Agent-based Modeling of Electricity Markets in a Smart Grid Environment

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***Abstract*— The electric power systems are undergoing major modernization process due to demands that are placed on the electrical grid, including environmental compliance, energy efficiency, improved grid reliability and customer-centric relationship management. All this has the effect on energy business from both technical and economic points of view and hence the *smart* changes are needed. The introduction of new technologies to the electrical grid is not enough to make the grid smart. Instead, the grid should produce the added-value for both energy companies and retail customers. Therefore, this paper provides an overview of the smart grid as a technical foundation for making new emerging services in the energy business. It also focuses on the energy market layer and arguments why the electricity markets should be modeled in the first place. Market modeling is described 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 modeling since it is conceived as a viable approach for addressing the issue of the market modeling, especially in the complex environment such as the smart grid.**

Keywords - agents; agent-based computational economics; electricity markets; market modeling; smart grid

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 priority for energy business. Nowadays, with the ever-growing reliance on renewables (e.g., wind turbines and solar panels), all the known problems are amplified due to their distributive and intermittent nature. 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" [1], will be developed due to use of ICT in energy distribution systems. This will serve as the basis for the development of advanced grid management, i.e., dealing with energy layer that includes *production*, *transmission*, *distribution* and *consumption* of energy. The smart grid extends an *existing electrical grid* with various functionalities that are above 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.

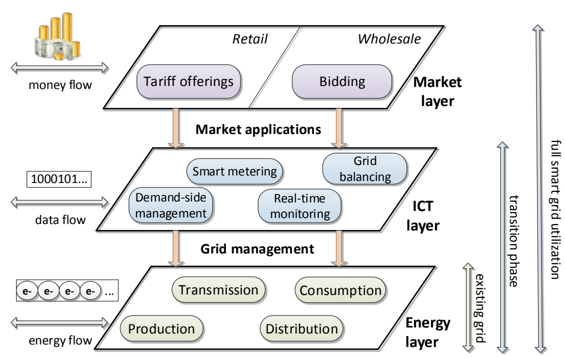

Fig. 1. A multi-layered conceptual model of a smart grid

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. In contrast to a regular energy meter, whose purpose is to measure the energy consumption, a *smart meter* is an advanced energy meter which provides added information to the utility company, including the values of voltage, phase angle and the frequency [2]. The smart meter's other major difference from the regular meter is in its ability to provide bidirectional communication between the power utility and end-customers. Therefore, the smart meter is an important technical foundation for providing value-added electricity services.

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.

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 a market layer which is placed on top of the 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 briefly presents the smart grid which provides technical foundations for new market applications. Section III gives the introduction for the domain of electricity markets. Electricity markets are experiencing major change due to processes of deregulation and liberalization. These acts are not trivial and therefore we present the potential problems regarding the market design based on historical examples. In order to prevent market failures, a special caution must be taken. Thus, there is a lot of work that needs to be carried out before the market design is going to be deployed in real-world markets. Section IV presents market modeling 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 modeling since it is conceived as a viable approach for addressing the issue of the market modeling. Section V concludes the paper by summarizing the key statements and stressing out the potential significance of the agent-based electricity market modeling for Croatia.

II. Smart Grid

The electric power systems are undergoing a profound transition from an aging infrastructure to a modern system. The change is driven by a number of reasons, such as: environmental compliance, energy efficiency, improved grid reliability and customer-centric relationship management. The special emphasis is placed on the electricity distribution grid, whose transformation into the „smart grid“ will act as a key enabler for meeting environmental targets. It will also put a greater emphasis on demand response (DR) than the existing grid, support plug-in hybrid electric vehicles (PHEVs) and provide a set of technologies to deal with storage capacities and intermittent and distributed nature of renewables [3].

