Energy Informatics in Smart Grids: Agent-based Modelling of Electricity Markets

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Abstract — The electric power systems are undergoing major modernization process due to latest demands that are placed on the electrical grid. A new generation of electric power systems, called the smart grid, emerges through the modernization process. The "smarts" in the smart grid are mainly achieved through vertical extension of the existing electric power systems with the (i) information and communication technology (ICT); and (ii) market layers. This paper provides conceptual study of modelling the latter of these layers, i.e., the smart grid electricity market modelling. The special focus is placed on the agent-based modelling as a viable energy informatics approach for addressing the issue of market modelling, especially in the complex environment such as the smart grid.

Keywords—energy informatics; smart grid; agent-based computational economics; electricity markets; market modelling

I. INTRODUCTION

The electric power systems are undergoing major modernization process due to demands that are placed on the electrical grid. The grid *reliability*, along with many others (e.g., *security of supply* and *energy efficiency*), has always been the top

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priority for energy business. Nowadays, with the ever-growing reliance on renewables (e.g., wind turbines and solar panels), all known problems of existing electric power systems are amplified due to distributive and intermittent nature of renewables. For example, blackouts, i.e., sudden losses of electricity, are often the consequence of the inability to sustain critical peak loads during the period of high electricity consumption.

This all has the effect on energy business from both *technical* and *economic* points of view and hence the *smart* changes are needed. The introduction of information and communications technology (ICT) enables integration of smart components and two-way communication between the entities in the smart grid environment. It is believed, the "Internet of Energy" (Bui, Castellani, Casari, & Zorzi, 2012), will be developed due to application of ICT in energy distribution systems. This will serve as the basis for the development of advanced grid management, i.e., smart coordination of the *energy layer* that includes functions such as *production*, *transmission*, *distribution* and *consumption* of energy. The smart grid extends an *existing electrical grid* with various advanced functionalities that use basic functions of the energy layer. Noticeable client-side functionalities are *smart metering* and *demand-side management*, while the grid operator can benefit from *grid balancing* and *real-time monitoring* of the grid. Multi-layered smart grid concept along with its functionalities and corresponding flows is depicted in Fig. 1.

The smart grid *energy layer* deals with the same activities as the traditional power grid although its implementation is far more complex. Production no longer ties to a couple of larger power plants; instead, it is consisted of numerous distributed energy sources. Limitations in transmission and distribution line capacities are now more critical, due to uncertainty in electricity production and consumption.

