International Journal of Electrical and Computer Engineering (IJECE)
Vol. 11, No. 4, August 2021, pp. 2733~2742
ISSN: 2088-8708, DOI: 10.11591/ijece.v11i4.pp2733-2742

Determination of the price for a hydro resource with consideration of operating conditions of hydropower plants using complex criteria of profit maxmization

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Article Info

Article history:

Received Apr 14, 2020
Revised Feb 21, 2021
Accepted Mar 1, 2021

Keywords:

Complex exergy criteria
Flexible electricity market
Hydropower plant
Novosibirsk
Thermal power plant
Thermodynamic

ABSTRACT

In this paper, a universal method has been developed to determine the price of a hydro resource (one cubic meter) for the operational regulation of a hydropower plant (HPP), which is a combination of an optimization method and a method for assessing the marginal utility. The proposed approach is based on the correct representation of differential incremental rate characteristics of water at an HPP and fuel at a thermal power plant (TPP). To know the price of a hydro resource used for electricity generation at a hydropower plant. This gives the possibility to increase the efficiency of management both at a hydropower plant, and in a water utilization system as a whole. Using the examples of Novosibirsk HPP, it is expected to develop an estimation of economic effect from the implementation of the developed criteria, the proposed method of the calculation of a hydro resource price at HPP, and the method of separating fuel costs at CHPP. As a result of the implementation the developed method for the HPP, a price of electricity sold in the flexible energy market will be compared to the price of the electricity produced and sold at CHPP, being equal to approximately 330 rubles/MW h.

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1. INTRODUCTION

In this paper, a universal method which is a combination of an optimization method and a method for assessing the marginal utility has been developed [1]. Using this method, it is reasonable to solve the problem of short-term operational optimization of load distribution in hydrothermal power systems. Consider in detail the novelty and the efficiency of the proposed method in comparison with the existing approach [2].

At present, the problem of optimal distribution of the power system load between hydropower plant **(**HPP) and thermal power plant (TPP) is solved using the equality of the differential incremental rate characteristics of fuel consumption at TPP and water consumption at HPP. Even in the USSR, such characteristics were called the incremental rate characteristics [3]. It can be said that the problem of evaluating the price of a hydro resource associated with the operating conditions of an HPP in the power system has never been solved [4]. This issue will be focused on in the further presentation of the investigation.

Despite the fact that this task is related to the short-term optimization of operating conditions of power plants in the power system due to the limited energy resources at the HPP, it cannot be solved separately from the optimization of the long-term operating conditions of the power system [5]. In this paper, the short-term optimization implies daily optimization, while the long-term optimization means water-power operating conditions of the HPP throughout the year taking into account the seasonal operating conditions of the HPP [6].

2. THE MATHIMATICAL MODEL OF POWER PLANTS MANAGEMENT

In general, the criterion for the optimal load distribution in the power system without taking into account the technical constraint is as (1) [7].

$$b1 = b2 = \cdots = bn = \lambda q = idem \quad (1)$$

where $b_1, b_2, \ldots, b_n$–incremental fuel rate characteristics at TPP (*n* is the number of TPP in the power system):
q: incremental water rate characteristics at the HPP;
λ: conversion factor, the meaning of which will be considered.

It should be noted that TPPs are presented in optimization tasks as generating sources with "unlimited energy resources" [8]. This implies that any power of a power plant within the permissible range of its operation at a given moment will be provided with a reserve of energy resource, regardless of the power value carried by the power plant at the previous moment. This gives the reason for combining all thermal power plants into one equivalent TPP, taking into account all the technical constraints [9].

Hydropower plants belong to generating sources with "limited energy resources", since their amount is determined by the hydrograph of the river and the final useful capacity of the reservoir. This suggests that the HPP power at a given moment depends on the power, with which the HPP operated in the previous time interval [10]. Therefore, the hydropower plants cannot be equivalent, since each of them is unique with the above-considered conditions.

