Improving the Electricity Market Participation Management of Hydropower Plants in Ukraine

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Abstract

This research presents a comprehensive mathematical model aimed at improving the management efficiency of hydropower plant (HPP) participation in the electricity market of Ukraine. The model focuses on the optimal daily allocation of available hydro resources, integrating the nonlinear nature of technological electricity consumption specific to HPP operations. A profit function is formulated to represent revenue from electricity sales across different market segments, with a particular emphasis on the "day-ahead" market. The model also incorporates both linear and nonlinear functions of the costs associated with purchasing electricity needed to meet the internal operational requirements of HPP generators under various load conditions. The objective function is designed to maximize profit by balancing electricity sales with the associated costs of technological energy use, accounting for variations in generation modes. In addition, the model includes a detailed system of operational constraints tied to the hydro resource management within the "Reservoir – HPP" hydraulic engineering node, ensuring the feasibility and sustainability of energy dispatch solutions. Test calculations have been carried out using real and simulated input data to evaluate the model's practical applicability. The results demonstrate the effectiveness of the proposed approach in optimizing HPP operation within the current regulatory and market environment of Ukraine. The model offers valuable insights for enhancing both economic returns and operational reliability of HPPs, contributing to more efficient integration of renewable hydro resources in the national electricity market.

Keywords: *hydropower plants, electricity market, market participation, energy management, power system operation, renewable energy integration*

INTRODUCTION

Hydroelectric power plants (HPPs) play a significant role in the structure of the production capacities of the Integrated Power System (IPS) of Ukraine [1]. These facilities contribute to the overall stability and flexibility of the energy system, particularly during peak load periods and in regulating frequency and voltage [2]. HPPs operate under market conditions, participating in various electricity market segments to maximize their economic efficiency [3]. Their operation is aligned with the requirements of synchronous operation with the European Network of Transmission System Operators for Electricity (ENTSO-E), which imposes specific technical and regulatory constraints [4]. In addition to electricity production, hydroelectric power plants (HPPs) currently serve a critical role in ensuring the stability of the Integrated Power System (IPS) of Ukraine [5]. They are the primary providers of frequency restoration services, which are essential for maintaining the balance between electricity supply and demand in real time [7]. These services are delivered to the Transmission System Operator (TSO), supporting the operational reliability of the entire grid [7]. The high flexibility and rapid response capabilities of HPPs make them especially effective in delivering such ancillary services under both normal and emergency conditions [5, 6]. Active regulation of the modes of the IPS of Ukraine using dam-type HPPs results in significant deviations of their actual operating schedules from the planned ones and, accordingly, results in deviations of the consumption of hydro resources from the planned values, as well as in appearing violations of technological constraints of the water balance of reservoirs [7, 8].

The problem of improving the efficiency of the operation of HPP cascades has been the subject of many publications in scientific and scientific and technical literature [9]. The objective of optimization is usually associated with the planning horizon, functions of HPPs, and features of the electricity market structure [10]. The main objective of planning the operation schedules of HPPs is to rationally use available hydro resources for generation of electricity while adhering to technological and environmental restrictions [11]. However, the optimization objectives are largely consistent with the features of the electricity market structure [12]. For example, the implementation of competitive trading for Chinese electricity producers resulted in a change in the objectives for the formulation of problems of short-term planning of HPP loading schedules from maximizing electricity supply volumes to maximizing the profit [11, 12, 13]. There are different approaches to short-term [14, 15] and multi-year [16] planning problems. In addition, depending on the detailing level of the HPP technical characteristics, various formalisms are used to find optimal solutions, e.g., a simulation model with an expert assessment system [17], a particle swarm optimization algorithm [18], as well as nonlinear optimization methods [6]. Detailed models of the operation modes of HPP hydroelectric generators use integer and Boolean type variables. They include the application of mixed integer linear programming (MILP) [11, 12] or mixed integer nonlinear programming (MINLP) methods [19].

In [7], a mathematical model is provided, in which the profit from the electricity sale is determined by the difference between the actual sale price and some averaged price of costs of electricity production. This formulation of the problem made it possible to quite simply calculate the price of sold electricity and, in some cases, not to take into account the costs associated with electricity production at all [20]. For a more detailed consideration of the costs associated with electricity production, it is necessary to study the features of taking into account the cost function associated with electricity production at HPPs and the impact of this component on the optimization results.

The research focuses on optimizing the integration of hydropower into Ukraine's electricity market while aligning with ecological priorities and thermochemical advancements [21]. It is highlighted that the strategic role of hydropower plants (HPPs) in balancing the grid, particularly in the context of increasing renewable energy penetration and the growing need for low-carbon solutions [22]. Adaptive management models that enhance operational flexibility allow HPPs to respond dynamically to market signals and environmental regulations [23]. By incorporating thermochemical principles, especially in the assessment of energy transformation efficiency and environmental impacts, the study underscores the importance of sustainable resource utilization and reduced greenhouse gas emissions [24, 25]. A harmonized approach combining market reform, ecological responsibility, and innovative thermochemical methodologies can significantly enhance the resilience and competitiveness of Ukraine's hydropower sector in the evolving energy landscape.

