UDC: 621.039.7

RW MANAGEMENT AND ECONOMY OF ELECTRICITY PRODUCTION

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Article received on November 8, 2019

Electricity market model developed by IBRAE RAN enables to assess the effect of radioactive waste (RW) management on the market competition between available energy production technologies. The paper summarizes RW impact on product market costs and stock market capitalization components. Assessment of RW management impact on overall NPP capitalization and the entire electricity market was performed based on data from "Proryv" project.

Keywords: *radioactive waste, nuclear power, electricity market model, radioactive waste management system, nuclear power plant, NPP capitalization.*

It's commonly believed that environmentally sound and cost-effective approaches implemented to address radioactive waste (RW) management challenges provide most effective development of nuclear power. Global experience on arranging for RW management systems is currently subject to intensive studies and practical implementation. Development of a unified state system for RW management is currently underway in Russia exploring the possibilities for arranging safe RW disposal at a lower cost. At the same time, methods proposed for business process evaluations based on "reduced costs" (in particular, an approach presented in [1]) do not allow for well-founded solutions of market problems associated with NPP endeavor to comply with relevant RW management funding requirements.

Economic optimization of RW management decision-making process on the energy market is viewed as a key issue for the state policy and the national economy [2, 3]. Therefore, further, models based on general conservation laws and economic dynamics are used to analyze market processes in the power industry involving NPPs. The study specifies market prices and growth rates of energy technologies in the commodity market, their capitalization in the stock market accounting for relevant investments in the development of power production corresponding to a certain part of the resulting market profit. The paper focuses on the market processes in which RW management costs are playing an essential role showing how important is to search for more efficient technical and financial approaches addressing such costs.

To exemplify the proposed model applications, the paper further considers the impact of RW management cost on market performance depending on the predicted fossil fuels prices (primarily gas) [4]. Market prices and capitalization indicators are identified for a number of energy technologies: combined cycle gas turbine units (CCGT), coal-fired condensing power plants (CPP) and nuclear power plants with WWER-1000 thermal reactors (for example, WWER-TOI). Investment and innovative components of NPP capitalization are also specified accounting for two approximate RW management cost options and various forecasted prices of gas supplied to CCGT. Basic laws of a market economy are discussed as a preliminary stage of the study addressing the task specified above.

Law of economic dynamics and pricing formula

Economic assessments to be presented below assume that certain part of profit ("net" profit) from generated power sales is channeled to ensure the production development to meet the increasing energy demand [5]. Law of economic dynamics enables to determine a possible increase in the production during the "net" profit reinvestment:

$$dq/dt = \eta \cdot (P - C) \cdot q/k, \qquad (1)$$

where q stands for the power generation (MW·h/year); dq/dt is the acceleration in power generation (MW·h/year^2);
C is the cost and P is the market price of electric power (RUB/MWh);
$(P - C)$ is the profit from production unit sales (RUB/MW·h);
$k = K/q$ are the specific investments (or unit investments) into production development (RUB·year/MW·h), where K are the total production investments (RUB).

"Investment coefficient" $\eta \approx 0.7$ has been also introduced into the above expression (1) allowing to account for the profit tax, which, in turn, determines the amount of "net" profit converted into investments. To calculate effective specific investments $R = k/\eta$, expression (1) can be presented as follows:

$$P = C + R \cdot Y, \qquad (2)$$

where $Y = (dq/dt)/q$ is the production growth rate (1/year).

Expression (2) implicitly presents the law of economic dynamics (analogous to Newton's law of dynamics), where the profit $(P - C)$ stands for a "driving force", R is a production momentum unit ("mass"), growth rate Y stands for relative production acceleration ("second derivative").

Conservation law and regulated market

Technologies n competing in the energy market, usually gas, coal and nuclear power ($i \leqslant n = 3$), generating some specific amount of electricity q_i (MW·h/year) provide a total power output that can be calculated using the following expression:

$$q = \Sigma q_i. \qquad (3)$$

By differentiating in time and dividing the right and left parts of expression (3) by q, production growth rate ("acceleration") conservation law can be expressed as follows:

$$Y_m = \Sigma S_i \cdot Y_i, \qquad (4)$$

where $Y_m = (dq/dt)/q$ is the production growth rate for the entire market (1/year); $S_i = q_i/q$ represent the market shares ($\Sigma S_i = 1$ is always equal to 1); $Y_i = (dq_i/dt)/q_i$ is the growth rate of the market participants (1/year). The market is considered as "regulated" if the growth rate Y_m is set in accordance with the forecasted electricity demand.