Note that the aim of this paper is not to present the technical details about the smart grid. Instead, we stress out why the policy makers decided to invest in smart grid development and what are the potential economic benefits of the smart grid. Nevertheless, since the smart grid is a necessity for supporting emerging electricity markets, we summarize key differences between the existing grid and the smart grid in TABLE I. The key difference is that the existing grid is used to carry the electricity from a few central generators to a large number of customers while the smart grid uses *two-way flows* of *electricity* and *information* to create highly automated electrical system [4]. A more detailed description on smart grid functionalities can be found in [5].

TABLE I. A COMPARISON OF THE EXISTING GRID AND THE SMART GRID[5]

	Existing Grid	**Smart Grid**
Infrastructure	Electromehanical	Digital
Communications	One-way communication	Two-way communication
Generation type	Centralized generation	Distributed generation
Topology	Hierarchical	Network
Sensor deployment	Few sensors	Sensors throughout
Monitoring capabilities	Blind	Self-monitoring
Grid recovery	Manual restoration	Self-healing
Reliability	Failures and blackouts	Adaptive and islanding
Testing	Manual check/test	Remote check/test
Control	Limited control	Pervasive control
Customers involvement	Few Customer Choices	Many Customer Choices

A. Smart grid definitions

There are numerous definitions for the smart grid, however, all of them pinpoint the ultimate goals of the smart grid deployment, i.e., providing *secure*, *reliable*, *efficient* and *sustainable* electricity system.

According to the definition from the European Strategic deployment document [6], the European Union (EU) definition states that the smart grid is defined as “*an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies*”.

One of the most common definition is the United States (US) version [7]. It says that the smart grid: “*uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed-generation and storage resources*”.

Third definition is from Gharavi and Ghafurian, who offer a description [8] which thoroughly covers the power system from the generation to end users. The definition says the smart grid is defined as “*an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient, and sustainable.*”

B. *Drivers for the smart grid in EU and US*

Energy needs account for 80% of all European greenhouse gas (GHG) emissions [6]. Following efforts of the Kyoto protocol to reduce GHG emissions and thus reduce the negative impact on the climate changes, Europe made an ambitious commitment to reach three objectives by the year 2020 [9]: (i) 20% share of energy consumption from renewable sources; (ii) reduce 20% of primary energy usage by promoting energy-efficiency measures, (iii) reduce GHG emission by 20% of the 1990 level.

In US, one of turning points that triggered research and development in the smart grid was in 2005 when US Congress passed the 2005 Energy Policy Act. This act was preceded by the Northeast blackout of August 2003 and it has changed US energy policy by providing tax incentives and loan guarantees for renewable energy production and development of energy-efficient technologies. In 2007, Energy Independence and Security Act of 2007 (EISA07) [10] envisioned the smart grid technology by making a statement of policy on modernization of electricity grid in US Smart Grid Initiative.

It is noticeable that the EU and the US have different drivers for employing smart grid technology. Apart from reaching environmental targets, Europe has also been influenced by the *diversity* and *evolution* of electrical grids throughout Europe, while the primary concern for US is to *increase security* and to *respond to the predicted growth in demand* for a long-term vision [11].

C. *Economic benefits of the smart grid*

Throughout years, there have been a number of research papers relating to benefits of the smart grid, such as [12], [13], [14]. In order to get a notion on whether the smart grid could lead to a financial savings over existing grids, we outline the case of Great Britain, which is one of leaders of smart grid development in Europe. We also outline major findings of Electric Power Research Institute (EPRI) for the potential benefits of smart grid deployment for US. Apart from EU and US, the smart grid development is also active in other parts of the world. Hence, the cost benefit analysis for the Sultanate of Oman is briefly presented. Finally, we stress out the significance of reliability costs, a problem which smart grids are likely to address.