By analyzing the heat exchange mechanisms and energy transformation efficiency within auxiliary systems, such as turbine oil cooling or water heating for system support, this approach helps minimize energy losses and optimize internal consumption [26]. The integration of thermodynamic principles into the management of hydropower operations allows for a more precise allocation of hydro resources, especially under variable market conditions and environmental regulations [27]. This supports Ukraine's broader goal of increasing the flexibility and competitiveness of its hydropower sector while ensuring compliance with ecological and energy efficiency standards [28].

The purpose of the article is to develop a model for the optimal allocation of available hydro resources for electricity production. This model takes into account both the linear and nonlinear characteristics of electricity consumption for the internal needs of hydropower plants (HPPs). By accurately reflecting the real energy demands of HPP operations, the model aims to enhance efficiency in resource use and reduce operational losses. Ultimately, it provides a more reliable framework for decision-making in the management of hydroelectric assets within the electricity market.

RESEARCH METHODOLOGY AND METHODS FOR THE IMPROVING THE ELECTRICITY MARKET MANAGEMENT

This research applies a quantitative systems modeling approach to enhance the management of hydropower plants' participation in Ukraine's electricity market. The study begins with a thorough regulatory analysis of the Ukrainian market framework, including the Law of Ukraine "On Electricity Market" (2017) and resolutions of the National Energy and Utilities Regulatory Commission (NEURC) governing the Day-Ahead and Intraday Markets [1-3]. A systems analysis is then conducted to map the interaction between hydropower operations and market requirements, including participation in energy balancing, reserve provisioning, and bidding processes [29]. The study emphasizes the practical alignment of hydropower generation capabilities with the dynamic market environment, especially under Ukraine's synchronization with the ENTSO-E power system [30].

To model optimal participation strategies, the study utilizes a range of advanced optimization methods tailored to the unique dynamics of hydropower operations within electricity markets [31]. These include conditional optimization with penalty functions for day-ahead bid scheduling, mixed-integer nonlinear programming (MINLP) to address head-dependent characteristics of hydro units, and stochastic modeling to incorporate uncertainties related to hydrological inflows and market price volatility [32]. Together, these methodologies enable the development of robust and flexible operational models that enhance the economic efficiency and reliability of hydropower plants in Ukraine's evolving energy landscape [31, 33]. For short-term planning, successive linear programming (SLP) is employed [34]. These models are implemented using software tools such as Matlab/Simulink, GAMS, and Python (Pyomo) [35]. Input data include historical dispatch records and bidding results from Ukrainian Energy Exchange platforms, along with operational parameters from major hydroelectric facilities like DniproHES and KyivHES.

The developed models are tested through scenario-based simulations and comparative validation using international benchmarks from countries with advanced hydro scheduling tools such as Brazil, Norway, and the USA. Performance indicators such as water-use efficiency, economic dispatch

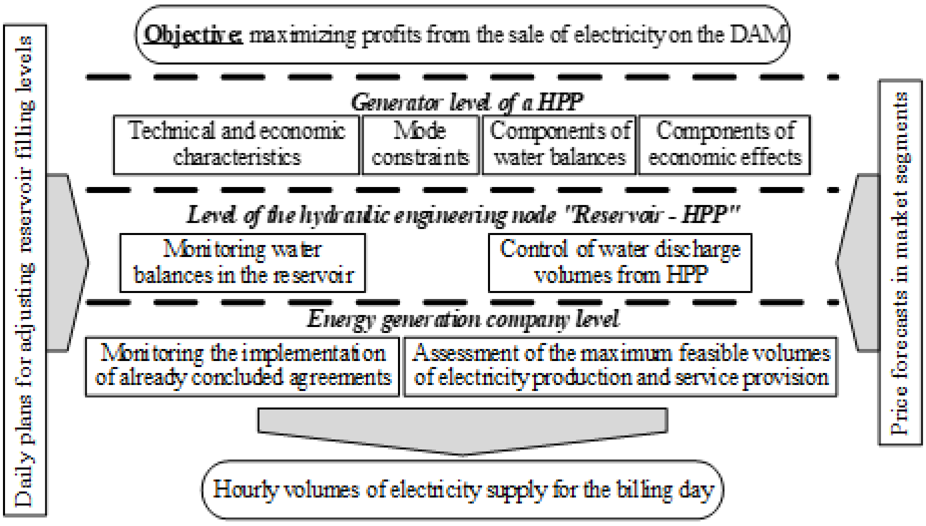

Fig. 1. Architecture of the model of optimal allocation of hydro resources for electricity production at a dam-type HPP
Rys. 1. Architektura modelu optymalnego podziału zasobów hydroelektrycznych do produkcji energii elektrycznej w elektrowni wodnej typu zaporowego

cost, and the ability to provide ancillary services are evaluated. The research contributes to the strategic enhancement of HPP operations by offering scalable modeling tools and policy-aligned decision frameworks, aiming to maximize both energy output and economic return within Ukraine's evolving electricity market.

Architecture of the mathematical model of allocation of hydro resources

In order to solve the problem of optimal allocation of hydro resources available per day for a hydraulic engineering node "Reservoir – HPP," a mathematical model was built, the basis of which is formed by the functions of formalized mapping of technological processes in the hydraulic engineering unit (Fig. 1), as well as a system of technical, mode and environmental restrictions.