Under electricity production market conditions, various participants compete ("investment projects") with relevant production costs C_i and unit investments R_i. Equilibrium (market) price for electricity P_m (RUB/MWh) is set indicating that the development of each market participant occurs at an individual rate of Y_i that can be calculated based on the law of economic dynamics (2) using a system of equations:

$$Y_i = (P_m - C_i)/R_i. \qquad (5)$$

Substitution of (5)-type expressions into conservation law (4) enables to calculate the market price P_m as follows:

$$P_m = C_m + R_m \cdot Y_m, \qquad (6)$$

where $R_m = 1/\Sigma(S_i/R_i)$ is the investment indicator; $C_m = R_m \cdot \Sigma(S_i \cdot C_i/R_i)$ is the cost indicator. Ranges of possible changes in R_m and C_m indicators are specified based on the minimum and maximum values of the corresponding R_i and C_i indicators given a specific number of competing market participants.

Innovative and investment components of market profit

Substitution of expression (6) into (5)-type expressions allows to calculate the composition of the market profit for each market participant:

$$R_i \cdot Y_i = (C_m - C_i) + R_m \cdot Y_m. \qquad (7)$$

Expression (7) shows that in the general case (for $C_m \neq C_i$) market participant profits consist of two components. The first component $(C_m - C_i)$ turns out to be positive for market participants with the electricity cost of $C_i < C_m$. Obviously, these are investment projects based on new developments resulting in lower electricity costs. Therefore, the first component of expression (7) can be basically seen as the innovative profit component. However, the competitive market certainly involves for some participants with $C_i > C_m$. Therefore, the innovative profit component for these participants is negative, however, the market profit (7) may remain positive in case of a sufficient demand.

The second component $R_m \cdot Y_m$ in the expression (7) specifies the *investment* profit component which at any time can turn to be equal for all the participants constituting to a "regulated" market. At rates $Y_m > 0$, the investment component of profit is always positive.

Based on expression (7), the "status" of each regulated market participant can be identified: participants with $Y_i > Y_m$ capture the market eventually ousting those participants with $Y_i < Y_m$, or even totally removing them from the market if Y_i turns out to be < 0. Thus, the *innovative* component of profit depending on the relative level of innovation (usually resulting from the implementation of advanced scientific and design developments) produces a decisive influence on the nature of market processes, while the *investment* component affects the speed of these processes.

Evaluating the stock market capitalization of assets

Competing market participants usually seek to maximize their profits and increase their fixed assets. At the stock market ("exchange"), capitalization (relative valuation of fixed assets) of each market participant ("technology") depends on the sum of initial investments in fixed assets $K_i = k_i{\cdot}q_i$ and the possible "net" profit, which is supposed to be obtained at the commodity market. "Net" profit over an effective lifetime T_i [5] of each i-th market participant can be calculated as a sum of assets within $(0, T_i)$ range and based on expression (1) can be presented as follows:

$$Pr_i = \sum\eta_i{\cdot}(P_m - C_i){\cdot}q_i = \sum k_i{\cdot}q_i{\cdot}Y_i = K_i{\cdot}Y_i{\cdot}T_i. \quad (8)$$

Capitalization (K_{api}) of assets for each market participant can be calculated as a sum of the initial investments into the project and the "net" profit:

$$K_{api} = K_i + Pr_i = K_i{\cdot}(1 + Y_i{\cdot}T_i). \quad (9)$$

Proceeding with the relative indicator of fixed assets (assuming that $K_i = 100\,\%$), expressions (7) and (9) can be used to calculate relative capitalization for each market participant using the following expression:

$$K_{api} = 100{\cdot}\{1 + (C_m - C_i){\cdot}T_i/R_i + R_m{\cdot}Y_m{\cdot}T_i/R_i\}\ (\%), \quad (10)$$

where the *innovative* component of capitalization can be calculated as:

$$K_{api}\ (\text{in}) = 100{\cdot}(C_m - C_i){\cdot}T_i/R_i\ (\%) \quad (11)$$

whereas the *investment* component of capitalization can be calculated using the below expression:

$$K_{api}\ (\text{iv}) = 100{\cdot}R_m{\cdot}Y_m{\cdot}T_i/R_i\ (\%). \quad (12)$$

Calculated capitalization shows the attractiveness of the shares associated with corresponding technologies put up for sale on the stock market. Capitalization under (10) allows to compare relative investment efficiency into various projects ("technologies"). Therefore, the innovative component (11) is responsible for the share of capitalization arising from the introduced innovations, while the investment component (12) expresses the share of capitalization depending on the growth rate of market demand.