Differential incremental rate characteristics of HPP and TPP have different dimensions, namely:

$$b = \frac{dB}{dN} \quad (2)$$

$$q = \frac{dQ}{dN} \quad (3)$$

where B–fuel consumption rate (ton of coal equivalent/hour), Q–water consumption rate (m^3/second).

Therefore, the coefficient λ in (1) represents a conversion factor being called a measure of the effective use of hydro resources in the power system [11]. Therefore, it is necessary to experimentally select the value of λ taking into account the limited hydro resources at the HPP. In this case, the number of iterations can be five or more until condition (4) is fulfilled [12]. These circumstances lead to a serious complication of calculations associated primarily with an increase in the number of iterative procedures, solution time, and the convergence of this process.

Based on the considerations, the condition of optimal load distribution in a hydrothermal power generation system can be presented in (4) [13].

$$\begin{gathered} b = \lambda q = idem \\ Q_{HPP} = Q_{GIV}, \\ H = const, \\ P_S = N_{TPP} + N_{HPP}, \\ N_{TPP\,min} \le N_{TPP} \le N_{TPP\,max}, \\ N_{HPP\,min} \le N_{TPP} \le N_{HPP\,max}, \\ \lambda = const \end{gathered} \quad (4)$$

where b and q–incremental rate characteristics for water and fuel at the equivalent TPP and the HPP respectively; P_S, N_{TPP}, N_{HPP}–power system load, values of power served by the equivalent TPP and the HPP respectively; $N_{TPP\,min}$, $N_{TPP\,max}$, $N_{HPP\,min}$, $N_{HPP\,max}$–minimum and maximum power for the equivalent TPP and the HPP respectively: Q_{GIV}–permissible water flow rate at the HPP determined by water-power calculations; λ–the dimension conversion factor. The condition *H=const* should be considered separately.

At high-head HPPs and the HPP cascade, the downstream changes (in other words, the head changes) is about 1%, since in this case the error for the head fluctuations is approximately 1%, then it can be neglected. In the cascade of HPPs, the downstream of one station is the upstream of the other. As is known, the upstream changes to a lesser extent when 1 m^3/s of water flows from the upstream to the downstream, since the surface of the upstream is much larger than the downstream [14].

At medium-head and low-head HPPs, head fluctuations are more significant than at high-head HPPs. However, the head at any HPP changes insignificantly during 24 hours. Therefore, when deriving optimization criteria, most often, the head changes during 24 hours (under operational control) is not taken into account. The proposed approach is based, first of all, on the correct representation of the differential characteristics (2) and (3). Indeed, these characteristics should be derivatives not from the consumption of energy resources, but from the costs of their use:

$$U_B=P_B *B \tag{5}$$

$$U_Q=P_Q *Q \tag{6}$$

where P_B and P_Q–the price of fuel at thermal power plants and the price of hydro resource at hydropower plants respectively. Then, expressions (2) and (3) will be calculated in (7) and (8).

$$b^* = c\frac{dB}{dN} \tag{7}$$

$$q^* = c\frac{dQ}{dN} \tag{8}$$

As for the price of fuel at thermal power plants PB, there are no fundamental difficulties with its calculation. Even in the case of an equivalent thermal power plant, it can be calculated (with some assumptions) as a weighted average price. It can be said that the problem of evaluating the price of a hydro resource associated with the operating conditions of an HPP in the power system has never been solved. It is this issue that will be focused on in the further presentation of the paper.

Despite the fact that this task is related to the short-term optimization of operating conditions of power plants in the power system due to the limited energy resources at the HPP, it cannot be solved separately from the optimization of the long-term operating conditions of the power system. In this paper, the short-term optimization implies daily optimization, while the long-term optimization means water-power operating conditions of the HPP throughout the year taking into account the seasonal operating conditions of the HPP. Therefore, the condition of optimal load distribution in a hydrothermal power system can be presented in the new formulation as (9).

$$\begin{aligned} & b^* = q^* = idem \\ & H = \text{const}, \\ & P_S = N_{TPP}+N_{HPP}, \\ & N_{TPP\ min} \le N_{TPP} \le N_{TPP\ max}, \\ & N_{HPP\ min} \le N_{TPP} \le N_{HPP\ max} \end{aligned} \tag{9}$$

The fundamental differences between the new optimization condition (9) and the previous one (4) are obvious. Consider them in more detail. Here b^* and q^* are determined from (7) and (8) being derivatives of the costs associated with the use of energy resources at TPP and HPP, respectively.