The mathematical model reflects a description of technological processes in the hydraulic engineering unit as structured with distinguishing the following main components:

- description of technological processes for hydraulic generators (HGs);
- description of technological processes for HPPs;
- description of technological processes for the water reservoir.

The description of technological processes for the HG is formed based on the dependence of the consumption of hydro resources on the production of electricity. The volumes of electricity sup-ply are selected as optimization variables. If optimization is performed out according to price criteria, the search for optimal solutions is carried out using the functions of the cost of selling electricity in market segments and taking into account the costs for implementing the functions of electricity pro-duction, primarily the cost of electricity to meet the own needs of the HG.

The system of constraints in the formalized representation of the HG functions is formed from the following components:

- technological limits of the HG operating modes, primarily the technological minimum and technological maximum of the HG load;
- mode constraints on the HG load level, which include, in particular, the volumes of production capacity reserves for the provision of auxiliary services.

At the structural level of the HPP, a description of functions of general station costs that de-pend on the HG load is formalized. If necessary, at this structural level, equations of the total electricity supply from the HPP and equations of the total useful consumption of hydro resources are formed. In addition, for HPPs, systems of mode constraints are formalized regarding the minimum and maximum hourly volumes of electricity supply, which the Transmission System Operator, in some cases, imposes on the power plant.

The reservoir is presented in the mathematical model with the characteristics of the techno-logical minimum, technological maximum. and useful volume.

Finally, at the level of the hydraulic engineering node "Reservoir – HPP," equations of hydro resource balances for the calculation period are formed. The following main components of the balances are distinguished:

- a function of the flow of hydro resources into the reservoir during the calculation period, which, in the general case, is determined by dependencies on the water outflow at the HPP upstream along the river bed;
- a water outflow function, which is determined as the total volume of useful consumption and idle discharge of water downstream along the river bed;
- functions of controlling the level of filling of the reservoir during the calculation period;
- the difference at the levels of filling of the reservoir at the beginning and end of the calculation period as the basis for determining the available volume of hydro resources;
- environmental restrictions on the volume of water outflow during the calculation period.

RESULTS AND DISCUSSIONS

Structurally, the objective function for solving the problem of optimal allocation of hydro resources by HPP generators is formed as the difference between the profit from the sale of electricity and the costs for purchasing electricity to cover own electricity consumption needs. Since in the organized segments of the electricity market of Ukraine, in particular on the "day-ahead" market (DAM) of Ukraine, a period of one hour is taken as the calculation period (i.e., the period for which the price of purchase/sale of electricity is determined separately), in the objective function the calculation of the difference between profit and costs is calculated separately for each hour of the day:

$$Max\left(B_D^{HPP}\right)=\sum_{h=1}^{24}\left(Prof_{sell}\left(V_h^{HPP}\right)-Cost_{buy}\left(V_h^{HPP}\right)\right) \quad (1)$$

where, V_h^{HPP} is the volume of electricity supply by HPP generators in the calculation hour h, (MWh); $Prof_{sell}(V_h^{HPP})$ is the function for calculating the profit from the sale of the hourly volume of electricity V_h^{HPP} in market segments, (₴); $Cost_{buy}(V_h^{HPP})$ is the function for calculating the costs for purchasing electricity to cover own needs in producing electricity in the volume of V_h^{HPP}, (₴).

The profit from the sale of electricity on the DAM is generally determined by the product of the volume of electricity sold and the price at which the power generating company actually received financial revenues:

$$Prof_{sell}\left(V_h^{HPP}\right)=C_{sell,h}^{HPP}\cdot V_h^{HPP}:\forall h=[1..24],$$

where, $C_{sell,h}^{HPP}$ is the price at which the actual financial revenues from the sale of electricity are determined (₴/MWh).

The main components of the price of electricity at which financial revenues are calculated for the power generating company are formed from the following main components:

$$C_{sell,h}^{HPP}=C_h^{DAM}-T^{MO}-T_T^{TSO}-T_{DC}^{TSO}:\forall h=[1..24] \quad (2)$$

where, C_h^{DAM} is the predicted marginal price in the DAM segment for hour h (₴/MWh); T^{MO} is the tariff for the services of the market operator (₴/MWh); T_T^{TSOT} is the tariff for the services of the transmission system operator in terms of electricity transmission (₴/MWh); T_{DC}^{TSO} is the tariff for the services of the transmission system operator in terms of dispatching control (₴/MWh).

The tariffs for the services of the market operator and the transmission system operator allow a more accurate calculation of the actual amount of financial revenues from the sale of electricity. Such clarification affects the results of solving the problem of allocation available hydro resources for electricity production during the day in cases where the mathematical model of the operation of HPP generators is provided by functions with a nonlinear dependence of costs on the level of generators load. If the model of the operation of HPP generators is provided by linear functions, in which the costs per unit of electricity supply do not depend on the level of generator load, the tariffs of the market operator and of the transmission system operator do not affect the results of allocation of available resources by hours of the day for electricity production. Therefore, in linear models of the operation of HPP generators, it is sufficient to use only the predicted values of hourly prices in the DAM segment to estimate the profit from the sale and supply of electricity:

$$Prof_{sell}\left(V_h^{HPP}\right)=C_{sell,h}^{HPP}\cdot V_h^{HPP}\rightarrow C_h^{DAM}\cdot V_h^{HPP}:\forall h=[1..24]$$

Financial costs associated with the implementation of technological processes for electricity production are primarily associated with the purchase of electricity to cover the power supply for the own needs of the HPP:

$$Cost_{buy}\left(V_h^{HPP}\right)=C_{buy,h}^{HPP}\cdot\Delta V_h^{HPP}\left(V_h^{HPP}\right):\forall h=[1..24]$$

where, $C_{buy,h}^{HPP}$ is the price of purchasing electricity to provide for supply for the own needs of the HPP in hour h (₴/MWh); is the volume of electricity consumption for the own needs of the HPP in hour h (MWh).

