The method of planning the energy consumption for electricity market

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Abstract. The limitations of existing forecast models are defined. The offered method is based on game theory, probabilities theory and forecasting the energy prices relations. New method is the basis for planning the uneven energy consumption of industrial enterprise. Ecological side of the offered method is disclosed. The program module performed the algorithm of the method is described. Positive method tests at the industrial enterprise are shown. The offered method allows optimizing the difference between planned and factual consumption of energy every hour of a day. The conclusion about applicability of the method for addressing economic and ecological challenges is made.

1. Introduction

The digital methods of informational technologies (IT) are widely involved into great number of practical and scientific tasks nowadays. Modern IT methods allow performing calculations of any complexity and simulating investigated processes in a real-time mode. Thereby the signification of IT methods greatly rises for all scientific fields. For example Energetics has been affected by IT methods too. Electric energy price depends on indications of meters since electricity has become the commodity. But energy market has transformed while the number of energy consumers has increased. Energy price has divided into several parts: night, day, peak and others. Electric meters have become electronic devices with separate metering function. It was just first step of IT invasion. Electricity markets (EM) has been appeared in developed countries since the 1980s. The rules of forming energy price have been sizeable complicated [1]. Servers with special software became the main center of new markets. The computers are forming all hour prices and energy real-time distribution now.

The most of industrial enterprises consumes energy from electricity markets because EM price is less than retail one. However EM imposes strict requirements in terms of planning energy consumption. In particular EM participant must send an auction bid every noon. The bid contains energy prices and volumes for 24 hours of next day. The price of difference between factual and planned energy consumption is knowingly unprofitable. It stimulates enterprise accuracy of planning. Therefore all participants have to find any forecast model to improve accuracy. There is great number of forecast models successfully using for prediction of energy consumption all over the world today [2]. Best forecast models are exploited in electricity markets. For example Autoregressive models are used in European Energy Exchange [3], Neural Network models are utilized in Swedish Energy Agency [4], Exponential Smoothing models are applied in South Asia markets [5]. China market prefers Markov Chains models [6], Frankfurt energy forecast company uses Classification and Regression Trees models [7]. Nevertheless all existing forecast models have important disadvantage. It

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is the dependence of forecast precision on energy consumption type. The precision greatly reduces due consumption unevenness [8]. The enterprises that use the existing models for forecasting uneven energy consumption have low planning accuracy and big difference between planned and factual hour consumption. Moreover their results are worse than results of simplest forecast model called «Naive Straw Man» where planned hour energy volumes equal to flat graph [9]. The lot of metallurgical enterprises has uneven energy consumption due to the prevalence of the production technology requirements over the compliance of energy planning. This is the reason for the decline of forecast accuracy and the inability of own energy consumption control as well [10]. Therefore such enterprises have a big difference between factual and planned hour consumption [11]. As the result the price of electric energy sizeable increases. Indeed, EM System Operator has to additionally load the energy generators to support unplanned consumption increase. The energy system of the country forcedly expends additional energy resources (the most of ones are nonrenewable, e.g. coal or oil) so Earth atmosphere is damaged without a strong reason.

That is why the developing new methods of planning uneven energy consumption is very actual scientific, industrial and ecological task despite of other forecast models existence. New IT methods take into consideration the close relations between energy prices and volumes in algorithms of EM organizations [12]. The implementation of these methods enables to save energy recourses and solve ecological problems all over the world.

2. The method of planning energy consumption based on game theory

The main EM principles should be examined before description of the new method features.

2.1 The trading at the electricity market

EM consists of 2 sectors - the Day-Ahead Market (DAM) and the Balancing Market (BM). DAM bid includes energy volumes and prices for every 24 hours of day X+1 and should be sent until 13:00 of the day X (figure 1).