There is also no verification in the condition for the requirement that the average daily water flow rate at the HPP is equal to the given flow rate obtained from the water-power calculations in the annual context. This is due to the fact that when plotting incremental rate characteristics for the HPP (q^*), the power is considered, with which the HPP will operate in a given period of the year [15]. This means that the flow rate and water head were taken into account. Therefore, the verification for the equality of the average daily water flow rate at the HPP to the given flow rate is redundant. Then, the iterative nature of calculations mentioned above disappears that is the main advantage of the proposed approach. In addition, there is no verification for $\lambda=const$, because the differential characteristics of the costs for the use of energy resources at TPP (fuel) and HPP (water) have the same dimension in monetary terms.

This makes it possible to use more understandable and correct optimization criteria for optimal load distribution in a hydrothermal power generation system. Moreover, knowledge of the cost of water resources that are used to generate electricity at a hydroelectric power station is in itself valuable and informative. It gives the possibility to increase the efficiency of management both at the hydropower plant, and in the water utilization system as a whole.

3. DEVELOPMENT OF THE METHOD TO CALCULATE A HYDRO RESOURCE PRICE FOR OPERTONAL CONTROL OF THE HPP

Up-to-day level of technological development requires to combine three aspects of optimization: thermodynamic, technical-economic and environmental-into one system [16]. Hydro resources play a very important role in saving primary energy and material resources at the input of the technical system. In the long run they reduce harmful impacts on humans and environment as a whole.

To convert a hydro resource price in [rubles/(m^3/s)] with the consideration of the HPP operational features to the price of 1 kW in [rubles/MW h], the profit maximization criterion MR=MC was applied [17]. It is necessary to determine the marginal costs at the HPP for power output, or, in other words, to form the proportion. $U_q = {}^{U_b}/_{tga}$ The incremental rate of fuel at the TPP (b) and water (q) at the HPP are considered as products.

If utility as a whole is not quantifiable, the same can be related to marginal utility. But the theory of value does not need any precise definition of marginal utility [18]. If it needs something, then only the following: when a system of needs for an individual is known and he owns a specified set of goods X, Y, Z, we can find out his marginal rate of substitution between any two goods. The marginal rate of substitution of a certain good Y for any other good X is defined as the amount of Y that can compensate an individual for the loss of the marginal unit of X. Therefore, there should be some value that would leave it in the same state, in which it was before substitution. Obviously, this marginal rate of substitution is nothing more than the exchange ratio of utility for X to marginal utility for Y. This ratio is called relative marginal utility [19].

If the quantities of X and Y are plotted on the indifference diagram (assuming the quantities of all other goods to be given), the marginal rate of substitution between X and Y will be measured by the slope of the indifference curve that passes through the point, at which the individual is located. It simply depends on a system of indifference curves [20]. Using the given indifference map, we can directly determine the slope at any point. If the slopes are given at all points within the area, we can develop the indifference map for that area. If an individual intends to be in equilibrium with respect to the system of market prices, his marginal rate of substitution between some two goods should be equal to the ratio of their prices, otherwise he could undoubtedly benefit by replacing a certain amount of one good with an equal value (at market rate) of the other good [21]. This is the framework into which the law of proportionality between marginal utilities and prices fits.

Marginal utility can be represented by the indifference line. Moreover, according to the rules for constructing the line, see in Figure 1 [22]. In this case, according to the rules for plotting indifference curves, it is necessary to derive reciprocals of b and q, i.e. 1/b and 1/q, and put them on X-axis and Y-axis, after that connecting this point by a line as shown in Figure 1.

