OPTIMIZATION MODELS OF THE UKRAINIAN POWER INDUSTRY

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***Abstract**. The paper deals with the environmental aspect of power industry development and uses unilateral and bilateral auction and games theory optimization modeling to simulate competitive market introduction to the Ukrainian electric power industry. The main goal of the research is to investigate how the transition will influence prices', volumes' dynamics and benefit distribution among market players while also addressing the problem of possible market fluctuations due to price sensitivity.*

***Key words:** electric power market, environment, competitive market introduction, auctions, games theory*

Introduction

In today's world, power industry is a basis for the progress of the key branches of economy. Its development outpaces the growth of other branches in all industrialized countries. However, the power industry is also a source of an adverse influence on the environment. It affects the atmosphere (oxygen consumption, gas, damp, and particulate emissions), the hydrosphere (water consumption, artificial reservoirs' development, polluted and hot water disposal, liquid wastes disposal) and the lithosphere (consumption of minerals, landscape modification, toxic emissions).

Despite these adverse influences, the growth of power consumption had not been causing alarm among general public almost until the end of the previous century. At that time, experts discovered an abundant evidence of negative effects of the rapid development of power industry on the climate system. Since then, the issue of climate change has become the most actively discussed scientific problem.

It is widely believed that one of the main causes of climate change is power industry, which has become one of the strongest reasons for environmental problems. Power industry implies any area of human activity associated with the production and consumption of energy. A significant part of power industry is related to the combustion of organic fossil fuels such as oil, coal, and gas, which causes air pollutant emissions.

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Environmental problems of traditional power industry

An outstanding feature of power industry is its solid long-time development under various conditions. The principal portion of power is produced at traditional power stations, most of which have units of electrical power exceeding 1000 MW. In terms of power production, thermal power plants (TPPs) are followed by hydroelectric plants (HEPs) and nuclear power plants (NPPs).

The traditional power industry is comprised of several types of power generating plants:

1) Thermal power plants

Thermal power industry prevails among other traditional types: 39% of power generated in the world is produced at oil fuelled plants, 27% at coal fueled plants, and 24% at gas fuelled plants. This brings the share of the traditionally generated power to 90% (see *http://www.nuclphys.sinp.msu.ru/ecology/ecol/ecol05.htm/* (Accessed in May 2013)). Power industry of such countries as Poland and South Africa is almost completely based on the use of coal, the Netherlands heavily depend on gas. China, Australia, and Mexico are also among the countries where the prevailing share of power is produced at TPSs.

Coal, gas, black oil, and slate are commonly used as a fuel at TPPs. Fossil fuels are non-renewable resources. According to various estimates, current coal reserves will last for another 100–300 years, oil reserves will last 40–80 years, and gas will last 50–120 years.

TPPs are massive producers of the radioactive and toxic pollution of the environment. The reason is the fact that coal ashes contain higher concentrations of trace components of uranium and other toxic elements than the earth shell does.

The construction of TPPs causes pollution which is even more adverse. New influences may emerge during this process. One of such issues is caused by the fact that the speed of oxygen burning may be exceeding the speed of its production by plants during photosynthesis.

2) Hydroelectric plants

The key advantages of HEPs are the low cost of power, the rapid time to value (cost is about four times lower and the pay-off period is three to four times less than that of TPPs), the ability to accumulate energy, and a high flexibility which is critically important during the peak demand.

Nevertheless, the quality of water in reservoirs is deteriorating and the integrity of the ecosystem is disturbed. The construction of reservoirs destroys hatchery ponds, fertile lands are flooded, and the groundwater level is changing.

3) Nuclear power plants

NPPs do not produce carbon dioxide, the amount of other air pollution is also insignificant as compared to TPPs. Until recently, NPPs have been considered the most environment-friendly alternative to hazardous TPPs. However, the safety of NPPs is still questionable.

The global nuclear industry began to develop in the 1950s. The most nuclear-power-advanced nations are the USA, France, Japan, Russia, and Great Britain. They produce 60% of nuclear power generated in the world.