The structure of the price of purchasing electricity to cover the power supply for the own needs of the HPP has the following main components:

$$C_{buy,h}^{HPP}=C_h^{DAM}+T^{MO}+T_T^{TSO}+T^{Prov}:\forall h=[1..24] \quad (3)$$

where, C_h^{DAM} is the predicted marginal price in the DAM segment in hour h (₴/MWh); T^{MO} is the tariff for the services of the market operator (₴/MWh); T_T^{TSO} is the tariff for the services of the transmission system operator in terms of the transmission of electricity (₴/MWh); T^{Prov} is the margin of the electricity supplier (₴/MWh).

The volume of electricity consumption for the own needs of the HPP has a nonlinear dependence, since with an increase in the load level of the HG at the HPP, the electricity losses in the electrical connection scheme of the plant also increase in a nonlinear mode. Therefore, to determine the formula for calculating the costs for purchasing electricity, it is necessary to study and determine the dependencies of electricity losses and the impact of these dependencies on the objective function (1).

The function of electricity consumption for the own needs of the HPP

In the structure of costs for the operation of the power plant, a constant component is usually distinguished, which does not change in different operating modes of the power plant and a variable component, which depends on the load levels of the power plant generators [7]. The invariable cost component does not affect the results of the allocation of available hydro resources for electricity production within the day and therefore is not taken into account in the mathematical optimization model. For the HPP, the basis of costs for the implementation of electricity production modes is formed by the cost of electricity purchased in order to cover the own electricity consumption needs. In the structure of the own HPP electricity consumption needs, it is also possible to distinguish certain invariable component, which may not be taken into account in the mathematical optimization model, and a component of electricity consumption, which depends on the load modes of the HG. Let's consider the features of taking into account the linear and nonlinear characteristics of electricity consumption for the own needs of the HG at the HPP in the objective function (1).

To construct the functions of technological electricity consumption depending on the loading of the HG at the HPP, the following assumptions were used:

- assuming that the technological costs of the HG readiness state at the HPP are taken into account as a component of the total station costs, therefore, for the HG in the "reserve" state, technological electricity losses are equal to zero;
- assuming that the electricity consumption are characterized by a linear or quadratic dependence on the HG loading power at the HPP.

The latter assumption introduces a methodological error into the mathematical model. In effect, technological electricity losses are characterized primarily by electricity losses, i.e., they have a quadratic dependence on the HG loading currents. Although the dependence of technological electricity losses on the HG loading power at the HPP is nonlinear in nature, the curvature of this characteristic is less than the curvature of the quadratic dependence. In the article, the quadratic dependence is used solely for the purpose of illustrating the use of nonlinear functions in (1) due to the simplicity of the formal representation of the quadratic dependence. When solving practical problems of planning the HPP operating modes, the nonlinear function is determined that most adequately determines the volumes of electricity consumption for own needs in different operating modes of the HPP.

At the same time, the linear dependence on the HG load levels at the HPP significantly simplifies the formal representation of the mathematical model but in this case, the methodological error is determined by the linearization of the electricity loss function in the electrical connection schemes of the HPP.

As input data for constructing the function of technological electricity consumption in the HG at the HPP, two main mode characteristics are taken:

- the state of zero electricity supply from the HPP $P_g^{HPP}=0$ is taken as the initial point of the function graph, at which the technological electricity consumption is equal to the value of the consumption for ensuring the idle mode $\Delta S(0)=\Delta S_{g,idl}^{HPP}$;
- the maximum load mode of the HG at the HPP $P_g^{HPP} = P_{max}^{HPP}$ is characterized by the maximum value of the technological electricity consumption $\Delta S_{g,max}^{HPP}$.

The linear characteristic of the consumption of own needs of the HPP generator is determined by the line formula:

$$C_{buy,h}^{HPP} = C_h^{DAM} + T^{MO} + T_T^{TSO} + T^{Prov} : \forall h = [1..24] \quad (3)$$

$$f^{(l)}\left(P_{g,h}^{HPP}\right) = A_{\Delta S(l)}^{HPP} \cdot P_{g,h}^{HPP} + B_{\Delta S}^{HPP} \left[\begin{array}{l} A_{\Delta S(l)}^{HPP} = \dfrac{\Delta S_{g,max}^{HPP} - \Delta S_{g,idl}^{HPP}}{P_{max}^{HPP}} \\ B_{\Delta S}^{HPP} = \Delta S_{g,idl}^{HPP} \end{array} \right. : \forall h = [1..24] \quad ,(4)$$

where, $\Delta S_{g,max}^{HPP}$ is technological electricity consumption in the maximum load mode of the HG at the HPP (MW); $\Delta S_{g,idl}^{HPP}$ is technological electricity consumption in the idle mode of the HG at the HPP (MW); P_{max}^{HPP} is maximum capacity of the HG at the HPP (MW); $P_{g,h}^{HPP}$ is capacity of the HG load in the calculated hour h (MW).