Profit components and production development

It is supposed to invest the "net" profit obtained through the use of appropriate technologies under relevant market conditions in the development of a number of industries providing construction and operation of energy technologies. It's believed necessary that this profit is also channeled to the development of fuel production, enhanced RW management arrangements and further nuclear decommissioning to cover relevant NPP decommissioning costs. According to expression (2), the amount of unit investments contributing to market price formation should be known to calculate relevant profit. However, since such a purely market method aimed at assessing the whole lot of indicators is not yet applied and R_i indicators are usually not available in relevant market information, then R_i values are identified based on the costs invested in the development of energy technology fuel and production basis. In the case of nuclear power plants, Ri should also cover the cost of RW management and subsequent nuclear decommissioning. Since only costs are usually indicated as part of technology indicators, and R_t values are not available, the ways by which these can be estimated and applied are provided below.

The cost of electricity production directly involves the cost of consumed fuel C_f being expressed as follows:

$$C_f = K_f/(q_{tf}{\cdot}T_f) + c_f\ (\text{RUB/unit prod.}), \quad (13)$$

where K_f stands for the investments in fixed fuel assets (RUB);
q_{tf} is the amount of fuel produced and consumed per year t (fuel units/year);
T_f is the depreciation period of fixed fuel assets (year);
c_f are direct fuel production costs (RUB/unit of fuel).

Applying $k_f = K_f/q_{tf}$ to (13), the following expression can be obtained: $k_f = (C_f - c_f){\cdot}T_f$. Proceeding with the "net" profit at $\eta_f < 1$, fuel production development indicator can be derived: $R_f = k_f/\eta_f = (C_f - c_f){\cdot}T_f/\eta_f$. By introducing $L_f = (1 - c_f/C_f)/\eta_f$, the following expression is obtained $R_f = L_f{\cdot}C_f{\cdot}T_f$. In particular, when $c_f/C_f = 0.3$ and $\eta_f = 0.7$, $L_f = 1$ and $R_f = C_f{\cdot}T_f$.

To identify the market price of electricity, consideration should be also given to the profit $R_f \cdot Y_f$, required for fuel production development at a rate of Y_f being equal to the market growth rate. In this case, the cost of fuel consumed in a developing electricity market can be calculated as follows:

$$P_f = C_f + L_f \cdot C_f \cdot T_f \cdot Y_f \equiv C_f \cdot (1 + L_f \cdot T_f \cdot Y_f), \qquad (14)$$

where $L_f \cdot C_f \cdot T_f \cdot Y_f$ is the profit required for fuel production development. The service life of fixed fuel assets T_f may differ from the service life of an NPP itself [5]. Therefore, T_f, C_f and c_t values should be agreed upon under fuel cost calculations and the real values of R_f should be estimated correctly. Under a general case, market prices of fuel consumed by CCGTs and CPPs should also be calculated in a similar way.

RW management costs and the state of the energy market

Nuclear power sector development largely depends on a safe and cost-effective nuclear fuel cycle, including relevant RW management aspects. Presented below are the estimated impacts of RW management on the economic performance of WWER nuclear power plants and, as a result, on the anticipated electricity market as a whole. Estimates use the data on the internal prices of gas (two options) and coal [3], presented in Table 1, and the technical and economic indicators of CCGTs, CPPs and NPPs given in [5] and assumed under the PRORYV project. Accordingly, specific investments are assumed to be equal (in \$/kW): at NPP with WWER power units — 2,880, at CCGTs — 1,200, at CPPs — 2,000. Operating costs were assumed to be as follows (in \$/MW·h): for CCGTs — 6, for CPPs — 7, for NPPs with WWER power units — 8.8.