The top five states where at least 50% of power is generated at NPPs are Lithuania (80%), France (76%), Slovak Republic (57%), Belgium (55%), Sweden (51%)).

In the meantime, the atomic boom causes a dramatic concern among scientists around the world. The matter is that the nuclear power industry carries the most adverse threat to the environment and human health due to its potential radioactive pollution. The major accidents at the Chernobyl and Fukushima NPPs confirm the anticipations.

Considering the above–mentioned, it becomes more and more sensible to use alternative sources of energy such as solar radiation, wind energy, river energy, tidal and ocean waves energy, bioenergy.

Alternative sources of energy carry a substantial potential, but it is still evident that the traditionally used oil and gas will not be fully replaced in the foreseeable future. The current level of technologies only approaches the development of promising and unconventional sources of energy such as bituminous sandstone, slate oil, and gas hydrates.

Therefore, the construction of optimization auction models of power utilization is a timely challenging problem in modern European countries, Ukraine including.

General formulation of the problem

An important part of the supply–demand interaction in the power industry is the algorithm of price design. To date, there is no globally accepted best practice in modeling an efficient planning and management of power markets. The widely used approaches to modeling competitive power markets are pooling and bilateral trading, where the fundamental difference lies in the way bids are processed (Klemperer, 2002, Dasgupta and Maskin, 2000, Milgrom and Ausubel, 2002).

Pool was developed during free market introduction and served to aid the adaptation of power industry to competitive relations. In this model, supply and demand interact through the market of available goods (pool), where the necessary production volumes are estimated by maximizing the welfare function.

Bids and offers are accumulated in the integrated financial system in which independent systems' operator provides the dispatch of the model modes. The entries are standardized and contain bidding or asking prices and volumes. Electric power markets around the world usually use this model jointly with bilateral trading. Pooling prevails on operational and day-ahead markets. Bilateral trading is used to support long-term contracts which cover time frames ranging between a week and two years. Pooling allows achieving economic efficiency by selecting the least expensive power output given the assumption of price-cost correspondence holds. Therefore, the model allows maintaining centralized pricing, and in these circumstances the dispatch management is often considered an auction (Stoft, 2002).

In the 1990s, a number of developed countries began the liberalization of electric power markets due to the accumulation of substantial excess capacities in the national power systems, emergence of low-power plants, growth of gas utilization. The economy liberalization policy and the reduction of state regulation of natural monopolies were also substantial reasons.

The progress of Ukrainian science in modeling the domestic competitive wholesale electric power market is basic. The available developments concern transition from the 'single buyer' model to a simple bilateral centralized auction with sealed bids and step-by-step trading. The transition is scheduled for 2014 and involves a minimal use of mathematical optimization.

Usually mentioned among the main objectives of the introduction of a competitive domestic electric power market are establishing a civilized competition among producers and suppliers of electric power, securing a competitive pricing, and formation of a transparent payment system.

This study was aimed at modeling the domestic competitive electric power market by using game models, unilateral and bilateral auctions, and researching the possibilities of practical implementation of such models in Ukraine.

The main goal of the research was to investigate how the transition would influence prices, volumes, the distribution of the dynamics and benefits among market players while also addressing the problem of possible market fluctuations due to price sensitivity.

Literature review

Scientists around the globe pay special attention to simulating the so-called efficient auctions. Dasgupta and Maskin (2000) argue that one can consider an auction as efficient, provided that goods fall into the hands of the highest bidder. Stoft (2002) is one of the researchers who define the auction to be efficient when welfare functions of producers and consumers reach their peaks.