In order to comply with the conditions for the passage of the consumption characteristic through two given points of minimum and maximum, the quadratic characteristic of the technical electricity consumption in the HG at the HPP should be described by the following function:

$$f^{(2)}\left(P_{g,h}^{HPP}\right) = A_{\Delta S(2)}^{HPP} \cdot \left(P_{g,h}^{HPP}\right)^2 + B_{\Delta S}^{HPP} \left[\begin{array}{l} A_{\Delta S(2)}^{HPP} = \dfrac{\Delta S_{g,max}^{HPP} - \Delta S_{g,idl}^{HPP}}{\left(P_{max}^{HPP}\right)^2} \\ B_{\Delta S}^{HPP} = \Delta S_{g,idl}^{HPP} \end{array} \right. : \forall h = [1..24] \quad (5)$$

The non-zero value of electricity consumption in the HG idle mode at the HPP $\Delta S_{g,idl}^{HPP}$ allows to distinguish in optimization problems the states of cold and hot reserves for the HG at the HPP. If the features of these states are not taken into account in the calculations, the electricity consumption in the idle mode is determined as an invariable component of the electricity balance. Amounts of payments for the purchase of this volume of electricity in different times of the day depend on the values of hourly market prices. However, this consumption component does not depend on the HG load level at the HPP. The total daily costs for the purchase of electricity to cover the consumption for the HG idle mode at the HPP are not changed regardless of the results of solving the problem of allocation of available hydro resources for electricity production and therefore in no way affect the objective function of the optimization problem:

$$\sum_{h=1}^{24}\left(C_{buy,h}^{HPP} \cdot \Delta S_{g,idl}^{HPP}\right) = \Delta S_{g,idl}^{HPP} \cdot \sum_{h=1}^{24} C_{buy,h}^{HPP} \rightarrow \text{const}.$$

Thus, if the calculations do not take into account the difference in costs in the cold and hot reserve states of the HG at the HPP, the component $B_{\Delta S}^{HPP}$ in (4) and (5) may not be taken into account in the calculations: $B_{\Delta S}^{HPP}=0$.

With an invariable HG operation mode, the volume of electricity supply within the calculation hour will numerically correspond to the value of the HG load capacity:

$$V_h^{HPP} = 1 \cdot P_{g,h}^{HPP} : \forall h = [1..24],$$

where, 1 is the formal coefficient for conversion from the dimension of power (MW) to the dimension of electricity volume (MWh) with an invariable HG load mode within the calculation hour.

Then, taking into account the linear characteristic of electricity consumption at the HPP, the objective function (1) is obtained in the following form:

$$Max\left(B_{D(l)}^{HPP}\right) = \sum_{h=1}^{24}\left(C_{sell,h}^{HPP} \cdot V_h^{HPP} - C_{buy,h}^{HPP} \cdot \left(A_{\Delta S(l)}^{HPP} \cdot P_{g,h}^{HPP} + B_{\Delta S}^{HPP}\right)\right)$$

By separating the hourly price values into a separate multiplier, the following canonical form of the objective function is obtained:

$$Max\left(B_{D(l)}^{HPP}\right) = \sum_{h=1}^{24}\left(\left(C_{sell,h}^{HPP} - C_{buy,h}^{HPP} \cdot A_{\Delta S(l)}^{HPP}\right) \cdot V_h^{HPP} - C_{buy,h}^{HPP} \cdot B_{\Delta S}^{HPP}\right) \quad (6)$$

As noted above, the component $B_{\Delta S}^{HPP}$ may affect the results of solving the problem of optimal allocation of available hydro resources for electricity production only if the difference in costs for consumption of own needs in the cold and hot reserve states of the HG at the HPP is taken into account. Similarly, the component $C_{buy,h}^{HPP} \cdot A_{\Delta S(l)}^{HPP}$ s calculated at the stage of preparation for the optimization procedure and is not changed during the optimization process. Therefore, the use of the component $C_{buy,h}^{HPP} \cdot A_{\Delta S(l)}^{HPP}$ in (6) allows to specify the amount of profit from the sale of electricity supply by the HPP generators.

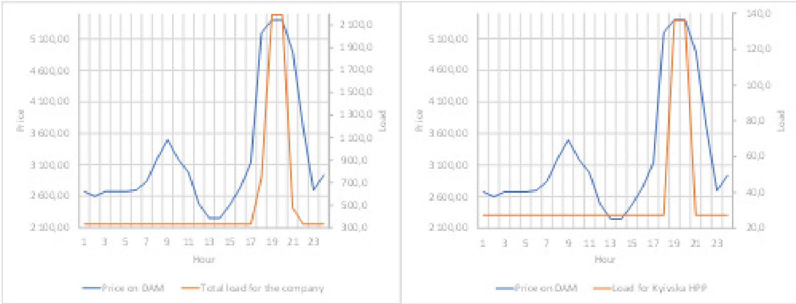

Fig. 2. Daily load schedules of the GC and Kyivska HPP according to statistics as of 02/19/2024
Rys. 2. Dzienne harmonogramy obciążeń GC i Kijowskiej Elektrowni Wodnej według statystyk z dnia 19.02.2024 r.