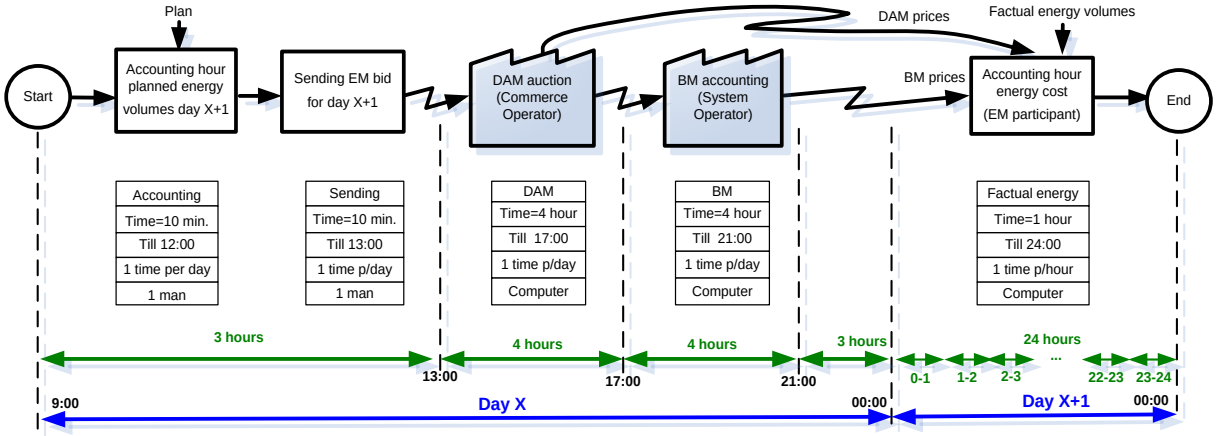


Figure 1. Cycle of the planning and the consuming energy at EM

The Commerce Operator generates DAM prices according to the results of the auction among bids of all EM participants. BM prices are generated regardless of DAM ones [11]. The enterprise buys the planned volume for DAM price. The difference between factual and planned volume buys if factual volume more than planned one; the difference sells otherwise (figure 2). Both EM markets are virtual ones for enterprise-consumer.



Figure 2. EM buying and sale operations

BM prices are always unprofitable than DAM prices (Eq. 1):

$$\text{Price}_{BM}^{sell} \le \text{Price}_{DAM} \le \text{Price}_{BM}^{buy} \tag{1}$$

Total hour EM energy cost depends on DAM and BM prices and energy volumes (Eq. 2):

$$S_{DAM+BM} = \text{Price}_{DAM} \cdot V_p + \begin{cases} (V_f - V_p) \cdot \text{Price}_{BM}^{buy}, \text{if } (V_f > V_p) \\ (V_f - V_p) \cdot \text{Price}_{BM}^{sell}, \text{if } (V_f < V_p), \end{cases} \tag{2}$$

where V_f – the volume of factual energy consumption; V_{plan} – planned energy volume.

Besides after the end of every month enterprise should pay another additional payment depending on the ratio of its own difference between planned and factual energy to differences of all EM participants (Eq. 3):

$$S^i = \frac{\sum_{l=1}^{L} \Delta V_{D+}^{buyi,l} + \sum_{l=1}^{L} \Delta V_{D-}^{buyi,l}}{\sum_{j=1}^{K} \left(\sum_{l=1}^{L} \Delta V_{D+}^{buyj,l} + \sum_{l=1}^{L} \Delta V_{D-}^{buyj,l} + \sum_{l=1}^{L} \Delta V_{D+}^{sell,j,l} + \sum_{l=1}^{L} \Delta V_{D-}^{sell,j,l} \right)} \cdot \delta_z, \tag{3}$$

where i – EM participant; K – number of participants; L – number of hours in respective month; $\Delta V_{D+}^{buyj,l}$, $\Delta V_{D-}^{buyj,l}$ - the various signs difference of consumer j; $\Delta V_{D+}^{sell,j,l}$, $\Delta V_{D-}^{sell,j,l}$ - the various signs difference of generator j, δ_z - total EM financial unbalance.

Therefore additional penalty price C_{dif} of difference volume for enterprise depends on total difference volume of all EM participants and total EM financial unbalance δ_z (figure 3).