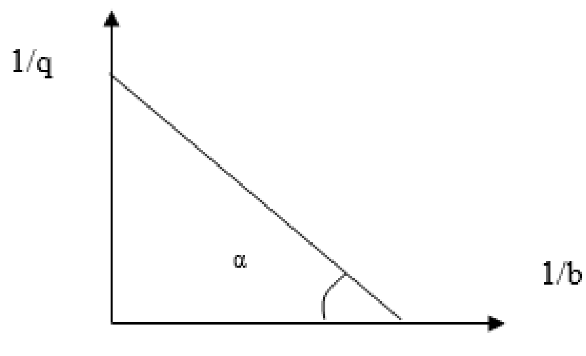

Figure 1. The indifference curve

Such curves should be plotted as many as the power system operating conditions will dominate during optimization. Typically, this is the number of months in a year that represents the full range of operating conditions within seasons and a year. Thus, we obtain the condition:

$$\frac{1}{b} = \frac{1}{q} \text{ at U=const} \tag{10}$$

where U is the location of an individual (in our case, an electricity consumer) on the indifference curve.

From the power industry perspective, the producer will maximize profits by producing output at the point where marginal revenue equals marginal cost [23]. A graphic illustration of this condition is shown in Figure 2.

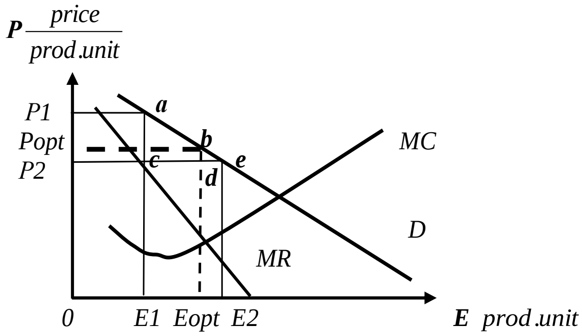

Figure 2. Calculation of the optimal volume of production: here D is the demand for energy produced for each season of the year; E opt-the optimal output for each season of the year; R opt is the stated price for the optimal volume of electricity production

The algorithm for solving the problem is shown in Figure 3. Moreover, it should be noted that it is necessary to convert physical quantities 1/q [s*kW/m^3] and 1/b [kW*h/ton of coal equivalent] into relative units, since this will allow comparing the indifference curve represented in relative units and the incremental rate characteristics for water at the HPP (q) and fuel at the CHPP (b) in one diagram as shown in Figure 4. When plotting the incremental rate characteristics for water at the HPP and fuel at the CHPP, the current values of incremental rates were divided by the average incremental rate. From the power industry perspective, the manufacturer will maximize profits by producing output at the point where marginal revenue equals marginal cost, see Figure 5 [24]. A graphic illustration of this condition is shown in Figure 6 of water and fuel, respectively.

