the points to be made in this section and so are omitted here for simplicity.

[3] Jensen's inequality in the form needed here is as follows. For any concave function $\phi(x)$ defined over the real line, real numbers $x_1, \ldots, x_n$, and positive weights $a_1, \ldots, a_n$, $\phi(\sum a_i x_i / \sum a_i) \geq \sum a_i \phi(x_i) / \sum a_i$.

[4] As explained more carefully in [20], TNS is the area between the aggregate demand curve derived from LSE demand bids and the aggregate supply curve derived from GenCo supply offers. When all demand bids are price inelastic, the TNS-maximization objective of the ISO reduces to the minimization of GenCo operational costs.

During the morning of each day D, each LSE j reports a *demand bid* to the ISO for the day-ahead market for day $D + 1$. Each demand bid consists of two parts: fixed demand (i.e., a 24-hour load profile) that can be sold downstream at a regulated rate r to retail customers with flat-rate pricing contracts; and 24 price-sensitive inverse demand functions (one for each hour) reflecting price-sensitive demand by retail customers with real-time pricing contracts.[5]

The objective of each GenCo i is to secure for itself the highest possible net earnings each day through the sale of power in the day-ahead market. During the morning of each day D, each GenCo i uses its current action choice probabilities to choose a supply offer from its action domain AD_i to report to the ISO for use in all 24 hours of the day-ahead market for day $D + 1$. This *supply offer* consists of a marginal cost function defined over an operating capacity interval. GenCo i's ability to vary its choice of a supply offer from AD_i permits it to adjust its reported marginal cost function and/or its reported operating capacity interval in an attempt to increase its daily net earnings.

After receiving demand bids from LSEs and supply offers from GenCos during the morning of day D, the ISO determines and publicly posts hourly LMP and dispatch levels for the day-ahead market for day $D + 1$. These hourly outcomes are determined via hourly *Security-Constrained Economic Dispatch (SCED)* formulated as hourly bid/offer-based DC optimal power flow (OPF) problems. Grid congestion is managed by the inclusion of congestion cost components in LMPs. At the end of each day D the ISO settles the day-ahead market for day $D + 1$ by receiving all purchase payments from LSEs and making all sale payments to GenCos based on the LMPs for the day-ahead market for day $D + 1$.

Each GenCo i at the end of each day D uses stochastic reinforcement learning[6] to update the action choice probabilities currently assigned to the supply offers in its action domain AD_i, taking into account its day-D settlement payment ("reward"). In particular, if GenCo i's supply offer on day D results in a relatively good reward, GenCo i increases the probability it will choose to report this same supply offer on day $D + 1$, and conversely.

In the absence of system disturbances (e.g., weather changes) or shocks (e.g., line outages), the dispatch levels determined on each day D for the day-ahead market for day $D + 1$ are carried out as planned without need for settlement of differences in the real-time market.

B. The GridLAB-D Platform

GridLAB-D [6] is an open-source software platform developed by the U.S. Department of Energy at Pacific Northwest National Laboratory (PNNL). It is designed for the study of

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[5]In the current released version (V2.05) of AMES, LSEs have no learning capabilities; LSE demand bids are user-specified at the beginning of each simulation run. However, as explained more carefully in [19], AMES includes a general learning module, JReLM, that can be used to implement a wide variety of stochastic reinforcement learning methods for cognitive agents. Extension to include LSE learning is planned for future AMES releases.

[6]This learning is implemented via the JReLM learning module; see footnote 5.

power distribution systems composed of retail customers with power loads arising from a variety of modeled appliances and equipment. Its core operating principles are its open-source architecture and its integration and interoperability with other software, such as AMES.

GridLAB-D currently has the functionality to simulate and solve AC power flow using three flow solvers (Gauss-Seidel, Kersting's method, and Newton-Raphson), which are selected depending on the circumstances and the modeler's preferences. Weather patterns from historical data [21] gathered by the National Renewable Energy Laboratory (NREL) are used to create random but realistic weather patterns from various regions throughout the United States.

