Experimental and game-theoretic analysis of electricity markets

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Abstract. There is a wide range of game-theoretic tools for electricity market analysis. An experiment is naturally formulated for any game-theoretic model verifying its validity or allowing the weak points of the theory, which cannot be realized in practice, to be identified. This paper discusses the applicability of the method of economic experiments for the electricity markets analysis. Despite the growing popularity of economic experiment as a method of cognition, not all branches of economic knowledge equally use the experimental approach. So, the experiments are most in demand in the theory of consumer behavior, neuroeconomics and theory of auctions. The experimental results of auction theory can significantly enrich studies of economics of the electric power industry. In addition, being introduced as a business game in the process of training students – the prospective top-level managers of the fuel and energy complex, economic experiments will also help to fulfill an educational function, as evidenced by the experience of their performance by the authors at the Financial University under the Government of the Russian Federation.

1. Introduction

Electricity markets are distinguished by an important feature: they did not appear spontaneously, but were “developed” to a greater extent by government bodies responsible for economic development and planning (as, for example, the structure of the Russian market is the result of the RAO UES reform carried out in 2002-2008). Typically, the organization of the electricity market is the result of research in the field of design mechanisms [1]. The theoretical foundations of the design of electricity markets are based on microeconomic and game-theoretic models, while econometrics and experimental economics “are responsible” for the practical sections. The present work is devoted to the discussion and review of the main successes in these areas.

The main literature on experimental analysis of electricity markets has been published in the last 25-30 years, the surge of interest in the topic coincides with the pioneering experience in restructuring the industry in the United States in the mid 1980’s. Compared to other areas of experimental economics (for example, game theory and individual decision making) the number of publications in this area is not too large. This is due to both the novelty of the statement of the problem and the chosen approach, as well as the features of the electric power industry itself and the complexity of the existing market structures arising from the technological processes of the industry. The experimental methodology, as in other scientific disciplines, in economic science serves as a tool for testing
assumptions about economic behavior and/or economic efficiency of a system in the controlled and reproducible environment. These properties make it possible to study the influence of various variables “all other things being equal” and generate enough data to summarize the results.

2. Game-theoretic approach to modeling electricity markets: review of works

As a rule, electricity markets are oligopolies: on the one hand, the energy industry has a high entry barrier due to the need for large-scale investments to build generating capacities. On the other hand, the requirements of the antimonopoly legislation of most countries impede the concentration of the entire industry in the hands of the same group of individuals. Moreover, one of the most important problems for the study of which mathematical models of electricity markets are applied is the limitation of the market power of its individual participants. The concentration of generating capacities in the hands of major producers allows it to be used for the increase of the market price, which reduces public welfare, consumer surplus and the total amount of energy produced. However, in the case of the electricity market, the task of reducing the market power of firms cannot be solved by the standard method of splitting large companies into small ones due to an accompanying decrease in the reliability of electricity supplies and an increase in costs that the newly formed “more competitive” companies will encounter [2]. Another method is selection of the market mechanism that will minimize the deviation of the market price from the competitive equilibrium, optimal in terms of the total gain of market participants [3].

In most theoretical works on the economics of electricity markets, individual consumers are considered as price takers, their aggregated behavior is characterized by a well-known demand function with low price elasticity. Adhering to the tradition that has developed in microeconomics, researchers model the interaction of market participants in the form of games in normal form. The manufacturers are the players, their payoff functions are their profits depending on the chosen strategies and many strategies are determined depending on the form of market organization. Nash equilibria or their modifications (equilibria, performed according by subgames; equilibria with feedback, etc.) are usually used as the outcome of the interaction.

The game-theoretic models used in the study of electricity markets are largely determined by the experience of the functioning and organization of real markets. For example, in Russia the electricity market model assumes the existence of three sectors of electricity trade: long-term bilateral agreements, the day-ahead market and the balancing market [4]. Volumes of electricity not covered by public welfare, consumer surplus and the total amount of energy produced. However, in the case of the electricity market, the task of reducing the market power of firms cannot be solved by the standard method of splitting large companies into small ones due to an accompanying decrease in the reliability of electricity supplies and an increase in costs that the newly formed “more competitive” companies will encounter [2]. Another method is selection of the market mechanism that will minimize the deviation of the market price from the competitive equilibrium, optimal in terms of the total gain of market participants [3].

