

Economic aspects of introducing pumped-storage hydroelectric power plants into the mine dewatering system for distributed power generation

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Abstract. The paper examines the pumped hydroelectric energy storage potential of mine dewatering system for power generation in a distributed power system. Based on the water inflows that can be used to fill the drainage basins, the following options for pumped-storage hydroelectric power plants (PSHPP) are considered: when groundwater is discharged from only one mine, one hydraulic turbine is installed on the horizon below the surface; with additional discharge of groundwater from neighboring mines – installation of two or four hydraulic turbines at the drainage stages closest to the surface. Comparison was made with grid only system. It is based on net present value (NPV) and levelized cost of energy (LCOE) criteria. Variable parameters were hydraulic turbine water flow and mine power consumption. Also, for a certain combination of parameters, the optimal mine power system was determined. The area of use of the PSHS is estimated. It was found that the smallest economic effect is achieved when the power generation of one hydraulic turbine is close to the power consumption. The area of expedient use of the PSHPP within the limits of parameter variation is 17.2%, 19.6% (base and peak costs of power). This is because power generation drops when the water flow decreases. It does not cover the needs of the mine and there is a power shortage. Thus, the mine power system autonomy is very low. With an increase in water inflow and the number of hydraulic turbines, first up to two and then up to four units, the area of expedient use of PSHPP increases to 51.5%, 55.9% and 50.6%, 72.8%, respectively. However, with low energy consumption and a low water flow, it is still rational to receive electricity from the grid. This is due to a sharp drop in the efficiency of hydraulic turbines and high costs for maintenance and repair of PSHPP equipment, which are not comparable to the cost of purchasing power. So it was noted that with the base cost of electricity and an increase in the number of hydro turbines from two to four, the area of conditions under which the use of PSHPP is justified even decreased by 0.9%. At peak cost, the area increases by 16.9%. The mine power system autonomy is not achieved. In general, the efficiency of using PSHPP for mine dewatering systems is high, but the feasibility of their use should be studied for specific conditions of use.

1. Introduction

Improvement of energy efficiency in mining production aims to enhance competitiveness of Ukrainian enterprises on global and domestic markets. This can be done either by optimizing operational modes of available equipment or replacing, where possible, obsolete power machines with up-to-date, more energy efficient ones. On the other hand, introduction of additional generation facilities into the enterprise power system is able to reduce costs when purchasing electric power from external distribution operators. In this respect, wind and solar power is

the most promising energy resources for creating local power plants. However, their use is constrained by peculiarities of technological processes at ore underground ore mines, namely location of main consumers underground, as well as availability and location of areas purchased for installing power generation equipment. Location of alternative energy generation plants at dumps is currently one of the options under study [1].

Yet, considering their distance from consumers of the main production facility and a low level of initial voltage, power supply from helio- and wind power plants will cause significant power losses. We also emphasize a high level of possible contamination of the surface of photoelectric panels, this reducing their initial power and making location of powerful wind generation equipment at dumps impossible because of their instability.

All of the above makes feasibility of introducing these generation facilities into the power system of a mining enterprise disputable. Technological facilities located directly in or next to mine workings can be viewed as an alternative method of producing power. The mine water drainage system is one of such facilities and its energy potential is not currently used to the fullest. It is mainly used as a load regulator in the enterprise power system [2].

With this approach applied, either under the maximum load or during peak hours with tariffs differentiated at intervals when the power cost is the highest, drainage pumps are disconnected from the grid, so mine water is not pumped. In other conditions, especially with minimal power consumption, pumps are in operation and perform their function. This results in balancing power loads by adjusting drainage capacities of consumers. At the same time, this approach requires sufficient pumped-storage capacity which is three or even four times higher than the daily water inflow. Also, to observe safety conditions, pumps cannot be turned off with a significant increase in the mine water level. On the other hand, treating mine water drainage as a set of reservoirs located at different heights relative to each other, it can be stated that there are appropriate preconditions for creating a pumped-storage hydroelectric power plant (PSHPP) on this basis.

2. Literature review

Implementation of a PSHPP in the power system of mining enterprises is the subject of research in a number of works [3–13].

[3–5] consider application of the PSHPP to water drainage during open pit mining operations; [6–13] look into pumped-storage equipment use at water intake facilities of underground mine workings.

[6–12] are mostly devoted to studying the impact of water drainage design elements, in particular, intake facilities, hydraulic systems and technological modes of PSHPP operation at underground mines.

[6] analyzes geomechanical characteristics of the water intake facility used with PSHPP hydroturbines and studies the influence of the material of reservoir gallery supports on their mechanical strength.

[7] investigates into the influence of the water intake design on PSHPP operation and considers the use of interconnected tunnels and galleries as a lower reservoir of the network. The research determines atmospheric pressure and the rate of mixing mine water in intake compartments for water discharge and inflow.

[8] deals with atmospheric pressure changes in the underground intake facility during the water drainage mode of the PSHPP, i.e. the pump station mode, and its impact on design elements of the reservoir.

[9] analyzes waves occurring in underground water intakes during PSHPP operation and their possible impact on mechanical strength of reservoir structures (walls and supports).

[10] focuses on the impact of water inflows on PSHPP efficiency.

[11] evaluates PSHPP operation, namely the influence of water discharge and drainage on inflows, i.e. the nature of ground water inflows. In particular, the intake level and hydraulic

pressure are analyzed for different PSHPP modes. When modelling the required generation volumes of PSHPPs that affect intensity of water discharge and drainage, data on power costs for 14 days in winter, spring and summer is used.

[12] investigates into the intake level during PSHPP operation under different modes.

However, economic aspects of PSHPP implementation for mine water drainage are somewhat ignored. [13] looks into economic indices of PSHPP operation with power being sold to external consumers. Dependences of economic indices, in particular power costs, the NPV, the IRR, the payback period on investments and turbine cycles are built.

At the same time, the main approach to developing state-of-the-art power supply systems involves efficient design of distributed generation systems with PSHPPs and improvement of power flows considering economic terms [14–16].

[14] deals with optimization of power system design for wind farms and PSHPPs according to criteria of power production cost and the level of carbon dioxide emissions. The number of storage pumps and wind turbines to reduce these indices is determined as well.

[15] determines efficient designs of the power supply system for wind, photoelectric, biomass and pumped-storage power plants guided by the criterion of minimal power production costs.

[16] suggests a multi-staged method of adjusting active power production in the power system with wind, photoelectric, thermal and pumped-storage power plants and power storage devices installed. The power system is planned and optimized on a daily, hourly and real time basis. This approach reduces power fluctuations caused by a changeable nature of renewable energy sources. The cost of power production is also used as an optimization criterion.

[17] determines the power generation level of the PSHPP depending on the water level in the upper reservoir as in the case of the pumped-storage facility located on the Sebeş River (Gâlceag, Romania).

Efficiency of the distributed generation system in mine conditions can be improved by introducing either wind generators with modern control systems [18] or power storage systems [19] to reduce generation fluctuations caused by a changeable nature of renewable energy sources.

3. Materials and methods

3.1. Description of iron ore mines power systems configurations

To increase efficiently of an energy resource, a mini pumped-storage hydroelectric power plants (mini-PSHPPs) are suggested to be installed in sections of mine water drainage. Thus, mine waters can be discharged backward either from upper horizons or the surface to lower horizons, thus generating power via hydroturbines. It is assumed that pumps will not be turned off to avoid overflow of reservoirs. Constant water discharge for generating power eliminates the need to expand reservoirs for mine waters.

Different designs of the distributed generation system can be applied to building PSHPPs for underground mines. Installation of a hydroturbine next to a reservoir on a separate level is the simplest option when using only one target mine for producing power from water resources. Advantages of this approach include autonomous application of power generated and control of balancing the enterprise power system, low investments and easy engineering implementation. Yet, power production constrained by mine inflows can be considered a disadvantage. Alternatively, an option that involves accumulation of water from several underground mines in surface intakes of a target mine followed by its discharge to a lower level can be suggested. Thus, the energy potential of water drainage increases enhancing the level of power generation. Simultaneously, this option requires installation of additional hydroturbines that increases required investments for their purchase and installation. In addition, it is necessary to determine how to distribute the economic effect from mini-PSHPPs among underground mines supplying water.