Another substantial issue which is widely discussed in scientific circles is a collusion among producers. While Milgrom and Ausubel (2002) write that English, or open ascending price, auctions guarantee resource allocation efficiency, Klemperer (2002) turns to a striking example of 1999 public auction in Germany where 10 blocks of spectrum were sold. The auction has the rule that a new bid had to exceed the previous one by at least 10%; it was essentially an English auction. Klemperer (2002) writes:

"Mannesman's first bids were 18.18 million Deutschmarks per megahertz on blocks 1–5 and 20 million DM per MHz on blocks 6–10; the only other credible bidder – T-Mobil – bid even less in the first round. The point is that 18.18 plus a 10 percent raise equals approximately 20. It seems T-Mobil understood that if it bid 20 million DM per MHz on blocks 1–5, but did not bid again on blocks 6–10, the two companies would then live and let live with neither company challenging the other on the other's half. Exactly that happened. So the auction closed after just two rounds with each of the bidders acquiring half the blocks for the same low price".

The "winner curse" is another underlying feature of open ascending price auctions and to a lesser extent that of sealed auctions. Capen et al. (1971) discuss that often during auctions goods fall into the hands of the bidder who overestimates the price most. One of the prominent cases describing the issue, mentioned in Crampton (1998), is Bell-South $2.5 billion bid during the first mobile license auctions in Brazil, which took place in 1997. The second highest bid was $1 billion less. BellSouth shares took a $1.25 fall after the outcomes of the auction had been made public. The Vickrey auction addresses the problem by introducing the rule of the second price where the winner pays the second highest bid.

Models and results

Overwies of approaches. The unilateral centralized sealed bid auction model minimizes the cost of meeting the demand. A bilateral centralized sealed-bid auction maximizes the benefit of producers and consumers while balancing supply and demand. The models are solved by constructing the so-called "step jogged lines" of supply and demand and calculating the equilibrium price by finding the interception of such lines.

Distributed auctions are used to model a competitive domestic wholesale electric power market and a transition market (Davidson et al., 2004). Such auctions imply that an electric system consists of power units, or nodes, $\{i, j, ...\}$ and A (i, j) branches which connect these units. A unit is a symbolic place on the market with a certain set of producers and consumers. A distributed auction maximizes the benefit of producers and consumers simultaneously and allows for energy flow between the nodes.

During the transition period, the electric power market consists of two parts. The model of such auction is a two-step one. The optimal loading on producers and consumers is estimated according to the planned output and consumption, which is followed by calculating the volumes of power to be traded freely.

Bilateral centralized auction. The formalization of a bilateral centralized auction for the domestic wholesale electric power market is a system (1)–(4) (Davidson et al., 2004):

$$\max\{\sum_{j \in C} c_j V_j - \sum_{i \in G} c_i V_i\}; \qquad (1)$$

$$\sum_{i \in G} V_i - \sum_{j \in C} V_j = 0; \tag{2}$$

$$0 \le V_i \le V_i^{'}; \tag{3}$$

$$0 \le V_j \le V_j^{'}. \tag{4}$$

where C_i, V_i are prices and volumes in producers' offers, respectively;
C_j, V_j are prices and volumes in consumers' bid entries.

Volumes in entries are maximal volumes which can be sold or bought by producers and consumers, respectively.

The object function (1) is called a welfare function and maximizes the total benefit of consumers and producers:

$$\sum_{j \in C} c_j V_j - \sum_{i \in G} c_i V_i = \sum_{j \in C} (c_j - c^*) V_j + \sum_{i \in G} (c^* - c_i) V_i. \tag{5}$$

The graphical solution of the problem is depicted in Fig. 1 and is essentially an intersection of the supply and demand steps.

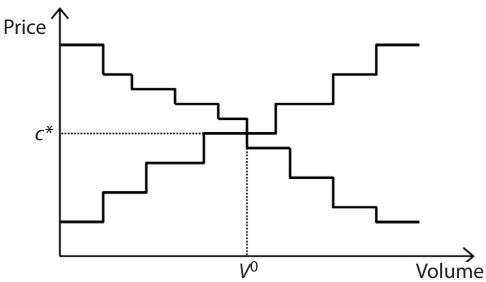

FIG. 1. **Graphical solution of the (1–4) problem**

Source: author's calculations.