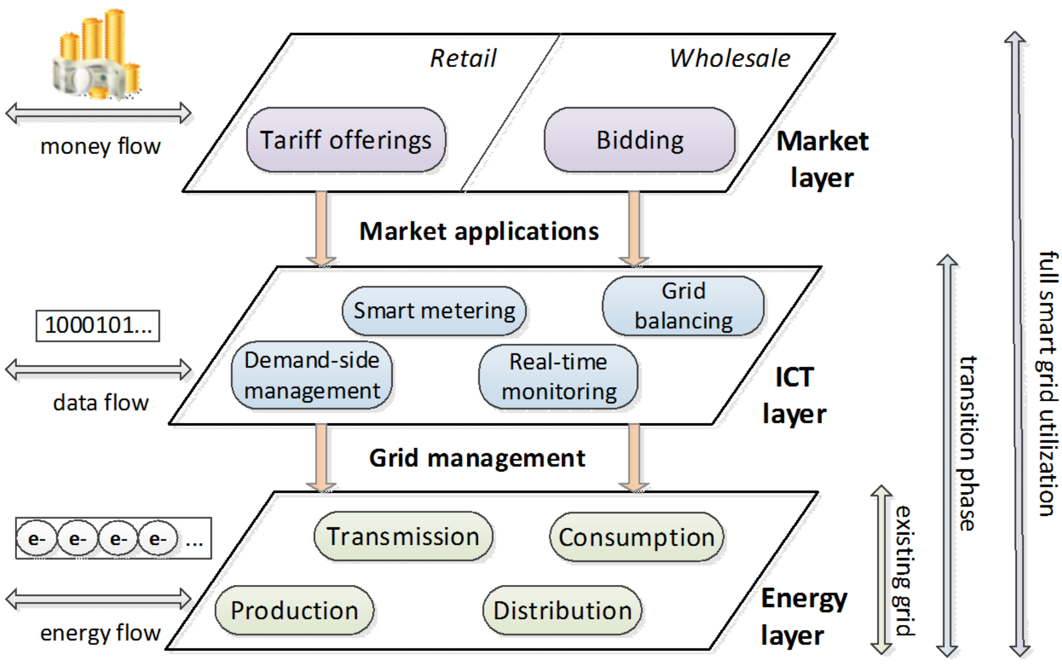

Fig. 1. A multi-layered conceptual model of a smart grid

The *ICT layer* provides the necessary infrastructure for wholesale and retail market applications and thus acts as a middleware between *energy* and *market layers* in the smart grid architecture. However, we argue that the introduction of new technologies to the grid is not the only thing necessary for the whole electric power system to be *smart*. Instead, apart from the enhanced grid management, the grid should produce the *added value* for both market participants and end-users.

Hence, the added value resides in the *market layer* which is placed on top of technical layers and consists of the *retail* and *wholesale* market. Retail customers use the extensive set of information provided by their ICT equipment to review and choose the appropriate tariff from the retail market offered by energy companies. The wholesale market represents a deregulated market that is used by competitive energy companies that want to obtain necessary capacity for their customers.

The remainder of the paper is organized as follows: Section II gives the introduction into the domain of electricity markets. Section III presents market modelling as the means to test and evaluate the market design prior to its real-world deployment. The special focus is placed on the agent-based modelling as a viable energy informatics approach for addressing the issue of the smart grid market modelling. Section IV concludes the paper by summarizing the key statements.

II. Electricity Markets

Electricity is a special kind of commodity that must be consumed shortly after its production since storing of the electricity is rather expensive and limited, especially in high quantities. From an economic point of view, the electricity is a produced good which can be bought or sold on an electricity market.

A. Electricity market types

Essentially, there are two main types of electricity markets: (i) *wholesale markets* typically involve sales of electricity among electric utilities and electricity traders before it is eventually sold to consumers; and (ii) *retail markets* involve the sales of electricity to consumers by retailers.

The wholesale market trading usually incorporates: (i) *Day-ahead spot market* in which contracts are made between seller and buyer for the delivery of power the following day; (ii) *Bilateral trading* or *Over-the-Counter (OTC) trading* takes place outside the power exchange, and prices and volumes are not made public; (iii) *Intraday market* is the "in between market" which takes place during the day of operation when the power exchanges (i.e., day-ahead market) are closed; and (iv) *Balancing market* handles participant imbalances recorded on the previous 24-hour period of operation.

The retail electricity market enables end-use consumers to have the "energy choice", i.e., the ability to choose their supplier from competing retailers. They may also opt to pay more for the electricity sourced from renewable energy generation such as wind power or solar. Retailers can provide fixed prices or real-time prices (i.e., prices based on the variable wholesale price) for electricity to their customers and manage the risk involved in purchasing electricity from spot markets or electricity pools.

The wholesale market and retail market are highly interdependent since the wholesale price is the largest component of the retail price of electricity. The restructuration of the electricity industry is expected to trigger more competitive wholesale market that will presumably set lower wholesale prices. This will allow electricity retailers to set lower retail prices for their product and still remain financially viable. However, the traditional retail tariff design (e.g., two-part tariff pricing scheme) is not able to incorporate the dynamics of the wholesale price within the retail price in a timely fashion. Retail customers should be encouraged to shift their consumption from peak hours to off-peak hours to prevent peak loads and thus maintain the reliability of the grid. Since retail customers can also be producers (e.g., electric vehicles), they can offer their capacities for balancing purposes as well. In order to do so, customers should have some kind of benefits (e.g., lower prices in off-peak hours, bonuses) since they are required to change their behaviour. New and innovative retail products (e.g., real-time pricing, time-of-use pricing and critical-peak pricing) offered by retailers are placeholders for such benefits.