To increase power generation, multi-staged water discharge from higher to lower levels can be performed with mini-PSHPPs installed next to a reservoir at each level mark.

Because of the above disadvantages, there is a need for coordinated control over individual mini-PSHPPs on different levels, which significantly complicates engineering implementation of the system. Yet, among all the options considered, the outlined design provides the highest power production and, therefore, it is the most economically feasible.

Efficiency of introduction of mini-PSHPPs for combined power supply of mine consumers is considered by taking water drainage of Rodina mine as an example (figure 1). Main drainage facilities including pumps and reservoirs are located on the 500m, 940m, 1240m, 1315m, 1465m and 1540m levels. When conducting computational experiments, installation of 1 MW hydrogenerators of CJ A237-W-90/1x5.5 type is envisaged (table 1).

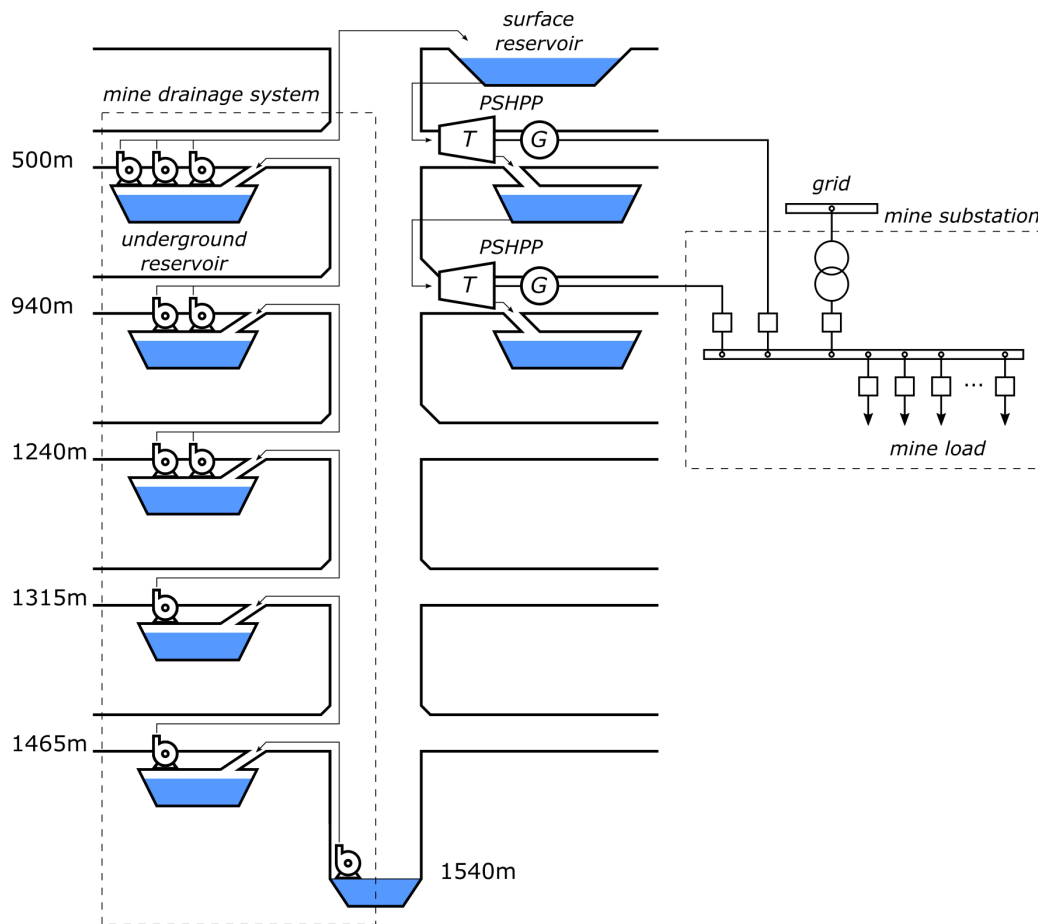


Figure 1. Scheme of mine pumped-storage hydroelectric power plant: T – water turbine; G – generator.

Table 1. Nominal parameters of the hydroturbine CJA 237.

h, m	$Q, m^3/sec$	P, kW	n, rpm	Generator	P_n, kW	U, kV
540	0.23	1075	1000	SFW 1000-6/1180	1000	6300

Let us evaluate the energy potential of each water drainage stage by calculating the power generation level of a hydroturbine at the maximum allowable water consumption [20]:

$$P = \eta \rho g h Q, \quad (1)$$

where:

- η is the hydroturbine efficiency factor;
- ρ is the water density, kg/m^3 ;
- g is the gravitational acceleration, m/s^2 ;
- h is head, m ;
- Q is water flow rate, m^3/s .

For multi-staged water discharge on the 0m, 500m, 940m, 1240m, 1315m levels, power production makes 1015.3 *kWh*, 893.49 *kWh*, 609.2 *kWh* and 152.3 *kWh* respectively. Therefore, it is advisable to consider options for placing hydroturbines on the 500m and 940m levels. Power generation for 940m-1240m and 1240m-1315m levels makes 60 % and 1.5 % of the nominal capacity of a storage pump, this indicating its inefficient load.

When conducting the research, three designs of the distributed generation system via mini-PSHPPs are considered:

- a single hydroturbine ($N_{HT} = 1$) on the 500m level using water from one mine;
- two hydroturbines ($N_{HT} = 2$) on the 500m level using water from several mines;
- four hydraulic turbines ($N_{HT} = 4$) – two on the 500m level and two on the 940m level using water from several mines.

For each system design, a comparative analysis is performed with two options of power consumption considered:

- from the industrial power grid supplied by the external power system;
- combined power supply of the grid and the mini-PSHPP.

The first option involves purchasing power from the power supplying company at current tariffs to fully satisfy the facility's needs. The second one provides power supply of drainage pumps from both mini-PSHPP hydrogenerators and the enterprise grid in case of power shortage due to either increased power consumption because of additional pumps installed when increasing water inflow to the mine or reducing water consumption of a storage pump.

The net present value (NPV) of the system is used as a criterion for comparing efficiency of the above two options [21]:

$$NPV = \sum_{i=1}^N \frac{R_i}{(1+d)^i}, \quad (2)$$

where:

- R_i is the difference between profits and expenses during system operation, UAH;
- d is the discount rate;
- N is the number of years of system operation.

The economic index is used for modelling to take into account the cost of purchasing and maintaining generation equipment of mini-PSHPPs. The power obtained from the external power system and paid for at current tariffs of the power supplying company can be an obvious criterion of the system efficiency. Yet, this criterion is unrepresentative as any additional power supply source reduces the level of power supplied by the external grid.

Additionally, the value of levelized cost of energy (LCOE) for the combined power system was calculated.

3.2. Description of modeling conditions

Computational experiments are conducted by using MATLAB.

When modelling, the nominal power load seems to be uniformly distributed during 24 hours of operation with average and peak capacities of 900 kW and average daily consumption of 21600 kWh . There are calculations for cases with additional power equipment installed, when average daily consumption increases up to 43200 kWh and decreases to 10800 kWh .

Calculations of the mini-PSHPP option consider investments for purchasing a hydroturbine (540 000 UAH) and various expenses for scheduled and preventive repair and maintenance works amounting to 80 000 UAH per year. Power generation of mini-PSHPPs is performed at the nominal hydrostatic pressure of 500m (0m–500m) and 440m (500m–940m) and losses in the hydraulic system of 15%. When modelling, the amount of water passing through the hydroturbine tends to decrease compared to the nominal value and makes 0.23 m^3/sec ; 0.15 m^3/sec , and 0.07 m^3/sec . The hydroturbine efficiency is 90%. The cost of power received from the power supplying company is 93.38 UAH/MWh for first-category industrial (non-household) power consumers. Besides, power costs during peak hours are also modelled and make 140.07 UAH/MWh. The service life of the system makes 25 years with the nominal discount rate of 8%.