The c^* is and equilibrium price on the market. This is the price which is paid by all buyers. All producers whose asked prices are lower than or equal to c^* and all buyers whose bidding prices are higher than or equal to c^* sell or buy volumes $V_i^0 = V_i^{'}$, $V_j^0 = V_j^{'}$. Entries of all other sellers and bidders are not processed, the volumes are: $V_i^0 = V_j^0 = 0$.

Constraint (2) implies that there are no losses of electric power in the system which does not hold on the real life markets. To address the problem, one can use distributed auctions with nodes where the no-loss condition holds. The general case is that the equilibrium prices fixed during auctions conducted in each unit separately are not equal. Therefore, conditions for electric power cross-flow are created.

Thus, a simple two-node distributed auction is a (1)–(4) system where additional constraints are introduced:

$$\sum_{j \in C(1)} V_j = \sum_{i \in G(1)} V_i - p_{(1,2)}; \tag{6}$$

$$\sum_{j\in C(2)} V_j = \sum_{i\in G(2)} V_i - p_{(1,2)}; \tag{7}$$

$$p^{\min} \le p_{(1,2)} \le p^{\max}; \tag{8}$$

where $p_{(1,2)}$ is a cross-flow from one node to another, $p_{(1,2)} \in R$.

Unilateral auctions cover either the buy or the sell party. Each unilateral auction model optimizes the welfare function of a producer or a consumer, meaning that the object function contains only those components that correspond to bidding or asking prices.

Games theory approach. Each auction consists of four main constituents: market players (participants), goods (or services), the pricing mechanism, and players' strategies. Market players are informed about the auction rules before the trading session and choose their strategies based on the past experience and expectations on entries of other participants. The main goal of each participant is to determine the strategy which maximizes the accepted objective (utility) function.

The important matter which emerges during strategy identification is to define the exogenous variables which are invariant to participants' decisions. For example, one must take into account that prices might change due to actions of other participants.

In modeling auctions, the games theory approaches are often used to research the application of different strategies. Each A_i strategy for an *i-th* participants is defined by the utility function U_i. Such function does not uniquely correspond to the chosen strategy, but is rather a response to a set of other participants' strategies: $U_i = f(x_1^k, x_2^k, ..., x_n^1)$, where k is the quantity of calculation intervals (for a electric power auction in Ukraine $k = 24$), n is the number of participants. The utility function $U(\overrightarrow{X}^k)$ is used to assign the utility value $U_i(x_i^{*k})$ to each outcome based on the strategy x_i^k and each alternative.

One step bid implies that a participant assumes which strategies $\overrightarrow{X}_{-i}^{*k}$ are chosen by other participants, while an individual strategy is chosen under the maximization of the utility function for x_i^{*k}:

$$U(x_i^{*k}, \overrightarrow{X}_{-i}^{*k}) = \max_{\alpha\in A_i}(U_i(\alpha, \overrightarrow{X}_{-i}^{*k})). \tag{9}$$

The function's minimum or maximum can be found by equating its first derivative to zero; therefore, (9) can be transformed to

$$\frac{\partial U_i(x_i^{*k}, \overrightarrow{X}_{-i}^{*k})}{\partial x_i} = 0. \tag{10}$$

Assuming that all other participants accept the expected strategies, the following expression holds:

$$U_i(x_i^k, \overrightarrow{X}_{-i}^{*k}) = (U_i(x_i^k)).$$

The research simulates a unilateral selling auction; three types of the utility function $U_i(x_i^k)$ were used; calculations were completed for each hour:

- when the maximizing profit under a certain price bid: $U_i(P_i^k) = C_0^k \cdot P_i^k - C(P_i^k)$; C_0^k is a marginal equilibrium price fixed during trading; P_i^k is the capacity of the *i*-th participant; $C(P_i^k) = a_i(P_i^k)^2 + b_i P_i^k + c_i$ costs per hour of the *i*-th participant;
- when maximizing the profit-to-cost ratio:

$$U_i(P_i^k) = \frac{(C_0^k \cdot P_i^k - C(P_i^k))}{C(P_i^k)};$$

- when maximizing the capacity given a certain profitability $P_{i_{\max}}^k = const, k = \overline{1,24}$. In this case, the utility function is $U_i(P_i^k) = C_0^k \cdot P_{i_{\max}}^k - C(P_{i_{\max}}^k) = r \cdot (C(P_{i_{\max}}^k))$.