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In market models, organized by the principle of Cournot auction, each manufacturer offers a fixed volume of goods regardless of price ([5-8]). The parameters necessary to build a market model in the form of a game in normal form are as follows: the set of firms $A$, $C^a(v^a)$ – the cost function, $V^a$ – is the production capacity of a firm $a$, $a \in A$, the demand function is $D(p)$. The volume of production $v^a \in [0,V^a]$ is the strategy of the producer $a \in A$. The market price is $p(v) = p(v^a, a \in A) = D^{-1}(\sum v^a)$, and the payoff function determines the profit $u^a(v) = p(v) \cdot v^a - C^a(v^a)$. The vector $v^* = (v^a, a \in A)$ is called the Cournot equilibrium if it serves as a Nash equilibrium in the emerging game, that is, the state from which it is unprofitable for any of the participants to deviate separately. The first-order conditions on the maximum of profit function of each market participant generate a set of Cournot supply functions $S^a_C(p)$, $a \in A$. The Cournot price is defined as the solution of the equation $\sum_{a \in A} S^a_C(p) = D(p)$ – the aggregate demand is equal to the Cournot aggregate supply. If demand is a decreasing and differentiable function and its price elasticity does not increase, then there is a unique Cournot equilibrium. The relative deviation of the Cournot price from the price of perfect competition does not exceed the share of the largest company in total sales divided by the elasticity of demand [7]. In general, this ratio coincides with the value of the Lerner index for the largest company operating in the market, which, according to [8], contradicts statistics for many European markets.
3. Results and discussion
The theory of auctions is largely enriched precisely by experimental results, a brief review of which we will provide in this section. In addition to the review, this section describes an experiment conducted by the authors in 2019 at the Faculty of Economics and Finance of the Fuel and Energy Complex of the Financial University under the Government of the Russian Federation. This experiment was not only research, but also pedagogical in nature: its participants were undergraduate students majoring in economics and modeling of business processes of the fuel and energy complex. Taking part in the experiment, students, on the one hand, simulated the behavior of market entities and, on the other hand, learned to make market decisions acting as heads of electricity producing companies.

3.1. A Brief overview of experimental studies of electricity auctions
In the experiments network markets consisting of several nodes are of special interest. Single-node markets can typically be researched analytically using the models described in the previous section. But for the analysis of network markets, a generalization of game-theoretic models of auctions leads to the appearance of models of such complex structure that the analytical search for equilibrium is practically an impossible task. Therefore, to analyze network markets of complex structure, either imitation (agent-oriented) modeling or the economic experiments are most often used. So, for example, the work [9] is devoted to the answer to the following question: which of the electricity producers, consuming companies and owners of power lines receives charges for overloading and how the distribution of profits between participants changes according to different rules of holding an auction.

The participants in the experiment were combined into a radial network with three nodes (central, “upper” and “lower”). In the central node, four participants were consumer companies, and in the upper and lower nodes the participants were the generating companies (3 in the upper, 4 in the lower node). The nodes were connected by two power lines, which were characterized by power transmission limitations and a non-zero loss factor. Both sides of the market participated in electricity pricing, which took place according to the rules of a double auction of a single price. The experiment showed that with such a market organization, power line owners do not have incentives to invest in new transmission capacities, since their possible gain from this is in the hands of generating companies.

Zimmerman [10] gives the analysis results of an experiment conducted on the basis of a self-developed web platform (“PowerWeb”). This experiment examined how power transmission losses and line capacity limitations affect market prices and network performance of thirty nodes at different market sizes (two, four and six competitors), built on the basis of a single price auction. Six manufacturing companies have the same production technology, but two of them belong to units nodes-acceptors. On the consumer side, decision makers are absent; consumers are described only by the aggregate demand function. The experiment showed that market prices are close to the duopoly level in nodes-acceptors, where two generators can use their market power and are more volatile from period to period than when market power cannot be used. In addition, in the case of limitations of transmission capacity in the experiment, supercompetitive prices were expected to occur.

Another direction in the experimental literature directly concerns the analysis of auctions properties that underlie the functioning of the market. Historically, the first work within this direction [11] is devoted to comparing the oligopolistic market of two types of single-price auction: a standard auction of the first price with closed offers and an auction of the second price. These mechanisms differ only in terms of a single-market price setting scheme. The market structure in the experiments remained oligopolistic, regardless of the number of competing manufacturers (2, 4 or 6 participants). The behavior of price-taking consumers was characterized by a low-elasticity function of expected demand. The experiment showed that the auction of the first price “works” slightly better than the second, and that concentration in the market leads to a significant increase in market prices in this
institution. This result confirms the correctness of the experience of organizing real electricity markets, in which the auction of the first price is most often used.

A separate direction in the experimental analysis of electricity markets is the study and comparison of various auction options with price discrimination. For example, Rassenti [12] showed that in discriminatory auction markets in the absence of market power, the prices have higher values than in experiments with a single price auction and the presence of market power in firms. Thus, discriminatory pricing in the absence of market power is as anti-competitive as single-price auctions in markets where producers have market power.