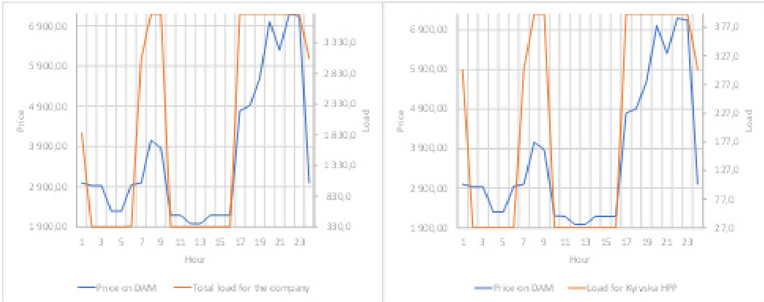

Fig. 3. Daily load schedules of the GC and Kyivska HPP according to statistics on 07/17/2023
Rys. 3. Dzienne harmonogramy obciążeń GC i Kijowskiej Elektrowni Wodnej według statystyk na dzień 17.07.2023 r.

To assess the impact of the numerical values of this component on the results of solving the problem of optimal allocation of available hydro resources for electricity production, the formal representation of the price difference in (6) is detailed using equations (2) and (3):

$$C^{HPP}_{sell,h} - C^{HPP}_{buy,h} \cdot A^{HPP}_{\Delta S(l)} = C^{DAM}_{h} - T^{MO} - T^{TSO}_{T} - T^{TSO}_{DC} - \left(C^{DAM}_{h} + T^{MO} + T^{TSO}_{T} + T^{Prov}\right) \cdot A^{HPP}_{\Delta S(l)} =$$
$$C^{DAM}_{h} \cdot \left(1 - A^{HPP}_{\Delta S(l)}\right) - T^{MO} \cdot \left(1 + A^{HPP}_{\Delta S(l)}\right) - T^{TSO}_{T} \cdot \left(1 + A^{HPP}_{\Delta S(l)}\right) - T^{TSO}_{DC} - T^{Prov} \cdot A^{HPP}_{\Delta S(l)} .$$

Hourly market prices affect only the value of the component $C^{DAM}_{h} \cdot (1 - A^{HPP}_{\Delta S(l)})$. In this case, since the difference is not changed for a separate HG at the HPP, this component will affect only the numerical value of the objective function and will not affect the results of the allocation of available hydro resources at different market prices.

Thus, the linear characteristic of electricity consumption for the HG at the HPP may affect the results of solving the problem of optimal selection of equipment composition for implementing a given electricity production schedule but does not affect the results of solving the problem of optimal d allocation of available hydro resources for electricity production by hours of the day according to price criteria. Therefore, for HPPs with the same type of generators and using an equivalent HPP generator in the problem of optimal allocation of available hydro resources for electricity production by hours of the day according to price criteria, the use of the linear characteristic of consumption does not affect the result and may not be taken into account.

By substituting the quadratic characteristic of the volumes of own electricity consumption depending on the HG load level at the HPP (5) in the objective function (1), the following is obtained:

$$Max\left(B^{HPP}_{D(2)}\right) = \sum_{h=1}^{24} \begin{pmatrix} C^{HPP}_{sell,h} \cdot V^{HPP}_{h} \\ -C^{HPP}_{buy,h} \cdot \left(A^{HPP}_{\Delta S(l)} \cdot \left(V^{HPP}_{h}\right)^2 + B^{HPP}_{\Delta S}\right) \cdot V^{HPP}_{h} \end{pmatrix} \qquad (7)$$

The quadratic characteristic of the costs for powering the own needs of the HPP generators reduces the additional economic profit from increasing the load level of the HPP generators, which stimulates equalizing of electricity supply schedules in hours with insignificant fluctuations in market prices. As practical calculations have demonstrated, the application of the quadratic characteristic of the costs for powering the own needs of the HPP generators results in generating daily schedules with the same load levels in hours with the same market prices. That is, the application of the quadratic characteristic of the costs for powering the own needs of the HPP generators eliminates the need for performing additional optimization according to non-price criteria for hours with the same market prices.

System of constraints for the optimization problem

The system of constraints for solving the problem of optimal allocation of available hydro resources by estimated hours of the day generally corresponds to the mathematical model provided in [5]. Let's briefly present this system of constraints for the formation of a unified calculation model with objective functions (6) and (7).

The permissible load levels of the HPP generators are as follows:

$$V^{HPP}_{min} \le V^{HPP}_{h} \le V^{HPP}_{max} : \forall h = [1..24] ,$$

where, V^{HPP}_{min}, V^{HPP}_{max} is, respectively, the minimum and maximum volumes of electricity supply for the HPP based on the ecological conditions of water runoff, the volumes of electricity already sold, and the mode conditions of the IPS of Ukraine (MWh).

The equations of the balance of hydro resources determine the constraints on water flows. The relationship between the volume of electricity and the water flow is determined by the dependence:

$$F_{\text{con},h}^{\text{HPP}} = V_h^{\text{HPP}} \cdot \gamma_{\text{a}}^{\text{HPP}} : \forall h = [1..24],$$

where, $F^{\text{HPP}}_{\text{con,h}}$ is water consumption for the electricity production in the calculated hour h (m³), $\gamma^{\text{HPP}}_{\text{a}}$ is average water consumption for the electricity production at the HPP (m³/MWh).