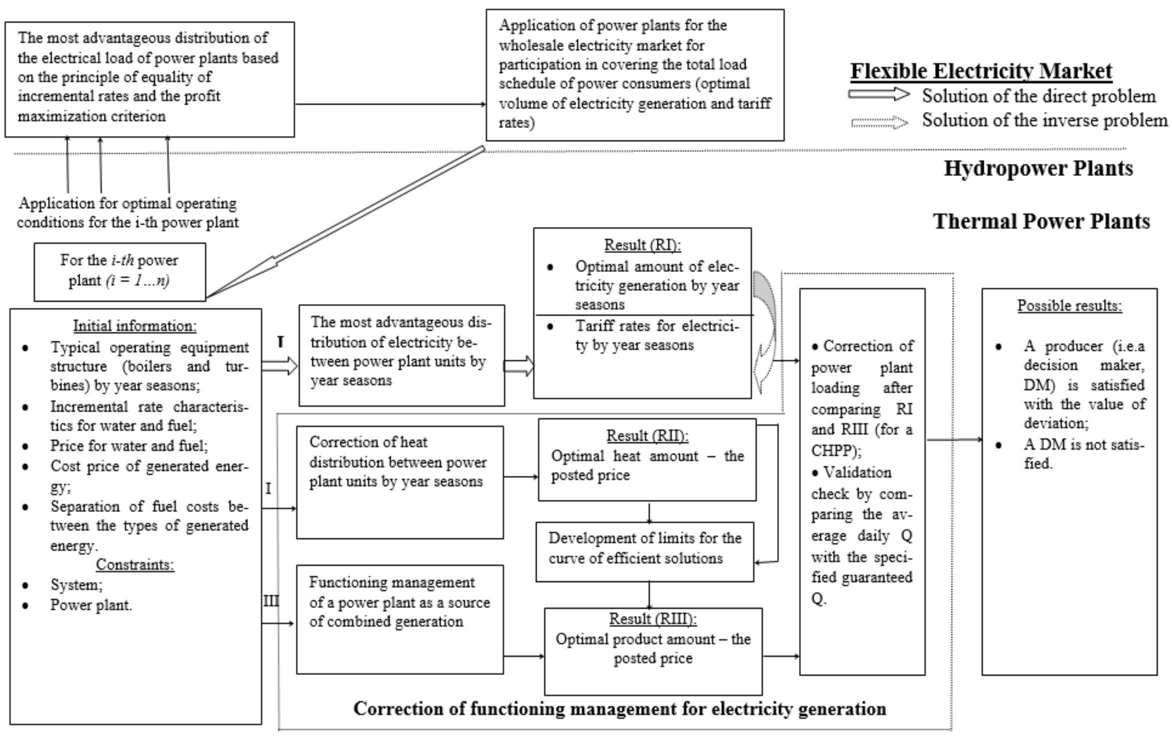

Figure 3. Block diagram of operational control on a flexible market

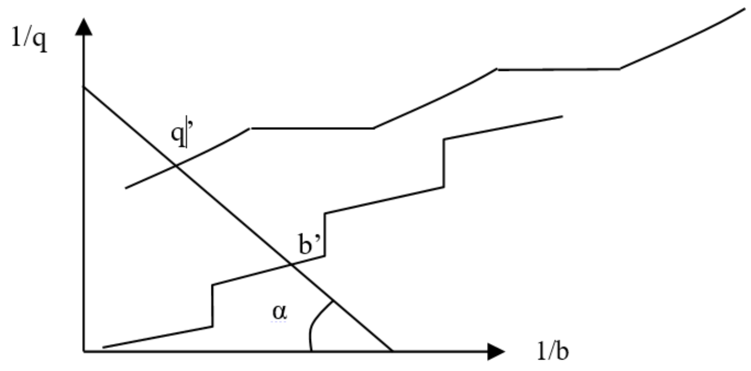

Figure 4. Incremental rate characteristics for water at the HPP and fuel at the CHPP combined with the indifference curve

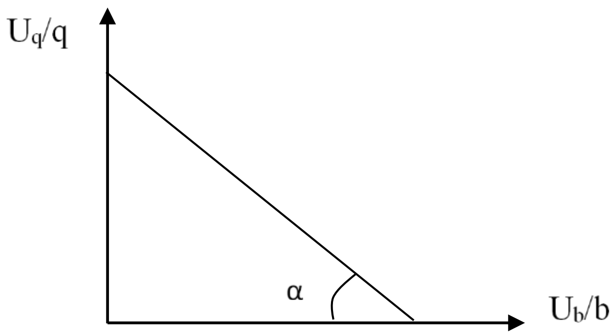

Figure 5. Marginal cost indifference line: where U_q–marginal costs at an HPP, U_b–marginal costs at a CHPP, b–incremental fuel rate at a CHPP, q–incremental water rate at a HPP, wp–hydro source price for operation control of the HPP