The general conclusion of all the mentioned works is that a discriminatory auction can help reduce market power, in contrast to a single-price auction, which helps to increase prices in the face of uncertainty concerning the demand, but there is no evidence that it gives more effective results from the point of view of public welfare.

3.2. Description of the conducted experiment and review of its results

The experiment conducted by the authors of this work was performed in May 2019 with the participation of undergraduate students of the Faculty of Economics and Finance of the Fuel and Energy Complex of the Financial University under the Government of the Russian Federation. Its aim was to investigate how real market actors deviate from equilibrium behavior at various options of electricity market organization. The choice of students of this particular direction as subjects of the experiment is due to the fact that they are the ones who are trained in managing enterprises of the fuel and energy complex, and to the greatest extent possess the knowledge and competencies that are required from the heads of real enterprises participating in the electricity market.

The participants in the experiment were divided into groups of 3-5 people. The experiment consisted of 5 approaches, which were a repeated auction within the same groups corresponding to the Cournot oligopoly. The experiment was carried out using an automated system for setting up economic experiments of our own design, which is based on the open ecosystem oTree [13]. Each participant in the experiment was asked to make a decision as a head of a company that owns one generating capacity with linear costs and a given capacity limit, the exceedance of which was prohibited by software. Its marginal costs were determined randomly for each participant and did not change.

Participants selected the amount of energy produced by their generating company, subject to the linear law of demand known to them. After all participants selected their production volumes, a single energy sale price was calculated as the price at which the demand and the total supply of all firms were balanced. Profit of each company was defined as the difference between its revenue and production costs. An individual instruction was shown to all participants in the experiment, which indicated unique values of marginal costs, maximum power, and demand function coefficients. The pages shown to each participant had the appearance shown in figure 1.

Brief results of the experiment are presented in table 1 and figure 2, where the relative average deviations of the real strategies of the participants from the calculated equilibrium values are shown. The calculated values are the production volumes corresponding to the Cournot equilibrium ([2]) for the cost structure corresponding to the participants in the groups.

In total, 15 people took part in 5 approaches of the experiment (2 groups of 5 people, one out of 4 and one player turned out to be a “monopolist” in his group).

On the whole, the dynamics of the market price in all groups corresponded to the process of gradual approach to equilibrium. While the relative deviation of the price from the equilibrium value at the first approach turned out to be very different for different groups and markedly differed from zero, over time, the participants “felt” for equilibrium strategies, and the deviation of the situation from equilibrium decreased.

The experiment confirmed the assumption that the behaviour of participants of electric power market at a low level of competition in the conditions of repeated interaction and the invariance of the technological structure converges to an equilibrium value. In addition to theoretical significance, the
The experiment turned out to be very useful from an educational point of view: the future top-managers of energy companies were able to first-hand understand the basic mechanisms of the market functioning and learn how to determine the equilibrium strategies for the companies-participants in the electric power market in which they “hold the key position”.

![Figure 1. The appearance of the pages shown to the experiment participants in the browser.](image1)

| Table 1. Estimated equilibrium values for approaches 1-5 and average values of parameters. |
|-----------------------------------------------|--------------------------------|---------------------------------|---------------------------------|--|
| Estimated price | Group 1 (5 part.) | Group 2 (5 part.) | Group 3 (4 part.) | Group 4 (1 part.) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| Actual price (average for approaches 1-5) | 240.25 | 196.125 | 185.625 | 425 |
| Relative deviation, % | +38% | -19% | +63% | +13% |

![Figure 2. Dynamics of the average relative deviation of the market price from the equilibrium one (percentage).](image2)
4. Conclusions
In this paper, the approaches to the analysis of electricity markets were reviewed. In addition to game-theoretic models corresponding to various types of auctions, methods of experimental economics are also used to study them, and in the increasing number of modern works these two approaches are combined complementing and enriching each other. An experiment is naturally formulated for any game-theoretic model verifying its validity or allowing the weak points of the theory, which cannot be realized in practice, to be identified. Experimental analysis allows the effectiveness of market organization to be compared for different types of auction underlying it. The authors of the work conducted an economic experiment aimed at identifying the compliance with the theoretically predicted (equilibrium) behavior of real people associated with the electricity industry – undergraduate students of the Faculty of Economics and Finance of the Fuel and Energy Complex of the Financial University under the Government of the Russian Federation. For analysis there was a type of market organization like the Cournot auction.

In this case, as a rule, the participants in the experiments either immediately demonstrate close to equilibrium behavior, or their behavior converges to equilibrium one with an increase in the number of approaches in the experiment. This experiment turned out to be useful from two points of view: first, it gave one more confirmation of the correctness of the assumption about the equilibrium behavior of electric power market participants, and, second, participation in it allowed the students to understand while playing the basic mechanisms of the market functioning.

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