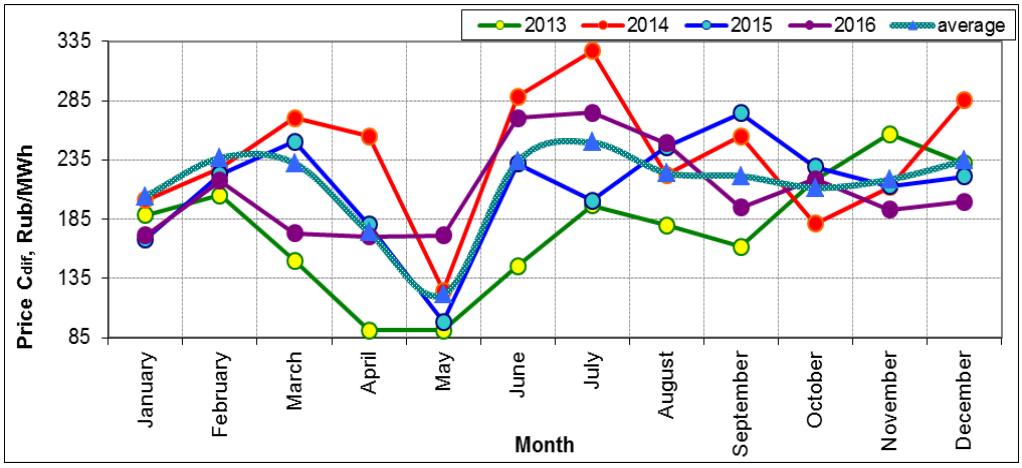


Figure 3. Price C_{dif} according to statistics of enterprise in Volgograd region by 2013-2016 years

2.2. The relations of the hour prices

The System Operator forming BM prices is responsible for the balance of generation and consumption in the energy system of the country. DAM and BM prices relations are the signals for consumers about recommended volume of factual energy consumption every hour. Correct reaction of consumer means the support of system balance and consumer haven't penalty - BM price will equal to DAM price in this case. Over against incorrect reaction leads to a change of generators operational mode, expense of additional energy resources and buying or sale for unprofitable BM price. An enterprise with uneven energy consumption has great number of difference volumes [10]. However there is the opportunity to reduce their cost without decrease of difference volumes. It is the analysis of EM hour prices relations. According to EM order document [11] one of BM prices (for buy or for sell) equals to DAM price every hour of a day (figure 4).

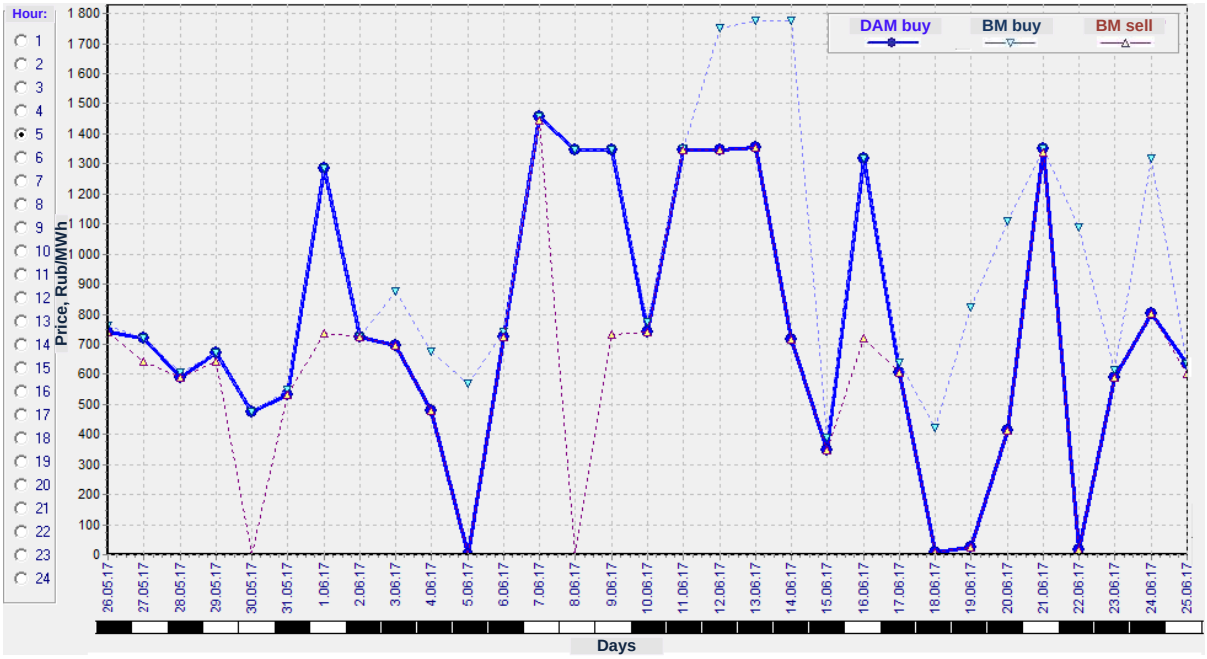


Figure 4. EM prices relations by statistics of enterprise in Volgograd region, hour 4-5, May-June 2017

It means that the enterprise can be protected from unprofitable BM operations by buying deficient energy volume or selling excessive volume in BM for DAM price. Therefore enterprise have a possibility to buy own factual energy just for DAM prices.