1) *The case of Great Britain*

Ernst & Young (EY) made a study of economic benefits of smart grid for the British economy in [15]. The analysis is based on existing British and international studies, interviews conducted with relevant stakeholders and EY economic analysis as well as on some assumptions in cases where the access to the detailed information was limited. The study showed that the benefits of smart grid development in a timely fashion outweighs the risks and appears robust in a number of different scenarios. They also found out that the timely creation of a smart grid can trigger substantial benefits in other industries, and have a positive impact on growth, jobs and exports. The report also estimates the costs required to upgrade the distribution network in Great Britain between 2012 and 2050: \$36 billion net present value (NPV) for smart upgrades to distribution networks, \$42 billion NPV for deployment of a smarter grid and \$72 billion NPV for deployment of conventional technologies. This results lead to a conclusion that a smarter grid investment strategy could save as much as \$30 billion NPV over conventional technologies investment strategy.

2) *The case of US*

The EPRI made a report [16] which estimates the net investment needed to realize the US grid in 20 years. The report summarizes the total smart grid costs across the transmission network, distribution network and consumers side. The maximum calculated costs were \$90 billion, \$340 billion and \$46 billion, respectively. The costs include the technical foundation to integrate distributed energy resources and to achieve full customer connectivity. The report concludes that the total cost of enabling a fully functioning smart grid for about 130 million homes ranges between \$338 and \$476 billion while the net benefits (e.g., productivity, quality of life, security and reliability) are as high as \$2028 billion.

3) *The case of Oman*

In [17], authors made a cost-benefit analysis on the smart grid in terms of avoided cost of generation, transmission and distribution in Sultanate of Oman. Although the results of analysis showed the smart grid potential to outweigh the cost of smart grid investments, the case study itself was fairly constrained so the results should be used with the extra caution. For instance, due to difficulties in assessing the cost of investments in smart grid technologies, authors opted to scale the cost of making the grid smarter in US. In the next 20 years, the projected benefits from the smart grid range from \$2.3 billion to \$4.2 billion, which covers \$2 billion worth of assumed grid upgrading cost for 560,000 households.

4) *Reliability costs in traditional grids*

As the countries around the world introduce changes in the way electricity is produced and the grid is experiencing the modernization, the reliability of a electricity service has become increasingly more challenging due to [18]:

- *grid congestion* imposed by uncertainty, diversity and distribution of the growing share of renewables in the power system;
- increased *volatility* due to growing number of large transfers of the electricity over long distances;
- power system *works on the limit* more often because of increasing production and consumption, aging infrastructure;
- power system is not able to handle *massive utilization of distributed resources* which blurs the line between transmission and distribution, therefore, there is an increase in complexity of the grid management.

The requirement for reliability in the smart grid is primarily to secure a high-level quality of service (QoS), but it is also identified as a potentially substantial money saver due to high cost of electricity interruptions. For instance, the annual cost of US electricity interruption in 2002 was estimated [19] from \$22 billion to \$135 billion, averaging at \$79 billion. This number takes as high as 1/3 of the total revenue from retail sales of electricity in the US, which had the value of $249 billion for 2002 [20]. In [21], Linares and Rey used a production function to estimate the cost of electricity interruptions in Spain. They found that in 2008 the cost of one kWh of electricity not supplied (*Value of Lost Load, VoLL*) was around $8 for Spanish economy which is around 30 times more than the Spanish retail electricity price, i.e., $0.25 per kWh in 2013 [22].

III. 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 [11]. 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 the sales of electricity among electric utilities and electricity traders before it is eventually sold to consumers; (ii) *retail markets* involve the sales of electricity to consumers by retailers.

The wholesale market trading usually incorporates:

- *Day-ahead spot market* in which the contracts are made between seller and buyer for the delivery of power the following day, the price is set and the trade is agreed;
- *Bilateral trading or over the counter (OTC) trading* takes place outside the power exchange and prices and volumes are not made public;
- *Intraday market* is the “in between market” which takes place during the day of operation when the power exchanges (day-ahead market) are closed;
- *Balancing market* handles participant imbalances recorded on the previous 24-hour period of operation.