Table 1. Forecasted gas and coal prices [4]

Year	2020	2025	2030	2035	2040
P_{gaz1} (\$/thous. m³)	115	137	163	195	234
P_{gaz2} (\$/thous. m³)	95	106	119	135	154
P_{coal} (\$/thous. m³)	92.5	106	113.5	121	128

Electricity production growth rate Y_m in 2020—2040 is assumed to be equal to 0.5%/year. The prices of electricity generated at CCGTs, CPPs and NPPs were calculated using the methods discussed in detail in [5].

For 2020, total fuel component of the electricity cost generated at nuclear power plants with WWER reactor units was assumed to be equal to \$8.75/MWh and is distributed over two fuel cycle stages (Table 2). The initial stage (natural uranium mining, conversion, enrichment and fuel production) is initially assumed to cost C_{f1} = \$5.625/MWh with the final stage (radioactive waste management) accounting for C_{f2} = \$3.125/MWh. In the future, due to an increased cost of uranium mining, the cost of the initial stage is supposed to increase with the cost of the final stage remaining the same. Since fuel production and RW management should evolve accordingly to the increasing total capacity of nuclear power plants, the corresponding profit indicators Pr_{f1} and Pr_{f2} should be calculated as a price component of electricity generated at operating nuclear power plants (Table 2), invested respectively in the development of the initial and final stages of the fuel cycle.

Table 2. Forecasted time dependences of the initial P_{fc1} (\$/ MW·h) and final P_{fc2} (\$/ MW·h) stages of nuclear fuel cycle at NPPs

Year	2020	2025	2030	2035	2040
C_{f1} (\$/MW·h)	5.625	6.521	7.56	8.764	10.159
$P_{fc1} = P_{rf1} + C_{f1}$	6.049	7.207	8.586	10.257	12.264
C_{f2} (\$/MW·h)	3.125	3.125	3.125	3.125	3.125
$P_{fc2} = P_{rf2} + C_{f2}$	4.302	4.769	5.247	5.788	6.361
$P_{fc} = P_{fc1} + P_{fc2}$	10.351	11.976	13.833	16.045	18.625

It is assumed that 30% is exempted from the profits of all market participants (taxes and other expenses, i. e., η = 0.7). NPPs also have liability insurance against accidents (with a probability of $2 \cdot 10^{-4}$ 1/year) resulting in a complete loss of all fixed assets (assets) owned by nuclear power plants, but without any environmental loss due to the availability of appropriate containment envelopes.

To assess the impact of indicators associated with the final stage of the fuel cycle on energy market parameters, relevant effects produced on the market price indicators due to a decrease in the RW management cost from C_{f2} = 3.125 \$/MW·h to C_{f3} = 0.3125 \$/MW·h (Table 3) were identified. The calculations performed demonstrated that this can prompt only some relatively small changes in market prices.

Table 3. Forecasted time dependencies of the market price P_m (\$/MW·h) from RW management costs C_{f2} or C_{f3} (\$/MW·h)

Year	2020	2025	2030	2035	2040
P_{m1} (C_{f2} = 3.125)	39.857	43.822	48.164	53.307	59.227
P_{m2} (C_{f3} = 0.3125)	39.293	43.152	47.35	52.282	57.9
$\Delta P_m = P_{m1} - P_{m2}$	0.564	0.67	0.814	1.025	1.327
$(\Delta P_m/P_{m1}) \cdot 100\%$	1.42	1.53	1.69	1.92	2.24

Figure 1 presents market capitalization indicators for CCGT, CPP and NPP technologies calculated assuming the above conditions. Hereinafter, the depreciation periods of nuclear fuel production (Tf1) and RW management equipment (Tf23) are taken equal to 50 years. Corresponding calculations showed that a change in these timeframes only slightly affects the final results.

CCGT capitalization decreases over time and may turn out to be less than 100% by 2040, which marks the beginning of CCGT technology ousting from the market (Figure 1).