4. Results and discussion

4.1. Economic performance of the distributed generation power system based on pumped-storage hydroelectric power plant, containing one hydroturbine located on the underground horizon of 500 meters

4.1.1. Basic power tariff case. The computational experiment results are given in table 2 and table 3.

Table 2. NPV (UAH) and LCOE (UAH/kWh) when introducing the distributed generation system with the mini-PSHPP at the 500m level with the tariff of $\alpha_{base} = 93.38 \text{ UAH/MWh}$, $N_{HT} = 1$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	LCOE	NPV	LCOE
10800	0.07	3929427.39	0.09338	4744160.92	0.112742
	0.15			2095383.12	0.049795
	0.23			1820973.14	0.043274
21600	0.07	7858854.77	0.09338	8673588.3	0.103061
	0.15			6024810.51	0.071588
	0.23			2727270.31	0.032406
43200	0.07	15717709.55	0.09338	16532443.08	0.09822
	0.15			13883665.28	0.082484
	0.23			10586125.09	0.062893

In figure 2 and figure 3, there are discounted operating costs and NPVs of the power supply system for individual consumers of the mine when introducing an additional generation facility – a mini-PSHPP containing a single hydroturbine with the tariff of $\alpha_{base} = 93.38 \text{ UAH/MWh}$. The graphs specify economic indices for the enterprise power grid and mini-PSHPPs as well as total indices of the distributed generation system.

The graphs indicate that at low power consumption and hydroturbine water consumption close to the nominal value when $Q = 0.23 \text{ m}^3/sec$ and $E = 10800 \text{ kWh}$, the NPV of the

Table 3. NPV (UAH) and LCOE (UAH/kWh) when introducing the distributed generation system with the mini-PSHPP at the 500m level with the tariff of $\alpha_{peak} = 140.07$ UAH/MWh, $N_{HT} = 1$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	LCOE	NPV	LCOE
10800	0.07	5894141.08	0.14007	6205754.8	0.147475
	0.15			2232588.11	0.053056
	0.23			1820973.14	0.043274
21600	0.07	11788282.16	0.14007	12099895.89	0.143773
	0.15			8126729.19	0.096563
	0.23			3180418.9	0.037790
43200	0.07	23576564.32	0.14007	23888178.05	0.141921
	0.15			19915011.36	0.118316
	0.23			14968701.06	0.08893

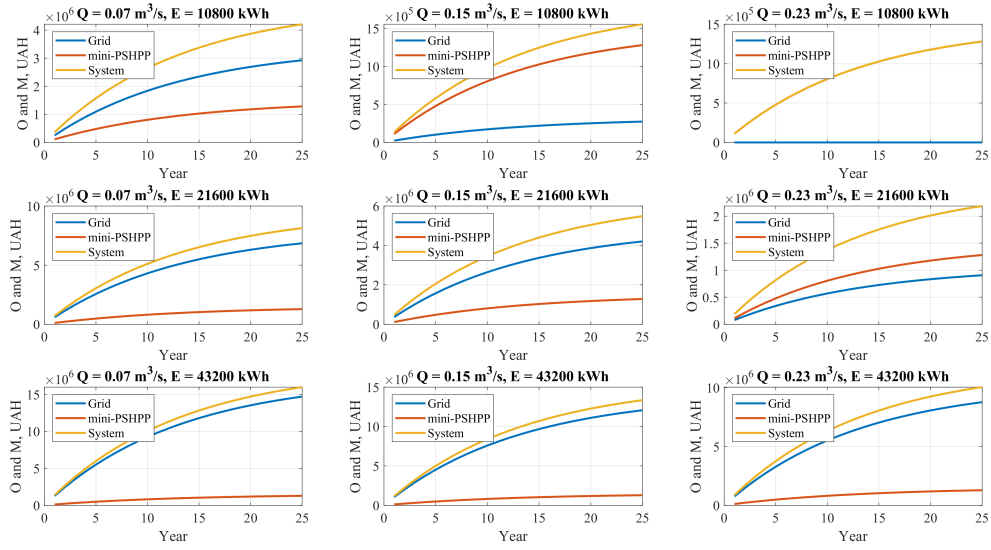


Figure 2. Operating costs of the power supply system with the mini-PSHPP for different values of hydroturbine water consumption and average daily power consumption with the power cost of 93.38 UAH/MWh.

system is determined by operating costs of the mini-PSHPP. This is due to the fact that power generation of the hydroturbine fully satisfies the current power consumption, so the purchase of power from the external power grid of the distribution power operator is not carried out. The distributed generation power system operates autonomously.

Under typical operation conditions with $Q = 0.23$ m³/sec and $E = 21600$ kWh as well as $Q = 0.15$ m³/sec and $E = 10800$ kWh, the NPV of the system is actually conditioned by the NPV of the mini-PSHPP. Thus, the fraction of the NPV resulted from power generation via hydroturbines makes 86.9% with $Q = 0.15$ m³/sec and $E = 10800$ kWh and 66.76% with $Q = 0.23$ m³/sec and $E = 21600$ kWh.

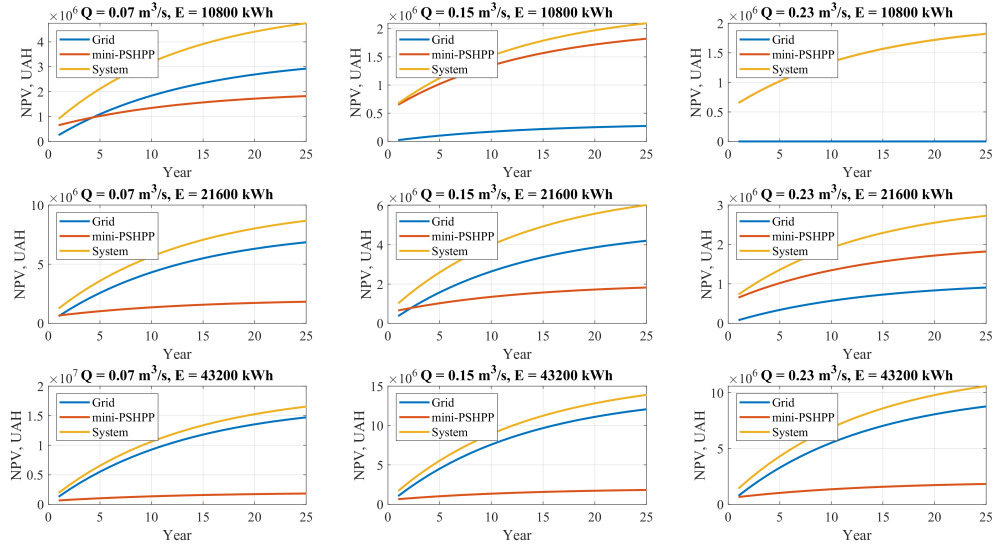


Figure 3. NPV of the power supply system with the mini-PSHPP for different values of hydroturbine water consumption and average daily power consumption with the power cost of 93.38 UAH/MWh.

With an increase in power consumption, the capacity shortage of the mini-PSHPP begins to be covered by external power supply. With $Q = 0.07 \text{ m}^3/\text{sec}$ and $E = 21600 \text{ kWh}$; $Q = 0.07 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$; $Q = 0.15 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$; $Q = 0.23 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$, the NPV of the system almost entirely depends on the cost of power purchased from the distribution operator which is explained by the low generation level of the mini-PSHPP.

Thus, the fraction of the NPV from hydroturbine operation in the total structure of the NPV system is only 11.01% with $Q = 0.07 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$, 13.12% with $Q = 0.15 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$, 20.99% with $Q = 0.07 \text{ m}^3/\text{sec}$ and $E = 21600 \text{ kWh}$, and 17.2% with $Q = 0.07 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$ respectively. In these cases, it is inefficient to use the system design in question.

Comparing economic indices of the two suggested options of power supply – only from the grid and from the combined power supply system with the mini-PSHPP (see table 2) – it is established that with the increased Q to the nominal value of the hydrogenerator ($0.23 \text{ m}^3/\text{sec}$), the NPV for the mini-PSHPP system decreases. Thus, during the operation of power equipment with $E = 21600 \text{ kWh/day}$ and $Q = 0.15 \text{ m}^3/\text{sec}$, the NPV of the mini-PSHPP system is 23.34% smaller as compared to the system without the mini-PSHPP, and with $Q = 0.23 \text{ m}^3/\text{sec}$ it is 65.3% smaller (41.96% greater than with $Q = 0.15 \text{ m}^3/\text{sec}$).