Under each set of conditions, the participant must define the optimal strategy using the dominant strategy and Bernoulli's principles.

During simulation, linear models were used to assure a better understanding by market participants. The model assumptions are as follows:

- The sensitivity matrix is used to link the general electric lines and units' capacities;
- all unit capacities are positive values;
- price bids are one-step;
- the optimal solution was found through the linear programming approach;
- the model employs node pricing; transactional costs were ignored.

Unilateral centralized auction is another example of the simulation of trading on the domestic wholesale electric power market. The problem of finding outcomes of the auction, which meet the demand V on the market, is to find the constrained extremum which is constructed according to the auction entries with the components c_i and V_i':

$$\min \sum_i c_i V_i; \qquad (11)$$

$$\sum_i V_i = V; \qquad (12)$$

$$0 \le V_i \le V_i', \qquad (13)$$

where $\boldsymbol{c_i}$ is an offering price of a certain producer;
V_i' is a maximum volume which can be met by a producer i at a certain price $\boldsymbol{c_i}$;
V_i are the volumes which are to be fixed during the auction.

The prices $\boldsymbol{c_i}$ need to be arranged in ascending order before finding the solution to (11)–(13). The solution, vector V^0, therefore, becomes:

$$V_i^0 = V_i^{'}\ \forall i < i^0,\ V^0 = 0\ \forall i > i^0,$$

where $i^0 = \min\{i^{'} : \sum_{i=1}^{i^{'}} V_i^{'} \geq V\}$, $V_i^0 = V - \sum_{i=1}^{i^0-1} V_i^{'}$.

The Lagrange multiplier λ^0 to constraint (12) is equal to the price in the offer of producer, i^0, and is an equilibrium price. The graphical solution of the problem is shown in Fig. 2.

The model (11)–(13) was calculated for the Ukrainian market under the assumption that there are five producers which correspond to five types of power plants. During the auction, these producers make offers containing volumes and prices they are willing to accept. The data used was retrieved from the official web page of the public enterprise "Energorynok". The structure of power volumes sold at the wholesale market by nuclear power plants, thermal power plants, hydroelectric plants, combined heat and power plants and wind power plants corresponds to V_1, ..., V_5 components measured in MWh. The volumes of power bought by suppliers compose the demand components denoted as V, also measured in MWh. Selling prices at the wholesale power market correspond to the c_1, ..., c_5 components.

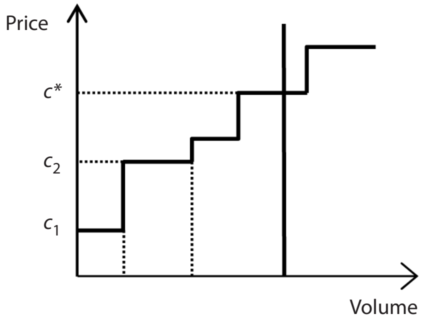

FIG. 2. **Graphical solution to (11)–(13)**
Source: author's calculations.

These data can be found at *http://www.er.gov.ua/ and http://www.ukrenergoenergy.gov.ua.* (accessed in June 2013).

It is assumed that the auction takes place three times a month.