Clearly, in order to support new emerging retail markets, it is important to set the right market regulations. This will enable retailers to offer products at the competitive price. Thus, policy makers have a challenging task of determining rules that will not restrict retailers' creativity in designing products but will protect customers as well as ensure the grid stability.

B. Considerations on new electricity markets

Traditionally, electricity markets had little or no competition involved and were tied to integrated monopoly structures that managed all the functions of the energy layer: *production*, *transmission*, *distribution* and *consumption of electricity*. Recently, the process of electricity deregulation unbundled the monopolistic nature of the electricity industry and allowed more competitors in producing and retailing of electricity, while keeping the infrastructure (e.g., transmission lines) under a natural monopoly since the running costs of the infrastructure are significantly lower than non-monopoly due to economies of scale (Koster, 1998).

Apart from the market deregulation, policy makers focus on making the retail market a highly competitive market with the price signals, ensuring the choice and simplicity for customers. That way, customers will be able to actively participate in making the supply and demand in balance all the time and thus provide new market opportunities for the economic growth.

All things considered, it is obvious there are still a lot of unknowns regarding the electricity markets. The market design based only on economic theories without serious testing will most certainly not yield desired properties. The better approach is, prior the real-world deployment, to thoroughly test and evaluate all the possible outcomes to prove robustness of the market design. Testing on a production environment is expensive and practically impossible since the electricity market is a complex system with a lot of entities and interactions among them. Therefore, there is a need for a test bed that will help policy makers in determining what set of regulations are appropriate based on a given market requirements. A prerequisite for this is a good electricity market model.

III. Agent-based Electricity Market Modelling

In order to identify and limit the problems of the electricity market prior to its real-world deployment, it is necessary to offer a simulation environment to test ideas about the design of electricity markets. Several modelling methods (Weidlich & Veit, 2008) can be used for modelling electricity markets:

- *equilibrium models* (Díaz, Villar, Campos, & Reneses, 2010; Zhang, Chung, Member, Wong, & Chen, 2009);
- *game theory* (Bompard et al., 2008; Lise et al., 2006); and
- *human-subject research* (Trinh, Saguan, & Meeus, 2013).

Table 1: A comparison table of different approaches for market modelling

Modelling approach	Capacity for details*	Volume of insights+	Ease of analyses^x	Level of formal model specification^y
Equilibrium models	LOW	LOW	MED	HIGH
Game theory	LOW	LOW	MED	HIGH
Human-subject research	LOW	MED	LOW	LOW
Agent-based Computational Economics (ACE)	HIGH	HIGH	LOW	MED

* Specifies with how many details modelling approach can describe a real-world problem.
\+ Specifies the expected volume of outputs per observation.
x Specifies how easy one can interpret outputs.
y Specifies the degree of model formalization.

However, all mentioned methods have some shortcomings. First, *equilibrium models* do not incorporate strategic behaviour of market participants and have unrealistic design which assumes that market participants have all relevant information about the characteristics and behaviour of competitors. In addition, equilibrium models neglect the consequences of the knowledge that a participant could get through the daily operation on the electricity market. Second, *game theory* is largely limited to the specific situation in the market that depends on few factors, and thus achieves stringent, sometimes unreal assumption of behaviour of participants. Third, employing *human-subject research* can be rather difficult to research related to the electricity market since it takes great expertise to describe the behaviour of electricity generators in a realistic manner.

A possible solution which addresses all listed issues is market modelling based on software agents called the *Agent-based Computational Economics (ACE)*. A comparison of aforementioned modelling approaches is given in Table 1. In contrast to other modelling approaches, ACE offers much more detailed modelling of a real-world problem and hence it provides more insights per observation. In the ACE it is also able to describe a model to some extent (e.g., definition of agents and interactions among them). In contrast, game theory and equilibrium models have a better model formalization since they are inherently supported by mathematical formalization while human-subject research has no formalization at all. Due to the sheer size of data obtained from the experiment, the analysis process in the ACE is indeed more complex than in the other modelling approaches and it often incorporates the use of big data analytics.