2.3. The correction of planned energy volume

EM is the market where informatics, energetics and economics are faced. The system analysis allows researchers to find the optimal solution for choice of optimal planned volume every hour. Enterprise with uneven unregulated consumption usually exploits flat graph for the purpose of minimization of difference between planned and factual volumes. Enterprise which wants to avoid unprofitable BM operations should select volume and sign of planned volume correction in accordance with expected relation of DAM and BM prices (figure 5).



Figure 5. The correction of planned energy volume for every hour of a day

The optimization task involves selecting one optimal variant from the set of alternatives X in according with the principle of optimality [13]. Main factors [11, 14] that determine the relations of EM prices and therefore the principle of optimality are examined below:

1. Energy volumes and prices in the DAM bids of other EM participants. The absence of opportunity for an enterprise to know about the data in the DAM bids of other EM participants is one of EM features. DAM bid of each participant is confidential information.

2. The changes of actual energy consumption of other EM participants. The situation is similar - just EM participant and System Operator know about the change of consumption.

3. The actual limitations of an energy flow in the energy system of the country. Just System Operator knows about system limitations of energy flow too.

Therefore an enterprise as a simple EM participant has no actual information scribed above and there is no opportunity to take it into account in the analysis. So an enterprise has to solve the optimization task under uncertainty. Forecasting relations of prices is the undetermined experiment with two anticipatorily unknown results (DAM price equals to BM buying price or BM sale price). Consequently the forecasting may be realized on the basis of the statistical stability. This approach is used by some researchers as a basic method of prices relations forecast [15]. Except that the forecasting may be realized on the basis of game theory. Indeed all EM participants compete with each other to maximize profit (or avoid disadvantage) by sending the DAM bids while they frequently haven't actual information about bids of other participants and even about own expected hour consumption of energy [10]. And the bid of EM participant influences the level of the prices of other participants (figure 6).

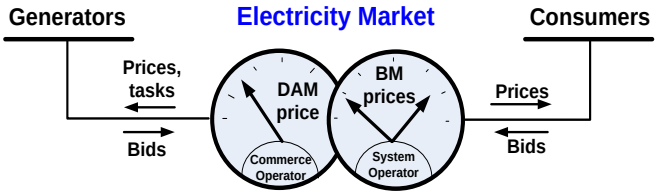


Figure 6. «The game» of EM participants

The game theory is used by researchers of USA electricity market too [16]. Because of multiple realization, statistical stability and uncertainty of experiment result (EM prices relation) the approach based on probability theory and game theory is correct [13]. The offered approach uses comparison of disadvantage risk and profit probability. The target function of the method is described below (Eq. 4):

$$\begin{cases} \sum_{i=1}^{N} S^{i}_{DAM+BM} < \sum_{i=1}^{N} S^{*i}_{DAM+BM} \\ \sum_{i=1}^{N} V_i \le \sum_{i=1}^{N} V^*_i \end{cases}, \quad (4)$$

where S^{i}_{DAM+BM} - total energy cost and V_i – volume of energy difference after correction of planned energy volume, S^{*i}_{DAM+BM} - total energy cost and V^*_i – volume of energy difference before correction, i – index of an hour in a day, N – number of hours in a month.

The offered method is based on multicriterial decision-making task. One criterion of the task is the reduction of total energy cost. Another one is the reduction of the difference between planned and factual energy volumes. The difference volumes could be transformed into the cost using price C_{dif} (figure 3). Therefore the task transforms into one-criterion task.

There is a stable predominance one type of prices relations over another one (figure 7).