Houses modeled within the simulation have their own thermal characteristics and will heat, cool, and operate appliances according to weather conditions and the household's economic constraints. GridLAB-D is bundled with a plethora of load models including clothes washers and driers, water heaters, electric vehicle chargers, lights, and others.

The ability of GridLAB-D to model distribution systems arising from realistic load models unlocks the ability to do countless possible studies regarding distribution equipment, lines, and transformers. One such possibility is calculating the loss-of-life effects on transformers due to loads arising from electric vehicle chargers, as mentioned in [22]. Looking at these factors can allow a more complete view of the economic impacts of various retail market pricing mechanisms.

C. Retail and Wholesale Market Seaming

In the current version of AMES, the LSE is the sole intermediary between the wholesale power market and downstream retail demand. On each day D the LSE forecasts its electric energy needs for each hour H of day $D + 1$ and then submits a 24-hour demand bid to the ISO for the day-ahead market on day $D + 1$ in an attempt to secure sufficient electric energy to meet these forecasted electric energy needs. Consequently, the LSE is the lynch pin for the proposed seaming of AMES with GridLAB-D at the market level.

In this project we intend to investigate three types of contracts for retail customers: FP, TOU, and RTP. Under an FP contract, the LSE promises to service its customers' electric energy demands at a flat rate $\overline{p}$, regardless of the wholesale electric energy price. Under a TOU contract, the LSE promises to service its customer's electric energy demands at a rate dependent only on time of use. Consequently, for any given hour, retail demands arising under either FP or TOU contracts translate into a fixed (price insensitive) demand for the LSE at wholesale for that hour.

On the other hand, under an RTP contract, a consumer's electric energy demand varies inversely with the wholesale electric energy price. Consequently, for any given hour, retail demands arising under RTP contracts translate into a price-sensitive demand function for the LSE at wholesale for that hour.

Fig. 5 illustrates the hourly wholesale demand bid of an LSE that services its retail customers under FP, TOU, and RTP contracts. The fixed demand under its FP and TOU contracts
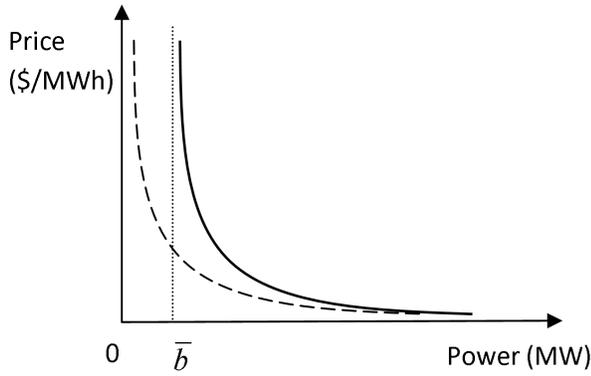
Fig. 5. Illustration of an hourly wholesale demand bid for an LSE with retail customers serviced under FP, TOU, and RTP contracts

is denoted by $\bar{b}$, whereas the price-sensitive demand under its RTP contracts is denoted by the dashed curve. The solid curve then represents the overall demand bid that the LSE submits to the ISO. A change in the portfolio of FP, TOU, and RTP contracts held by an LSE's retail consumers translates into a change in the shape of this solid curve.

As noted in Section IV-A, AMES already models hourly LSE demand bids as consisting of fixed and price-sensitive parts. Consequently, contract choice involving FP, TOU, and RTP contracts should be relatively easy to implement without extensive additional coding.

D. Transmission and Distribution Network Seaming

Currently we are envisioning seaming AMES and GridLAB-D via co-simulation as shown in Fig. 6. AMES will be used to simulate GenCos, LSEs, and an ISO engaging in a wholesale power market operating over a high-voltage (HV) transmission network. GridLAB-D will be used to simulate a TDU managing a lower-voltage (LV) distribution network servicing a region of retail consumers.