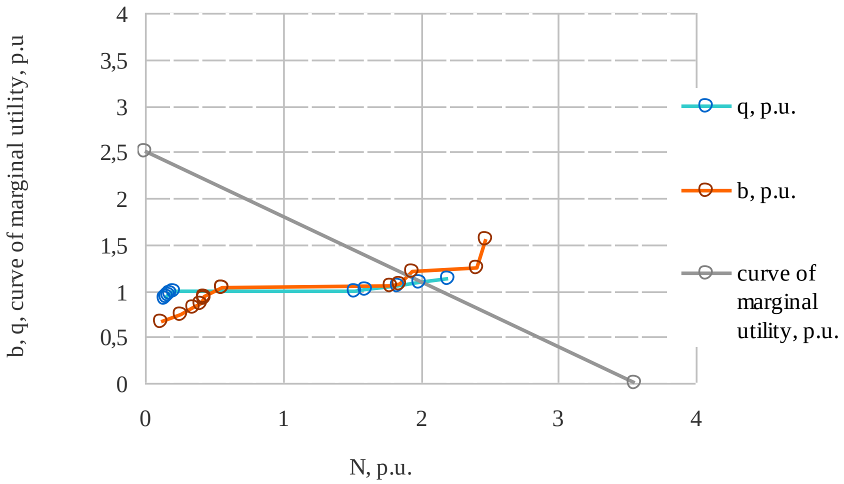

Figure 6. The indifference curve and the incremental rate characteristics for water at the HPP and fuel at the CHPP in the high-water period

Combining three curves in one diagram (i.e. the indifference curve and the incremental rate characteristics for water at the HPP and fuel at the CHPP), we obtain a new rule for the transition from the incremental water rate to the incremental fuel rate without using conversion factor λ [25]. Figure 4 show the value of the incremental water rate at the HPP q' locating on the indifference curve, will be equal to the corresponding value of the incremental fuel rate at the TPP locating on the same curve, since water and fuel in this case will have the same importance to the consumer. Moreover, in order to obtain the corresponding power value for a particular hour according to the daily load schedule, it is necessary to shift the indifference curve in parallel to itself.

At the same time, for the transition from a hydro resource price in [rubles/(m^3/s)] with the consideration of the HPP operational features to the price of 1 kW in [rubles/MW·h], the profit maximization criterion MR=MC was applied. To convert water price into [rubles/MW·h], it is necessary to determine the marginal costs at the HPP for power output, or, in other words, to form the proportion $U_q = {}^{U_b}/_{tga}$.

As products, the incremental rate of fuel at the TPP (b) and water (q) at the HPP are considered. The indifference curve in relative units for the high-water period is illustrated in Figure 7. According to the developed methodology, it is necessary to plot the incremental water rate characteristics for a given structure of operating equipment at the HPP for each optimization interval, which is a month or a decade for the period of filling the HPP reservoir [26]. To verify the operability of the proposed model, the simplified HPP operating modes were used, in particular, seasonal periods of the year is shown in Figure 8.

Taking into account the price of hydro source obtained using the proposed model, it is necessary to plot the marginal costs characteristics for water flow rate at the HPP, and then calculate the optimal amount of electricity generation at the HPP is shown in Figure 9. For the head of H=14.05 m the optimal amount of electricity generation at the Novosibirsk HPP was calculated using the developed criterion is shown in Figure 10.

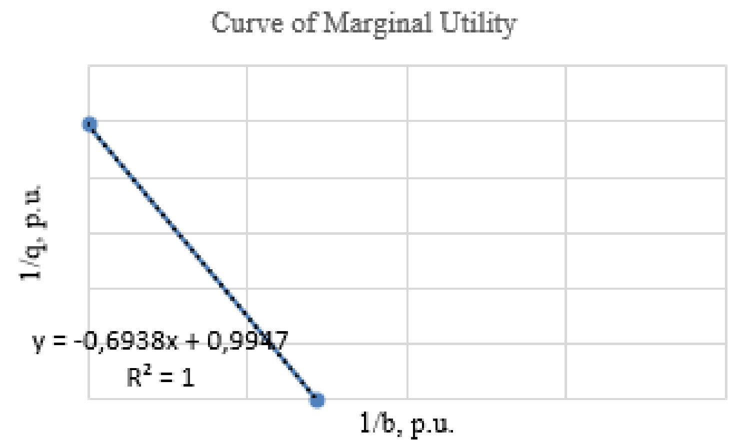

Figure 7. The indifference curve for the relative units for the high-water period