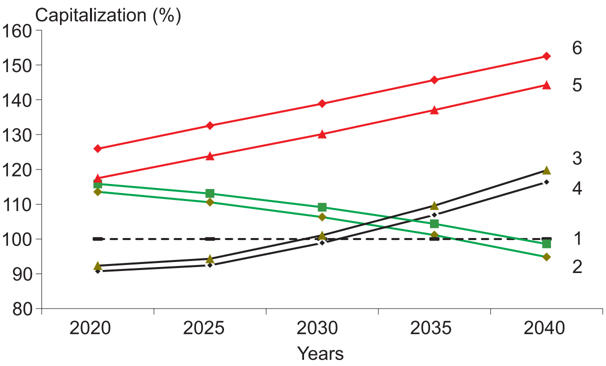

Figure 1. Time dependence of CCGT, CPP and WWER NPP capitalization at nuclear fuel costs of C_{f2} (3.125 \$/MW·h), C_{f3} (0.3125 \$/MW·h) and gas cost of P_{gaz1} (115–234 \$/thousand m³):
1, 2 – CCGT capitalization at C_{f2} and C_{f2}, respectively;
3, 4 – CPP capitalization at C_{f2} and C_{f3}, respectively;
5, 6 – NPP capitalization at C_{f2} and C_{f3}, respectively.

CPP capitalization until 2030 appears to be lower than 100 %, thus, it will not be able to evelove on its own under relevant market conditions. However, after 2030 the situation may change significantly, and CPP will be able to oust CCGT from the market. NPP capitalization appears to be higher than 100% and may significantly surpass the one of CCGT and CPP over time. As shown in Figure 1, the change in the amount of required RW management funding (change over from C_{f2} to C_{f3}) is assumed to cause a change in the capitalization of all market participants, however, in case of NPPs this change is believed to be more significant. For example, a decrease in the cost of RW management from C_{f2} to C_{f3} can result in CCGT capitalization decrease by ≈ –3.8 % and CPP by ≈ –3.4 %, while NPP capitalization may increase by ≈ 8.3 %.

The change in RW management cost during the transition from C_{f2} to C_{f3} also leads to a change in the innovative and investment components of NPP capitalization, as shown in Figure 2, where the innovative component basically exceeds the investment component to a great extent.

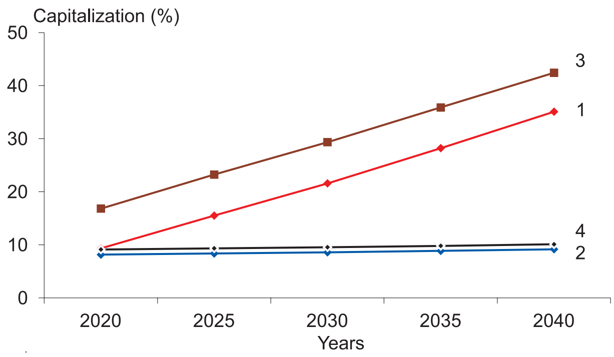

Figure 2. Dependencies of innovative (1,3) and investment (2,4) components of NPP WWER capitalization at relevant costs of nuclear fuel (C_{f2}, C_{f3}) and gas cost of P_{gas1} = (115–234) \$/thousand m³):
1 – innovative,
2 – investment at C_{f2} = 3.125 \$/MW·h;
3 – innovative,
4 – investment at C_{f3} = 0.3125 \$/MW·h.

Under a RW management cost decrease from C_{f2} to C_{f3}, the innovative component of capitalization is supposed to increase by ≈ 7.4 %, while the investment component is said to increase only by ≈ 0.96 %. As a result, the estimated overall capitalization for nuclear power plants may change by ≈ 8.3 %.

An increase in the cost of RW management C_{f2} to even greater values than those presented in Table 2 is supposed to lead to an even more noticeable deterioration of NPP position at the energy market compared to the one shown in Figure 1.

If the gas prices are lower (similar to P_{gas2} in Table 1), the state of the entire energy market changes. Figure 3 presents the estimated CCGT, CPP and NPPs capitalization values for this case. As expected, in this case CCGT capitalization will decrease slower over time and may turn out to be quite positive by 2040, while CPP with a capitalization of ~ 85 % is going to be ousted out of the market.