The constraints of the balances of hydro resources are intended to control the hourly levels of filling of the reservoir and to summarize the total balance for the calculated day. Thus, the control of the hourly levels of filling of the reservoir is implemented by the dependencies:

$$F_{\text{con},h}^{\text{HPP}} = V_h^{\text{HPP}} \cdot \gamma_{\text{a}}^{\text{HPP}} : \forall h = [1..24],$$

where, $W^{\text{WS}}_{\text{min}}$, $W^{\text{WS}}_{\text{max}}$ is, respectively, the technological minimum and maximum of the reservoir filling (m³), $W^{\text{WS}}_{\text{beg}}$ is the level of the reservoir filling at the beginning of the billing day (m³); $F^{\text{WS}}_{\text{inf,g}}$ is the predicted water flow into the reservoir for the calculation hour h (m³), $F^{\text{HPP}}_{\text{con,k}}$ is water consumption for the electricity production at the HPP in an hour h (m³).

Summary of the total balance of hydro resources for the billing day is as follows:

$$\sum_{h=1}^{24}\left(F_{\text{inf},h}^{\text{WS}} - F_{\text{con},h}^{\text{HPP}}\right) = W_{\text{end}}^{\text{WS}} - W_{\text{beg}}^{\text{WS}},$$

where, $W^{\text{WS}}_{\text{end}}$ is the reservoir filling level at the end of the billing day (m³).

The difference between the final and initial reservoir filling levels on the right-hand side of the equation along with the prediction of water inflow within the billing day determine the volume of hydro resources, the use of which should be allocated by individual hours to obtain the optimal result.

Planning the activities of a power generating company in the electricity market

The need for generating a comprehensive model for optimizing the loading schedules of a HPP cascade may be due to the requirement to take into account additional conditions for the activities of a power generating company (GC) in the electricity market, in particular the need for ensuring minimum volumes of electricity production and supply to execute already concluded bilateral agreements, as well as the requirement to ensure the total volume of production capacities reservation for the generating company to provide auxiliary services to the transmission system operator in terms of unloading. The constraint of the maximum HPP load level is due to the reservation of production capacities for providing auxiliary services in terms of loading. Then the system of level constraints of the power generating company will take the following form:

$$V_{min,h}^{\text{PGC}} \leq \sum_{HP} V_{h,HP}^{\text{HPP}} \leq V_{max,h}^{\text{PGC}} : \forall h = [1..24],$$

where, HP is indexation by HPPs that are part of the GC; $V^{\text{HPP}}_{\text{h,HP}}$ is the volume of electricity supply from an individual HPP in an hour h (MWh); $V^{\text{PGC}}_{\text{min,h}}$, $V^{\text{PGC}}_{\text{max,h}}$ is, respectively, the minimum and maximum volumes of electricity supply from all power plants of the GC in an hour h, taking into account the agreements already concluded in the market segments, (MWh).

When planning electricity supply schedules for the DAM bids at the GC level, it is necessary to take into account the volumes of already sold electricity under bilateral agreements, since for these volumes the agreement has already been concluded and additional financial revenues will not occur. Then the objective function (6) with linear cost characteristics, taking into account the already sold volumes of electricity, will have the following form:

$$Max\left(B2_{D(l)}^{\text{HPP}}\right) = \sum_{h=1}^{24}\begin{pmatrix} C_{\text{sell},h}^{\text{HPP}} \cdot \left(\sum_{HP} V_{h,HP}^{\text{HPP}} - V_{\text{CA},h}^{\text{HPP}}\right) \\ -C_{\text{buy},h}^{\text{HPP}} \cdot \sum_{HP}\left(A_{\Delta S(l)}^{\text{HPP}} \cdot V_{h,HP}^{\text{HPP}} + B_{\Delta\text{S}}^{\text{HPP}}\right) \end{pmatrix} \quad (8)$$

where, $V^{\text{HPP}}_{\text{CA,h}}$ is the volume of already sold electricity in an hour h (MWh).

The objective function (7) with nonlinear cost characteristics, taking into account the already sold volumes of electricity will have the following form:

$$Max\left(B2_{D(2)}^{\text{HPP}}\right) = \sum_{h=1}^{24}\begin{pmatrix} C_{\text{sell},h}^{\text{HPP}} \cdot \left(\sum_{HP} V_{h,HP}^{\text{HPP}} - V_{\text{CA},h}^{\text{HPP}}\right) \\ -C_{\text{buy},h}^{\text{HPP}} \cdot \sum_{HP}\left(A_{\Delta S(2)}^{\text{HPP}} \cdot \left(V_{h,HP}^{\text{HPP}}\right)^2 + B_{\Delta\text{S}}^{\text{HPP}}\right) \end{pmatrix} \quad (9)$$

Using electricity consumption cost functions in the problems of planning HPP loading schedules

The presented mathematical models were used to solve the problem of constructing an optimal schedule of electricity supply for DAM bids based on retrospective data on available hydro resources and prices in the segment of the DAM of Ukraine for 02/19/2024. Fig. 2 shows the loading schedules for the Kyivska HPP and for the GC.