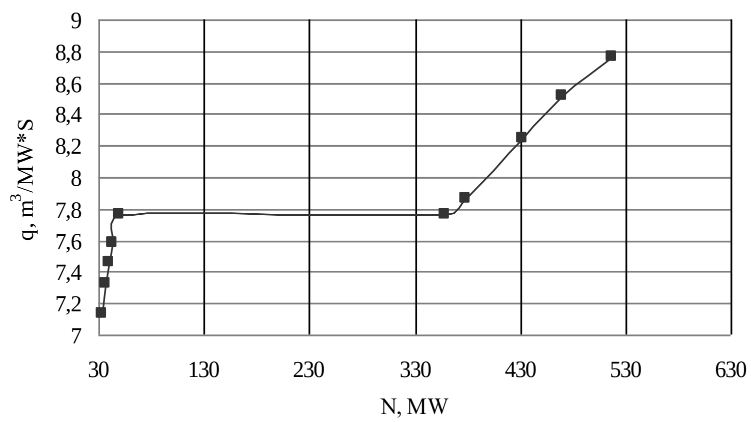

Figure 8. Incremental water rate characteristic for the Novosibirsk HPP for H=14.05 m

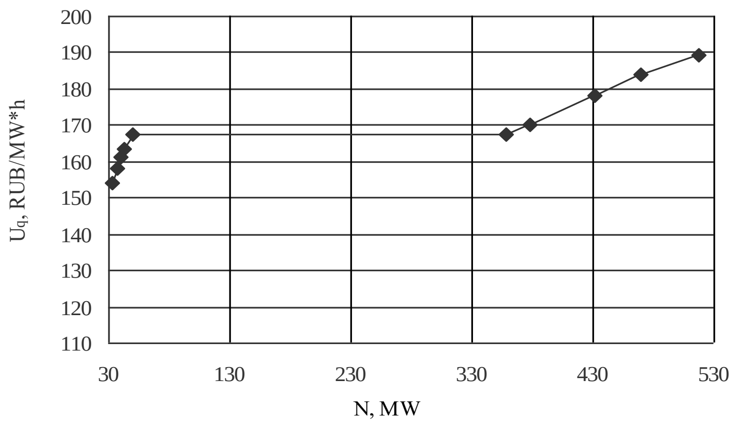

Figure 9. Marginal costs characteristics for the Novosibirsk HPP for H =14/05 m

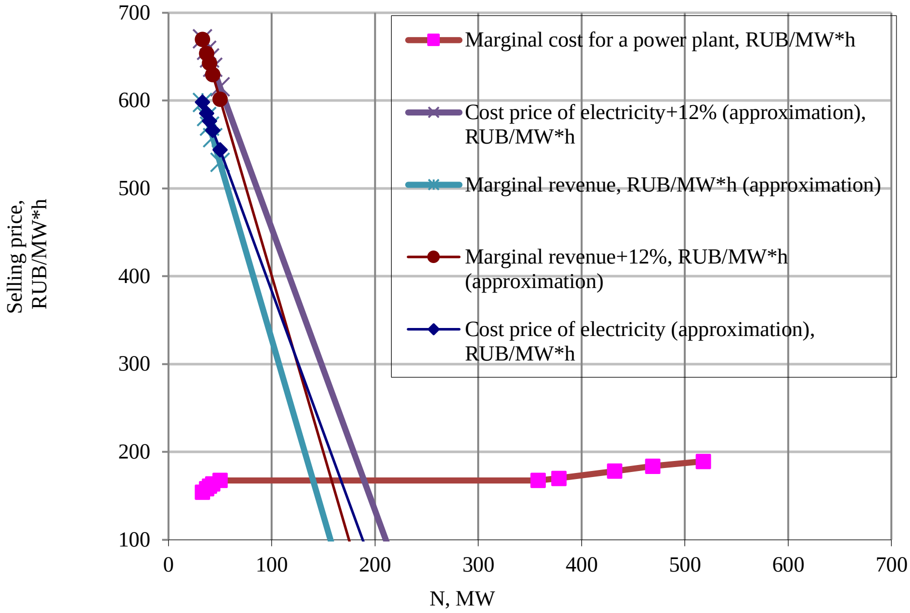

Figure 10. The schedule of operating modes optimization at HPP for H=14.05

The results of calculations are given in Table 1. The data obtained as a result of calculations correspond to the real values. To verify the developed methodology, it is necessary to compare the found values of the average daily water flow rate, which are obtained after the distribution of the daily load of the generation company between the HPP and the equivalent TPP according to the developed methodology, with the specified guaranteed value of the water flow rate at the HPP.

The calculation results showed that the comparison of the average daily water flow rate obtained by the developed methodology with the specified guaranteed water flow rate for each period gave an error of about 5% for the high-water period, 4% for the low-water period, and 1% for operation with natural river flow, being amounted to 2034.097 m^3/s for the high-water period, 241.98 m^3/s for the low-water period, and 630.87 m^3/s for operation with natural river flow. This indicates the reliability of the results according to the developed methodology and allows making a conclusion about its validity and the possibility for application of the methodology to determination of the price for water as a hydro resource taking into account the operational features of HPP based on based on the maximization profit criteria.

Similar calculations using the conventional methodology for distributing the load of the power system between its power plants by the Lagrangian multiplier method showed comparable results. For this methodology, there is an increase in the share of CHPP in electricity production for the needs of an electricity consumer and an increase of the error when comparing the average daily water flow rate obtained by the Lagrangian multiplier method with the specified guaranteed value of water flow rate for each period. The comparison gave an error of