In case of introducing two pumps, i.e. with increased power consumption up to $E = 43200 \text{ kWh/day}$ with $Q = 0.15 \text{ m}^3/\text{sec}$ for the mini-PSHPP system, the NPV is 11.67% smaller and with $Q = 0.23 \text{ m}^3/\text{sec}$ – 32.65% smaller (20.98% greater as compared to $Q = 0.15 \text{ m}^3/\text{sec}$). So, with increased capacity of water drainage consumers, efficiency of the mini-PSHPP system is not growing so intensively. This is due to the fact that for some reason a hydroturbine cannot fully meet the needs of the facility, this causing capacity shortages.

Table 2 contains calculated data on power costs of the combined power supply system for different operation conditions.

The results of calculations reveal that at low intensity of the water flow passing through the

mini-PSHPP hydroturbine during mine water discharge, in particular with $Q = 0.07 \text{ m}^3/\text{sec}$ and power consumption of the nominal value and higher, the power cost exceeds the tariff set by the distribution operator. This is due to maintenance and repair costs of hydroturbines exceeding the economic effect of additional generation leading to a great difference between the volume of power produced and consumed.

Additionally, there is a dependence of the NPV of the combined power supply system on hydroturbine water consumption and power consumption. There are also determined application areas of parameters within which it is advisable to use a particular design. Graphical interpretation of optimal applications of a certain power supply option is similar to the Optimal System Plot of the Homer Pro application package [22]. To perform calculations, intervals of changing independent parameters (hydroturbine water consumption and power consumption) are reduced. Thus, Q changes within $[0.07 \text{ m}^3/\text{sec}; 0.23 \text{ m}^3/\text{sec}]$ in increments of $1 \cdot 10^{-4} \text{ m}^3/\text{sec}$; average daily capacity – within $[450 \text{ kW}, 180 \text{ kW}]$ in increments of 10 kW .

In figure 5 and further in yellow, the area of the power supply system efficiency is indicated, which provides for power supply from the grid without the mini-PSHPP, in blue – distributed generation systems with mini-PSHPPs.

Analysis of the obtained results (figure 4, figure 5) shows that with the current power tariff of $\alpha_{base} = 93.38 \text{ UAH}/\text{MWh}$, the combined power supply system with a hydrogenerator should be used for water flow intensity above $0.1339 \text{ m}^3/\text{sec}$ and average daily power consumption of $10800 \text{ kWh}/\text{day}$; $0.1899 \text{ m}^3/\text{sec}$ – with $21600 \text{ kWh}/\text{day}$ and $0.23 \text{ m}^3/\text{sec}$ – with $29520 \text{ kWh}/\text{day}$. Reduced water consumption leads to the increased NPV for systems without mini-PSHPPs as compared to the option without it, which indicates inefficiency of the combined power supply system. Power consumption over 29520 kWh makes application of the mini-PSHPP system inefficient.

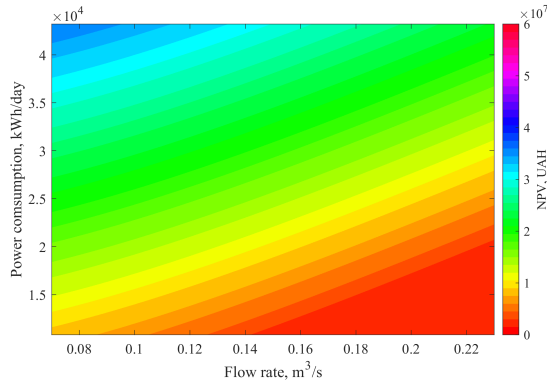


Figure 4. Dependence of the NPV of the combined power supply system on hydro-turbine water consumption and the level of power consumption $NPV = f(Q, E)$ with a single hydroturbine introduced on the 500m level with the tariff of $93.38 \text{ UAH}/\text{MWh}$.

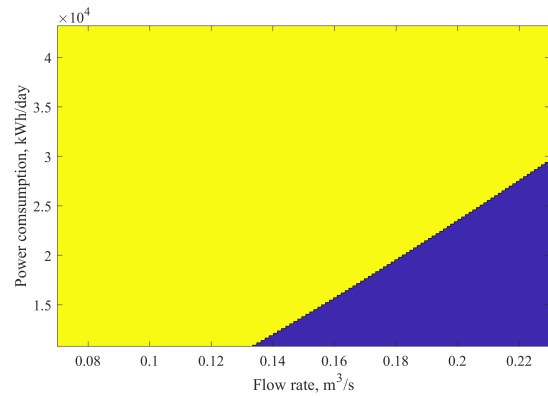


Figure 5. Power supply system of the 500m level with a single turbine introduced which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of $93.38 \text{ UAH}/\text{MWh}$.

The area of effective application of the combined power supply system with its own distributed generation facilities within the considered change of parameters ($\alpha_{base} = 93.38 \text{ UAH}/\text{MWh}$) is 17.2%. These are the most unfavourable conditions for modernization of the power system, as their totality indicates the lowest area of distributed generation applied making it inefficient.

4.1.2. *Peak power tariff case.* Application of the tariff for peak hours ($\alpha_{peak} = 140.07 \text{ UAH}/\text{MWh}$ – table 3, figure 6, figure 7) is expected to increase efficiency of the combined power supply system, with the single hydroturbine-based mini-PSHPP on the 500 m level.

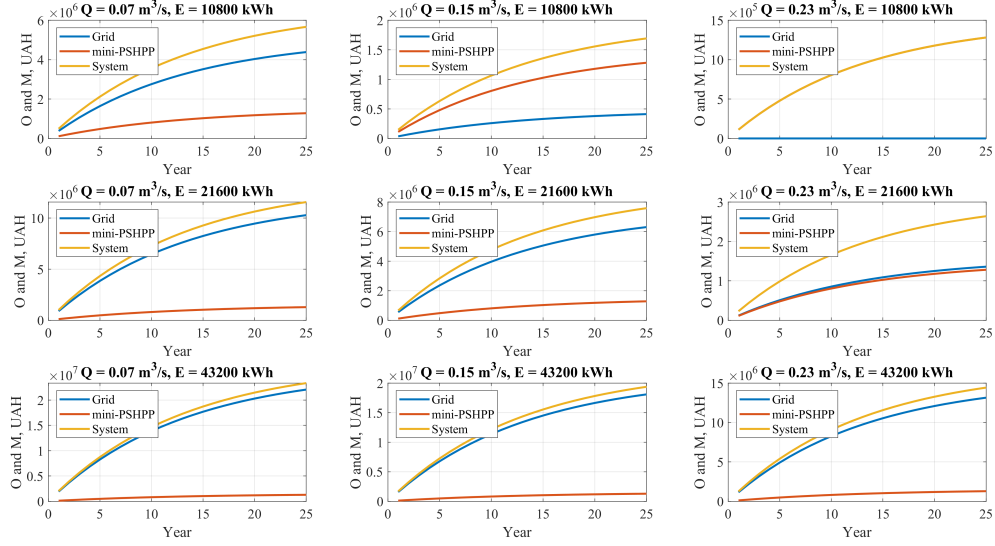


Figure 6. Operating costs of the power supply system with mini-PSHPPs during the operation period for different values of hydroturbine water consumption and average daily power consumption with the power cost of $140.07 \text{ UAH}/\text{MWh}$.

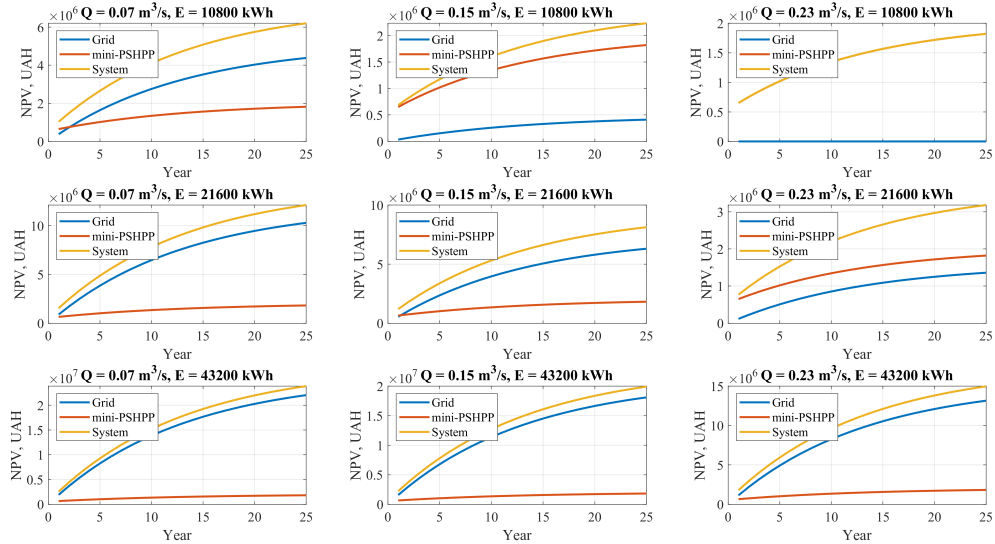


Figure 7. NPV of the power supply system with mini-PSHPPs during the operation period for different values of hydroturbine water consumption and average daily power consumption with the power cost of $140.07 \text{ UAH}/\text{MWh}$.