As a result, the auction completed with offers accumulated from April 20, 2010 to April 30, 2010 takes the form of the system:

$$159.54 \cdot V_1 + 446.53 \cdot V_2 + 96.98 \cdot V_3 + 663.28 \cdot V_4 + 1227.7 \cdot V_5 \to \min; \quad (14)$$

$$V_1 + V_2 + V_3 + V_4 + V_5 = 4188160; \quad (15)$$

$$V_1 \leq 2216742; V_2 \leq 1407744; V_3 \leq 530225; V_4 \leq 228740; V_5 \leq 743; \quad (16)$$

$$V_i \geq 0, i = \overline{1.5}. \quad (17)$$

This system is solved by using the Lagrange multipliers, and the results of the auctions are: NPPs, TPPs and HPPs sell maximal offering volumes, while combined heat and power plants sell 33.449 MWh out of 228.740 MWh they were ready to offer. Total power volumes sold at the market amount to 4,188,160 MWh. Therefore, the price fixed at the market is equal to the offering price of combined heat and power plants, which is 663.28 UAH per MWh.

The problems of the energy sector in Ukraine

Trends in international relations in the recent decades indicate an increasing role of the energy sector in any country for its political and economic independence. The problems of energy security balance the level of the development of the energy sector and the functioning of the national electricity market topical for Ukraine, which is 15 years old and is at the stage of transition to market mechanisms for the domestic energy sector.

Power industry in Ukraine is rapidly developing for the last few years and already in 2011 exceeded the pre-crisis figures (see Fig. 4).

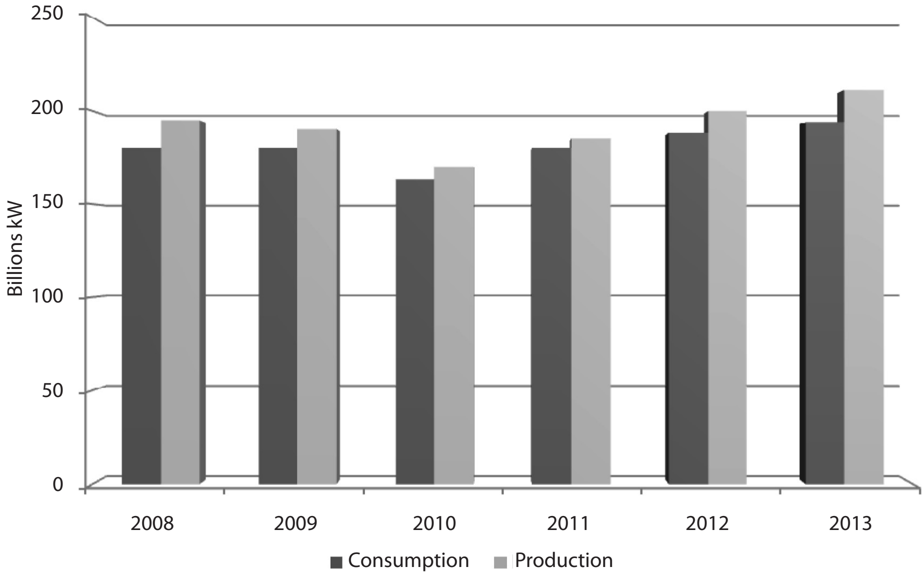

FIG. 4. **The dynamics of power industry in Ukraine for the period 2008–2013**

Source: author's calculations based on the public enterprise "Energorynok" data.

The importance of the energy sector lies in the fact that the product of its activity – electricity – is one of the most important components for all sectors of the economy, especially industry (Fig. 5).

The key problems of national energy networks are an ineffective approach to the basics of the functioning of markets and the lack of financial resources to implement the changes.