The retail electricity market enables end-use customers 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 poor risk management can be devastating for a retailer, the most notable example is the 2001 California electricity crisis, when Pacific Gas and Electric and Southern California Edison companies went bankrupt for purchasing electricity at high spot prices and selling at low fixed rates. Currently, consumers are not motivated to reduce or shift demand at times of peak demand and high wholesale prices. Demand response addresses this problem by introducing pricing mechanisms or technical solutions for reducing peak demand.

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. Apart from the requirement of the retail price to reflect the wholesale price, the other requirement for the retail price is to aid in the real-time balancing of supply and demand of the electricity. Specifically, 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. 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 behavior. New and innovative retail products (e.g., real-time pricing, time-of-use pricing and critical-peak pricing) offered by retailers are the 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 also protect customers as well as ensure the grid stability.

B. Markets driven by smart grid

Since there are many changes in the technical aspects of the electrical grid systems, which were briefly outlined in the previous chapter, it is also expected to have changes in the markets domain as well. Fig. 2, adapted from National Institute of Standards and Technology (NIST) report [23],

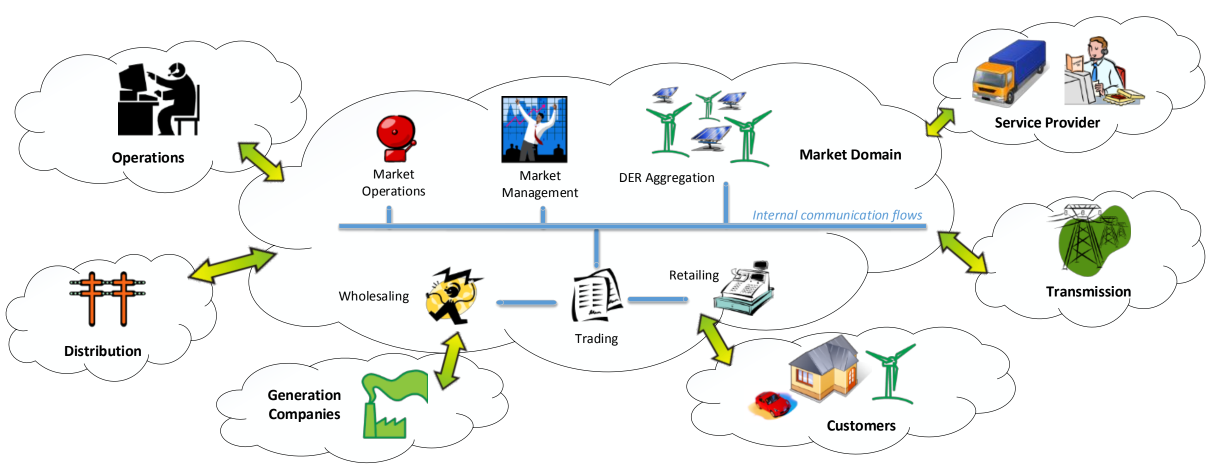

Fig. 2. Market entities and interactions in smart grid market layer

shows a conceptual model of the markets domain that works on top of smart grid technologies. This figure outlines key entities and interactions inside the markets domain. It also maps interactions between markets domain and other entities in a smart grid. The interdependence between the market and generation and production entities is critical because matching of production with consumption relies on markets. *Market managers* are responsible for administering (i.e., coordinating, controlling and monitoring) power systems and electricity markets. This work is typically carried out by Independent System Operators (ISOs), or Regional Transmission Organizations (RTOs). Note that the RTO is the US term for the organization that is responsible for transferring electricity over large interstate areas. The EU equivalent for RTOs are cross state Transmission System Operators (TSOs) within European Network of Transmission System Operators for Electricity (ENTSO-E) association. ISO and RTO are two organizations that share the same aforementioned tasks. However, in contrast to the ISO, the RTO additionally has a greater responsibility for the transmission network. Since the ultimate goal is to provide the efficient market, the market operator needs to run the market by carrying out *market operations*, such as market clearing, audit and balancing.