This is due to increased costs for power purchased from the external power grid at higher prices. At the same time, expenses for purchasing, maintaining and repairing a hydrogenerator remain unchanged as compared to the basic tariff.

Thus, in the most unfavourable operating conditions, the fraction of the NPV of mini-PSHPPs for the peak tariff in the total structure of the system NPV decreases as compared to the basic tariff ($\alpha_{base} = 93.38 \text{ UAH/MWh}$). For example, it makes 7.62% with $Q = 0.07 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$; 9.14% with $Q = 0.15 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$; 12.17% with $Q = 0.23 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh}$; 15.05% with $Q = 0.07 \text{ m}^3/\text{sec}$ and $E = 21600 \text{ kWh}$. For the basic tariff, the fraction is 11.01%, 13.12%, 20.99% and 17.2% respectively.

It is also worth mentioning that the fraction of the NPV of mini-PSHPPs decreases greatly for such conditions as $Q = 0.07 \text{ m}^3/\text{sec}$, $E = 10800 \text{ kWh}$ and $Q = 0.15 \text{ m}^3/\text{sec}$, $E = 21600 \text{ kWh}$ and amounts to 29.34% and 22.41% (38.38% and 30.22% with $\alpha_{base} = 93.38 \text{ UAH/MWh}$) respectively. This is due to increased costs for power purchased from the external grid.

Under nominal conditions of $Q = 0.23 \text{ m}^3/\text{sec}$ and $E = 21600 \text{ kWh}$ as well as $Q = 0.15 \text{ m}^3/\text{sec}$, $E = 10800 \text{ kWh}$, the NPV is conditioned by the power purchased from the external power grid and still remains lower than the NPV of the mini-PSHPP.

The NPV of mini-PSHPP systems increases more significantly with increased water consumption up to the nominal value as compared to the basic tariff. For example, with $E = 21600 \text{ kWh/day}$ corresponding to the consumer's capacity of 900 kW, the NPV with $Q = 0.15 \text{ m}^3/\text{sec}$ is 31.06% lower for the combined power supply system as compared to power supply only from the external power system (it is decreased by 23.34% for the basic tariff), while with $Q = 0.23 \text{ m}^3/\text{sec}$, it is 73.02% lower (65.3% for the basic tariff).

In case of simultaneous operation of two consumers with the capacity of 900 kW, i.e. $E = 43200 \text{ kWh/day}$, the NPV of the mini-PSHPP system is 15.53% lower with $Q = 0.15 \text{ m}^3/\text{sec}$ (11.67% for the basic tariff) and 36.51% lower with $Q = 0.23 \text{ m}^3/\text{sec}$ (32.65% for the basic tariff).

In other words, with the increased hydroturbine water consumption up to the nominal value, the fraction of the NPV reduction for the system with mini-PSHPPs is almost comparable – 73.02% vs. 65.3% for $E = 21600 \text{ kWh/day}$ and 36.51% vs. 32.65% for $E = 43200 \text{ kWh/day}$.

Also, when increasing the established capacity, a difference of the reduced NPV is not so significant for the two considered options of power costs (basic and peak).

The reduced power cost in the mini-PSHPP system (table 3) exceeds the peak tariff with $Q = 0.07 \text{ m}^3/\text{sec}$ for all considered options of power consumption, which indicates low efficiency of the distributed generation system with low water consumption via a storage pump. Power costs in combined power supply systems are close to the peak tariff with $Q = 0.15 \text{ m}^3/\text{sec}$ and $E = 43200 \text{ kWh/day}$ and lower by only 15.53%.

In figure 8, the dependence graph shows a more intensive increase in the NPV with increased power consumption and reduced hydroturbine water consumption.

The graph (figure 9) reveals that the system without mini-PSHPPs should be used with water flow intensity below $0.1264 \text{ m}^3/\text{sec}$ for $E = 10800 \text{ kWh/day}$, $0.1839 \text{ m}^3/\text{sec}$ – for $E = 21600 \text{ kWh/day}$ and $0.23 \text{ m}^3/\text{sec}$ – for $E = 30960 \text{ kWh/day}$. That is, the application area of the distributed generation system with mini-PSHPPs increases to 19.6% compared to the tariff of $\alpha_{base} = 93.38 \text{ UAH/MWh}$, yet not significantly – only by 2.4%. With the level of power consumption above 30960 kWh/day , the use of the mini-PSHPP system is inefficient.

4.2. Economic performance of the distributed generation power system based on pumped-storage hydroelectric power plant, containing two hydro turbines, which are located on the underground horizon of 500 meters

4.2.1. Basic power tariff case. At the next stage of the research, calculations are made for the option with two hydroturbines installed on the 500m level of Rodina mine.

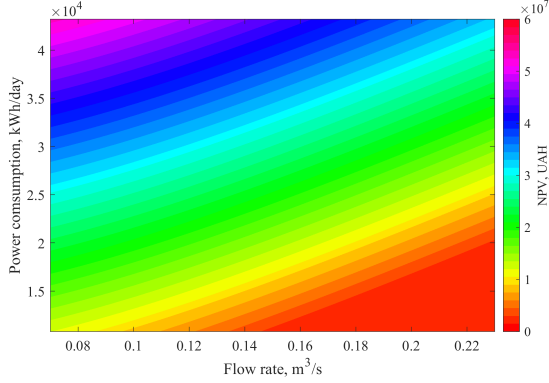


Figure 8. Dependence of the NPV of the combined power supply system on hydroturbine water consumption and power consumption $NPV = f(Q, E)$ with a single hydroturbine introduced on the 500m level with the tariff of $140.07 \text{ UAH}/MWh$.

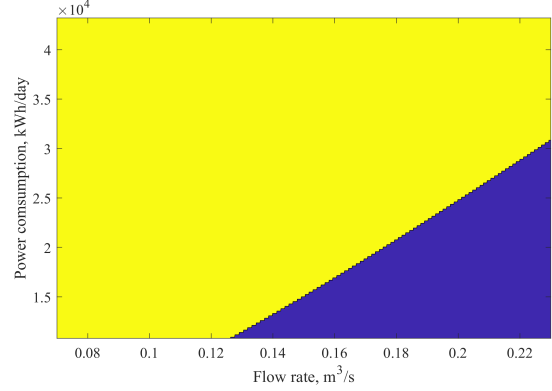


Figure 9. Power supply system of the 500m level with a single turbine introduced which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of $140.07 \text{ UAH}/MWh$.

Computational experiment results for the basic tariff of $\alpha_{base} = 93.38 \text{ UAH}/MWh$ are summarized in table 4 and table 5.

Table 4. NPV (UAH) and $LCOE$ (UAH/kWh) for the distributed generation system with the mini-PSHPP (two hydroturbines) introduced on the 500 m level with the tariff of $93.38 \text{ UAH}/MWh$, $N_{HT} = 2$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	3929427.39	0.09338	5558894.45	0.132103
	0.15			3641946.29	0.086548
	0.23			3641946.29	0.086548
21600	0.07	7858854.77	0.09338	9488321.83	0.112742
	0.15			4190766.25	0.049795
	0.23			3641946.29	0.043274
43200	0.07	15717709.55	0.09338	17347176.61	0.103061
	0.15			12049621.02	0.071588
	0.23			5454540.63	0.032406

The data obtained reveals an increase in the fraction of the NPV of mini-PSHPPs in the structure of the system NPV. This is due to increased volumes of power generation by storage pumps and reduction of power shortages. As a result, expenses for power purchased from the external distribution operator are reduced.