In his seminal paper, Tesfatsion (2002) outlined the main characteristics of the ACE and defined it as "*the computational study of economies modelled as evolving systems of autonomous interacting agents*". He also defined a decentralized market economics as an example of complex adaptive systems, because a large numbers of adaptive agents[1] are involved in local interactions. Since such local interactions have an impact on macroeconomic regularities (e.g., shared market protocols and behavioural norms) which in turn affects local interactions, the result of decentralized market economics is a complicated system that couples individual behaviours,

[1] *Software agent is an autonomous computer program that carries out tasks on behalf of users.*

interaction protocols and social welfare outcomes. In a more illustrative way, Tesfatsion phrased those local to macroeconomic interactions as a *two-way feedback* between microstructure[2] and macrostructure[3], a known phenomenon (Olson, 1965; Schelling, 1978) recognized by the economics.

A. Two-way feedback between microstructure and macrostructure

The ACE derived as a possible approach for studying economic models to capture the two-way feedback quantitatively in its full complexity and thus overcome some of disadvantages of traditional modelling techniques. Most notably, a majority of traditional economics models rely on the *top-down approach* in which the „bottom“ part is usually left out of the important details, and consequently, limits the extent to which the model realistically fits the observed problem. In those models, agents are not able to reflect the real-life entities since they are constrained with non-adaptable decision process, assumed common knowledge, market equilibrium and they often represent a decision maker with a high level of abstraction (e.g., a *consumer* instead of multiple different consumers forming a *heterogeneous consumer*).

All this is in contrast with ACE methodology since it utilizes a *bottom-up* approach which builds the whole model from the bottom and offers a larger level of freedom than the traditional methodologies. This in turn puts more emphasis on the microstructure of agents and less on the global model. Once the model is completed, a researcher tweaks agents' parameters to set-up the initial state of the economy for each agent. After that, the experiment starts without further interference from a researcher. The result of the experiment is a set of regularities that emerged due to interactions among all the agents from a culture dish.

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[2] *In the context of the ACE, the microstructure entails decisions and actions taken by individual agents.*

[3] *Decisions and actions taken by individual agents lead to significant unintended consequences for the macrostructure, i.e., emergent market conditions.*

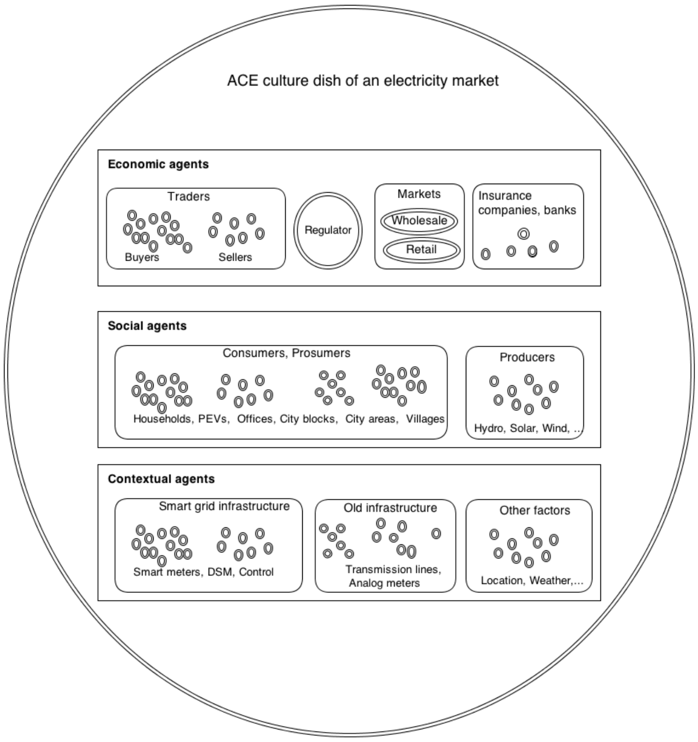

Fig. 2. ACE culture dish of an electricity market.

An example of ACE modelling applied to a domain of electricity markets is shown on Fig. 2. The outline of the sketch resembles a culture dish[4] to show how the ACE approach follows the way microbiology study works, e.g., growing of bacterial colonies on some kind of a growth medium. However, instead of bacterial colonies, in the ACE there are usually three sets of agents: (i) *economic agents*; (ii) *social agents*; and (iii) *contextual agents*.