Market participants are trading in wholesale and retail markets. Competing *generation companies* (gencos) and *retailers* are participants of the wholesale market. Generation companies (e.g., fossil-fuel or hydro power stations) participate in the wholesale market by selling large-scale quantities of energy. Retailers are companies that offer electricity to end customers over the *distribution network* and in the future they may aggregate production capacities of *Distributed Energy Resources (DER)* and place them on the market. Most retailers take part in a trading organization to allow participation in the wholesale market. DER consists of many small energy sources and it is conceived as a concept to enable distributed resources to play in the wholesale market. The example implementation of DER is the *virtual power plant* (VPP). VPP is a cluster of distributed generation installations which are collectively run by a central control entity. An example of a planned virtual power plant project is the four-year, $28 million EcoGrid project for the Danish island of Bornholm [24].

Operations domain relates to the proper operation of the smart grid infrastructure, which is a technical prerequisite for running the markets. Example functions that fit in this domain include grid monitoring, grid control and fault management. This domain also makes sure *distribution* network and *transmission* network mediate the electricity from gencos to *customers*. In this conceptual model, customers are no longer only the consumers tied to a one retailer, instead, they may also be prosumers[1] and are able to choose their own retailer from a competitive retail market. *Service providers* are companies that create new services driven by the opportunities presented by the smart grid. The companies may be the existing electric service provider or new participants coming from the energy business or other domains (e.g., telecommunication companies). The new emerging services, based around customer management, represent the new area of economic growth. For instance, remote work scheduling of home appliances (e.g., washing machines and air-conditioners), is the typical example of new services that will be offered to *customers* as means to reduce load peaks during the period of high electricity usage.

C. *Considerations on new electricity markets*

Traditionally, electricity markets had little or no competition involved and were tied to vertically integrated monopoly structures that managed all the functions from the energy layer: production, transmission and distribution 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 [25].

Electricity deregulation is the act of removing or reducing state regulations from electricity markets with the intent of encouraging the efficient operation of markets. The basic premises for deregulation are that fewer and simpler regulations will raise the level of competitiveness of market participants. This will in turn lead to a higher productivity, more efficiency and lower prices. This act commonly goes along with electricity liberalization which refers to the process of liberalizing electricity markets, i.e. relaxing the market rules for greater participation of private entities. The driver for electricity liberalization is, in the long run, to promote efficiency gains, to stimulate technical innovation and to lead to efficient investments. Economic efficiency for the electricity market is achieved when consumers pay prices that are equal to the marginal cost of production [26]. In [27], Woo et al. investigate potential threats of the electricity market deregulation. They summarize concerns regarding the market deregulation process based on the real-world history examples. The most important findings are:

- Electricity deregulation is a complicated process. The process of transforming the market from a regulated monopoly into a competitive market with the ability to support wholesale electricity and retail services is difficult.
- Traders and retailers will engage in gaming due to a complicated market design. Also, market power abuse is common in deregulated generation markets. The most famous example of the market exploitation is the so-called „Enron scandal“, where the Enron Corporation went bankrupt after years of playing destructive strategies (e.g., „Death Star“, „Fat Boy“ and „Ricochet“ strategies) on the Californian market in the early 2000s.
- In contrast to monopoly markets where the price is stable, electricity spot prices in deregulated markets are highly volatile.

[1] *Prosumer* is a portmanteau formed by contracting the word producer with the word consumer. In the energy business, it is used to denote a customer who is able to consume and produce energy (e.g., electric vehicle).

- Residential users, industrial users, and electricity suppliers do not have equally distributed benefits of electricity deregulation.

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 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.