However, comparing the results are in table 2 and table 4, it can be seen that the reduced power cost in the mini-PSHPP system with two hydroturbines is growing. This is due to double capital expenses for purchasing generation equipment and annual expenses for maintenance and repairs.

4.2.2. *Peak power tariff case.* When applying the peak power tariff (table 5) compared with the option with the basic tariff (table 4), it can be seen that the NPV criterion indicates increased efficiency of distributed generation systems because the difference between NPVs becomes more significant.

Table 5. *NPV (UAH) and LCOE (UAH/kWh) for the distributed generation system with two hydroturbines introduced on the 500m level with the tariff of 140.07 UAH/MWh, $N_{HT} = 2$.*

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	5894141.08	0.14007	6517368.53	0.154881
	0.15			3641946.29	0.086548
	0.23			3641946.29	0.086548
21600	0.07	11788282.16		12411509.61	0.147475
	0.15			4465176.23	0.053056
	0.23			3641946.29	0.043274
43200	0.07	23576564.32		24199791.77	0.143773
	0.15			16253458.39	0.096563
	0.23			6360837.8	0.03779

Data on the calculated reduced power cost in the system with two storage pumps (table 5) operating with the peak tariff shows that compared to the option where the power shortage is covered by purchasing power at the basic tariff (table 4), its cost increases.

4.3. *Economic performance of the distributed generation power system based on pumped-storage hydroelectric power plant, containing four hydro turbines, which are located on the underground horizons of 500 and 940 meters (two on each)*

4.3.1. *Basic power tariff case.* At the final stage, efficiency of introducing the distributed generation system with mini-PSHPPs on the 500m and 940m levels of Rodina mine is considered. As this option has the energy potential of water discharge from several mines, four storage pumps are envisaged – two on each level.

The obtained data (table 6) indicates that the NPV of the mine power supply system with the mini-PSHPP is growing significantly. It remains lower than the NPV when consumers are supplied from the external power grid only in four cases: $Q = 0.15 m^3/sec$ and $E = 21600 kWh/day$ (7.32% less), $Q = 0.23 m^3/sec$ and $E = 21600 kWh/day$ (7.32% less), $Q = 0.15 m^3/sec$ and $E = 43200 kWh/day$ (46.67% less), and $Q = 0.23 m^3/sec$ and $E = 43200 kWh/day$ (53.66% less).

In general, the NPV of the mini-PSHPP system consisting of four hydroturbines with the basic tariff under nominal operating conditions ($Q = 0.23 m^3/sec$ and $E = 21600 kWh/day$) increases compared to the use of one or two storage pumps by a factor of 2.67 and 1.99 respectively.

Analysis of the components of the NPV system with combined power supply (figure 10, figure 11) indicates a greater increase in the fraction of the NPV of mini-PSHPPs in the NPV system compared to the option in which power is generated by two storage pumps installed next to the water intake of the 500m level. In this case, the level of power generation sufficient for autonomous power supply is provided in all the cases except for $Q = 0.07 m^3/sec$ and $E = 21600 kWh/day$, $Q = 0.07 m^3/sec$ and $E = 43200 kWh/day$ and $Q = 0.15 m^3/sec$ and $E = 43200 kWh/day$. Yet, with $Q = 0.07 m^3/sec$ and $E = 21600 kWh/day$ and $Q = 0.15 m^3/sec$ and $E = 43200 kWh/day$, the NPV of the system mainly depends on the

Table 6. NPV (UAH) and $LCOE$ (UAH/kWh) for distributed generation systems with mini-PSHPPs introduced on the 500m and 940m levels with the tariff of 93.38 UAH/MWh, $N_{HT} = 4$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	3929427.39	0.09338	7283892.57	0.173096
	0.15			7283892.57	0.173096
	0.23			7283892.57	0.173096
21600	0.07	7858854.77	0.09338	11117788.9	0.132103
	0.15			7283892.57	0.086548
	0.23			7283892.57	0.086548
43200	0.07	15717709.55	0.09338	18976643.67	0.112742
	0.15			8381532.49	0.049795
	0.23			7283892.57	0.043274

NPV of the mini-PSHPP the fraction of which makes 65.52% and 86.9%. It means that with $Q = 0.07 m^3/sec$ and $E = 21600 kWh/day$, the NPV of the system and that of the mini-PSHPP are actually equal.

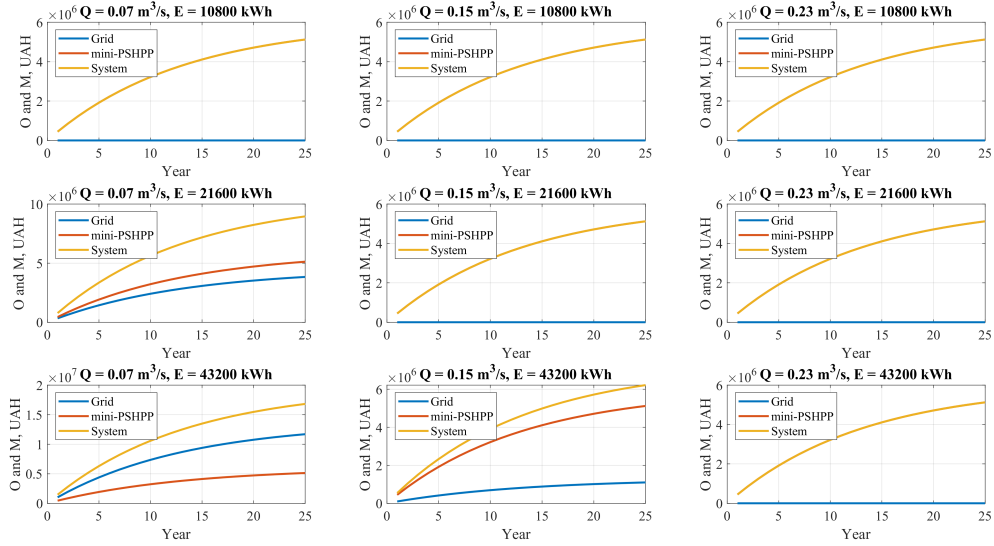


Figure 10. Operating costs of the power supply system with the mini-PSHPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of 93.38 UAH/MWh.

As a result, only with $Q = 0.07 m^3/sec$ and $E = 43200 kWh/day$, the NPV of the system is conditioned by the power purchased from external companies, its fraction making 61.62%.

A significant increase in the costs of generation equipment (four hydroturbines) and its further maintenance leads to exceeding the tariff of $\alpha_{base} = 93.38 UAH/MWh$ by the reduced power cost

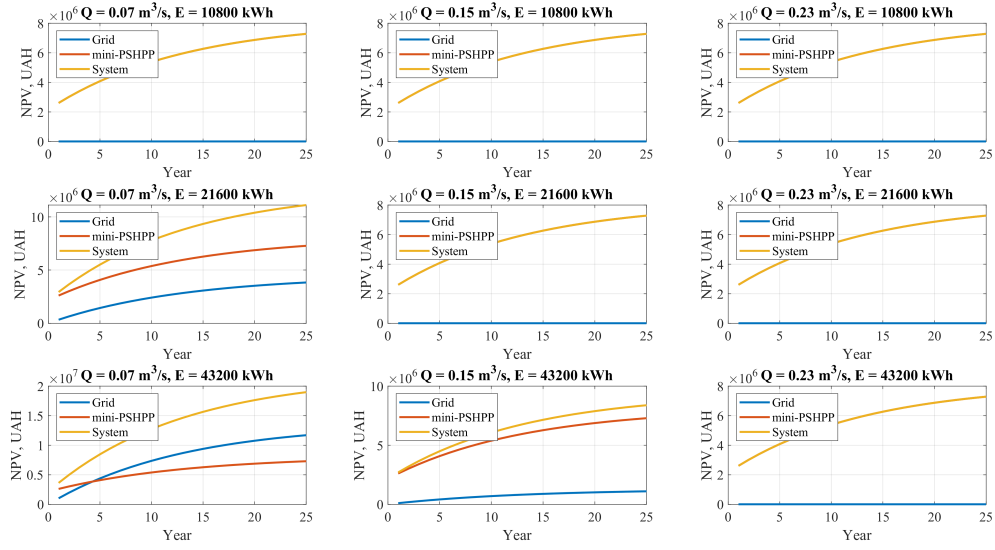


Figure 11. NPV of the power supply system with the mini-PSHPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of $93.38 \text{ UAH}/\text{MWh}$.

in the distributed generation system except for $E = 21600 \text{ kWh/day}$ and $E = 43200 \text{ kWh/day}$ with water consumption $Q = 0.15 \text{ m}^3/\text{sec}$ and $Q = 0.23 \text{ m}^3/\text{sec}$. With low power consumption and water flow intensity, it is favourable to supply power only from the grid and purchase power from the distribution operator. Modernization of the mine power grid by building a mini-PSHPP is not feasible because the economic effect of power generation for 25 years does not cover capital investments and operating costs. To make the energy potential of mini-PSHPPs on the 500m and 940m levels more efficient, it is necessary to supply power to more consumers.