B. Electricity market model in a culture dish

In an electricity market model, *economic agents* are market stakeholders (i.e., buyers and sellers) and financial institutions such as banks and insurance companies. An important feature of the ACE is the ability to capture the two-way feedback between microstructure and macrostructure, therefore, it also includes the social agents as well as the contextual agents. *Social agents* resemble social groups and in

[4] *A culture dish, or Petri plate, is a shallow lidded dish commonly used by biologists as a container for experiment samples.*

an electricity market they can be: (i) *consumers* (e.g., households and city blocks); (ii) *producers* (e.g., dedicated generation units such as wind farms, virtual power plants); and (iii) *prosumers* (e.g., households with solar panels). Finally, *context agents* are included in a model to capture the environmental aspect of the real-life problem. In the context of an electricity market, those are used to test the technical feasibility of the grid. For instance, the experiment designer can set-up the experiment to see will the user be able to spot a price signal from the market. The efficient and reliable energy service is one of the most critical aspects of energy business (Wissner, 2011), therefore, a good ACE model, for instance, is able to see what rules should a regulator make in order to secure reliable transport of energy on a transmission lines. Finally, due to an increasing importance of renewables in the world, the experiment designer may incorporate geo-location and weather service to a model in order to study the feasibility of future investments in renewable capacities, evaluate forecasting schemes for electricity production and usage, and study the correlation between the wholesale electricity price and wind or solar production.

IV. CONCLUSIONS

The agent-based modelling is particularly suitable for the domain of energy business since electricity markets can be defined as complex adaptive systems of interactive agents. As defined in Agent-based Computational Economics (ACE), the agents of electricity market model reside in a placeholder (so-called "culture dish") and are divided in market, social and contextual groups.

Essentially, there are at least two fundamental questions to be answered after the ACE experiment has finished. First, one should discuss why particular behaviours have emerged and persisted in an economy model and why not others, even though there is the absence of top-down planning. A simple example for an electricity markets is, for instance, to study how the wholesale electricity price has changed throughout experiments that had different market forms, e.g., a monopoly, an oligopoly and a perfect competition. This discussion should be backed-up by data about local interactions between autonomous agents. Second, one should study what implications each of entities has on the economy, given the emergent regularities from the experiment. For instance, in the electricity market this may include a discussion on how did a particular set of market rules influence the market participants. Also, by departure from tight constraints imposed by equilibrium models, with the ACE it is possible to more thoroughly test non-desired states of the economy, such as having a large number of market participants with extreme strategies, trading on a different set of rules with each experiment cycle.

Electricity market simulators are used to model and simulate electricity markets. There are many electricity market simulators existing and the Power Trading Agent Competition (Power TAC) is one of them[5]. Power TAC (Ketter, Collins, & Reddy, 2013) is an open, competitive market simulation platform that aims to provide an insight to the structure and operation of smart grid electricity markets. Power TAC has counterpoised ACE as alternative to traditional game-theoretic approaches for testing policies for complex systems (Babic & Podobnik, 2013). Research results obtained from Power TAC are used to derive market rules for future retail-level electricity markets (Babic, & Podobnik, 2014). In the Power TAC simulation competitors are brokers that provide energy services to retail customers using tariff offerings (Matetic, Babic, Matijas, Petric, & Podobnik, 2012), while managing their energy loads by trading in a wholesale market (Babic et al., 2012). Power TAC is conceived as an annual competition between research teams who prepare intelligent

[5] *Electricity market simulators are mostly agent-based and they differ in the level of complexity and in scenario they are portraying. An in-depth analysis of relevant agent-based simulators for studying a domain of electricity markets is given in (Zhou, Chan, & Chow, 2009).*

and autonomous software agents called brokers that compete against each other. Competition settings specify the number of competing brokers: groups of two, four or eight brokers, which can vary for each simulation. Different group sizes serve to examine broker behaviours in different market scenarios, such as oligopolies and highly competitive markets.

To conclude, agent-based modelling is a viable energy informatics approach for addressing the issue of market modelling, especially in the complex environment such as the smart grid. Further analyses of the Power TAC and other agent-based energy market simulations promise to be an important step in the process of real-world smart-grid deployment.

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