IV. Electricity Market Modeling

The roots of electricity market modeling can be traced back to early 1990s when Marks [28] employed genetic algorithms (GA) to study optimal behavior for oligopolists. The GA was also used by Arifovic [29] in 1994 on cobweb model[2]. The model contained competitive firms which used GA to trade in a market for a single good by updating their decision rules about next-period production and sales.

In 1994, Räsänen [30] introduced the object-oriented paradigm to the modeling of electricity markets and therefore was a pioneer of using this techniques for modeling electricity demand-side load. A year later, Hämälainen and Paratainen [31] put themselfs a step forward for the sake of introducing more abstract, agent-based modeling framework for analyzing demand-side load. In 1997, Hämälainen et al. [32] introduced a two-level multi-agent model with both consumers and producers with a bounded rationality.

In 1998, James Hoecker, the US Federal Energy Regulatory Commission (FERC) chairman, has expressed faith in a computer-based model for the electricity market. In particular, he said [33] that a computer-based model could be beneficial for their competitive analysis in at least two ways: (i) „by explicitly representing economic interactions between suppliers and loads at various locations on the transmission network“; and (ii) „by accounting for the actual transmission flows that result from power transactions“. Hoecker also made a word of caution by stating that to efficiently employ the computer-based modeling techniques it takes time, education and consistent refinement.

Since 1998, there has been a growing number of researches in electricity markets modeling. Marks offers a systematic approach to history of electricity market modeling and discussion of the most relevant academic and economic papers in [34].

A. *Electricity market as a Complex Adaptive System*

Complex Adaptive Systems (CAS) are defined [35] as a system containing a large amount of semi-autonomous entities. Each of such entities has a set of only a few individual behaviors which, in interaction with other entities, are able to cause a complex system with emergent properties. As the name implies, the common property of such systems are adaptation, i.e., the ability to learn and change common behavior of an entity or a system in whole by optimizing some of its features over time. The pioneering work on CAS, which allowed researchers to understand basic and unique principles of such systems, has been carried out by Santa Fe Institute (SFI) [36]. John Holland coined the term CAS to describe the nature of a complex system which permanently evolves [37].

The electricity market, made up of many interacting entities such as producers, consumers and regulators, is itself a CAS that is able to exhibit global change in a system as a result of local actions made by several or even by an individual entity. In [38], Wildberger argued CAS can be used in power industry applications by putting an emphasis on the grid level and development of a distributed power control system.

In [39], the authors explained how Electric Power Research Institute (EPRI) employed CAS to develop simulation and modeling tools for adaptive and reconfigurable control of the electric power grid. Following the bottom-up approach of CAS, the concept of distributed and self-healing control of an electric power system implies having system components backed up by intelligent agents. The goal of those agents is to achieve global optimization in the context of the whole system's environment while competing and cooperating with other agents in the system's pool.

B. *Market design guidelines*

The infamous California electricity crisis of 2000, which caused power blackouts for the whole year, triggered the thought process about the design principles for the design of the electricity markets. In 2003, the FERC derived four primary objectives for wholesale electricity market design [34], [40]:

- *„reliable service (no blackouts or brownouts[3]);*
- *fair and open access to the transmission grid at reasonable prices;*

[2] The *cobweb model* or cobweb theory is an economic model that explains why prices might be subject to periodic fluctuations in certain types of markets.

[3] A *brownout* is an intentional or unintentional drop in voltage in an electrical power supply system. The term comes from the dimming experienced by lighting when the voltage sags.

- *effective price signals to provide incentives for appropriate investment in generation and transmission capacity; and*
- *effective procedures for market oversight and mitigation of exercise of market power.*"

In [41], Crampton identifies two key prerequisites for a good market design. First is in *finding the objective of a market*. In terms of electricity market, the author says the objective is to secure efficient and reliable production of energy to satisfy demand. Apart from the objective, the second prerequisite is to *understand the preferences and constraints of market participants*. He also stresses out the importance for a good knowledge of basic economics relating to the market since it aids in making design as simple as possible but not trivial.