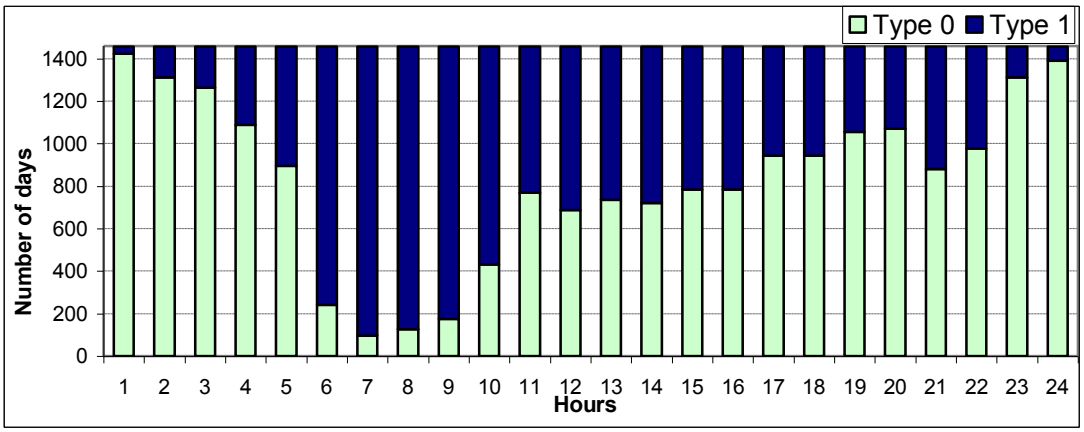


Figure 7. Types of prices relations by Volgograd region enterprise statistics for 2013-2017 years

The probability of the energy difference type (factual consumption more than planned one or in contrast) is calculated on basis of statistics for previous 31 day for every hour (figure 8).

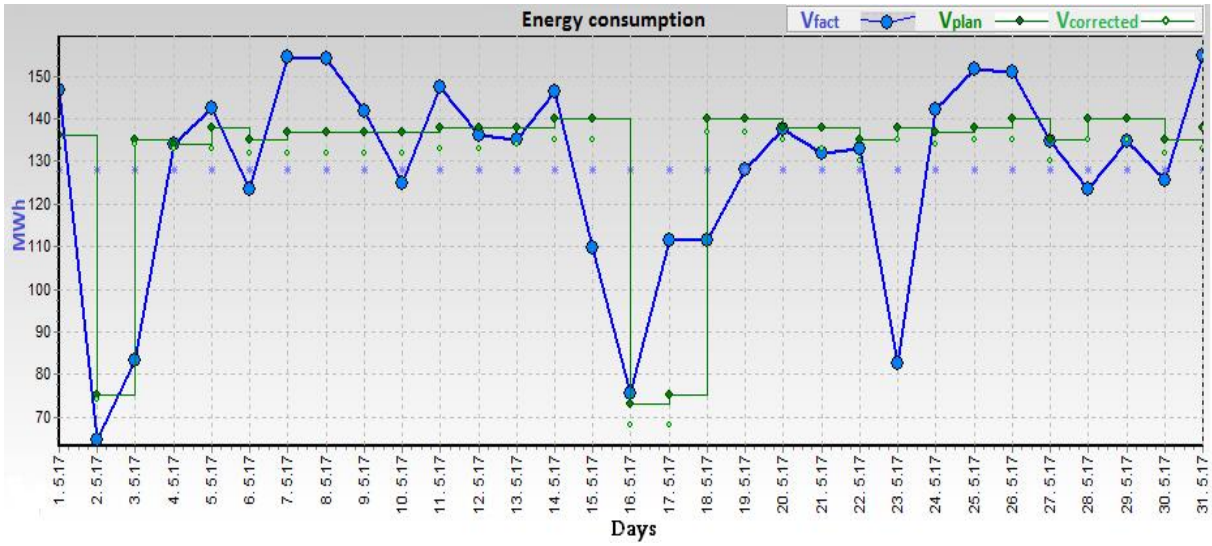


Figure 8. Factual, planned and corrected volumes by Volgograd region enterprise statistics for May 2017

The range of possible relationships of original planned V_p, corrected V_c and factual V_f energy volumes, types of prices relations (0; 1) and results of negative correction made for decrease of planned volume (figure 7) is shown at the figure 9.

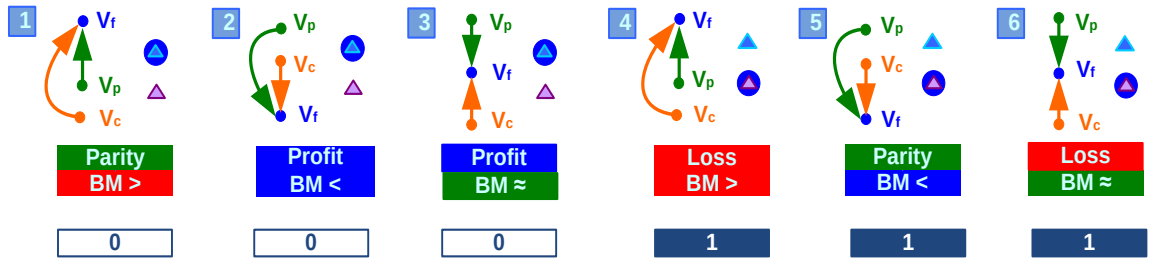


Figure 9. The relationships of prices and volumes for negative correction

The negative correction ($V_p > V_c$) is used when type 0 of prices relations is expected in forecasted hour. Single-criteria equations of expected profit for cases of negative correction in accordance with probabilities of relations types are shown below (Eq. 5):