about 3% for the high-water period, 7% for the low-water period, and 3% for operation with natural river flow, being amounted to 2086.62 m^3/s for the high-water period, 235.06 m^3/s for the low-water period, and 613.47 m^3/s for operation with natural river flow. Therefore, it can be concluded that the developed methodology allows not only determining a price of a hydro resource using the operational features of the HPP, but also solving energy-saving and ecological problems.

Table 1. Optimal values of Novosibirsk HPP power output

Season	For H=14.05 m		For H=17.5 m		For H=17.9 m	
Profit rate	0%	12%	0%	12%	0%	12%
Power, MW	140	159	118	136	120	137
Electric energy, MW·h	100800	114480	84960	97920	86400	98640
Posted price, RUB/MW·h	257	270	325	336	315	320
Revenue, RUB	77716800	92728800	27612000	32901120	27216000	31564800
Profit, RUB		15012000		5289120		4348800

4. CONCLUSION

The criterion apparatus for a comprehensive assessment and optimization of the processes of electric power generation at hydroelectric power plants has been substantiated on the basis of the exergy approach with substantiation of the conceptual apparatus of "environmental parameters". A method has been developed to determine the price of water for hydroelectric power plants, which allows not only to improve the environmental situation in the region, but also to increase the competitiveness of power plants. Relevance of the concept of marginal utility for determining the price of water for hydroelectric power plants has been substantiated. A mathematical apparatus has been developed for exergy optimization of the integrated efficiency of processing primary energy resources on the basis of interrelated thermodynamic and environmental-economic criteria for the purpose of generating electrical energy. Approbation of the developed exergo-economic and technical criteria for comparing various technologies for the generation of electricity and heat based on the optimization of HPP operation modes was carried out. The model for the joint functioning of HPPs in the electricity market has been developed.

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BIOGRAPHIES OF AUTHORS

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