Based on the volumes of hydro resources available as of 02/19/2024 for the Kyivska HPP, a schedule was formed with operation in the minimum load mode for 22nd hour of the day. The maximum load for the Kyivska HPP was determined only for 19th and 20th hours of maximum market prices. For individual HPPs included in the GC on this day, the volumes of available hydro resources allow implementing the schedules with increased (compared to the minimum load mode) load additionally at 18th and 21st hours. For comparison, according to statistics on 07/17/2023, larger volumes of available hydro resources allow ensuring maximum electricity supply at the morning and evening peak hours of electricity consumption (Fig. 3).

Based on the results of experimental studies carried out using the presented mathematical models, the following conclusions have been made:

- using the linear cost function in the objective function (6) does not solve the problem of stochastic optimization results in the situations provided in [6,7];
- using the nonlinear cost function in the objective function (7) allows to equalize the HPP load schedules in the situations provided in [6,7];
- for the Dnieper HPP cascade, using the nonlinear cost function in the objective function (7) allows to equalize the HPP load schedules for fluctuations in market prices up to 10%;
- taking into account the volumes of already sold elec-

tricity in the objective functions (8) and (9) does not affect the results of solving the problem of optimal allocation of hydro resources by hours of the day for the electricity production.

CONCLUSION

The mathematical model presented in the publication allows solving the problem of optimal allocation of available hydro resources according to the price criterion for forming a daily schedule of loading of hydroelectric power plant generators, taking into account the plan for maintaining the reservoir filling level and technological constraints. At the same time, two options of mathematical models with linear and nonlinear functions of calculating the costs for own needs of electricity consumption of the HPP are formed. Using the function of calculating the costs for own needs of electricity consumption of the HPP allows to more accurately determine the amount of profit from the sale of electricity and to obtain more adequate solutions of the problem of planning schedules of HPPs loading.

As practical calculations have demonstrated, the linear function of calculating the costs for own needs of electricity consumption of the HPP generally preserves the linearity of the mathematical model, which may result in appearance of an infinite plurality of equally optimal solutions for hours of the day with the same market prices. Therefore, when using the linear function of calculating the costs for own electricity consumption of the HPP, it is necessary to take additional measures to obtain adequate results, in particular, performing additional optimization steps using nonlinear functions or using additional nonlinear penalty functions in the objective function as a method for implementing an additional optimization objective according to a non-price criterion.

The nonlinear function of calculating the costs for the own electricity consumption of the HPP allows to obtain the same levels of the HPP load in hours with the same market prices, which gives a result similar to the results of optimization with an additional non-price criterion, namely: the criterion of equalizing the HPP load in hours with the same market prices. This, in turn, eliminates the need to introduce additional non-price optimization criteria in the mathematical model.

Taking into account the volumes of already sold electricity when calculating the revenue part of the activities of the power generating company in the electricity market does not affect the results of solving the problem of optimal allocation of hydro resources by hours of the day for electricity production.

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Poprawa zarządzania udziałem w rynku energii elektrycznej elektrowni wodnych na Ukrainie

Niniejsze badania przedstawiają kompleksowy model matematyczny mający na celu poprawę efektywności zarządzania udziałem elektrowni wodnych (HPP) w rynku energii elektrycznej Ukrainy. Model koncentruje się na optymalnej dziennej alokacji dostępnych zasobów hydroenergetycznych, uwzględniając nieliniowy charakter technologicznego zużycia energii elektrycznej, charakterystycznego dla działalności elektrowni wodnych. Sformułowano funkcję zysku, która reprezentuje przychody ze sprzedaży energii elektrycznej w różnych segmentach rynku, ze szczególnym uwzględnieniem rynku „dnia następnego". Model uwzględnia również zarówno liniowe, jak i nieliniowe funkcje kosztów związanych z zakupem energii elektrycznej niezbędnej do zaspokojenia wewnętrznych potrzeb eksploatacyjnych generatorów elektrowni wodnych w różnych warunkach obciążenia. Funkcja celu ma na celu maksymalizację zysku poprzez zbilansowanie sprzedaży energii elektrycznej z powiązanymi kosztami technologicznego zużycia energii, uwzględniając zmiany w trybach wytwarzania. Ponadto model zawiera szczegółowy system ograniczeń operacyjnych związanych z zarządzaniem zasobami hydroenergetycznymi w węźle hydrotechnicznym „Zbiornik – HPP", zapewniając wykonalność i zrównoważony charakter rozwiązań w zakresie dystrybucji energii. Obliczenia testowe przeprowadzono z wykorzystaniem rzeczywistych i symulowanych danych wejściowych w celu oceny praktycznej przydatności modelu. Wyniki dowodzą skuteczności proponowanego podejścia w optymalizacji eksploatacji elektrowni wodnych w obecnym otoczeniu regulacyjnym i rynkowym Ukrainy. Model oferuje cenne informacje na temat zwiększenia zarówno korzyści ekonomicznych, jak i niezawodności operacyjnej elektrowni wodnych, przyczyniając się do efektywniejszej integracji odnawialnych źródeł energii wodnej na krajowym rynku energii elektrycznej.

Słowa kluczowe: *elektrownie wodne, rynek energii elektrycznej, udział w rynku, zarządzanie energią, eksploatacja systemu elektroenergetycznego, integracja odnawialnych źródeł energii*