$$\begin{cases} P_1 \,|P_2 : -V \cdot C_{dif.}; \\ P_1 \,|\, P_3 : V \cdot \Delta_0 + V \cdot C_{dif.}; \\ P_1 \,|\, P_4 : (V_p - V_f) \cdot \Delta_0 + (V_p - 2 \cdot V_f + V_c) \cdot C_{dif}; \\ 1 - P_1 \,|\, P_2 : -V \cdot \Delta_1 - V \cdot C_{dif}; \\ 1 - P_1 \,|\, P_3 : V \cdot C_{dif}; \\ 1 - P_1 \,|\, P_4 : -(V_f - V_c) \cdot \Delta_1 + (V_p - 2 \cdot V_f + V_c) \cdot C_{dif}, \end{cases} \quad (5)$$

where V_p, V_f, V_c - hour planned, factual and corrected energy volume; V = $V_p - V_c$; P_1 - the probability of prices relation type; P_2 - probability of predomination V_f over V_p; P_3 - the probability of predomination V_p over V_f; P_4 - probability of situation when $V_c \le V_f \le V_p$; Δ_0, Δ_1 - the average difference between BM prices in analyzed period for the types of prices relations 0 and 1; C_{dif} - the price of energy difference for specific enterprise (figure 3).

The factual energy volume V_f of future consumption is really unknown at the moment of analysis in the conditions of uneven unregulated energy consumption [10]. Therefore V_f can't be exactly forecasted before the end of consumption hour. Moreover cases 3 and 6 where parameter V_f is used are uncommon. Total their probability is ≈0.03 for average consumption of an enterprise ≈150 MWh and volume of correction ≈5 MWh. So equation 5 can be simplified by extraction of cases 3, 6 and renaming probability P_2 (Eq. 6):

$$\begin{cases} P_1 \,|P_2 : -V \cdot C_{dif}; \\ P_1 \,|1 - P_2 : V \cdot \Delta_0 + V \cdot C_{dif}; \\ 1 - P_1 \,|\, P_2 : -V \cdot \Delta_1 - V \cdot C_{dif}; \\ 1 - P_1 \,|1 - P_2 : V \cdot C_{dif}, \end{cases} \quad (6)$$

where P_2 - the probability of situation when V_f is more than V_c and V_p.

Target function of profit for negative correction is derived from Eq.6 by summation of each case in accordance with the formula of total probability and simplification (Eq. 7):

$$F_0 = V \cdot (P_1 \cdot \Delta_0 - P_2 \cdot \Delta_1 + P_1 \cdot P_2 \cdot (\Delta_1 - \Delta_0) - 2 \cdot P_2 \cdot C_{dif} + C_{dif}) \quad (7)$$

The range of possible relationships of volumes V_p, V_c, V_f, types of prices relations and results of the correction made for increase of planned volume (figure 7) is shown at the Fig. 10. The positive correction is used when type 1 is expected in forecasted hour.

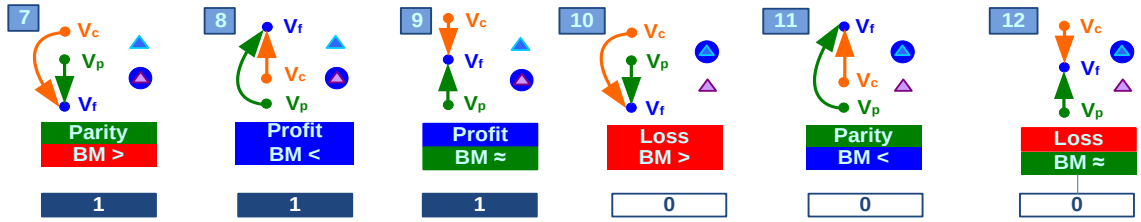


Figure 10. The relationships of prices and volumes for positive correction

Simplified equations for the cases of positive correction are shown below (Eq. 8):

$$\begin{cases} 1-P_1 \,|\, 1-P_2 : -V \cdot C_{dif}; \\ 1-P_1 \,|\, P_2 : V \cdot \Delta_1 + V \cdot C_{dif}; \\ P_1 \,|\, 1-P_2 : -V \cdot \Delta_0 - V \cdot C_{dif}; \\ P_1 \,|\, P_2 : V \cdot C_{dif}; \end{cases} \quad (8)$$