International practice shows that the model of the energy that is used in Ukraine does not give the expected economic effect and is generally unacceptable to the realities of

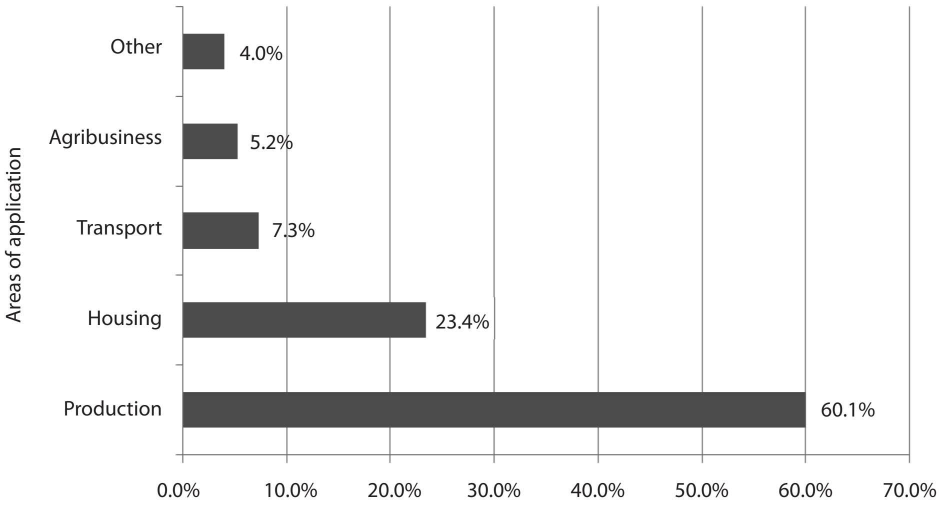

FIG. 5. **Structure of electricity use for areas of application in Ukraine (%), 2012**

Source: author's calculations based on the NPC "Ukrenergo" data.

the Ukrainian economy. The obstacles to borrowing investments in the sector are the monopolized market and its corruption.

The electric power industry in Ukraine is developing rapidly in recent years and in 2011 exceeded the pre-crisis figures.

The structure of Ukraine's exports also reflects the development of its power industry. If in 2009 there was only 1% of exports, in 2011 there are 3%, the same as the chemical industry, and in 2012–2013 it is planned to increase this level to 5–7%.

Despite the rather good macroeconomic performance, there are many problems of various kinds, which greatly hinder the development of the industry.

The primary task of the Ukrainian energy becomes the reformation of the energy sector, based on the market principles with the need to simplify the interaction between the suppliers and consumers of the product, increasing the reliability of the whole system, and attracting investments to the country.

The models which, in the opinion of experts, are more appropriate to apply in Ukraine, are diverse and contradictory. The most acceptable proposal in the literature is the balancing of the electricity market.

Balancing the market is a new form of relationship which maximally reconciles the market mechanisms and the technologies of electric power systems. Balancing market designed to neutralize fluctuations in the system and significantly improve its stability and reliability.

The exchange trading power industry system pursues the same goal which will work on a "day ahead". In a specialized trading platform, market participants can buy and sell electricity, minimizing the risks of imbalances by clarifying its contractual position a day ahead. When using an appropriate model, the state influence on the market is weakened.

The exchange system can increase the time of the decision and, therefore, organic supplements, and completes the holistic view of the new organization of the functioning electric power market in Ukraine.

The model balancing market has several features. Buying and selling electricity are carried out in parallel through bilateral contacts and market exchange. This pattern of trade can increase the accuracy of the market.

Conclusions

This research investigates the optimization of a competitive wholesale electric power market in Ukraine by using models of sealed-bid unilateral and bilateral auctions and games theory.

The free electric power market is said to be operating under optimum, where the first right to sell receive the producers whose prices are the lowest, and the right to buy is given to the buyers who bid the highest. Furthermore, during the transition period, the prices come out to be higher than on the competitive market.

Examination of a number of models which simulate free market introduction prove that such a transition is not an overnight process and needs to be carefully planned in order to avoid market disruption due to significant fluctuations of prices and electric power shortages. The research, therefore, heavily focuses on investigating the outcomes of liberalization of the Ukrainian wholesale electric power market: the possible price and volume fluctuations, as well as the benefit distribution among market players are studied.

The scope of the research is forward-looking in terms of the generation of investment in the power economy and the integration of Ukraine into a single energy system of Europe in the light of market liberalization in progress since the 1990s.

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