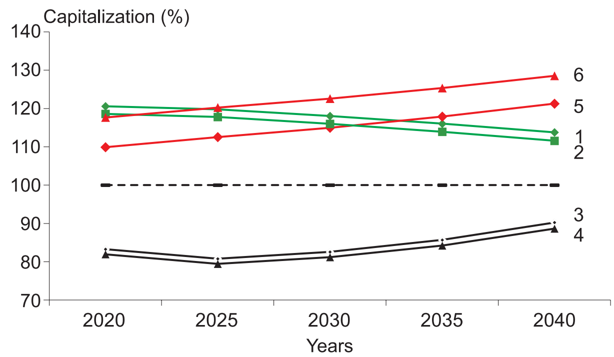

Figure 3. Time dependence of CCGT, CPP and WWER NPP capitalization from nuclear fuel costs of C_{f2} (3.125 \$/MW·h), C_{f3} (0.3125 \$ /MW·h) and gas cost of P_{gas2} = (95-154) \$/thousand m³):
1, 2 – CCGT capitalization at C_{f2} and C_{f3}, respectively;
3, 4 – CPP capitalization at C_{f2} and C_{f3}, respectively;
5, 6 – NPP capitalization at C_{f2} and C_{f3}, respectively.

If RW management cost is equal to C_{f2}, the initial (until 2030) NPP capitalization is supposed to be lower than the one of CCGT, i. e. NPPs will be able to evolve on the market, however, slower as compared to CCGTs. Only after 2033, NPPs may start overtaking the CCGTs in their development. If RW management cost is reduced to C_{f3}, NPPs will be able to compete with CCGT from 2025 already.

Figure 4 shows the changing RW management cost (change over from C_{f2} to C_{f3}) resulting in relevant changes of the innovative and investment NPP capitalization components, similar to those shown in Figure 2 However, in this case, the innovative capitalization component will exceed the investment one only at the C_{f3} RW management cost. At a RW management cost being equal to C_{f2}, the innovative NPP capitalization component during 2020—2030 will tend to be lower than the investment one. However, the innovative NPP capitalization component will tend to be positive manifesting the influence of scientific developments on the market conditions.

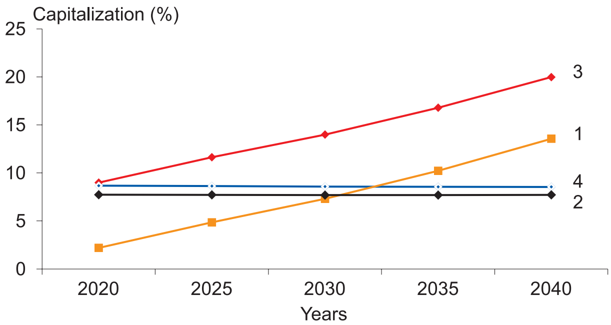

Figure 4. Dependences of WWER NPP innovative (1, 3) and investment (2, 4) capitalization components at relevant nuclear fuel C_{f2}, C_{f3} and gas R_{gas2} (95–154 \$/thousand m^3) costs:

1 – innovative,
2 — investment at C_{f2} = 3.125 \$/MW·h;
3 — innovative;
4 — investment at C_{f3} = 0.3125 \$/MW·h

With a decrease in the RW management cost from C_{f2} to C_{f3}, the innovative capitalization component increases by ≈ 6.6 %, while the investment component in this case increases only by ≈ 0.9 %. As a result, the total change in NPP capitalization can amount to ≈ 7.5 %, which is only ≈ 0.8 % lower than in the case of gas prices being equal to P_{gas1} (Table 3).

Conclusion

The paper evaluates the electricity market involving combined cycle gas turbine plants (CCGT), coal-fired condensing power plants (CPP) and nuclear power plants with WWER-TOI thermal reactors. The findings clearly indicate that RW management aspects should be studied to estimate the NPP efficiency under free market economy. The paper indicates the methods by which RW management cost analysis can be introduced into the evolving market assessment method to accomplish this goal.

The paper focuses on two related markets: commodity market (product market) and stock market (asset market or exchange). Commodity market sets the market prices for products and specifies the profit gained by each market participant. The stock market specifies capitalization, i. e., the investment effectiveness into assets applied, and primarily into innovative NPP designs.

The study presents the influence of RW management on the development of the commodity and stock markets. It provides the dependences of market prices and NPP capitalization under conditions suggesting that RW management costs, gas and coal prices change significantly. The study reveals a relatively weak impact of RW management cost on the market price of electricity and a noticeable effect on NPP capitalization.

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Bibliographic description

Karkhov A. N. RW Management and Economy of Electricity Production, 2019, no. 4 (9), pp. 32—38. DOI: 10.25283/2587-9707-2019-4-32-38. (In Russian).