The target function of profit for the positive correction equals to the target function for the negative correction but has another sign evidently (Eq. 9):

$$F_1 = V \cdot (P_2 \cdot \Delta_1 - P_1 \cdot \Delta_0 + P_1 \cdot P_2 \cdot (\Delta_0 - \Delta_1) + 2 \cdot P_2 \cdot C_{dif} - C_{dif}) = -F_0 \quad (9)$$

The functions F_0 и F_1 are the expressions of optimality principle for the task of single-criteria optimization when the positive and negative corrections of planned volumes are used for enterprise with uneven unregulated energy consumption. The target functions depend on the relations of factual and planned volumes probabilities P_1; $1-P_1$, prices relations probabilities P_2; $1-P_2$ and the differences between BM prices Δ_0, Δ_1 (figure 4). The difference between BM prices clearly defines the amount of correction profit or loss. The significance of target functions is the mathematically reasonable predomination of the profit over the loss for any month of the year in accordance with the statistical stability. While the loss will be fixed in few hours (cases 1, 4, 6 for function F_0 and 7, 10, 12 for F_1), the profit earned in other hours (cases 2, 3, 5 for F_0 and 8, 9, 11 for F_1) will be unambiguously more than total loss.

3. The results of the testing offered method

The offered method being realized as the derivation of optimization task for every hour of the day is tested at the metallurgical enterprise (EM participant) in Volgograd region. If $F_0 > 0$ or $F_1 > 0$, the enterprise expects profit in a specific hour theoretically. However the reinforced criterion is used during the real tests. The ratio of plus and minus parts of each target function is calculated every hour. Volume of correction V_c depends on this ratio (Eq. 10).

$$\begin{cases} F_0 > 0 : \begin{cases} F_{0+} / F_{0-} \le 1{,}5 : V_c = V_p; \\ 1{,}5 < F_{0+} / F_{0-} \le 2 : V_c = V_p - 1; \\ 2 < F_{0+} / F_{0-} \le 3 : V_c = V_p - 3; \\ 3 < F_{0+} / F_{0-} \le 4 : V_c = V_p - 5; \\ F_{0+} / F_{0-} > 4 : V_c = V_p - 7; \end{cases} \\ F_1 > 0 : \begin{cases} F_{1+} / F_{1-} \le 1{,}5 : V_c = V_p; \\ 1{,}5 < F_{1+} / F_{1-} \le 2 : V_c = V_p + 1; \\ 2 < F_{1+} / F_{1-} \le 3 : V_c = V_p + 3; \\ 3 < F_{1+} / F_{1-} \le 4 : V_c = V_p + 5; \\ F_{1+} / F_{1-} > 4 : V_c = V_p + 7; \end{cases} \\ F_0 = F_1 = 0 : V_c = V_p \end{cases} \quad (10)$$

where F_{0+}, F_{1+} - the plus parts of F_0 and F_1; F_{0-}, F_1 - the minus parts of F_0 and F_1.

The software realizing this algorithm is the module of program written in C++ language. The number of rows in module is about 3700. The module has certificate of registration program in Russia.

Module has an access to enterprise database which includes hour energy volumes and EM prices. The tests are performed in retrospective mode of forecast of the prices relations when the program has all information just about past volumes and prices. The financial result is defined by comparison of 2 DAM bids results. First bid consists of original planned volumes; second one includes corrected volumes. The program performs calculations for the period 1 year. Total volumes of difference between factual and planned energy have been decreased by 2 855 MW*h. Total profit is more than 1 million rub (Table 1).