Seaming at the level of the two networks involves two key entities: the TDU, who reports data to the ISO for load forecasting and other purposes; and the distribution substation which steps down power from the HV transmission grid to the LV distribution grid for ultimate distribution to retail consumers.

AMES will resolve the HV transmission system and settlements in the real-time market with a timestep of ΔT_A on the order of 5 minutes. Concurrently, GridLAB-D will simulate the thermal and electrical status of the distribution network with a timestep of ΔT_G on the order of 1 second.

The two test beds will communicate every ΔT_C, on the order of 5 minutes. GridLAB-D will share with AMES actual load data arising from the retail consumers serviced by the distribution network, and AMES will share with GridLAB-D updated price and settlement information as needed to implement contractual arrangements between the LSEs and retail consumers. Each day, ΔT_D, GridLAB-D will share the weather forecast with AMES and AMES will share with GridLAB-D updated LSE contract information.

V. CONCLUDING REMARKS

Modern power systems are extraordinarily complex, involving trade networks operating over physical transmission networks at both the wholesale and retail customer levels. Fortunately, spectacular advances in computational power are increasing our ability to study the performance of such systems, taking into account both the power engineer's concern with network reliability and the economist's concern with market efficiency.

One such advance is *agent-based modeling (ABM)*, the representation and study of interactive processes as dynamic systems of interacting agents. Based on object-oriented programming concepts, ABM is a "culture dish" modeling approach that can accommodate a variety of real-world structural conditions, institutional constraints, and behavioral modes with relative ease. Starting from initial conditions specified by the modeler, all subsequent system events are driven solely by agent interactions. Those interactions are determined dynamically in run-time by the internal structures, informational states, beliefs, motivations, and data-processing methods of cognitive agents as channeled and constrained by their external environments.

This study summarizes proposed work on a challenging project involving the integrated study of retail and wholesale power system operation with smart-grid functionality. Our particular concern is pre-testing the reliability and efficiency implications of introducing advanced metering and contracting capabilities for retail customers.

Our project is innovative in three key regards. First, the project team has extensive professional expertise in power engineering, economics, and ABM test bed development. Second, each team member is committed to the goal of transforming the study of power system operations through the development of open-source, extensible, micro-validated ABM test beds. Third, to our knowledge, no prior research has focused on enabling the open-source pre-testing of smart grid functionality for integrated retail/wholesale power system operations through controlled ABM test-bed experiments.

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Fig. 6. Co-Simulation Software Data Exchange

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Dionysios C. Aliprantis (SM'09) received the Diploma in Electrical and Computer Engineering from the National Technical University of Athens, Greece, in 1999. He was awarded the Ph.D. from Purdue University, West Lafayette, IN, in 2003. He is currently a Litton Industries Assistant Professor of Electrical and Computer Engineering at Iowa State University, Ames, IA, USA. His interests include the modeling and simulation of electric machines and power systems, power electronics and controls, and renewable energy applications.

Scott Penick (S'09) received his B.S. degree in Electrical and Computer Engineering from Iowa State University in 2009. He is currently pursuing an M.S. degree in Electrical and Computer Engineering at Iowa State University. His principal research interests are the capabilities of smart-grid technologies and their effects on power systems, with a particular focus on advanced metering infrastructure.

Leigh Tesfatsion (M'05) received her Ph.D. in Economics from the University of Minnesota in 1975. She is Professor of Economics, Mathematics, and Electrical and Computer Engineering at Iowa State University. Her principal research area is agent-based test bed development, with a particular focus on restructured electricity markets. She is an active participant in IEEE PES working groups and task forces focusing on power economics issues and a co-organizer of the ISU Electric Energy Economics (E3) Group. She serves as associate editor for a number of journals, including J. of Energy Markets.

Huan Zhao received his B.S. degree in Mechanical Engineering, and M.S. degree in Economics from Xi'an Jiaotong University in 2003 and 2006 respectively. He is currently pursuing a Ph.D. degree in Economics at Iowa State University. His main research interest is electricity market design, particularly the restructuring of retail electricity markets.