C. Common modeling approaches

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 modeling methods [42] can be used for modeling electricity markets:

- *equilibrium models* [43], [44],
- *game theory* [45], [46], and
- *human-subject research* [47].

However, all mentioned methods have some shortcomings.

First, *equilibrium models*, do not incorporate strategic behavior of market participants and have unrealistic design which assumes that market participants have all relevant information about the characteristics and behavior 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 behavior 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 behavior of electricity generators to market in a realistic manner.

A possible solution which addresses all listed issues of other methods is market modeling based on software agents.

D. Agent-based computational economics

In a seminal paper, Tesfatsion [48] outlined the main characteristics of the Agent-based computational economics (ACE) and defined the aforementioned term as "*the computational study of economies modeled 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[4] are involved in local interactions. Since such local interactions have an impact on macroeconomic regularities (e.g., shared market protocols and behavioral norms) which in turn affects local interactions, the result of decentralized market economics is a complicated system that couples individual behaviors, 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[5] and macrostructure[6], a known [49], [50] phenomenon recognized by the economics.

1) 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 modeling 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 *heterogenous 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.

An example of ACE modeling applied to a domain of electricity markets is shown on Fig. 3. The outline of the sketch resemble a culture dish[7] 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:

- *economic agents*,
- *social agents*, and
- *contextual agents*.

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

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

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

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

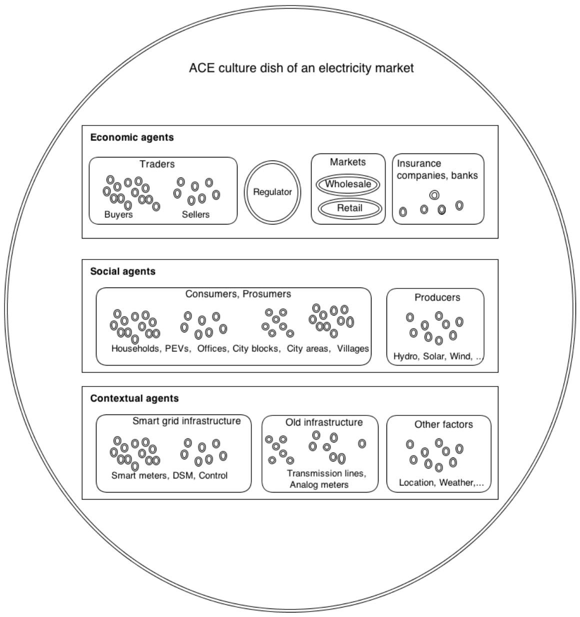

Fig. 3. ACE culture dish of an electricity market.

A culture dish methodology in the ACE, defined by Tesfatsion, is the same as *artificial life* (*ALife*) [51] methodology. The main difference, apart from the domain of life, is that the ALife has *soft*, *hard* and *wet* approaches, denoting the kinds of artificial life, i.e. software, hardware and biochemistry, respectively. In contrast, ACE deals with the domain of the economy and it is a *soft* approach, because all the modeling is carried out by the use of software.

2) 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. The detailed design of those agents forms the core of the economic model but they alone restrict the correlation between the model and the real life. 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 an electricity market they can be: (i) consumers (e.g., households and city blocks), (ii) prosumers (e.g., households with solar panels), and (iii) producers (e.g., dedicated generation units such as wind farms, virtual power plants). Finally, environmental 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 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 [52], therefore, a good ACE model, for instance, is able to see what rules should the regulator make in order to secure reliable transport of energy on a transmission lines. Finally, due to an increasing importance [53] of renewables in the world, a designer may incorporate geolocation 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.

3) The ACE research approach

Essentially, there are at least two fundamental questions [48] to be answered after the experiment has finished.

First, one should discuss why particular behaviors 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 the 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.