Table. 1. The results of the retrospective tests of planning the energy from June 2016 to May 2017

Month	Price Cdif	Volumes, MWh		Profit, Rub			
	Rub/MWh	BM buy	BM sell	BM	DAM	DAM+BM	DAM+BM+VAT
June 2016	234	*-734*	389	80 501	25 911	106 411	125 565
July 2016	250	*-683*	403	69 798	14 311	84 108	99 247
August 2016	224	*-350*	305	10 125	-6 419	3 706	4 373
September 2016	222	*-48*	*-24*	15 931	20 073	36 003	42 484
October 2016	212	*-278*	226	10 990	21 797	32 787	38 688
November 2016	219	*-193*	110	18 335	67 765	86 100	101 597
December 2016	235	*-734*	463	63 807	77 270	141 077	166 471
January 2017	204	*-926*	397	107 912	10 894	118 806	140 191
February 2017	237	*-1 465*	648	193 501	-32 137	161 364	190 410
March 2017	232	*-609*	331	64 719	-10 690	54 029	63 754
April 2017	174	*-170*	107	10 955	16 336	27 291	32 203
May 2017	122	*-222*	202	2 542	41 859	44 401	52 393
Total		-2 855		649 115	246 968	896 083	1 057 378

The distribution of the cases 1-12 (figure 9,10) numbers is shown below (figure 11). The case 13 means the absence of planned volume correction when $V_c = V_p$.

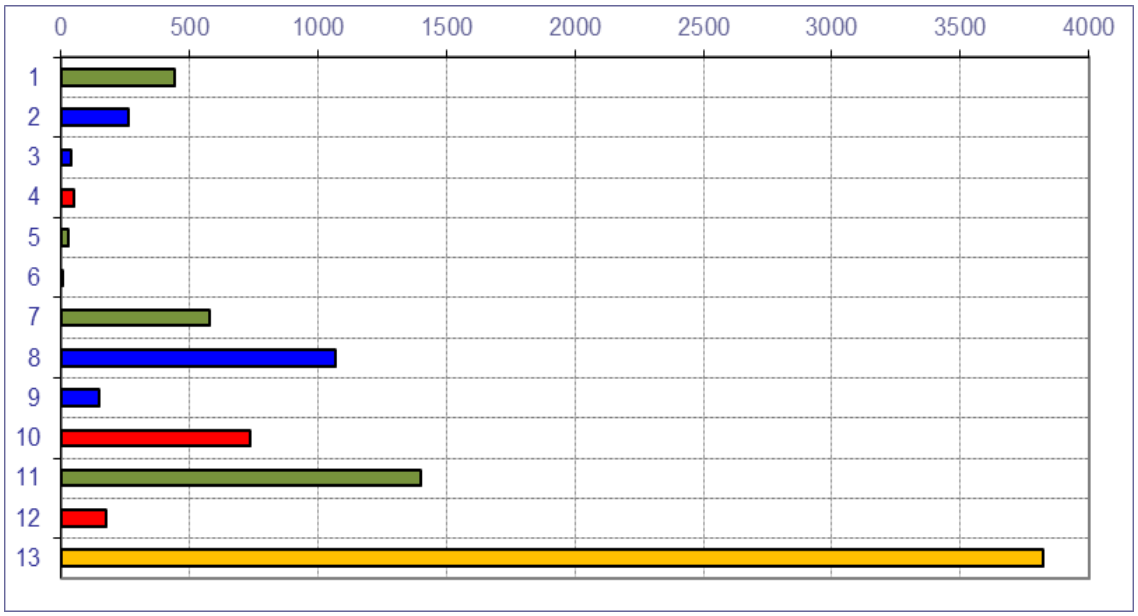


Figure 11. The distribution of 12 cases during testing method of planning the energy from June 2016 to May 2017

Positive results of retrospective tests of the program allowed starting its commercial using at the enterprise. The corrected DAM bids are actually sent to EM since December 2016. The operator

sending the DAM bid can adjust values recommended by the program. The profit from implementation of program is about 430 000 rubles from December 2016 to June 2017.

4. Conclusions

The offered method allows optimizing the difference between planned and factual energy consumption of enterprise – electricity market participant – by correction of planned energy volumes based on probability and game theories. The correction of planned energy performs every hour in accordance with the signals of System Operator. It guarantees the optimal load of generators in the energy system of the country and therefore saving non-renewable energy resources. An application of this method allows reducing the total energy cost of enterprise and solving ecological problems. The tests of the method at the enterprise with uneven unregulated energy consumption in Volgograd region show positive results. The difference of this method from the others is the deriving the formulas of target functions based in the relations of the volumes and prices of electric energy. The method is potentially applicable for industrial enterprises with any character of energy consumption. Consequently it may be recommended for enterprises as the instrument of positive development in conditions of worldwide economic and ecological crises.

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