The dependence graph $NPV = f(E, Q)$ in figure 12 shows an increase in the system NPV in the area of increasing power consumption from $E = 10800 \text{ kWh/day}$ to $E = 32100 \text{ kWh/day}$ and water consumption from $Q = 0.12 \text{ m}^3/\text{sec}$ to $Q = 0.23 \text{ m}^3/\text{sec}$ (indicated in orange).

The graph (figure 13) shows that the system without mini-PSHPPs should be used for water flow intensity below $0.1011 \text{ m}^3/\text{sec}$ with $E = 21600 \text{ kWh/day}$ and $0.1336 \text{ m}^3/\text{sec}$ – with $E = 43200 \text{ kWh/day}$. The peculiarity of this case is that with power consumption below $E = 20160 \text{ kWh/day}$ mini-PSHPPs in the power supply system are inefficient for any value of hydroturbine water consumption. As a result, the area of parameters change of the distributed generation system slightly decreases (by 0.93% to 50.64%) compared to the case with the basic tariff in action and two hydroturbines installed on the 500m level.

4.3.2. Peak power tariff case. With the peak tariff of $\alpha_{peak} = 140.07 \text{ UAH}/\text{MWh}$ in action, the NPV of the proposed power supply system with the mini-PSHPP is lower than the NPV of the system in which consumers are supplied only from the external power grid with power consumption $E = 21600 \text{ kWh/day}$ and $E = 43200 \text{ kWh/day}$ and water consumption $Q = 0.15 \text{ m}^3/\text{sec}$ and $Q = 0.23 \text{ m}^3/\text{sec}$ (table 7). Thus, with $Q = 0.15 \text{ m}^3/\text{sec}$, $E = 21600 \text{ kWh/day}$ and $Q = 0.23 \text{ m}^3/\text{sec}$, $E = 21600 \text{ kWh/day}$, it reduces by 62.12%, while with $Q = 0.23 \text{ m}^3/\text{sec}$, $E = 43200 \text{ kWh/day}$ – by 69.11%. At the basic tariff, these percentages for similar conditions make 7.32%, 7.32%, 46.67% and 53.66%. The increased difference of NPVs is explained by increased costs of purchasing power from the power supplying company due to the peak tariff

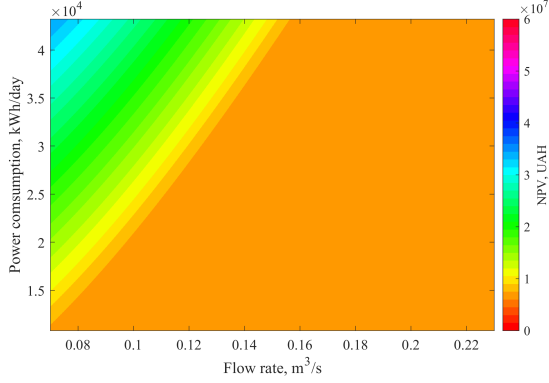


Figure 12. Dependence of the NPV of the combined power supply system on hydroturbine water consumption and the level of power consumption $NPV = f(Q, E)$ with two hydroturbines introduced on the 500m level and two hydroturbines introduced on the 940m level with the tariff of 93.38 UAH/MWh .

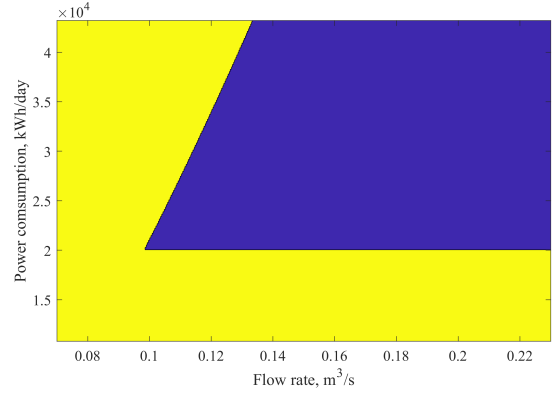


Figure 13. Power supply system with four hydroturbines introduced on the 500m and 940m levels which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of 93.38 UAH/MWh .

while maintaining the level of power generation via their own storage pumps as well as capital and operating costs and those for scheduled and preventive repairs.

Table 7. NPV (UAH) and $LCOE$ (UAH/kWh) for distributed generation systems with mini-PSHPPs introduced on the 500m and 940m levels with the tariff of 140.07 UAH/MWh , $N_{HT} = 4$.

$E, kWh/day$	$Q, m^3/sec$	Grid only		Grid and mini-PSHPP	
		NPV	$LCOE$	NPV	$LCOE$
10800	0.07	5894141.08	0.14007	7283892.57	0.173096
	0.15			7283892.57	0.173096
	0.23			7283892.57	0.173096
21600	0.07	11788282.16	0.14007	13034737.06	0.154881
	0.15			7283892.57	0.086548
	0.23			7283892.57	0.086548
43200	0.07	23576564.32	0.14007	24823019.22	0.147475
	0.15			8930352.45	0.053056
	0.23			7283892.57	0.043274

Analysis of the NPV components of the combined power supply system (figure 14 and figure 15) shows that with parameters $Q = 0.07 \text{ m}^3/sec$, $E = 43200 \text{ kWh/day}$, the NPV of the system is conditioned by the discounted power cost the fraction of which is 70.66%, which is 9.04% higher than with $\alpha_{base} = 93.38 \text{ UAH/MWh}$.

In such conditions as $Q = 0.15 \text{ m}^3/sec$ and $E = 43200 \text{ kWh/day}$, the fraction of the NPV of the mini-PSHPP exceeds the NPV of the enterprise grid by 63.12% and is 81.56% vs. 18.44% respectively (figure 14, figure 15). With $Q = 0.07 \text{ m}^3/sec$ and $E = 21600 \text{ kWh/day}$, they take

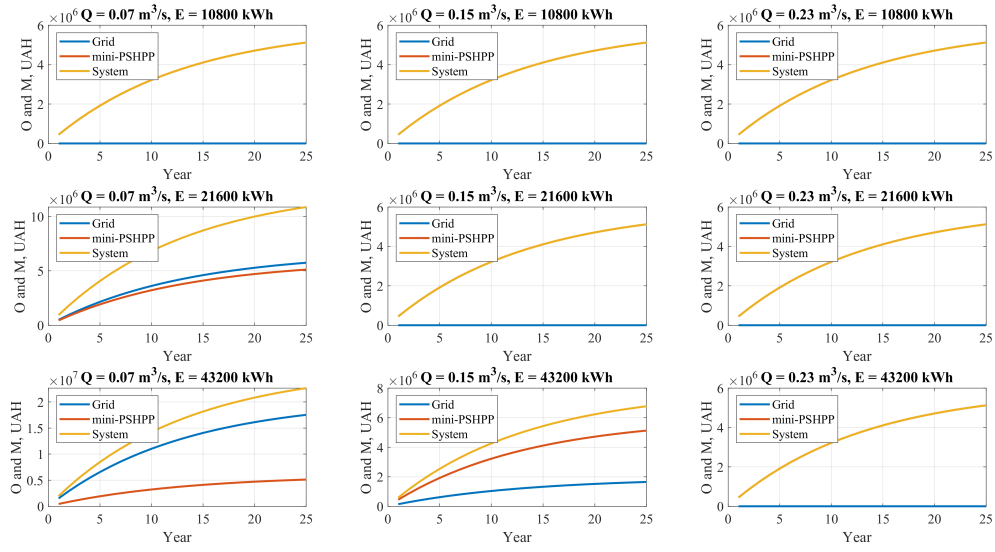


Figure 14. Operating costs of the power supply system with the mini-PSHPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of 140.07 UAH/MWh.