There are many possible areas of research within the ACE, such as [54]:

- understanding and evaluating the market design,
- exploring the regulatory framework for markets,
- assessing interactions between automated markets and trading agents,
- development of rich environment for economic decision-making,
- proposing business policy based on expected market behavior.

E. Important Agent-based Electricity Market Simulators

Electricity market simulators are used to model and simulate electricity markets. There are many electricity market simulators existing out on the market. They are mostly agent-based and they differ in the level of complexity and in scenario they are portraying. Simulators listed below share the following similarities: (i) agent-based simulation, (ii) non-trivial model of the electricity markets and (iii) good impact on the academia in terms of cited relevant papers. More in-depth analysis of relevant agent-based simulators for studying a domain of electricity markets is given in [55].

1) Electricity Market Complex Adaptive Systems Model (EMCAS)

EMCAS [56] is an agent simulation of electricity markets, which describes the behavior of producers and consumers in the electricity market, simulates the activities of the electricity system and calculates the electricity price for each hour and location within the transmission network. Electricity prices depend on demand, production costs, congestion of the transmission system, and external factors such as delays in production or disturbances in the system and strategies applied by the power company. The EMCAS model results contain information about the economic consequences for individual companies and consumer groups in different scenarios. A basic example of EMCAS applied to the Croatian electricity market can be found in [57]

2) Multi Agent Intelligent Simulator (MAIS)

MAIS [58] is a system based on agents for analysis and understanding of the dynamic changes in prices in the US wholesale electricity market in the period before and during the energy crisis in California [16]. The software agents in MAIS represent market entities that can adjust their trading strategies in the simulation process based on previous trading efforts' success or failure.

3) Multiagent Simulation System for Competitive Electricity Markets (MASCEM)

MASCEM [59] is a market simulator that uses reinforcement learning algorithms to provide market participants with strategic capabilities in electricity markets. It implements the day-ahead market, forward market, balancing market and bilateral contracting. Agents in MASCEM are implemented by research team from Portugal and each of them can contain a predefined set of behavior and strategies. The simulator is used to evaluate a proposed method for trading in the electricity market.

4) Power Trading Agent Competition (Power TAC)

Power TAC [60] is an open, competitive market simulation platform that aims to provide an insight to the structure and operation of retail electricity markets. Power TAC extends the portfolio of TAC scenarios (e.g., TAC AA for trading with keywords in sponsored advertising and TAC SCM for supply-chain management), "open simulations" that have counterpoised ACE as alternative to traditional game-theoretic approaches for testing policies for complex systems [61]. Research results obtained from Power TAC are used to derive market rules for future retail-level electricity markets. In this simulation competitors are brokers that provide energy services to retail customers using tariff offerings [62], while managing their energy loads by trading in a wholesale market [63]. Power TAC is conceived as an annual competition between research teams who prepare intelligent 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 behaviors in different market scenarios, such as oligopolies and highly competitive markets.

V. Conclusions

The electric power systems are undergoing major modernization process due to demands that are placed on the electrical grid. This has an effect from both technical and economic points of view. The smart grid is an important foundation for supporting new emerging services in the market layer. Electricity markets also experience an upgrade due to processes of deregulation and liberalization. Apart from the wholesale market, the retail market also has a lot of unknowns and thus a good market model is required to propose, test and evaluate necessary market rules.

The agent-based modeling 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 computational economics, the agents of electricity market model reside in a placeholder (so-called "culture dish") and are divided in market, social and contextual groups. Electricity market simulators are used for modeling and simulating electricity markets.

Finally, the agent-based modeling may be applicable for the Croatian electricity market. Since the major changes in the Croatian electricity market are currently underway, including the entrance of new retailers, we propose a research of the retail-level markets to determine what is necessary in terms of technical and regulatory foundations to support the evolution of energy business. This requires an open and rich test bed that specializes in simulating the structure and operation of innovative retail markets. Consequently, Power Trading Agent Competition (Power TAC) is arguably the most appropriate choice for meeting the aforementioned requirements.

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