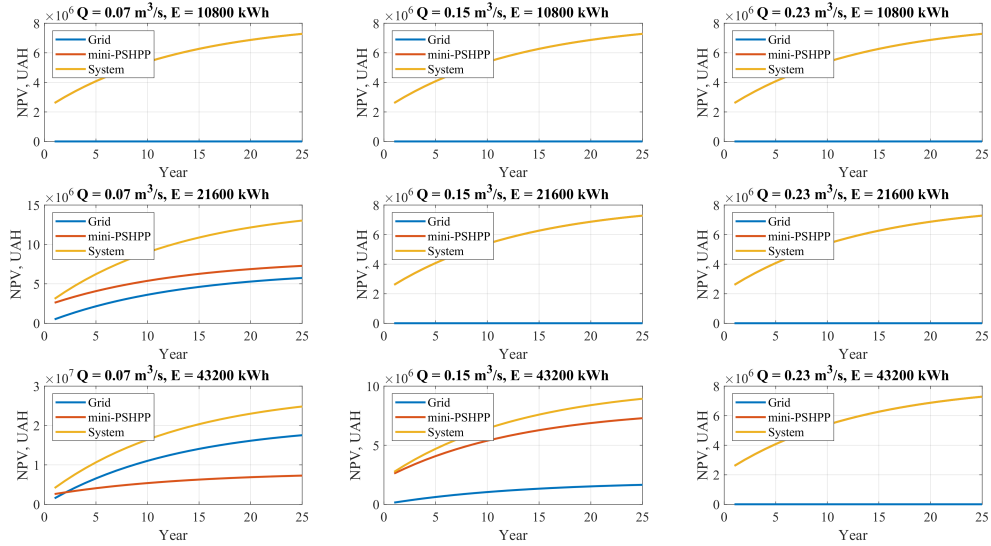


Figure 15. NPV of the power supply system with the mini-PSHPP (two and two hydroturbines on the 500m and 940m levels) during the operation period for different values of hydroturbine water consumption and average daily power consumption with power costs of 140.07 UAH/MWh.

almost the same values – the NPV of the grid exceeds that of the mini-PSHPP by only 2.75%.

In all other conditions, except those mentioned, the NPV of the system is completely

determined by the NPV of the mini-PSHPP as the generated power is sufficient for autonomous power supply of water drainage consumers.

Given that in this case the power tariff increases by a factor of 1.5 up to $\alpha_{peak} = 140.07 \text{ UAH/MWh}$ and, accordingly, the cost of its purchase from the distribution operator increases, the reduced power cost of the distributed generation system with the mini-PSHPP (table 7) becomes lower than the current tariff not only with $Q = 0.23 \text{ m}^3/\text{sec}$ as for $\alpha_{base} = 93.38 \text{ UAH/MWh}$, but also with $Q = 0.15 \text{ m}^3/\text{sec}$, i.e. the energy potential of water drainage is used more efficiently.

The dependence graph $NPV = f(Q, E)$ in figure 16 shows a more intensive increase in the NPV with increased power consumption and reduced hydroturbine water consumption.

The graph (figure 17) shows that the system without mini-PSHPPs should be used for water flow intensity below $0.0926 \text{ m}^3/\text{sec}$ with $E = 21600 \text{ kWh/day}$ and $0.1259 \text{ m}^3/\text{sec}$ with $E = 43200 \text{ kWh/day}$. In this case, in contrast to the basic tariff, the mini-PSHPP system should not be applied to reduced power consumption below $E=13400 \text{ kW}\cdot\text{h/day}$ (for $\alpha_{base} = 93.38 \text{ UAH/MWh}$ this limit is $E = 20160 \text{ kWh/day}$ as in figure 13). This significantly expands the application area of the distributed generation power supply system compared to the previous case. It is worth noting that comparing the efficiency area of the system with four storage pumps with the corresponding areas with one or two hydroturbines installed, this one appears to be the largest and makes 72.84%.

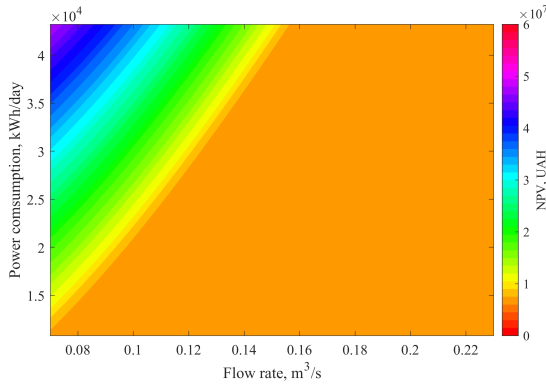


Figure 16. Dependence of the NPV of the combined power supply system on hydroturbine water consumption and the level of power consumption $NPV = f(Q, E)$ with two hydroturbines introduced on the 500m level and two hydroturbines introduced on the 940m level with the tariff of 140.07 UAH/MWh .

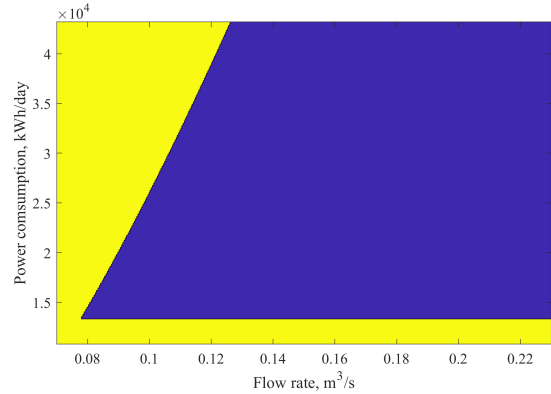


Figure 17. Power supply system with four hydroturbines introduced on the 500m and 940m levels which is efficient in terms of the NPV depending on changes in load and water consumption with the tariff of 140.07 UAH/MWh .

It means that despite high capital costs for purchasing generation equipment and its subsequent maintenance, this option is the best in terms of power supply with varied power consumption or hydroturbine water consumption.

5. Conclusions

Application of mining enterprises' drainage systems with hydroturbine-based mini-PSHPPs of various capacity to producing additional power enables increasing efficiency of power supply to consumers by reducing the cost of purchasing power from external grids. This also reduces the cost of final products and increases their competitiveness.

However, in order to provide the proper level of power generation, it is necessary to maintain intensity of the water flow passing through the hydroturbine above a certain limit. Also, when the installed capacity of consumers of a production facility increases, efficiency of the combined power supply system decreases because of the shortage of power generated by a storage pump. Therefore, feasibility of using mini-PSHPPs should be specified in each case.

Analysis of different designs of mine power supply systems, in particular installation of one or two hydroturbines on the 500 m level and four hydroturbines (two and two) on the 500m and 940m levels of Rodina mine of the JSC Kryvbaszalizrudkom reveals that mini-PSHPPs are efficient when generated capacity is close to the installed capacity of consumers. Application of different criteria to determining the most efficient design of the power supply system indicates opposite results. For example, in terms of power costs, the distributed generation system with a single hydroturbine installed on the 500m level is the most effective option.

In this case, the reduced power cost exceeds the current tariff for almost all the considered operating conditions, except for cases with very low water consumption via a storage pump. This is due to the optimal ratio between investments in the purchase of mini-PSHPP equipment, the cost of its maintenance and scheduled repairs and, on the other hand, the level of coverage of consumer needs in generated power. The system with mini-PSHPPs (four storage pumps on the 500m and 940m levels) appears to be the best option for the peak tariff as it reveals the lowest value of the NPV in conditions close to nominal and the highest application area.

However, the analysis of the NPV indicates that under conditions close to nominal, the use of mini-PSHPPs with a single hydroturbine has the highest reduced cost due to low generation, thus making it inexpedient to use compared to other designs.

With the basic tariff, it is advisable to use the distributed generation system with only two storage pumps installed on the 500m level as it has the highest efficiency among all studied designs.

Thus, the greatest economic effect can be achieved by introducing the mini-PSHPP system consisting of four hydroturbines, two of which are used during the basic tariff hours and when the peak tariff is used, all units are involved. Such balancing should be introduced by means of the power supply control system of mine consumers [23].

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